International Communications in Heat and Mass Transfer 36 (2009) 921–924

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

An investigation of a mixed convection in a ⊔ shape channel moving with a reciprocating motion☆

Wu-Shung Fu *, Sin-Hong Lian, Yu-Chih Lai

Department of Mechanical Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu, 30056, Taiwan, ROC

ARTICLE INFO

Available online 1 July 2009

Keywords:
Mixed convection
Moving boundary
ALE
Reciprocating motion

ABSTRACT

This study focuses on utilizing numerical calculation to investigate the heat transfer mechanisms in a ⊔ shape reciprocating channel system comprised of a horizontal channel at the bottom and vertical channels on both left and right sides. The issue is considered one kind of moving boundary problems and the finite element and Arbitrary Lagrangian–Eulerian (ALE) kinematic methods can be applied to this study. Due to the high temperature at the bottom surface of the horizontal channel and the direction of inlet cooling fluids in the same direction of the gravity, the heat transfer mechanisms induced by the mixed convection flow become extremely complex. The results show that thermal layers near the heat surface are disturbed drastically and the effect of reciprocating motion upon the heat transfer mechanisms strongly depends on a relationship between Reynolds and Grashof numbers.

1. Introduction

Protecting a piston from heat damage could effectively enhance the thermal efficiency of the heat engine and economize the usage of energy [1]. Numerous studies were then to investigate similar objects. In order to simulate the heat transfer phenomena of pistons in a reciprocating motion more realistically, the heat dissipation phenomena in a ⊔ shape reciprocating channel assumed as the piston action have been studied numerically by the authors and the related studies were reviewed in detail in [2].

In the previous study [2] the forced convection mechanisms were investigated exclusively. However, the temperature of pistons is usually very high and the effect of natural convection on the heat transfer mechanisms of the reciprocating object needs to be considered also. Thus this study aims to investigate the numerical calculation of the mixed convection mechanisms in the ⊔ shape reciprocating channel. Effects of Reynolds and Grashof numbers on the heat transfer mechanisms are examined in detail.

Usually when the problem of mixed convection is investigated, the relationship between the directions of inlet cooling fluids and gravity, and the positions of heat region relative to the direction of gravity should be examined first. In this study the vertical channels on the left and right sides provide the cooling fluids to flow into and out of the ⊔ shape channel, respectively. A heat region is installed at the bottom of the horizontal channel in the ⊔ shape channel system. The inlet cooling fluids have the same direction as the gravity. Due to the position of heat region, the phenomena of opposite and aiding flows can be observed in the left and right channels, respectively. Additionally, because of the mutual counteractions caused by the buoyancy of upward direction and the impulse of cooling fluids in a horizontal direction, thermal layers attaching to the heat region of horizontal channel will be disturbed drastically. As a result, the local Nusselt numbers distributed on the heat surface vary with time in a periodical duration. These interesting and complicated phenomena have not been investigated yet.

2. Physical model

A physical model implemented in this study is shown in Fig. 1. The total channel width and length are w_0 and h_0, respectively, and the channel width is w. The horizontal channel means the region surrounded by $\overline{BO'FGP'C}$. The bottom surface $\overline{BC}$ is heat surface and at constant temperature $T_{H.}$ Besides, the temperature and velocity of inlet cooling fluids are T_0 and v_0, respectively. Other surfaces of the channel are insulated. The original length between $\overline{OP}$ and $\overline{MN}$ is w and the maximum elongation length is $2w$. A part of the channel circled by $\overline{M'BCN'G'GFF'}$ is called as a reciprocating channel. The adjustable length w is the moving distance of the reciprocating channel. Therefore, computational grids in this region are flexible. As the channel moves downward, $\overline{MN}$ is fixed and $\overline{OP}$ moves downward with a velocity of v_c, the original region is then elongated. Afterward the $\overline{OP}$ moves upward and returns to the original position. The mesh velocity of the computational grids inside the horizontal channel is equal to that of $\overline{OP}$. The right channel length h_l is long enough for satisfying the convergent conditions of the temperature and velocity at the outlet of the channel. The reciprocating velocity of the horizontal channel is v_c,

☆ Communicated by W.J. Minkowycz.

* Corresponding author.
E-mail addresses: wsfu@mail.nctu.edu.tw (W.-S. Fu), edenas.me94g@nctu.edu.tw (S.-H. Lian).

0735-1933/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.icheatmasstransfer.2009.06.006

Nomenclature

F_c	dimensionless reciprocating frequency of the piston
Gr	Grashof number
h_1	dimensional height of the inlet channel and outlet channel [m]
L_c	dimensionless reciprocating amplitude of the piston
Nu_X	local Nusselt number
$\overline{Nu}_X$	average Nusselt number on the heat surface
$\overline{Nu}_c$	time-average Nusselt number per cycle
p	dimensional pressure [N m^{-2}]
p_∞	reference pressure [N m^{-2}]
P	dimensionless pressure
Pr	Prandtl number
Re	Reynolds number
t	dimensional time [s]
T	dimensional temperature [K]
u, v	dimensional velocities of in x and y directions [m s^{-1}]
v_0	dimensional velocities of the inlet fluid [m s^{-1}]
U, V	dimensionless velocities of in X and Y directions
V_c	dimensionless reciprocating velocity of the piston
V_m	dimensionless maximum reciprocating velocity of the piston
$\hat{V}$	dimensionless mesh velocity in y-direction
x, y	dimensional Cartesian coordinates [m]
X, Y	dimensionless Cartesian coordinates

Greek symbols

α	thermal diffusivity [m^2 s^{-1}]
ν	kinematics viscosity [m^2 s^{-1}]
η_0	total length of the moving mesh region
η_1	length counted from the bottom of the moving mesh region
θ	dimensionless temperature
ρ	density [kg m^{-3}]
τ	dimensionless time

and can be expressed as the equation, $v_c = v_m \sin(2\pi f_c t)$, where v_m is the maximum reciprocating velocity of the piston and equals to $2\pi f_c l_c$. When the channel moves reciprocally, it will cause the motions of the cooling fluids to be time-dependent. The circumstance is regarded as a moving boundary problem and therefore the Arbitrary Lagrangian–Eulerian (ALE) method is properly applied to this study.

For facilitating the analysis, the following assumptions are made.

(1) The fluid is air and the flow field is two-dimensional, incompressible and laminar.
(2) Except the density of the fluid, other properties of the fluid are assumed to be constant, and Boussinesq assumption is adopted.
(3) Apply the no-slip condition to all boundaries. Thus the fluid velocity on the moving boundaries is equal to the moving velocity of the boundaries.

Based upon the characteristics scales of w, v_0, ρv_0^2, and T_0, the dimensionless variables are defined as follows:

$$X = \frac{x}{w},\quad Y = \frac{y}{w},\quad U = \frac{u}{v_0},\quad V = \frac{v}{v_0},\quad \hat{V} = \frac{\hat{v}}{v_0},\quad V_m = \frac{v_m}{v_0},\quad V_c = \frac{v_c}{v_0}$$
$$F_c = \frac{f_c w}{v_0},\quad P = \frac{p - p_\infty}{\rho v_0^2},\quad \tau = \frac{t v_0}{w},\quad \theta = \frac{T - T_0}{T_h - T_0},\quad Re = \frac{v_0 w}{\nu},\quad Pr = \frac{\nu}{\alpha}$$
$$Gr = \frac{g\beta(T_h - T_0)w^3}{\nu^2},\quad V_c = V_m \sin(2\pi F_c \tau) \tag{1}$$

and $\hat{v}$ is defined as the mesh velocity.

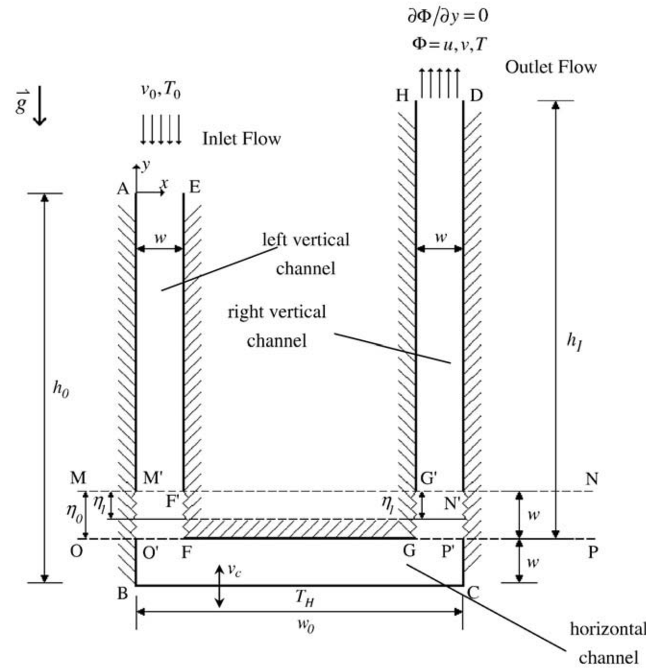

Fig. 1. Physical model of the ⊔ shape channel.

According to the above assumptions and dimensionless variables, the dimensionless ALE governing equations are expressed as the following equations:

Continuity equation

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{2}$$

Momentum equation

$$\frac{\partial U}{\partial \tau} + U\frac{\partial U}{\partial X} + \left(V - \hat{V}\right)\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{1}{Re}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \tag{3}$$

$$\frac{\partial V}{\partial \tau} + U\frac{\partial V}{\partial X} + \left(V - \hat{V}\right)\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{1}{Re}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + \frac{Gr}{Re^2}\theta \tag{4}$$

Energy equation

$$\frac{\partial \theta}{\partial \tau} + U\frac{\partial \theta}{\partial X} + \left(V - \hat{V}\right)\frac{\partial \theta}{\partial Y} = \frac{1}{Re\,Pr}\left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2}\right) \tag{5}$$

In this study, the cooling channel moves only in a vertical direction and therefore the horizontal mesh velocity is absent in the above governing equations. According to ALE method, the mesh velocity $\hat{V}$ is linearly distributed in the region between $\overline{MN}$ (fixed) and $\overline{OP}$ (movable). The mesh velocity $V_{\eta 1}$ at the position η_1 is proportional to the distance between $\overline{MN}$ and $\overline{OP}$, and is defined as the following equation,

$$V_{\eta_1} = \frac{\eta_1}{\eta_0} \cdot V_c \tag{6}$$

In the other regions, the mesh velocities are all set to be 0. The boundary conditions and solutions method used in this study are similar to those adopted in [2] except the term Gr/Re^2 taken into consideration in Eq. (4).