"Research Note"

SIMULATION OF LAMINAR MIXED CONVECTION RECESS FLOW COMBINED WITH RADIATION HEAT TRANSFER[*]

M. ATASHAFROOZ AND S. A. GANDJALIKHAN NASSAB[**]

Dept. of Mechanical Engineering, School of Engineering, Shahid Bahonar University, Kerman, I. R. of Iran
Email: ganj110@uk.ac.ir , ganjali2000@yahoo.com

Abstract– In the current work, two-dimensional simulations are presented for incompressible laminar mixed convection flow of a radiating gas over a recess including two backward and forward facing steps in a vertical duct. The continuity, momentum and energy equations for fluid flow are solved by the computational fluid dynamic (CFD) techniques. The fluid is treated as a gray, absorbing, emitting and scattering medium. For computation of the radiative term in the energy equation, the radiative transfer equation (RTE) is solved numerically by the discrete ordinates method (DOM). The effects of Grashof number, radiation-conduction parameter and optical thickness on heat transfer behavior of the system are studied.

1. INTRODUCTION

Laminar mixed convection flow over a backward or forward facing step in a channel is widely encountered in engineering applications systems, such as cooling of electronic systems, power generating equipment, combustion chamber and etc. In some of the mentioned devices, especially when soot particles exist in the combustion product, the radiation effect may be important. Therefore, to have more accurate and reliable results, the flowing fluid must be considered as a radiating medium and all of the heat transfer mechanisms including convection, conduction and radiation, must be taken into account. Although the geometry of BFS or FFS flow is very simple, the heat transfer and fluid flow over these types of step contain several complexities. There are many studies about laminar forced and mixed convection flows over BFS and FFS in ducts by several investigators [1- 2].

An experimental study of laminar mixed convection flow over a right angle BFS in a vertical duct was done by Abu-Mulaweh et al. [3]. Bahrami and Gandjalikhan Nassab [4] analyzed a convection flow over FFS in a duct to investigate the amount of entropy generation in this type of flow. A review of research on laminar mixed convection flow over backward and forward facing steps was done by Abu-Mulaweh [5]. In all of the mentioned studies, the effect of radiative heat transfer in fluid flow was neglected, such that the gas energy equation only contains the convection and conduction terms. In a mixed convection problem, when the flowing gas behaves as a participating medium, its complex absorption, emission and scattering introduce a considerable difficulty in the simulation of these flows.

A two-dimensional forced convection laminar flow of radiating gas over an inclined BFS in a duct was analyzed by Ansari and Gandjalikhan Nassab [6]. The study of mixed convection heat transfer in 3D horizontal and inclined ducts by considering gas radiation effects has been numerically examined in detail by Chiu and Yan [7]. Yan and Li [8-9] and Lari and Gandjalikhan Nassab [10] have similar studies on this subject with different flow geometries.

[**]Corresponding author

Although there are limited studies about laminar mixed convection flow of radiating gas over a BFS and FFS, based on the author's knowledge, laminar mixed convection flow of a radiating gas over a recess is still not studied theoretically or experimentally. Since this flow geometry has many engineering applications, the present research work deals with the 2-D analysis of an incompressible laminar mixed convection flow of a radiating gas over a recess in a vertical duct to investigate the thermal behavior of such systems.

2. THEORETICAL ANALYSIS

A schematic of the computational domain is shown in Fig. 1. The upstream and downstream heights of the duct are h_1 and h_2, respectively. The height of the duct inside the recess region is H, so this geometry provides the step height of s, with expansion (ER=H/h_1) and contraction (CR=h_2/H) ratios of 2 and 0.5, respectively. The upstream length of the duct is considered to be L_1=2H and the rest of the channel length is equal to L_2=28H. The length of recess depicted by D is considered to be 20H in different test cases.

For incompressible, steady and two-dimensional laminar mixed convection flow, the governing equations are the conservations of mass, momentum and energy that can be written as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - \rho g \tag{2}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

$$\frac{\partial}{\partial x}(\rho u c_p T) + \frac{\partial}{\partial y}(\rho v c_p T) = \kappa\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) - \nabla.\vec{q}_r \tag{4}$$

In the energy equation, besides the convective and conductive terms, the radiative term as the divergence of the radiative heat flux, i.e. $\nabla.\vec{q}_r$ is also presented. This radiative term can be computed as follows [11]:

$$\nabla.\vec{q}_r = \sigma_a\left(4\pi I_b(\vec{r}) - \int_{4\pi} I(\vec{r},\vec{s})d\Omega\right) \tag{5}$$

For calculation of $\nabla.\vec{q}_r$, the radiation intensity field ($I(\vec{r},\vec{s})$) is primarily needed. To obtain this term, it is necessary to solve the RTE. This equation for an absorbing, emitting and scattering gray medium can be expressed as [11]:

$$(\vec{s}.\nabla)I(\vec{r},\vec{s}) = -\beta I(\vec{r},\vec{s}) + \sigma_a I_b(\vec{r}) + \frac{\sigma_s}{4\pi}\int_{4\pi} I(\vec{r},\vec{s})\phi(\vec{s},\vec{s}')d\Omega' \tag{6}$$

In the above equation σ_a, σ_s and $\beta = \sigma_a + \sigma_s$ are the absorption, scattering and extinction coefficients, respectively. RTE is an integro-differential equation that can be solved with the discrete ordinates method. The details of numerical solution of RTE by DOM were described in the previous work by the second author [12].

The boundary conditions are treated as no slip condition at the solid walls with constant wall emissivity, $\varepsilon_w = 0.8$ and constant temperature of T_h at the bottom wall including step surfaces and constant temperature T_c at the top wall, such that $T_c < T_h$. At the inlet duct section, the flow is fully developed with uniform temperature of $T_{in} = T_c$. At the outlet section, according to fully develop

condition, zero axial gradients for velocity components and gas temperature are employed. In addition, the inlet and outlet sections are considered for radiative transfer as black walls at the fluid temperatures in these sections, respectively.

The main physical quantities of interest in the heat transfer study are convective, radiative and total Nusselt numbers. These parameters are given as follows [6]:

$$Nu_t = Nu_c + Nu_r = \frac{-1}{\Theta_w - \Theta_b} \frac{\partial \Theta}{\partial Y}\bigg|_{Y=0} + \frac{RC.\theta_1.\theta_2}{\Theta_w - \Theta_b} q_r^* \qquad (7)$$

Where Θ_b is the fluid bulk temperature and $\Theta = \dfrac{T - T_{in}}{T_h - T_{in}}, \theta_1 = \dfrac{T_{in}}{T_h - T_{in}}, \theta_2 = \dfrac{T_h}{T_{in}}, RC = \dfrac{\sigma T_h^3 H}{k}$.
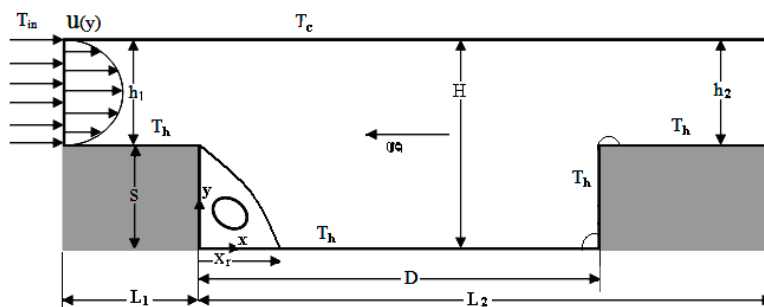

Fig. 1. Schematic of computational domain

3. RESULTS

In this work, mixed convection flow of a radiating gas over a recess is analyzed numerically. Validations of the applied mathematical model and numerical method were done in the previous works by the authors [6-10-13].

First, in order to show the effect of Grashof number on mixed convective flow combined with radiating heat transfer, the variations of convective, radiative and total Nusselt numbers along the recess on the bottom wall at different values of the Grashof number are presented in Figs. 2(a), (b) and (c), respectively. These figures show that the convective, radiative and total Nusselt numbers increase by increasing the Grashof number. This increase in the Nusselt number is attributed in part to the increase in the fluid bulk temperature and the bottom wall's outgoing radiative heat flux.

Radiation-conduction parameter (RC) is one of the main parameters in the combined radiation-conduction systems, which shows the relative importance of the radiation mechanism compared with its conduction counterpart. Figure 3 illustrates that the total Nusselt number increases by increasing the RC parameter. This is due to the fact that under the effective presence of radiation mechanism at high values of RC, the amount of the bottom wall's outgoing radiative heat flux increases, causing an increase in the value of total Nusselt number.

Optical thickness ($\tau = \beta.H$) is another important parameter in a participating medium that affects the temperature distribution. High values for τ means that the medium has great ability to absorb and emit radiant energy. Distributions of total Nusselt number on the bottom wall at different values of the optical thickness are plotted in Fig. 4. It is seen that as the medium's ability to absorb and emit thermal radiation becomes greater at high values of the optical thickness, such systems have high values for the total Nusselt number.

(a) Convective Nusselt number

(b) Radiative Nusselt number
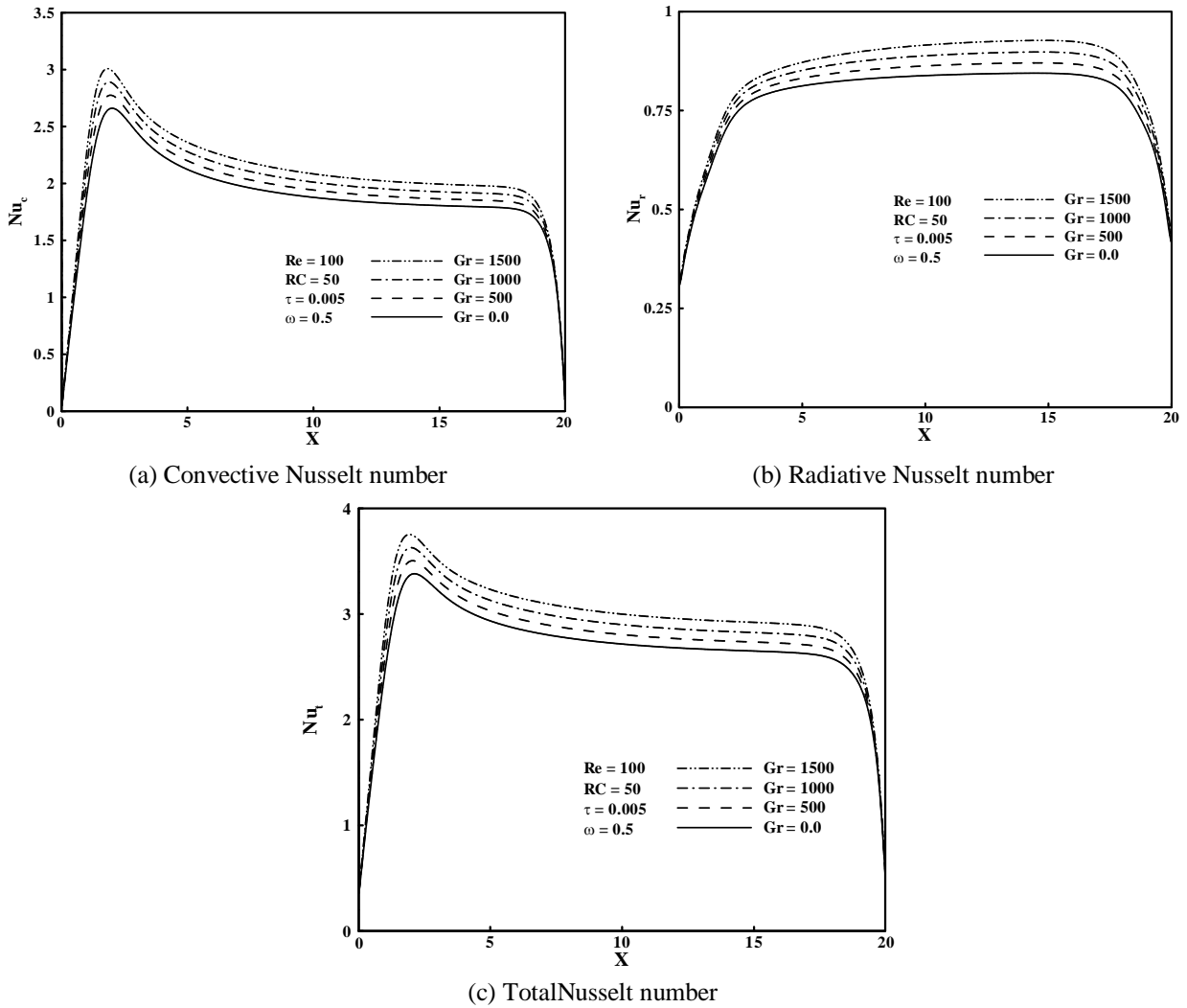

(c) TotalNusselt number

Fig. 2. Effect of Grashof number on the Nusselt number distributions along the bottom wall
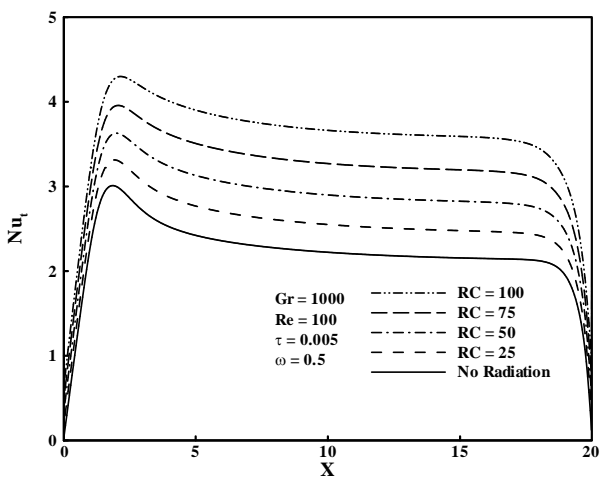

Fig. 3. Effect of RC on the total Nusselt number distribution along the bottom wall
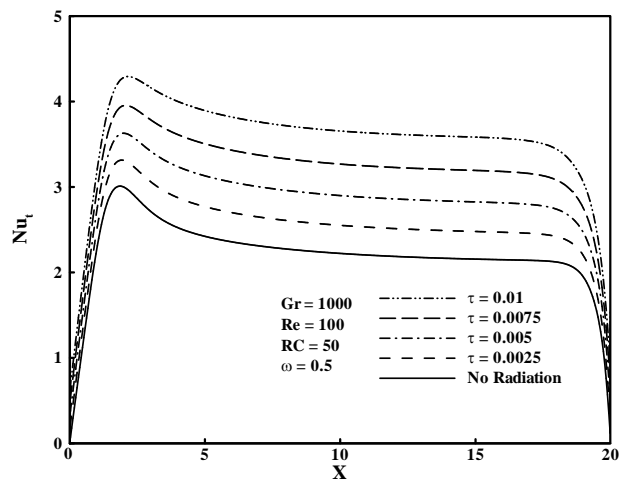

Fig. 4. Effect of optical thickness on the total Nusselt number distribution along the bottom wall

4. CONCLUSION

The interaction between thermal radiation and mixed convection in a 2-D laminar radiating gas flow over a recess including two backward and forward facing steps has been studied in this research work. The set of governing equations for fluid flow is solved numerically by the CFD techniques, while the radiative heat flux distribution inside the participating media is obtained by DOM. The effects of Grashof number, radiation-conduction parameter and optical thickness on thermal behavior of the convection-radiation system are thoroughly explored. It was revealed that increases in the values of these important parameters led to an increase in the total Nusselt number along the heated duct's wall.

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