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Numerical study of the Impact of the Flow Direction on Energy Harvesting from Induced Vibration in a Heated Semi-Circular Cylinder

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Abstract

In the presence of buoyancy, a two-dimensional computer simulation explores flow and heat around low-mass arched forebodies (AF), flat forebodies (FF), and circular cylinders (CC). The Prandtl number of 0.71, the Reynolds number of 100, and the Richardson number of 1.5 are all used in this investigation. Selecting five semi-circular cylinders with various length-to-diameter ratios (L*=L/D) aims to investigate the influence of L* on energy harvesting. Our goal is to determine a bluff body that captures maximum energy through more vibration. Having compared some of the outcomes of present work with other studies, a good agreement is achieved to validate the simulations. Energy harvesting is augmented when Richardson numbers are prescribed higher. Not having applied buoyancy force, the circular cylinders with L^* of 0.5 and 0.6 for the flat forebody configuration gain the highest extracted power at Reynolds numbers of 100 and 200, respectively, resulting in 3.5 and 5.3 more times extracted power. Moreover, the flat forebody configuration always brings about more harvested energy compared to the same body with opposite flow direction. As a result of these findings, we can gain a deeper understanding of the characteristics of thermal systems able to dissipate heat loads as well as produce maximum power output.

Keywords: Buoyancy force; Flow- induced vibration; Energy harvesting; Semi-circular.

1. Introduction

In recent years, scientists have been looking for methods to extract energy from renewable sources such as fluid motion, which can be a viable solution. When the flow passes over a bluff body, Von Karman Vortex Street forms vortices; if the bluff body is free to move, it can create vibrations called vortex-induced vibration. Researchers have continuously been studying methods to suppress this phenomenon [1, 2, 3], and few investigations have been conducted with respect to extracting energy from this phenomenon [4]. In this regard, Aerodynamics forcing, and vorticity dynamics can be found in Ref. [5-8].

In addition to studying fluid dynamics in vortex-induced vibration, researchers have also explored the influences of thermal buoyancy on stationary bluff bodies [9-10]. In addition, the thermal buoyancy has a vital role in achieving the suppression, as deliberated by Rashidi et al. [11]. The importance of including buoyancy force on the patterns of vortex has been studies [12, 13], and as far as suppression is concerned, employing buoyancy could lead to the complete suppression of vortex in the lee of the semicircular and circular cylinders and for different Reynolds numbers [14]. In this context, it was proved that thermal buoyancy has a vital role in the vortex-induced vibration of the solid structures since this is capable of either suppressing or agitating the vortex shedding [15].

With respect to energy harvesting, a vortex shedding phenomenon has been explored comprehensively using a circular cylinder as a reference owing to their rotational symmetry [16]. A representative sample of an aeroelastic vibration phenomenon is vortex-induced vibration [17], resulting from the unstable flow pattern in the course of time [18]. The inherent potential of flow passing the bluff body to create vorex is an asset because of generating an acting force, which is responsible for producing renewable energy [19].

Recently, Barati et al. [20] studied the flow patterns around inverted D-shaped cylinders at the Reynolds number of 100, in this study, however, the important factors affecting energy harvesting were not determined. Against this background, evidently, there is still lacking in insights into characteristics of the vortex-induced vibration of D-shaped and inverted D-shaped cylinders. Therefore, the objective of this research is to provide an original insight into different features of the D-section and its reversed case, by numerical investigation in a laminar flow regime. Two different orientations with different L* ranges are considered during numerical computations, while the Reynolds numbers prescribed are 100 and 200 in the presence of buoyancy force. In this research, a forced system model for computing the heat transfer and energy harnessing is employed [21], and the maximum amplitude is considered to occur in the lock-in as is mentioned in other published studies [22, 23].

2. Physical problem

Fig.1 displays the configuration of the concerned problem studied in the current study. The system is comprised of a semi-cylinder of diameter D, and this bluff body is assumed to be long enough in the span-wise direction, and subsequently, it is acceptable to ignore the ending influences. Two orientations of the semi-cylinder are investigated, wherein the forebody shape of the cylinder facing incoming flow is different. If the fluid is striking the arched surface, we have an arched forebody (AF), and the opposite flow direction means having the flat forebody (FF). In order to reduce the impact of boundary conditions on the flow patterns in close proximity to the solid object, the length of the upstream and downstream is the same and equal to 30D.

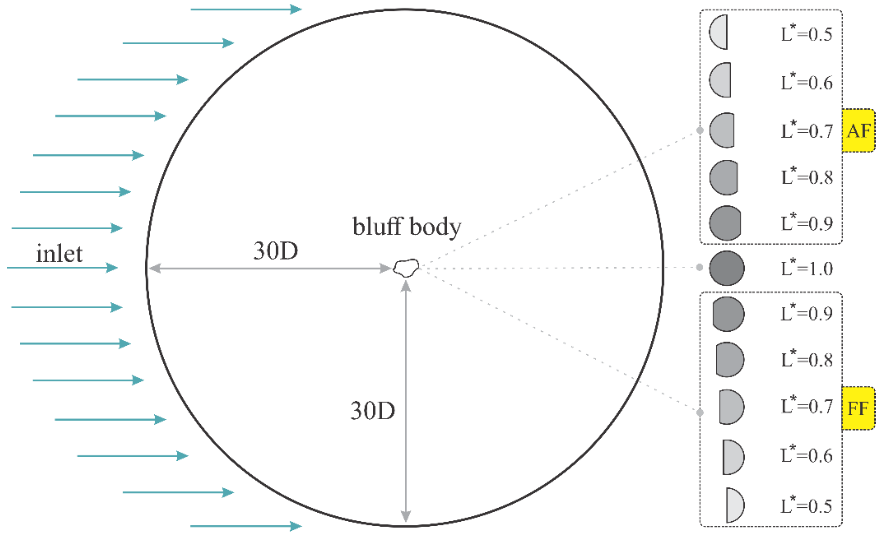

Fig.1. Computational domain around the bluff body and all L* of the study.

The vortex-induced vibration energy harvesting system is composed of a D-shaped cylinder or an inverted one, a spring and generator, which is presented in Fig.2. Furthermore, the influence of L^* on the heat transfer as well as energy harvesting is explored. Considering Fig. 2, two orientations of the cylinder, namely arched forebody (*AF)* and flat forebody (*FF)* configurations are considered. The bluff body is presumed to be long enough in *z* – direction; therefore, the simulations are two-dimensional. It should be mentioned that the computational domain is optimized, which is 30D, guaranteeing the accuracy of simulation.

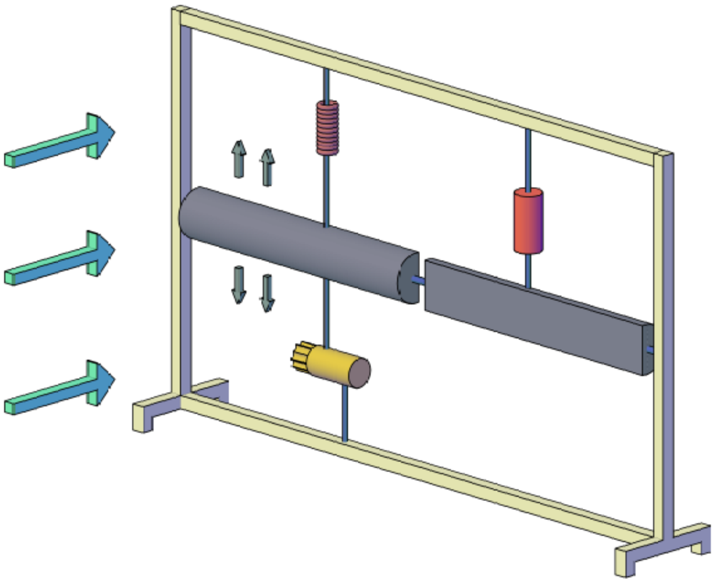

Fig.2. VIV energy harvesting system.

3. Numerical simulation

In this study, computer simulations are carried out in a two-dimensional flow field at the sub-critical Reynolds numbers of 100 and 200 by using the commercial CFD package ANSYS FLUENT [24], which employs the control volume technique to solve the governing equations with the aid of SIMPLE algorithm. Having solved the governing equations with double precision, the pressure field value is obtained. The system of equations is discretized by using an implicit method. In order to model the effect of buoyancy, the Boussinesq approximation is employed. The density of the fluid varies with the temperature in the buoyancy equation and other properties are considered to be constant.

4. Validation

It is safe to believe that the present computer simulation can lead to reliable results, resulting in reliability of employed method to capture the variation of heat transfer as well as power extractions. Barati et al. [20] proved that in spite the simplicity of the model, the extracted power is well obtained provided that the prescribed Skop-Griffin number is greater than 0.2. To ensure the accuracy of this simulation, Maximum vibration amplitude obtained by this work is compared with Ref. [25], and the maximum deviation is less than 6 percent. In this study $m^*=260.42$, SG =0.412 and 0.552 for the Reynolds number of 100 and 200, respectively, with the absence of buoyancy force. It is noteworthy that buoyancy force increases the Skop-Griffin number.

5. Results and discussions

Fig. 3 displays the dimensionless vibration amplitude at Ri=0.0-1.5 and L*=0.5-1.0 for both configurations, the Richardson number is capable of effecting a dramatic change in the dimensionless vibration amplitude. It is interesting to mention that the behavior dimensionless vibration amplitude is not predictable as L^* varies at the constant Richardson number. This could account for the interplay between the lift coefficient and Strouhal number. Changing the Reynolds number from 100 to 200 effects a dramatic change in the flow patterns, resulting in a rise in the value of the dimensionless vibration amplitude. For a D-shaped configuration, there is a solid aspiration to a more negative value as the Richardson number rises. Surprisingly, the predicted displacement of body decreases as the shape of bluff body shifts from a D-shaped configuration to a circular cylinder.

The extracted power is plotted against L^* for different values of Richardson number in Fig.4. The larger value of energy prevails with an increase in L*. It is obvious that an increase in the Richardson number is responsible for the asymmetric pressure, subsequently, creating force to promote flow instability, thereby giving rise to a larger extracted power. With respect to extracted power, it is clear that a D-shaped configuration is less dependent on Buoyancy force compared to an inverted D-Shaped configuration, more importantly, extracted power largely depends on the Reynolds number. Therefore, an increase in Reynolds number corresponds with a decrease in the effects of other parameters. For Ri=0 and inverted D-shaped cylinder, the maximum energy is extracted when L^* are selected to be 0.5 and 0.6 at Reynolds numbers of 100 and 200, respectively, resulting in 3.5 and 5.3 more times power harvesting. Also, in the same sectors cylinder, the cylinder with the flat forebody configuration always has more power generation than the cylinder with an arched forebody placement direction.

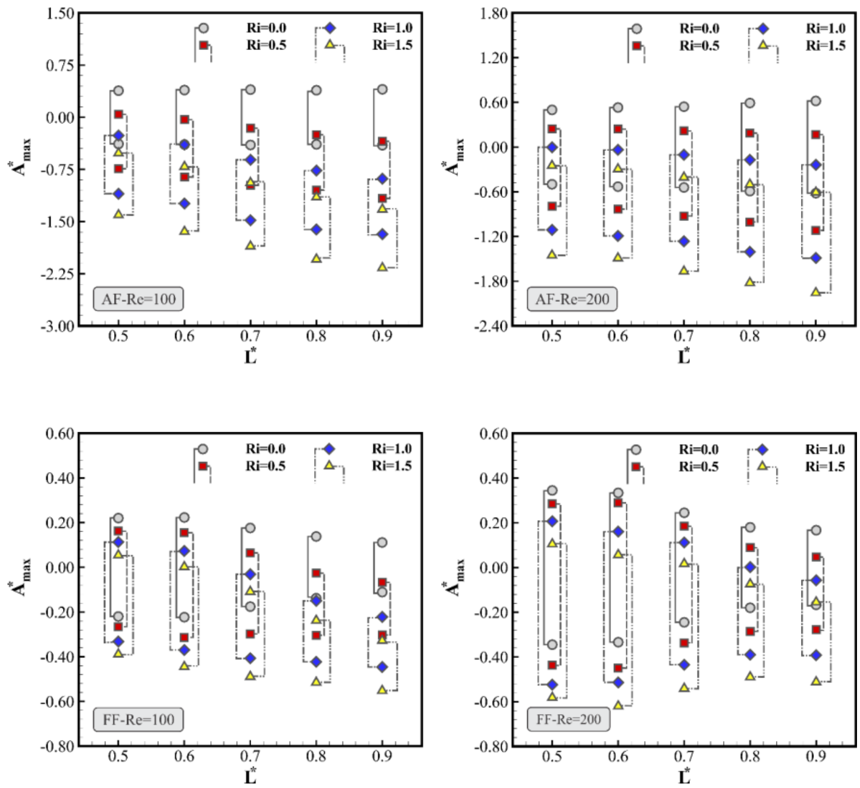

Fig.3. Non-dimensional vibration amplitude for various L*, Ri, and Re.

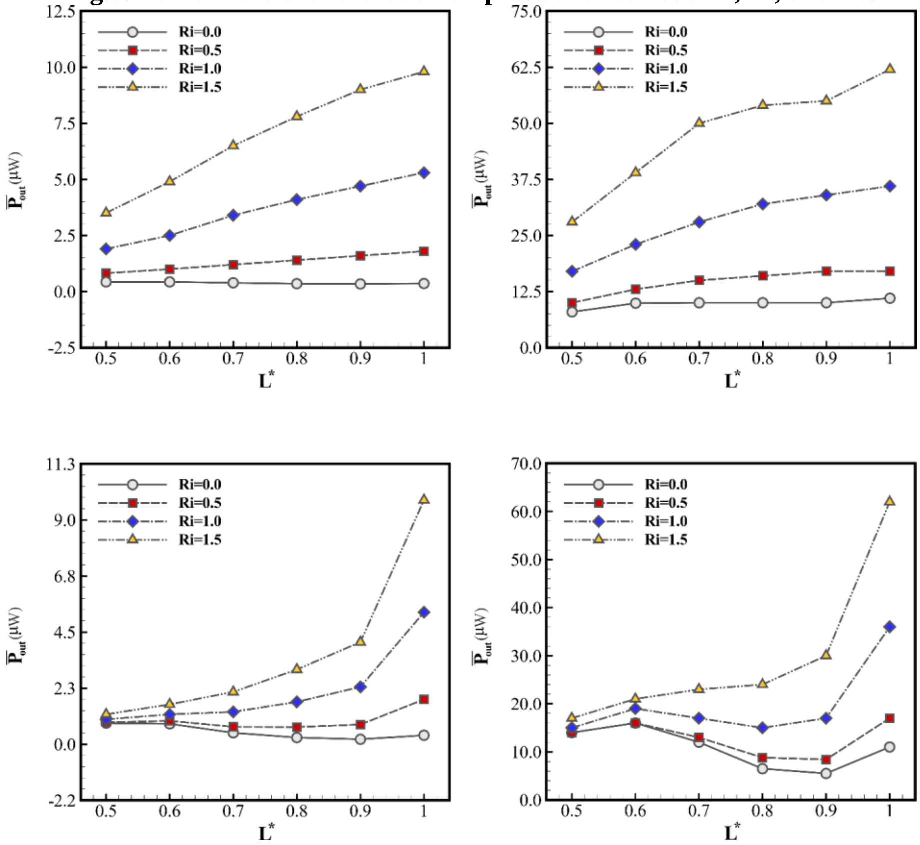

Fig.4. Output power of fluid alternation for various L*, Ri, and Re.

6. Conclusions

In this study, computer simulations are conducted by assuming that the laminar incompressible Newtonian fluid is passing over the bluff body, and the effect of flow direction, bluff body type, and Reynolds number in the presence of buoyancy force is studied. The length-to-diameter ratios L*=0.5, 0.6, 0.7, 0.8, 0.9, and 1 at Re=100 and 200 under the sway of the Richardson number, Ri=0, 0.5, 1, 1.5, are studied. The main results of this investigation are as follows:

In the same sectors cylinder, the cylinder with the flat forebody configuration always has more power generation than the cylinder with an arched forebody placement direction.

For both configurations, an increase in the Richardson number is responsible for increased dimensionless vibration amplitude.

The bluff bodies which are more similar to a circular cylinder can result in higher harvested power provided that buoyancy force is applied.

Further research is suggested understanding the nature of flow in turbulent flow.

7. References

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