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Numerical study of a vortex-induced vibration technique for passive heat transfer enhancement in internal turbulent flow

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HIGHLIGHTS

- Investigation of the turbulent flow in the heated channel comprises a deformable plate.
- Disruption of thermal boundary layer by the fluid–structure-thermal interaction.
- Heat transfer enhancement of channel flow by adding a flexible plate up to 17.5% over a clean channel.
- Investigation of different fluid and structure characteristics

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ABSTRACT

Due to many applications in engineering, the study of the vortex-induced vibration is of great importance. In the present study, a passive heat transfer enhancement technique for turbulent flow through the channel with constant wall temperature at $Re_D = 1000$ (based on the cylinder diameter) is studied. A flexible plate is attached to the stationary cylinder and the numerical analysis are carried out over a wide range of solid and fluid parameters such as density ratio (2.54-127), dimensionless Young's modulus (1.1-11 *106), Reynolds number (300–1000), Prandtl Number (6.8 and 68), velocity and temperature profiles. As a result, although the variation of natural frequency by density and Young's modulus of the plate alters the frequency and amplitude of oscillation, the performance evaluation criteria (PEC) number does not change. Velocity profile has a significant effect on increasing heat transfer rate and PEC number while temperature profile only increases heat transfer without any change in PEC number. Similar numerical analysis for the case without the flexible plate is also carried out to be compared to that with flexible plate. The results show that adding the flexible plate behind the stationary cylinder decreases the amplitude of lift coefficient 86%, the frequency of vortex shedding 35.8%, and total pressure loss 31.1%. The average Nusselt number is also improved by 2.3% and eventually, PEC increases by 23%.

1. Introduction

There are various methods for increasing heat transfer coefficient. Bergles [1] carried out a comprehensive study to increase convective heat transfer. In fact, he categorized these methods into 13 methods as the two groups of active and passive techniques. Inserting plates is one type of these passive methods And many numerical and experimental researches have been carried out to enhance heat transfer in both laminar and turbulent flows.

Chen and Hsieh [2,3] investigated the effect of inserting adiabatic rectangular plates inside a tube with constant heat flux. The flow was laminar, thermally fully developed and steady state. Both heat transfer and pressure loss increased by inserting the plates in this study. Then, they studied the effect of the plate inserts in a horizontal tube with a longitudinal square core. They found that the heat transfer enhancement for the square insert is more than that for the rectangular one. A numerical investigation of the unsteady laminar flow and forced convective heat transfer in a channel with a rectangular cylinder was done by Valencia [4]. He showed that the enhancement of heat transfer is about 45% for the perpendicular cylinder. Hung and colleagues [5] studied the role of adiabatic eccentric plate in a horizontal tube with constant-heat flux wall. They concluded that eccentric inserts reduce pressure drop and heat transfer. Numerical simulation of forced convection heat transfer around a heated equilateral triangular at low Reynolds numbers was performed two-dimensionally by Chatterjee and Mondal [6]. Reynolds number was varied from 50 to 250 with different fluids such as water, air and engine oil. Their results showed that as the Reynolds number increased, the local

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Nomenclature

D	Diameter of cylinder
E	Young's modulus
P	Pressure
T	Temperature
t	Time
u_{in}	Inlet velocity
u, v	x-and-y component velocities

Subscripts

h	Hydraulic
in	Inlet
m	Bulk
w	Wall

Dimensionless numbers

C_p	Pressure coefficient
Nu	Nusselt number
PEC	Performance evaluation criteria
Pr	Prandtl number
Re_D	Reynolds number
St	Strouhal number

Acronyms

ALE	Arbitrary Lagrangian–Eulerian
FFT	Fast furrier transform
FSI	Fluid–solid interaction
RMS	Root mean square
VIV	Vortex induced vibration

Nusselt number and amplitude of oscillations of both lift and drag coefficient increased too. Rigid obstacles were considered in the mentioned research.

Here, in the current study, a flexible plate is inserted in a channel to increase heat transfer rate. Using thin flexible plate in the flow is used in engineering like biological systems. For the first time, the oscillation of flexible sheets was addressed by Rayleigh [7]. Then, Taneda [8] performed an experimental study to investigate the effect of rectangular or triangular flags in a uniform air flow. The first study in the FSI modeling emerged during the late 1970's by different researchers [9–15]. Nowadays, the ability of computers has increased the fluid–structure interaction modeling. Several FSI analyses for flexible plate without considering heat transfer have been carried out. Turek and Hron [16] described a benchmark setting and performed the numerical study of laminar flow over a cylinder with a flexible plate attached to its backside. Lee and You [17] simulated the dynamic interaction between an unsteady flow and a flexible plate attached to the backside of a cylinder. They investigated the effect of material property on the drag and lift coefficient of a cylinder. A fixed cylinder with a thick rubber tail was used by Nayer and Kalmbach [18] in the turbulent flow regime.

There are very few numerical studies that use flexible plate oscillation to enhance heat transfer. Shi and colleagues [19] numerically investigated the enhanced heat transfer by a flexible plate swinging in the air flow through a channel with constant wall temperature at Re = 205–328. This obstacle could increase the heat transfer rate up to 90 percent with an acceptable pressure loss. They did not study the fluid properties, natural frequency or displacement frequency of plate. Soti and colleagues [20] analyzed the effect of an elastic plate in incompressible, laminar and Newtonian fluid through the channels. The results show that if the flexible plate is attached to a rigid cylinder, the average Nusselt number at a Reynolds number of 500 is almost twice that in a clean channel.

The influence of an oscillating plate in the turbulent flow on the heat transfer and pressure loss has not been studied yet. In this study, the flow–structure-thermal interaction of a cooling water flow passing over a flexible plate attached to a stationary cylinder inside a channel with constant wall temperature for the turbulent flow is numerically simulated. Then, the Nusselt number, pressure loss, PEC, frequency and amplitude of oscillation and lift coefficient is calculated. The frequency response is obtained by using Fast Fourier Transform (FFT). After that, the influence of material properties like Young's modulus and density of the plate, are studied. Finally, the effect of Reynolds number, Prandtl number and velocity and temperature profile are assessed.

2. Computational models

Fluid–solid interaction occurs when a fluid flow interacts with a solid structure. The flow exerts pressure and solid deforms due to forces. So, shear and pressure forces acting on the structure are determined by solving the Navier–Stokes and continuity equations. Since the Re number is 1000 (based on the diameter of the cylinder) and based on the Lienhard's work [21], vortexes are fully turbulent in the present study and turbulent flow is often unsteady and as such often contains time dependent forms, we will not ignore the unsteady terms. The equations in Cartesian flow are:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(u_i u_j) = \rho g_i - \frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

The fluid is assumed to be Newtonian and shear stress (τ_{ij}) is proportional to the time-rate-of-strain, i.e. velocity gradients:

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu\frac{\partial u_i}{\partial x_i}\delta_{ij} \tag{3}$$

$$\frac{\partial T}{\partial t} + u_i\frac{\partial T}{\partial x_i} = \alpha\frac{\partial^2 T}{\partial x_i \partial x_j} \tag{4}$$

Where "u" is the velocity and ρ, T, α are the density, temperature, and thermal diffusivity of the fluid, respectively.

Assuming that the density fluctuations are negligible, the equations for turbulent flow can be averaged. A modified set of transport equations by introducing average and fluctuating components can then be solved for turbulent simulations. Substituting the averaged quantities into the equations (for example the instantaneous velocity is replaced by average and fluctuating components) results in the Reynolds average equations given below [22]:

$$\partial \bar{u}_i / \partial x_i = 0 \tag{5}$$

$$\rho\left(\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j\frac{\partial \bar{u}_i}{\partial x_j}\right) = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\frac{\partial \bar{u}_i}{\partial x_j}\right) + \frac{\partial R_{ij}}{\partial x_j} \tag{6}$$

The averaging procedure introduces additional unknown terms containing products of the fluctuating quantities which act like additional stresses in the fluid. These terms, called 'turbulent' or 'Reynolds' stresses (Eq. (7)), must be determined as further unknowns. Therefore the eddy viscosity model assumes that the Reynolds stresses are related to the mean velocity gradients and turbulent viscosity by the gradient diffusion hypothesis is used:

$$R_{ij} = -\rho\overline{u_i' u_j'} \tag{7}$$

The RANS model is closed in K-w (based SST) model because of the Rahman's work [23] which is an Eddy Viscosity Model and by