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Forced convection heat transfer from a circular cylinder with a flexible fin

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ABSTRACT

Forced convection heat transfer from a circular cylinder with a flexible fin in laminar flow with $Re = 200$ and $Pr = 0.7$ is investigated numerically. The two-dimensional incompressible Navier-Stokes equations and energy equation are coupled with the Euler-Bernoulli beam equation to describe the flow-induced vibration (FIV) of the flexible fin considering the convection heat transfer process. The modified characteristic-based split scheme, Galerkin finite element method, semi-torsional spring analogy method and loosely coupled partitioned approach are employed irrespectively for the flow and convection heat transfer, fin vibration, mesh movement and fluid–structure interaction. The accuracy and stability of the proposed numerical method are validated using three benchmark models including the forced convection heat transfer from a stationary cylinder, forced convection heat transfer from a transversely oscillating cylinder and FIV of a flexible plate behind a square cylinder. Finally, forced convection heat transfer characteristics from a circular cylinder with a flexible fin with fin length $l = 0.5D$–$1.5D$ (D is the cylinder diameter) and elastic modulus $E = 10^4$ - 5×10^5 are analyzed in detail. The numerical results show that, when the vortex shedding frequency approaches the natural frequency of the flexible fin, the FIV frequency is locked on the natural frequency and the fin exhibits large-amplitude vibration. As a result, the 'dead water' region behind the cylinder is reduced and the convection heat transfer is improved. In the combinations of parameters considered, a maximum of 11.07% enhancement in heat transfer is obtained by the flexible fin.

1. Introduction

For the purpose of heating or cooling, heat exchangers are used widely in the oil, chemical, refrigeration, power and electronic industries. In most heat exchangers, the convective thermal resistance is much larger than the conductive thermal resistance. Hence, the convection heat transfer usually plays a decisive role in the overall heat transfer process. To make the heat exchangers more efficient and compact, the convection heat transfer enhancement is very important and has attracted many attentions in the past decades [1,2]. As is well-known, the convection heat transfer from a solid wall is strongly associated with the near-wall flow features. Generally speaking, the boundary layer and the "dead water" regions are two major sources of convection thermal resistance. To enhance convection heat transfer, one way is to introduce perturbations to improve the advection between the boundary layer or "dead water" regions and the main flow. Following this idea, various methods of convection heat transfer enhancement have been proposed. One of them is the surface vibration method [1].

As the name implies, the surface vibration method employs structure vibration to change the flow structure as well as heat transfer in the vicinity of the wall. Based on the driving way of the vibration, the surface vibration method can be divided into two types: forced vibration method and self-excited vibration method. For the forced vibration method, the heat transfer structure is driven mechanically or electrically by external energy input. This method was first proposed in 1923 and its effectiveness for forced convection heat transfers has been confirmed both experimentally and numerically. For example, Scanlan [3] investigated experimentally the effect of normal vibration on the forced convection heat transfer from a heating surface in water flows with $Re = 360$, 720, 1460 and 2170. At certain combination of vibrating amplitude, frequency and flow speed, up to 300% improvement in local heat transfer coefficient was obtained. Takahashi and Endoh [4] studied the forced convection heat transfer from a

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Nomenclature

a	thermal diffusivity
A	cross-section area of the plate/fin normalized by D^2
A_C	amplitude of the oscillating cylinder normalized by D
$C_{D,av}$	time-averaged drag coefficient of the cylinder
$C_{L,\max}$	maximum lift coefficient of the cylinder
Δt	real time step normalized by D/u_∞
$\Delta\tau$	pseudo time step normalized by D/u_∞
D	diameter of the circular cylinder
δ	displacement of a grid node in time interval$[t^n, t^{n+1}]$ normalized by D
δ'	displacement of a grid node in time interval$[t^{n-1}, t^{n+1}]$ normalized by D
Δp	pressure difference between the lower and upper surface of the flexible plate/fin normalized by $\rho_\infty u_\infty^2$
ξ	local coordinate on the plate/fin normalized by D
E	elastic modulus of the flexible plate/fin normalized by$\rho_\infty u_\infty^2$
f	domain frequency of the flow-induced vibration normalized by u_∞/D
f_C	frequency of the oscillating cylinder normalized by u_∞/D
f_{n1}	natural frequency for the first mode of the plate/fin normalized by u_∞/D
I	second moment of area of the fin's cross-section normalized by D^4
h	fin thickness normalized by D
l	length of the fin
l'	length of the fin normalized by D
L	edge length of the square cylinder
N_J	Hermite shape function at the node J of the plate/fin
NE	total number of grid elements in the flow domain
NM	total number of grid elements on the plate/fin
NP	total number of grid nodes in the flow domain
n_P	total number of grid nodes connected to grid node P
Nu	overall Nusselt number on the cylinder or cylinder with a fin
Nu_{av}	time-averaged overall Nusselt number on the cylinder or cylinder with a fin
$\overline{Nu}_{\text{av}}$	time-averaged mean Nusselt number on the cylinder
Nu_θ	instantaneous local Nusselt number on the cylinder
$Nu_{\theta,av}$	time-averaged local Nusselt number on the cylinder or cylinder with a fin
p	pressure normalized by $\rho_\infty u_\infty^2$
p_r	Prandlt number, $p_r = v/a$
Re	Reynolds number, $Re = u_\infty D/v$
ρ_∞	density of the incompressible flow
ρ_S	density of the flexible fin normalized byρ_∞
St	vortex shedding frequency from the cylinder normalized by u_∞/D
t	real time normalized by D/u_∞
τ	pseudo time normalized by D/u_∞
τ_{p}	oscillating period of the cylinder normalized by D/u_∞
τ_{Nu}	oscillating period of the overall Nusselt number on the smooth cylinder or cylinder with a fin
T	temperature
T_∞	temperature of the free stream
T_w	wall temperature of the circular cylinder and fin
Θ	non-dimensional temperature defined by $\Theta = (T - T_\infty)/(T_w - T_\infty)$
u_∞	velocity component of the free stream in x direction
u_i	velocity components of the flow field normalized by u_∞
u_i^*	intermediate velocity components of the flow field normalized by u_∞
v	fluid kinematic viscosity
w	displacement of the plate/fin normalized by D
x_i	coordinate components of the flow domain normalized by D
$y_{\max}$	Maximum vibrating amplitude at the free end of the plate/fin normalized by D

vibrating sphere, a cylinder and a square-section tube in water flows with Re = 3000–8000, 1000–2600 and 1500–4500, respectively. In their experiments, convection heat transfer coefficients from the sphere, cylinder and square-section tube were enhanced respectively by about 200%, 200% and 180% at very small energy dissipation ratio. Cheng et al. [5] investigated experimentally the forced convection heat transfer characteristics of a circular cylinder oscillating transversely in air flows with $Re \leq 4000$. A maximum of 34% increase in heat transfer was obtained within the parameter range considered. Using the transient test technique and smoke flow visualization method, they also found that the heat transfer enhancement is attributed to the lock-on effect and the turbulence effect. Cheng and Hong [6] carried out a numerical study on the influence of transversely oscillation on the forced convection heat transfer from a cylinder in laminar flows with $Re \leq 300$. The enhancement of the convection heat transfer was achieved only in the lock-on regime, and an approximate 13% enhancement was obtained at Re = 200. Bronfenbrener et al. [7] studied theoretically and experimentally the heat transfer from a tube with rings rotating on the external surface. For the model they proposed, about 40% enhancement in the heat transfer coefficient was achieved by the vibration. Gau et al. [8] investigated the forced convection heat transfer from an inline oscillating circular cylinder in air flows with Re = 1600–3200. In their experiments, nearly 40% enhancement in heat transfer was obtained although the oscillating amplitude was very small. They also found that the greatest enhancement in heat transfer can be achieved when the inline oscillating frequency is closer to twice the natural vortex shedding frequency. Yang and Fu [9] performed a numerical investigation on heat transfer from a heated oscillating rectangular cylinder in cross flows with Re = 250 and 500 using the arbitrary Lagrangian-Eulerian (ALE) method, and an augment up to 115% was obtained in heat transfer. Fu and Tong [10] investigated numerically the flow and thermal fields of laminar flows with Re = 100, 200 and 500 over a heated transversely oscillating cylinder in a channel. In the parameter range considered, a maximum of 28.7% increase in convection heat transfer was achieved. Açikalin et al. [11] studied experimentally and numerically the application of the piezoelectric fans in the cooling of low-power electronics. In their study, the periodical vibration of a plate was generated based on the reverse piezoelectric effect to improve the flow around a heat source, and an enhancement up to 375% was obtained in heat transfer. Ghazanfarian and Nobari [12,13] investigated numerically the convection heat transfer from a rotating cylinder with cross-flow and inline oscillations at $Re \leq 300$. Their numerical results also showed that the heat transfer coefficient of the circular cylinder can be increased significantly in the lock-on regime. Léal et al. [14] studied the effect of dynamic deformation of the wall on the convection heat transfer in a straight channel. In their numerical study, the heat transfer coefficient was enhanced by 450% when one wall of the channel was deformed in the form of a progressive sinusoidal wave.