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SUCTION INLET VORTEX INVESTIGATION AT LOW REYNOLDS NUMBERS

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ABSTRACT

Under certain flow conditions, when an inlet is aspirated in close proximity to a solid boundary, a vortex will form between the surface and the inlet. The formation and ingestion of such vortices could potentially lead to inefficient fluid suction by pumps or catastrophic damages in high-speed jet engines. Previous studies established the basic relationship of such inlet vortices formation threshold and geometry and flow conditions, though they were typically considered at significantly high Reynolds numbers. It remains unclear if there is a lower limit to the Reynolds number at which this phenomenon ceases to exist. This study shows that this phenomenon exists even at low Reynolds number of Re = 160. In particular, the results are generally in agreement with the previously established relationships at much higher Reynolds numbers but certain correlations are not as significant. This suggests that formation of inlet vortices may be less sensitive to Reynolds numbers effects than previously thought.

Keywords: Inlet vortex; suction inlet; low Reynolds numbers.

ENQUÊTE SUR L'ENTRÉE DE VORTEX D'ASPIRATION À FAIBLES NOMBRES DE REYNOLDS

RÉSUMÉ

Dans certaines conditions d'écoulement, quand un orifice est aspiré à proximité d'une frontière solide, un tourbillon se forme entre la surface et d'entrée de l'orifice. La formation et l'ingestion de ces tourbillons peuvent potentiellement conduire à une aspiration inefficace de fluide par des pompes ou des dommages catastrophiques dans les moteurs de jet à grande vitesse. Des études antérieures ont établi une relation fondamentale de seuil de formation de ces tourbillons d'entrée et de géométrie et les conditions d'écoulement, si elles ont été généralement considérées comme à nombre de Reynolds élevé de manière significative. On ne sait pas s'il y a une limite inférieure pour le nombre de Reynolds à laquelle ce phénomène cesse d'exister. Cette étude montre que ce phénomène existe même à faible nombre de Reynolds Re = 160. En particulier, les résultats sont généralement en accord avec les relations déjà établies beaucoup pour les plus élevés des nombres de Reynolds, mais certaines corrélations ne sont pas aussi importantes. Ceci suggère que la formation de tourbillons d'entrée peut être moins sensible à des effets de nombre de Reynolds qu'on ne le pensait.

Mots-clés : entrée d'aspiration; orifice d'aspiration; faibles nombres de Reynolds.

NOMENCLATURE

V_0	free stream velocity (m/s)
D	inlet diameter (m)
V_i	intake velocity (m/s)
H	intake height (m/s)
DSLR	Digital Single Lens Reflex
Ro	Rossby number

1. INTRODUCTION

Suction or drainage of fluid close to a solid boundary is a common occurrence in many engineering applications, such as pump operations and drainage of fluids from reservoirs. While the assumption of uniform fluid flow rate entering the suction inlet generally holds true for most applications, it may not be the case when a solid boundary is sufficiently close, particularly if the inlet is of significant size relative to its distance from the solid boundary. What happens is that a surface-to-inlet vortex will form and be ingested into the inlet, impeding efficient fluid flow into the inlet and potentially creating cavitation effects in water-based applications. Interestingly, this phenomenon can also be observed in high-speed jet engines, particularly during aircraft engine ground runs and take-off or post maintenance tests in a test cell. However, it has always been an intriguing question of just how similar or dissimilar the characteristics of the inlet vortices between the two flow scenarios, considering the rather significant discrepancy in their Reynolds numbers.

Three conditions necessary for the formation of a vortex are a non-zero ambient vorticity, presence of a stagnation point on the solid surface in close proximity to the inlet and up-draught occurring above the stagnation point to the inlet [1]. The non-zero ambient vorticity condition is also called the headwind mechanism [2]. The headwind mechanism occurs when the capture stream tube intersects with the ground or walls, and results in the distortion and intensification of ambient or induced vorticity within the boundary layer. If the headwind is irrotational, two counter-rotating vortices will originate from the ground [3, 4]. Jermy and Ho [5] showed using computational methods that 0.001/s was the minimum shear required to trigger a vortex. Murphy argued against this value stating that vortices have been known to form under quiescent conditions [6]. Another possible condition in which a vortex forms has been reported by de Siervi et al. [3]. When an inlet is in a crosswind condition with yaw angle greater than 45°, and if the capture stream tube is not in contact with the ground, two counter-rotating vortices are formed on the leeward side. If the capture stream tube is in contact with the ground or wall, the lower of the two counter-rotating vortex will attach itself to the plane forming a ground standing vortex. However this type of vortex is not in the scope of this paper.

Karlsson and Fuchs [7] modelled unsteady vortex behaviour in a large eddy simulation of a scenario representative of the take-off situation. These results were validated using particle image velocimetry and laser Doppler anemometry measurements by Secareanu et al. [8]. Other similar studies include recent experimental work by Murphy and Macmanus [6, 9, 10]. Gulia et al. [11] and Kodres and Murphy [12] extracted information on thrust correlation factors or airflow rates by modelling airflow in test cells. Ho [13] and Ho and Jermy [14] used computational fluid dynamics to locate the threshold which forms a boundary between when a vortex forms or does not under various conditions such as different ambient vorticity, inlet diameter, and ground clearance. The threshold of vortex formation can be plotted on a graph of V_i/V_0 against H/D with V_i and V_0 denoting the velocity at the intake and free-stream respectively, H denoting the height of the centreline of the intake from the ground plane (or wall), and D denoting the diameter of the intake inlet.

Previous studies established the basic relationship of such inlet vortices formation threshold and geometry and flow conditions. It is not clear whether a lower limit to the Reynolds number exists at which this

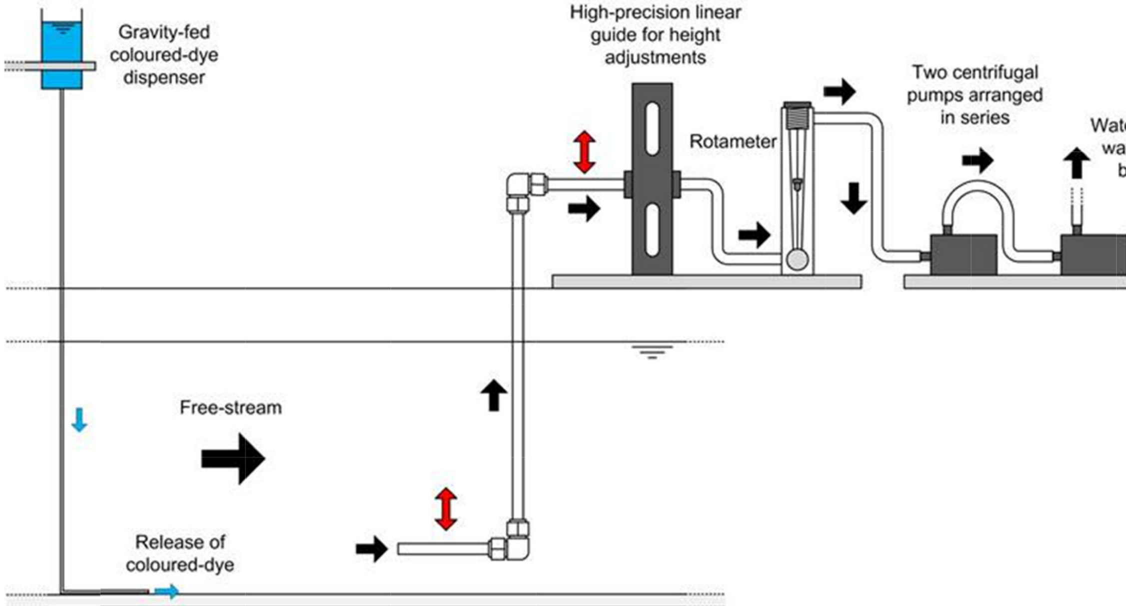


Fig. 1. Schematic of the experimental setup.

phenomenon ceases to exist. To date, the lowest Reynolds number at which such studies were conducted at 8000 [15]. This paper attempts to locate the vortex formation threshold using experimental flow visualisation to detect the formation of the vortex at a low Reynolds number of 160–320.

2. EXPERIMENTAL SET-UP

The experiments were conducted in a low-speed recirculating water tunnel with a test section size of 0.3 m (width) $\times$ 0.4 m (height) $\times$ 1.0 m (length). Driven by an axial water pump controlled by a frequency-inverter, water was channelled through a series of perforated steel, honeycombs, fine screens and a 4-to-1 ratio contraction chamber before entering the transparent test-section. The use of these flow-conditioning devices reduced the initial flow turbulence levels with the free-stream velocities within the test-section ranging (V_0) from 0.05 to 0.6 m/s. The engine inlet is simulated by an L-shaped stainless steel hollow tube of diameter 0.011 m (D). Intake suction is provided for by two EVO E04 submersible pumps connected in series giving a maximum flow rate (V_i) of 4 LPM. Flow rate through the intake was done using a Brooks Series 2540 rotameter with a measurement range of 1 to 19 LPM. Intake ground clearance (H) was achieved through the use of a Melles Griot linear slider to adjust the height of the hollow tube. Flow visualisations were conducted by releasing blue food dye using gravity-fed method, where it was released from dispensers located at approximately 0.6 m above the test-section water surface level. The coloured-dye travelled along small-diameter, L-shaped steel tubings with internal diameter of approximately 1mm, which terminated at the water tunnel floor. Coloured-dye would then flow out from the steel tubing and highlight the behaviour of the free-stream boundary layer. Figure 1 gives an illustration of the experimental set-up.

Two different intake positions were used to search for the vortex thresholds. The first position has the intake axis in line with the flow of the water tunnel and represents the headwind condition. The second position has the intake axis perpendicular to the flow of the water tunnel and represents the crosswind condition. Two different tunnel flow rates were conducted for the headwind condition but only one flow rate for the crosswind condition. Reynolds number for the experiments is calculated, as with previous studies, using intake diameter and flow channel flow rate. Lastly, to capture the flow visualisation, two

DSLR cameras were used to record short video clips at 30 frames-per-second of the flow behaviour from two different perspectives. One was mounted at 45° to the intake inlet on the side of the water tunnel and gives the side-profile, whilst the other was mounted directly above the intake inlet. To illuminate the flow fields, a halogen lamp was also used to increase the illumination for improved video quality.

The current set-up resembles those used in previous experiments which primarily consist of a suction inlet of idealised geometric profile in close proximity to a surface. For example Glenny [16] modified an existing suction line to accept intakes of different sizes and the ground plane was simulated using a fine mesh gauze. In the same set-up, spherical glass beads were used to simulate ground debris and the onset of vortex formation and ingestion (see [16, fig. 3]). Ambient vorticity was generated by placing a fan at different angles from the intake axis in-front of the intake. In other experiments [17–19] which was conducted in a flow facility similar to the current set-up, such as in a wind tunnel, ambient vorticity was similarly generated by placing the intake at an angle relative to the facility flow axis.

3. DETERMINATION OF VORTEX REGIMES

Previous investigations were conducted with aerospace applications in mind and thus the description of scenarios utilises the aerospace terminologies and will continue to be used here for ease of reference. Take-off scenario represents the suction inlet above one single solid surface only and test cell scenarios had solid surfaces at the bottom, side and top surfaces with the inlet at the centre. Experimental investigations reported occurrence of such vortices in actual operation, indicate that such vortices are always unsteady in nature. However it is not clear whether the unsteady nature of vortices in these reports originates from the unsteady ambient conditions or is inherently unsteady. Glenny reported that even small changes in the surrounding environment such as the opening of a door, would cause noticeable disturbance in the vortex [16]. Ho et al. [20] reported from CFD studies that such vortices are only steady in situations where there is only one single solid surface in proximity of the inlet. In all other configurations (i.e. in a test cell environment) with more than one solid surface in proximity of the inlet, there always exists an unsteady vortex regime.

In addition to having more than one solid surface in the proximity of the inlet, all solid surface should be equidistance from the inlet for the test cell environment. It is unclear how far should the "other" surfaces be from the inlet in order to replicate the take-off scenario [20] in experiments. Since this study is conducted in a water tunnel where there are side walls which are immoveable, it is similarly unclear if the unsteady nature of the vortex, observed in this study, was due to the unsteadiness of the ambient conditions or is in-fact the unsteady regime observed in the test cell scenario with steady ambient conditions [5].

Determination of vortex formation is done visually to detect presence of a rotation of fluid. Figure 2 shows one such case which was determined as a vortex being formed whilst Fig. 3 shows another case with no vortex being formed. In Fig. 2, there is clear fluid rotation from the top view which is distinctly absent in Fig. 3. If a vortex remains attached to the inlet throughout the entire duration of the experimental run, it is termed as steady vortex. Unsteady vortices tend to have more vortex breakdowns and are blown away and reforms.

4. RESULTS AND DISCUSSIONS

The results are presented in graphical form by way of plots of V_i/V_0 against H/D similar to approach of previous studies. The solid lines represent the threshold between steady and unsteady vortex regimes and dashed lines represent the threshold between unsteady and no vortex regimes. Above the broken lines, steady vortex is detected and below them, no vortex is detected. In between lies the region where unsteady vortex is detected.

Unsteady vortex was observed in the experiments but as discussed above, it is unclear if they are a result of the turbulence intensity of the water tunnel flow or the result of the side walls. Also although there was

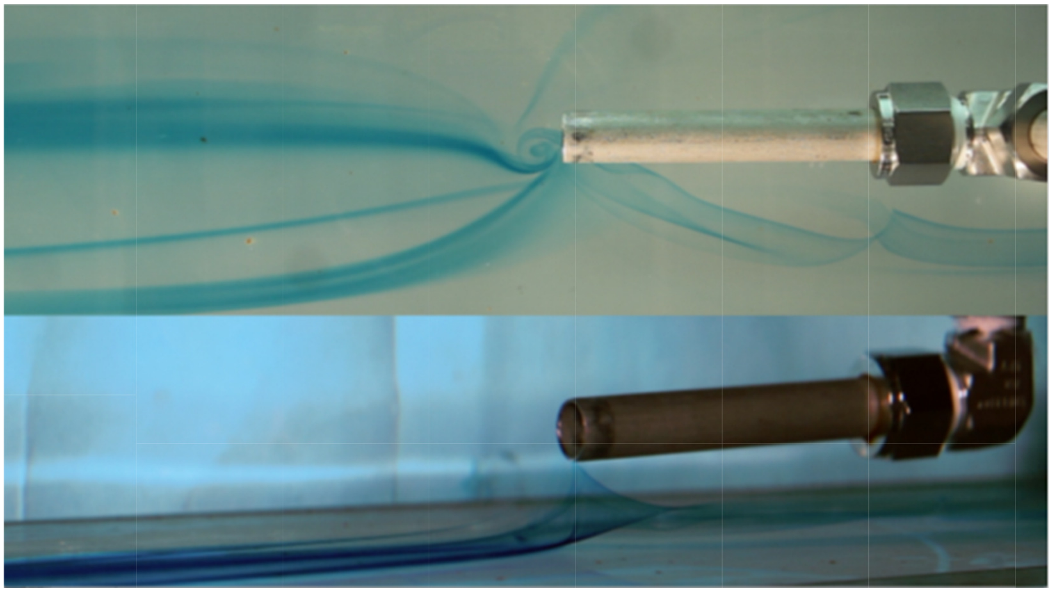


Fig. 2. Steady vortex formed.

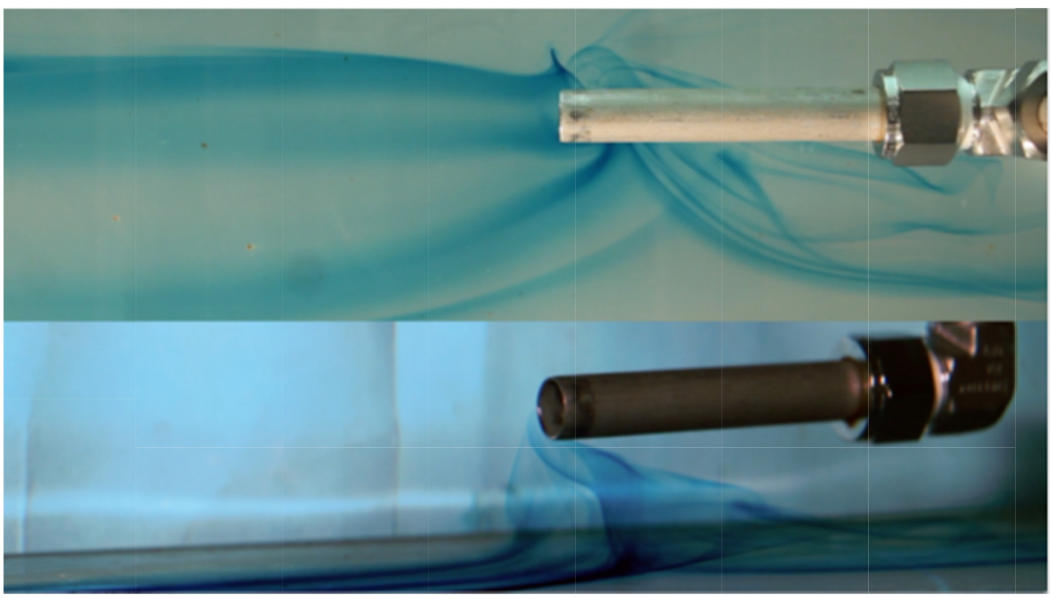
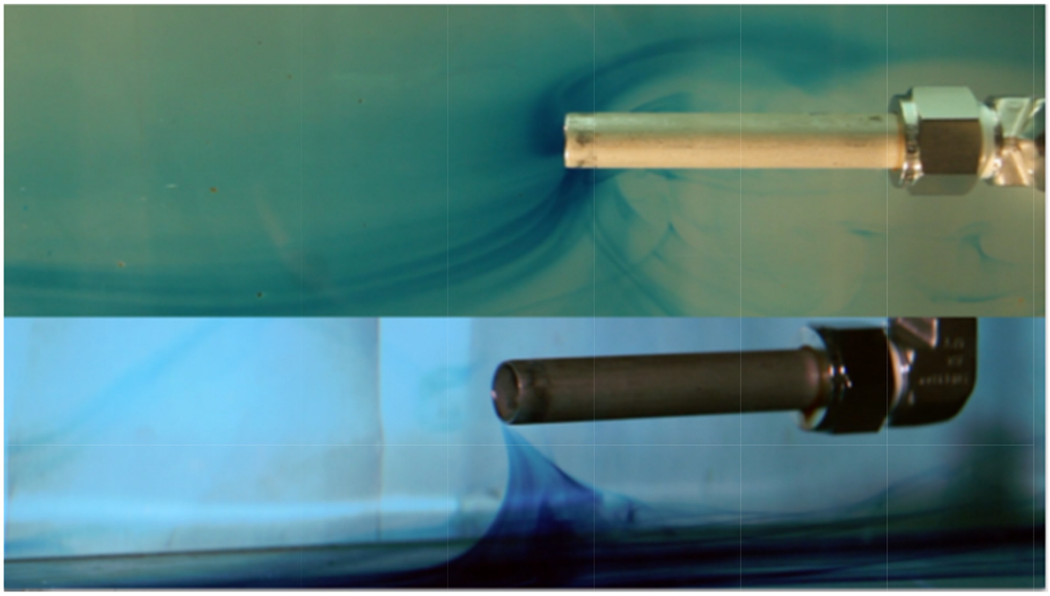


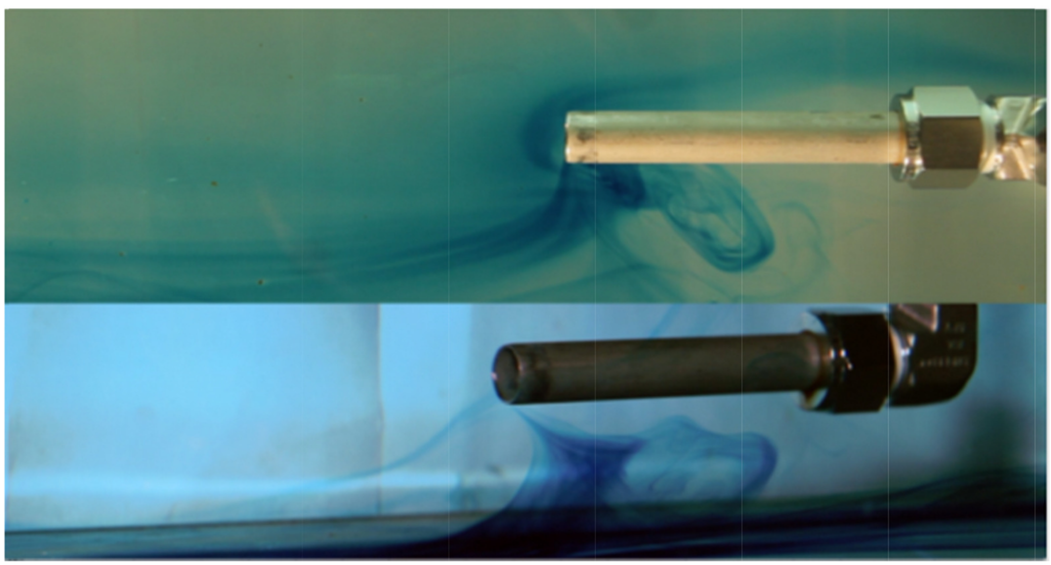
Fig. 3. No vortex being formed.

no intentional introduction of vorticity in the water tunnel flow, the presence of vortex indicate that some amount of vorticity must be present possibly due to imperfections in the water tunnel structures. Figure 5 shows the different thresholds for the headwind condition. The solid black line is the average threshold determined from different experiments [5] which were averaged from experiments conducted at much higher Reynolds number. The lower threshold extracted from current study is in agreement with previous studies that indicate a negative correlation between Reynolds number and ease of vortex formation.

It can be observed that the thresholds have a positive upward sloping trend. This is in line with previous studies. However the change in Reynolds number does not seem to have a pronounced effect on the thresh-



(a) Unsteady vortices before being blown away



(b) Unsteady vortices being blown away

Fig. 4. Unsteady vortex (a) before and (b) after being blown away.

old. However the unintentional vorticity due to structural imperfections in the water tunnel could possibly be affected by the flow rate. This hypothesis is further strengthen by the change in the gradient of the threshold. Jermy and Ho reported a clockwise rotation of the threshold with increasing vorticity [5]. If the hypothesis that there is unintentional vorticity due to structural imperfections, then the observed results are in agreement as the effects are expected to be amplified at higher Reynolds number. It is also unclear if the negative correlation between Reynolds number and ease of vortex formation is affected by the Reynolds number. At high Reynolds number, it is more difficult to form vortices because of increased flow instabilities, however this effect might be diminished or less obvious at such low Reynolds number.

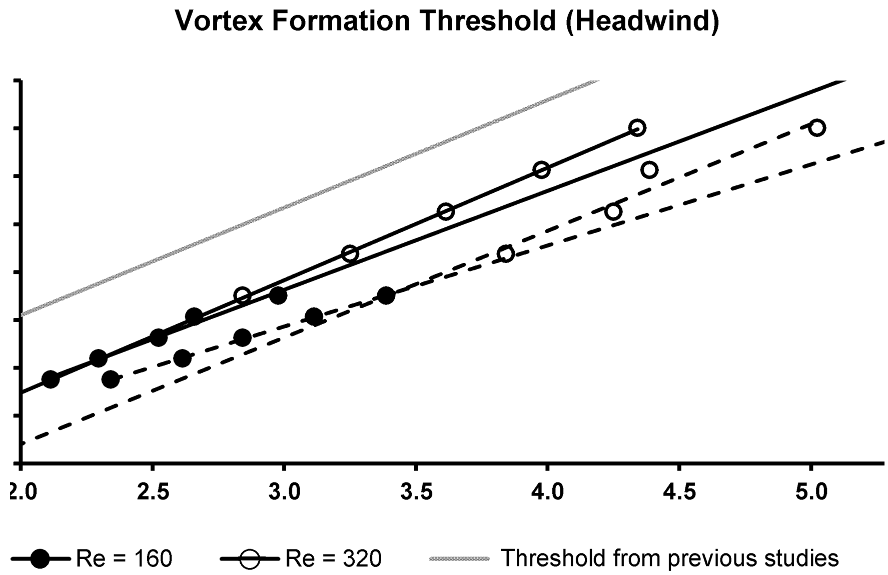


Fig. 5. Headwind vortex threshold.

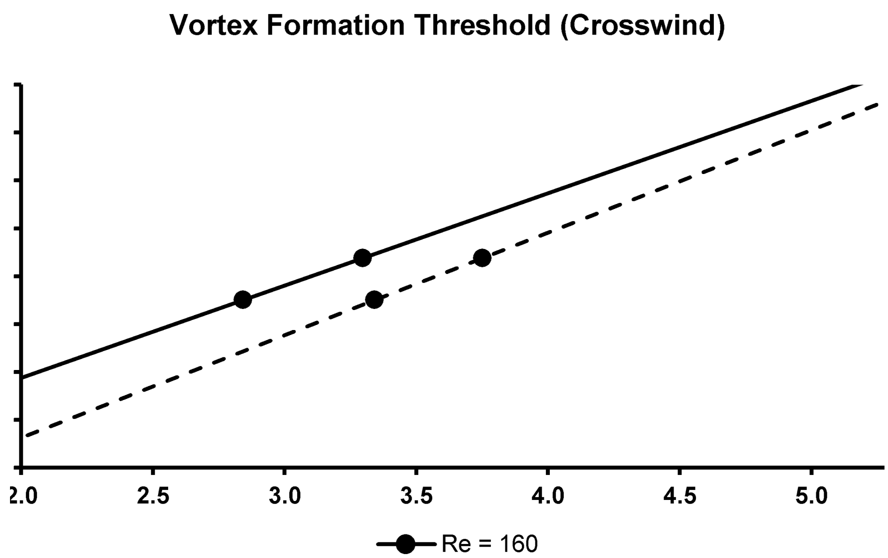


Fig. 6. Crosswind vortex threshold.

Similar to the headwind condition, unsteady vortices were also observed in the crosswind condition. Figure 6 shows the thresholds for the crosswind condition. The results presented are for $Re = 160$. Again the upward sloping gradient of the threshold is observed. Crosswind setup is expected to yield higher vorticity and Rossby number (Ro) [16] and lower the threshold. However this was not observed when comparing headwind and crosswind results at $Re = 160$ shown in Fig. 7. Also with the higher and significant Ro, vortices when formed are expected to be more consistent in their direction of rotation. However the reverse with more inconsistencies was observed, where unsteady vortices when formed often change rotational direction. The reasons for these two observations are not clear at this stage.

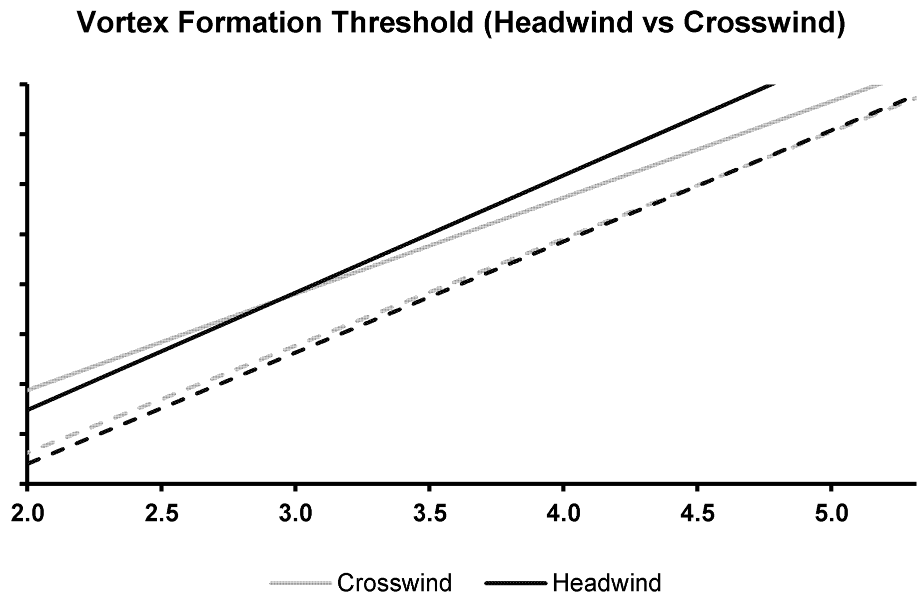


Fig. 7. Comparison of results for crosswind and headwind.

5. CONCLUSION

The suction intake vortex phenomenon has been studied and the threshold for its formation reported for low Reynolds number of between 160 and 320. Three cases of vortex formation, similar to previous studies, are observed: no vortex, unsteady vortex and steady vortex. This indicates that the inlet vortex phenomenon is still prevalent at this low Reynolds number. Similar to higher Reynolds number reports, the vortex threshold has a positive gradient. When compared to other higher Reynolds number experiments, the negative correlation between Reynolds number and ease of vortex formation is validated. However the same was not observed between the reports conducted at different Reynolds number in this study. It is unclear if the effect of Reynolds number on vortex formation threshold is diminished at low Reynolds number. Such vortices when formed will inhibit smooth flow through the inlet into the accompanying system(s) and may cause significant damage. In the design of systems similar to the simulated scenarios, one should avoid conditions that inhibit the formation of vortices completely (i.e. operate below the broken line).

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