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Heat transfer enhancement by flexible flags clamped vertically in a Poiseuille channel flow

Jae Bok Lee, Sung Goon Park, Boyoung Kim, Jaeha Ryu, Hyung Jin Sung *

Department of Mechanical Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea

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A B S T R A C T

A pair of flexible flags clamped vertically in a heated channel was numerically modeled to investigate the dynamics of the flexible flags and their effects on heat transfer enhancement. The penalty immersed boundary method was adopted to analyze the fluid–structure–thermal interaction between the surrounding fluid and the flexible flags. The flexible flags displayed three distinct movement modes: a flapping mode, a fully deflected mode, and an irregular mode that depended on the relationship between the hydrodynamic force and the restoring force. In the flapping mode, vortices shed from flexible flags merged and increased in magnitude. The merged vortical structures swept out the thermal boundary layer and enhanced thermal mixing between the fluid near the heated wall and the channel core flow. Compared to rigid flags, the flexible flags significantly improved the thermal efficiency. The effects of the bending rigidity, channel height, and Reynolds number on the thermal efficiency were observed, and an optimal parameter set was obtained. The presence of the flexible flags with the optimal parameter set resulted in an increase of up to 185% in the net heat flux and 106% in the thermal efficiency factor, compared to the baseline flow. The correlation between the vorticity and the temperature field was examined in detail using the dynamic mode decomposition (DMD) method.

1. Introduction

Much attention has been focused on heat transfer enhancement in the automotive, heating, electrical device, air-conditioning, and refrigeration engineering fields. Heat transfer enhancement has been achieved by enhancing surface roughness, in a variety of vortex generators, in fins, and in other systems. Heat transfer enhancement is considered to be an essential requirement because thermal damage due to internally generated heat may be avoided by introducing secondary devices into a heat sink system. The heat transfer on thermal systems is significantly enhanced, however, the pressure drop is crucial during the thermal development process. Improved heat transfer and the mechanical energy loss due to the pressure drop must be considered simultaneously in an assessment of the thermal efficiency. A trade-off between the pressure drop penalty and the thermal efficiency has been achieved in a variety of flexible structures.

Heat transfer has been enhanced by introducing into a channel flow a sequence of ribs that are small compared to the channel height. The heat transfer and friction characteristics of the rough wall have been analyzed extensively using semi-empirical formulations. Webb et al. [1] described the effects of the repeating-rib roughness on the friction and the heat transfer based on the law of the wall similarity and a heat–momentum transfer analogy, respectively. Han et al. [2] found that a rib's shape, spacing, and angle of attack can influence heat transfer and friction. The repeating-rib roughness provided better heat transfer at a given friction compared to a sand-grain roughness. Vortex generators in channel walls can provide a heat transfer benefit over the baseline flow by improving the synergy between the velocity and the temperature gradient [3]. Numerous numerical simulations have been conducted to optimize the parameter sets with respect to thermal efficiency [4–7]. Although thermal systems with rigid devices displayed substantially better heat transfer performances, the rigid devices also incurred significant mechanical energy losses due to pressure drops.

Researchers have attempted to minimize the pressure drop penalty and simplify thermal systems by designing flexible structures immersed in a channel flow. Vortex generation methods are classified into two categories: active and passive methods. An actuated oscillating reed was installed in a microchannel of an air-cooled heat sink system to obtain a remarkable heat transfer enhancement [8]. Mills et al. [9] simulated actuated synthetic cilia attached to a bottom channel wall and measured a significant improvement in the local heat transport. These active methods

* Corresponding author.

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Nomenclature

A	flapping amplitude
c_1, c_2	constants in the feedback law
c_p	heat capacity
E_{loss}	net energy loss
$\overline{E}_{loss}$	time-averaged value of the net energy loss
F	Lagrangian momentum force
f	Eulerian momentum force
f_A	flapping frequency
f_V	vortex shedding frequency
H	channel height
h	grid size
k	thermal conductivity coefficient
L	flag length
p	pressure
$\mathrm{Pr} = c_p\mu/k$	Prandtl number
Q_{net}	net heat flux
$\overline{Q}_{net}$	time-averaged value of the net heat flux
q_i	heat sources from immersed bodies
$\mathrm{Re} = \rho_0 UL/\mu$	Reynolds number
s_i	curvilinear coordinates
$\mathrm{St} = f_A A/U$	Strouhal number
T	fluid temperature
T_0	fluid temperature at inlet
T_s	flag temperature
t	time
U	bulk mean velocity at the inlet
u	fluid velocity
$U_{i,\ ib}$	velocity at the immersed boundary
X_i	flag position
$X_{i,\ ib}$	immersed boundary position
y_{tip}	y-position of the flag tip

Greek symbols

δ	delta function
Φ_j	dynamic modes
γ	bending rigidity
η	thermal efficiency factor
λ_j	dynamic mode eigenvalues
μ	dynamic fluid viscosity
ρ	density ratio
ρ_0	fluid density
ρ_1	flag density
σ_i	tension force
ω	dynamic mode frequency
Γ_i	temperature on the massive boundary
$\Gamma_{i,ib}$	temperature on the massless boundary

Subscripts

in	inlet
out	output plane
w	wall
0	channel without vortex generator/reference

require an external power source to oscillate the flexible structures. The passive method has been used more widely than the active method because the passive method does not require external power to induce the oscillating motions. Herrault et al. [10] experimentally designed a passively oscillating reed and obtained an increase in the heat transfer. Numerical simulations have been conducted to investigate these flow–structure–thermal interaction problems by using the immersed boundary method [11–19]. Shoele and Mittal [18] simulated the dynamics of a self-oscillating reed in a channel flow using the immersed boundary method, and they found that the heat sink system improved the thermal efficiency. The thermal efficiency factor is defined as the ratio of the performance (net heat flux and the pressure drop penalty) of a flexible reed in a channel flow to the corresponding performance in the absence of secondary devices. Park et al. [19] devised a heat sink system using an inverted flexible flag and numerically explored the dynamics of the inverted flag and the correlation between the vorticity and the temperature field. They found that the thermal efficiency factor increased to 20%; however, setting up the inverted flag required an additional device and considerable attention to clamping the edge of the flexible structure at the channel centerline. Attaching the flexible structures to the channel walls can resolve the shortcomings and broaden the applicability of these structures to heat sink systems.

The objective of the present study was to identify the key mechanisms in which vortices shed from flexible flags enhance the system's thermal efficiency. We simulated the dynamics of flexible flags clamped vertically in a channel flow using the penalty immersed boundary method. The flow dynamics and heat transfer enhancement by the flexible flags were examined as a function of the bending rigidity (γ), the channel height (H/L), and the Reynolds number (Re). For comparison, heat transfer enhancement by the rigid flags was simulated. Optimal conditions were obtained at higher thermal efficiencies over a range of bending rigidities ($0.008 \leqslant \gamma \leqslant 0.32$), channel heights ($2.5 \leqslant H/L \leqslant 4.0$), and Reynolds numbers ($200 \leqslant \mathrm{Re} \leqslant 700$). The correlation between the shedding vortices and the temperature field was analyzed by performing the dynamic mode decomposition (DMD). The effects of the dynamic modes on the heat transfer enhancement were examined.

2. Problem formulation

2.1. Problem description

A schematic diagram of the computational domain and the coordinate system is shown in Fig. 1. The length of the flexible flags is defined by L. The leading edges were clamped vertically at the top and bottom walls, and the trailing edges were free. The position of the clamped leading edge was $6L$ from the inlet ($x = -16L$). The initial positions of the trailing edges were $(-10L, L)$ and $(-10L, -L)$ for the upper and lower flexible flags. The channel height (H) and length were set as $4L$ and $32L$, respectively. Boundary conditions were applied to the inlet velocity based on the parabolic velocity profile $u_{in} = 1.5U(1 - 2y/H)(1 + 2y/H)$, and a constant temperature of $T = T_0 = 0$ was applied. No-slip conditions ($u = v = 0$) and a constant temperature ($T = T_w = 1$) were

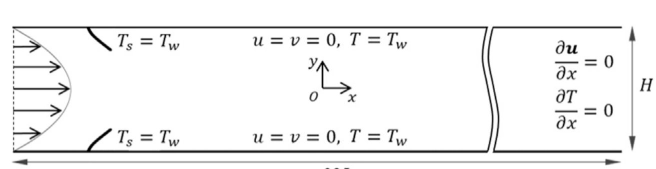

Fig. 1. Schematic diagram of the computational domain.