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Effects of plate angle on flow bifurcations and heat transfer characteristics in a channel with inclined plates

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ABSTRACT

Oscillatory flows and heat transfer characteristics in a channel with inclined plates have been numerically investigated. For the fully developed channel flow of $10 \leqslant \mathrm{Re} \leqslant 800$, the inclined plates as a vortex generator are installed at the upper wall. To examine the effects of inclined plates on flow bifurcation and attendant heat transfer rates, unsteady simulations are performed for various plate conditions. The resulting flows are classified into three vortical structures of recirculation bubble (RB), standing vortex (SV), and traveling vortices (TV) depending on the Reynolds number and geometrical conditions. The variation of flow pattern is closely related to the spectral characteristics of steady state, periodic state, and quasi-periodic state. Based on these flow patterns and unsteady features, the transition scenario is proposed with increasing the plate angle. The flow is evolved from the steady state to the periodic and quasi-periodic state, and the frequency-locking phenomenon is observed for specific Reynolds numbers at a certain range of plate angle. In addition, the heat transfer enhancement is discussed with flow patterns and unsteady characteristics. The Nusselt numbers continuously increases from the steady state of RB to the periodic state of SV, while their variations are discontinuous when the periodic state of SV is changed into the quasi-periodic state of TV. The flow analyses show that these discontinuities are related to the supercritical Hopf bifurcation and the additional appearances of fundamental frequency. Also, the frequency-locking state before the development of quasi-periodic state with multiple frequencies brings about a jump increase of heat transfer. The disturbed flows by the inclined plates exhibit the logarithmic variation and Nusselt number correlation similar to the transition flow.

1. Introduction

In the past few decades, considerable efforts have been made to obtain a better understanding of flow and heat transfer characteristics in a channel with various obstacles such as groove, rib, baffle, etc. Such obstacles mounted on channel walls play an important role in provoking the destabilized flow which is very effective for the mixing of hot and cold fluid. The flow destabilization may bring about earlier laminar-turbulent transition and it can enhance the rate of heat transfer between the fluid and the walls. So, considerable research takes place to understand the flow and heat transfer characteristics for obstructed channel flows. This kind of research may be extremely helpful for compact heat exchangers and microchannels, because conventional mixing methods are often not practical due to small length scales.

Among many methods of disturbance generation in a channel, the plate shape like rib or baffle is very effective for a destabilizing device. Although it is geometrically simple, the variation of geometrical parameters such as plate height, plate thickness, inclination angle, and plate pitch can induce various patterns of unsteady flows. The baffled or ribbed channel has been at the center of attention in heat transfer enhancement. However, most of research has been carried out for the channel flow having the plates or baffles perpendicular to flow direction [1–4]. Rowley and Patankar [1] investigated laminar flow and heat transfer for a circular tube with an array of circumferential internal fins. Cheng and Huang [2] studied laminar forced convection in a channel with transverse fin arrays. They pointed out that the correct arrangement of fins is important for the improvement of overall wall heat transfer and it is close related to the development of flow recirculation. On the basis of the importance of vortical flows, Fiebig [3] made an investigation of vortex direction's influence on the heat transfer under the condition of the same pressure loss. So, he found out that longitudinal vortices parallel to the primary flow direction

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Nomenclature

C_f	skin friction coefficient, $\tau_w/0.5\rho U_0^2$
d	plate length
D_h	hydraulic diameter of channel
f	friction factor, $\Delta P/0.5\rho U_0^2$
f_1, f_2	fundamental frequency
F_1	pressure drop to maintain a constant mass flow rate
H	channel height
h	local heat transfer coefficient
L	plate pitch
m, n	arbitrary integer
Nu	Nusselt number, $Nu = hH/\kappa$
Nu_{avg}	area-averaged Nusselt number, $Nu_{avg} = (1/L)\int_0^L Nudx$
P	pressure
ΔP	pressure difference
Pr	Prandtl number
Re	Reynolds number, $\rho U_0 D_h/\mu$
Re_{cr}	critical Reynolds number,
T	temperature
U_i	velocity components
U, V	x- and y-velocity
U_0	area averaged velocity
$u_{\tau 0}, u_{\tau N}$	friction velocity
$\overline{U}$	time-averaged streamwise velocity
x,y	coordinates

Greek symbols

α	plate angle
δ_{1j}	kronecker delta
κ	thermal conductivity
λ	growth rate of the vorticity history
μ	viscosity
ρ	density
σ	average vorticity, $\sigma = 1/A\int_A |\omega_z| dA$
τ_w	wall shear stress

are more effective for the heat transfer enhancement than transverse vortices perpendicular to the flow direction. Also, the influence of vortices on heat transfer for laminar channel flow with vortex generators was studied in a follow-up paper [4]. Self-sustained oscillations were obtained by transverse vortices at lower Reynolds number than by longitudinal vortices. So, he concluded that the heat transfer depending on the flow oscillations is higher for transverse vortices than for longitudinal vortices in a channel. In a grooved channel with oblique plates, also, Korichi et al. [5] proposed the influence of the self-sustained oscillatory flow on the thermal and flow characteristics. The heat transfer enhancement was obtained by the modified vortices using oblique plates in the grooved region. In a different way with increasing the surface area heating, a comprehensive review of the previous studies notes a matter of great importance to achieve the heat transfer augmentation by creating unsteady vortices in the flow.

In general, the unsteady variation of vortices can be easily obtained by increasing Reynolds number. Also, as the Reynolds number increases, the flow usually develops from steady state to chaotic state and finally becomes turbulent. This transition process has many routes depending on the geometrical condition, surface roughness, initial condition, etc., accordingly the understanding of primary mechanism is very challenging and still continuing. As discussed by Gollub and Benson [6], the transition processes need to be examined by the various sequences of instabilities leading to turbulence because of the diversity of spectral characteristics. From the researches of Sobey and Drazin [7] and Robert [8], a bifurcation theory is very useful to understand the transition from a steady state to an unsteady regime. Based on their works, fold and Hopf bifurcations can be observed in the unsteady fields of a channel flow. A transition of a stable flow with a state into a stable flow with two possible solutions is called a fold bifurcation and a Hopf bifurcation is the transition from a steady state to an unsteady flow. The Hopf bifurcation has two branches depending on the flow evolutions. One is the subcritical Hopf bifurcation which is migrated from a steady state to a nonlinear unsteady flow, and the other is the supercritical Hopf bifurcation which is a transition from a steady state to a stable limit cycle [8]. Guzman and Valle [9] tried to show the relation between the flow bifurcation and heat transfer characteristics in grooved channels. But they didn't draw a peculiar correlation and simply explained that the Nusselt number is higher for a quasi-periodic than for a periodic flow regime. However, Yang and Kang [10–12] gave a systematic presentation for the effect of the baffled interval and Reynolds number on the flow instability and heat transfer. It was found that flow instability is strongly related to the heat transfer enhancement and the vertical velocity fluctuation is main factor driving the thermal effectiveness. However various geometric parameters for a compact heat exchanger have not been fully considered.

A literature survey reveals that the investigations of transitional flow and unsteady vortices are mainly focused on the heat transfer regarding to the Reynolds number dependency. However, when keeping the Reynolds number of a channel flow, a variety of unsteady flows including flow bifurcations can be obtained by using various conditions of the inclined plate. In that case, the inclined plate can be regarded as a control device for realizing various flow structures like wavy flow, recirculation, and unsteady vortices. That is, the various patterns of unsteady flows are deduced from the geometrical change. In the present study, flow bifurcations and heat transfer characteristics in a channel with inclined plates are studied. To see the effects of diverse flows on the heat transfer for a laminar range of $10 \leqslant Re \leqslant 800$, the plate angle is selected as $\alpha = 10^\circ - 170^\circ$ under the various conditions of plate length and plate interval. As a result, the effects of the inclination angle on the critical Reynolds number for Hopf bifurcation are examined and the transition scenario of inclined plate is proposed for a flow disturber. In addition to this, spectral analysis is performed to analyze the various flow structures. Finally, the relation between the unsteady flows and heat transfer is closely investigated.

2. Numerical method and flow condition

2.1. Governing equation

For fully developed and time-dependent flows, the continuity, momentum and temperature equations of a incompressible Newtonian fluid are given by

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial \rho U_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_i U_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right] + F_1\delta_{1i} \quad (2)$$