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Reynolds and froude number effect on the flow past an interface-piercing circular cylinder

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ABSTRACT: *The two-phase turbulent flow past an interface-piercing circular cylinder is studied using a high-fidelity orthogonal curvilinear grid solver with a Lagrangian dynamic subgrid-scale model for large-eddy simulation and a coupled level set and volume of fluid method for air-water interface tracking. The simulations cover the sub-critical and critical and post critical regimes of the Reynolds and sub and super-critical Froude numbers in order to investigate the effect of both dimensionless parameters on the flow. Significant changes in flow features near the air-water interface were observed as the Reynolds number was increased from the sub-critical to the critical regime. The interface makes the separation point near the interface much delayed for all Reynolds numbers. The separation region at intermediate depths is remarkably reduced for the critical Reynolds number regime. The deep flow resembles the single-phase turbulent flow past a circular cylinder, but includes the effect of the free-surface and the limited span length for sub-critical Reynolds numbers. At different Froude numbers, the air-water interface exhibits significantly changed structures, including breaking bow waves with splashes and bubbles at high Froude numbers. Instantaneous and mean flow features such as interface structures, vortex shedding, Reynolds stresses, and vorticity transport are also analyzed. The results are compared with reference experimental data available in the literature. The deep flow is also compared with the single-phase turbulent flow past a circular cylinder in the similar ranges of Reynolds numbers. Discussion is provided concerning the limitations of the current simulations and available experimental data along with future research.*

KEY WORDS: Large-eddy simulation; Interface-piercing circular cylinder; Run-up; Wave breaking; Vortical structures.

INTRODUCTION

The turbulent flow past a circular cylinder has been investigated extensively for a long time due to its importance in many engineering applications. It shows different features at different Reynolds numbers (Re), based on the free-stream velocity, cylinder diameter, and kinematic viscosity. There are three states of the flow with different Re : sub-critical ($Re = 1000 \sim 2\times10^5$), critical ($Re = 2\times10^5 \sim 3.5\times10^6$), and super-critical ($Re > 3.5\times10^6$) flows. In the sub-critical range the boundary layer along the cylinder is laminar and the transition to turbulence happens in the free shear layer downstream of the cylinder. With an increase of Re , the location of the transition moves upstream (Wissink and Rodi, 2008). In the critical range the base suction and drag decrease dramatically and this is associated with a revitalized boundary layer characterized by events in the order of a

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laminar separation, a transition to turbulence, a reattachment, and a turbulent separation further downstream with much reduced downstream wake width. In the super-critical regime, the boundary layer along the cylinder becomes turbulent before the separation. The base suction and drag of this regime is low due to the later separation of the turbulent boundary layer (Kravchenko and Moin, 2000).

The two-phase flow past an interface-piercing circular cylinder is much more complicated than the single-phase flow due to the interaction between the viscous effect near the body and the air-water interface phenomena, including wave run-up, breaking waves, thin liquid sheet formation, and air entrainment. It also exists in many engineering applications such as ship, ocean, coastal, and hydraulic engineering. The effects of the interface on the force distribution on the body, vortex generation and turbulence structures, and air-water interface structures, especially, their changes with the Reynolds and Froude (Fr) numbers are not well understood. A better understanding of these effects is also important for the cases when vortex- and/or wave-induced vibrations are to be considered.

There are several experimental and numerical studies on the flow past a surface-piercing circular cylinder in mainly sub-critical Re regime. Inoue et al. (1993) conducted a towing tank experiment to investigate the characteristics of free surface turbulence for Re =27,000 and Fr =.8 and Re =29,000 and $Fr = 1$. They found that the periodic vortex shedding occurs in the deep flow, while this periodic vortex shedding is attenuated and higher frequency fluctuations are more prominent near the interface. Kawamura et al. (2002) investigated the wave-wake interaction about a surface-piercing circular cylinder using Large-Eddy Simulation (LES) based on a Smagorinsky Sub-Grid Scale (SGS) model at Re =27,000 with three different Fr =0.2, 0.5 and 0.8. At a low Fr , surface deformations were small and the influence on the wake was negligible. On the contrary, the generated surface wave was very steep and strongly unsteady at a high Fr . They also predicted significant surface fluctuations inside the recirculation zone immediately after the surface wave crest. In addition, they were able to visualize the attenuation of vortex shedding near the interface. Flows past an interface-piercing cylinder at various $Re = 1\times10^5$ and up to $Fr = 3$ simulated using LES based on a Smagorinsky SGS model and a Volume of Fluid (VOF) method by Yu et al. (2008). They also showed that the free-surface attenuates the organized vortex shedding at the interface. At a higher Re, the free surface effect was reduced whereas this effect was enhanced at a higher Fr . As Re increases, the mean drag coefficient increases; however, it decreases along with Fr . They also showed that the dominant Strouhal number of the lift force decreased along with Re . Recently, Suh et al. (2011) studied the effect of air-water interface on the vortex shedding from a vertical circular cylinder for Re =27,000 and Fr =0.2, 0.8 using a high-fidelity orthogonal curvilinear grid solver. The organized periodic vortex shedding was observed in the deep flow whereas it was attenuated and replaced by small-scale vortices near the interface. The attenuation of the organized vortex shedding at the interface is caused by the streamwise vorticity and the outward transverse velocity generated near the edge of the separated region. The anisotropy between the vertical and transverse Reynolds normal stresses is the primary source of the streamwise vorticity and the outward transverse velocity near the interface.

The abovementioned studies were focused on relatively low Re and Fr in the sub-critical Re / Fr regimes (Fr <1, sub-critical flow; Fr =1, critical flow; and Fr >1, super-critical flow). Chaplin and Teigen (2003) carried out an experimental study at higher Reynolds numbers up to 4.7×10^5 and larger Froude numbers up to 1.67 with a constant Re / Fr ratio of 2.79×10^5 . They found that the total resistance coefficient reached a maximum at $Fr \sim 1$. They also measured the run-up on the front of the cylinder and found that the run-up at a given Fr has a strong dependence on Re . However, their study was limited to resistance, run-up, and stagnation and base pressure measurements and analyses, many other flow features, such as the overall free surface and wave patterns, breaking waves near the cylinder, flow separation, vortex shedding, and other turbulent quantities, were not addressed. To the authors' knowledge, this is the only recent study in the literature done on the turbulent flow past a vertical surface-piercing circular cylinder in the critical and super-critical Re / Fr regimes. As discussed above, the turbulent flow past a circular cylinder in the critical Re regime has very different flow physics than those in the sub-critical Re regime. Also the bow wave breaks in front of the cylinder for large Fr cases. Near the interface, the interactions of turbulence and interface are more complicated than the sub-critical Re / Fr cases studied in Suh et al. (2011) and the other work. Further investigations are required for better understanding of the effect of Reynolds and Froude numbers on the flow, especially, near the air-water interface.

To this end, LES of the two-phase turbulent flow past an interface-piercing circular cylinder at different Re / Fr with a constant ratio, same as Chaplin and Teigen (2003), are performed in the present study. This work can also be regarded as an extension of the precursory work for sub-critical Re and Fr (Suh et al., 2011). The same two-phase Navier-Stokes solver and computational domain, and similar grid sizes reported in Suh et al. (2011) are utilized here. In Suh et al. (2011), the Froude