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Heat transfer enhancement by asymmetrically clamped flexible flags in a channel flow

Jae Bok Lee, Sung Goon Park, 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

Two flexible flags clamped in a heated channel were 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. A system comprising the thermally conductive flags in an asymmetric configuration (FAC) with respect to the channel centerline is described for the first time in the present study. The effect of the resulting vortices on heat transfer enhancement was investigated. The FAC generated a reverse Kármán vortex street that encouraged a greater degree of thermal mixing in the wake compared to the vortical structures generated by the flags in a symmetric configuration (FSC). The ratio of FAC occupying a cross-section to the channel height decreased, resulting in a decrease in the pressure drop compared to FSC. The FAC significantly improved the thermal efficiency compared to the FSC. The effects of the gap distance between FAC (G/L) and the ratio of the channel height to the flag length (H/L) on the thermal enhancement were characterized to identify the parameters that optimized the thermal efficiency. The relationship between the flapping dynamics and the heat transfer properties was examined in detail. The presence of the FAC with the optimal parameters increased convective heat transfer by 207% and the thermal efficiency factor by 135% compared to the baseline (open channel) flow. The thermal efficiency factor obtained in the present study was compared with that obtained in the previous studies.

1. Introduction

Efficient heat transfer is an essential function of electrical devices, heat sink systems, heat exchangers, and a variety of industrial applications. Researchers have enhanced heat transfer in pipe flow systems by introducing surface roughness and various types of vortex generators. In previous studies [1–3], rib-roughened surfaces were found to enhance convective heat transfer in pipe flows at a given friction compared to sand-grain roughened surfaces. An alternative method of enhancing heat transfer involves using vortex generators. Zhu et al. [4] investigated the effects of wing-type and winglet-type vortex generators on heat transfer enhancement in turbulent channel flows. They reported that longitudinal vortex generators, combined with roughness elements, could increase heat transfer by 450%. Biswas et al. [5] conducted experimental and numerical investigations to determine the flow structure generated by a winglet-type vortex generator. The generated vortices disrupted the growth of the thermal boundary layer and enhanced convective heat transfer at the channel walls. The transverse vortex generators induced swirling flows that significantly improved convective heat transfer in the internal flows. Rigid vortex-generating tabs, such as delta tabs, rectangular tabs, and trapezoidal tabs, were mounted on the inner walls of a pipe or a duct to enhance fluid mixing and enhance heat transfer [7–11]. The rigid vortex generators, however, blocked the streamwise flows, resulting in the significant pressure drop penalty, high manufacturing cost, and more complex thermal systems [4,6]. The augmentation of heat transfer and the pressure drop must be considered simultaneously in an assessment of the thermal efficiency.

Much attention has focused on the use of flexible structures in thermal systems to minimize the pressure drop and simplify the system. Fernandez and Poulter [12] enhanced convective heat transfer by inserting a rectangular sheet metal flag that was allowed to flap in a tubular turbulent flow. The flag significantly increased the heat transfer, and the pressure drop was not significant enough to detract from the heat transfer enhancement. An actuated flexible reed was installed into an air-cooled heat sink channel, leading to a remarkable improvement in the thermal performance [13]. A self-oscillating reed was used to increase the thermal performance in an air-cooled heat sink channel system [14,15]. The fluttering motion of the self-oscillating reed disrupted

* Corresponding author.
E-mail address: hjsung@kaist.ac.kr (H.J. Sung).

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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
$\bar{E}_{loss}$	time-averaged value of the net energy loss
F	Lagrangian momentum force
F_h	hydrodynamic force
F_r	restoring force
f	Eulerian momentum force
f_r	friction factor
f_f	flapping frequency
f_V	vortex shedding frequency
H	channel height
k	thermal conductivity coefficient
h_a	overall convective heat transfer coefficient
L	flag length
$Nu = h_aL/k$	Nusselt number
p	pressure
$Pr = c_p\ \mu/k$	Prandtl number
Q_{net}	net heat flux
q_i	heat sources from immersed bodies
$Re = \rho_0UL/\mu$	Reynolds number
s_i	curvilinear coordinates
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_d	length of the computational domain
X_i	flag position
$X_{i,ib}$	immersed boundary position
y_{tip}	y-position of the flag tip from the center of channel
y_w	y-position of the flag tip from the wall

Greek symbols

δ	delta function
γ	bending rigidity
η	thermal efficiency factor
μ	dynamic fluid viscosity
σ	tension force
ρ	density ratio
ρ_0	fluid density
ρ_1	flag density
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

the momentum and thermal boundary layers at the channel walls and enhanced fluid mixing between the thermal boundary layers and the channel core flow. Numerical simulations have been used to investigate the kinematics of flexible structures as they affect fluid mixing and heat transfer, while optimizing the parameters for a given flow condition [16–24]. Arbitrary Lagrangian Eulerian (ALE) and immersed boundary method (IBM) techniques have been widely used to simulate fluid–flexible structure–thermal interactions. Ali et al. [18,19] adopted an ALE method that required re-meshing procedures at each time step to simulate the kinematics of flexible flaps clamped at the channel walls and their effects on fluid mixing and heat transfer. The flexible flaps increased both the mixing between scalars and the thermal efficiency compared to the baseline flow. IBM has been preferentially used to simulate fluid–flexible structure–thermal interaction problems because it mitigates the difficulties associated with re-meshing at deforming or moving bodies immersed in a fluid domain [25–29]. Previous IBM studies [20–23] revealed that a self-oscillating reed clamped longitudinally at the channel centerline enhanced convective heat transfer; however, clamping the edge of the reed at the channel centerline required considerable attention and a need for additional devices that fixed the flexible reed [13,14]. To overcome these shortcomings, Lee et al. [24] proposed using a pair of flexible flags clamped transversally at the channel walls. They clamped the thermally conductive flags in a symmetric configuration (FSC) onto the channel walls to explore the effects of the clamped flags on heat transfer enhancement at various bending rigidities, channel heights, and Reynolds numbers. The presence of the clamped flags increased the net heat flux by 185% and the thermal efficiency by 106% compared to the baseline flow. The 6% increase in the thermal efficiency was insufficient, however, and the proposed thermal system will require additional improvements to the thermal efficiency. The FSC acted as an obstacle to the streamwise flow and generated significant mechanical energy loss by introducing a pressure drop that reduced the thermal efficiency.

In the present study, the system comprising the thermally conductive flags in an asymmetric configuration (FAC) with respect to the channel centerline was newly proposed in an effort to enhance the mean heat flux and alleviate the mechanical energy loss in the heat sink channel system. We adopted the penalty IBM and simulated the kinematics of flexible flags clamped asymmetrically with respect to the channel centerline. The effects of the vortical structures generated by the FSC and FAC on the heat transfer were analyzed. A parametric study was performed to obtain an optimal parameter set that maximized the thermal efficiency as a function of the channel height (H/L) and the gap distance between flexible flags (G/L). Based on the optimal parameter set proposed in the previous study [24], the bending rigidity (γ) and the Reynolds number (Re) were set to 0.04 and 600, respectively. The heat transfer as a function of the flapping dynamics was examined for various G/L and H/L values. The FAC defined over the optimal parameter set provided a higher thermal efficiency than the FSC and provided a superior thermal efficiency compared to other heat transfer enhancement techniques proposed in previous studies.

2. Problem formulation

2.1. Problem description

Fig. 1 presents a schematic diagram of the computational domain. The length of the flexible flags is L. The leading edges of the upper and lower flags were clamped vertically at the top and bottom walls, respectively. The gap distance between the leading edges is G. The trailing edges of the flexible flags were free. The clamped position of the upper flag was fixed at $6L$ from the inlet ($x = 0$). The clamped position of the lower flag was G/L upstream from that of the upper flag. The initial positions of the clamped leading edge were $(0, H/2L)$ and $(-G/L, -H/2L)$ for the upper and lower flexible flags, respectively. L_{out}/L indicates the distance