Effect of suction on flow characteristics and sediment transport in closed-conduit flows

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**EFFECT OF SUCTION ON FLOW
CHARACTERISTICS AND SEDIMENT
TRANSPORT IN CLOSED-CONDUIT
FLOWS**

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SCHOOL OF CIVIL & ENVIRONMENTAL ENGINEERING

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EFFECT OF SUCTION ON FLOW CHARACTERISTICS AND SEDIMENT TRANSPORT IN CLOSED-CONDUIT FLOWS

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SUMMARY

Suction effects on the flow behaviour and sediment transport have many practical applications. For example, suction has been reported to have an influence on bed erosion and deposition in a fluvial system. Another application of the phenomenon is membrane fouling, which involves foulant transport in closed-conduit flow subjected to suction.

A careful literature review shows that many studies have been conducted to study suction effects on flow and sediment transport in open channel flow while only a few of them are carried out in closed-conduit flow. Even in open channel flows, the conclusions drawn from the previous studies fall into two groups: one group believes that suction increases sediment transport rate while the other holds the exactly opposite viewpoint. The discrepancy between these two groups may be due to the fact that the water depth varies in open channel flow and this change may lead to uncertainty whether the mean streamwise velocity increases or decreases due to suction. Consequently, to clarify whether this uncertainty leads to the discrepancy of conclusions from previous studies in open channel flows, the present study is conducted to investigate the effect of suction on flow behaviour and sediment transport in closed-conduit flows subjected to suction, in which the water depth is always a constant.

First of all, suction effects on sediment transport for a coarse sand particle with a medium diameter, $d_{50} = 0.84$ mm in closed-conduit flows are experimentally investigated. The results show that the bedload transport rate generally increases with suction rate (with a constant undisturbed oncoming flow rate, Q_0). More specifically, the data reveal that the sediment transport rate essentially remains unchanged at lower values of suction rate, Q_s before increasing abruptly beyond a threshold. To account for this behavior, a conceptual model with consideration of the near-bed vertical and horizontal forces is presented. The model hypothesizes that (1) the bed particle experiences an additional downward vertical drag force induced by suction; and (2) increasing suction will lead to larger horizontal and vertical near-bed velocities, which enhances both the driving force and effective

weight of the particle. To qualitatively examine how suction affects the near-bed flow behaviour, the FLUENT model was used to simulate the physical system and the results confirm that the near-bed velocities increase with suction.

Second, to further examine how suction affects the flow characteristics in a closed conduit, Particle Image Velocimetry (PIV) is used to measure the flow behaviours, including the time-averaged flow field, turbulence, shear stress, etc. In addition, a modified log law is theoretically derived to fit the experimental data. Moreover, turbulent energy budget is conducted. The changes of the flow behaviour in the near-bed region in the presence of suction are as follows: (1) the streamwise velocity profile with suction deviates significantly from the universal log law, but fits the modified log law well; (2) the turbulence and Reynolds shear stress generally decreases with suction intensity, I_s before marginally increasing beyond a turning point. The possible reason of the turning point is discussed. (3) the variation of stream wise velocity, u with horizontal distance from the leading edge of the suction zone, x (with a constant $I_s = V_s/U_0$, V_s and U_0 are the suction velocity and undisturbed mean stream wise velocity, respectively) is generally similar to that of u with I_s (with a constant x) and its reason is discussed. (4) the turbulent energy budget shows that the stream wise flux of energy is transported upstream and the vertical flux of energy is transported in the upward direction.

Moreover, laboratory experiments were conducted to explore how the suction zone length and sediment size affect the sediment transport rate in closed-conduit flows. The experimental results show that the suction zone length, like suction intensity in the form of V_s/U_0 , also influences the sediment transport rate. Within a certain range of Q_s/Q_0 , the sediment transport rate increases with increasingly larger suction zone length for the same V_s/U_0 . Combining the effect of V_s/U_0 and suction zone length, the study shows that suction intensities in the form of Q_s/Q_0 is a superior variable to use in the analysis of sediment transport rate. Moreover, a new modified Froude number Ω_{Q_s} involving the effect of Q_s rather than V_s , is developed and the comparison of the data in the present study and that by Liu (2010) verifies the hypothesis that Q_s/Q_0 is better correlated to q_b than V_s/U_0 .

Finally, experiments are conducted to investigate the size effect on sediment transport rate in a closed conduit with suction. The data show that suction can increase the sediment transport rate for sand particles with $d_{50} = 0.39$ and 0.8 mm.

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LIST OF SYMBOLS

A	=	cross area of the conduit
A_s	=	area of suction zone
B	=	roughness function, which is taken as 8.5 for a completely rough flow
C_D	=	drag coefficient
C_L	=	lift coefficient
D	=	diameter of a spherical solitary sediment particle which rests over three closely packed spherical particles of identical diameter d in Dey and Zanke (2004)'s model
D_H	=	hydraulic diameter, $= \frac{4A}{P}$
d	=	diameter of particle in the suction zone
d_{16}	=	particle size for which 16% are finer by weight
d_{35}	=	particle size for which 35% are finer by weight
d_{50}	=	median size of sediment particles
d_{84}	=	particle size for which 84% are finer by weight
d_A	=	area of each grid element, $= \Delta x \times \Delta y$, where are the length and width of the grid element in vector field, respectively
d_s	=	maximum average scour depth over the suction zone
E_D	=	normalized turbulent dissipation, $= \frac{15\nu}{u^2} \left(\frac{\partial u'}{\partial t} \right)^2 \times h / u_*^3$

f	=	Darcy-Weisbach friction factor
F_D	=	total drag force, $= C_D(\pi d^2 / 8)\rho u_b^2$ when there is no suction or $= C_D(\pi d^2 / 8)\rho(u_b^2 + v_b^2)$ in the presence of suction
F_{Dh}	=	drag force in the horizontal direction
F_{Dv}	=	drag force in the vertical direction
F_i	=	injection force, $= (i\rho\pi d^3 / 6(1 - \varepsilon))$
F_{ku}	=	streamwise turbulent kinetic energy, $= \frac{0.75 \times (\overline{u'u'u'} + \overline{u'v'v'})}{u_*^3}$
F_{kv}	=	vertical turbulent kinetic energy, $= \frac{0.75 \times (\overline{v'v'v'} + \overline{v'u'u'})}{u_*^3}$
F_L	=	lift force, $= C_L(\pi d^2 / 8)\rho u_b^2$ when there is no suction, or $= C_L(\pi d^2 / 8)\rho(u_b^2 + v_b^2)$ when there is suction
F_{Lh}	=	drag force in the horizontal direction
F_{Lv}	=	drag force in the vertical direction
F_r	=	resistive force
F_s	=	seepage force, $= i\rho\pi d^3 / 6(1 - n)$
g	=	gravitational acceleration, $= 9.81 \text{ m}^2/\text{s}$
h	=	water depth
i	=	seepage hydraulic gradient
i_c	=	critical hydraulic gradient for a horizontal bed, which symbolizes the “boiling condition”

I_s	=	suction intensity, $= V_s/U_0$
k_s	=	a parameter used to calculate y_0 , can be taken as $2d_{50}$, which is the median diameter of sediment particles
K	=	coefficient of permeability
K_r	=	the roughness parameter
l	=	mixing length, $= \kappa y$
L	=	length of the seepage zone
M_0	=	the approach flow momentum without suction, $= \rho \times Q_0 \times U_0 = \rho \times U_0^2 \times bh$
M_0'	=	the approach flow momentum with suction, $= \rho \times Q_0' \times U_0' = \rho \times U_0'^2 \times bh$
M_t	=	momentum transfer across the sand bed, $= \rho \times V_s^2 \times Lh$
n	=	porosity of the sand particles
n_0	=	the number of particles transported per unit width per unit time
P	=	wetted perimeter, = perimeter of the cross section for the closed conduit used in the present study
P_D	=	normalized pressure energy diffusion, $= T_p - E_D - T_D$
q	=	flux of each grid element, $= \left \partial u / \partial x + \partial v / \partial y \right dA$
q_b	=	volumetric bedload transport rate per unit width
q_{bo}	=	sediment transport rate under zero seepage
q_{bs}	=	sediment transport rate per unit width with seepage
Q_0	=	main flow rate

Q_0'	=	effective approach flow rate, $= Q_0 - V_s.L.b$
Q_c	=	critical flow rate needed for bed sediment entrainment
Q_s	=	suction flow rate
R	=	Reynolds number, $= U_0.D_H/\nu$
R_p	=	particle Reynolds number, $= V_b.D_H/\nu$
S_s	=	specific gravity of sand particle
t	=	time
T_D	=	normalized turbulent energy diffusion, $= \partial F_{kv} / \partial y \times h$
T_P	=	normalized turbulent production, $= \overline{-u'v'}(\partial u / \partial y) \times h / u_*^3$
u	=	instantaneous velocity in the x axis
u'	=	turbulent velocity fluctuation in the x axis
u_b	=	approach horizontal velocity acting on particles at the bed
u_{b0}	=	approach horizontal velocity acting on particles at the bed without suction
u_{bs}	=	approach horizontal velocity acting on particles at the bed with suction
u_s	=	slip velocity at the interface
u_*	=	the friction velocity, $= \sqrt{\tau_b / \rho}$
u_{*c}	=	critical shear velocity with suction
u_{*0c}	=	critical shear velocity without suction

u_{*0}	=	local shear velocity without suction
u_{*s}	=	local shear velocity with suction
u^+	=	dimensionless root mean square of streamwise turbulent fluctuation, $=(\overline{u'u'})^{0.5} / u_*$
uv^+	=	dimensionless shear stress, $= -\overline{u'v'} / u_*^2$
U	=	mean flow velocity with seepage
U_0	=	depth-averaged velocity at the leading section of the seepage zone
U_{ro}	=	velocity at a reference depth without seepage
U_{rs}	=	velocity at a reference depth with seepage
U_{ox}	=	velocity at the bed at horizontal location x from the beginning of suction zone
v	=	instantaneous velocity in the y direction
v_b	=	approach vertical velocity acting on particles at the bed
v'	=	turbulent velocity fluctuation in the y axis
V_b	=	resultant velocity of u_b and v_b , $=\sqrt{u_b^2 + v_b^2}$
V_i	=	injection velocity
V_{cr}	=	critical injection velocity
V_s	=	seepage velocity or suction velocity, $= Q_s/A_s$
v^+	=	$(\overline{v'v'})^{0.5} / u_*$, dimensionless root mean square of vertical turbulent fluctuation
W	=	submerged particle weight, $= (\rho_s - \rho)g(\pi d^3 / 6)$

W'	=	the effective weight of the sand particle, $= W+F_{Dv}$
x	=	coordinates tangential to the bottom boundary or horizontal distance from the leading edge of the suction zone
y	=	coordinates normal to the bottom boundary or vertical distance from the bottom boundary
y_a	=	the position at which the sublayer equation intersects the law of the wall equation
y_0	=	zero-velocity displacement measured from the theoretical bed surface
β	=	bed slope
ϕ	=	angle of internal friction at the incipient motion
δ	=	boundary layer thickness
η	=	calibration factor or ratio between the resistive and the driving forces, F_r and $(F_{Dh}+F_{Lh})$
η'	=	force ratio with suction and that without a prime refers to that without suction
K	=	von Karman constant
ν	=	kinematic viscosity
θ	=	angle between u_b and V_b
ρ	=	mass density of fluid
ρ_b	=	bulk density
ρ_s	=	density of particle

$$\sigma_g = \text{geometric standard deviation, } = \sqrt{\frac{d_{84}}{d_{16}}}$$

$$\tau = \text{shear stress}$$

$$\tau_b = \text{boundary shear stress}$$

$$\tau_{bo} = \text{bed shear stresses without seepage}$$

$$\tau_{bs} = \text{shear stresses with seepage}$$

$$\tau_{*cs} = \text{critical shear stress with seepage}$$

$$\tau_{*0} = \text{Shields' parameter without seepage, } \tau_{*0} = \frac{u_{*0}^2}{(S_s - 1)d_{50}g}$$

$$\tau_{*0c} = \text{critical Shields' parameter without seepage}$$

$$\Phi = \text{Einstein's parameter with seepage, } = \frac{q_b}{\sqrt{(S_s - 1)gd^3}}$$

$$\Phi_0 = \text{Einstein's parameter without seepage}$$

$$\Omega_{Q_s} = \frac{U_0^2}{\left[(S_s - 1)(1 - n) - \frac{V_s}{K} \cdot \frac{L}{h} \right] d_{50}g}, \text{ a new modified Froude number based on } Q_s$$

$$\Omega_{V_s} = \frac{U_0^2}{\left[(S_s - 1)(1 - n) - \frac{V_s}{K} \right] d_{50}g}, \text{ a new modified Froude number based on } V_s$$

$$\Omega_0 = \frac{U_0^2}{(S_s - 1)(1 - n)d_{50}g}, \text{ Froude number in the absence of seepage}$$

Chapter 1

Introduction

1.1 BACKGROUND

Sediment transport, which is the movement of solid particles, is a very important process that can influence the daily life of human being. In natural rivers or streams, imbalance of sediment transport rate may lead to scour that can cause failure of banks or hydraulic structures such as bridge piers or abutments or undesirable sediment deposition that can result in blockage of the waterway.

Due to its importance, understanding the rate of sediment transport has been widely studied by previous researchers. Since Du Boys (1879) first published his bedload formula more than a century ago, much research has been devoted to the study not only on bed but also suspended sediment transport and many formulae have been proposed to predict sediment transport rates in steady, uniform conditions. With

these extensive research works in the intervening years, engineers can now predict sediment transport rate reasonably accurately in a quasi-steady, quasi-uniform rectilinear flow. Notwithstanding this, accurate or even reasonably accurate prediction of sediment transport rate in a large variety of flow conditions that do not conform to this limited condition still remains a challenge.

One of the flow conditions that render many published formulae for predicting sediment transport rate inaccurate is the presence of seepage flow in some natural situations, which is defined as a flow across a permeable boundary. Seepage can either be in the form of injection (seepage flow through a channel in the upward direction) or suction (seepage flow through a channel in the downward direction). As injection and suction can induce mass and momentum transfer across the interface between the fluid and permeable boundary, they may have a significant influence on the flow behavior and sediment transport rate. Notwithstanding the obvious correlation between seepage, the flow field and sediment transport, published literature to-date still cannot arrive at a consensus in describing their inter-dependent relationships (Engelund and Hansen, 1967; Oldenziel and Brink, 1974; Richardson et al., 1985; Cheng, 1997; Rao and Sitaram, 1999; Lu and Chiew, 2007; Liu, 2010; Liu and Chiew, 2012; Cao and Chiew, 2014; Cao et al., 2014). Because the present research topic focuses on suction effects, more of the discussions are related to suction in the thesis. A careful search of the literature reveals that two opposing conclusions can be found on suction effects on sediment transport. The first group of researchers (e.g., Oldenziel and Brink 1974, Francalanci et al. 2008) concludes that suction reduces the sediment transport rate, while Willetts and Drossos (1975), Lu and Chiew (2007), Liu and Chiew (2012) and Cao and Chiew (2014), amongst others, arrive at an opposite conclusion.

Because sediment transport is closely related to the characteristics of flow adjacent to the sediment bed, it is necessary to investigate the near-bed flow behavior and sediment transport together and correlate them with each other. Many researchers (Maclean, 1991a; Chen and Chiew, 2004; Dey and Nath, 2010; etc) have conducted experiments to investigate suction effects on the flow characteristics in open channel flow. Amongst them, Dey and Nath (2010) experimentally measured the

velocity and turbulence in open channel flow with seepage. In their experiments, they observed the water depth changes when injection or suction is introduced. They further commented that it was extremely difficult to experimentally adjust the water depth in the presence of seepage to be the same as that without. In order to eliminate the effect of flow depth, the present study is conducted in a closed conduit in which the flow depth, or more appropriately, the flow cross-sectional area remains constant regardless of the amount of flow abstraction caused by suction. With this approach, one can better examine suction effects on the flow behaviour and sediment transport rate and further attempt to clarify the discrepancy highlighted above. Few studies have been reported on suction effects on the flow characteristics in closed-conduit flows. Although some researchers (e.g., Elena et al. 1977, Schildknecht et al. 1979, So and Yoo 1987) have studied suction effects on the flow behavior in a closed conduit experimentally and numerically, they did not consider its influence on sediment transport rate. In addition to eliminating the effect of varying water depth in open channel flows, the study of suction effects on the flow and sediment transport rate in closed conduit flows can also find its applications in ice-covered channel in cold regions, as well as membrane science because flow in a cross-flow membrane system resembles that in closed-conduit flows with suction in many ways.

In summary, suction effects on sediment transport by directly measuring the bed load transport rate in a pipe subjected to suction has rarely been reported in the literature. Moreover, although some researchers have measured suction effects on flow behavior in open channel flows, few have measured flow characteristics in the very near-bed region in a closed conduit subjected to suction. To this end, the objective of this research is to study suction effects flow characteristics in the very near-bed region and its effect on sediment transport rate in a closed conduit by using direct measurement methods.

In the study, direct experimental measurement of suction effects on sediment transport rate have been carried out. Both CFD simulations using ANSYS FLUENT and physical measurements of the near-bed flow field using Particle Image Velocimetry have been conducted in closed-conduit flows.

1.2 LAYOUT OF THE THESIS

In Chapter 1, the background including the research development of the research topic and motivation of the study is briefly introduced and the layout of the thesis is presented.

Chapter 2 is a literature review that highlights previous studies on suction effect on the hydrodynamics and sediment transport rate in both open channel and closed-conduit flows.

Chapter 3 describes the experimental apparatus, methodologies for the measurement of the hydraulic parameters and the procedures for the collection of both the flow and sediment transport data in the study.

Chapter 4 presents the experimental results of suction effect on sediment transport in a closed-conduit flow, followed by a conceptual model and CFD simulations of the suction effect on flow characteristics in a closed-conduit flow in an attempt to explain the cause of suction effect on sediment transport rate.

In chapter 5, experimental measurement results of suction effects on flow characteristics in closed-conduit flows are presented. Suction effects on the averaged flow, turbulence and turbulent energy budget are described and discussed.

Chapter 6 is devoted to the analysis of some special issues in the study, including suction zone length effects, injection effects and suction effects for both coarse and fine sand particles.

Chapter 7 contains conclusions and recommendations of this study.

Chapter 2

Literature Review

2.1 INTRODUCTION

Seepage is not an uncommon occurrence in both nature and engineering practice. One example is in a natural stream, where a permeable bed comprising sand particles is present. Seepage flow would occur when the flow depth of the stream is higher or lower than the adjoining ground water table. Another example would be in a membrane module, where some portion of the feed water flowing over the membrane surface seeps through the membrane, thus forming seepage flow. Based on different seepage direction relative to the permeable interface, two typical types of seepage are commonly encountered in nature. One is parallel seepage, in which the seepage direction is tangential to the permeable boundary. The other is normal seepage, which means that the seepage direction is perpendicular to the permeable

wall. Normal seepage can be further divided into suction (water flow perpendicularly out of the main flow) or injection (water flow perpendicularly into the main flow), as shown in Fig. 2.1. Both injection and suction through the bed of an open channel or closed channel have an appreciable effect on the flow field and sediment transport, which will be discussed later. As the present study focuses on the effect of suction, most of the documents reviewed in this chapter are related to suction.

Figure 2.1 Sketches of Injection and Suction Definition

In this chapter, previous investigations of suction effects on hydrodynamics and sediment transport in both open channel and closed-conduit flows are presented. Moreover, applications of study of suction effects in a closed conduit are also reviewed.

2.2 SUCTION EFFECTS ON HYDRODYNAMICS AND SEDIMENT TRANSPORT IN OPEN CHANNEL FLOWS

Suction effects on hydrodynamics and sediment transport in open channel flows have been studied and reported by many researchers. Some researchers have already

given good reviews on some issues of this topic, e.g., Lu et al. (2008) and Dey et al. (2011), etc. However, due to other recent developments on the research topic, published documents are reviewed separately in more detail in this section.

2.2.1 Velocity Distributions

For a 2-dimensional flow over a horizontal impermeable bed, the velocity profile may be described by the famous law of the wall (Yalin, 1977):

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{y}{y_0} \quad (2.1)$$

where u is the stream wise velocity; $u_* = \sqrt{\tau_b / \rho}$, the friction velocity; τ_b is the boundary shear stress; ρ is the mass density of fluid; κ is the von Karman constant and y_0 is the zero-velocity displacement measured from the theoretical bed surface. y_0 can be calculated as:

$$y_0 = k_s \exp(-\kappa B) \quad (2.2)$$

where k_s may be taken as $2d_{50}$, and d_{50} is the median diameter of the sediment particles. B is the roughness function, which can be taken as 8.5 for a complete rough flow (Raudkivi, 1990).

Even when there is no seepage (here “seepage” means that the flow not only can penetrate across the boundary, but also seep out of the bed through the porous media), the velocity profiles over non-permeable and permeable boundaries could be significantly different. Many previous researchers (Manes et al., 2009; Manes et al., 2011; Pokrajac et al., 2007; Pokrajac and Manes, 2008 and 2009; etc) have inferred that porous interface may significantly change the flow above it. Pokrajac and Manes (2009) believed that there is a transition zone, whose lower boundary is defined as the depth where water above the porous zone can penetrate and they surmised that the porosity of the porous sand zone will significantly influence the flow behavior, especially near the fluid-solid interface region. Pokrajac and Manes (2009) experimentally measured the velocities over boundaries consisting of one-

layer and five-layer glass beads and found that the u profile in the latter case is more uniform than the former case.

In the presence of seepage, water penetrates through the entire depth of the porous zone and it can be imagined that this can cause even greater influence on flow than the permeable boundary without seepage. Many researchers have developed modified equations to describe the velocity profile on the basis of the abovementioned law of the wall. A summary of previous studies on the modified log law in flow with seepage are listed in Table 2.1. Clarke et al. (1955) and Stevenson (1963) developed a modified law of the wall with bed injection which was later verified by the data of experiment conducted by Verollet et al. (1977).

Almost all the modified laws of the wall in Table 2.1 are based on Prandtl's mixing length theory,

$$\frac{\tau}{\rho} = l^2 \left(\frac{du}{dy} \right)^2 \quad (2.3)$$

where l is the mixing length and $l = \kappa y$, where κ = von Karman constant.

For a 2-dimensional flow, the continuity equation and the streamwise momentum equation on a horizontal bed are as follows,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (2.4)$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{1}{\rho} \frac{\partial \tau}{\partial y} \quad (2.5)$$

Most of the previous studies assume that the pressure gradient and the variation of u with x in equation (2.5) are negligible as they cannot induce significant flow acceleration.

By assuming and integrating $\frac{\partial v}{\partial y} = 0$, $v = V_s$, equation (2.5) may be simplified as,

$$V_s \frac{du}{dy} = \frac{1}{\rho} \frac{d\tau}{dy} \quad (2.6)$$

Table 2.1 Summarized Studies on Modified Log Law in the Presence of Seepage

<i>Past researchers</i>	<i>S or I</i>	<i>O or C</i>	<i>Equations used</i>
Kay (1948)	S	O	$\frac{u}{U_0} = 1 - \frac{1}{\kappa^2} \frac{V_s}{U_0} \ln\left(\frac{y}{\delta}\right)$, δ is the thickness of the boundary layer
Clarke et al. (1955)	I	O	$\frac{u}{u_*} = a_0 + b_0 \ln \frac{u_* y}{\nu} + \frac{V_s}{4k^2 u_*} \left(\ln \frac{u_* y}{\nu}\right)^2$, a_0 and b_0 are two arbitrary coefficients
Stevenson (1963)	S & I	O	$\frac{2u_*}{V_s} \left[\left(\frac{V_s u}{u_*^2} + 1 \right)^{1/2} - 1 \right] = \frac{1}{\kappa} \ln \frac{y u_*}{\nu} - \left(c + \frac{2u_*}{V_s} \right)$ $c = \frac{1}{\kappa} \ln \frac{y_a u_*}{\nu} - \frac{2u_*}{V_s} \left(\frac{V_s u}{u_*^2} + 1 \right)^{1/2}$, where y_a is the position at which the sublayer equation intersects the law of the wall equation
Nezu (1977)	S & I	O	$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{y + y_0}{y_0} + \frac{u_s}{u_*}$
Raupach et al. (1991)	S	O	$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{y + y_0}{K_r}$, K_r is the roughness parameter
Cheng and Chiew (1999)	I	O	$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{y}{y_0} + \frac{V_s}{4u_*} \left(\frac{1}{\kappa} \ln \frac{y}{y_0} \right)^2$
Chen and Chiew (2004)	S	O	$\frac{u - u_s}{u_*} = \frac{1}{\kappa} \ln \frac{y + y_0}{y_0} + \frac{V_s}{4u_*} \left(\frac{1}{\kappa} \ln \frac{y + y_0}{y_0} \right)^2$

Note: S and I denote suction and injection, respectively; O and C denote open channel and closed-conduit flows, respectively.

Equation (2.6) is the same equation used in the derivations by Stevenson (1963), Cheng and Chiew (1999) and Chen and Chiew (2004). All of them have integrated Eq. (2.6), although using different boundary conditions. Stevenson (1963) integrated equation (2.6) using the boundary conditions $y = 0$ to $y = y$; $u = 0$ to $u = u$ and $\tau = \tau_b$ to $\tau = \tau$; Contrary to Stevenson (1963), Cheng and Chiew (1999) assumed that the distance at which $u = 0$, y_0 is elevated in the presence of upward seepage and used the boundary conditions $y = y_0$ to $y = y$; $u = 0$ to $u = u$ and $\tau = \tau_b$ to $\tau = \tau$.

Contrary to Stevenson (1963) and Cheng and Chiew (1999) and with reference to Nezu (1977) and Mendoza and Zhou (1992), Chen and Chiew (2004) postulated that there is a slip velocity, u_s in the presence of suction, and used the boundary conditions $y = 0$ to $y = y$; $u = u_s$ to $u = u$ and $\tau = \tau_b$ to $\tau = \tau$. Consequently, integration of equation (2.6) from $y = 0$ to $y = y$ leads to,

$$\tau = \tau_b + \rho V_s (u - u_s) \quad (2.7)$$

Note that Chen and Chiew (2004) have postulated the presence of a virtual layer under the bed surface (from $y = -y_0$ to $y = 0$) as having the same features as that above the bed surface and they modified the mixing length, $l = \kappa(y + y_0)$. By using the same hypothesis as that in Chen and Chiew (2004) and combining equation (2.3), the following equation can be obtained,

$$\frac{u - u_s}{u_*} = \frac{1}{\kappa} \ln \frac{y + y_0}{y_0} + \frac{V_s}{4u_*} \left(\frac{1}{\kappa} \ln \frac{y + y_0}{y_0} \right)^2 \quad (2.8)$$

where y_0 , u_* and u_s are measured experimentally. The authors used Laser Doppler Anemometry (LDA) to measure the streamwise velocity profiles in a 32 m length open channel with 2 m length suction zone and reported that the data can be described by using Eq. 2.8. The results confirmed the existence of the slip velocity and a significant increase in the near bed velocity. The streamwise velocity profile

for $I_s = |v_s/U_0| = 1.53\%$ at different locations x (x denotes the horizontal distance downstream from the leading edge of the suction zone) in the seepage zone is shown in Fig. 2.2, where U_0 is the depth-averaged velocity at the leading section of the seepage zone. This result shows good consistency with that obtained by Maclean (1991a), revealing an increase in flow velocity close to the bed and a reduced flow velocity near the free surface.

Figure 2.2 Streamwise Variation of Velocity Profiles (Chen and Chiew, 2004)

Faruque (2009) conducted experiments in an open channel flume with length = 9 m (cross-section = 1100 mm × 920 mm) and a suction zone of 2.4 m length to study seepage effects on the velocity distribution, turbulence distribution etc. The results, which are similar to those of Chen and Chiew (2004) and Maclean (1991a), show that suction leads to an increase of the streamwise velocity near the bed and a reduction near the surface, which makes the velocity more uniformly distributed.

2.2.2 Turbulence

Literature review shows that previous researchers have not been in complete agreement on how suction affects the turbulence intensities.

Watters and Rao (1971) studied the fluid dynamic forces acting on a typical bed particle and reported that suction decreases the turbulent fluctuations in the flow field resulting in less momentum exchange between fluid particles. An extreme case in their study was that the flow status in the boundary layer changes from a turbulent to laminar condition with very strong suction.

Nezu (1977) measured all three components of turbulence intensities, which also showed that suction reduces turbulence intensities.

By measuring the velocity profiles using a hot film anemometer on a plane and non-transporting bed for both suction and injection, Rao and Sitaram (1999) found qualitatively that turbulence become stronger in the presence of suction compared with that without suction. This result is contrary to those by Cheng (1997) and Nezu (1977).

Chen and Chiew (2007) experimentally measured the horizontal and vertical turbulence intensities in the same setup as that in Chen and Chiew (2004) at $x = -10$ cm where the flow is not subjected to suction and eight locations in the suction zone. Fig. 2.3 presents the horizontal turbulence intensities at the nine different locations along the flow direction based on Chen and Chiew (2007)'s experimental data. It may be inferred from Fig. 2.3 that the turbulence with suction are generally less than that without, indicating that suction tends to reduce turbulence. The reducing effects are more apparent in the near-bed region, which can be seen from both the experimental and simulated results. Dey and Nath (2010) used Acoustic Doppler Vetrino to measure the turbulence characteristics in open channel flow with small suction rates and they made similar observations as Chen and Chiew (2007).

Figure 2.3 Vertical Variation of Turbulence Intensities for Flow along Suction Zone (Chen and Chiew, 2007)

From the above, most researchers believed that suction decreases the turbulence except for Rao and Sitaram (1999). However, the reason of how seepage modifies the turbulence structure still remains uncertain. Some researchers believed that suction caused a reduction of the turbulent kinetic energy production rate and damping of the turbulent energy diffusion, leading to reduced turbulence intensities. Seepage may also result in significant near-bed turbulence anisotropy, which plays an important role in turbulence production. Such a modification has been investigated largely by direct numerical simulation (e.g. Antonia et al., 1994; Park and Choi, 1999; Chung and Sung, 2001; Chung et al., 2002). The results show that the near-bed anisotropy was enhanced in the presence of suction, but may not be affected significantly by injection. Some experimental evidences in this aspect can be found in Antonia et al. (1988), Krogstad and Kourakin (2000), Oyewola et al. (2004). More recently, Dey and Nath (2010) evaluated the turbulent energy budget in the presence of suction and compare it with that without. However, probably due to the small suction rates that they employed, the suction effects on the level of anisotropy were not apparent.

Faruque (2009) experimentally found that both the streamwise and vertical turbulence intensities are reduced by the introduction of higher suction rates.

2.2.3 Bed Shear Stress

Seepage affects the velocity near the bed particles, which changes the bed shear stress.

The bed shear stress, or shear velocity, with the latter being the most fundamental velocity scale for near-bed flow, may be determined by using different methods when there is no seepage. One typical approach is to measure the water surface slope under uniform flow conditions, which can then be used to compute the bed shear stress or shear velocity. The shear velocity may also be determined from measured velocity distributions in conjunction with the logarithmic law, or inferred from the measured Reynolds shear stress distribution. Another approach is to measure the bed shear stress directly with a Preston tube.

Because when suction is present, the permeable wall invalidates both flow uniformity and the no-slip boundary conditions, all the above-mentioned methods do not apply. As a result, many researchers (e.g. Oldenziel and Brink, 1974; Maclean and Willetts, 1986; Maclean, 1991b; Ramakrishna Rao et al., 1994; Cheng and Chiew, 1998; Chen and Chiew, 2004) have developed other approaches to determine bed shear stresses on a permeable boundary and conducted studies to investigate seepage effects on shear stresses.

Maclean (1991b) determined the bed shear stress in the presence of suction by using the same method as described in Maclean and Willetts (1986), i.e., by observation of the threshold condition of motion for indicator grains placed in the suction zone. His results agrees well with those computed using the equation suggested by Willetts and Drossos (1975), which is shown below, with full side-wall correction.

$$\tau_{bs} = \tau_{bo} + \rho U_{ox} V_s \quad (2.9)$$

where U_{ox} = velocity at the bed at a distance x from the beginning of the suction zone.

Maclean (1991b) proposed an alternative approach to relate the bed shear stress to the square of the water velocity at a given reference height above the bed:

$$\frac{\tau_{bs}}{\tau_{bo}} = \left(\frac{U_{rs}}{U_{ro}} \right)^2 \quad (2.10)$$

where U_{rs} and U_{ro} = velocity at a reference depth with and without seepage, respectively. Although Eq. (2.10) fits well with his experimental data, the choice of the reference height was arbitrary, which significantly affects its accuracy. The method was later verified numerically by Prinos (1995) for estimating the bed shear stress in open channel flow with suction.

Cheng (1997) derived the bed shear stresses based on the momentum integral equation, which compares well with the results determined from the measured Reynolds shear stress distribution. Clearly, this approach depends on accuracy of the measured water surface slope in the presence of seepage. Another method

proposed by Cheng and Chiew (1998) for evaluating the bed shear stress is by directly fitting the following integrated modified law to the velocity measurements ($y_0/h \ll 1$).

$$\frac{U}{u_*} = \frac{1}{\kappa} \left(\ln \frac{h}{y_0} - 1 \right) + \frac{V_s}{4\kappa^2 u_*} \left[\ln^2 \frac{h}{y_0} - 2 \left(\ln \frac{h}{y_0} - 1 \right) \right] \quad (2.13)$$

where U = mean flow velocity with seepage.

Figure 2.4 Bed Shear Stress Distribution over Suction Zone (Chen and Chiew, 2004)

An iterative procedure is required to determine the shear velocity by using Eq. (2.13) because y_0 is dependent on B , and thus on the shear velocity. This approach is not subjected to the uncertainty when fitting the modified logarithmic law to the measured velocity profile. Chen and Chiew (2004) used it to calculate the bed shear

stress over a suction zone and found that bed shear stresses increase with suction rates, and presented an empirical equation to calculate shear velocities with suction, u_{*s} , through an immobile bed for given V_s/U_0 and shear velocity without suction, u_{*0} value as follows:

$$\frac{u_{*s}}{u_{*0}} = 0.073 \left| \frac{V_s}{U_0} \right|^3 - 0.44 \left| \frac{V_s}{U_0} \right|^2 + 0.9 \left| \frac{V_s}{U_0} \right| + 1 \quad (2.14)$$

The results are re-plotted in Fig. 2.4.

The figure above shows that the shear stress increases sharply at the beginning of the suction zone and the increment becomes more apparent for higher suction intensity. However, a gradual reduction of bed shear stress has been found towards the middle of the suction zone, followed by a gradual increase to a value which is a bit lower than that of the beginning part towards the end of the suction zone.

Faruque (2009) reported that suction causes a reduction in Reynolds shear stress.

2.2.4 Incipient Motions of Bed Particles

In the presence of seepage, an additional force due to seepage will be exerted on the sediment particles. As a result, the critical shear stress which is defined as the bed shear stress at which the incipient sediment motion occurs will change accordingly. Previous research on seepage effects on critical shear stress have been done by Cheng and Chiew (1999), Rao and Sitaram (1999), Dey and Zanke (2004), Faruque (2009), Liu and Chiew (2012), etc.

Cheng and Chiew (1999) conducted a force analysis for the incipient condition of sediment movement by including an additional seepage force. Fig. 2.5 shows how force balance for a spherical particle on a slope at the threshold condition is considered and the following equation can be derived:

$$\tan \theta = \frac{F_D + W \sin \phi}{W \cos \phi - F_L - F_S} \quad (2.15)$$

where θ is the angle of repose of the sediment particles; ϕ is the bed slope; the submerged particle weight, $W = (\rho_s - \rho)g(\pi d^3 / 6)$; the drag force, $F_D = C_D(\pi d^2 / 8)\rho u_b^2$; the lift force, $F_L = C_L(\pi d^2 / 8)\rho u_b^2$; the seepage force, $F_S = (i\rho\pi d^3 / 6(1-n))$; the drag and lift coefficients, C_D, C_L , respectively; d , the diameter of particle; ρ_s , the density of particle; i , the seepage hydraulic gradient; n , the porosity of the granular materials and u_b , the approach velocity acting on particles at the bed, which may be related to the shear velocity in the following form (Chiew and Parker, 1994):

$$u_b = \frac{u_{*c}}{\sqrt{f_*}} \quad (2.16)$$

Figure 2.5 Forces Acting on a Sphere Resting on the Bed (Cheng and Chiew, 1999)

where f_* is a measure of friction; u_{*c} , the critical shear velocity with seepage. Comparing the situation with and without seepage, u_{*0c} one gets:

$$\left(\frac{u_{*c}}{u_{*0c}}\right)^2 = 1 - \frac{i}{i_c} \quad (2.17)$$

where $i_c = (1-n)(\rho_s - \rho) / \rho$ for a horizontal bed, which symbolizes the “boiling condition”, under which the seepage force acting on a particle just balances its submerged weight force at the inception of motion. Since the hydraulic gradient is related to seepage velocity, Eq. (2.17) can be rewritten as:

$$\left(\frac{u_{*c}}{u_{*0c}}\right)^2 = 1 - \left(\frac{V_s}{v_{cr}}\right)^m \quad (2.18)$$

Figure 2.6 Effect of Seepage Velocity on Critical Shear Velocity (Liu and Chiew, 2012)

where v_{cr} is the critical seepage velocity in a quick state and $m = 1-2$, which depends on the characteristics of sediments. Equation (2.17) or (2.18) shows the relationship between the critical shear velocities with and without injection under incipient motion condition. An increase in the hydraulic gradient or injection velocity results in a reduction of the critical shear velocity and vice-versa. Liu and Chiew (2012) found that equation (2.18) compares well with the experimental data of Cheng and Chiew (1999) and Kavcar and Wright (2009). Their results are replotted in Fig. 2.6.

Figure 2.7 Definition Sketch of the Model in Dey and Zanke (2004): (a) diagrammatic presentation of forces acting on spherical solitary particle under stream flow with upward seepage; (b) top view of solitary particle resting over three closely packed bed particles; and (c) tetrahedron formed joining centers of four particles

Dey and Zanke (2004) presented an analytical model to determine the critical bed shear stress for non-cohesive sediment motion subject to injection on a horizontal bed. In their model, the hydrodynamics of the flow, seepage and micro-mechanical forces acting on a solitary sediment particle resting over the bed under the slip-spinning conditions are analyzed. Moreover, the most stable three-dimensional configuration of a spherical solitary sediment particle of diameter D resting over

three closely packed spherical particles of identical diameter d forming the sedimentary bed in a unidirectional stream flow is simulated. The definition sketch of their model is shown in Fig. 2.7, in which γ = factor; δ = boundary layer thickness; X = horizontal lever arm; Z = vertical lever arm; F_L = lift force; F_D = drag force; and F_S = seepage force.

The model shows that critical shear stress of sand particle decreases with the increase of injection. However, the model compares poorly with the experimental data reported by Cheng and Chiew (1999) as shown in Fig. 2.8.

Figure 2.8 Comparison of Values of τ_{cs}^* Computed Using the Model Derived by Dey and Zanke (2004) and Experimental Data of Cheng and Chiew (1999)

Faruque (2009) carried out experiments and reported that suction reduces the stability of sand particles and argued that the reason is that suction can cause significant increment of near bed velocity than the relative reduction of friction velocity.

In an open channel flume with length = 32 m, width = 0.7 m, and a suction zone of 2 m long, 0.7 m wide located at 16 m downstream of the inlet, Liu (2010) conducted experiments to study seepage effects on bed stability and transport sand particles with medium diameters = 0.48 mm and 0.9 mm. Her results reveal that suction reduces the stability of both sand particles, showing that the sand particles may be entrained by the flow, although they cannot move without suction, when the mean streamwise velocity remains the same.

In summary, both Cheng and Chiew (1999) and Dey and Zanke (2004) infer from their studies that the critical shear velocity decreases with an increase of injection. Liu and Chiew (2012) experimentally found that suction will increase the instability of the two kinds of cohesionless sand particles used in their study.

2.2.5 Sediment Transport

Mass transfer at the interface between water and porous sediments or a permeable wall due to suction is of cardinal importance in sediment transport in an alluvial system. Although numerous investigations have been carried out over the past 40 years on this topic, results from these studies have led to two contradictory conclusions. Some researchers (Oldenziel and Brink, 1974; Francalanci et al., 2008; etc) stated that suction decreases it. However, other researchers (e.g. Maclean, 1991b; Rao and Sitaram, 1999; Lu and Chiew, 2007; Liu, 2010) held an opposite view. Table 2.2 summarizes previous experimental parameters and results of suction effects on sediment transport.

Oldenziel and Brink (1974) applied a suction rate, $Q_s/Q_0 < 3\%$ in an open channel with a permeable bed consisting of uniform sediments with median grain size ranging from 0.13 to 0.57 mm, to experimentally investigate suction effects on the variation of number of particles transported per unit width per unit time, n_o . They reported that n_o increases with larger injection rate and smaller suction rate. Fig. 2.9 shows the relative sediment transport rate with and without seepage $n(V_s)/[n(V_s = 0)]$ as a function of the hydraulic gradient in the sand bed for a constant flow discharge through the channel.

Table 2.2 Summarize Results of Previous Studies

Source	Flume dimensions		d_{50} of sand (mm)	Parameter used for analysis	Sediment transport rate
	Length (m)	Seepage zone (m)			
Oldenziel and Brink (1974)	15	4	0.13, 0.22, 0.38, 0.57	V_s	Decrease
Willets and Drossos (1975)	3.6	0.125	0.73, 1.03, 1.3	Q_s	Increase
Rao and Sitaram (1999)	3.6	2.4	0.32-3	V_s	Increase
O'Donnell et al. (2002)	10	0.36	0.13-0.57	V_s	Little effect
Lu and Chiew (2007)	30	2	0.9, 1.41, 1.64	V_s	Increase
Francalanci et al. (2008)	15	1.1	0.84	Q_s	Decrease
Liu (2010)	32	0.5, 1, 2	0.48, 0.9	V_s	Increase
Rao et al. (2011)	25	16	0.56	V_s	Increase
Liu and Chiew (2012)	32	2	0.48, 0.9	V_s	Increase
Qi et al. (2013)	32	2 suction points	0.48	Q_s	Decrease

Figure 2.9 Sand Transport with Injection and Suction (Oldenzien and Brink, 1974)

In an open channel with length = 3.6 m and width = 76 mm and a short suction zone of length = 125 mm, Willetts and Drossos (1975) applied a suction rate, $Q_s/Q_0 = 5\% \sim 12.5\%$, which is much larger than that used by Oldenzien and Brink (1974), and studied its effect on the sediment transport rate. They found that suction always caused a localized scour hole in the seepage zone and a dune at its downstream end for sand with $d_{50} = 0.73$ mm, 1.03 mm and 1.30 mm, and the size and shape of the scour hole stabilized quickly. It may be inferred from their results that increasing

suction rate leads to higher sediment transport rate, which is contrary to that by Oldenziel and Brink (1974). Moreover, Willetts and Drossos (1975) noticed the different suction zone lengths used by them and Oldenziel and Brink (1974). Based on their observations, they deduced that the sediment transport rate would be expected to decrease slowly with distance downstream in a long uniform suction zone.

Based on his experimental study of suction effects on bed shear stress and scour, Maclean (1991b) concluded that infiltration through a river bed causes local scour. The bed shear stress is directly proportional to the square of a representative near-bed velocity in the channel. As the scour hole developed, the near-bed velocity decreases until the bed shear stress reaches the threshold value and the rate of scour decreases until eventually a stable bedform is formed for a given suction velocity. In addition, he suggested that the net rate of erosion was directly equivalent to the rate at which the particles are eroded from rest, and not merely the difference between the rate of erosion and the rate of deposition.

O'Donnell et al (2002) applied a lower suction rates (80% of the seepage rate to cause liquefaction) and experimentally studied suction effects on the sediment transport rate in an open channel with a short suction zone length = 0.36 m and permeable bed consisting of sand particles with $d_{50} = 0.25$ mm. They found that the effect of suction on the sediment transport rate is marginal.

Lu and Chiew (2007) studied seepage effects on the dimensions of a dune, viz. its height, length and lee-side slope in a horizontal glass-sided flume, which is 30 m long and 0.7 m wide with a 2-m long seepage zone. In the presence of seepage, the critical slope, which is also named the angle of repose of cohesionless material, was found to be related to the ratio of the hydraulic gradient with seepage to its critical value under quick condition, i.e. i/i_c . Moreover, they assumed that the stable lee-side slope of a dune inclines at the critical slope with the same seepage rate when there is seepage. Furthermore, Lu and Chiew (2007) observed that the height and length of the dune were increased when suction is present.

Francalanci et al. (2008) conducted experiments in an open channel with length = 15 m, width = 0.61 m and depth = 0.4 m and a seepage zone of 1.1 m length using sediment particles with $d_{50} = 0.84$ mm in a glass-sided sediment-recirculating, water-feed flume for both seepage and no-seepage conditions. They conducted both experimental and numerical studies on seepage effects on bed load transport rate. Their experimental results measured in the presence of seepage showed that upward seepage (injection) induces scour and downward seepage (suction) causes deposition. It may be inferred from their results that injection and suction increases and decreases bedload transport rate, respectively.

In contrast to the result reported in Francalanci et al. (2008), Liu (2010) conducted experiments in a flume that is 30 m long, 0.7 m wide and 0.6 m deep, with a suction zone of 2 m long, 0.4 m deep, which is located in the middle of the flume. She found that suction increases bed load transport for both sands (0.48 mm and 0.9 mm) through direct measurement of the transported sand. Moreover, she also experimentally studied the effect of suction zone length on the sediment transport rate and found that a larger suction zone length leads to larger sediment transport rate when other parameters remain unchanged. By conducting a force analysis and dimensional analysis, three dimensionless groups, viz. Einstein's parameter (Φ), Shields's parameter without seepage (τ_{*0}) and modified densimetric Froude number (Ω_{V_s}) are selected to examine seepage effects on bed load transport rate. The three variables are defined as follows.

$$\Phi = q_b / \sqrt{d_{50}^3 g (S_s - 1)} \quad (2.19)$$

$$\tau_{*0} = u_*^2 / (S_s - 1) d_{50} g \quad (2.20)$$

$$\Omega_{V_s} = U_0^2 / [(S_s - 1)(1 - n) - V_s / K] d_{50} g \quad (2.21)$$

Fig. 2.10, which shows the results of suction effects on sediment transport rate by Liu (2010) (where Ω_0 is the densimetric Froude number in the absence of suction, Φ_0 is the Einstein's parameter without suction), reveals that as Ω_0 / Ω_{V_s} increases (which means that the suction velocity V_s increases, assuming sand permeability K

remains constant during the injection process), Φ/Φ_0 increases (which means that the volumetric bed load transport rate q_b increases) almost linearly in a semi-log coordinate. It also can be seen that in the case of a higher τ_{*0} (which means that the bed is more stable without seepage), the sediment transport rate increases more quickly as the suction rate increases.

Figure 2.10 Suction Effects on Sediment Transport (Liu, 2010)

However, at least three issues must be noted in the study of Liu (2010). One is that Liu (2010) did not measure seepage effects on the velocity and turbulence so that it is impossible to explain why the sediment transport rate increases with higher suction rates. Another is that Liu (2010) determined the shear velocity by using the empirical equation reported by Chen and Chiew (2004) instead of measuring it, which added some uncertainties to Liu (2010)'s conclusion. Last but not least, although Liu (2010) studied suction zone length effect and found that the effect is

significant, she did not take the length into effect when deriving the dimensionless parameters.

Rao et al. (2011) conducted experiments in a 25 m long open channel with a 15 m long suction zone subjected to uniform suction and a permeable bed consisting of sand particles with $d_{50} = 0.56$ mm. Their data showed that the sediment transport rate increases in the suction zone.

Qi et al. (2013) applied small suction rates ($Q_s/Q_0 < 2\%$) through two holes in an open channel with length = 32 m and inferred from their results that suction reduced sediment transport rate.

In summary, previous investigations on suction effects on sediment transport in open channel flow show that there are two groups of researchers. The first group, viz. Oldenziel and Brink (1974), Francalanci et al. (2008) and Qi et al. (2013) concluded that suction decreases sediment transport rate. On the other hand, Willetts and Drossos (1975), Maclean (1991b), Lu and Chiew (2007), Liu (2010) and Rao et al. (2011) obtained the exactly opposite findings. However, few researchers have studied suction effects on sediment transport rate in closed-conduit flow.

Willetts and Drossos (1975) mentioned that their observations were only valid for a short seepage zone, and agreed that the sediment behaviour might be different in a long zone of uniform suction. Therefore, besides the seepage velocity, the seepage zone length could also affect the sediment transport, which has been verified by Liu (2010)'s experimental data. However, most of the previous researchers only consider seepage velocity and neglect the effect of seepage zone length. Even Liu (2010) did not account for the suction zone length when deriving the dimensionless parameters. It should be noted that although most of the previous researchers used V_s/U_0 as the suction intensity, Q_s/Q_0 may be more appropriate if the effect of suction zone length, L and the water depth, h on sediment transport rate is taken into account as $Q_s/Q_0 = V_s/U_0 \times L/h$.

2.3 SUCTION EFFECTS ON HYDRODYNAMICS AND SEDIMENT TRANSPORT IN CLOSED-CONDUIT FLOWS

In this section, previous studies on suction effects on hydrodynamics and sediment transport in closed-conduit flows are reviewed, followed by applications of suction effects.

2.3.1 Suction Effects on Hydrodynamics and Sediment Transport in Closed-conduit Flows

Wall suction is known to have a significant effect on mass, momentum transfer rates for a pipe flow, which is dealt with in this study. Theoretically, wall suction considerably affects the near wall mean velocities, reduces the turbulence intensity and increases the wall shear stress in the suction region (Sofialidis and Prinos, 1996).

Previous studies regarding the effects of wall suction on both hydrodynamics and particle transport are rarely reported. Experimental studies on the wall suction effects on flow characteristics in a pipe flow have been conducted and reported by a handful of researchers (Weissberg and Berman, 1955; Aggarwal et al., 1973; Brosh and Winograd, 1974; Schildknecht et al., 1979; Elena, 1977; Pei, 2010; etc).

By applying uniform suctions that are less than $I_s = 2\%$ (I_s = suction intensity, = V_s/U_0 , where V_s and U_0 are suction or seepage velocity and depth-average velocity, respectively, $V_s = Q_s/A_s$, Q_s and A_s are suction flow rate and area of the suction zone, respectively) to a closed-conduit flow, Weissberg and Berman (1955) experimentally studied the effect of uniform wall suction on the structure of a fully developed pipe flow for a range of exit Reynolds numbers from 27,000 to 79,000. They found that suction reduces the streamwise turbulence intensity.

Aggarwal et al. (1973) applied uniform wall suction (up to $I_s = 2\%$) to a fully developed turbulent pipe flow for a length of 10 pipe diameters and found the turbulent intensities in the central core decreased at very low suction rates while increased at higher suction rates. However, the absolute value of turbulent fluctuation in the presence of suction was always lower than that without suction.

Schildknecht et al. (1979) performed a more extensive experimental study than Weissberg and Berman (1955) and Aggarwal et al. (1973) because suction rates up to 2.53% were introduced to a fully developed turbulent pipe flow using a $27D$ long porous strip. The results show that suction reduces turbulent intensities and in the meantime change the velocity profile. The near wall flow is accelerated while the core flow is decelerated with increase in suction rate.

Elena et al. (1977) experimentally studied wall suction effects on the flow and heat transfer in a pipe flow for suction rates up to 0.3%. They found that similar to turbulence intensity, the shear stress also decreases with increasing suction rate.

Figure 2.11 Injection Effects on Sediment Transport (Pei, 2010)

Few published literature has reported suction effects on sediment transport rate in closed-conduit flow. Pei (2010) conducted experiments in a water re-circulating closed-conduit to study the effect of injection on the sediment transport rate under

the quick condition. The conduit is 4.8m long, 0.25 m wide and 0.25 m deep, with the sand bed placed downstream with 1m length and 0.25 m width. The injection area is in the middle of the sand bed with length = 0.1m and width = 0.25 m. As shown in Fig. 2.11, Pei (2010) reported that with the increase of the injection, the volumetric bed load transport is almost constant at first and then suddenly shoots up at $V_i/V_{cr} = 10$ (V_{cr} denotes critical injection velocity when the sand is boiling). However, Pei (2010) focused only on injection and did not pay any attention to suction effects on sediment transport.

Numerical studies of suction effects on turbulent pipe flow are scarce. So and Yoo (1987) used a low- R stress turbulence model as well as a low- R k - ϵ turbulence model to simulate the experiment of Weissberg and Berman (1955) and made comparison between the simulated and experimental results. The k - ϵ model overestimated the pressure drop and under predicted the mean velocity in the bulk flow.

2.3.2 Suction Effects in Membrane Science

As described in Chapter 1, the study of suction effects in closed-conduit flows has potential applications in ice-covered channel (Faruque, 2009) as well as membrane science. Because the present study is funded by Singapore Membrane Technology Center, previous studies on suction effects in membrane science are reviewed in more detail.

Because a flat-sheet cross-flow microfiltration membrane system resembles a closed conduit subjected to suction in many ways, many researchers have improved the understanding of the hydrodynamics in a membrane system by investigating the flow in various ducts (slits, tubes and annuli). It should be noted that most of these studies have been conducted to numerically or analytically solve the Navier-Stokes equations of the flow in a closed conduit. Belfort (1985) gave an excellent summary of these studies, which are not reviewed in detail here as our research is mainly focused on experimental investigation.

Belfort (1989) reviewed the development of fluid mechanics in the membrane filtration up to 1989. In his paper, he reviewed different approaches in investigating

the effect of dilute suspensions on membrane fouling. For instance, the inertial lift which balances against suction drag (Altena et al., 1983), shear-induced hydrodynamic diffusion mechanism (Davis and Leighton, 1987), which is verified by Mondor and Moresoli (2000) and electrochemical interactions which may explain the existence of a threshold permeation velocity (Cohen and Probstein, 1986) are presented. Moreover, experimental results of the effect of transmembrane flux on the friction coefficient of a flow inside a porous tube subjected to suction are shown.

Many experiments and numerical simulations are reported on controlling membrane fouling by increasing the turbulence in the flow adjacent to the membrane surface (Willems et al., 2010; Krstić et al., 2002; Krstić et al., 2004; Krstić et al., 2006; Cao et al., 2001;).

Willems et al. (2001) used Particle Image Velocimetry to measure the velocity profiles in spacer filled channels and found the results agree well with that obtained from CFD studies in the literature. Krstić (2002, 2004 and 2006) conducted several studies to investigate the effect of turbulence promoters on cross-flow filtration. Cao et al. (2001) conducted CFD simulation to study the flow around the net-type turbulence promoters in a small channel.

Not many researchers have studied particle transport on the membrane surface. Altmann and Ripperger (1997) investigated particle deposition and layer formation on the surface of cross-flow membrane by using a microscopic model. Schmitz et al. (1993) developed a 2D finite-element model to compute the fluid flow near a membrane surface to study the particle deposition. Huisman and Tragardh (1999) used a model previously developed for calculating the limiting fluxes for cross flow microfiltration of non-interacting particles to study the effects of particle-particle interaction on microfiltration flux. Frey and Schmitz (2000) developed a 3D membrane model to study the behavior of suspended particles at the proximity of the membrane in a cross-flow microfiltration to better understand how the first layer of particle deposit is formed on the membrane surface. More recently, Li et al. (2012) conducted CFD simulation to study initial stages of particle deposition in membrane flow.

Some researchers have measured the velocity profile near the membrane surface (Willems et al., 2010; Gimmelshtein and Semiat, 2005). Others have studied suction effects on the cross flow performances (Velikovska, 2004; Herath et al., 2000).

However, to the best of the author's knowledge, very few published reports have studied suction effects on the flow near the membrane surface and particle transport by directly measuring the transported particles.

2.4 CONCLUDING REMARKS

In summary, the following inferences may be drawn from the review of studies on suction effects on flow and sediment transport in open channel flows,

- (1) The famous law of the wall cannot apply in open channel flows when suction is present. Many researchers (Stevenson, 1963; Nezu, 1977; Chen and Chiew, 2004; etc) have proposed different forms of formula to describe the velocity profile when suction is present.
- (2) Most previous researchers believed that suction reduces turbulence intensities except Rao and Sitaram (1999).
- (3) Different methods to calculate shear stress or shear velocity with suction have been proposed by Willetts and Drossos (1975), Maclean (1991b) and Chen and Chiew (2004), etc.
- (4) Both Cheng and Chiew (1999) and Dey and Zanke (2004) infer from their studies that the critical shear velocity decreases with an increase of injection. Liu and Chiew (2012) experimentally found that suction will increase the instability of the two kinds of cohesionless sand particles used in their study.
- (5) Some researchers (Oldenziel and Brink, 1974; Francalanci et al., 2008; etc) stated that suction decreases sediment transport rate. However, other researchers (e.g. Maclean, 1991b; Rao and Sitaram, 1999; Lu and Chiew, 2007; Liu, 2010) held an opposite view.

Compared with studies in open channel flows, suction effects on flow and sediment transport in closed-conduit flows are much less investigated and the following inferences may be made,

- (1) Most previous experimental studies on suction effects on turbulent pipe flow are focused on suction effects on the flow characteristics.
- (2) Few of studies have been reported on suction effects on sediment transport in a closed conduit. Only Pei (2009) has experimentally investigated injection effects on sediment transport by directly measuring the transported sand particles and she found that injection can significantly increase sediment transport when a large enough injection rate is applied.
- (3) Suction effects on flow and sediment transport in closed-conduit flows may have potential applications in membrane science. Many researchers have studied hydrodynamics of membrane by modelling flow in a closed conduit with suction numerically or experimentally.

Chapter 3

Experimental Apparatus and Measurement Techniques

3.1 INTRODUCTION

This chapter describes the apparatus and measurement techniques used in all the experiments conducted in this study. The experiments comprise three series of tests.

The first was designed to study suction effects on sediment transport rate in closed-conduit flow with uniformly distributed sediments.

In the second series of experiments, suction effects on the flow characteristics, including velocities and turbulence in closed-conduit flow are investigated.

The third series of experiments, the influence of suction zone length on sediment transport in closed-conduit flow is studied.

3.2 EXPERIMENTAL APPARATUS

The experimental apparatus is a closed conduit that is made of glass. The rectangular closed conduit is 9 m long, 0.3 m wide and 0.2 m deep, as shown in Fig. 3.1. The suction zone, in the form of a recess located 5.6 m downstream of the conduit inlet, was filled with sand with length = 0.5 m and width = 0.3 m. Cohesionless sand particles with median grain size, $d_{50} = 0.39, 0.8, 0.84$ mm and geometric standard deviation, $\sigma_g = 1.17\sim 1.48$, were used in the study. The geometric standard deviation, σ_g is defined as $\sqrt{\frac{d_{84}}{d_{16}}}$ in which d_{16} and d_{84} are the

particle size for which 16% and 84% are finer by weight, respectively. A layer of the same sand was glued on top of the false floor (it should be noted here that the water depth is 0.058 m and the false floor depth = 0.142 m in Fig. 3.1, which can be varied to different value) that was placed upstream of the suction zone to ensure uniform roughness. The depth of the sand bed in the suction zone is also 0.142 m in Fig. 3.1, which can be varied to other values corresponding with the false floor.

Figure 3.1 Schematic Drawing of Conduit (Unit: m, not to scale)

It should be noted that sediment feeding is not necessary in this study because there is negligible bed degradation associated with the short duration of each test (15

minutes). Therefore, it makes no significant difference whether sediment feeding is present or not. Additionally, one may argue that scouring may occur at the transition from the rigid bed to movable bed, was discussed in Chen and Chiew (2003). In this study, the concern is generally inconsequential because (1) The bed degradation is negligible even at the transition from the fixed to the movable bed because of the short test duration and low applied shear stress; and (2) The roughness of the fixed and movable bed is the same since the same sediment particles in the suction zone were glued onto the false floor (the fixed bed). As a result, no significant bed degradation is expected, as is verified experimentally.

Furthermore, one may be concerned over the effect of the abrupt widening of the conduit downstream of the suction zone on the flow behavior and sediment transport rate. It must be stated that a common method used to directly measure sediment transport rate is to collect the transported sediment particles by means of building a sand trap sampler (see “Manual Sediment Transport Measurements in Rivers, Estuaries and Coastal Seas”, van Rijn, 2007). Therefore, it is inevitable that a sudden widening downstream of the measured section will be present. As the sand trap not only is located downstream of the suction zone but also below the bed level, the flow is thus only confined to the region between the top of the conduit and the original bed level before arriving at the location of abrupt widening. Hence, it may be assumed that the box has little effect on the flow behaviour and hence the sediment transport rate on the suction zone. Preliminary results from numerical simulations of the closed-conduit flows with and without conduit widening reveal negligible difference between the flow fields.

Last but not least, one may be concerned with the side effect of the conduit, which may lead to the nonuniformity of sediment transport. However, experimental observations had revealed that the degradation in the middle of the conduit is less than one sand-grain layer, as that computed in section 4.2. Consequently, one may surmise that the secondary effect is not significant in the study.

A removable roof or ceiling that was 1.2 m long and 0.3 m wide was installed above the suction zone (see Fig. 3.1) to allow access into the conduit for the preparation and execution of the tests. The roof was secured by means of stainless screws.

Furthermore, holes with diameter = 10 mm were drilled uniformly onto a stainless steel plate, which was placed beneath the sand bed in the suction box. Moreover, a piece of filter cloth was placed between the perforated plate and sand to ensure a uniform suction through the sand bed.

Water was stored in three inter-connected tanks beneath the conduit, with length = 2.5 m, width = 0.6 m and height = 0.6 m. It is re-circulated in the conduit by using a single-phase submersible pump with a maximum flow rate of 8.5 L/s. Both the inlet and outlet of the conduit are in the form of a circular pipe with diameter = 0.1 m (see Fig. 3.1). The flow rate was measured with an electromagnetic flow meter. To avoid the formation of large scale turbulence and to ensure a uniform water distribution in the flow, a “honeycomb” in the form of 117 pipes with diameter = 20 mm and length = 10 cm was installed at the entrance to the conduit. A valve was installed under the suction zone to produce and regulate the suction flow rate Q_s . The suction rate was determined by using a measuring cylinder and stop watch.

A sand collection box or sand trap with length = 0.3 m, width = 0.3 m and depth = 5 cm, which has a movable sliding cover, was installed immediately downstream of the suction zone for collecting the sediment particles that were entrained and transported from the suction zone. A small hole with diameter = 30 mm was drilled on the roof of the conduit through which a stick was used to open and close the sliding cover of the sand trap. To prevent leakages when it is not in need, plasticine was used to fill the hole. At the beginning of each experiment, the sliding cover of the box was closed to prevent sand from falling into it. When it was time to collect the sand, the sliding cover was opened by means of the stick for the collection of the transported sand. After opening the cover, the stick was immediately pulled out so as not to disturb the flow.

3.3 SAND CHARACTERISTICS

3.3.1 Size Distribution

A total of three kinds of sand were used in the study. Fig. 3.2 shows their grain size distributions by plotting the cumulative weight percentage of sand that passes the sieves, in which d_{16} is the grain diameter when 16% of sand passing through the sieves and d_{84} is the grain diameter when 84% of sand passing through the sieves. The median grain size, d_{50} is the grain diameter when 50% of sand passing through the sieves, and the geometric standard deviation, $\sigma_g = (d_{84}/d_{16})^{0.5}$, which reflects the sand is uniformly distributed when it is less than 1.5.

Table 3.1 shows the properties of the sediment particles used in the study, including the result of the sieve analysis.

Figure 3.2 Grain Size Distribution for Samples of the Sand Used

3.3.2 Specific Gravity, S_s

The specific gravity of sand, which is defined as the sand density divided by the density of water, is a very important parameter. In this study, we need to determine the specific gravity S_s for the sediment used in the study for subsequent analyses. A laboratory tool that one may use to evaluate the variable is through the conduct of a permeability test (ASTM, 2006).

Table 3.1 Properties of Sediments Used in the Study

<i>Median Diameter</i> <i>d_{50} (mm)</i>	<i>Geometric</i> <i>Standard</i> <i>Deviation σ_g</i>	<i>Porosity</i> <i>n</i>	<i>Permeability</i> <i>K (cm/s)</i>	<i>Specific</i> <i>Gravity</i> <i>S_s</i>	<i>ρ_b</i> <i>(kg/m³)</i>
0.39	1.48	0.409	0.65	2.66	1.57
0.80	1.15	0.412	2.70	2.66	1.56
0.84	1.17	0.417	2.80	2.66	1.55

Equation 3-1 is used for the S_s calculation.

$$S_s = \frac{M_2 - M_1}{(M_4 - M_1) - (M_3 - M_2)} \quad (3.1)$$

where M_1 is the mass of container; M_2 is the mass of container and sand; M_3 is the mass of container and water with sand inside; M_4 is the mass of container water inside.

The experimental procedure is repeated six times to minimize measurement errors. The specific gravities of three sediments used in the study are shown in Table 3.1.

3.3.3 Bulk Density, ρ_b

Bulk density is a property of powders, granules and other "divided" solids, especially used in reference to mineral components (soil, gravel), etc. It is defined as the mass of many particles of the material divided by the total volume they occupy. The total volume includes particle volume, inter-particle volume and internal pore volume (Buckman and Brady, 1960).

Based on this definition, ρ_b may change as the sand is compacted or loosened. ρ_b is measured mass of the sand particles that are fully filled in a cylindrical container divided by the volume of the container. Due to the significant effect of the experimental procedures on porosity caused by compaction, the same experiments for each kind of sediment particle were repeated three times. The average value of porosity for each sediment sample was used for subsequent analysis. The computed results are tabulated in Table 3.1.

3.3.4 Porosity, n

Porosity is a measure of the void spaces, and is defined as the fraction of the volume of voids over the total space, occupied by sediment particles. It ranges between 0~1 and its magnitude is dependent on how the sand is packed, the shape of particle and uniformity. Loose sand will have a higher porosity.

In this study, the porosity was calculated with equation 3.2. The computed porosities of the three kinds of sand used in the study are tabulated in Table 3.1.

$$n = \frac{\rho_s - \rho_b}{\rho_s} = 1 - \frac{\rho_b}{\rho_s} \quad (3.2)$$

3.3.5 Permeability, K

Permeability K is a parameter that describes how easily the water can go through the sand.

In this study, we need to determine the coefficient of permeability, K for the sediment used in the study for subsequent analyses. A laboratory tool that one may use to evaluate these K is through the conduct of a permeability test (ASTM, 2009). To this end, the standard permeability test based on the method stipulated in ASTM (2009) was conducted with this objective in mind.

According to Darcy's Law:

$$K = V/i \quad (3.3)$$

where i is hydraulic gradient, V is the velocity of water passing through the sand.

K is measured by a typical constant head permeability test. $V = Q/A$, where Q denotes the volume of water passing through the sand per unit time, A is the cross area of the container. $i = h/L$, where h denotes the difference of the water level in the piezometer between top and bottom of the container, L is the distance between the top and bottom of the container.

The same experiments for each type of sediment particles were repeated three times and the average K values of three kinds of sand used are tabulated in Table 3.1.

3.4 MEASUREMENT TECHNIQUES

3.4.1 Measurement of Mean Streamwise Flow Velocity

For the closed-conduit flume, the streamwise flow velocity is calculated using the equation ($U = Q_0/A$), where Q_0 is the flow rate of the main pump which is measured with an electromagnetic flow meter, A is the cross area of the conduit.

3.4.2 Measurement of Mean Seepage Velocity

The suction flow rate Q_s was measured by using measuring cylinder and a stopwatch, and the suction velocities $V_s = Q_s/A_s$, where A_s is the seepage area.

3.4.3 Measurement of Mass of the Transported Sand

The transported wet sand particles are collected, and dried in an oven at 120°C for two hours. Then the dried sand is weighed.

3.4.4 Measurement of Velocity Distribution, Turbulence, Shear Stress, etc

In this study, the streamwise flow characteristics in the near-bed region were measured by using a high speed camera combined with the PIV technique. The PIV measuring system consisted of a 4 W air-cooling laser with wave length = 532 nm as the light source and a high speed camera, as shown in Fig. 3.3. The laser beam emitted from the laser source, which was 1mm thick, was cast downward into the water through the Perspex top of the flume. Aluminum particles having diameter = 10 μm with specific density = 2.7 were used as the seeding particles in the study. Using Stoke's law, the fall velocity of the aluminum particles is computed to be less than 10 $\mu\text{m/s}$, which is much smaller than the flow velocity of interest in this study.

The high speed camera (Olympus, i-speed 3), which has a 2-gigabyte memory storage, 1280×1024 pixel resolution, and 10^5 maximum framing rate, was used to capture images of the particle laden flow. A 105-mm focal lens was mounted with the high speed camera operated at 300 frames per second in the experiments. The images are transformed first by using the Laplacian method (Hsieh, 2008), which can enhance the resolution significantly. After that, velocity fields were determined by cross correlation analyses. Here, a multi-grid processing technique proposed by Hsieh (2008) is adopted to enhance the accuracy of velocity calculation. This multi-

Figure 3.3 Schematic Diagram of Experimental Setup for the Measurements of Velocities: (a) Top View; (b) Side View

grid process, which starts and ends with 32×32 and 8×8 pixels, respectively, uses interrogation windows with 50% overlap in the cross-correlation analysis.

In this study, the laser light source, which was mounted on top of the test section, could be controlled with an accuracy of 0.1 mm along the side wall of the flume. The camera captured the flow field from the glass sidewall. For the measurements of the axial (u) and vertical (v) velocities, the laser light sheet was cast vertically

downward from the Perspex top through the center-line of the conduit, as shown in Fig. 3.3. Both the light source and camera could be moved along and parallel to the sidewall of the conduit so that velocity measurements can be conducted for a suction zone with length = 50 cm, at different x locations (x denotes the horizontal distance from the leading edge of the suction zone). The origin ($y = 0$) is defined as the plain where the horizontal laser beam just passes the bed surface.

Table 3.2 List of Experimental Series

<i>Exp. Series No.</i>	<i>Sub Series No.</i>	<i>Exp. Aim</i>	<i>d_{50} (mm)</i>	<i>Water Depth (m)</i>	<i>u_{*0} (m/s)</i>	<i>Suction zone length (m)</i>
I	1	Main flow on sediment transport	0.84	0.058	0.958	0.5
	2	Suction flow on sediment transport	0.84	0.058	0.958	0.5
II	1	Main flow, Q_0 on flow characteristics	0.80	0.093	0.997	0.5
	2	Suction flow, Q_s on flow characteristics	0.80	0.093	0.997	0.5
	3	Location along suction zone, x on flow	0.80	0.093	0.997	0.5
III	1	Suction zone length on sediment transport	0.80	0.093	0.997	0.1, 0.2, 0.5
	2	Size of sand particle on sediment transport	0.39, 0.80	0.093	0.997, 0.96	0.5

Note that in Table 3.2, u_{*0} = undisturbed approach shear velocity and u_{*0c} = critical shear velocity for bed sediment entrainment.

3.5 EXPERIMENTAL PROCEDURES

A total of three experimental series have been conducted in the present study, which are listed in Table 3.2. Details of each series are presented in sections 3.5.1 to 3.5.3.

3.5.1 Experiment Series I

Experiment series I was designed to investigate suction effects on the sediment transport in closed-conduit flow. Only sand particles with $d_{50} = 0.84$ mm were used in Series I and the water depth and the false floor depth are 0.058 and 0.142 m, respectively.

A total of two sub-series of tests were conducted in the study.

The first series of tests or Series I-1 aims to study the effect of the main flow rate, Q_0 on the sediment transport rate in a closed-conduit flow. In the second series of or Series I-2, Q_0 was kept constant while Q_s was systematically changed to investigate suction effects on sediment transport rate.

The procedure of Series I-1 is as follows:

- (i) Open the roof of the conduit and level the sand surface to the adjacent bed (false floor). Then close the conduit top and tighten the screws.
- (ii) Turn on the pump to allow water to fill the conduit at a very low flow rate.
- (iii) Adjust the pump to Q_0 that ranges from 4.8 to 5.63 L/s.
- (iv) After about two minutes during which the flow stabilizes, open the cover of the sand trap to collect the sand.
- (v) This continued for fifteen minutes; after which the pump was turned off.
- (vi) Open the roof of the conduit and collect the sand in the collection box.

- (vii) The sand, which was dried in a 120°C oven for two hours, was then weighed to calculate the sediment transport rate.

The procedure of Series I-2 is very similar to that of Series I-1, except that in this series, the main flow rate, Q_0 was kept at a constant = 4.8 L/s while the suction rates were varied from 0 to 1.1 L/s.

3.5.2 Experiment Series II

In Experiment Series II, suction effects on flow characteristics in closed-conduit flow are measured. Uniformly distributed sediment with median grain size, $d_{50} = 0.80$ mm, geometric standard deviation = 1.15 and specific gravity = 2.66 is used as the bed sediment. Note that the sand with $d_{50} = 0.39$ and 0.84 mm is white and their reflection is quite significant when the laser beam impinges on it, leading to significant errors in the measurement of flow characteristics, especially in the very near-bed region. Consequently, a green sand with $d_{50} = 0.80$ mm, which has a very similar particle size and distribution as the white sand was used. The green sand significantly reduces the reflection of the laser light. Three series of tests were conducted in the conduit to measure the near-bed flow field. The water depth and false floor depth are 0.093 and 0.107 m, respectively.

The first series of tests or Series II-1 aim to study the effect of different main flow rate, Q_0 on the near-bed flow field in closed-conduit flow. The procedure of Series II-1 is as follows:

- (i) Open the roof of the flume and level the sand surface to the adjacent bed (false floor). Then close the flume top and tighten the screws.
- (ii) Place the laser on top of the flume and fix the PIV as mentioned previously.
- (iii) Turn on the pump slowly at a low flow rate and allow the water to fill the flume.
- (iv) Adjust the pump to $Q_0 = 7$ L/s. Adjust the suction valve and keep $Q_s = 0$ L/s.
- (v) After about two minutes when the flow stabilizes, measure the near bed flow field at $x = 25$ cm (x denotes the horizontal distance from the leading

edge of the suction zone) using the high-speed camera. After that, turn off the main pump and the suction valve.

(vi) Repeat the above steps and adjust Q_0 to be 6.24, 6.44, 6.62 and 6.83 L/s.

The second Series or Series II-2 aims to measure the flow fields under different suction flow rates. The procedures in this series of test are the same as in Series II-1 except that the suction rate, Q_s was varied to be different values from 0 to 1.1 L/s. while Q_0 in step (iv) was kept a constant = 6.83 L/s. A total of seven different Q_s were tested, namely, $Q_s = 0, 0.264, 0.446, 0.682, 0.85, 0.97$ and 1.10 L/s. These Q_s values yield the corresponding mean suction velocity, $V_s = 0.00, 0.176, 0.297, 0.455, 0.567, 0.647$ and 0.733 cm/s, respectively.

The objective of the third Series or Series II-3 is to measure the flow fields at different locations along the suction zone. The procedures in this series of test are the same as in Series II-2 except that Q_s was kept constant at 0.9 L/s while measurements were conducted at four locations, namely, $x = 0, 10, 25, 32$ cm ($x/L = 0, 0.35, 0.5$ and 0.64).

In addition to using the green sand, the reflection from the sand can be further handled by following the image processing procedures proposed by Cowen and Monismith (1997), which were used to highlight the solid boundary (bed particles). Briefly, 100 images at different time are selected and the variation of the lightness near the boundary is further analysed, thus the location of the boundary can be determined to be where limited change of lightness is detected. Moreover, the reflection signal by the sand bed is removed by using a Laplacian transformation, which can highlight the high frequency domain in the image (the flow field) and can significantly reduce the influence of the boundary and its reflection (Hsieh, 2008).

After obtaining the flow field data, a continuity check was performed following the method proposed in Chang et al. (2001) and used by Lin et al. (2004) to calculate the flux of each grid element $q = \left| \partial u / \partial x + \partial v / \partial y \right| dA$ (in which Δx and Δy are the length and width for each grid and dA is the area of a grid in vector field) in the mean velocity field. Assuming the flow to be two-dimensional, the possible error can be estimated by using continuity as $\varepsilon = \left| \partial u / \partial x + \partial v / \partial y \right|$. Additionally, by assuming that ε could be equally split into $\bar{u}$ and $\bar{v}$, the error in each velocity

component can be estimated as $\bar{u}_{\text{error}} = \bar{v}_{\text{error}} \approx (\varepsilon/2)\Delta x$. Similarly, by substituting $\bar{u}_{\text{error}} = \bar{v}_{\text{error}}$ into $q = \left| \partial u / \partial x + \partial v / \partial y \right| dA$ for flux error analysis, the flux error is found to be larger and more sensitive than the velocity error. The error in the flux of the velocity field is defined as q/q_0 where $q_0 = U_0 \cdot \Delta y$, U_0 = mean velocity of approaching flow.

3.5.3 Experiment Series III

The third series of experiments are designed to investigate some special issues, i.e., suction effects on sediment transport rate of sand particles with various sizes and the influence of suction zone length on sediment transport in closed-conduit flow. The water depth and false floor depth are the same as those in Series II, i.e., 0.093 and 0.107 m, respectively.

Figure 3.4 Schematic Drawing of Shortened Suction Zone (Suction Zone Length = 0.2 m) (Unit: m, not to scale)

Series III-1 aims to investigate suction zone length effects on the sediment transport rate. All the setups and experimental procedures are the same as Series I-2 except that the water depth is 0.093 m instead of 0.058 m and the suction zone length, L is not fixed to be 0.5 m but varied ($L = 0.1, 0.2$ m) in the same way as that used in Liu (2010), so that meaningful comparison with her data may be conducted, i.e., by placing plastic plates on the bottom of the suction zone as illustrated in Fig. 3.4 ($L =$

0.2 m). Uniformly distributed sediment with median grain size, $d_{50} = 0.80$ mm, geometric standard deviation = 1.15 and specific gravity = 2.66 is used as the bed sediment. Q_0 was kept a constant = 7 L/s.

In Series III-2, suction effects on the sediment transport rate of sand particles with two different sizes are studied. All the experimental setups and procedures in this series are the same as those in experiment series I-2 except that the water depth is 0.093 m instead of 0.058 m and two different sand particles with $d_{50} = 0.39$ and 0.8 mm are used.

Chapter 4*

Experimental Results of Suction Effect on Sediment Transport & Analysis

4.1 INTRODUCTION

Literature review shows that despite the obvious role suction plays in affecting the near-bed flow behavior and the consequential impact on sediment entrainment and transport, few researchers have thus far directly measured the near-bed turbulent flow field and sediment transport rate to explain how they are related to each another. A possible reason is the difficulty involved in measuring the flow field without disturbing the flow by using equipments available to researchers before 1980. Moreover, the near-bed flow characteristics, which are the most significant in affecting bed particle motion, are notoriously difficult to measure even by using

* This chapter is part of Cao and Chiew (2014), which has been published in Journal of Hydraulic Engineering

modern non-intrusive instruments, such as Particle Image Velocimetry or Laser Doppler Anemometry.

Some previous researchers did measure the flow field in the presence of suction. For example, Maclean (1991a) conducted experiments in a 12-m long open channel flume with a suction zone with length = 0.2 m, and measured the horizontal and vertical velocity profile under different suction intensities up to $I_s = V_s/U_0 = 9\%$ ($V_s = Q_s/A_s$, $U_0 = Q_0/A$, where Q_0 and Q_s are the main and suction flow rates, respectively; A and A_s are the cross sectional area of the flume and area of suction zone, respectively). He found that the absolute value of both the horizontal and vertical velocities increased with increasing I_s . More recently, Chen and Chiew (2004) experimentally measured suction effects on the velocity profile in a 32-m long open channel flume that comprises a 2-m long suction zone located at a distance 16 m downstream of the flume inlet. They applied a suction intensity $I_s = 1.53\%$, and found that the flow field changed significantly compared to that without suction. Both the near-bed horizontal and vertical velocities increased in the presence of suction. Their results are consistent with those presented by Maclean (1991a). Unfortunately, neither of these two groups of researchers measured the flow characteristics at the very near-bed region, probably due to limitation of their equipments, and the sediment transport rate.

A thorough search of the literature over the past forty years reveals that inferences have been drawn concerning suction effects on sediment transport in open channel flow. Regrettably, two completely opposite conclusions can be found. The first group of researchers, viz., Oldenziel and Brink (1974) and Francalanci et al. (2008) opined that suction decreases the sediment transport rate, while Willetts and Drossos (1975), Maclean (1991b), Lu and Chiew (2007), Liu (2010), Rao et al. (2011) and Liu and Chiew (2012) obtained the exact opposite results. Although the problem has been partially solved by some recent researchers, e.g., Lu et al. (2008) and Liu and Chiew (2012), both the conclusion and the reason behind it are not completely agreed yet. One may argue that due to the abstraction of water in the near-bed region in an open channel flow with suction, both the flow rate and water depth will reduce. However, their reduction leads to an indeterminate change in the

local flow velocity. This is because whether the velocity increases or decreases is related to the relative reduction of the flow rate and flow depth when suction is applied. In other words, if the depth of flow is reduced more than the flow rate, the resulting velocity evidently will increase. This uncertainty could be an important factor in contributing to the disagreement amongst these researchers.

In order to eliminate the effect of one of these variables, namely the flow depth, the present study is conducted in a closed conduit in which the flow depth, or more appropriately, the flow cross-sectional area remains constant regardless on the amount of flow abstraction caused by suction. With this approach, one can better examine suction effects on sediment transport rate and attempt to clarify the discrepancy highlighted above. Additionally, the study of suction effects on sediment transport in a closed conduit has rarely, if ever been reported. Although previous researchers, e.g., Schildknecht et al. (1979), Elena et al. (1977), So and Yoo (1987), etc. have studied suction effects on the flow behavior experimentally or numerically, they did not consider its influence on sediment transport.

Consequently, this study not only examines the influence of suction on the flow behavior but also sediment transport rate in closed-conduit flows. Both numerical simulations and physical experiments are conducted to achieve the objective. This is followed by the development of a conceptual model, which is verified by using results from both the laboratory experiments and numerical simulations.

4.2 EXPERIMENTAL RESULTS

A permeable boundary may lead to modification to forces exerting on the bed particles. The chapter focuses on how suction affects the physics of sediment transport behavior in closed-conduit flow.

Table 4.1 shows the experimental data of both Test Series I-1 and I-2 in Series I described in Chapter 3. It must be stated at the outset that the lowest value of Q_0 used in the study is 4.8 L/s, which corresponds to the computed approach shear velocity ratio, $u_{*0} / u_{*0c} = 0.958$ (without suction), in which u_{*0} = undisturbed

approach shear velocity and u_{*0c} = critical shear velocity for bed sediment entrainment. The former is conducted using the mean velocity computed from Q_0 and the friction factor estimated by using the revised Nikuradse friction factor diagram after Brownlie (1981) (Garcia, 2008). By adopting the side-wall correction method described in Chiew and Parker (1994), the different roughness on the bottom and top of the conduit can be accounted for. The latter is calculated by using the Shields function in van Rijn (1984). Tests I-1-1 and I-2-1, which are the same test, correspond to such a condition and the sediment transport rate q_b is measured to be $0.0143 \times 10^{-6} \text{ m}^2/\text{s}$. On the other hand, Test B-18 shows the test with the largest measured volumetric bedload transport rate per unit width, with $q_b = 0.432 \times 10^{-6} \text{ m}^2/\text{s}$, giving the maximum average scour depth over the suction zone with length = 0.5 m, $d_s = q_b \times t/L = 0.432 \times 10^{-6} \times 15 \times 60 / 0.5 \approx 0.78 \text{ mm}$. As $d_{50} = 0.84 \text{ mm}$, less than one layer of sand is entrained by the flow at this transport rate and scouring is almost negligible. Neither ripples nor dunes were observed during the experiments. Therefore, the sediment bed remains plane within the entire 15-minute test duration for all the tests. In the experiments, the undisturbed approach flow rate, $Q_0 = 4.8 \text{ L/s}$ is chosen to be the baseline condition and all tests in Series I-2 (where suction is present) was conducted with this approach flow rate.

Table 4.1 Experimental Data

<i>Test Number</i>	<i>Main flow rate, Q_0 (L/s)</i>	<i>Mean streamwise velocity, U_0 (m/s)</i>	<i>Suction rate, Q_s (L/s)</i>	<i>Suction velocity, V_s (m/s)</i>	<i>Bedload transport rate, q_b ($10^{-6} \text{ m}^2/\text{s}$)</i>
I-1-1 ^a	4.8	0.276	0.000	0.0000	0.0143
I-1-2	4.89	0.281	0.000	0.0000	0.0139
I-1-3	4.97	0.286	0.000	0.0000	0.0181
I-1-4	5.06	0.291	0.000	0.0000	0.0358
I-1-5	5.14	0.295	0.000	0.0000	0.0606
I-1-6	5.25	0.302	0.000	0.0000	0.1204
I-1-7	5.36	0.308	0.000	0.0000	0.1378

I-1-8	5.51	0.317	0.000	0.0000	0.2005
I-1-9	5.63	0.324	0.000	0.0000	0.259
I-2-1 ^a	4.8	0.276	0.000	0.0000	0.0143
I-2-2	4.8	0.276	0.057	0.0004	0.0119
I-2-3	4.8	0.276	0.118	0.0008	0.0175
I-2-4	4.8	0.276	0.145	0.0010	0.0168
I-2-5	4.8	0.276	0.180	0.0012	0.0226
I-2-6	4.8	0.276	0.260	0.0017	0.0061
I-2-7	4.8	0.276	0.273	0.0018	0.0179
I-2-8	4.8	0.276	0.298	0.0020	0.0291
I-2-9	4.8	0.276	0.333	0.0022	0.0298
I-2-10	4.8	0.276	0.465	0.0031	0.0269
I-2-11	4.8	0.276	0.520	0.0035	0.0185
I-2-12	4.8	0.276	0.528	0.0035	0.0395
I-2-13	4.8	0.276	0.750	0.0050	0.058
I-2-14	4.8	0.276	0.790	0.0053	0.0796
I-2-15	4.8	0.276	0.870	0.0058	0.1229
I-2-16	4.8	0.276	0.950	0.0063	0.1659
I-2-17	4.8	0.276	1.020	0.0068	0.2785
I-2-18	4.8	0.276	1.100	0.0073	0.432

Note: The data with test number starting with I-1 and I-2 are from the first and second experiment series, respectively. ^aTests I-1-1 and I-2-1 are the same test. The data in the Columns 2, 4 and 6 are directly measured while $U_0 = Q_0/A$, $V_s = Q_s/A_s$. The Reynolds number R for all the tests ranges between 26816 and 31453, which shows the flow is turbulent, where $R = \frac{U_0 D_H}{\nu}$; ν = kinematic viscosity; and

$$D_H = \frac{4A}{P}.$$

Figure 4.1 Effect of Flow Rate Q_0 on q_b in Closed-Conduit Flow Without Suction (Series I-1)

Figure 4.2 Comparison of Suction Effects on Sediment Transport Rate in Closed-Conduit (Present Study, Series I-2) and Open Channel Flow (Data from Liu, 2010)

By varying the approach main flow rate Q_0 but keeping a zero suction rate, the corresponding sediment transport rates were measured and plotted as a function of Q_0 in Fig. 4.1 (Series I-1). The data clearly show that q_b increases with Q_0 , which is not unexpected as a larger flow rate expectedly increases the sediment transport and the present data verify this behavior in a closed-conduit flow.

Fig. 4.2 shows the dimensionless sediment transport rate $\Phi = \frac{q_b}{\sqrt{(S_s - 1)gd^3}}$ plotted

against suction intensity I_s , with the undisturbed approach flow rate $Q_0 = 4.8$ L/s (Series I-2) using the data of Liu (2010) and those from the present study. The result reveals that Φ remains essentially constant for small values of I_s before increasing abruptly beyond a critical value. More specifically, Φ remains at an average value of 1.56×10^{-4} for $0 \leq I_s \leq 0.66\%$. Beyond this value, Φ progressively increases and when I_s reaches around 1.81%, the sediment transport rate increases abruptly so much so that at $I_s = 2.66\%$, $\Phi = 4.4 \times 10^{-3}$ or an increase in excess of 28 times when compared to the baseline value. This significant quantitative increase of the bedload transport rate is supported by visual inspection in which the amount of sediment particles in motion clearly had increased significantly compared to those without suction or with low suction rates.

It must be noted that Fig. 4.2 appears to show that Φ will increase indefinitely with increasing I_s . However, this is not likely to be true as on the one hand, the formation of bedforms associated with high I_s will have a profound influence on sediment transport rate. Based on the knowledge on sediment transport in open channel flow, the rate of sediment transport will change with the formation of bedforms associated with form drag. Moreover, due to the limitations of the experimental setup, we cannot apply higher suction rates. Therefore, it is not possible to ascertain whether Φ will continue to increase or not as suction increases further, although it is unlikely due to the formation of bedform discussed earlier. However, the phenomenon that Φ increases with increasing I_s for $0 < I_s < 2.66\%$, is both validated by visual observation and the present data and those of Liu (2010). Additionally, due to lack of experiments with finer or coarser sand particles, the present data only show that Φ increases with increasingly larger I_s in a certain

range for sand with $d_{50} = 0.48, 0.84$ and 0.9 mm. Much larger or smaller bed sediment could lead to different results.

In her study, Liu (2010) conducted the experiments in an open channel flume that is 30 m long, 0.7 m wide and 0.6m deep, with a suction zone = 0.5 m length, 0.4 m depth located in the middle of the flume. She found that suction significantly increases the bed load transport for two different uniform sand ($d_{50} = 0.9$ and 0.48 mm) through direct measurement of the transported sand. Note that in Liu (2010)'s study, $u_{*0} / u_{*0c} = 0.91$ for the coarser bed sediment and 0.98 for the finer bed sediment. In an open channel flow, one could argue that the increasing bedload transport rate with suction is due to the decreasing local flow depth (see Francalanci et al., 2008) that may have increased the local flow velocity U in the suction zone. This argument, however, fails when it is used to account for the increasing Φ with increasing I_s in a closed-conduit flow. This is because the water depth, h and cross-sectional area, A remain unchanged regardless of the amount of suction so long as the flow continues to be a closed-conduit flow, as is the case in this study. Accordingly, a different explanation from that for open channel flow needs to be explored.

It may be surmised from these data that a reason why previous researchers did not come to a consensus on whether suction increases or decreases q_b is probably because of the very different suction intensities used. The use of a small suction rate could lead one to infer that suction would have a negligible effect on or even reduces sediment transport rate. For instance, Oldenziel and Brink (1974) utilized a suction intensity I_s of less than 0.5% and concluded that sediment transport rate generally decreases with increasing suction. The amount of transported sand decreases by as much as 60%, which is much smaller than the maximum increase of q_b of around 30 times in the present study. In the present study, the maximum suction intensity is $I_s = 2.66\%$, which may significantly change the flow field, thus influencing sediment transport appreciably. However, the small suction rate used in Oldenziel and Brink (1974)'s study causes different changes in the flow behavior, and hence the sediment transport rate responds differently. Thus, researchers who

had used larger suction rates would have found that suction significantly increases sediment transport rate.

The present study shows that sediment transport rate increases not only with increasing main flow rate, but also with increasing suction rate. It clearly is not difficult to understand why sediment transport rate increases with Q_0 as the mean velocity increases, but why should it also increase with suction since the mean velocity keeps decreasing along the suction zone? A theoretical consideration and conceptual model is presented to explain this phenomenon in the following section.

4.3 THEORETICAL CONSIDERATION & CONCEPTUAL MODEL

Many previous researchers have proposed different models to examine seepage effects on the initiation of cohesionless bed sediment motion. For instance, Cheng and Chiew (1999) and Dey and Zanke (2004) proposed a model to analyze the forces acting on a spherical particle by introducing an additional upward seepage force in an open channel flow subjected to injection. Liu and Chiew (2012) proposed a similar model to analyze the forces acting on a spherical particle in open channel flow with suction by including a downward seepage force. Francalanci et al. (2008), on the other hand, opined that seepage induces the formation of a non-hydrostatic pressure distribution that may affect sediment entrainment and transport.

In the present study, we attempt to explore sediment entrainment and transport by considering changes to the near-bed velocity and its impact on the bed sediment. Published literature has categorically shown that the mean streamwise velocity increases and decreases with increasing Q_0 and Q_s , respectively. Arising from this observation, a reasonable question is: Why does q_b increase with both increases in Q_0 and Q_s ? Most previous researchers have focused on sediment transport in open channel flow. It can be easily accepted that an increased main flow can increase sediment transport. Why does suction enhance sediment transport in a closed conduit is as yet unclear. This is because the mean streamwise velocity will inevitably reduce by the introduction of suction.

A possible reason is that the velocity at the bed or particle level u_b , rather than the mean velocity, is the most significant factor in affecting bed particle entrainment and transport. Under the influence of suction, whether it be an open channel or closed-conduit flow, u_b actually increases with Q_s , as is illustrated in Fig. 4.3. The figure reveals how the near-bed velocity with suction, u_{bs} is larger than that without suction, u_{b0} although the mean flow velocity farther from the bed exhibits a completely opposite trend. It should be noted that the concept of the velocity at the particle level has been used by many researchers in the older generation, such as Egiazaroff (1965); Mavis and Laushey (1949); Sutherland (1966), etc. This study attempts to investigate seepage effects on sediment mobility following this classical approach.

Figure 4.3 Velocity Profiles Associated with Flows with and without Suction

With this conceptual model in mind, we consider a horizontal plane bed consisting of uniform, cohesionless sediment particles subjected to suction in a closed-conduit flow as shown in Fig. 4.4(a) (Note that this concept also applies to an open channel flow). Fig. 4.4(b) shows the velocity vector of flow approaching a bed particle subjected to suction and the total drag force is calculated using the resultant velocity V_b . For simplicity, the bed sediments may be assumed to be spheres with diameter d .

At the onset of motion, the cohesionless sediment particle on the surface of the porous bed experiences the drag force, F_D , lift force F_L , submerged weight force, W .

All these forces acting on the particle may be grouped into two components: vertical and horizontal.

The submerged weight of the particle may be calculated using

$$W = (\rho_s - \rho)g \frac{\pi d^3}{6} \quad (4.1)$$

where ρ_s and ρ = densities of sediment particle and water, respectively.

Figure 4.4 (a) Forces and Notations for A Single Grain in Closed-Conduit Flow with Suction; (b) Velocity of Flow Approaching A Bed Particle in Closed-Conduit Flow with Suction

The drag force F_D consists of skin and form drag. For the same spherical sediment particle, it may be expressed as

$$F_D = C_D \frac{\pi d^2}{8} \rho V_b^2 = C_D \frac{\pi d^2}{8} \rho (u_b^2 + v_b^2) \quad (4.2)$$

where u_b = horizontal flow velocity over the particles; v_b = vertical flow velocity over the particles due to suction; and C_D = drag coefficient. F_D may be resolved into two forces in the horizontal and vertical direction, namely, F_{Dh} and F_{Dv} , respectively.

$$F_{Dh} = C_D \frac{\pi d^2}{8} \rho (u_b^2 + v_b^2) \cdot \cos \theta = C_D \frac{\pi d^2}{8} \rho \sqrt{u_b^2 + v_b^2} \cdot u_b \quad (4.3)$$

$$F_{Dv} = C_D \frac{\pi d^2}{8} \rho (u_b^2 + v_b^2) \cdot \sin \theta = C_D \frac{\pi d^2}{8} \rho \sqrt{u_b^2 + v_b^2} \cdot v_b \quad (4.4)$$

As W and F_{Dv} are both in the downward direction, we may define $(W + F_{Dv})$ as the effective weight of the sand particle, W' . On the other hand, the lift force, which has a similar form as its drag counterpart, is expressed as follows:

$$F_L = C_L \frac{\pi d^2}{8} \rho V_b^2 = C_L \frac{\pi d^2}{8} \rho (u_b^2 + v_b^2) \quad (4.5)$$

where C_L = lift coefficient.

Similar to F_D , F_L can also be resolved into two forces in the horizontal and vertical direction, namely F_{Lh} and F_{Lv} , respectively.

$$F_{Lh} = C_L \frac{\pi d^2}{8} \rho (u_b^2 + v_b^2) \cdot \sin \theta = C_L \frac{\pi d^2}{8} \rho \sqrt{u_b^2 + v_b^2} \cdot v_b \quad (4.6)$$

$$F_{Lv} = C_L \frac{\pi d^2}{8} \rho (u_b^2 + v_b^2) \cdot \cos \theta = C_L \frac{\pi d^2}{8} \rho \sqrt{u_b^2 + v_b^2} \cdot u_b \quad (4.7)$$

By balancing the moments about the axis through the pivot point (Zanke, 2003), the following requirement must be satisfied for the entrainment of grain particles

$$(W + F_{Dv} - F_{Lv}) \frac{d}{2} \cdot \sin \phi = (F_{Dh} + F_{Lh}) \frac{d}{2} \cdot \cos \phi \quad (4.8)$$

where ϕ is the angle of internal friction at the inception of motion, which is about 30° for sand and can be taken as 20° as the layer of single grains are scattered on a sediment surface (Zanke, 2003). Defining the resistive force,

$F_r = (W + F_{Dv} - F_{Lv}) \tan \phi$, thus $\frac{F_{Dh} + F_{Lh}}{F_r} = 1$ is the critical condition for the

entrainment of grain particles. The introduction of suction changes the near-bed flow field, increasing not only the near-bed vertical v_b but also the near-bed horizontal velocity u_b . Thus, increasing u_b will increase the driving force, hence the sediment transport rate, while increasing v_b will lead to an increased effective weight W' , and hence F_r . This opposing effect causes the uncertainty on whether the ratio $\frac{F_{Dh} + F_{Lh}}{F_r}$ would increase or not with increasing suction. However, based on

the measured q_b with increasing suction rate in Table 4.1, $\frac{F_{Dh} + F_{Lh}}{F_r}$ is shown to increase with increasing suction rates for $0 < I_s < 2.66\%$.

To verify the conceptual model stated above, it is important that the flow characteristics in the presence of suction be known. Consequently, a CFD simulation using the commercial software package, FLUENT is used to qualitatively examine suction effects on the flow behavior in closed-conduit flow.

4.4 NUMERICAL SIMULATION & RESULTS

The CFD simulation was carried out to simulate suction effects on the flow behavior in a closed-conduit flow. It must be stated that the dimension of the conduit used in the numerical simulation is identical to that used in the physical experiments. The commercial software FLUENT 13 developed by ANSYS, Inc. was used in this study. As the sand bed in the suction zone remains planar in the experiments, it is assumed to be immobile in the numerical model and the suction zone is simplified as a porous zone. The realizable $k-\varepsilon$ and porous media models

were chosen to model the flow. The details of the models are illustrated in the appendix AIII.

The inlet of the conduit was defined as a velocity inlet and the outlets of the conduit and suction zone were defined as pressure outlets. The rest of the boundaries were treated as no-slip walls. The roughness for the rough bed is 0.00084 m and that for the rest of the no-slip walls is 0 m.

The simulation was conducted with the assumption of a single phase flow, i.e., only water is present. Initially, water with density and viscosity = 998.2 kg/m³ and 1.003×10⁻⁶ kg/m.s, respectively, enters the conduit at the inlet with a velocity = 0.276 m/s in the horizontal direction.

The simulations were carried out with the SIMPLE (semi-implicit method for pressure linked equations) algorithm for pressure–velocity coupling and QUICK (quadratic upstream interpolation for convective kinetics) algorithm for discretization of the conservation equations. A computational accuracy of 10⁻⁶ was chosen for convergence.

In this section, attention is given to the near-bed flow behavior as suction mainly affects and sediment transport is mostly related to the flow behavior in this flow region, as was hypothesized in the theoretical consideration and conceptual model discussed earlier.

Figs 4.5 (a) and (b), which show the flow field around the suction zone with $I_s = 0$ and 3.17%, respectively, reveal that the flow behavior changes significantly when a large suction is present compared to that without suction. More specifically, both u_b and v_b increase significantly under such a large suction intensity.

The conceptual model presented in this chapter requires the use of a near-bed horizontal and vertical velocity for analyses. In this study, it is assumed to be the velocity at the location 0.2 mm vertically above the bed level ($y = 0.2$ mm). This distance is chosen with reference to Einstein and El-Samni (1949)'s study in which they used the velocity at a vertical distance = $0.35d_{35}$ above the theoretical bed level

(a)

(b)

Figure 4.5 Flow Field around the Suction Zone When (a) $I_s = 0$; (b) $I_s = 3.17\%$

to compute the lift force, where d_{35} = particle size for which 35% are finer by weight. As a result, $0.35d_{35} \approx 0.2$ mm in this study.

A total of 7 simulation runs were conducted to study the effect of the main flow rate, Q_0 on the horizontal velocity at the bed particle, u_b ; and 11 simulation runs carried out to study the effect of suction intensity, I_s on both the horizontal and vertical velocities at the bed particle, u_b and v_b . Moreover, point velocity measurements were carried out on the near-bed horizontal velocity along the center-line of the suction zone for $Q_s = 0$ L/s. Limited measurements also were conducted with $Q_s = 0.03$ L/s. The measured data are compared with the numerically

Figure 4.6 Effect of Simulated Main Flow Rate, Q_0 on Horizontal Velocity at the Particle Level, u_b in Closed-Conduit Flow without Suction

computed horizontal velocity at the same flow condition and the difference between the numerical and measured data range from -5.2% to 8.0%, which is acceptable as

we only try to obtain a qualitative trend of suction effects on sediment transport in the present study.

Fig. 4.6 illustrates how the horizontal velocity at the bed particle level, u_b increases with the main flow rate without suction in a closed-conduit flow. According to the conceptual model, the driving force increases while resistive force decreases. Consequently, sediment transport rate, q_b should increase with Q_0 , which is confirmed by the experimental data.

The simulated results of suction effects on u_b and v_b at the same near-bed level in closed-conduit flow are shown in Figs. 4.7 and 4.8, respectively. Fig. 4.7 shows how u_b increases with I_s and Fig. 4.8 reveals that v_b also increases with I_s . Based on the conceptual model, increasing u_b will lead to an increase in the driving force, while increasing v_b will increase the effective weight and hence the resistive force. Therefore, whether q_b increases or not depends on whether the increasing effect of u_b outweighs that of v_b .

Figure 4.7 Effect of Simulated Suction Velocity on Horizontal Velocity at the Particle Level, u_b in Closed-Conduit Flow with Suction

By assuming that the computed horizontal and vertical velocities at this bed level are appropriate for use in Eqns. 4.2-4.7, one can calculate the respective horizontal and vertical forces if the drag and lift coefficients are known. This will enable us to have a better appreciation on the influence of suction on the initiation of bed sediment motion and sediment transport rate.

Figure 4.8 Effect of Simulated Suction Velocity on Vertical Velocity at the Particle Level, v_b in Closed-Conduit Flow with Suction

The drag coefficient C_D is obtained from Rouse (1937), who stated that it is a function of the particle Reynolds number, R in the flow direction, which is defined as follows:

$$R = \frac{V_b D_H}{\nu} \quad (4.9)$$

The ratio between lift coefficient C_L and drag coefficient C_D , for simplicity of calculation, is assumed to be a constant (Apperley, 1968). Note that $\frac{C_L}{C_D} = \frac{F_L}{F_D}$ and according to Zanke (2003), the value of $(\frac{F_L}{F_D})_{\max}$ lies between 2 and 3, the real value is proportional to the square of turbulence intensity at bed level, can be 0 ~

Table 4.2 - Increase in Force Ratio, η'/η with Increasing Suction Intensity, I_s

I_s (%)	u_b (m/s)	v_b (m/s)	V_b (m/s)	R	C_D	C_L	η'	η'/η
0	0.043	2.75E-05	0.043	36.42	2	1.20	0.65	1.00
0.04	0.043	-8.61E-05	0.043	36.30	1.96	1.18	0.63	0.98
0.36	0.044	-9.90E-04	0.044	37.10	1.92	1.15	0.63	0.99
0.66	0.045	-1.79E-03	0.045	38.10	1.88	1.12	0.65	1.01
1.04	0.047	-2.88E-03	0.047	39.64	1.77	1.05	0.65	1.01
1.42	0.049	-3.93E-03	0.049	41.38	1.68	1.01	0.66	1.03
1.88	0.052	-5.25E-03	0.052	44.02	1.66	1.00	0.73	1.15
2.29	0.055	-6.38E-03	0.056	46.77	1.64	0.98	0.82	1.28
2.58	0.058	-7.18E-03	0.058	49.07	1.56	0.94	0.86	1.34
2.97	0.062	-8.22E-03	0.063	52.80	1.53	0.92	0.98	1.54
3.17	0.065	-8.71E-03	0.066	55.07	1.5	0.90	1.06	1.65

Figure 4.9 Effect of V_s/U_0 on η'/η

2.5, depending on the turbulence intensity. For this study, the ratio is estimated to be 0.6 and ϕ is taken as 20° as stated previously. Both the resistive and the driving forces, F_r and $(F_{Dh}+F_{Lh})$ can be calculated by using Eqs. 4.1-4.7. Their ratio, $\eta = (F_{Dh}+F_{Lh})/F_r$ may be interpreted as the ease with which the bed particle moves, as stated in the conceptual model section; a high η means a higher rate of transport and vice-versa. η' refers to the force ratio with suction and that without a prime refers to that without suction. Table 4.2 shows the calculated value of η' under different suction intensities using the data in Figs. 4.7 and 4.8 and the methods outline above. It must be noted that u_b and v_b are, respectively, the horizontal and vertical velocities at the particle level ($y = 0.0002$ m) in the middle of the suction zone ($x = 0.25$ m downstream of the leading edge of the suction zone as suction effect on flow behavior is more apparent here). It should be noted that the force ratio η' can also

be expressed as $\eta' = \frac{F_{Dh} + F_{Lh}}{F_r} = \frac{\tau_*}{\tau_{*c}} = \frac{u_*^2}{u_{*c}^2}$, thus $u_* / u_{*c} = \sqrt{\eta'}$ can be computed,

which varies from 0.80 at $I_s = 0$ to 1.03 at $I_s = 3.17\%$. It must be stated that the calculation here only serves as a qualitative appreciation of suction effects on the flow behavior in a closed conduit, rather than a precise quantitative analysis.

The computed η'/η is plotted as a function of I_s in Fig. 4.9. The figure shows that the ratio remains low and essentially a constant with small suction intensities ($I_s \leq 0.66\%$) before increasing abruptly when $I_s \geq 0.66\%$. The increasing trend of η'/η with I_s is remarkably similar to the plot of the experimental data of Φ , as a function of I_s as shown in Fig. 4.2. It may therefore be inferred that the effect of suction on sediment transport rate is modest at best when the suction rate is low. Beyond a critical value, the sediment rate increases abruptly. This inference may be drawn from both the empirical data and the conceptual model deduced from the consideration of the near-bed horizontal and vertical velocities.

4.5 CONCLUDING REMARKS

This chapter aims to explore how vertical bed suction affects the sediment transport rate in closed-conduit flows. Both physical experiments in a laboratory conduit and numerical simulations using FLUENT were conducted to achieve the stated objective.

The experimental results show that the bedload transport rate increases with suction rate (with a constant Q_0). The data also reveal that the dimensionless sediment transport rate, Φ firstly increases marginally at low values of I_s . Beyond a certain threshold, Φ increases abruptly. To account for this behavior, a conceptual model with consideration of the near-bed vertical and horizontal forces is presented. It shows that the near-bed velocities are closely related to the sediment transport rate with suction.

To qualitatively verify this model, CFD simulations were conducted to model how suction influences the near-bed flow behavior in a closed conduit with the same

dimension as that in the physical experiments. The results support the conceptual model and show that both the horizontal and vertical near-bed velocities increase with increasing suction rate.

In summary, the present study investigates suction effect on sediment transport in a closed-conduit flow by directly measuring the sediment transport rate. By introducing a conceptual model that involves a suction induced force and using numerical simulation to model the flow behavior in the presence of suction, it provides a rational explanation on suction effects on sediment transport.

Chapter 5

Suction Effects on Flow Characteristics

5.1 INTRODUCTION

Because seepage can induce mass and momentum transfer across the interface between a fluid and permeable boundary, it may be surmised that it has a significant influence on the flow behavior. The present study focuses on suction effects on the flow characteristics of closed-conduit flows. Many previous researchers have reported suction effects on the flow behavior in open channel flow (Maclean, 1991a; Chen and Chiew, 2004; Dey and Nath, 2010). Maclean (1991a) used a Dantec Laser Doppler Anometry system to measure the velocities in an open channel with strong suction intensity (I_s up to 9%). In the same paper, he reported the use of two perpendicular hot wire probes to simultaneously measure the horizontal and vertical velocities in a wind tunnel with strong suction (I_s up to 14%). His experiment results showed that the velocity gradient in the logarithmic region decreases as suction velocity increases. Chen and Chiew (2004, 2007) used LDA to measure the velocity and turbulence in an open channel flow with suction

(I_s up to 1.53%). They found that suction made the streamwise velocity more uniform and decreased the turbulence intensity. Similar results are obtained by Dey & Nath (2010).

However, to the best of the author's knowledge, very few researchers have hitherto directly measured suction effects on the turbulent flow field in the very near-bed region. One of the reasons may be the difficulty involved in measuring the flow field without disturbing the flow by using the equipment available to the earlier researchers. Even with modern non-intrusive equipment such as Particle Image Velocimetry (PIV) or Laser Doppler Anemometry (LDA), the near-bed flow characteristics remain difficult to measure.

Additionally, few researchers have measured the flow behavior in closed-conduit water flows with suction to-date. Since the water depth, contrary to that in an open channel flow, will remain unchanged in a closed-conduit flow, whether the flow and turbulence variation with suction in closed-conduit flows will exhibit the same behavior as those in an open channel flow are as yet unknown and will be explored in the study.

Consequently, the present study aims to use the PIV technique combined with a high speed camera to obtain a continuous near-bed flow field in closed-conduit flows subjected to suction. The experimental setups and procedures can be found in section 3.5.2 of Chapter 3.

5.2 THEORETICAL ANALYSIS

Due to the boundary seepage effect, the streamwise velocity profile deviates from the law of the wall. Many previous studies have been conducted to explore a modified log law in the presence of seepage, as shown in Table 2.1.

Almost all of listed modified laws of the wall in Table 2.1 are based on the Prandtl's mixing length theory,

$$\frac{\tau}{\rho} = l^2 \left(\frac{du}{dy} \right)^2 \quad (5.1)$$

where l is the mixing length and $l = \kappa y$, where κ = von Karman constant.

For a two-dimensional flow, the continuity equation and the streamwise momentum equation on a horizontal bed are as follows,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (5.2)$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{1}{\rho} \frac{\partial \tau}{\partial y} \quad (5.3)$$

Most of the previous studies assume that the pressure gradient and the variation of u with x in Eq. (5.3) are negligible as they cannot induce significant flow acceleration.

As the present study is conducted in a closed conduit in which the flow is pressure driven, the assumption $\frac{\partial p}{\partial x} = 0$ may not be valid any more. However, by assuming that (1) the variation of the horizontal velocity, u is related to the pressure gradient as follows:

$$u \frac{\partial u}{\partial x} = -\frac{1}{\rho} \frac{\partial p}{\partial x} \quad (5.4)$$

and (2) that the variation of vertical velocity at a certain distance, y above the sand bed is negligible,

$$\frac{\partial v}{\partial y} = 0 \quad (5.5)$$

By integrating Equation (5.4), $v = V_s$ and Eq. (5.3) can then be simplified as,

$$V_s \frac{du}{dy} = \frac{1}{\rho} \frac{d\tau}{dy} \quad (5.6)$$

Eq. (5.6) is the same equation used in the derivations by Stevenson (1963), Cheng and Chiew (1999) and Chen and Chiew (2004). Stevenson (1963) integrated Eq. (5.6) from $y = 0$ to $y = y$; $u = 0$ to $u = u$ and $\tau = \tau_b$ to $\tau = \tau$; Different from

Stevenson (1963), Cheng and Chiew (1999) assumed that the distance at which $u = 0$, y_0 is elevated in the presence of upward seepage and used the boundary conditions $y = y_0$ to $y = y$; $u = 0$ to $u = u$ and $\tau = \tau_b$ to $\tau = \tau$; Chen and Chiew (2004) referred to Nezu (1977) and Mendoza and Zhou (1992) and postulated that there is a slip velocity at the bed surface, u_s in the presence of suction, and used the boundary conditions $y = 0$ to $y = y$; $u = u_s$ to $u = u$ and $\tau = \tau_b$ to $\tau = \tau$.

The present study uses the same boundary condition as Chen and Chiew (2004) because it investigates suction effects on flow field as Chen and Chiew (2004), and the only difference is that the present study is conducted in a closed conduit while that in Chen and Chiew (2004) was conducted in open channel flow. Note here that it is assumed that only the flow in the half part lower than the center line of the conduit is affected by suction. Consequently, integration of Eq. (5.6) from $y = 0$ to $y = y$ ($y < 0.5h$, h is the conduit depth) leads to,

$$\tau = \tau_b + \rho V_s (u - u_s) \quad (5.7)$$

where $\tau_b = \rho u_*^2$, u_* is the shear velocity.

Note that Chen and Chiew (2004) stated that a virtual layer under the bed surface (from $y = -y_0$ to $y = 0$) has the same features as that above the bed surface and they modified the mixing length, $l = \kappa(y + y_0)$. By using the same hypothesis as that in Chen and Chiew (2004) and combining Eq. (5.1), the following equation can be obtained,

$$\frac{u - u_s}{u_*} = \frac{1}{\kappa} \ln \frac{y + y_0}{y_0} + \frac{V_s}{4u_*} \left(\frac{1}{\kappa} \ln \frac{y + y_0}{y_0} \right)^2 \quad (5.8)$$

Eq. (5.8), which has the same form as that derived by Chen and Chiew (2004) in open channel flow, can also be used to describe the velocity profile in closed-conduit flow with suction. The values of u_* , u_s and y_0 are determined by fitting the experimental data.

5.3 SUCTION EFFECTS ON FLOW FIELD

5.3.1 Effect of Main Flow Rates ($Q_0 = 6.24 \sim 7$ L/s) on Flow Field (Experimental Series II-1)

Figure 5.1 Streamwise Velocity Profile with Different Main Flow Rates ($x = 25$ cm)

For each different test, 19400 images were captured and used for the calculation of the flow characteristics. The qualities of most of the images are considered to be high enough (the resolution), especially after the Laplacian transformation. The images has a field of view with the size = $5.6 \text{ cm} \times 3.5 \text{ cm}$. After the calculation, the continuity check described in section 3.5.2 was conducted, which shows that the maximum error in the flux of the velocity field is about 5.8%, which may be considered to be small, indicating that the PIV measurement in the study is reliable.

Figure 5.1 plots the dimensionless streamwise velocity u/u_* in the middle of the suction zone ($x = 25$ cm) against $\ln(y/d_{50})$ under five different main flow rates ($Q_0 = 6.24, 6.44, 6.62, 6.83$ and 7 L/s). It shows that the data under different main flow rates collapse into one single line and they all agree well with the universal log law, $\frac{u}{u_*} = 2.5 \ln(y/d_{50}) + 8.6$. And the values of u_* for $Q_0 = 6.24, 6.44, 6.62, 6.83$ and 7 L/s are $0.0155, 0.0159, 0.0163, 0.017$ and 0.0175 m/s, respectively and these u_* , which are used to non-dimensionalize the streamwise velocity u . The shear velocity u_* is calculated using the mean velocity U_0 and the friction factor estimated by using the revised Nikuradse friction factor diagram after Brownlie (1981) (Garcia, 2008), is used to normalize the streamwise velocity.

Figure 5.2 Vertical Velocity Profile with Different Main Flow Rates ($x = 25$ cm)

For a better display of the different magnitudes of the streamwise and vertical velocities, Fig. 5.2 plots the dimensionless vertical velocity v/u_* in the middle of the suction zone ($x = 25$ cm) against $\ln(y/d_{50})$ under five different main flow rates ($Q_0 = 6.24, 6.44, 6.62, 6.83$ and 7 L/s), using the above-mentioned u_* for non-dimensionalization. It shows that all the vertical velocities almost collapse to a vertical line and the value is about zero, albeit a small deviation. This is to be expected because no seepage is present.

Figs. 5.3, 5.4 and 5.5 present the variation of the profiles of u^+ , v^+ and uv^+ with the above-mentioned five different main flow rates rates Q_0 , where $u^+ = (\overline{u'u'})^{0.5}/u_*$, $v^+ = (\overline{v'v'})^{0.5}/u_*$, $uv^+ = -\overline{u'v'}/u_*^2$; u' and v' = horizontal and vertical velocity fluctuation, respectively and u_* are the five shear velocities mentioned previously.

Figure 5.3 Profile of u^+ with Different Main Flow Rates ($x = 25$ cm)

Figures 5.3 and 5.4 show different profiles of u^+ and v^+ ($0 < y/h < 0.3$) at $x = 25$ cm in the presence of different main flow rates. The profiles of u^+ and v^+ show very similar trends, e.g., in the region $0 < y/h < 0.3$, u^+ and v^+ generally decrease with increasing y/h for all the $Q_0 = 6.24$ to 7 L/s.

Figure 5.4 Profile of v^+ with Different Main Flow Rates ($x = 25$ cm)

Figure 5.5 show different profiles of uv^+ ($0 < y/h < 0.3$) at $x = 25$ cm in the presence of different main flow rates. It can be clearly seen that the normalized shear stress profiles almost collapse into one curve, which indicates that the uv^+ profile is invariant with Q_0 . More specifically, in the region $0.02 < y/h < 0.3$, uv^+ and v^+ generally decrease with increasing y/h , while in the very near-bed region, uv^+ starts to increase with increasing y/h .

5.3.2 Effect of Suction Rates ($I_s = 0 \sim 3.0\%$) on Flow Field (Experimental Series II-2)

Figure 5.5 Profile of uv^+ with Different Main Flow Rates ($x = 25$ cm)

Figure 5.6 shows the flow fields in the near-bed region (from 0 to 2 cm above the sand bed) when the closed-conduit flow is subjected to various intensities of suction ($I_s = 0 \sim 3.0\%$). It must be noted that the dotted areas in the figures denote the sand bed and it is assumed that $y = 0$ refers to the interface between water and sand. The data clearly reveal that suction can significantly change the near-bed flow field in closed-conduit flows, especially in the very near-bed region for $0 \leq I_s \leq 2.32\%$ (from 0 to 0.2 cm above the sand bed). As I_s increases when $0 \leq I_s \leq 2.32\%$, the lengths of the velocity vector in the region from 0 to 0.2 cm above the sand bed increases, while it does not change much when $2.32\% \leq I_s \leq 3.0\%$. This means that suction can significantly increase streamwise velocity in the near-bed region when $0 \leq I_s \leq 2.32\%$, and it does not influence streamwise velocity in the near-bed region significantly when $2.32 \leq I_s \leq 3.0\%$. The change that occurs at $I_s = 2.32\%$ can be seen in many data sets of the study and the reason for this variation is discussed later.

Figure 5.6 Flow Fields in the Near-bed Region ($y = 0$ to 2 cm) with Different I_s

Figure 5.7 Horizontal Velocity Profiles with Different I_s ($x = 25$ cm, in the Middle of Suction Zone)

Figure 5.8 Vertical Velocity Profiles with Different I_s ($x = 25$ cm, in the Middle of Suction Zone)

Figure 5.7 shows different horizontal velocity profiles (from 0 to 2.8 cm above the sand bed) at $x = 25$ cm under different suction intensities ($I_s = 0 \sim 3.0\%$). The figure clearly shows that when $0 \leq I_s \leq 2.32\%$, the horizontal velocity profile becomes more uniform with increasing I_s . Moreover, the near-bed velocity u_b increases with increasing I_s in the near-bed region when $0 \leq I_s \leq 2.32\%$ (especially in the very near-bed region), which is consistent with previous researchers (Maclean, 1991a; Chen and Chiew, 2004; etc). However, variations of both the velocity profile and u_b with increasing I_s is not significant when $2.32\% < I_s \leq 3.0\%$.

Figure 5.8 shows the effect of suction intensity on the vertical velocity profiles at $x = 25$ cm with different suction intensities. The near-bed vertical velocity v_b becomes more negative with increasing I_s . This is not unexpected as water is being abstracted from the near-bed region in the presence of suction.

Figure 5.9 shows the normalized time-averaged streamwise velocity in the near bed region with $I_s = 0, 0.72, 1.21$ and 2.32% , respectively, which are fitted using both the universal and the modified log laws (Eq. 5.8). The shear velocity u_* at $x = 25$ cm from the leading edge of the suction zone, which is calculated to be 0.017 m/s ($Q_0 = 6.83$ L/s), is used to normalize the streamwise velocity. The figure shows that the streamwise velocity profile agrees well with the log law, $\frac{u}{u_*} = 2.5 \ln(y/d_{50}) + 8.6$. When fitting the data with suction using Eq. 5.8, the three unknown parameters, i.e., u_* , y_0 and u_s , are determined using the method described in Chen and Chiew (2004). The function of a second order polynomial was used in a software package (MATLAB 2013) to fit the data, which causes Eq. 5.8 to be rewritten as,

$$u = aX^2 + bX + c \quad (5.9)$$

where

$$X = \frac{1}{\kappa} \ln \frac{y + y_0}{y_0}, \quad a = \frac{v_s}{4}, \quad b = u_*, \quad c = u_s \quad \text{and} \quad \kappa = 0.4.$$

First, an arbitrary y_0 was assigned and the values of X for all the measured data calculated. After that, based on the fitted second order polynomial, the parameters v_s , u_* and u_s are computed. Then the computed v_s is compared with the measured v_s ($= Q_s/A_s$ and A_s is the area of the suction zone); if the error is larger than 0.2% , another y_0 would be assigned and the above procedures repeated until the error is less than 0.2% . Fig. 5.9 reveals that, the normalized streamwise velocity profile deviates more significantly from the universal log law when I_s becomes larger, but it agrees very well with the modified log law (Note that $u_* = 0.017$ m/s used for normalization of u in Fig. 5.9, with $I_s = 0$ for a meaningful comparison).

Figure 5.9 Comparison of Streamwise Velocity Profile with Different Suction Intensities ($I_s = 0, 0.72\%, 1.21\%$ and 2.32% ; $x = 25$ cm)

Although the streamwise velocity profiles with $I_s = 1.86, 2.64$ and 3.0% are not shown in Fig. 5.9, the values of u_* for all these suction intensities tested also are computed giving $u_* = 0.0305, 0.0467, 0.0669, 0.103, 0.088$ and 0.083 m/s for $I_s = 0.72, 1.21, 1.86, 2.32, 2.64$ and 3.0% , respectively, each increases with increasing I_s compared with $u_* = 0.017$ when $I_s = 0$. Note that u_* monotonically increases with I_s (from 0 to 2.32%), reaching a maximum of 0.103 m/s at $I_s = 2.32\%$, which corresponds to a more than 6-fold increment when compared to that without suction. Beyond this point, u_* decreases although the data still indicate a net increase when compared to that without suction. This reversal behaviour, although not mentioned in published literature hitherto except that inferred in Cao et al. (2014), is not unexpected. The turning point, which is also shown in Figs. 5.6 and 5.7, likely is due to the fact that if a significantly large amount of suction is applied, the net flow on the bed would have been reduced to such an extent that the bed shear stress would correspondingly reduce. In addition to the momentum influence

due to suction that augments the shear velocity, the reduced mass effect due to flow abstraction (suction) would lead to an opposite effect on the shear velocity. It is not unreasonable to surmise that if the suction rate approaches the in-coming flow rate, the net flow would be reduced to zero, leading to a zero shear stress on the bed. Based on the present experimental results, the mass effect appears to exert a certain influence on the resulting flow field when $I_s > 2.32\%$.

Figure 5.10 Profile of u^+ with Different I_s ($x = 25$ cm, in the Middle of Suction Zone)

Figures 5.10, 5.11 and 5.11 show the vertical variation of u^+ , v^+ and uv^+ profiles with different I_s . Figure 5.10 shows the profiles of u^+ at $x = 25$ cm in the presence of various suction intensities ($u_{*0} = 0.017$ m/s is used for normalization). In the region $0 \leq y/h < 0.3$, u^+ generally decreases as I_s increases from 0 to 2.32% and then increases from $I_s = 2.32\%$ to 3.0%, the turning point at $I_s = 2.32\%$, as previously discussed, likely is the reflection of the interplay between the mass and momentum influence on the flow field due to suction.

Figure 5.11 illustrates how the v^+ profiles at $x = 25$ cm vary with suction intensities. Similar to changes of the u^+ profile, for $0 \leq y/h < 0.3$, v^+ generally decreases as I_s increases from 0 to 2.32%, then increases with I_s again afterwards. Figure 5.12 shows how the uv^+ profiles at $x = 25$ cm vary with suction intensities. A similar behavior as the u^+ and v^+ profiles is observed in that uv^+ first decreases as I_s increases from 0 to 2.32%, then it increases with I_s afterwards.

Finally, the effect of suction intensity I_s on the flow characteristics is summarized in Table 5.1.

Figure 5.11 Profile of v^+ with Different I_s ($x = 25$ cm, in the Middle of Suction Zone)

Figure 5.12 Profile of uv^+ with Different I_s ($x = 25$ cm, in the Middle of Suction Zone)

5.3.3 Flow Variation with Distance in the Longitudinal Direction

In addition to examining the effect of suction intensities on the flow characteristics, the longitudinal development of the streamwise velocity profiles in the near bed region with a fixed suction rate at $I_s = 2.45\%$ also was investigated. Fig. 5.13 shows the streamwise velocity profiles at four horizontal locations, i.e. $x = 0, 10, 25, 32$ cm. The measured results show that the streamwise velocity profile has deviated from the universal log law, even at the leading edge of the suction zone ($x = 0$ cm). The variation of u with x (with a constant I_s) is generally similar to that of u with I_s (with a constant x). More specifically, the horizontal velocity in the near bed region increases and that in the upper region decreases. As a result, the velocity profile has become more uniform as x increases. Note that this is different from the results of Chen and Chiew (2004) who found that the near-bed streamwise velocity in an open channel flow first increases within certain distance x from the leading edge of the

suction zone before gradually decreasing with distance as the flow adapts to the sudden introduction of suction. The reason of the difference is as yet unclear and a possible reason is that the flow depth in the present study is constant while that in Chen and Chiew (2004)'s study was varied and the variation of the flow depth may have caused the difference.

Table 5.1 Summary of I_s -Effects on Flow Characteristics

<i>Flow characteristics</i>	<i>Effect of suction intensity, I_s</i>
Horizontal velocity, u	The profile of u becomes more uniform; u_b increases with I_s when $0 \leq I_s \leq 2.32\%$, while it decreases marginally beyond $I_s = 2.32\%$
Vertical velocity, v	v becomes more negative with increasing I_s for $0\% \leq I_s \leq 3.0\%$
u^+	u^+ generally decreases with increasing I_s for $I_s = 0$ to 2.32% and then increases with I_s for $I_s = 2.32\%$ to 3.0%
v^+	v^+ generally decreases with increasing I_s for $I_s = 0$ to 2.32% and then increases with I_s for $I_s = 2.32\%$ to 3.0%
uv^+	uv^+ generally decreases with increasing I_s for $I_s = 0$ to 2.32% and then increases with I_s for $I_s = 2.32\%$ to 3.0%

Figure 5.13 Streamwise Velocity Profiles at Different Horizontal Distance from the Leading Edge of the Suction Zone ($I_s = 2.45\%$)

In summary, it may be inferred that changing the suction intensity (I_s) has a similar effect on the streamwise velocity profile as changing the suction zone length, both of which increase the near-bed horizontal velocity u_b , resulting in a more uniformly distributed near-bed streamwise velocity profile. This is because I_s denotes the velocity effect, while the suction zone length represents the mass effect and the overall effect on the flow is attributed to the combined effects of velocity and mass.

Figure 5.14 shows how the u^+ profile varies with the horizontal distance x . It shows that in the region from $y/h = 0$ to 0.3 , u^+ generally decreases with increasing x (from 0 to 32 cm). However, u^+ from $y/h = 0$ to 0.05 at $x = 25$ and 32 cm increases with y/h , which is different from that at $x = 0$ and 10 cm. This likely is because as more of the water is abstracted with increasing x , the larger mass transfer that occurs near the fluid-solid interface would have caused a larger turbulence in the near-bed region.

Figure 5.14 Profile of u^+ at Different Horizontal Distance from the Leading Edge of the Suction Zone ($I_s = 2.45\%$)

Figure 5.15 Profile of v^+ at Different Horizontal Distance from the Leading Edge of the Suction Zone ($I_s = 2.45\%$)

Figure 5.16 Profile of uv^+ at Different Horizontal Distance from the Leading Edge of the Suction Zone ($I_s = 2.45\%$)

Table 5.2 Summary of the Effects of x on Flow Characteristics

<i>Flow characteristics</i>	<i>Effect of horizontal distance, x</i>
Horizontal velocity, u	u becomes more uniform with increasing x for $0 \leq x \leq 32$ cm
u^+	u^+ decreases with increasing x for $0 \leq x \leq 32$ cm
v^+	v^+ decreases with increasingly larger x for $0 \leq x \leq 32$ cm
uv^+	uv^+ decreases with increasing x and becomes more uniform for $0 \leq x \leq 32$ cm

Figure 5.15 describes how the v^+ profile varies with the horizontal distance x . It shows that in the region from $y/h = 0$ to 0.3 , v^+ decreases x from 0 to 32 cm. However, the decreasing trends of v^+ with y/h at $x = 25$ and 32 cm is not as apparent as those at $x = 0$ and 10 cm, leading to a more uniform v^+ profile as x increases.

Figure 5.16 describes the effect of x on the uv^+ profile. It shows that when $0 < y/h < 0.3$, uv^+ decreases with x from 0 to 32 cm, while when $0 < y/h < 0.05$, the uv^+ profiles at $x = 25$ and 30 cm are somewhat different from those at $x = 0$ and 10 cm, i.e., they decrease with increasing y/h for $0 < y/h < 0.05$, contrary to those at $x = 0$ and 10 cm. Generally, the uv^+ profiles become more uniform as x becomes larger.

In summary, the effect of distance from the leading edge of the suction zone, x on the flow characteristics when $I_s = 2.45\%$ is tabulated in Table 5.2.

5.4 TURBULENT ENERGY BUDGET

Figure 5.17 Profile of F_{ku} with Different I_s ($x = 25$ cm, in the Middle of Suction Zone)

Figures 5.17 and 5.18 show suction effects on the profiles of the normalized streamwise and vertical turbulent kinetic energy fluxes F_{ku} and F_{kv} , respectively,

where $F_{ku} = \frac{0.75 \times (\overline{u'u'u'} + \overline{u'v'v'})}{u_*^3}$ and $F_{kv} = \frac{0.75 \times (\overline{v'v'v'} + \overline{v'u'u'})}{u_*^3}$ (Raupach, 1981;

Krogstadt and Antonia, 1999). F_{ku} and F_{kv} reflect the turbulent energy fluxes in the streamwise and vertical directions, respectively. Fig. 5.17 shows that F_{ku} generally decreases with y/h for the entire measured depth when there is no suction. When suction is present, the F_{ku} profile changes appreciably. More specifically, F_{ku} first decreases with increasing I_s from $I_s = 0$ to 1.86%; followed by an abrupt increase in F_{ku} when I_s increases from $I_s = 1.86$ to 2.32%. As I_s continues to increase from 2.32 to 3.0%, F_{ku} decreases marginally again. Moreover, there is a turning point for the F_{ku} profile at $y/h \approx 0.25$ when suction is introduced. Generally, F_{ku} with suction is smaller than that without suction, supporting the hypothesis that introducing suction leads to more of the turbulent energy to be transported upstream (Dey and Nath, 2010).

Figure 5.18 Profile of F_{kv} with Different I_s ($x = 25$ cm, in the Middle of Suction Zone)

Similar to F_{ku} , Fig. 5.18 shows that F_{kv} generally decreases with y/h for the entire measured depth in the absence of suction. However, the influence of suction on the F_{kv} profile is not as obvious as F_{ku} , which is consistent with Dey and Nath (2010)'s findings. From $y/h = 0$ to 0.1, F_{kv} first increases from $I_s = 0$ to 1.86%. Later there is an abrupt decrease in F_{kv} when I_s increases from 1.86 to 2.32%. As I_s continues to increase from 2.32 to 3.0%, F_{kv} decreases marginally again. Generally, the F_{kv} profile becomes more uniform as I_s increases. It is worthwhile to note that F_{kv} is mostly positive while F_{ku} is generally negative. The negative value of F_{ku} and positive value of F_{kv} over the entire measured depth signify that the turbulent flux of energy is transported upstream and the vertical flux of energy is transported in the upward direction, respectively.

Figures 5.19 to 5.22 show suction effects on the profiles of the normalized turbulent production T_P , turbulent dissipation E_D , turbulent energy diffusion T_D and pressure energy diffusion P_D , respectively, where $T_P = \overline{-u'v'}(\partial u / \partial y) \times h / u_*^3$, $E_D = \frac{15\nu}{u^2} \left(\frac{\partial u'}{\partial t} \right)^2 \times h / u_*^3$, $T_D = \partial F_{kv} / \partial y \times h$ and $P_D = T_P - E_D - T_D$ (Dey & Nath, 2010).

T_P represents the rate of turbulent energy that is transferred from the mean flow to turbulence. Figure 5.19 shows that when there is no suction, T_P decreases rapidly with y/h from $y/h = 0$ to 0.2 until it becomes almost invariant with y/h from $y/h = 0.2$ to 0.3. The influence of suction on the T_P profile is appreciable in that T_P generally decreases with increasing I_s for $y/h = 0$ to 0.3. A positive value of T_P means that the energy is readily converted from the time-averaged flow to turbulence, and vice versa. Therefore, it may be inferred from Fig. 5.19 that suction reduces turbulence in the region from $y/h = 0$ to 0.3 when $0 \leq I_s \leq 2.32\%$ and the effect of suction is not significant when $2.32 \leq I_s \leq 3.0\%$. Generally, variation of T_P with I_s reflects that of $\overline{-u'v'}$ with I_s .

Figure 5.19 Profile of T_P with Different I_s ($x = 25$ cm, in the Middle of Suction Zone)

E_D represents the diffusion of turbulent energy due to molecular transport process of fluid. Figure 5.20 shows that when there is no suction, E_D decreases rapidly with y/h from $y/h = 0$ to 0.3. The effect of suction on the E_D profile is clear: E_D decreases with a much slower rate with y/h for the entire measured depth when $I_s = 1.86\%$ is applied and the values of E_D with $I_s = 1.86\%$ are smaller for $0 \leq y/h \leq 0.1$ and larger for $0.1 \leq y/h \leq 0.3$ compared to those without suction. As I_s increases from 1.86 to 2.32%, the E_D profile becomes more uniform and smaller compared to that without suction over the entire measured depth. As I_s continues to increase from 2.32 to 3.0%, E_D increases marginally although the values over the entire depth are less than those without suction. Moreover, the profile becomes more uniform.

T_D represents the rate at which turbulent kinetic energy is transported through the fluid by turbulent fluctuation. Figure 5.21 shows that when there is no suction, T_D increases rapidly first from $y/h = 0$ to 0.2 and decreases with y/h from $y/h = 0.2$ to

0.3. Although the effect of suction on the T_D profile is not as apparent as T_P and E_D , its influence is sufficiently clear. Generally, the T_D profiles become more uniform as suction intensities increase, which means that T_D increases in the lower region ($y/h = 0$ to 0.2) and decreases with increasing I_s in the upper region ($y/h = 0.2$ to 0.3).

P_D represents the rate at which turbulent kinetic energy is transported through the fluid due to pressure. Figure 5.22 shows that when there is no suction, P_D first decreases from $y/h = 0$ to 0.2 and later increases with y/h from $y/h = 0.2$ to 0.3 . The effect of suction on P_D is significant: over the entire depth, P_D decreases when I_s increases from 0 to 1.86% . Later it increases significantly as I_s continues to increase from 1.86 to 2.32% and finally it decreases marginally from $I_s = 2.32$ to 3.0% , with the profiles remaining essentially unchanged. Since negative values of T_D and P_D indicate an increase in turbulent production, Fig. 5.22 reveals that the introduction of a small suction will lead to a larger turbulence production, while a larger suction would lead to a decrease in turbulence compared to that without suction.

Figure 5.20 Profile of E_D with Different I_s ($x = 25$ cm, in the Middle of Suction Zone)

Figure 5.21 Profile of T_D with Different I_s ($x = 25$ cm, in the Middle of Suction Zone)

Figure 5.22 Profile of P_D with Different I_s ($x = 25$ cm, in the Middle of Suction Zone)

Nezu and Nakagawa (1993) reported that T_P is almost balanced by E_D and T_D nearly equals to P_D . It is interesting to note here that the profiles of E_D resemble those of T_P with a gap. The gap becomes larger when $0 \leq I_s < 2.32\%$ and later becomes smaller when $2.32\% \leq I_s \leq 3.0\%$. Moreover, the profiles of T_D are almost mirror images of those of P_D . In summary, the present results are similar to those reported in Dey and Nath (2010).

Finally, the effect of I_s on turbulent energy budget is summarized in Table 5.3.

Table 5.3 Summary of I_s -Effects on Turbulent Energy Budget

<i>Flow characteristics</i>	<i>Effect of suction intensity, I_s</i>
F_{ku}	F_{ku} first decreases with increasing I_s when $0 \leq I_s < 1.86\%$. There is an abrupt increase in F_{ku} when $1.86\% \leq I_s < 2.32\%$. When $2.32\% \leq I_s < 3.0\%$, F_{ku} decreases marginally again.
F_{kv}	The effect of I_s on F_{kv} is small
T_P	T_P generally decreases and becomes more uniform with increasing I_s
E_D	E_D generally decreases and becomes more uniform with increasing I_s
T_D	T_D generally becomes more uniform with increasing I_s for $I_s = 2.32$ to 3.0%
P_D	P_D generally becomes more uniform with increasing I_s for $I_s = 2.32$ to 3.0%

5.5 CONCLUDING REMARKS

Past researchers, e.g., Clark et al. (1955), Chen & Chiew (2004), etc. have found that the universal log law is not valid in an open channel flow with suction and have theoretically derived appropriate equations to describe the velocity profile in such cases. In the present study, a modified log law in a closed conduit was derived theoretically and the flow characteristics, including horizontal and vertical velocities and turbulence, were experimentally measured by using PIV techniques. The measured results show that the flow near-bed characteristics of closed-conduit flows change significantly in the presence of suction. The following specific conclusions are drawn from the study:

- 1) The streamwise velocity in the very near-bed region increases substantially as the suction intensity increases, making the profile more uniform. The vertical velocity becomes more negative with increasing suction intensities.
- 2) The turbulence intensities and Reynolds shear stress generally decrease with increasing suction intensity within a certain range ($0 \leq I_s \leq 2.32\%$); beyond this range they start to increase gradually above the very-near bed region. The turning point at $I_s = 2.32\%$ is probably because a large amount of suction would cause a significantly large reduction of net flow on the bed and thus a reduced bed shear stress. In addition to the momentum influence due to suction that augments the shear velocity, the reduced mass effect due to flow abstraction (suction) would lead to an opposite effect on the shear velocity.
- 3) The universal log law does not fit the data with suction, especially in the very near-bed region, while the modified log law show very good agreement with the data. The fitted value of u_* increases with I_s when $0 \leq I_s \leq 2.32\%$ and decreases marginally with I_s when $2.32 \leq I_s \leq 3.0\%$.
- 4) The experimental data associated with the longitudinal development of the streamwise velocity profiles show that the near bed horizontal velocity increases as the flow moves into the suction zone, rendering the profile in the near-bed region to become more uniform. The variation of u with x (with

a constant I_s) is generally similar to that of u with I_s (with a constant x) because increasing either x or I_s will both lead to more mass and momentum transfer across the permeable interface.

- 5) Generally, the profiles of F_{ku} , F_{kv} , T_P , E_D , T_D and P_D become more uniform with increasing suction. The turbulent energy budget shows that the streamwise flux of energy is transported upstream and the vertical flux of energy is transported in the upward direction.

Chapter 6

Special Issues on the Effect of Suction Zone Length and Sediment Size, etc

6.1 INTRODUCTION

Few researchers have hitherto reported the effect of suction zone length on sediment transport. In this chapter, the effect of suction zone length on sediment transport rate is investigated and discussed.

The data in Chapter 4 have shown that suction can increase the transport rate of coarse sand particles with $d_{50} = 0.84$ mm. In this chapter, the effect of suction on the transport rate of finer sand particles with $d_{50} = 0.39$ and 0.8 mm is studied and compared.

In addition, only suction effects on flow and sediment transport rate are studied and discussed in the previous chapters. In this chapter, the comparison of suction and injection effects on sediment transport rate in both open channel and closed-conduit flows are presented.

6.1.1* Suction Zone Length Effect on Sediment Transport Rate

Table 2.2 clearly reveals that different results have been obtained by different researchers in the study of seepage effects. It also shows how some of these researchers utilized suction velocity, V_s , while others had used suction rates, Q_s as the variable in analyzing suction effects on sediment transport rate. It may be inferred from this observation that conflicts still exist on whether V_s or Q_s is a more appropriate factor to account for sediment transport rate. Finally, as the suction zone length is fixed in most of these studies, its effect has rarely, if ever, been reported. In her doctoral study, Liu (2010) did change the suction zone length and studied its effect on sediment transport rate. However, she chose V_s as the variable in her analysis, which is different from the approach in this study.

Consequently, the present experiments were carried out to investigate suction effects on sediment transport in a closed conduit with three different suction zone lengths. In the results, comparison was made with Liu (2010)'s data conducted in open channel flow. Moreover, velocity measurements were conducted using Particle Image Velocimetry and the data are used to explain the effect of suction zone length. Finally, with the present data and those from Liu (2010), a modified dimensionless Froude number is developed.

6.1.2 Sediment Size Effect on Sediment Transport Rate

Although the data of the present study (see Chapter 4) have shown that suction can increase sediment transport rate in closed-conduit flow for sand particles with $d_{50} = 0.84$ mm, whether the same inference can be made for sand particles with a different d_{50} is still unknown. To clarify this uncertainty, suction effects on sediment transport rate for sediment particles with $d_{50} = 0.8$ and 0.39 mm are studied and discussed in this chapter.

The detailed experimental setup and procedures are the same as that for sand with $d_{50} = 0.84$ mm and can be found in Chapter 3, which will not be reproduced here.

* Suction zone length effect is part of Cao et al. (2015), which has been published in Journal of Hydraulic Research

6.2 EXPERIMENTAL RESULTS AND DISCUSSIONS

6.2.1 Suction Zone Length Effect on Sediment Transport Rate (Experimental Series III-1)

Table 6.1 shows the test conditions and measured sediment transport rates for Test Series III-1A ($L = 0.5$ m and $L/h = 5.40$, h = water depth), III-1B ($L = 0.2$ m and $L/h = 2.16$) and III-1C ($L = 0.1$ m and $L/h = 1.08$). It must be noted at the outset that Q_0 used in all the tests is 7 L/s, which corresponds to a computed approach shear velocity ratio, $u_{*0}/u_{*0c} = 0.997$ (without suction), in which u_{*0} = undisturbed approach shear velocity and u_{*0c} = critical shear velocity for bed sediment entrainment. The methods of calculating u_{*0} and u_{*0c} are the same as those mentioned in Chapter 4. Test III-1B-1 corresponds to such a condition (with suction zone length = 0.2 m) and the sediment transport rate q_b is measured to be 0.3×10^{-9} m²/s. In the other extreme, Test III-1A-9 shows the largest measured volumetric bedload transport rate per unit width, $q_b = 0.2012 \times 10^{-6}$ m²/s. Thus the maximum average scouring depth over the suction zone with length = 0.5 m, $d_s = q_b \times t/L = 0.2012 \times 10^{-6} \times 5 \times 60 / 0.5 \approx 0.12$ mm. As $d_{50} = 0.80$ mm, less than one layer of sand is entrained by the flow and scouring is negligible. Moreover, neither ripples nor dunes were observed during the experiments. Therefore, the sediment bed remains essentially planar for the given sediment transport rates within the entire 15-minute test duration for all the tests. In the experiments, the undisturbed approach flow rate, $Q_0 = 7$ L/s is chosen to be the baseline condition and all tests were conducted with this approach flow rate.

Table 6.1 Test Conditions and Experimental Data ($Q_0 = 7$ L/s, $u_{*0}/u_{*0c} = 0.997$)

<i>Test Number</i>	<i>Suction zone length (m)</i>	<i>Suction rate, Q_s (L/s)</i>	<i>Suction velocity, V_s (m/s)</i>	<i>Bedload transport rate, q_b (10^{-6} m²/s)</i>
(1)	(2)	(3)	(4)	(5)

III-1A-1	0.5	0.000	0.0000	0.0011
III-1A-2	0.5	0.150	0.0010	0.0011
III-1A-3	0.5	0.294	0.0020	0.0008
III-1A-4	0.5	0.400	0.0027	0.0030
III-1A-5	0.5	0.563	0.0038	0.0038
III-1A-6	0.5	0.670	0.0045	0.0046
III-1A-7	0.5	0.810	0.0054	0.0280
III-1A-8	0.5	0.960	0.0064	0.0631
III-1A-9	0.5	1.200	0.0080	0.2012
III-1B-1	0.2	0.000	0.0000	0.0003
III-1B-2	0.2	0.120	0.0020	0.0005
III-1B-3	0.2	0.256	0.0043	0.0006
III-1B-4	0.2	0.380	0.0063	0.0016
III-1B-5	0.2	0.486	0.0081	0.0025
III-1B-6	0.2	0.610	0.0102	0.0050
III-1B-7	0.2	0.840	0.0140	0.0263
III-1B-8	0.2	0.950	0.0158	0.0505
III-1B-9	0.2	1.100	0.0183	0.0764
III-1C-1	0.1	0.000	0.0000	0.0009
III-1C-2	0.1	0.130	0.0043	0.0008
III-1C-3	0.1	0.294	0.0098	0.0009
III-1C-4	0.1	0.352	0.0117	0.0012
III-1C-5	0.1	0.420	0.0140	0.0017
III-1C-6	0.1	0.550	0.0183	0.0052
III-1C-7	0.1	0.670	0.0223	0.0102
III-1C-8	0.1	0.800	0.0267	0.0163
III-1C-9	0.1	0.930	0.0310	0.0305

Note: The data with test number starting from III-1A, III-1B and III-1C are the experimental results with suction zone length = 0.5, 0.2 and 0.1m, respectively. The data in columns 2, 3 and 5 are measured directly.

Figs. 6.1(a) and (b) show the dimensionless volumetric sediment transport rate, Φ plotted against the normalizing parameters V_s/U_0 and Q_s/Q_0 , respectively. Although Φ increases with both V_s/U_0 and Q_s/Q_0 , the increasing trends for different suction zone lengths show variations as illustrated in the figure. Fig. 6.1(a) reveals that at the same V_s/U_0 , Φ differs significantly for different suction zone lengths. Generally, Φ increases with increasing suction zone length for the same V_s/U_0 . For instance, Fig. 6.1(a) shows that at $V_s/U_0 = 3.2\%$, $\Phi \approx 9 \times 10^{-6}$, 2.5×10^{-5} and 2×10^{-3} for the case with $L/h = 1.08$, 2.16 and 5.40 respectively. The volumetric sediment transport rate associated with $L/h = 5.40$ is found to be more than 220 times that associated with $L/h = 1.08$. In other words, a five-fold increase in suction zone length has led to more than 220-fold increase in sediment transport rate! On the other hand, Fig. 6.1(b) shows that the data collapse into one unique curve for different suction zone lengths. Therefore, it may be inferred from the figure that sediment transport rate is better correlated with Q_s/Q_0 than V_s/U_0 . Another inference one may deduce from the data in the figure is that the effect of either Q_s/Q_0 or V_s/U_0 on Φ is negligible for small values of these parameters until a critical value is reached. Beyond this threshold, the sediment transport rate increases abruptly.

A cursory examination reveals that $Q_s/Q_0 = V_s/U_0 \times L/h$, which means that Q_s/Q_0 includes both the effects of the suction velocity ratio, V_s/U_0 and mass rate transferred across the permeable bed due to suction (mass rate = $\rho \times V_s \times b \times L = \rho \times Q_s$) on sediment transport rate. Fig. 6.1 shows that increasing L when keeping V_s as a constant has the same effect as increasing V_s when keeping L as a constant. In both instances, the sediment transport rate is increased because of the increase in either the mass or velocity. In order to confirm this behavior, a comparison is conducted with the data in Liu (2010) conducted in open channel flow. In order to carry out a logical comparison, dimensionless numbers are determined through the conduct of a dimensional analysis to account for all the possible factors that may influence sediment transport rate. It is assumed that the volumetric sediment transport rate per

unit width, q_b is a function of the following independent variables, including d_{50} ; sediment density, ρ_s ; water density, ρ ; gravitational acceleration, g ; sediment porosity, n ; hydraulic conductivity, K ; V_s , U_0 , shear velocity without suction, u_{*0} ; L and h . Hence, the general function of q_b may be expressed as follows:

$$q_b = f(d_{50}, \rho_s, \rho, g, n, K, U_0, V_s, u_{*0}, L, h) \quad (6.1)$$

The variables d_{50} , ρ and g were chosen as repeating variables for the dimensional analysis, resulting in the following nine pi terms: $\frac{q_b}{\sqrt{d_{50}^3 g}}$, $\frac{\rho_s}{\rho} = S_s$, n , $\frac{K}{\sqrt{d_{50} g}}$,

$\frac{U_0}{\sqrt{d_{50} g}}$, $\frac{V_s}{\sqrt{d_{50} g}}$, $\frac{u_{*0}}{\sqrt{d_{50} g}}$, $\frac{L}{d_{50}}$ and $\frac{h}{d_{50}}$, which are reduced to the following three

dimensionless groups:

$$\Phi = \frac{q_b}{\sqrt{d_{50}^3 g (S_s - 1)}} = f \left\{ \frac{u_{*0}^2}{(S_s - 1) d_{50} g}, \frac{U_0^2}{\left[(S_s - 1)(1 - n) - \frac{V_s}{K} \cdot \frac{L}{h} \right] d_{50} g} \right\} \quad (6.2)$$

where Shields' parameter, which describes the initial condition of sediment bed

before seepage is introduced, $\tau_{*0} = \frac{u_{*0}^2}{(S_s - 1) d_{50} g}$ and $\Omega_{Q_s} =$

$\frac{U_0^2}{\left[(S_s - 1)(1 - n) - \frac{V_s}{K} \cdot \frac{L}{h} \right] d_{50} g}$, which is a new modified Froude number that includes

the effect of L and h ($\Omega_{V_s} = \frac{U_0^2}{\left[(S_s - 1)(1 - n) - \frac{V_s}{K} \right] d_{50} g}$).

Because $Q_s/Q_0 = V_s/U_0 \times L/h$, Ω_{Q_s} may be re-written as,

$\Omega_{Q_s} = \frac{U_0^2}{\left[(S_s - 1)(1 - n) - \frac{Q_s}{Q_0} \cdot \frac{U_0}{K} \right] d_{50} g}$, which contains the ratio of the suction rate

and undisturbed flow rate, Q_s/Q_0 .

Figure 6.1 Dimensionless Volumetric Sediment Transport Rate, Φ Plotted against (a) V_s/U_0 ; (b) Q_s/Q_0 in Closed-conduit Flow

The new dimensionless parameter Ω_{Q_s} contains Q_s/Q_0 , which is the product of V_s/U_0 and L/h . The former accounts for the suction velocity effect, which is implied in the original Ω_{V_s} while the latter accounts for the mass effect. The product of the suction velocity and mass rate across the sediment bed is equivalent to the momentum transfers across the sediment bed, which is related to the combined effects of V_s/U_0 and L/h on sediment transport. When there is no suction, the undisturbed approach flow momentum, $M_0 (= \rho \times Q_0 \times U_0 = \rho \times U_0^2 \times bh)$ will affect the sediment transport rate, q_{b0} . When suction is present, V_s and L will reduce the effective approach flow rate, Q_0' as $Q_0' = Q_0 - V_s.L.b$ (b = width of the conduit), causing the approach momentum, $M_0' [= \rho \times Q_0' \times U_0' = \rho \times (U_0 - V_s.L/h)^2 \times bh]$ to be smaller. With the momentum transfer across the sand bed $M_t (= \rho \times V_s^2 \times Lh)$, they will influence the sediment transport rate, q_b . Hence, the ratio of q_b/q_{b0} should be a function of $(V_s/U_0 \times L/h)$ or Q_s/Q_0 rather than V_s/U_0 per se.

By re-looking at the whole physical process with an integral analysis over the entire suction zone length, the data of sediment discharge in the present study are not related to the sediment flux along the reach, but to the sediment flux exiting it, which is equal to the integral scoured volume (as no entering sediment flux is present). From these considerations, it appears conceptually clearer that the seepage flux, Q_s (integral variable over the entire zone length), rather than the seepage velocity, V_s (distributed along the suction zone), is the dominant control parameter for the problem.

The hypothesis that Ω_{Q_s} is a better parameter than Ω_{V_s} for use to correlate suction with sediment transport rate may be validated by using the experimental results of Liu (2010). In her doctoral study, Liu (2010) conducted the experiments in an open channel flume that is 30 m long, 0.7 m wide and 0.6 m deep, with a suction zone = 0.4 m depth located in the middle of the flume. The flume and suction zone is filled with uniform sand with $d_{50} = 0.48$ mm and three different zone lengths = 0.5, 1 and 2 m. The way the suction zone length was varied is the same as that in the present study, i.e., by inserting an impervious plastic plate with the specific length below the sand (see Fig. 3.4). In total, four sets of experiments with four different values

of $u_{*0}/u_{*0c}=0.98, 1.05, 1.08$ and 1.16 , were conducted. Figs. 6.2(a) and (b) plot all the data of the present study in closed-conduit flow ($u_{*0}/u_{*0c}=0.997$) and those from Liu (2010). It should be noted that Fig. 6.2(a) and (b) are plotted with Φ as a function of Ω_{V_s} and Ω_{Q_s} , respectively on a log-log scale in order to provide a better display of all the data.

Fig. 6.2 clearly shows that Φ is empirically better correlated to Ω_{Q_s} than Ω_{V_s} . Since sediment transport rate is closely related to the flow field, the results in Fig. 6.2(a) and (b) may be explained by examining the flow behavior. Consideration of the data in Fig. 6.2(a) reveals that on the one hand, decreasing Ω_{V_s} leads to an increase in Φ , indicating that larger V_s/U_0 will result in larger q_b when the suction zone length is fixed. This probably is because the horizontal approach velocity at the particle level, u_b increases with larger V_s/U_0 , leading to a larger driving force that increases sediment transport rate. Chen and Chiew (2004) had earlier used Laser Doppler Anemometry to measure the flow characteristics in a 32 m long open channel with a 2-m length suction zone. They found that the slip velocity (streamwise velocity at the interface between fluid and particle) increases when a larger V_s/U_0 is present. Similar results also can be found in Maclean (1991a). To verify if the same result also applies in a closed conduit, streamwise velocity profiles at a fixed horizontal location $x = 25$ cm (x denotes the horizontal distance from the leading edge of the suction zone) in the near-bed region subjected to 8 different V_s/U_0 were measured using the PIV in the present study and the result is shown in Fig. 6.3. The figure, which shows the near-bed streamwise velocity profile at the same distance from the leading edge of the suction zone, reveals that the streamwise velocity in the near-bed region (below the dashed line in Fig. 6.3; $y < 0.2$ cm), u_b generally increases with increasing V_s/U_0 . Consequently, one may surmise that a larger driving force is present to entrain the sediment particles at a high rate, resulting in a larger q_b .

On the other hand, Fig. 6.2(a) also shows that with the same V_s/U_0 , a larger L/h leads to a larger q_b , a phenomenon that is also related to the flow field. Chen and Chiew (2004) found that the streamwise velocity profile becomes more uniform as the flow moves into the suction zone.

Figure 6.2 Φ as a Function of (a) Ω_{V_s} ; (b) Ω_{Q_s} (Notes: 0.997, 0.98, 1.05, 1.08 and 1.16 denote the value of u_{*0}/u_{*0c} , while the rest of the data denote the value of L/h in Fig. 6.2a. They are written only in forms of number due to space constraint.)

Figure 6.3 Horizontal Velocity Profiles in the Near-bed Region under Different V_s/U_0 at $x = 25$ cm (Figure 5.7 reproduced here)

Figure 6.4 Horizontal Velocity Profiles in the Near-bed Region at Different Horizontal Distance from the Leading Edge of the Suction Zone

To examine if the same behavior is present in closed-conduit flow, streamwise velocity profiles in the near-bed region at four horizontal locations, i.e. $x = -1, 2, 10$ and 25 cm were measured and the results shown in Fig. 6.4. The measured data show that the near-bed velocity increases significantly (below the dashed line in Fig. 6.4; $y < 0.2$ cm) and the velocity in the upper region does not change as significantly as that in the lower region, which means that the velocity profile has become more uniform as x increases, a behavior that is consistent with the data of

Chen and Chiew (2004). It can thus be inferred that the approach velocity at the near-bed particle level, u_b increases as L becomes larger.

Based on these comparisons, one may deduce that the effect of suction by varying the suction intensity (V_s/U_0) is the same as that by varying the suction zone length, e.g. both of which causes the streamwise velocity profile in the near-bed region to become more uniform and the horizontal velocity, u_b at the particle level to increase. Since increasing u_b will lead to a larger driving force, the sediment transport rate will correspondingly increase. Examination of the data in Fig. 6.2(b) reveals that decreasing Ω_{Q_s} also leads to an increase in Φ , showing that increasing Q_s/Q_0 leads to a larger q_b . This trend supports the hypothesis outlined above. However, a major difference between Figs. 6.2(a) and (b) is that all the data with the same u_{*0}/u_{*0c} and different L/h collapse when Φ is plotted with Ω_{Q_s} . This confirms that increasing V_s/U_0 (velocity effect) and increasing L/h (mass effect) has the same effect, i.e., both can increase the sediment transport, and their combined effects may be incorporated into a single parameter, namely Ω_{Q_s} .

At this juncture, one may ask the question: When V_s/U_0 and h remain constant, will q_b increase indefinitely with L ? In section 5.3.2, a relatively simple explanation is given for the turning point of u_* at $I_s = 2.32\%$. Because q_b is related to u_* , a more detailed explanation of the turning point is discussed here. One may conduct a thought experiment and the result is illustrated in Fig. 6.5, which shows that q_b will first increase with increasing L until a critical value, beyond which q_b will decrease and gradually approaches zero when L becomes very large. The reason for the reduced sediment transport rate is because in the presence of suction, water is continuously abstracted from the suction zone. Although the velocity effect dominates initially, causing q_b to increase (as is seen in Fig. 6.1); at some length L , the mass effect becomes important when Q_s approaches Q_0 . At this juncture, much of the incoming water is abstracted from the suction zone, resulting in significantly less flow on the bed. Consequently, the momentum of the bed decreases, resulting in a reduction of the sediment transport rate. Therefore, a turning point as shown in Fig. 6.5 should occur due to the interplay between the velocity and mass effects.

The same occurrence also should occur if V_s is allowed to increase indefinitely for given values of Q_0 and L . This is because very large V_s will similarly lead to large Q_s that may significantly reduce the flow rate on the bed. At this juncture, the reduced sediment transport rate likely will cause significant sediment deposition because the sediment particles transported from upstream are no longer able to continue their motion downstream due to large changes to the local flow condition. At the limiting condition, one may also hypothesize that if the flow rate is reduced to be equal to the critical flow rate needed for bed sediment entrainment, Q_c , the sediment transport rate will become zero because the applied bed shear stress is less than that needed for sediment entrainment. In summary, decreasing L or V_s likely will have similar effect because they both directly influence the effective flow rate on the bed. The turning point of u_* at $I_s = 2.32\%$ in Chapter 5 also confirms the thought experiment.

Figure 6.5 Effect of Suction Zone Length, L on q_b When L Becomes Infinitely Large

In fact, the effect of suction zone length on sediment transport rate has been noticed by past researchers. Oldenziel and Brink (1974), who conducted their tests in a 4-m

long suction zone in a 15-m long flume, found that suction decreased sediment transport rate. Willets and Drossos (1975), on the other hand, applied a short suction zone (0.125 m) in a 3.6 m long open channel flume and found that sediment transport rate increased with suction rate. Willets and Drossos (1975) were confused with the conflicting inferences deduced from their own results when compared with those of Oldenziel and Brink (1974). They surmised that the disparity was due to different suction zone lengths used and deduced the grain transport rate would decrease in a long zone of uniform suction. However, based on the experimental results of Liu (2010) (with tests conducted in a 32 m long flume with a 2 m long suction zone, the data shows that sediment transport rate increases in the suction zone) and Rao et al. (2011) (with tests conducted in a 25 m long flume with a 15 m long suction zone, the data also shows that sediment transport rate increases in the suction zone), the grain transport rate did not decrease with this significantly larger length. On the contrary, the data in Fig. 6.1(a) and those in Liu (2010) and Rao et al. (2011) show that a larger suction zone length will lead to larger sediment transport rate when $V_s/U_0 = \text{constant}$.

Then what could have caused the different conclusions obtained by different researchers shown in Table 2.2? Fig. 6.1(b) show that q_b increases marginally with Q_s before a certain critical value of Q_s/Q_0 . In other words, the effect of Q_s on q_b will only be apparent when the applied suction rate is large enough. The different values of Q_s/Q_0 used by Oldenziel and Brink (1974) and Willets and Drossos (1975) may be the cause of the different conclusions drawn by them. The former used small suction rates ($Q_s/Q_0 < 3\%$) while the latter used suction rates Q_s/Q_0 of 5% to 12.5%. The data in Table 6.1 and Fig. 6.1(b) shows that q_b is not sensitive to the change of Q_s/Q_0 when $Q_s/Q_0 < 5.6\%$ ($Q_s < 0.4$ L/s). Furthermore, O'Donnell et al (2002) experimentally found that suction effect is marginal on sediment transport rate, which is probably because they applied a low Q_s/Q_0 .

The notion that Q_s/Q_0 rather than V_s/U_0 better correlates sediment transport rate not only have potential application in fluvial erosion, but also in the field of membrane science. Up to now, many researchers in the field of membrane research used flux ($= Q_s/A_m$, where A_m = membrane surface area. Note that membrane scientists have

used the term flux to denote velocity) to study the performance of membrane (Field et al. 1995, Li et al. 1998, etc), as it is widely believed that increasing flux beyond a certain threshold value would lead to membrane fouling or foulant accumulation on the membrane surface. It should be noted that a closed-conduit flow subjected to suction resembles a cross-flow membrane system in many ways. Because the length of the membrane surface can be designed and varied in the manufacturing process, the effect of suction zone length should be incorporated into the design. Therefore, Q_s/Q_0 could be a better parameter as it is better related to the suction effect in the membrane treatment process.

6.2.2 Sediment Size Effect on Sediment Transport Rate (Experimental Series III-2)

In all the previous studies that involves sediment transport rate, only sand particles with $d_{50} = 0.8$ and 0.84 mm were used. In this experiment series (Series III-2), sediment particles with $d_{50} = 0.8$ and 0.39 mm were used.

Table 6.2 shows the test conditions and measured sediment transport rates for Test Series III-2A ($d_{50} = 0.8$ mm) and III-2B ($d_{50} = 0.39$ mm). It should be noted that Series III-2A is in fact the same as Series III-1A, which is put here in order to compare with Series III-2B.

Fig. 6.6 presents the dimensionless volumetric sediment transport rate, Φ plotted against the normalizing parameters Q_s/Q_0 for tests III-2A and III-2B in Table 6.2. It should be noted that u_{*0}/u_{*0c} (without suction) is calculated to be 0.997 and 0.96, respectively for tests III-2A and III-2B, which is less than 1, indicating that the sediment particles are expected to be slowly entrained by the flow. In addition, as the hydraulic conductivity decreases for sand particles with decreasing d_{50} , the maximum suction rates that can be applied to the setup for sand with different sizes will be different, namely, 1.2 and 0.75 L/s for particles with $d_{50} = 0.8$ and 0.39 mm, respectively.

Table 6.2 Test Conditions and Experimental Data ($h = 9.3$ cm, $L = 0.5$ m)

<i>Test Number</i>	<i>Main flow rate (Q_0 (L/s))</i>	<i>Suction rate, Q_s (L/s)</i>	<i>Suction velocity, V_s (m/s)</i>	<i>Bedload transport rate, q_b (10^{-9} m³/s)</i>
(1)	(2)	(3)	(4)	(5)
III-2A-1	7	0.000	0.0000	1.1
III-2A-2	7	0.150	0.0010	1.1
III-2A-3	7	0.294	0.0020	0.8
III-2A-4	7	0.400	0.0027	3.0
III-2A-5	7	0.563	0.0038	3.8
III-2A-6	7	0.670	0.0045	4.6
III-2A-7	7	0.810	0.0054	28.0
III-2A-8	7	0.960	0.0064	63.1
III-2A-9	7	1.200	0.0080	201.2
III-2B-1	5.52	0.000	0.0000	0.0487
III-2B-2	5.52	0.125	0.0008	0.0362
III-2B-3	5.52	0.300	0.0020	0.1462
III-2B-4	5.52	0.456	0.0031	0.3801
III-2B-5	5.52	0.490	0.0033	0.3431
III-2B-6	5.52	0.600	0.0040	0.4024
III-2B-7	5.52	0.680	0.0045	0.7602
III-2B-8	5.52	0.750	0.0050	0.9190

Note: The data with test number starting from III-2A and III-2B are the experimental results for sand particles with $d_{50} = 0.8$ and 0.39 mm, respectively.

The data in columns 2, 3 and 5 are measured directly.

Figure 6.6 Suction Effects on Sediment Transport Rate for Sand with $d_{50} = 0.39$ and 0.8 mm

Fig. 6.6 shows that when u_{*0}/u_{*0c} is almost the same, the increasing trend of Φ with Q_s/Q_0 for the two kinds of sediment particles are very similar, which means that suction effects on sediment transport rate for these two kinds of particles are almost the same, e.g. suction can increase sediment transport rate for both of them. The inference is consistent with the experimental data for sand with $d_{50} = 0.84$ mm in closed-conduit flow in the present study and also is consistent with the data of Liu (2010) who experimentally found that suction can increase transport rate of sediment particles with $d_{50} = 0.48$ and 0.9 mm in open channel flow.

6.2.3 Comparison with Injection Effects on Sediment Transport Rate in Closed-conduit Flow

To the best of the author's knowledge, only Pei (2010) has investigated injection effects on sediment transport rate in closed-conduit flow. Liu (2010) has studied both injection and suction effects on sediment transport rate in open channel flow.

Figure 6.7 Effect of Injection on Bed-load Transport Rate (Pei, 2010)

Pei (2010) has conducted experiments in a closed conduit with length = 4.8 m with an injection zone with length = 0.1 m, which was filled with cohesionless sand particles with median grain size $d_{50} = 0.2$ mm and geometric standard deviation, $\sigma_g = 1.29$. The sediment particle size is smaller than that used in Liu (2010)'s study, namely, 0.48 and 0.9 mm.

Their results are plotted in Fig. 6.7, using the dimensionless sediment transport rate Φ plotted against the injection intensity (defined as the ratio between injection

velocity, V_i and critical injection velocity, V_{cr} ; and V_{cr} denotes the injection velocity at which the quick sand condition occurs), V_i / V_{cr} . With the increase of V_i / V_{cr} , Φ does not change much initially. When $V_i / V_{cr} > 10$, however, the data show that Φ increases abruptly. Clearly, one can identify two distinct zones in the figure, known as “zone 1”, is represented by a low sediment transport rate confined to $1 < V_i / V_{cr} < 10$. The second zone, i.e., zone 2, is represented by an abrupt increase of sediment transport rate, which occurs when $V_i / V_{cr} \geq 10$. In addition, all the experimental data could be fit well with an exponential equation, $\Phi = 2.4 \times 10^{-5} e^{0.255 V_i / V_{cr}}$, which indicates that the injection effects on sediment transport rate could be described by an exponential function.

Fig. 6.8 shows a plot of Φ/Φ_0 against Ω_0 / Ω_{Vs} ($\Omega_{Vs} = \frac{U_0^2}{[(S_s - 1)(1 - n) - V_i / K] d_{50} g}$), which was developed through dimensional analysis by Liu (2010) and

$\Omega_0 = \frac{U_0^2}{(S_s - 1)(1 - n) d_{50} g}$) for a complete comparison of both injection and suction effects on sediment transport rate in open channel and closed conduit from the data from, Pei (2010), Liu (2010) and that of the present study, where Φ_0 and Ω_0 are Einstein’s Number and Modified Froude Number without seepage condition.

Fig. 6.8 clearly shows that sediment transport rate increases with increasing suction velocity both in open channel (Liu, 2010) and closed conduit flows, for sand with $d_{50} = 0.9$ and 0.84 mm, respectively; while the increasing trends of sediment transport rate with increasing larger injection velocity show completely different behaviours, e.g. q_b decreases with injection velocity in open channel flow (Liu, 2010) while it does not change much initially as injection velocity increases and suddenly shoots up beyond a certain threshold ($V_i / V_{cr} = 10$). Therefore, it may be inferred from Fig. 6.8 that suction can increase sediment transport rate for sand with $d_{50} = 0.84$ and 0.9 mm as both data in open channel and closed-conduit flows verify this. On the other hand, no inference can be made for injection currently as the data of Liu (2010) show that injection decreases sediment transport rate in open channel while that of the present study indicates injection can increase sediment transport

rate in closed-conduit flows. The cause for the discrepancy will be explained below. Moreover, a theoretical analysis is presented to explain this phenomenon.

Figure 6.8 Comparison of Suction and Injection Effects on Sediment Transport Rate in Open Channel and Closed-conduit Flows

In order to simplify the analysis, the sand particles are all assumed to be spherical with an average diameter, i.e., $d = d_{50}$. Fig. 6.9 shows a cohesionless particle that experiences submerged weight force W , drag force F_D , lift force F_L and injection force F_i at the onset of motion. All these forces may be grouped into two components: vertical and horizontal.

Figure 6.9 Forces Applied on A Particle on the Porous Sand Bed

The submerged weight of the particle may be expressed as

$$W = (\rho_s - \rho)g \frac{\pi d^3}{6} \quad (6.3)$$

where ρ_s is the density of particles.

The horizontal drag force F_D is formed due to the pressure difference between the up and down stream sides of the particle; it can be expressed as follows:

$$F_D = C_D \frac{\pi d^2}{8} \rho u_b^2 \quad (6.4)$$

where u_b = horizontal flow velocity over the particles; and C_D = drag coefficient.

The lift force, which has a similar expression as the drag force, can be similarly calculated as follows:

$$F_L = C_L \frac{\pi d^2}{8} \rho u_b^2 \quad (6.5)$$

where C_L = lift coefficient.

According to Cheng and Chiew (1999), the injection force F_i may be expressed as follows:

$$F_i = \frac{i\rho g \pi d^3}{6(1-n)} \quad (6.6)$$

where i = hydraulic gradient, which can be calculated based on Darcy's Law, i.e., $i = V_i/K$; and n = porosity of the particle.

By balancing the moments about the axis through the pivot point (Zanke, 2003), the following requirement must be satisfied for the entrainment of the grain particle

$$(W - F_i - F_L) \frac{d}{2} \sin \phi = F_D \frac{d}{2} \cos \phi \quad (6.7)$$

where ϕ is the angle of internal friction at the inception of motion. Defining the resistive force, $F_r = (W - F_i - F_L) \tan \phi$ and when $F_r = 0$, boiling occurs.

Combining Eqs (6.3) to (6.7), one gets:

$$F_D - F_r = \left\{ u_b^2 \left(\frac{C_D}{4} + \frac{C_L}{4} \tan \phi \right) - \frac{\tan \phi}{3(1-n)} g d_{50} \left[(S_s - 1)(1-n) - \frac{V_i}{K} \right] \right\} \times \frac{\pi d^2}{2} \quad (6.8)$$

Thus $F_D - F_r = 0$ is the critical condition for the entrainment of grain particles. Cheng and Chiew (1999) analytically derived an equation to describe the velocity profile in the presence of injection and fitted it with his experimentally measured data. Their equation, which has a similar form as that derived by Stevenson (1963) and Schlichting (1979), is as follows,

$$\frac{u}{u_*} = \frac{1}{k} \ln \frac{y}{y_0} + \frac{v_i}{4u_*} \left(\frac{1}{k} \ln \frac{y}{y_0} \right)^2 \quad (6.9)$$

where u = streamwise velocity, u_* = shear velocity, y_0 = the vertical distance where $u = 0$.

Cheng and Chiew (1999) found that the introduction of injection increases y_0 , which is synonymous to a reduction of the near-bed horizontal velocity u_b and reducing u_b

will lead to reducing F_D . Moreover, reducing u_b will lead to reducing F_L (Based on Eqs. (6.5)) and hence increasing F_r . On the other hand, the permeability, K is not a constant when injection is introduced, especially in the top layer that is near the interface between the sand and water above. This is consistent with van Rhee (2010), who believed that the permeability in the top layer of the sand bed would change as it was subjected to flow. As injection rate increases, the dilation of the sand particles will occur, resulting in an inevitably increase in K . Based on Darcy's law $i = V_i/K$, i will not necessarily increase with increasing V_i as both V_i and K will increase. Consequently, whether increasing injection leads to increasing F_i or decreasing F_r is not certain (Based on Eq. (6.6)). Or even if F_r decreases as injection rate increases, whether the decreasing effect of F_r outweighs the decreasing effect of F_D , i.e., whether the difference $(F_D - F_r)$ would increase or not with increasing injection is still an uncertainty.

In equation (6.7), when $(S_s-1)(1-n) = V_i/K$, the resistive force F_r or the effective stress is zero, boiling occurs and $V_i = V_{cr}$. And $(F_D - F_r)$ should be ≥ 0 as F_D is always positive as long as u_b is in the streamwise positive direction. Consequently, the sediment transport rate should increase as long as V_i is large enough so that $(S_s-1)(1-n) \leq V_i/K$. However, based on the data in Fig. 6.8, q_b does not change much initially, even when V_i/V_{cr} approaches 10. A possible explanation is that on one hand, K is increasing with increasing V_i as stated previously, increasing V_i not necessary leads to increasing F_i , causing the actual $(S_s-1)(1-n) > V_i/K$. On the other hand, although the sand particles are raised by the injection flow, the vertical position of the floating particles $y < y_0$ where $u_b = 0$, which means that u_b at the particle is theoretically or at least close to zero so that there is not enough streamwise force to drag the floating particles forward. However, when $V_i/V_{cr} \geq 10$, the injection momentum is so large that the particles are almost all blown up to the position where $y > y_0$ and $u_b > 0$ and K value does not increase any more. Consequently, when $V_i/V_{cr} \geq 10$, increasing V_i leads to increasing i and F_i , thus $(F_D - F_r)$ should be ≥ 0 and the particles are entrained. In other words, the increasing trend of sediment transport rate with injection rate will be apparent only after $V_i/V_{cr} \geq 10$.

This hypothesis is consistent with the measured data in the present study and that from Liu (2010). It is noteworthy that from Fig. 6.9, the calculated Ω_0 / Ω_{V_s} for the data of Liu (2010) ranges from 0.2 to 1. Because

$$\frac{\Omega_0}{\Omega_{V_s}} = \frac{(S_s - 1)(1 - n) - \frac{V_i}{K}}{(S_s - 1)(1 - n)} = 1 - \frac{i}{(S_s - 1)(1 - n)}, \quad 0 < \frac{i}{(S_s - 1)(1 - n)} < 0.8. \quad \text{If the}$$

increase in K with increasing V_i is taken into account, the actual ratio of

$$\frac{i}{(S_s - 1)(1 - n)} \text{ is even less, which means } V_i/V_{cr} \text{ is significantly less than 1,}$$

indicating that the injection flow is not large enough. Based on the force analysis, $(F_D - F_r)$ does not change much as both F_D and F_r decrease with injection when $V_i/V_{cr} < 10$. Consequently, q_b will not change much and the measured data of injection effect on q_b from Liu (2010) validates this point and the largest $(q_b - q_{b0})/q_{b0}$ (q_b and q_{b0} denote the sediment transport rate per unit width, with and without seepage, respectively) is about 40%, which is almost negligible compared to the largest $q_b/q_{b0} \approx 28$ for the injection data in the present study.

6.3 CONCLUDING REMARKS

6.3.1 Suction Zone Length Effect on Sediment Transport Rate

Laboratory experiments were conducted in this study to explore how suction zone length affects the sediment transport rate in closed-conduit flows.

The experimental results show that suction zone length, like suction intensity in the form of V_s/U_0 , can influence sediment transport rate. Within a certain range of Q_s/Q_0 , the sediment transport rate increases with suction zone length for the same V_s/U_0 . Combining the effect of V_s/U_0 and suction zone length, the study shows that suction intensity in the form of Q_s/Q_0 is a superior variable to use in the analysis of sediment transport rate subjected to suction. Moreover, a new modified Froude number Ω_{Q_s} involving the effect of Q_s rather than V_s , is developed and the comparison of the data in the present study and those by Liu (2010) verifies the

hypothesis that Q_s/Q_0 is better correlated to q_b than V_s/U_0 . Finally, PIV measurement of the velocity profile shows that the streamwise velocity in the very near-bed region increases with increasing V_s/U_0 at fixed L/h and also with increasing L/h at fixed V_s/U_0 , which is used to explain how suction zone length affects sediment transport rate.

6.3.2 Sediment Size Effect on Sediment Transport Rate

The experimental data shows that suction can increase the sediment transport rate for sand particles with $d_{50} = 0.39$ and 0.80 mm in closed-conduit flows, which is consistent with Liu (2010)'s findings in open channel flow.

6.3.3 Comparison with Injection Effects on Sediment Transport Rate in Closed-conduit flow

The injection effects on sediment transport rate are compared with the data for suction effects in both open channel and closed-conduit flows. The results show that suction can increase the transport rate of sediment particles with similar sizes in open channel (0.48 and 0.9 mm) and closed-conduit flows (0.84 mm) are similar. However, Liu (2010) inferred that injection decreases the transport rate of sediment particles with $d_{50} = 0.48$ and 0.9 mm in open channel, contrary to Pei (2010)'s opinion that it increases transport rate of sediment particles with $d_{50} = 0.2$ mm in closed-conduit flows. A tentative explanation by using the force analysis is presented to account for the different results for injection effects by Pei (2010) and Liu (2010).

Chapter 7

Conclusions and Recommendations

7.1 CONCLUSIONS

This study presents the experimental results and their analysis of suction effects in a closed conduit on sediment transport and flow characteristics like velocity profile, turbulence distribution, shear stress, etc. The following conclusions are drawn from the study.

7.1.1 Suction Effects on Sediment Transport

In the present study, suction effects on the bedload transport rate of sediment particles with $d_{50} = 0.84$ mm in a closed conduit is experimentally investigated by directly measuring the amount of sediment particles transported from the suction zone into a specially designed sand trap with a given duration.

The experimental results show that the bedload transport rate increases with suction rate (with a constant Q_0). The data also reveal that the dimensionless sediment transport rate, Φ first increases marginally at low values of I_s (It should be noted here I_s instead of Q_0/Q_s is used because a fixed suction zone length is employed and in such cases, there is no need to differentiate the use of I_s and Q_0/Q_s). Beyond a certain threshold, Φ increases abruptly. To account for this behavior, a conceptual model with consideration of the near-bed vertical and horizontal forces is presented. It shows that the near-bed velocities are closely related to the sediment transport rate with suction and they both increase with increasing I_s .

To qualitatively verify this model, CFD simulations were conducted to model how suction influences the near-bed flow behavior in a closed conduit with the same dimension as that in the physical experiments. The results support the conceptual model and show that both the horizontal and vertical near-bed velocities increase with increasing suction rate.

In summary, the present study investigates suction effects on sediment transport in a closed-conduit flow by directly measuring the sediment transport rate. By introducing a conceptual model that involves a suction induced force and using numerical simulation to model the flow behavior in the presence of suction, it provides a rational explanation on suction effects on sediment transport.

7.1.2 Suction Effects on Flow Characteristics

Past researchers, e.g., Clark et al. (1955), Chen & Chiew (2004), etc. have found that the universal log law is not valid in an open channel flow with suction and have theoretically derived appropriate equations to describe the velocity profile in such cases. In the present study, a modified log law in a closed conduit was derived theoretically and the flow characteristics, including horizontal and vertical velocities and turbulence, were experimentally measured by using PIV techniques. The measured results show that the near-bed flow characteristics of closed-conduit flows change significantly in the presence of suction. The following specific conclusions are drawn from the study (similar to the reason mentioned in section 7.1.1, I_s instead of Q_0/Q_s is used here).

- 1) The streamwise velocity in the very near-bed region increases substantially as the suction intensity increases, making the profile more uniform. The vertical velocity becomes more negative with increasing suction intensities.
- 2) The turbulence intensities and Reynolds shear stress generally decrease with increasing suction intensity within a certain range ($0 \leq I_s \leq 2.32\%$); beyond this range they start to increase gradually above the very-near bed region. The turning point at $I_s = 2.32\%$ probably is because a large amount of suction would cause a significantly large reduction of net flow on the bed and thus a reduced bed shear stress. In addition to the momentum influence due to suction that augments the shear velocity, the reduced mass effect due to flow abstraction (suction) would lead to an opposite effect on the shear velocity.
- 3) The universal log law does not fit the data with suction, especially in the very near-bed region, while the modified log law show very good agreement with the data. The fitted value of u_* increases with I_s when $0 \leq I_s \leq 2.32\%$ and decreases marginally with I_s when $2.32 \leq I_s \leq 3.0\%$.
- 4) The experimental data associated with the longitudinal development of the streamwise velocity profiles show that the near bed horizontal velocity increases as the flow moves into the suction zone, rendering the profile in the near-bed region to become more uniform. The variation of u with x (with a constant I_s) is generally similar to that of u with I_s (with a constant x) because increasing either x or I_s will both lead to more mass and momentum transfer across the permeable interface.
- 5) Generally, the profiles of F_{ku} , F_{kv} , T_P , E_D , T_D and P_D become more uniform with increasing suction. The turbulent energy budget shows that the streamwise flux of energy is transported upstream and the vertical flux of energy is transported in the upward direction.

7.1.3 Suction Zone Length and Size Effects

Laboratory experiments also were conducted in this study to explore how the suction zone length affects the sediment transport rate in closed-conduit flows.

The experimental results show that the suction zone length, like the suction intensity in the form of V_s/U_0 , can influence sediment transport rate. Within a

certain range of Q_s/Q_0 , the sediment transport rate increases with increasingly larger suction zone length for the same V_s/U_0 . Combining the effect of V_s/U_0 and suction zone length, the study shows that the suction intensity in the form of Q_s/Q_0 is a superior variable to use in the analysis of sediment transport rate. Moreover, a new modified Froude number Ω_{Q_s} involving the effect of Q_s rather than V_s , is developed and the comparison of the data in the present study and that by Liu (2010) verifies the hypothesis that Q_s/Q_0 is better correlated to q_b than V_s/U_0 . Finally, PIV measurement of the velocity profile shows that the streamwise velocity in the near-bed region increases with increasing V_s/U_0 at fixed L/h and also with increasing L/h at fixed V_s/U_0 , which is used to explain how the suction zone length affects the sediment transport rate.

The experimental data shows that suction can increase the sediment transport rate for sand particles with $d_{50} = 0.39$ and 0.80 mm in closed-conduit flows, which is consistent with Liu (2010)'s findings in open channel flow.

7.1.4 Comparison with Injection Effects on Sediment Transport Rate in Closed-conduit flow

The injection effects on sediment transport rate are compared with the data for suction effects in both open channel and closed-conduit flows. The results show that suction can increase the transport rate of sediment particles with similar sizes in open channel (0.48 and 0.9 mm) and closed-conduit flows (0.84 mm) are similar. However, Liu (2010) inferred that injection decreases the transport rate of sediment particles with $d_{50} = 0.48$ and 0.9 mm in open channel, contrary to Pei (2010)'s opinion that it increases the transport rate of sediment particles with $d_{50} = 0.2$ mm in closed-conduit flows. A tentative explanation by using the force analysis is presented to account for the different results for injection effects by Pei (2010) and Liu (2010).

7.2 RECOMMENDATIONS

Although some results have been obtained in the conduct of this study, additional work is needed to have a complete understanding of the subject.

First of all, due to the limit of the experimental setup, in this study only a maximum suction rate of 3.0% ($I_s = V_s/U_0$) may be applied. It is recommended that a higher suction rate be used to further explore its effect on flow and sediment transport. Although a thought experiment is presented to evaluate the condition when a sufficiently high suction is applied, it is important to experimentally verify this hypothesis.

Second, currently only cohesionless sediments with $d_{50} = 0.39, 0.8$ and 0.84 mm are studied. It is important to further explore whether suction can increase sediment transport rate for sand or even cohesive particles with a wider range of diameters.

Last but not least, only suction effects on flow and sediment transport rate in closed-conduit flows are investigated experimentally in the study. It is equally important to extend the work to investigate injection effects on flow and sediment transport rate.

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APPENDIX

Appendix AI: Data on Sediment Transport

AI.1 Effect of main flow rate Q_0 on sediment transport

<i>Test Number</i>	<i>Q_0 (L/s)</i>	<i>Mean streamwise velocity, U_0 (m/s)</i>	<i>Suction rate, Q_s (L/s)</i>	<i>Suction velocity, V_s (m/s)</i>	<i>Bedload transport rate, q_b (10^{-6} m²/s)</i>
1	4.8	0.276	0	0	0.0143
2	4.89	0.281	0	0	0.0139
3	4.97	0.286	0	0	0.0181
4	5.06	0.291	0	0	0.0358
5	5.14	0.295	0	0	0.0606
6	5.25	0.302	0	0	0.1204
7	5.36	0.308	0	0	0.1378
8	5.51	0.317	0	0	0.2005
9	5.63	0.324	0	0	0.259

Note: The data in the Columns 2, 4 and 6 are directly measured while $U_0 = Q_0/A$, $V_s = Q_s/A_s$. The Reynolds number R for all the tests ranges between 26816 and 31453, which shows the flow is turbulent, where $R = U_0 D_H / \nu$; Water depth, $h = 0.058$ m; Sediment, $d_{50} = 0.84$ mm; $u_{*0} / u_{*c} = 0.958$, when $Q_0 = 4.8$ L/s; Suction zone length, $L = 50$ cm.

AI.2 Effect of suction flow rate Q_s on sediment transport

<i>Test Number</i>	<i>Q_0 (L/s)</i>	<i>Mean streamwise velocity, U_0 (m/s)</i>	<i>Suction rate, Q_s (L/s)</i>	<i>Suction velocity, V_s (m/s)</i>	<i>Bedload transport rate, q_b (10^{-6} m^2/s)</i>
1	4.8	0.276	0	0	0.0143
2	4.8	0.276	0.057	0.0004	0.0119
3	4.8	0.276	0.118	0.0008	0.0175
4	4.8	0.276	0.145	0.001	0.0168
5	4.8	0.276	0.18	0.0012	0.0226
6	4.8	0.276	0.26	0.0017	0.0061
7	4.8	0.276	0.273	0.0018	0.0179
8	4.8	0.276	0.298	0.002	0.0291
9	4.8	0.276	0.333	0.0022	0.0298
10	4.8	0.276	0.465	0.0031	0.0269
11	4.8	0.276	0.52	0.0035	0.0185
12	4.8	0.276	0.528	0.0035	0.0395
13	4.8	0.276	0.75	0.005	0.058
14	4.8	0.276	0.79	0.0053	0.0796
15	4.8	0.276	0.87	0.0058	0.1229
16	4.8	0.276	0.95	0.0063	0.1659
17	4.8	0.276	1.02	0.0068	0.2785
18	4.8	0.276	1.1	0.0073	0.432

Note: The data in the Columns 2, 4 and 6 are directly measured while $U_0 = Q_0/A$, $V_s = Q_s/A_s$. The Reynolds number R for all the tests is 26816, which shows the flow is turbulent, where $R = U_0 D_H / \nu$; Water depth, $h = 0.058$ m; Sediment, $d_{50} = 0.84$ mm $u_{*0} / u_{*c} = 0.958$, when $Q_0 = 4.8$ L/s; Suction zone length, $L = 50$ cm.

AI.3 Effect of suction zone length, x on sediment transport

<i>Test Number</i>	<i>Suction zone length (m)</i>	<i>Suction rate, Q_s (L/s)</i>	<i>Suction velocity, V_s (m/s)</i>	<i>Bedload transport rate, q_b (10^{-6} m²/s)</i>
III-1A-1	0.5	0	0	0.0011
III-1A-2	0.5	0.15	0.001	0.0011
III-1A-3	0.5	0.294	0.002	0.0008
III-1A-4	0.5	0.4	0.0027	0.003
III-1A-5	0.5	0.563	0.0038	0.0038
III-1A-6	0.5	0.67	0.0045	0.0046
III-1A-7	0.5	0.81	0.0054	0.028
III-1A-8	0.5	0.96	0.0064	0.0631
III-1A-9	0.5	1.2	0.008	0.2012
III-1B-1	0.2	0	0	0.0003
III-1B-2	0.2	0.12	0.002	0.0005
III-1B-3	0.2	0.256	0.0043	0.0006
III-1B-4	0.2	0.38	0.0063	0.0016
III-1B-5	0.2	0.486	0.0081	0.0025
III-1B-6	0.2	0.61	0.0102	0.005
III-1B-7	0.2	0.84	0.014	0.0263
III-1B-8	0.2	0.95	0.0158	0.0505
III-1B-9	0.2	1.1	0.0183	0.0764
III-1C-1	0.1	0	0	0.0009
III-1C-2	0.1	0.13	0.0043	0.0008
III-1C-3	0.1	0.294	0.0098	0.0009
III-1C-4	0.1	0.352	0.0117	0.0012
III-1C-5	0.1	0.42	0.014	0.0017
III-1C-6	0.1	0.55	0.0183	0.0052
III-1C-7	0.1	0.67	0.0223	0.0102
III-1C-8	0.1	0.8	0.0267	0.0163
III-1C-9	0.1	0.93	0.031	0.0305

Note: The data with test number starting from III-1A, III-1B and III-1 C are the experimental results with suction zone length = 0.5, 0.2 and 0.1m, respectively. The data in columns 2, 3 and 5 are measured directly, while V_s is calculated by $V_s = Q_s/A_s$. The Reynolds number R for all the experiments is 35481, which shows the flow is turbulent; Water depth, $h = 0.093$ m; Sediment, $d_{50} = 0.8$ mm; $u_{*0}/u_{*c} = 0.997$, when $Q_0 = 7$ L/s; Suction zone length, $L = 50$ cm.

AI.4 Effect of sediment size, d_{50} on sediment transport

<i>Test Number</i>	<i>Main flow rate Q_0 (L/s)</i>	<i>Suction rate, Q_s (L/s)</i>	<i>Suction velocity, V_s (m/s)</i>	<i>Bedload transport rate, q_b (10^{-9} m²/s)</i>
III-2A-1	7	0.000	0.0000	1.1
III-2A-2	7	0.150	0.0010	1.1
III-2A-3	7	0.294	0.0020	0.8
III-2A-4	7	0.400	0.0027	3.0
III-2A-5	7	0.563	0.0038	3.8
III-2A-6	7	0.670	0.0045	4.6
III-2A-7	7	0.810	0.0054	28.0
III-2A-8	7	0.960	0.0064	63.1
III-2A-9	7	1.200	0.0080	201.2
III-2B-1	5.52	0	0	0.0487
III-2B-2	5.52	0.125	0.0008	0.0362
III-2B-3	5.52	0.3	0.002	0.1462
III-2B-4	5.52	0.456	0.0031	0.3801
III-2B-5	5.52	0.49	0.0033	0.3431
III-2B-6	5.52	0.6	0.004	0.4024
III-2B-7	5.52	0.68	0.0045	0.7602
III-2B-8	5.52	0.75	0.005	0.919

Note: The data with test number starting from III-2A and III-2B are the experimental results for sand particles with $d_{50} = 0.8$ and 0.39 mm, respectively. The data in columns 2, 3 and 5 are measured directly, while V_s is calculated by $V_s = Q_s/A_s$. The Reynolds number R for all the experiments is larger than 28000, which shows the flow is turbulent; Water depth, $h = 0.093$ m; Suction zone length, $L = 50$ cm.

Appendix AII: Data on Flow Characteristics

AII.1 Effect of main flow rate Q_0 on flow

AII.1.1 Effect of main flow rate Q_0 on streamwise velocity, u at $x = 25$ cm (in the middle of suction zone)

Q_0 (L/s)	6.24	6.44	6.62	6.83	7.00
y (cm)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)
2.83	27.84	28.66	29.21	30.65	30.43
2.79	27.77	28.61	29.26	30.64	30.46
2.76	27.67	28.60	29.10	30.55	30.40
2.72	27.64	28.50	29.05	30.44	30.38
2.69	27.52	28.44	29.00	30.34	30.23
2.65	27.45	28.38	28.94	30.26	30.14
2.62	27.39	28.30	28.86	30.19	30.06
2.58	27.31	28.21	28.78	30.12	29.98
2.55	27.22	28.13	28.69	30.05	29.89
2.51	27.13	28.05	28.60	29.99	29.81
2.48	27.06	27.98	28.53	29.91	29.74
2.44	26.99	27.91	28.45	29.83	29.66
2.41	26.91	27.83	28.38	29.74	29.58
2.37	26.83	27.74	28.31	29.65	29.51
2.34	26.75	27.67	28.24	29.56	29.43
2.30	26.69	27.58	28.17	29.47	29.35
2.27	26.62	27.50	28.09	29.38	29.27
2.23	26.56	27.41	28.01	29.30	29.18
2.20	26.51	27.33	27.93	29.22	29.10
2.16	26.45	27.24	27.85	29.14	29.01
2.13	26.38	27.14	27.76	29.05	28.92
2.09	26.31	27.04	27.67	28.95	28.83
2.06	26.23	26.94	27.58	28.85	28.75
2.02	26.16	26.84	27.48	28.74	28.65
1.99	26.07	26.74	27.37	28.63	28.54
1.95	25.99	26.66	27.27	28.52	28.44
1.92	25.90	26.57	27.16	28.42	28.32
1.88	25.81	26.48	27.04	28.32	28.20
1.85	25.71	26.39	26.92	28.22	28.07
1.81	25.60	26.31	26.80	28.12	27.95

Q_0 (L/s)	6.24	6.44	6.62	6.83	7.00
y (cm)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)
1.78	25.51	26.23	26.70	28.01	27.85
1.74	25.41	26.13	26.59	27.91	27.74
1.71	25.30	26.03	26.46	27.81	27.64
1.67	25.20	25.93	26.35	27.71	27.52
1.64	25.10	25.85	26.24	27.60	27.40
1.60	25.01	25.76	26.12	27.49	27.26
1.57	24.91	25.66	26.00	27.37	27.11
1.54	24.80	25.56	25.90	27.25	26.98
1.50	24.70	25.47	25.80	27.13	26.87
1.47	24.58	25.38	25.70	27.02	26.76
1.43	24.46	25.29	25.60	26.91	26.65
1.40	24.34	25.19	25.48	26.80	26.53
1.36	24.21	25.10	25.37	26.69	26.41
1.33	24.08	25.00	25.25	26.56	26.28
1.29	23.96	24.90	25.13	26.44	26.15
1.26	23.84	24.81	25.02	26.31	26.04
1.22	23.74	24.72	24.90	26.19	25.93
1.19	23.63	24.62	24.77	26.05	25.81
1.15	23.52	24.51	24.63	25.92	25.68
1.12	23.40	24.40	24.50	25.77	25.55
1.08	23.29	24.28	24.37	25.62	25.40
1.05	23.16	24.14	24.24	25.45	25.23
1.01	23.01	23.99	24.10	25.28	25.04
0.98	22.85	23.84	23.94	25.11	24.87
0.94	22.69	23.70	23.79	24.95	24.71
0.91	22.53	23.54	23.62	24.78	24.55
0.87	22.38	23.37	23.45	24.61	24.37
0.84	22.23	23.20	23.28	24.42	24.12
0.80	22.06	23.02	23.06	24.20	23.88
0.77	21.86	22.81	22.79	23.93	23.62
0.73	21.64	22.59	22.46	23.66	23.40
0.70	21.43	22.40	22.19	23.43	23.15
0.66	21.25	22.23	22.07	23.26	22.91
0.63	21.07	22.06	21.93	23.09	22.68
0.59	20.88	21.86	21.75	22.90	22.43
0.56	20.67	21.63	21.55	22.68	22.33
0.52	20.43	21.39	21.31	22.43	22.13
0.49	20.17	21.13	21.04	22.16	21.88

Q_0 (L/s)	6.24	6.44	6.62	6.83	7.00
y (cm)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)
0.45	19.90	20.84	20.73	21.88	21.57
0.42	19.61	20.55	20.41	21.59	21.26
0.38	19.30	20.23	20.08	21.29	20.93
0.35	18.96	19.86	19.70	20.95	20.55
0.31	18.56	19.43	19.24	20.56	20.09
0.28	18.10	18.93	18.71	20.10	19.55
0.24	17.54	18.32	18.04	19.54	18.86
0.21	16.78	17.49	17.05	18.84	17.77
0.17	15.67	16.25	15.50	17.88	15.98

AII.1.2 Effect of main flow rate Q_0 on vertical velocity, v at $x = 25$ cm (in the middle of suction zone)

Q_0 (L/s)	6.24	6.44	6.62	6.83	7.00
y (cm)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)
2.83	-0.008	-0.024	-0.014	0.020	0.008
2.79	-0.033	-0.024	-0.013	0.008	-0.024
2.76	0.002	-0.019	-0.006	0.018	0.009
2.72	-0.018	-0.009	-0.023	0.014	-0.009
2.69	-0.014	-0.013	-0.008	0.021	0.016
2.65	-0.016	-0.010	-0.006	0.022	0.021
2.62	-0.018	-0.006	-0.004	0.022	0.023
2.58	-0.018	-0.001	-0.003	0.022	0.027
2.55	-0.017	0.001	-0.001	0.021	0.033
2.51	-0.014	0.000	-0.002	0.020	0.041
2.48	-0.011	-0.002	-0.002	0.020	0.045
2.44	-0.008	-0.001	0.001	0.022	0.046
2.41	-0.007	0.001	0.006	0.024	0.045
2.37	-0.007	0.003	0.011	0.025	0.044
2.34	-0.004	0.004	0.016	0.025	0.045
2.30	0.001	0.004	0.021	0.028	0.047
2.27	0.008	0.001	0.028	0.034	0.050
2.23	0.012	-0.002	0.032	0.040	0.052
2.20	0.013	-0.006	0.034	0.043	0.056
2.16	0.011	-0.008	0.032	0.043	0.061
2.13	0.009	-0.009	0.030	0.044	0.066
2.09	0.008	-0.010	0.031	0.045	0.067
2.06	0.009	-0.011	0.034	0.047	0.065
2.02	0.012	-0.012	0.041	0.050	0.065
1.99	0.013	-0.013	0.050	0.054	0.068
1.95	0.014	-0.015	0.057	0.059	0.073
1.92	0.016	-0.018	0.062	0.063	0.080
1.88	0.020	-0.019	0.065	0.068	0.088
1.85	0.026	-0.020	0.067	0.073	0.095
1.81	0.031	-0.020	0.067	0.077	0.099
1.78	0.035	-0.019	0.065	0.081	0.103
1.74	0.041	-0.017	0.064	0.082	0.110
1.71	0.046	-0.016	0.064	0.080	0.119
1.67	0.049	-0.014	0.067	0.080	0.126
1.64	0.049	-0.011	0.072	0.081	0.129
1.60	0.049	-0.007	0.077	0.084	0.132

Q_0 (L/s)	6.24	6.44	6.62	6.83	7.00
y (cm)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)
1.57	0.048	-0.003	0.081	0.086	0.136
1.54	0.049	0.000	0.086	0.088	0.141
1.50	0.046	0.000	0.091	0.090	0.146
1.47	0.042	-0.002	0.097	0.091	0.149
1.43	0.038	-0.006	0.103	0.093	0.149
1.40	0.037	-0.011	0.107	0.093	0.144
1.36	0.040	-0.017	0.107	0.093	0.134
1.33	0.044	-0.022	0.104	0.094	0.124
1.29	0.049	-0.025	0.100	0.097	0.119
1.26	0.052	-0.026	0.100	0.098	0.118
1.22	0.054	-0.027	0.106	0.097	0.118
1.19	0.057	-0.027	0.116	0.094	0.120
1.15	0.059	-0.026	0.126	0.088	0.121
1.12	0.061	-0.025	0.133	0.083	0.122
1.08	0.061	-0.023	0.137	0.080	0.124
1.05	0.063	-0.019	0.135	0.078	0.126
1.01	0.067	-0.016	0.129	0.078	0.125
0.98	0.070	-0.016	0.121	0.079	0.119
0.94	0.068	-0.020	0.114	0.078	0.111
0.91	0.066	-0.028	0.109	0.077	0.105
0.87	0.068	-0.036	0.108	0.077	0.104
0.84	0.076	-0.040	0.112	0.079	0.105
0.80	0.085	-0.043	0.114	0.081	0.105
0.77	0.090	-0.049	0.109	0.083	0.104
0.73	0.084	-0.063	0.093	0.074	0.094
0.70	0.070	-0.080	0.070	0.053	0.070
0.66	0.058	-0.088	0.054	0.031	0.044
0.63	0.053	-0.084	0.054	0.020	0.028
0.59	0.050	-0.076	0.061	0.018	0.026
0.56	0.046	-0.071	0.066	0.020	0.025
0.52	0.039	-0.073	0.063	0.019	0.019
0.49	0.033	-0.078	0.053	0.016	0.007
0.45	0.023	-0.085	0.041	0.011	-0.005
0.42	0.010	-0.093	0.032	0.002	-0.017
0.38	-0.003	-0.097	0.027	-0.010	-0.028
0.35	-0.014	-0.096	0.024	-0.024	-0.040
0.31	-0.022	-0.092	0.020	-0.036	-0.051
0.28	-0.032	-0.090	0.016	-0.044	-0.059
0.24	-0.043	-0.091	0.013	-0.050	-0.061

Q_0 (L/s)	6.24	6.44	6.62	6.83	7.00
y (cm)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)
0.21	-0.050	-0.093	0.012	-0.054	-0.050
0.17	-0.054	-0.098	0.007	-0.060	-0.028

AII.1.3 Effect of main flow rate Q_0 on $(\overline{u'u'})^{0.5}$ at $x = 25$ cm (in the middle of suction zone)

Q_0 (L/s)	6.24	6.44	6.62	6.83	7.00
y (cm)	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$
	(cm/s)	(cm/s)	(cm/s)	(cm/s)	(cm/s)
2.83	4.685	4.940	4.930	5.355	6.035
2.79	4.730	4.997	4.941	5.335	6.114
2.76	4.570	4.957	4.896	5.406	6.086
2.72	4.573	4.985	4.951	5.446	6.095
2.69	4.663	5.037	5.005	5.445	6.048
2.65	4.684	5.064	5.029	5.455	6.040
2.62	4.709	5.088	5.052	5.465	6.036
2.58	4.737	5.108	5.071	5.480	6.040
2.55	4.769	5.127	5.091	5.502	6.053
2.51	4.802	5.149	5.113	5.532	6.073
2.48	4.837	5.173	5.138	5.566	6.100
2.44	4.870	5.200	5.166	5.602	6.129
2.41	4.899	5.227	5.195	5.636	6.157
2.37	4.921	5.250	5.222	5.664	6.180
2.34	4.936	5.269	5.245	5.686	6.197
2.30	4.944	5.284	5.265	5.701	6.207
2.27	4.948	5.295	5.281	5.710	6.213
2.23	4.952	5.305	5.295	5.713	6.216
2.20	4.959	5.313	5.308	5.712	6.217
2.16	4.969	5.322	5.320	5.708	6.220
2.13	4.982	5.331	5.332	5.704	6.224
2.09	4.995	5.343	5.343	5.701	6.230
2.06	5.005	5.357	5.355	5.703	6.238
2.02	5.012	5.374	5.368	5.709	6.246
1.99	5.016	5.391	5.384	5.720	6.255
1.95	5.019	5.405	5.403	5.732	6.264
1.92	5.021	5.414	5.423	5.745	6.274
1.88	5.024	5.419	5.445	5.756	6.285
1.85	5.027	5.421	5.464	5.765	6.296
1.81	5.032	5.423	5.481	5.773	6.303
1.78	5.039	5.428	5.492	5.778	6.306
1.74	5.047	5.435	5.499	5.781	6.305
1.71	5.057	5.443	5.503	5.782	6.299
1.67	5.067	5.449	5.507	5.783	6.290

Q_0 (L/s)	6.24	6.44	6.62	6.83	7.00
y (cm)	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$
	(cm/s)	(cm/s)	(cm/s)	(cm/s)	(cm/s)
1.64	5.076	5.451	5.513	5.784	6.280
1.60	5.084	5.449	5.522	5.785	6.271
1.57	5.089	5.446	5.534	5.784	6.265
1.54	5.093	5.441	5.547	5.782	6.264
1.50	5.095	5.437	5.561	5.777	6.270
1.47	5.096	5.433	5.572	5.769	6.283
1.43	5.096	5.429	5.581	5.759	6.298
1.40	5.095	5.427	5.588	5.748	6.310
1.36	5.092	5.424	5.594	5.736	6.315
1.33	5.086	5.423	5.600	5.724	6.311
1.29	5.077	5.421	5.607	5.711	6.301
1.26	5.067	5.418	5.614	5.698	6.289
1.22	5.057	5.415	5.621	5.686	6.278
1.19	5.047	5.409	5.626	5.676	6.271
1.15	5.037	5.402	5.630	5.669	6.268
1.12	5.026	5.392	5.633	5.665	6.267
1.08	5.014	5.382	5.635	5.665	6.267
1.05	5.001	5.372	5.637	5.669	6.267
1.01	4.991	5.363	5.638	5.678	6.266
0.98	4.984	5.356	5.639	5.693	6.267
0.94	4.984	5.352	5.640	5.713	6.275
0.91	4.994	5.354	5.648	5.744	6.283
0.87	5.014	5.367	5.667	5.791	6.291
0.84	5.048	5.394	5.704	5.799	6.299
0.80	5.092	5.436	5.758	5.807	6.307
0.77	5.141	5.486	5.818	5.815	6.315
0.73	5.182	5.528	5.868	5.823	6.323
0.70	5.206	5.549	5.888	5.831	6.331
0.66	5.207	5.541	5.872	5.839	6.339
0.63	5.191	5.510	5.825	5.847	6.347
0.59	5.167	5.469	5.765	5.855	6.355
0.56	5.148	5.435	5.709	5.876	6.363
0.52	5.141	5.414	5.669	5.826	6.371
0.49	5.146	5.408	5.651	5.801	6.379
0.45	5.163	5.415	5.652	5.796	6.387
0.42	5.189	5.431	5.669	5.805	6.395
0.38	5.222	5.454	5.698	5.826	6.403
0.35	5.262	5.485	5.738	5.858	6.411

Q_0 (L/s)	6.24	6.44	6.62	6.83	7.00
y (cm)	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$
	(cm/s)	(cm/s)	(cm/s)	(cm/s)	(cm/s)
0.31	5.307	5.525	5.784	5.905	6.419
0.28	5.353	5.573	5.832	5.967	6.457
0.24	5.390	5.617	5.871	6.036	6.521
0.21	5.396	5.633	5.888	6.081	6.554
0.17	5.327	5.567	5.862	6.040	6.489

AII.1.4 Effect of main flow rate Q_0 on $(\overline{v'v'})^{0.5}$ at $x = 25$ cm (in the middle of suction zone)

Q_0 (L/s)	6.24	6.44	6.62	6.83	7.00
y (cm)	$(\overline{v'v'})^{0.5}$	$(\overline{v'v'})^{0.5}$	$(\overline{v'v'})^{0.5}$	$(\overline{v'v'})^{0.5}$	$(\overline{v'v'})^{0.5}$
	(cm/s)	(cm/s)	(cm/s)	(cm/s)	(cm/s)
2.83	1.684	1.712	1.742	1.827	2.082
2.79	1.695	1.734	1.724	1.857	2.102
2.76	1.649	1.737	1.746	1.844	2.093
2.72	1.662	1.738	1.748	1.878	2.128
2.69	1.685	1.742	1.764	1.891	2.108
2.65	1.695	1.744	1.772	1.904	2.106
2.62	1.704	1.748	1.781	1.915	2.106
2.58	1.712	1.756	1.790	1.928	2.109
2.55	1.719	1.768	1.800	1.942	2.117
2.51	1.726	1.780	1.811	1.956	2.129
2.48	1.733	1.792	1.823	1.972	2.143
2.44	1.741	1.801	1.836	1.986	2.160
2.41	1.750	1.809	1.849	2.000	2.176
2.37	1.758	1.816	1.861	2.011	2.191
2.34	1.766	1.823	1.871	2.021	2.203
2.30	1.773	1.831	1.881	2.030	2.212
2.27	1.780	1.840	1.889	2.037	2.220
2.23	1.787	1.849	1.896	2.044	2.226
2.20	1.792	1.859	1.901	2.051	2.233
2.16	1.797	1.869	1.906	2.057	2.242
2.13	1.802	1.879	1.910	2.063	2.252
2.09	1.807	1.888	1.914	2.070	2.261
2.06	1.813	1.899	1.919	2.077	2.268
2.02	1.819	1.910	1.924	2.084	2.273
1.99	1.827	1.921	1.930	2.092	2.277
1.95	1.835	1.931	1.937	2.099	2.282
1.92	1.843	1.938	1.944	2.107	2.291
1.88	1.852	1.944	1.951	2.115	2.304
1.85	1.860	1.947	1.958	2.122	2.318
1.81	1.869	1.950	1.965	2.128	2.332
1.78	1.876	1.953	1.971	2.131	2.342
1.74	1.883	1.955	1.977	2.132	2.346
1.71	1.889	1.958	1.981	2.130	2.347
1.67	1.894	1.961	1.986	2.129	2.346

Q_0 (L/s)	6.24	6.44	6.62	6.83	7.00
y (cm)	$(\overline{v'v'})^{0.5}$	$(\overline{v'v'})^{0.5}$	$(\overline{v'v'})^{0.5}$	$(\overline{v'v'})^{0.5}$	$(\overline{v'v'})^{0.5}$
	(cm/s)	(cm/s)	(cm/s)	(cm/s)	(cm/s)
1.64	1.899	1.965	1.990	2.131	2.348
1.60	1.904	1.971	1.994	2.135	2.353
1.57	1.908	1.977	1.999	2.142	2.361
1.54	1.913	1.984	2.004	2.148	2.370
1.50	1.918	1.991	2.010	2.154	2.380
1.47	1.922	1.995	2.017	2.157	2.389
1.43	1.925	1.996	2.025	2.158	2.397
1.40	1.928	1.995	2.033	2.159	2.404
1.36	1.931	1.993	2.040	2.160	2.410
1.33	1.933	1.991	2.048	2.162	2.412
1.29	1.935	1.990	2.054	2.165	2.413
1.26	1.937	1.990	2.060	2.169	2.412
1.22	1.940	1.991	2.066	2.174	2.411
1.19	1.945	1.993	2.070	2.180	2.410
1.15	1.950	1.995	2.075	2.186	2.410
1.12	1.956	1.997	2.079	2.193	2.412
1.08	1.962	1.999	2.083	2.199	2.416
1.05	1.967	2.002	2.086	2.204	2.421
1.01	1.972	2.006	2.090	2.209	2.425
0.98	1.975	2.010	2.094	2.212	2.426
0.94	1.978	2.017	2.097	2.216	2.426
0.91	1.981	2.024	2.102	2.220	2.426
0.87	1.986	2.033	2.110	2.228	2.428
0.84	1.994	2.044	2.121	2.241	2.436
0.80	2.003	2.059	2.136	2.258	2.451
0.77	2.013	2.075	2.154	2.276	2.470
0.73	2.020	2.090	2.169	2.291	2.490
0.70	2.024	2.102	2.179	2.297	2.506
0.66	2.023	2.108	2.182	2.293	2.515
0.63	2.018	2.108	2.180	2.282	2.516
0.59	2.011	2.104	2.174	2.268	2.513
0.56	2.003	2.099	2.168	2.255	2.510
0.52	1.997	2.094	2.163	2.247	2.509
0.49	1.991	2.089	2.160	2.244	2.512
0.45	1.987	2.085	2.157	2.243	2.518
0.42	1.982	2.081	2.154	2.243	2.523
0.38	1.976	2.076	2.148	2.241	2.525
0.35	1.966	2.068	2.140	2.236	2.520

Q_0 (L/s)	6.24	6.44	6.62	6.83	7.00
y (cm)	$(\overline{v'v'})^{0.5}$	$(\overline{v'v'})^{0.5}$	$(\overline{v'v'})^{0.5}$	$(\overline{v'v'})^{0.5}$	$(\overline{v'v'})^{0.5}$
	(cm/s)	(cm/s)	(cm/s)	(cm/s)	(cm/s)
0.31	1.950	2.054	2.125	2.226	2.506
0.28	1.924	2.033	2.102	2.210	2.480
0.24	1.882	1.998	2.065	2.182	2.437
0.21	1.819	1.942	2.008	2.132	2.367
0.17	1.723	1.851	1.922	2.041	2.252

AII.1.5 Effect of main flow rate Q_0 on $-\overline{u'v'}$ at $x = 25$ cm (in the middle of suction zone)

Q_0 (L/s)	6.24	6.44	6.62	6.83	7.00
y (cm)	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$
2.83	1.089	1.057	1.199	1.244	1.312
2.79	1.009	1.108	1.190	1.272	1.472
2.76	1.047	1.169	1.183	1.351	1.415
2.72	1.058	1.216	1.274	1.429	1.451
2.69	1.102	1.207	1.259	1.389	1.499
2.65	1.128	1.226	1.273	1.405	1.511
2.62	1.155	1.247	1.288	1.422	1.523
2.58	1.182	1.269	1.307	1.443	1.538
2.55	1.210	1.293	1.331	1.470	1.556
2.51	1.240	1.317	1.357	1.503	1.577
2.48	1.269	1.339	1.385	1.543	1.601
2.44	1.299	1.362	1.415	1.587	1.624
2.41	1.326	1.387	1.444	1.632	1.649
2.37	1.350	1.414	1.471	1.675	1.675
2.34	1.371	1.444	1.497	1.711	1.706
2.30	1.388	1.476	1.522	1.739	1.741
2.27	1.403	1.509	1.547	1.763	1.780
2.23	1.417	1.539	1.573	1.784	1.819
2.20	1.434	1.565	1.598	1.805	1.857
2.16	1.453	1.584	1.622	1.828	1.891
2.13	1.473	1.598	1.644	1.851	1.922
2.09	1.495	1.609	1.662	1.869	1.951
2.06	1.517	1.620	1.677	1.882	1.979
2.02	1.538	1.633	1.691	1.889	2.008
1.99	1.559	1.646	1.706	1.893	2.036
1.95	1.578	1.660	1.723	1.896	2.063
1.92	1.596	1.671	1.742	1.901	2.088
1.88	1.612	1.680	1.761	1.909	2.106
1.85	1.626	1.686	1.779	1.918	2.119
1.81	1.640	1.694	1.793	1.926	2.126
1.78	1.653	1.703	1.802	1.932	2.131
1.74	1.665	1.715	1.808	1.934	2.138
1.71	1.677	1.727	1.811	1.933	2.146
1.67	1.689	1.739	1.816	1.932	2.154
1.64	1.701	1.747	1.825	1.930	2.160

Q_0 (L/s)	6.24	6.44	6.62	6.83	7.00
y (cm)	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$
1.60	1.712	1.753	1.839	1.931	2.161
1.57	1.722	1.756	1.859	1.933	2.158
1.54	1.730	1.760	1.882	1.941	2.154
1.50	1.737	1.767	1.907	1.953	2.153
1.47	1.740	1.776	1.931	1.970	2.156
1.43	1.743	1.787	1.954	1.989	2.165
1.40	1.745	1.799	1.975	2.009	2.179
1.36	1.747	1.811	1.993	2.026	2.199
1.33	1.749	1.819	2.010	2.042	2.222
1.29	1.751	1.826	2.024	2.055	2.248
1.26	1.753	1.833	2.036	2.065	2.272
1.22	1.755	1.842	2.046	2.073	2.293
1.19	1.757	1.853	2.055	2.077	2.311
1.15	1.760	1.867	2.062	2.076	2.326
1.12	1.763	1.883	2.068	2.069	2.341
1.08	1.763	1.897	2.072	2.057	2.358
1.05	1.763	1.908	2.076	2.043	2.379
1.01	1.763	1.914	2.080	2.033	2.400
0.98	1.766	1.916	2.083	2.031	2.416
0.94	1.775	1.914	2.087	2.039	2.426
0.91	1.791	1.913	2.092	2.056	2.425
0.87	1.811	1.916	2.101	2.078	2.416
0.84	1.835	1.924	2.114	2.100	2.399
0.80	1.860	1.939	2.134	2.116	2.381
0.77	1.884	1.959	2.159	2.124	2.369
0.73	1.903	1.981	2.186	2.127	2.368
0.70	1.913	1.998	2.206	2.126	2.382
0.66	1.913	2.008	2.214	2.124	2.407
0.63	1.906	2.012	2.209	2.121	2.435
0.59	1.896	2.011	2.197	2.121	2.457
0.56	1.887	2.009	2.184	2.123	2.469
0.52	1.882	2.009	2.178	2.130	2.474
0.49	1.880	2.011	2.181	2.142	2.478
0.45	1.880	2.014	2.193	2.159	2.485
0.42	1.879	2.019	2.212	2.180	2.500
0.38	1.877	2.026	2.234	2.203	2.521
0.35	1.873	2.036	2.257	2.225	2.543
0.31	1.863	2.043	2.276	2.239	2.559
0.28	1.844	2.038	2.286	2.236	2.552

Q_0 (L/s)	6.24	6.44	6.62	6.83	7.00
y (cm)	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$
0.24	1.807	2.005	2.282	2.199	2.504
0.21	1.739	1.927	2.249	2.110	2.396
0.17	1.631	1.792	2.169	1.959	2.216

AII.2 Effect of suction flow rate Q_s on flow

AII.2.1 Effect of suction flow rate Q_s on streamwise velocity, u at $x = 25$ cm (in the middle of suction zone)

Q_s (L/s)	0	0.264	0.445	0.682	0.85	0.97	1.1
y (cm)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)
2.83	30.65	30.04	29.99	29.79	29.24	29.33	29.08
2.79	30.64	29.98	29.94	29.74	29.20	29.32	29.03
2.76	30.55	29.93	29.88	29.66	29.16	29.24	28.96
2.72	30.44	29.90	29.86	29.60	29.14	29.20	28.97
2.69	30.34	29.82	29.79	29.57	29.10	29.16	28.91
2.65	30.26	29.76	29.73	29.53	29.08	29.17	28.85
2.62	30.19	29.69	29.67	29.48	28.99	29.05	28.80
2.58	30.12	29.60	29.60	29.40	28.94	29.04	28.73
2.55	30.05	29.50	29.52	29.30	28.82	28.91	28.57
2.51	29.99	29.40	29.45	29.22	28.84	28.87	28.56
2.48	29.91	29.31	29.38	29.15	28.72	28.74	28.47
2.44	29.83	29.22	29.30	29.09	28.70	28.74	28.43
2.41	29.74	29.13	29.21	29.03	28.62	28.64	28.33
2.37	29.65	29.04	29.14	28.97	28.58	28.63	28.32
2.34	29.56	28.96	29.07	28.92	28.49	28.56	28.27
2.30	29.47	28.87	28.99	28.86	28.48	28.53	28.21
2.27	29.38	28.77	28.92	28.79	28.36	28.41	28.04
2.23	29.30	28.68	28.86	28.72	28.33	28.40	28.04
2.20	29.22	28.58	28.79	28.65	28.23	28.33	28.01
2.16	29.14	28.49	28.72	28.58	28.22	28.31	27.99
2.13	29.05	28.40	28.65	28.51	28.09	28.21	27.88
2.09	28.95	28.32	28.57	28.44	28.09	28.21	27.90
2.06	28.85	28.23	28.49	28.36	27.96	28.10	27.80
2.02	28.74	28.15	28.40	28.28	27.88	28.03	27.76
1.99	28.63	28.06	28.32	28.21	27.78	27.94	27.62
1.95	28.52	27.97	28.23	28.13	27.71	27.94	27.62
1.92	28.42	27.87	28.14	28.05	27.64	27.78	27.48
1.88	28.32	27.78	28.04	27.96	27.60	27.77	27.42
1.85	28.22	27.69	27.94	27.88	27.44	27.65	27.29
1.81	28.12	27.60	27.84	27.79	27.39	27.60	27.24
1.78	28.01	27.51	27.74	27.70	27.33	27.47	27.15
1.74	27.91	27.40	27.65	27.60	27.29	27.47	27.15
1.71	27.81	27.30	27.56	27.51	27.22	27.34	27.06

Q_s (L/s)	0	0.264	0.445	0.682	0.85	0.97	1.1
y (cm)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)
1.67	27.71	27.21	27.47	27.43	27.14	27.30	27.01
1.64	27.60	27.11	27.38	27.36	27.03	27.26	26.86
1.60	27.49	27.02	27.30	27.28	26.96	27.22	26.82
1.57	27.37	26.91	27.22	27.19	26.88	27.10	26.66
1.54	27.25	26.81	27.13	27.10	26.82	27.07	26.63
1.50	27.13	26.72	27.05	27.02	26.72	26.91	26.52
1.47	27.02	26.62	26.96	26.93	26.71	26.92	26.48
1.43	26.91	26.53	26.87	26.83	26.57	26.77	26.32
1.40	26.80	26.42	26.78	26.73	26.55	26.76	26.32
1.36	26.69	26.31	26.69	26.63	26.40	26.63	26.17
1.33	26.56	26.21	26.59	26.52	26.36	26.57	26.14
1.29	26.44	26.12	26.50	26.42	26.27	26.44	26.01
1.26	26.31	26.02	26.41	26.32	26.15	26.34	25.91
1.22	26.19	25.93	26.34	26.24	26.06	26.21	25.80
1.19	26.05	25.83	26.26	26.16	26.02	26.22	25.76
1.15	25.92	25.73	26.18	26.08	25.90	26.05	25.67
1.12	25.77	25.63	26.10	26.00	25.87	26.00	25.65
1.08	25.62	25.53	26.01	25.92	25.74	25.87	25.50
1.05	25.45	25.43	25.92	25.84	25.67	25.85	25.50
1.01	25.28	25.33	25.82	25.75	25.56	25.69	25.37
0.98	25.11	25.22	25.71	25.67	25.53	25.63	25.35
0.94	24.95	25.11	25.61	25.58	25.38	25.57	25.23
0.91	24.78	24.99	25.51	25.48	25.38	25.47	25.22
0.87	24.61	24.87	25.41	25.38	25.22	25.37	25.05
0.84	24.42	24.73	25.30	25.28	25.18	25.32	24.99
0.80	24.20	24.52	25.17	25.17	25.05	25.18	24.93
0.77	23.93	24.21	25.00	25.04	24.99	25.12	24.83
0.73	23.66	23.82	24.81	24.91	24.65	24.46	24.30
0.70	23.43	23.56	24.63	24.77	24.31	24.07	23.96
0.66	23.26	23.58	24.60	24.74	24.62	24.63	24.38
0.63	23.09	23.66	24.57	24.70	24.59	24.60	24.39
0.59	22.90	23.69	24.54	24.65	24.52	24.70	24.40
0.56	22.68	23.64	24.48	24.59	24.46	24.67	24.38
0.52	22.43	23.52	24.41	24.52	24.39	24.62	24.29
0.49	22.16	23.36	24.32	24.44	24.37	24.59	24.27
0.45	21.88	23.18	24.22	24.36	24.29	24.46	24.16
0.42	21.59	22.99	24.11	24.28	24.26	24.42	24.16
0.38	21.29	22.77	23.99	24.19	24.14	24.30	24.04

Q_s (L/s)	0	0.264	0.445	0.682	0.85	0.97	1.1
y (cm)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)	u (cm/s)
0.35	20.95	22.54	23.86	24.11	24.09	24.26	24.01
0.31	20.56	22.29	23.71	24.03	23.98	24.11	23.90
0.28	20.10	22.01	23.53	23.94	23.95	24.10	23.90
0.24	19.54	21.66	23.31	23.83	23.83	24.06	23.81
0.21	18.84	21.20	22.99	23.67	23.78	23.99	23.76
0.17	17.88	20.50	22.48	23.37	23.63	23.79	23.61

AI1.2.2 Effect of suction flow rate Q_s on vertical velocity, v at $x = 25$ cm (in the middle of suction zone)

Q_s (L/s)	0	0.264	0.445	0.682	0.85	0.97	1.1
y (cm)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)
2.83	0.020	-0.155	-0.337	-0.437	-0.509	-0.597	-0.593
2.79	0.008	-0.182	-0.363	-0.452	-0.498	-0.607	-0.606
2.76	0.018	-0.159	-0.343	-0.438	-0.493	-0.591	-0.601
2.72	0.014	-0.183	-0.350	-0.446	-0.504	-0.605	-0.608
2.69	0.021	-0.169	-0.343	-0.442	-0.497	-0.610	-0.611
2.65	0.022	-0.169	-0.342	-0.442	-0.498	-0.614	-0.613
2.62	0.022	-0.171	-0.342	-0.441	-0.498	-0.618	-0.613
2.58	0.022	-0.173	-0.341	-0.437	-0.498	-0.620	-0.611
2.55	0.021	-0.175	-0.337	-0.432	-0.498	-0.620	-0.607
2.51	0.020	-0.175	-0.333	-0.427	-0.499	-0.618	-0.605
2.48	0.020	-0.173	-0.328	-0.423	-0.500	-0.616	-0.605
2.44	0.022	-0.169	-0.323	-0.420	-0.500	-0.615	-0.606
2.41	0.024	-0.166	-0.321	-0.417	-0.499	-0.614	-0.609
2.37	0.025	-0.163	-0.321	-0.415	-0.497	-0.614	-0.610
2.34	0.025	-0.161	-0.322	-0.413	-0.494	-0.613	-0.611
2.30	0.028	-0.159	-0.323	-0.410	-0.492	-0.612	-0.611
2.27	0.034	-0.156	-0.324	-0.407	-0.492	-0.610	-0.610
2.23	0.040	-0.153	-0.325	-0.404	-0.493	-0.608	-0.609
2.20	0.043	-0.149	-0.326	-0.402	-0.493	-0.606	-0.609
2.16	0.043	-0.145	-0.325	-0.399	-0.491	-0.604	-0.608
2.13	0.044	-0.143	-0.322	-0.395	-0.488	-0.600	-0.605
2.09	0.045	-0.142	-0.318	-0.391	-0.486	-0.596	-0.600
2.06	0.047	-0.141	-0.315	-0.389	-0.484	-0.592	-0.595
2.02	0.050	-0.137	-0.308	-0.387	-0.482	-0.591	-0.593
1.99	0.054	-0.131	-0.301	-0.386	-0.480	-0.592	-0.593
1.95	0.059	-0.124	-0.293	-0.382	-0.478	-0.593	-0.594
1.92	0.063	-0.118	-0.286	-0.375	-0.475	-0.593	-0.595
1.88	0.068	-0.112	-0.277	-0.366	-0.473	-0.591	-0.596
1.85	0.073	-0.106	-0.268	-0.357	-0.472	-0.588	-0.597
1.81	0.077	-0.102	-0.260	-0.352	-0.471	-0.586	-0.596
1.78	0.081	-0.102	-0.254	-0.350	-0.468	-0.585	-0.595
1.74	0.082	-0.100	-0.250	-0.350	-0.464	-0.584	-0.591
1.71	0.080	-0.097	-0.245	-0.351	-0.460	-0.583	-0.588
1.67	0.080	-0.093	-0.241	-0.352	-0.455	-0.584	-0.585
1.64	0.081	-0.089	-0.239	-0.352	-0.451	-0.584	-0.582

Q_s (L/s)	0	0.264	0.445	0.682	0.85	0.97	1.1
y (cm)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)
1.60	0.084	-0.086	-0.236	-0.349	-0.448	-0.583	-0.580
1.57	0.086	-0.082	-0.232	-0.345	-0.444	-0.579	-0.579
1.54	0.088	-0.080	-0.227	-0.339	-0.442	-0.574	-0.577
1.50	0.090	-0.078	-0.220	-0.332	-0.441	-0.571	-0.575
1.47	0.091	-0.075	-0.214	-0.323	-0.443	-0.568	-0.572
1.43	0.093	-0.069	-0.210	-0.315	-0.444	-0.565	-0.570
1.40	0.093	-0.063	-0.208	-0.307	-0.442	-0.562	-0.569
1.36	0.093	-0.060	-0.207	-0.300	-0.439	-0.561	-0.568
1.33	0.094	-0.057	-0.205	-0.295	-0.440	-0.560	-0.569
1.29	0.097	-0.054	-0.204	-0.291	-0.444	-0.559	-0.570
1.26	0.098	-0.051	-0.203	-0.286	-0.449	-0.557	-0.570
1.22	0.097	-0.049	-0.202	-0.282	-0.451	-0.553	-0.568
1.19	0.094	-0.045	-0.200	-0.279	-0.452	-0.548	-0.566
1.15	0.088	-0.040	-0.200	-0.278	-0.453	-0.543	-0.562
1.12	0.083	-0.038	-0.199	-0.277	-0.454	-0.538	-0.558
1.08	0.080	-0.041	-0.197	-0.276	-0.454	-0.533	-0.555
1.05	0.078	-0.045	-0.194	-0.275	-0.456	-0.531	-0.556
1.01	0.078	-0.047	-0.192	-0.277	-0.457	-0.529	-0.558
0.98	0.079	-0.048	-0.192	-0.279	-0.457	-0.530	-0.561
0.94	0.078	-0.047	-0.193	-0.281	-0.457	-0.533	-0.565
0.91	0.077	-0.045	-0.191	-0.279	-0.455	-0.537	-0.571
0.87	0.077	-0.042	-0.186	-0.276	-0.454	-0.541	-0.578
0.84	0.079	-0.040	-0.181	-0.274	-0.453	-0.542	-0.584
0.80	0.081	-0.038	-0.179	-0.278	-0.452	-0.542	-0.587
0.77	0.083	-0.035	-0.181	-0.287	-0.451	-0.543	-0.588
0.73	0.074	-0.039	-0.192	-0.305	-0.453	-0.549	-0.591
0.70	0.053	-0.054	-0.211	-0.325	-0.459	-0.559	-0.598
0.66	0.031	-0.070	-0.227	-0.341	-0.466	-0.567	-0.605
0.63	0.020	-0.075	-0.233	-0.347	-0.471	-0.570	-0.610
0.59	0.018	-0.072	-0.232	-0.347	-0.476	-0.574	-0.615
0.56	0.020	-0.070	-0.230	-0.349	-0.482	-0.579	-0.619
0.52	0.019	-0.074	-0.232	-0.357	-0.492	-0.589	-0.626
0.49	0.016	-0.081	-0.237	-0.369	-0.506	-0.599	-0.634
0.45	0.011	-0.090	-0.246	-0.383	-0.523	-0.610	-0.645
0.42	0.002	-0.102	-0.260	-0.400	-0.542	-0.624	-0.659
0.38	-0.010	-0.119	-0.280	-0.420	-0.563	-0.641	-0.677
0.35	-0.024	-0.140	-0.303	-0.443	-0.588	-0.663	-0.700
0.31	-0.036	-0.163	-0.326	-0.470	-0.616	-0.689	-0.728

Q_s (L/s)	0	0.264	0.445	0.682	0.85	0.97	1.1
y (cm)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)	v (cm/s)
0.28	-0.044	-0.188	-0.348	-0.500	-0.649	-0.723	-0.761
0.24	-0.050	-0.213	-0.371	-0.533	-0.685	-0.764	-0.799
0.21	-0.054	-0.236	-0.396	-0.572	-0.726	-0.813	-0.846
0.17	-0.060	-0.256	-0.422	-0.615	-0.770	-0.864	-0.901

AII.2.3 Effect of suction flow rate Q_s on $(\overline{u'u'})^{0.5}$ at $x = 25$ cm (in the middle of suction zone)

Q_s (L/s) y (cm)	0 $(\overline{u'u'})^{0.5}$	0.264 $(\overline{u'u'})^{0.5}$	0.445 $(\overline{u'u'})^{0.5}$	0.682 $(\overline{u'u'})^{0.5}$	0.85 $(\overline{u'u'})^{0.5}$	0.97 $(\overline{u'u'})^{0.5}$	1.1 $(\overline{u'u'})^{0.5}$
2.83	4.953	5.266	5.198	5.128	4.033	4.417	4.414
2.79	4.976	5.294	5.163	5.104	4.040	4.347	4.429
2.76	4.840	5.170	5.130	5.094	4.123	4.375	4.379
2.72	4.923	5.185	5.198	5.071	4.102	4.372	4.427
2.69	4.959	5.148	5.057	5.022	4.091	4.355	4.390
2.65	4.862	5.231	5.120	5.097	4.157	4.441	4.435
2.62	4.912	5.141	5.088	4.990	4.164	4.426	4.404
2.58	4.938	5.158	5.074	4.966	4.117	4.415	4.380
2.55	5.013	5.143	5.094	5.159	4.158	4.450	4.482
2.51	4.964	5.092	5.014	5.106	4.124	4.418	4.487
2.48	5.056	5.118	5.130	5.121	4.110	4.401	4.494
2.44	5.064	5.153	5.114	5.106	4.136	4.395	4.509
2.41	5.049	5.238	5.259	5.300	4.187	4.510	4.502
2.37	5.096	5.258	5.289	5.379	4.162	4.513	4.506
2.34	5.045	5.299	5.238	5.302	4.178	4.484	4.475
2.30	5.071	5.266	5.210	5.267	4.155	4.528	4.473
2.27	5.078	5.352	5.265	5.407	4.190	4.527	4.587
2.23	5.027	5.374	5.238	5.368	4.209	4.508	4.601
2.20	5.027	5.356	5.348	5.411	4.195	4.509	4.550
2.16	5.039	5.315	5.282	5.384	4.162	4.460	4.580
2.13	5.127	5.279	5.274	5.237	4.221	4.458	4.478
2.09	5.124	5.295	5.295	5.274	4.218	4.424	4.454
2.06	5.113	5.312	5.293	5.254	4.192	4.452	4.512
2.02	5.112	5.308	5.302	5.291	4.180	4.474	4.501
1.99	5.145	5.302	5.280	5.364	4.220	4.547	4.525
1.95	5.103	5.295	5.245	5.310	4.276	4.536	4.549
1.92	5.121	5.286	5.253	5.246	4.243	4.494	4.530
1.88	5.149	5.253	5.278	5.247	4.219	4.456	4.525
1.85	5.203	5.339	5.363	5.268	4.257	4.473	4.560
1.81	5.266	5.368	5.316	5.217	4.251	4.474	4.579
1.78	5.288	5.359	5.368	5.299	4.313	4.521	4.635
1.74	5.332	5.382	5.409	5.304	4.264	4.530	4.626
1.71	5.290	5.401	5.409	5.410	4.264	4.519	4.603
1.67	5.300	5.401	5.412	5.411	4.298	4.536	4.677

Q_s (L/s) y (cm)	0 $(\overline{u'u'})^{0.5}$	0.264 $(\overline{u'u'})^{0.5}$	0.445 $(\overline{u'u'})^{0.5}$	0.682 $(\overline{u'u'})^{0.5}$	0.85 $(\overline{u'u'})^{0.5}$	0.97 $(\overline{u'u'})^{0.5}$	1.1 $(\overline{u'u'})^{0.5}$
1.64	5.300	5.451	5.449	5.401	4.377	4.555	4.673
1.60	5.296	5.426	5.448	5.468	4.389	4.555	4.660
1.57	5.314	5.452	5.424	5.334	4.347	4.587	4.597
1.54	5.237	5.510	5.392	5.377	4.310	4.601	4.543
1.50	5.311	5.450	5.328	5.340	4.322	4.560	4.556
1.47	5.302	5.410	5.290	5.298	4.332	4.554	4.553
1.43	5.400	5.402	5.343	5.402	4.346	4.587	4.622
1.40	5.424	5.391	5.352	5.350	4.304	4.534	4.600
1.36	5.446	5.466	5.409	5.358	4.383	4.574	4.672
1.33	5.433	5.437	5.396	5.309	4.379	4.529	4.646
1.29	5.416	5.569	5.433	5.295	4.363	4.574	4.616
1.26	5.394	5.498	5.424	5.338	4.370	4.583	4.635
1.22	5.430	5.545	5.435	5.306	4.347	4.590	4.619
1.19	5.453	5.546	5.396	5.328	4.358	4.637	4.638
1.15	5.370	5.454	5.350	5.306	4.306	4.621	4.590
1.12	5.360	5.471	5.351	5.291	4.304	4.610	4.587
1.08	5.386	5.362	5.329	5.319	4.286	4.567	4.614
1.05	5.396	5.377	5.276	5.323	4.245	4.516	4.618
1.01	5.387	5.299	5.304	5.140	4.253	4.549	4.539
0.98	5.374	5.338	5.286	5.145	4.258	4.566	4.536
0.94	5.344	5.315	5.208	5.172	4.232	4.539	4.472
0.91	5.394	5.279	5.138	5.128	4.207	4.474	4.406
0.87	5.326	5.246	5.231	5.073	4.167	4.438	4.475
0.84	5.335	5.232	5.249	5.062	4.177	4.438	4.445
0.80	5.326	5.224	5.208	5.127	4.206	4.442	4.432
0.77	5.320	5.252	5.234	5.104	4.230	4.439	4.493
0.73	5.356	5.906	5.915	5.784	4.124	4.577	4.558
0.70	5.045	5.647	5.640	5.577	3.922	4.445	4.358
0.66	5.643	6.187	6.178	6.081	4.222	4.769	4.685
0.63	5.649	6.219	6.170	6.086	4.196	4.790	4.655
0.59	5.408	5.235	5.078	5.080	4.085	4.390	4.409
0.56	5.416	5.273	5.046	5.021	4.075	4.352	4.397
0.52	5.354	5.182	5.009	4.992	4.054	4.313	4.319
0.49	5.347	5.154	4.995	4.968	4.017	4.261	4.293
0.45	5.386	5.311	5.072	4.938	3.989	4.287	4.267
0.42	5.378	5.297	5.061	4.933	3.988	4.281	4.226
0.38	5.352	5.265	5.033	4.909	3.948	4.236	4.225
0.35	5.407	5.228	5.020	4.892	3.909	4.205	4.220

Q_s (L/s) y (cm)	0	0.264	0.445	0.682	0.85	0.97	1.1
	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$
0.31	5.403	5.237	4.948	4.826	3.886	4.209	4.124
0.28	5.394	5.214	4.926	4.777	3.872	4.175	4.100
0.24	5.414	5.283	4.907	4.684	3.801	4.178	4.085
0.21	5.529	5.288	4.909	4.654	3.837	4.158	4.073
0.17	5.429	5.217	4.940	4.703	3.834	4.054	4.042

AII.2.4 Effect of suction flow rate Q_s on $(\overline{v'v'})^{0.5}$ at $x = 25$ cm (in the middle of suction zone)

Q_s (L/s) y (cm)	0 $(\overline{v'v'})^{0.5}$	0.264 $(\overline{v'v'})^{0.5}$	0.445 $(\overline{v'v'})^{0.5}$	0.682 $(\overline{v'v'})^{0.5}$	0.85 $(\overline{v'v'})^{0.5}$	0.97 $(\overline{v'v'})^{0.5}$	1.1 $(\overline{v'v'})^{0.5}$
2.83	1.673	1.843	1.869	1.848	1.443	1.621	1.642
2.79	1.689	1.867	1.881	1.842	1.449	1.630	1.646
2.76	1.685	1.853	1.875	1.822	1.444	1.606	1.604
2.72	1.712	1.844	1.863	1.833	1.452	1.597	1.612
2.69	1.709	1.846	1.881	1.851	1.447	1.634	1.632
2.65	1.703	1.862	1.897	1.867	1.454	1.650	1.645
2.62	1.700	1.876	1.881	1.854	1.450	1.640	1.609
2.58	1.722	1.892	1.861	1.862	1.446	1.638	1.614
2.55	1.749	1.930	1.897	1.867	1.479	1.653	1.643
2.51	1.744	1.958	1.870	1.866	1.458	1.646	1.647
2.48	1.763	1.947	1.917	1.840	1.472	1.654	1.655
2.44	1.780	1.933	1.922	1.835	1.481	1.660	1.653
2.41	1.846	2.024	1.991	1.918	1.460	1.670	1.666
2.37	1.860	2.037	2.029	1.925	1.451	1.666	1.677
2.34	1.843	2.048	2.004	1.943	1.458	1.720	1.672
2.30	1.841	2.032	2.013	1.930	1.455	1.698	1.657
2.27	1.892	2.070	2.025	1.991	1.525	1.716	1.666
2.23	1.901	2.085	2.035	2.005	1.531	1.702	1.679
2.20	1.899	2.095	2.019	2.006	1.533	1.733	1.658
2.16	1.923	2.091	2.013	2.003	1.544	1.733	1.677
2.13	1.916	2.061	2.024	2.007	1.531	1.736	1.690
2.09	1.962	2.054	2.025	2.001	1.538	1.739	1.693
2.06	1.926	2.095	2.065	2.021	1.534	1.741	1.723
2.02	1.893	2.080	2.096	2.025	1.537	1.747	1.717
1.99	1.960	2.117	2.116	2.003	1.523	1.741	1.713
1.95	1.947	2.106	2.144	2.002	1.539	1.743	1.707
1.92	1.983	2.108	2.073	2.003	1.574	1.758	1.728
1.88	1.961	2.126	2.122	2.018	1.567	1.760	1.718
1.85	1.999	2.199	2.131	2.033	1.578	1.791	1.761
1.81	1.999	2.216	2.110	2.015	1.584	1.773	1.779
1.78	2.002	2.200	2.081	1.998	1.589	1.789	1.793
1.74	2.023	2.199	2.126	1.983	1.602	1.767	1.801
1.71	2.045	2.184	2.138	2.051	1.600	1.806	1.814
1.67	2.049	2.158	2.131	2.034	1.591	1.820	1.824

Q_s (L/s) y (cm)	0 $(\overline{v'v'})^{0.5}$	0.264 $(\overline{v'v'})^{0.5}$	0.445 $(\overline{v'v'})^{0.5}$	0.682 $(\overline{v'v'})^{0.5}$	0.85 $(\overline{v'v'})^{0.5}$	0.97 $(\overline{v'v'})^{0.5}$	1.1 $(\overline{v'v'})^{0.5}$
1.64	2.040	2.172	2.174	2.030	1.594	1.805	1.834
1.60	2.056	2.213	2.150	2.025	1.610	1.816	1.814
1.57	2.076	2.256	2.203	2.015	1.589	1.789	1.799
1.54	2.081	2.248	2.178	2.045	1.606	1.804	1.805
1.50	2.083	2.245	2.134	2.073	1.619	1.803	1.824
1.47	2.066	2.253	2.158	2.072	1.619	1.799	1.817
1.43	2.116	2.247	2.114	2.075	1.615	1.806	1.844
1.40	2.083	2.224	2.179	2.097	1.626	1.822	1.857
1.36	2.101	2.230	2.149	2.117	1.644	1.822	1.843
1.33	2.092	2.243	2.148	2.124	1.644	1.808	1.831
1.29	2.093	2.308	2.167	2.065	1.662	1.867	1.846
1.26	2.105	2.301	2.164	2.079	1.667	1.867	1.839
1.22	2.125	2.312	2.177	2.130	1.674	1.884	1.854
1.19	2.145	2.284	2.147	2.138	1.679	1.891	1.884
1.15	2.158	2.319	2.182	2.095	1.671	1.853	1.857
1.12	2.174	2.303	2.158	2.081	1.673	1.842	1.866
1.08	2.182	2.317	2.122	2.046	1.672	1.849	1.883
1.05	2.178	2.313	2.117	2.078	1.692	1.853	1.889
1.01	2.194	2.249	2.132	2.126	1.685	1.902	1.847
0.98	2.180	2.268	2.143	2.140	1.687	1.889	1.830
0.94	2.171	2.236	2.151	2.116	1.692	1.894	1.832
0.91	2.190	2.262	2.115	2.114	1.705	1.886	1.827
0.87	2.187	2.212	2.157	2.021	1.681	1.848	1.831
0.84	2.172	2.238	2.163	2.028	1.679	1.854	1.822
0.80	2.190	2.162	2.170	2.045	1.699	1.830	1.800
0.77	2.173	2.170	2.154	2.055	1.697	1.805	1.807
0.73	2.247	2.257	2.203	2.021	1.654	1.886	1.849
0.70	2.292	2.292	2.204	2.044	1.658	1.918	1.846
0.66	2.308	2.241	2.169	2.057	1.659	1.818	1.836
0.63	2.329	2.279	2.185	2.060	1.635	1.819	1.828
0.59	2.378	2.275	2.086	2.076	1.646	1.808	1.793
0.56	2.350	2.295	2.114	2.077	1.648	1.783	1.802
0.52	2.325	2.277	2.069	2.093	1.605	1.783	1.763
0.49	2.302	2.274	2.104	2.081	1.591	1.752	1.744
0.45	2.406	2.327	2.085	2.057	1.572	1.784	1.747
0.42	2.428	2.301	2.055	2.045	1.549	1.773	1.750
0.38	2.422	2.332	1.979	2.019	1.512	1.731	1.717
0.35	2.408	2.302	1.988	2.019	1.470	1.718	1.721

Q_s (L/s) y (cm)	0 $(\overline{v'v'})^{0.5}$	0.264 $(\overline{v'v'})^{0.5}$	0.445 $(\overline{v'v'})^{0.5}$	0.682 $(\overline{v'v'})^{0.5}$	0.85 $(\overline{v'v'})^{0.5}$	0.97 $(\overline{v'v'})^{0.5}$	1.1 $(\overline{v'v'})^{0.5}$
0.31	2.346	2.328	1.998	1.834	1.472	1.666	1.653
0.28	2.339	2.348	1.992	1.822	1.426	1.638	1.622
0.24	2.354	2.261	1.917	1.748	1.359	1.612	1.564
0.21	2.353	2.260	1.929	1.737	1.315	1.578	1.507
0.17	2.137	2.010	1.728	1.683	1.223	1.426	1.398

AII.2.5 Effect of suction flow rate Q_s on $-\overline{u'v'}$ at $x = 25$ cm (in the middle of suction zone)

Q_s (L/s)	0	0.264	0.445	0.682	0.85	0.97	1.1
y (cm)	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$
2.83	1.106	0.772	0.759	0.931	0.710	0.804	0.591
2.79	1.125	0.763	0.728	0.900	0.724	0.699	0.708
2.76	1.023	0.638	0.841	1.014	0.824	0.623	0.683
2.72	1.017	0.801	0.755	0.981	0.860	0.712	0.686
2.69	0.982	0.904	1.050	0.894	0.663	0.818	0.831
2.65	0.952	0.855	1.080	0.974	0.766	0.840	0.862
2.62	1.218	1.116	0.910	1.077	0.836	0.833	0.861
2.58	1.327	1.084	0.933	1.055	0.884	0.832	0.859
2.55	1.321	1.131	0.950	1.057	1.000	1.023	1.079
2.51	1.156	1.041	1.030	1.064	0.968	0.987	0.940
2.48	1.219	1.021	1.081	1.154	1.027	0.977	0.995
2.44	1.197	1.021	1.019	1.013	1.003	0.927	0.955
2.41	1.406	1.115	1.008	1.110	1.029	1.094	1.074
2.37	1.432	1.204	1.001	1.141	1.067	1.026	0.964
2.34	1.339	1.193	1.086	1.259	1.088	0.987	1.044
2.30	1.434	1.134	1.101	1.309	1.057	0.975	1.073
2.27	1.450	1.182	1.205	1.367	1.158	1.153	1.138
2.23	1.370	0.974	1.455	1.259	1.220	1.181	1.217
2.20	1.440	1.163	1.500	1.248	1.318	1.179	1.186
2.16	1.489	1.127	1.356	1.230	1.208	1.325	1.175
2.13	1.619	1.325	1.468	1.399	1.289	1.219	1.307
2.09	1.672	1.310	1.330	1.416	1.326	1.243	1.268
2.06	1.658	1.382	1.627	1.417	1.345	1.280	1.478
2.02	1.473	1.325	1.610	1.300	1.344	1.285	1.453
1.99	1.585	1.153	1.687	1.571	1.408	1.484	1.410
1.95	1.475	1.107	1.744	1.548	1.364	1.433	1.407
1.92	1.648	1.282	1.555	1.485	1.311	1.440	1.465
1.88	1.658	1.243	1.526	1.604	1.384	1.383	1.467
1.85	1.777	1.388	1.515	1.706	1.330	1.492	1.548
1.81	1.735	1.331	1.427	1.542	1.374	1.502	1.467
1.78	1.749	1.485	1.440	1.606	1.365	1.535	1.460
1.74	1.781	1.333	1.345	1.468	1.341	1.532	1.332
1.71	1.739	1.569	1.811	1.742	1.474	1.502	1.492
1.67	1.717	1.841	1.579	1.747	1.492	1.578	1.456
1.64	1.500	1.556	1.827	1.585	1.459	1.717	1.440

Q_s (L/s)	0	0.264	0.445	0.682	0.85	0.97	1.1
y (cm)	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$
1.60	1.596	1.425	1.634	1.608	1.464	1.633	1.398
1.57	1.926	1.626	1.824	1.612	1.558	1.605	1.518
1.54	1.863	1.542	1.806	1.867	1.512	1.651	1.433
1.50	1.990	1.564	1.558	1.786	1.576	1.644	1.637
1.47	2.097	1.398	1.507	1.769	1.501	1.655	1.558
1.43	2.052	1.386	1.815	1.635	1.566	1.622	1.574
1.40	1.959	1.539	1.896	1.695	1.656	1.694	1.559
1.36	1.944	1.411	1.789	1.516	1.532	1.568	1.625
1.33	1.888	1.600	1.876	1.528	1.570	1.491	1.603
1.29	2.021	1.729	2.042	1.723	1.651	1.759	1.625
1.26	2.029	1.732	2.009	1.651	1.664	1.822	1.552
1.22	1.966	1.855	1.835	1.818	1.500	1.633	1.534
1.19	2.057	1.790	1.791	1.813	1.662	1.626	1.473
1.15	1.911	1.627	1.763	1.566	1.597	1.705	1.440
1.12	1.925	1.344	1.616	1.611	1.550	1.772	1.476
1.08	1.993	1.360	1.659	1.673	1.578	1.614	1.555
1.05	2.021	1.277	1.451	1.583	1.630	1.622	1.477
1.01	2.076	1.601	1.381	1.802	1.569	1.724	1.671
0.98	2.136	1.522	1.391	1.753	1.565	1.687	1.712
0.94	2.047	1.476	1.238	1.614	1.497	1.739	1.703
0.91	1.851	1.457	1.228	1.547	1.596	1.669	1.638
0.87	2.098	1.606	1.657	1.449	1.545	1.750	1.645
0.84	2.180	1.679	1.657	1.420	1.576	1.746	1.676
0.80	1.893	1.744	1.529	1.562	1.473	1.529	1.720
0.77	2.013	1.554	1.467	1.426	1.349	1.560	1.719
0.73	1.340	0.787	0.792	1.069	1.245	1.327	1.229
0.70	1.518	0.970	0.921	1.302	1.206	1.454	1.237
0.66	2.416	1.704	1.899	1.875	1.372	1.678	1.617
0.63	2.194	1.630	1.666	1.723	1.285	1.641	1.486
0.59	2.153	1.497	1.181	1.067	1.327	1.238	1.422
0.56	1.926	1.390	1.047	1.135	1.282	1.239	1.389
0.52	2.034	1.569	0.999	1.111	1.214	1.268	1.250
0.49	2.114	1.536	0.943	1.070	1.120	1.197	1.243
0.45	2.053	1.494	0.963	1.014	1.016	1.291	1.092
0.42	2.115	1.424	1.035	1.047	1.047	1.218	1.024
0.38	1.944	1.521	0.969	1.109	0.935	1.238	0.963
0.35	2.107	1.424	0.819	1.104	0.860	1.226	1.054
0.31	2.344	1.751	0.963	1.080	0.927	0.956	1.115
0.28	2.142	1.625	1.016	1.144	0.894	0.887	1.063

Q_s (L/s)	0	0.264	0.445	0.682	0.85	0.97	1.1
y (cm)	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$	$-\overline{u'v'}$
0.24	2.227	1.422	0.919	0.959	0.710	0.940	1.019
0.21	2.373	1.335	1.107	0.847	0.689	0.904	0.971
0.17	2.333	1.739	1.064	0.805	0.803	0.888	0.887

AII.3 Effect of suction zone length, x on flow

AII.3.1 Effect of suction zone length, x on streamwise velocity, u at $x = 25$ cm (in the middle of suction zone)

$x(\text{cm})$	0	10	18	25	32
$y(\text{cm})$	$u(\text{cm/s})$	$u(\text{cm/s})$	$u(\text{cm/s})$	$u(\text{cm/s})$	$u(\text{cm/s})$
2.70	28.40	26.95	27.65	27.66	27.48
2.66	28.29	26.90	27.58	27.57	27.44
2.61	28.17	26.85	27.53	27.48	27.38
2.57	28.07	26.76	27.44	27.34	27.32
2.52	27.95	26.69	27.38	27.20	27.24
2.48	27.85	26.60	27.29	27.05	27.17
2.43	27.75	26.53	27.19	26.95	27.12
2.39	27.66	26.46	27.07	26.86	27.07
2.34	27.54	26.41	26.99	26.80	26.99
2.30	27.44	26.33	26.89	26.76	26.92
2.25	27.34	26.25	26.81	26.74	26.82
2.21	27.23	26.15	26.72	26.69	26.72
2.16	27.14	26.06	26.66	26.67	26.57
2.12	26.99	25.96	26.57	26.64	26.45
2.07	26.86	25.88	26.51	26.60	26.31
2.03	26.76	25.75	26.38	26.53	26.22
1.98	26.61	25.65	26.27	26.47	26.10
1.94	26.46	25.52	26.16	26.41	26.01
1.89	26.28	25.41	26.07	26.34	25.92
1.85	26.14	25.26	25.92	26.26	25.85
1.80	25.99	25.15	25.83	26.22	25.76
1.76	25.88	25.02	25.74	26.14	25.68
1.71	25.82	24.91	25.62	26.05	25.61
1.67	25.67	24.76	25.46	25.92	25.55
1.62	25.46	24.64	25.33	25.81	25.49
1.58	25.31	24.52	25.17	25.62	25.42
1.53	25.13	24.41	25.01	25.45	25.35
1.49	25.02	24.25	24.81	25.25	25.27
1.44	24.84	24.12	24.66	25.08	25.18
1.40	24.85	23.98	24.49	24.91	25.08
1.35	24.58	23.85	24.37	24.79	24.98
1.31	24.45	23.70	24.20	24.67	24.91
1.26	24.32	23.58	24.08	24.60	24.84
1.22	24.22	23.42	23.93	24.51	24.73

$x(\text{cm})$	0	10	18	25	32
$y(\text{cm})$	$u(\text{cm/s})$	$u(\text{cm/s})$	$u(\text{cm/s})$	$u(\text{cm/s})$	$u(\text{cm/s})$
1.17	23.79	23.29	23.65	24.45	24.65
1.13	23.69	23.09	23.51	24.27	24.56
1.08	23.54	22.91	23.38	24.10	24.39
1.04	23.45	22.71	23.25	23.93	24.23
0.99	23.28	22.54	23.12	23.77	24.12
0.95	23.10	22.38	22.98	23.62	24.00
0.90	22.89	22.28	22.85	23.59	23.93
0.86	22.82	22.17	22.72	23.53	23.89
0.81	22.42	22.05	22.58	23.48	23.84
0.77	22.34	21.91	22.45	23.38	23.78
0.72	22.00	21.78	22.32	23.27	23.75
0.68	21.96	21.59	22.22	23.14	23.70
0.63	21.51	21.43	22.12	23.03	23.63
0.59	21.37	21.26	21.99	22.87	23.55
0.54	21.09	21.09	21.90	22.77	23.50
0.50	21.03	20.91	21.78	22.63	23.44
0.45	20.54	20.75	21.67	22.53	23.39
0.41	20.28	20.58	21.55	22.41	23.35
0.36	19.90	20.45	21.46	22.32	23.31
0.32	19.69	20.31	21.37	22.19	23.26
0.27	19.09	20.18	21.30	22.13	23.21
0.23	18.65	19.66	20.27	21.61	23.16
0.18	17.41	19.15	19.26	21.12	21.83

AI1.3.2 Effect of suction zone length, x on $(\overline{u'u'})^{0.5}$ at $x = 25$ cm (in the middle of suction zone)

$x(\text{cm})$ $y(\text{cm})$	0 $(\overline{u'u'})^{0.5}$ (cm/s)	10 $(\overline{u'u'})^{0.5}$ (cm/s)	25 $(\overline{u'u'})^{0.5}$ (cm/s)	32 $(\overline{u'u'})^{0.5}$ (cm/s)
2.70	3.754	3.322	2.679	2.423
2.66	3.763	3.341	2.687	2.427
2.61	3.769	3.362	2.696	2.432
2.57	3.775	3.384	2.705	2.437
2.52	3.782	3.404	2.713	2.444
2.48	3.792	3.421	2.719	2.451
2.43	3.806	3.436	2.723	2.459
2.39	3.826	3.452	2.724	2.467
2.34	3.849	3.468	2.725	2.477
2.30	3.876	3.487	2.727	2.487
2.25	3.906	3.508	2.732	2.497
2.21	3.937	3.530	2.741	2.507
2.16	3.969	3.551	2.753	2.519
2.12	4.002	3.572	2.768	2.532
2.07	4.034	3.593	2.786	2.548
2.03	4.067	3.614	2.804	2.567
1.98	4.097	3.636	2.821	2.589
1.94	4.125	3.657	2.836	2.612
1.89	4.150	3.678	2.851	2.636
1.85	4.169	3.700	2.865	2.659
1.80	4.184	3.722	2.879	2.680
1.76	4.193	3.743	2.894	2.699
1.71	4.198	3.762	2.908	2.717
1.67	4.200	3.781	2.923	2.735
1.62	4.201	3.797	2.937	2.755
1.58	4.201	3.814	2.951	2.777
1.53	4.200	3.830	2.965	2.801
1.49	4.197	3.846	2.978	2.823
1.44	4.194	3.863	2.987	2.842
1.40	4.190	3.879	2.991	2.855
1.35	4.188	3.894	2.990	2.862
1.31	4.190	3.909	2.984	2.864
1.26	4.197	3.922	2.975	2.863
1.22	4.209	3.934	2.967	2.860

	0	10	25	32
$x(\text{cm})$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$	$(\overline{u'u'})^{0.5}$
$y(\text{cm})$	(cm/s)	(cm/s)	(cm/s)	(cm/s)
1.17	4.223	3.945	2.960	2.857
1.13	4.237	3.956	2.956	2.852
1.08	4.252	3.967	2.955	2.846
1.04	4.266	3.979	2.957	2.837
0.99	4.280	3.991	2.961	2.825
0.95	4.296	4.000	2.967	2.812
0.90	4.311	4.003	2.974	2.798
0.86	4.326	3.999	2.978	2.786
0.81	4.338	3.988	2.981	2.778
0.77	4.346	3.972	2.980	2.774
0.72	4.350	3.954	2.976	2.771
0.68	4.350	3.937	2.969	2.769
0.63	4.349	3.919	2.960	2.766
0.59	4.349	3.902	2.948	2.759
0.54	4.349	3.883	2.936	2.750
0.50	4.350	3.860	2.925	2.739
0.45	4.350	3.835	2.918	2.728
0.41	4.346	3.806	2.920	2.718
0.36	4.333	3.774	2.943	2.717
0.32	4.305	3.736	3.000	2.734
0.27	4.246	3.687	3.107	2.790
0.23	4.129	3.616	3.267	2.907
0.18	3.919	3.518	3.462	3.099

AII.3.3 Effect of suction zone length, x on $(\overline{v'v'})^{0.5}$ at $x = 25$ cm (in the middle of suction zone)

$x(\text{cm})$	0	10	25	32
$y(\text{cm})$	$(\overline{v'v'})^{0.5}$	$(\overline{v'v'})^{0.5}$	$(\overline{v'v'})^{0.5}$	$(\overline{v'v'})^{0.5}$
	(cm/s)	(cm/s)	(cm/s)	(cm/s)
2.70	1.752	1.571	1.472	1.399
2.66	1.764	1.583	1.478	1.401
2.61	1.773	1.594	1.483	1.404
2.57	1.782	1.605	1.489	1.408
2.52	1.791	1.618	1.496	1.413
2.48	1.800	1.632	1.503	1.419
2.43	1.810	1.649	1.511	1.425
2.39	1.818	1.665	1.520	1.431
2.34	1.826	1.680	1.529	1.437
2.30	1.832	1.691	1.537	1.441
2.25	1.839	1.700	1.546	1.445
2.21	1.845	1.707	1.555	1.448
2.16	1.851	1.715	1.563	1.450
2.12	1.858	1.724	1.570	1.453
2.07	1.867	1.737	1.578	1.456
2.03	1.879	1.751	1.587	1.460
1.98	1.894	1.767	1.597	1.466
1.94	1.911	1.785	1.608	1.472
1.89	1.927	1.802	1.619	1.479
1.85	1.941	1.817	1.629	1.485
1.80	1.951	1.831	1.639	1.491
1.76	1.960	1.841	1.647	1.498
1.71	1.968	1.849	1.655	1.504
1.67	1.978	1.858	1.663	1.510
1.62	1.991	1.868	1.669	1.515
1.58	2.005	1.882	1.674	1.520
1.53	2.017	1.898	1.677	1.524
1.49	2.024	1.915	1.679	1.528
1.44	2.023	1.931	1.679	1.531
1.40	2.030	1.946	1.680	1.534
1.35	2.040	1.960	1.680	1.535
1.31	2.050	1.975	1.678	1.536
1.26	2.060	1.991	1.677	1.535
$x(\text{cm})$	0	10	25	32

y (cm)	$(\overline{v'v'})^{0.5}$ (cm/s)	$(\overline{v'v'})^{0.5}$ (cm/s)	$(\overline{v'v'})^{0.5}$ (cm/s)	$(\overline{v'v'})^{0.5}$ (cm/s)
1.22	2.070	2.008	1.676	1.534
1.17	2.080	2.025	1.676	1.535
1.13	2.090	2.038	1.678	1.537
1.08	2.100	2.048	1.681	1.541
1.04	2.120	2.053	1.684	1.546
0.99	2.146	2.055	1.686	1.549
0.95	2.163	2.055	1.686	1.548
0.90	2.175	2.054	1.685	1.544
0.86	2.184	2.050	1.684	1.538
0.81	2.194	2.046	1.682	1.529
0.77	2.209	2.042	1.678	1.519
0.72	2.227	2.038	1.672	1.508
0.68	2.247	2.035	1.662	1.496
0.63	2.263	2.033	1.650	1.482
0.59	2.273	2.032	1.635	1.466
0.54	2.275	2.030	1.616	1.447
0.50	2.269	2.025	1.595	1.423
0.45	2.256	2.015	1.572	1.395
0.41	2.235	1.997	1.545	1.362
0.36	2.204	1.970	1.514	1.324
0.32	2.158	1.929	1.477	1.283
0.27	2.086	1.867	1.431	1.242
0.23	1.975	1.776	1.376	1.205
0.18	1.810	1.650	1.313	1.172

AII.3.4 Effect of suction zone length, x on $-\overline{u'v'}$ at $x = 25$ cm (in the middle of suction zone)

$x(\text{cm})$	0	10	25	32
$y(\text{cm})$	$-\overline{u'v'}$ (cm/s)	$-\overline{u'v'}$ (cm/s)	$-\overline{u'v'}$ (cm/s)	$-\overline{u'v'}$ (cm/s)
2.70	1.292	0.846	0.503	0.445
2.66	1.328	0.885	0.530	0.467
2.61	1.366	0.921	0.557	0.487
2.57	1.408	0.955	0.584	0.508
2.52	1.455	0.989	0.611	0.528
2.48	1.506	1.023	0.636	0.548
2.43	1.559	1.059	0.659	0.568
2.39	1.611	1.097	0.679	0.586
2.34	1.658	1.135	0.700	0.602
2.30	1.703	1.173	0.724	0.618
2.25	1.748	1.213	0.750	0.634
2.21	1.795	1.253	0.780	0.650
2.16	1.842	1.292	0.811	0.668
2.12	1.887	1.330	0.842	0.687
2.07	1.924	1.366	0.871	0.706
2.03	1.949	1.399	0.897	0.726
1.98	1.962	1.430	0.919	0.745
1.94	1.985	1.460	0.938	0.764
1.89	2.012	1.488	0.954	0.782
1.85	2.030	1.505	0.968	0.798
1.80	2.050	1.521	0.982	0.814
1.76	2.080	1.548	0.997	0.830
1.71	2.095	1.562	1.014	0.847
1.67	2.099	1.580	1.033	0.864
1.62	2.101	1.612	1.050	0.881
1.58	2.103	1.635	1.065	0.896
1.53	2.106	1.662	1.075	0.910
1.49	2.108	1.692	1.079	0.921
1.44	2.131	1.725	1.078	0.928
1.40	2.155	1.762	1.074	0.932
1.35	2.174	1.801	1.068	0.933
1.31	2.192	1.833	1.062	0.932
1.26	2.209	1.861	1.055	0.929
1.22	2.225	1.885	1.048	0.923

	0	10	25	32
$x(\text{cm})$ $y(\text{cm})$	$-\overline{u'v'}$ (cm/s)	$-\overline{u'v'}$ (cm/s)	$-\overline{u'v'}$ (cm/s)	$-\overline{u'v'}$ (cm/s)
1.17	2.237	1.909	1.041	0.914
1.13	2.240	1.933	1.034	0.902
1.08	2.237	1.958	1.025	0.888
1.04	2.231	1.980	1.016	0.870
0.99	2.225	2.000	1.005	0.851
0.95	2.223	2.014	0.993	0.831
0.90	2.227	2.022	0.980	0.811
0.86	2.235	2.023	0.966	0.791
0.81	2.245	2.014	0.949	0.771
0.77	2.252	1.996	0.928	0.749
0.72	2.255	1.967	0.902	0.724
0.68	2.251	1.929	0.871	0.697
0.63	2.240	1.885	0.834	0.667
0.59	2.221	1.834	0.795	0.636
0.54	2.194	1.779	0.755	0.603
0.50	2.160	1.717	0.714	0.566
0.45	2.117	1.650	0.674	0.527
0.41	2.061	1.576	0.638	0.484
0.36	1.988	1.494	0.609	0.441
0.32	1.885	1.401	0.598	0.400
0.27	1.740	1.294	0.616	0.367
0.23	1.543	1.170	0.671	0.348
0.18	1.293	1.027	0.762	0.343

Appendix AIII: Numerical Scheme

This appendix mainly covers a range of issues, i.e., choice of the turbulence model, near-wall mesh and wall treatment, theory for the porous media model and boundary conditions, etc. It should be noted that a lot of information in the paper is directly cited from FLUENT Theory Guide 13.0 and FLUENT 13 user's guide.

1. Choosing a turbulence model

Many turbulence models are available in FLUENT 13, for instance, RANS (Reynolds-averaged Navier Stokes equations) based models, including $k-\varepsilon$ models, $k-\omega$ models, RSM (Reynolds stress model) and large eddy simulation, etc. No single turbulence model is universally considered as better than others for any problem. The choice of a turbulence model depends on the available computing resources and the physics that governs the problems, etc. In the following section, an overview of the turbulence models is presented and their applicability in the present study is discussed.

Compared to LES, RANS-based models require much less computational efforts, which have been widely used in practical engineering applications. Due to the limited computing resources, we have selected RANS-based models.

Amongst RANS-based models, RSM is also computationally expensive, which is out of our choices. Recognizing that realizable $k-\varepsilon$ model is a relatively recent development that is believed to be able to provide better performance for flows involving boundary layers with an adverse pressure gradient, it is chosen in this study.

All the RANS-based models follow the Reynolds-averaged Navier Stokes equations.

Reynolds-averaged Navier Stokes equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (\text{AIII-1})$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_l}{\partial x_l} \right) \right] + \frac{\partial}{\partial x_j} (-\rho \overline{u_i' u_j'}) \quad (\text{AIII-2})$$

The above two equations have similar form as the instantaneous N-S equations, except the additional term $\frac{\partial}{\partial x_j} (-\rho \overline{u_i' u_j'})$, which includes the Reynolds stress that needs to be modeled.

Boussinesq hypothesis:

Boussinesq hypothesis is commonly used to correlate the Reynolds shear stress to the mean velocity gradient,

$$-\rho \overline{u_i' u_j'} = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} (\rho k + \frac{\partial u_k}{\partial x_k}) \delta_{ij} \quad (\text{AIII-3})$$

k - ε models solve two additional transport equations (for turbulent kinetic energy, k and turbulence dissipation rate, ε) and compute μ_t as a function of k and ε .

Equations AIII-4 and AIII-5 show the transport equations for realizable k - ε model:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (\text{AIII-4})$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 S_\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon \quad (\text{AIII-5})$$

2. Standard wall treatment

The log-law, which is valid for equilibrium boundary layers and fully developed flows, sets upper and lower limits on the acceptable distance between the near-wall cell centroid and the wall. Usually, the dimensionless wall units, y^+ ($=\rho u \Delta y / \mu$) are used to measure the distance.

(i) For standard or non-equilibrium wall functions, each wall-adjacent cell's centroid should be located within the log-law layer, $30 < y^+ < 300$. A y^+ value close to the lower bound ($y^+ \approx 30$) is most desirable.

(ii) The conventional wall functions can be used with fine near-wall meshes of $y^+ < 11.2$. However, such use should be avoided ideally. This is because the wall functions in this region become much less accurate and the turbulence models employed inside the laminar sublayer might not be able to account for the low-Reynolds number effects. Both of these factors can significantly reduce the accuracy of the calculation and cause convergence problems. The enhanced wall treatment should be used in such cases.

(iii) The mesh should be made either coarse or fine enough as much as possible to prevent the wall-adjacent cells from being placed in the buffer layer ($y^+ = 5 \sim 30$).

Mesh density:

Two different meshes are used, which are uniform mesh = 0.004 and 0.005 m, respectively. The comparison of the results did not show significant difference.

Consequently, the mesh = 0.004 m is chosen. Based on the above principles and the initial simulation results, a uniform mesh = 0.004 m (a mesh of nearly 508,000 grids) is selected, which leads to a $y^+ \approx 200$ and considered fine enough. A finer grid will lead to a much more computational effort. Taking into consideration that the numerical simulation is not the essence of the PhD study and its aim is to show qualitatively the suction effects on near-bed flow field, this choice is not unacceptable.

3. Porous media model

In this simulation, another important feature in addition to the turbulence is that it involves a suction zone, which can be modelled by using the porous media conditions in FLUENT.

The porous media model can be used for various kinds of single phase and multiphase problems, including flow through packed beds, filter papers and perforated plates among others.

The porous media model involves an empirically determined flow resistance in a region defined as “porous”. The porous media model is in fact an added momentum sink in the governing momentum equations. Consequently, the following assumptions and limitations should be recognized (note that there are other limitations which are not very related and thus not listed here):

- i. Because the volume blockage that is physically present is not represented in the model, ANSYS FLUENT uses and reports a superficial velocity inside the porous medium, based on the volumetric flow rate, to ensure continuity of the velocity vectors across the porous interface (Please see Section 7.2.3 of FLUENT user’s guide: Modelling Porous Media Based on Physical Velocity for details). In a multiphase flow system, all phases share the same porosity.
- ii. The effect of the porous medium on the turbulence field is only approximated (Please see Section 7.2.3 of FLUENT 13 user’s guide: Treatment of Turbulence in Porous Media for details).
- iii. Generally, the ANSYS FLUENT porous medium model assumes the porosity is isotropic for both single phase and multiphase and it can vary with both space and time.

The following section describes the momentum equations and Darcy’s law for porous media in the ANSYS FLUENT.

Momentum equations for porous media:

Porous media are modeled by adding a momentum source term to the standard fluid flow equations. The source term consists of two parts: a viscous loss term (Darcy, the first term on the right-hand side of Equation AIII-6), and an inertial loss term (the second term on the right-hand side of Equation AIII-6),

$$S_i = -(\sum_{j=1}^3 D_{ij} \mu v_j + \sum_{j=1}^3 C_{ij} \frac{1}{2} \rho |v| v_j) \quad (\text{AIII-6})$$

where S_i is the source term for the i th (x , y , or z) momentum equation, $|v|$ is the magnitude of the velocity and D and C are prescribed matrices. This momentum sink contributes to the pressure gradient in the porous cell, resulting in a pressure drop that is proportional to the fluid velocity (or velocity squared) in the cell.

Darcy's law in porous media:

Typically, the pressure drop in laminar flows through porous media is proportional to velocity. Ignoring convective acceleration and diffusion, the porous media model then reduces to Darcy's Law:

$$\nabla p = -\frac{\mu}{\alpha} \vec{v} \quad (\text{AIII-7})$$

Then the pressure drop in each of the three (x , y , z) coordinate directions that ANSYS FLUENT computes (note: only 2D in our case) within the porous region is,

$$\nabla p_x = \sum_{j=1}^3 \frac{\mu}{\alpha_{xj}} v_j \Delta n_x \quad (\text{AIII-8})$$

$$\nabla p_y = \sum_{j=1}^3 \frac{\mu}{\alpha_{yj}} v_j \Delta n_y \quad (\text{AIII-9})$$

$$\nabla p_z = \sum_{j=1}^3 \frac{\mu}{\alpha_{zj}} v_j \Delta n_z \quad (\text{AIII-10})$$

where $1/\alpha_{ij}$ are the entries in the matrix D in Equation AIII-6, v_j are the velocity components in the x , y , and z directions, and Δn_x , Δn_y , and Δn_z are the thicknesses of the medium in the x , y , and z directions. Here, Δn_x , Δn_y , or Δn_z is the actual thickness of the porous region in the model. Thus if the thicknesses used in the model differ from the actual thicknesses, some adjustments in the inputs for $1/\alpha_{ij}$ should be made.

but the origins of the density-based formulation may be better than the pressure-based solver for high-speed compressible flows.

Because flows in the study are incompressible, pressure-based solver is chosen.

Two algorithms also exist under the pressure-based solver in ANSYS FLUENT: a segregated algorithm and a coupled algorithm. In the segregated algorithm the governing equations are solved sequentially, segregated from one another, while in the coupled algorithm the momentum equations and the pressure-based continuity equation are solved in a coupled manner. In general, the coupled algorithm significantly improves the convergence speed over the segregated algorithm. In order to improve the convergence speed, the coupled algorithm is selected.

In the study, we want to obtain a steady-state simulation, thus we have selected the pressure-based, coupled, steady solver.

6. Discretization schemes

ANSYS FLUENT has many discretization schemes, from first order to higher order. Since the QUICK (quadratic upstream interpolation for convective kinetics) algorithm may provide better accuracy than first and second order schemes, it is selected in the study.

7. Monitor

A computational accuracy of 10^{-6} was chosen for convergence. In addition to monitoring residuals for checking the convergence of the simulation, the variation of drag force along the wall before the suction zone is also monitored. Once there is no variation in this parameter, then the simulation can be considered to be converged.

Moreover, the masses of inlet and outlet flow are calculated to ensure that they are equal when the computation is converged.