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Effect of cylinder proximity to the wall on channel flow heat transfer enhancement

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ABSTRACT

Heat-transfer enhancement in a uniformly heated slot mini-channel due to vortices shed from an adiabatic circular cylinder is numerically investigated. The effects of gap spacing between the cylinder and bottom wall on wall heat transfer and pressure drop are systemically studied. Numerical simulations are performed at $Re = 100$, $0.1 \leqslant \mathrm{Pr} \leqslant 10$ and a blockage ratio of $D/H = 1/3$. Results within the thermally developing flow region show heat transfer augmentation compared to the plane channel. It was found that when the obstacle is placed in the middle of the duct, maximum heat transfer enhancement from channel walls is achieved. Displacement of circular cylinder towards the bottom wall leads to the suppression of the vortex shedding, the establishment of a steady flow and a reduction of both wall heat transfer and pressure drop. Performance analysis indicates that the proposed heat transfer enhancement mechanism is beneficial for low-Prandtl-number fluids.

1. Introduction

With the advances in state-of-the-art mini- and micro-scale technologies and demands for higher cooling efficiency in electronic chips, compact heat exchangers and other heat transfer devices, research work on thermal–hydraulic characteristics of mini- and micro-channels is gaining increasing attention. Thermal performance of cooling systems can be improved by different approaches [1–3]. For example, casting artificial roughness or placing obstacles on the solid boundary can substantially increase the wall heat transfer coefficient. Such boundary modifications can generate vortices, which increase mixing, reduce the thickness of the thermal boundary layer, and thereby enhance heat transfer. Since fluid velocities and characteristic length scales are relatively small in mini- and micro-scale devices, the flow Reynolds number is low or moderate. Therefore, these devices are often operating in laminar conditions. Utilizing a proper vortex generation mechanism can effectively enhance heat transfer in such devices. The focus of the present study is to assess how vortices shed from a stationary confined cylindrical obstacle influence thermal and hydraulic characteristics when their position approaches the lower wall.

Heat transfer, both from the channel walls and from the vortex promoter itself, has been the subject of several investigations. For example, Rahnama and Moghaddam [4] studied convective heat transfer over a square cylinder confined in a channel and proposed a correlation between Nusselt and Reynolds numbers. The blockage ratio was 1/8, while the Reynolds number based on the mean flow velocity and chord length of the square cylinder was less than 200. Their results showed a linear increase in the recirculation length and a decrease in the drag coefficient with increasing the Reynolds number for Reynolds numbers lower than 70. They reported an increase in the Nusselt number and the drag coefficient

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with a Reynolds number's increase for the unsteady flow regime, where vortex shedding was observed from the cylinder. Heat transfer augmentation and entropy generation were determined experimentally at $Re = 3450$ for an air flow through a ribbed duct with a circular vortex generator placed immediately above or just downstream from the selected rib elements by Yrum et al. [5]. Their results showed that the smaller diameter generators have small effects on the Nusselt number and entropy generation. In all cases examined, a generator-induced local Nusselt enhancement occurred in the inter-rib space behind the rib pair, regardless of the generator's diameter. Wang and Jaluria [6] also investigated fluid flow and mixed heat transfer in a grooved channel in the presence of a rectangular obstacle and examined the effect of obstacle's geometry on flow characteristics at $600 \leqslant Re \leqslant 2250$. Their results showed that buoyancy strength Gr/Re^2 largely determines the base frequency of the oscillation. They also found that using larger diameter vortex generators and larger pitch space between the ribs increases wall heat transfer. Korichi et al. [7] studied heat transfer enhancement in self-sustained oscillatory flow in a grooved channel with oblique plates on the opposite wall at $250 \leqslant Re \leqslant 1000$ and analysed the fluid flow and heat transfer at different plate length, plate angle and Reynolds numbers. The presence of vortex generators at the upper surface was found to be a powerful mean to enhance the heat transfer compared to the basic grooved channel. For example, the heat transfer enhanced up 200% for $Re = 600$ and for a given geometric configuration of the oblique. Icoz and Jaluria [8] studied heat transfer enhancement in a rectangular channel with an aspect ratio of 6 with obstacles of various shapes at Reynolds numbers lower than 6000. The vortex promoters had circular, square, and hexagonal shapes, and were located, with several blockage ratios, ahead of two tandem heating sources. The circular promoter was found to be the best choice when the pressure loss is the main criteria concern. As the importance of the pressure drop is reduced relative to the heat transfer rates, hexagonal and square geometries were found to have better performances. Abbassi et al. [9] studied heat transfer enhancement due to triangular vortex promoter and reported 85% increase in the time-averaged Nusselt number at a Reynolds number of 250. Nitin and Chhabra [10] considered a rectangular vortex promoter immersed in a non-Newtonian fluid. They reported heat transfer variations of the order of 10% and a strong sensitivity on the power law used to describe non-Newtonian behaviours. Meis et al. [11] investigated heat transfer enhancement in micro-channels caused by elliptical, rectangular, or triangular obstacles in a Reynolds number range between 600 and 1200. For all types of vortex promoters, they reported a heat transfer enhancement with a blockage ratio increase up to 1/2. Among the various cross-sections examined, the triangular vortex generator produced the best heat transfer augmentation. They found performance improvement with aspect ratio decrease. Chattopadhyay [12] investigated convective heat transfer in a channel in the turbulent flow regime up to the Reynolds number of 40 000 in the presence of a triangular obstacle and showed a heat transfer enhancement of about 15% compared to the plane channel. As expected, heat transfer augmentation was associated with pressure drop increase. However, performance analysis was not performed to compare the heat transfer augmentation and pressure loss penalty. Recently, Moussaoui et al. [13] applied the Lattice Boltzmann method to investigate fluid flow and heat transfer in a channel with a confined inclined 45° square cylinder at $Re < 300$ and $\mathrm{Pr} = 0.7$. Their results were presented in terms of streamline contours, isotherms, Strouhal number, Nusselt number and drag coefficient for various Reynolds numbers. The computed results showed that the presence of square cylinder significantly influences the fluid flow and causes an enhancement of heat transfer from the channel wall. Herman and Kang [14] have performed an experimental work to compare heat transfer enhancement in a grooved channel using a curved vane and a circular cylinder at the inlet. They compared their results with a simple grooved channel and two parallel plates in a Reynolds number range between 530 and 6200. They found that each of the three methods offered some advantages in electronic cooling.

More recently, heat transfer enhancement by oscillating vortex generators has been the topic of several investigations. For example, Celik et al. [15] using Spectral Element Method studied heat transfer enhancement in a channel via a transversely oscillating adiabatic circular cylinder at a Reynolds number of 100 and in a Prandtl number range between 0.1 and 10. The authors reported that cylinder oscillations with 75% of the natural vortex shedding frequency yields the best heat transfer augmentation with only 10% more power to pump the fluid compared to the case of a fixed cylinder. Yang [16] has carried out a similar investigation for a square obstacle and discussed the effect of amplitude, frequency, and maximum velocity. In the same oscillating amplitude of the bar, the heat transfer increment is decreased significantly as the maximum oscillating speed or the oscillating frequency of the bar is larger. Fu and Tong [17] carried out a numerical simulation of the effect of an oscillating cylinder on the heat transfer from heated blocks in a channel flow. Their results proved that heat transfer was remarkably enhanced as the oscillating frequency of the cylinder was in the lock-in region. A numerical study of convective heat transfer from a rotating cylinder with cross-flow oscillation has been done by Ghazanfarian and Nobari [18]. It was found that, in a similar manner to the fixed cylinder case, beyond a critical rotating speed, vortex shedding is mainly suppressed. Also, by increasing the non-dimensional rotational speed of the cylinder, both the Nusselt number and the drag coefficient decrease rapidly. In our last work [19], heat transfer enhancement in a channel via a rotationally oscillating cylinder was investigated. It was found that the maximum heat transfer was achieved when the oscillating frequency is 80% of the natural frequency of vortex shedding in presence of a stationary cylinder.

According to the author's knowledge, there is no research in which the effect of the distance from the cylinder to the lower wall on the vortex shedding phenomenon and heat transfer augmentation was investigated. Besides, just in few researches, the effect of the fluid type (Prandtl number) on the efficiency of the vortex generator has been studied. The main objective of the present study is to fill in these gaps. In addition, by calculating the pressure drop in the channel, we obtain a performance analysis at different Prandtl numbers.