Analysis on the flow field around a rigid body in a small-diameter pipe

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A sensing/transporting system that moves along with fluid inside a small-diameter tube is recently studied by many researchers and expected to be developed for engineering applications such as a PIG for a pipeline and a micro machine. Flow field ahead, inside, and behind a rigid body has been experimentally observed and analyzed with a support of a unique numerical program. It was observed that there exists a Rankine compound vortex at the inner-rear part of the body. A flow layer where the flow is trailed along with the moving top surface was also observed. It is concluded that a Rankine compound vortex appears at the inner-rear part of the body. It is also concluded that, as the Reynolds number increases, the layer becomes thin and the flow only moves within the layer.

Key Words: Rankine Compound Vortex, Boundary Layer, Non-linear Fluid-Solid Interaction, Small-diameter Tube, MAC Method, Micro Machine

INTRODUCTION

A sensing/transporting system that moves along with fluid inside a small-diameter tube is recently studied by many researchers and expected to be developed for engineering applications. One example is a micro machine that operates in a blood vessel to transport medicines to a certain part of a body. However, few studies have been conducted to observe and analyze the flow characteristics around a system. An opaque tube that prevents observers to study inside and a possible appearance of nonlinear phenomena induced by the fluid complicate the problem. The objective of the study is to elucidate the nature of the dynamics of the system, especially in terms of flow fields by conducting experiments and with a support of a unique numerical program.

EXPERIMENTAL DESIGN/DEVELOPMENT/SETUP

The approach was to build a scaled representative model of a system, which consists of a scaled exterior apparatus that simulates a water-flowing tube and a scaled object that runs inside the tube (Figure 1).

The modeling of the system is based on a pipeline with 30cm inner-diameter. To represent the full-scale flow-field conditions accurately the Reynolds number must be matched. The expression for Reynolds number, \( Re = \frac{UI}{v} \) relates the flow velocity, the reference length, and the dynamic viscosity.

Typical Reynolds numbers for a sensing/transporting system range from 100-10000. The exterior system consists of an acrylic pipe and a pump, which allows the circulation of the fluid. The total length of the test section is 6m, enough to make the flow fully developed. The PIV system is incorporated with the system along with the transparent pipe (Figure 2), which enables to observe and record the flow field inside. The pressure is the only driving force for the object and the force is exerted on the rear disk.

Figure 2 Experimental apparatus

NUMERICAL ANALYSIS

The thick red line in the numerical model (Figure 3) represents the computational area. The non-dimensionalization with the Galilei transformation of the governing equations was performed. The non-dimensionalized cylindrical coordinate system is defined as \((x', r', \theta)\) and therefore the velocity is defined as \((U', U'_r, U'_\theta)\). The prime refers to the non-dimensionalized component. The distance between the object and the wall \(H\) is taken as the reference length, the average fluid velocity \(\bar{U}\) is the reference velocity, and \(\rho\bar{U}^2\) is the reference pressure. \(\bar{U}\) is assumed to be constant, i.e. the steady state. The non-dimensional governing equations in the relative-to-the-object cylindrical coordinate are presented below.

\[
\begin{align*}
\nabla \cdot \mathbf{V} &= 0 \quad (1) \\
(V \cdot \nabla)V &= -\nabla p + \frac{1}{Re} \Delta \mathbf{V} \quad (2)
\end{align*}
\]

The non-dimensional parameter is the Reynolds number. The boundary conditions on the walls were determined under the no-slip condition. The above equations were solved with MAC method.

Figure 3 Analytical model (non-dimensionalized)
INVESTIGATION AND RESULTS

The investigations were developed by observing the vector field and varying the flow conditions \(Re=500, 1000, \text{and } 10000\). Figure 4 displays the vector fields obtained from experiments for each Reynolds number. It is noticed that a vortex forms in the rear part of the object. It is also observed that, at these Reynolds numbers, \(U_r\) and \(U_z\) are the main velocity components and there is no noticeable \(U_\theta\). Besides, there exists a layer of flow that is trailed along with the moving top surface. It should be also noted that the disk vibration disturbed the flow at high Reynolds numbers (Figure 4 (c)). Since the experimental results qualitatively agree with the numerical results (Figure 5), further investigations were developed by using the numerical results.

The formed vortex is considered as the Rankine vortex. A Rankine vortex is characterized by a forced vortex in the central core, which is surrounded by a free vortex. The forced vortex changes to the free vortex when the vorticity \(\omega = \nabla \times \nabla \) becomes zero and the region is observed from Figure 6. The layer of trailed flow was also analyzed and it was observed that the layer becomes thinner as the Reynolds number increases (Figure 7). Also, as the Reynolds number increases, the flow only moves within the layer. The thickness of the layer can be evaluated by using the idea of mass conservation and by using the boundary layer theory.

SUMMARY AND CONCLUSION

Conclusions are as follows:

- A compound vortex is observed in the rear part of the object both experimentally and numerically.
- The \(\theta\) component of velocity is much smaller than the \(r\) and \(x\) components of velocity, even at high Reynolds numbers.
- A thin trailed-flow layer is numerically observed and it becomes thinner as the Reynolds number increases.

Figure 4 Velocity vector field (Experimental results)

a) \(Re\approx500\)

b) \(Re\approx1000\)

c) \(Re\approx10000\)

Figure 5 Velocity vector field (Numerical results)

Figure 6 Flow vorticity \(\omega\) (Numerical results)

Figure 7 Variation of layer thickness \(r_0\) with Reynolds number