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Oscillating-grid turbulence and its applications: a review

Turbulence de grille oscillante et ses applications: une revue

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ABSTRACT

Oscillating-grid turbulence (OGT) is characterized by its zero-mean flow, being two-dimensionally homogeneous in a certain region away from the grid plane. This homogeneous turbulence region that can be readily controlled is suitable for investigating hydraulic problems encountered in environmental engineering. This paper reviews a number of achievements obtained recently in the study of OGT and its applications. Several aspects are discussed including (1) characteristics of the turbulent structure; (2) mass transfer at the interface of air–fluid, solid–fluid or fluid–fluid; (3) sediment entrainment and suspension in zero-mean flow; and (4) utilization of OGT for investigating problems related to environmental engineering. Some suggestions for conducting further studies are also made.

RÉSUMÉ

La turbulence de grille oscillante (OGT) est caractérisée par son écoulement moyen nul, étant bidimensionelle homogène dans une certaine région éloignée du plan de grille. Cette région homogène de turbulence qui peut être aisément contrôlée convient à l'étude des problèmes hydrauliques rencontrés dans l'ingénierie environnementale. Cet article passe en revue un certain nombre de résultats obtenus récemment en étude d'OGT et de ses applications. Plusieurs aspects sont discutés comprenant (1) des caractéristiques de la structure turbulente; (2) le transfert de masse à l'interface air–fluide, solide–fluide ou fluide–fluide; (3) l'entraînement et la suspension de sédiment dans un écoulement moyen nul; et (4) l'utilisation d'OGT pour résoudre des problèmes liés aux technologies de l'environnement. Quelques suggestions pour entreprendre d'autres études sont également faites.

Keywords: Grid turbulence, homogeneous turbulence, sediment transport, diffusion, stratified flow, secondary flow, zero-mean flow.

1 Introduction

Many experiments on isotropic turbulence had been carried out in wind or water tunnels in which a fixed mesh generally served as a flow filter. As the turbulence so generated is subject to significant time-mean motion and decays rapidly, its application in hydraulic and environmental engineering is quite limited. As an effective alternative, oscillating-grid turbulence (OGT) has been introduced and widely used for various research purposes. Figure 1 shows the sketch of a typical experimental setup of OGT generation system. The grid is made of crossed bars, and is placed in a water tank. The grid assembly is driven by a motor, vibrating in the direction perpendicular to the grid plane. With the repetitive motion of the grid, jet flows develop largely by the movement of the grid openings through the water, with wakes being created simultaneously. The jets and wakes then interact further in the region away from the grid plane. As detailed subsequently, OGT is characterized by its zero-mean flows, being nearly isotropic and laterally homogenous in certain flow region. By varying the operational parameters of the grid, such as frequency and stroke, the intensity of turbulence can be easily controlled. This expediency is particularly evident when compared with isotropic turbulence in the wind tunnel or water flume.

Rouse (1939) appeared to be the first to use OGT to study sediment suspension. In recent decades, OGT had been widely extended to many other laboratory investigations. Though little was known at the early stage about the statistical properties of the turbulence itself, much knowledge was obtained later in the study of stratified flows. Major contributors include Rouse and Dodu (1955), Thompson and Turner (1975), Hopfinger and Toly (1976), McDougall (1979), and E and Hopfinger (1986), who used OGT to study interfacial mixing in stratified flows that is widely observed in the oceans, lakes and atmosphere. OGT is also employed to explore the mechanics of sediment transport, particularly for flow situations where sediment starts to move or to be entrained and suspended in the water due to flow fluctuation with high intensity other than the mean flow. Experimental works done by Tsai and Lick (1986), Huppert *et al.* (1995), Medina *et al.* (2001), Medina (2002), Liu and Huhe (2003), and Orlins and Gulliver (2003) have suggested that sediment transport phenomena such as incipient motion could be viewed in the approach that cannot be realized in open channel flow. Other relevant research topics include mass transfer across a shear-free water—air interface (Brumley and Jirka, 1987; Chu and Jirka, 1992; Herlina and Jirka, 2004), and desorption of contaminants from sediment (Connolly *et al.*, 1983; Valsaraj *et al.*, 1997). In its self-contained environment, OGT is particularly ideal for conducting studies of physical and chemical processes over long time spans that are difficult to carry out in a regular flume, where the time scale of the processes are limited by the longitudinal flume dimension (Brunk *et al.*, 1996).

2 Statistical characteristics of OGT

The OGT can be understood by means of its turbulence statistics including velocity fluctuation, Reynolds stress, turbulent kinetic energy, and frequency spectrum. These characteristics vary depending on grid configurations.

2.1 Turbulence generated by a single grid

Corrsin (1963) presented that the structure of jets and wakes shedding from the grid would become unstable if the solidity (defined as the ratio of the area of bars to the total area of the grid) was higher than 40%. This finding actually serves as a primary principle for designing appropriate

geometry of the grid. This may be the reason of that most of the studies were conducted with grid solidity less than 40%. In comparison, only a few exceptional examples were reported by early investigators such as Bouvard and Dumas (1967), who used a perforated plate with high solidity.

The first functional relationship between the turbulence generated and the operational parameters of oscillating grid was developed by Thompson and Turner (1975) based on their measurements performed with hot-film probe. They found that the turbulence integral length scale l increases linearly with the distance from the grid, and the root mean square (RMS) horizontal velocity u' could be expressed as

$$u' = 1.4 f S^{2.5} z^{-1.5} \tag{1}$$

where S is the stroke length, f is the oscillation frequency, and z is the distance measured from a "virtual origin" which was a little (1 cm for square bars and 2 cm for round bars) lower than the mid-position of the grid. They also reasoned that when a grid of crossed bars was oscillating vertically with the stroke comparable to the bar diameter, it generated an array of jets with the centerlines passing through the intersections, which were free of the wakes. It should be noted that the influence of the grid geometry on the turbulence has not been included in Eq. (1).

Hopfinger and Toly (1976) performed measurements with hot-film probe, confirming the linear relationship between l and z. Their data analysis led to the well-known H–T relationship,

$$u' = v' = C_1 M^{0.5} S^{1.5} f z^{-n} \quad \left(\text{or } \frac{u'}{fS} = \frac{v'}{fS} = C_1 \frac{\sqrt{MS}}{z} \text{ if } n = 1 \right)$$

$$w' = C_2 M^{0.5} S^{1.5} f z^{-n} \quad \left(\text{or } \frac{w'}{fS} = C_2 \frac{\sqrt{MS}}{z} \text{ if } n = 1 \right) \tag{2}$$

where u', v', and w' are the RMS velocities in the three directions (x, y, z), respectively; M is the mesh size (defined as the distance between centers of two neighboring openings); C_1 and C_2 are constants depending on the grid geometry (being equal to approximately 0.25 and 0.27, respectively); and n = 1. Besides, they also found that turbulent kinetic energy k decreases with z in the form of power law, i.e. $k \propto z^{-2}$, and the Reynolds number remains nearly constant during the decay. The

Reynolds number here is based on the turbulence integral scale and defined as $u'l/v$, where v is the kinematic viscosity of fluid. Due to its simplicity and applicability, Eq. (2) has been used widely for describing the characteristics of OGT. It should be noted that in order to make the experimental data agree with the linear relationship between l and z, a "virtual origin" rather than the physical mid-plane of the grid is often required for measuring the distance z. In Hopfinger and Toly's (1976) study, a rotating hot-film probe was employed and therefore the experimental results obtained implied an actual application of spatially averaged technique.

The variations of the two coefficients and decay power included in Eq. (2) have been reported by different investigators. For example, Nokes' (1988) experimental work yielded that the n-value ranged from 0.8 to 1.5 depending on the stroke. De Silva and Fernando (1992) used Laser Doppler Velocimetry (LDV) to measure the fluid field for the validation of Eq. (2), finding that the constants C_1 and C_2 were 0.22 and 0.26, respectively, which were slightly different from those determined by Hopfinger and Toly (1976). The frequency and stroke dependence of turbulence was discussed by Yi and Lyn (2000).

Cheng and Law (2001) conducted a detailed study of the turbulence properties using the digital particle imaging velocimetry (DPIV). The experimental results showed that the velocity fluctuations measured over the bar were always greater than those over the grid opening in the region near the grid. The difference decreased significantly with increasing distance from the grid. These authors also observed that obvious increase in u' and w' appeared at the locations above the bar intersection near the grid, and the homogeneity of turbulence could be achieved only when $z > 3M$, where z was measured from the midposition of the grid. Their study indicates that the use of the spatial averaging technique in evaluating the turbulence profiles is necessary, and the results so obtained agreed well with Eq. (2).

Liu and Huhe (2003) divided the flow field of OGT into homogeneous region and boundary-affected region. For the homogeneous region, the authors proposed an RMS velocity expression given by

$$u' = C_0 \left(\frac{z}{S}\right)^{-1.53} fS \quad \text{for } \frac{z}{S} > 2 \tag{3}$$

and the integral time scale τ in the form of

$$\tau = C\left(\frac{z}{S}\right)^{2.42} f^{-1} \quad \text{for } \frac{z}{S} > 2 \tag{4}$$

where C_0 and C are constants. Liu and Huhe (2003) study indicated that the averaged turbulent kinetic energy was modified by the boundary when $\Delta < 0.3l$ (Δ is the distance from the boundary). Dohan and Sutherland (2002) concentrated their study on the eddy time scales in OGT with laser induced fluorescence (LIF) technique. They found that the time scale was related to the ratio of flow depth to width of the tank, and the scaling exponent of the time scale increased with increasing flow depth.

Orlins and Gulliver's (2003) LDV measurements showed that Eq. (2) worked well when $z > 2M$. They further used Eq. (2) for defining the turbulent kinetic energy [$k = (u'^2 + v'^2 + w'^2)/2$] as

$$k = \frac{1}{2}\left(2C_1^2 + C_2^2\right)\left(M^{0.5}S^{1.5}fz^{-1}\right)^2 = \alpha\left(MS^3f^2z^{-2}\right) \tag{5}$$

where α is a coefficient. They reported that k was laterally homogeneous when $z > 2M$ or $z > 4S$. Their analysis seems to suggest that the upper limit of oscillating frequency may be set to 7 Hz to ensure that the RMS velocity fluctuation increases linearly with the frequency. Moreover, they also explored effects of the grid mounting system and the false floor. Their results showed that the overall spatial distribution of k appeared quite similar for the cases with and without the false floor that was placed at the bottom of the tank to simulate the physical boundary condition of the sediment–water interface.

In order to study the Eulerian-frequency spectra of homogeneous turbulence and the velocity–time relationship of the decaying turbulence, De Silva and Fernando (1994) examined the difference between sustained oscillation and decaying oscillation, the latter appearing after the removal of the driving force. The LDA measurement of the sustained oscillations showed that the Eulerian-frequency spectra were in good agreements with the theoretical result. For the case with the energy source being removed, there existed three phases of decay: an initial decay in which the turbulent energy varied with time approximately as $u'^2 \sim t^{-1}$, a final decay which followed the relationship of $u'^2 \sim t^{-5/2}$, and a transient region in between.

2.2 Turbulence generated by multi-grid

A single-grid generated turbulence is subject to an obvious power-law decay. The turbulence characteristics can be improved considerably by employing multiple grids. By comparing the LDV measurements for the two cases, one with a single grid and the other with a pair of grids, Shy *et al*. (1997) found that a pair of oscillating grids could produce two distinct flow regions. Near each grid, there was a highly turbulent region appearing in the form of wakes that was similar to turbulence generated by single grid. Formed in the core area between the two parallel grids was an isotropic turbulence region, which was characterized with essentially zero mean velocities, and nearly −5/3 energy decay slopes. For both cases, the upper limit of oscillation frequency f_m was taken to be 8 Hz, which was larger than 7 Hz as was proposed by McDougall (1979). Shy *et al*. defined the effective turbulent intensity q for a horizontal plane at a certain elevation as follows

$$q = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{u_i'^2 + v_i'^2 + w_i'^2}{3}\right)} \tag{6}$$

where u_i', v_i', and w_i' are the RMS velocities at the point i in the measured horizontal plane, N is the number of the measurement point. For the single-grid case, the turbulence near the grid was described by $q \sim z^{-n}$ with $n = 2$ at nodes and $n = 1$ at the openings. This observation implied that different decay behaviors existed for different locations, which might explain the reason of the discrepancy of n-values derived by the other investigators. When $z/M > 2$ (here, the origin of z was taken at the midplane of the single grid), the q at nodes was nearly the same as that at openings, and was given by

$$q \approx 0.25 S^{1.5} M^{0.5} f z^{-1.5} \tag{7}$$

For the double-grid case, the flow near the grid was similar to that observed for the single-grid case. However, when $4 \leq H/M \leq 6$ (H was the distance between the mid-planes of the two grids), the flow would be isotropic with the turbulent intensity given by

$$q = 0.89 S^{1.5} M^{0.5} f H^{-1.5} \tag{8}$$

where S, M and H are measured in centimeters. Note that both Eqs (7) and (8) could not meet the

requirement of dimensional homogeneity. Shy *et al.* (1997) also reported that in the isotropic region, the one-dimensional Eurlerian frequency spectrum displayed a slope of −5/3.

A more complicated multi-grid case was presented by Brunk *et al.* (1996), who applied five horizontally oscillating grids which were vertically spaced to simulate turbulence in natural hydrodynamic systems. With Acoustic Doppler Velocimetry (ADV) measurements, the Eurlerian time spectra of k were computed, showing the expected −5/3 slope for the inertial range of the turbulence. Their experiments also demonstrated that the use of multiple grids could generate homogeneous turbulence that obeyed the H–T relationship, and through a suitable configuration of the stroke and frequency for each grid, the apparatus could simulate open channel flows with turbulence decaying exponentially from the channel bed.

2.3 Secondary flow in OGT

As an intrinsic feature, it is impossible to remove secondary flow from the system of OGT. Therefore, how to minimize the effect of secondary flow is essential to achieve the zero-mean homogeneous turbulence. Limited observations appear to suggest that the secondary flow could be enhanced for a grid with solidity higher than 40% (Corrsin, 1963), the asymmetrical end condition of the grid (E and Hopfinger, 1986; Cheng and Law, 2001), large stroke of oscillation (Yi and Lyn, 2000), and high frequency of oscillation (McDougall, 1979; Shy *et al.*, 1997). Using ADV and PIV, McKenna and McGuillis (2004) observed the flow repeatability and secondary circulation in an oscillating grid stirred tank. The ADV measurements showed that the flow was sensitive to the initial conditions and any slight difference in the initial flow could cause different mean circulation, which then influenced the turbulent structure distinctly. McDougall (1979) pointed out that such sensitivity was due to the nonlinear characteristic of the formation of a mean flow. McKenna and McGuillis' (2004) results may imply that it is impossible to reproduce identical turbulence since it is hard to ensure the same initial conditions for a set of experiments and thus the same secondary flow. However, some special procedures could be taken to reduce the degree of variability. E and Hopfinger (1986) and De Silva and Fernando (1992) reported that correct end condition of the grid could reduce the secondary circulation significantly. Cheng and Law (2001) confirmed through experiments that a homogeneous flow field could be achieved if the end condition was designed in such a way that the wall acted as a plane of symmetry.

3 Applications of OGT

3.1 Use in the study of stratified flow

In natural systems, there are many situations where turbulence generated at one location in a fluid causes mixing across a density interface some distance away. Rouse and Dodu (1955) first employed OGT to study the mixing across an interface between two fluid layers of different densities. This technique has also been adopted in many other experimental studies on stratified flows, of which the outstanding examples have been given by Thompson and Turner (1975), and Hopfinger and Toly (1976).

Hopfinger and Toly (1976) found that the linear relationship between RMS velocity and f remained valid when an interface was present. The entrainment velocity u_e (defined as the rate at which the interface between the two layers advanced into the quiescent layer) was related to the local Richardson number Ri and Péclet number Pe:

$$\frac{u_e}{u'} = Ri^{-3/2}\left[K_1 + K_2\left(\frac{Ri}{Pe}\right)^{1/2}\right] \tag{9}$$

where $Ri = g\Delta\rho l/\rho u'^2$, g is the gravitational acceleration, $\Delta\rho$ is the density jump across the interface, ρ is the density of the mixed layer, u' is the RMS horizontal velocity at the interface, l is the turbulent integral length scale, $Pe = u'l/\kappa$, κ is the diffusivity, and K_1 and K_2 are constants. Moreover, their results also showed that the buoyancy flux was proportional to κ/D, where D is the interface thickness.

Many other researchers also used OGT in investigating the entrainment velocity, but ended up with different formulae. For example, the relationship proposed by Wolanski and Brush (1975), E and Hopfinger (1986) and Hannoun and List (1988) takes the form of $u_e/u' = KRi^{-1.5}$ (K is constant). Another expression is given by $u_e/u' = KRi^{-1.75}$, which were proposed by Folse *et al.* (1981), who used a finely woven mesh other than a grid. McDougall (1979) and Nokes (1988) suggested increasing the power from −1.5 to −1.2 in relating u_e to Ri. All those results indicate that u_e appeared to be independent of Pe.

3.2 Application for the study of sediment transport

Application of OGT for the study of sediment transport was initiated by Rouse (1939). The recent work by Tsai and Lick (1986), who used a small cylinder in which a vertically oscillating perforated plate (other than grid) generated turbulence to observe re-suspension of cohesive sediment. They found that the mass of material eroded from the sediment–water interface was proportional to the oscillation frequency. Huppert *et al.* (1995) utilized the oscillating grid to simulate the bottom stress in studying the conditions for the formation of a suspension layer and its maintenance. The difference between sediment-laden and particle-free fluid layers was that the particle could settle out of the suspension layer, while for the latter the interface would rise continuously as the lighter fluid was entrained across the interface. After comparing the characteristics of four type of flows and their effects on the particle suspension, Huppert *et al.* (1995) concluded that OGT was suitable to study sediment stratified flows in estuaries.

Medina *et al*. (2001) and Medina (2002) engaged OGT in investigating the incipient motion, suspension and the concentration variation of sediment. For the case without sediment, they first obtained the RMS velocity based on ADV measurements:

$$u' = 0.6S^{1.5}M^{0.5}fz^{-1} \tag{10}$$

Then, using Eq. (10), they calculated the critical incipient and lift-off velocities. Notice that Eq. (10) is similar to Eq. (2) except for the different coefficients used, which is obviously associated with the different dimensions of the tanks and grids employed in the studies of Medina *et al*. (2001) and Hopfinger and Toly (1976). They attempted to compare the critical RMS velocity with the conventional critical shear velocity used for the incipient sediment motion, finding that the critical RMS velocity was much lower than the critical shear velocity for the same particle size. They also reported that the minimum RMS velocity that made the sediment lift away from the bed was the function of sediment size, compaction and consolidation time. In spite of a series of experiments conducted in this study, no quantitative criterion that describes the sediment transport was finally presented. It should be noted also that there were uncertainties in computing the RMS velocity of sediment-laden flow using Eq. (10) which was obtained for the condition of clean water.

Liu and Huhe (2003) applied OGT in studying the incipient motion of sediment. They assumed

that the incipient condition of sediment particle was related to the averaged *k* at the edge of the viscous layer. This study is meaningful in that it demonstrates reasonable description of the incipient sediment motion in terms of critical turbulent energy, in contrast to the conventional consideration of force equilibrium.

3.3 Applications in other fields

Connolly *et al.* (1983) used OGT in investigating the influence of sediment concentration on the adsorption of hydrophobic pollutants in estuaries. They compared laboratory study of sediment suspension by turbulence generated in oscillating grid tank and in an annular tank, concluding that the annular tank would produce large scale tangential velocity and secondary flow while the oscillating grid system was a more convenient laboratory apparatus for studying the effect of sediment suspension on adsorption. They found that no linear relationship existed between the dissolved pollutant concentration and sediment concentration. Their results also show that desorption occurred first when sediment concentration decreased, and then adsorption took place after reaching the equilibrium condition, and vice versa.

Zhao *et al.* (1995) studied oil concentration distribution in OGT using the digital image processing technique. Their experiment showed that after discontinuing grid oscillation, the oil, which was already entrained into the water by the turbulent diffusion, would form a stable concentration distribution for a long period. This means that once the oil advances into the natural water bodies such as the lakes and the sea, it will be a constant threat to the aqueous environment for a long period of time. Both numerical results and experimental data presented by Zhao *et al.* indicated that the coefficient of turbulent diffusion of oil increased linearly with the turbulent intensity for the same oil percentage of the water body, while the coefficient decreased exponentially with the oil percentage for the same turbulent intensity. Another important dispersion problem is related to wastewater discharge, which may be affected considerably by ambient turbulence, as observed by Law *et al.* (2001) in their laboratory investigation of turbulence effect on the spreading of jet using OGT.

Brunk *et al.* (1996) applied the multigrid system to simulate hydrodynamic and chemical processes in natural flows. Similar to Huppert *et al.* (1995), Brunk *et al.* recommended that the tur-

bulence generated by multigrids be used particularly for studying complicated physical and chemical (especially the contaminant adsorption) processes in the estuarine environment.

In the experiment of desorption of compounds from sediment, Orlins and Gulliver (2003) first placed the contaminated sediment at the bottom of the tank, and then measured the chemical flux that discharged from the sediment for the condition of oscillating grid. The significant virtue of using OGT in this study was that the tests of sediment re-suspension and flux of contaminants to the vapor phase could be effectively duplicated because of the repeatability of the turbulent environment generated by oscillating grid.

Free-surface affected turbulence and the mass transfer across an air–water interface have also being studied using OGT. Brumley and Jirka (1987), and Chu and Jirka (1992) investigated the influence of turbulence below the free surface on the mass transfer rate. Chu and Jirka proposed that it was the large eddy that controlled the interfacial transfer process. Herlina and Jirka (2004) made comparison between OGT with open channel flows and suggested that the zero-mean velocity in the water tank would reduce the difficulty in performing measurements. They used OGT to simulate the bottom shear induced turbulence and applied the two dimensional LIF-oxygen quenching technique to visualize the oxygen transfer across the air–water interface. Being different from the conclusion made by Chu and Jirka (1992), they pointed out that the interaction of large and small turbulent structure was crucial to the mass transfer process.

4 Summary and suggestions for future study

This paper presents a review on the study of the characteristics of OGT as well as its various applications in the fields of hydraulic and environmental engineering. The RMS velocity, turbulent kinetic energy and frequency spectrum for both single grid and multi-grid configurations are described. Applications of OGT in the studies of stratified flow, sediment transport, open channel simulation, adsorption and desorption of compounds, and oil diffusion have demonstrated that OGT could serve as an effective laboratory means to experimentally explore relevant turbulence phenomena and mechanisms. In spite of the attempts made in the past decades to understand OGT, some results obtained can only be considered to be preliminary and the related

flow phenomena are not completely understood. Therefore, great challenges lie ahead for future study with OGT. Examples are given in the following.

1. The method of data analysis could be improved by emphasizing details in the spatial domain. While the use of the spatial-and-temporal average may yield picture of a general variation of the RMS velocity in the direction of grid oscillation, the result so obtained could be misleading. This is because in the near-grid region, the flow varies significantly in the direction parallel to the grid-plane. The flow can be considered two-dimensionally homogeneous only where the direct geometrical effect is significantly small. Depending on the grid geometry, the flow field should be partitioned so that data acquisition can be performed to manifest dominant geometrical effects such as those associated with bar intersections.

2. The way the turbulent fluctuation is associated with the operation parameters of OGT remains a puzzle to be solved. For example, the decay power may deviate from unity and its physical background is not clear at the current stage. To take into account effects of relevant factors including the grid geometry, the formulation that is based on dimensional reasoning presented in previous studies is incomplete. In addition, there is no quantitative study on the effects of the shape and size of the water tank, and the water depth. Note that water tank with square corners is often used in laboratory experiments perhaps because of design convenience. However, the presence of the square corner may inherently induce secondary flow that may not be negligible, as observed in rectangular open channel flows. To minimize the effects of secondary flows on OGT, a cylindrical water chamber may be a reasonable alternative.

3. Further efforts should be made to investigate the flow of OGT in numerical methods. Such an example was given by Matsunaga *et al.* (1999), who reported that the turbulent kinetic energy and dissipation rate of OGT could be computed from the k–ε turbulence model, and their analysis appeared in good agreement with experimental data. Michallet and Mory (2004) also extended the k–ε model to the study of sediment suspension induced by OGT. However, uncertainties could be involved in using k–ε model which is developed largely based on the characteristics of shear-affected flow for this purpose. It is therefore suggested that OGT be simulated with other high-order numerical models, in particular, for examining micro-scale flow information in the region very close to the grid, as it is the source of the turbulence.

4. Among factors that influence sediment transport, turbulence is the most important and complex. The mechanism of sediment transport in turbulence, which is poorly understood, could be more effectively studied by means of OGT than in open channel flows. Many relevant problems could be explored, including incipient sediment motion and initiation of suspension and the mechanism of suspension and its maintenance, which differ from those observed in shear-dominant flows. Besides, by means of OGT, one could also study the possible dampening or enhancing action of sediment on turbulence, which is an age-long unsolved problem encountered in evaluating resistance of particle-laden flows.

5. With its readily repeatable flow condition, OGT is suitable for observing turbulent diffusion processes of pollutants and transport properties of sediment-absorbed compounds. This is particularly true in the comparison with open channel flows, where a slow time-dependent process always requires significant increase in the channel length.

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Notation

C, C_0, C_1, C_2 = Constants
D = Interface thickness
f = Frequency of oscillation
H = Distance between the midplanes of the two grids
i = Measurement point
K, K_1, K_2 = Constants
l = Integral length scale
M = Mesh size of grid
n = Decay power
N = Number of measurement point
Pe = Péclet number
q = Effective turbulent intensity
Ri = Richardson number
Re = Reynolds number
S = Oscillation stroke
t = Period of time after the cease of oscillating
k = Turbulent kinetic energy
u', v', w' = RMS velocities
u_e = Entrainment velocity
x = Longitudinal axis
y = Lateral axis
z = Vertical axis; vertical distance from the virtual origin or midposition
α = Constant
ε = Turbulent dissipation rate
κ = Diffusivity
ρ = Density of mixed layer
$\Delta\rho$ = Density jump across the interface
τ = Integral time scale
ν = Kinematic viscosity
Δ = Distance from the wall

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List of Figure

Figure 1. Sketch of typical experimental setup and characteristic sections of grid. The vertical distance z is measured from the mid-plane of the grids or its virtual origin.

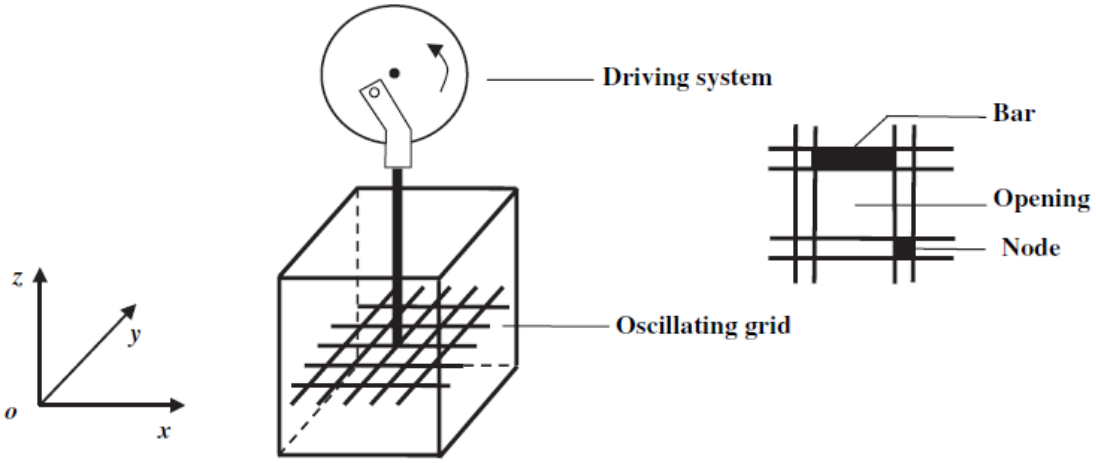

Figure 1.