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Numerical analysis of laminar forced convection recess flow with two inclined steps considering gas radiation effect

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ABSTRACT

In this work, a numerical analysis of combined convection–radiation heat transfer over a recess including two inclined backward and forward facing steps in a horizontal duct is presented. The fluid is treated as a gray, absorbing, emitting and scattering medium. Discretized forms of the continuity, momentum and energy equations are obtained by the finite volume method and solved using the SIMPLE algorithm, while the blocked off method is employed in simulation of the inclined surfaces. The radiative transfer equation (RTE) is solved numerically by the discrete ordinates method (DOM). Numerical results reveal that the radiation–conduction parameter, optical thickness, step inclination angle and recess length have considerable effects on heat transfer behavior of the recess flow. Comparison of numerical results with the available data published in open literature shows a good consistency.

1. Introduction

Forced convection flow over a backward or forward facing step in a channel is widely encountered in engineering applications. In these types of convection flow, separating and reattaching regions exist because of the sudden changes in flow geometry. Separation flows accompanied with heat transfer are frequently encountered in many systems, such as cooling of electronic systems, power generating equipments, gas turbine blades, heat exchangers, combustion chamber and ducts flows used in industrial applications. In some of the mentioned devices, specially, when soot particles exist in the combustion product, the radiation effect may be important. Besides, the trend toward increasing temperature in modern technological systems has promoted concerted effort to develop more comprehensive and accurate theoretical methods to treat radiation. Therefore, for having more accurate and reliable results in the analysis of these types of flow, 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. The flow over backward facing step (BFS) or forward facing step (FFS) has the most features of separated flows. Although the geometry of BFS or FFS flow is very simple, the heat transfer and fluid flow over these types of step contain most of complexities. Consequently, it has been used in the benchmark investigations. There are many studies about laminar convection flow over BFS in a duct by several investigators [1–4].

Kondoh et al. [5] studied laminar heat transfer in a separating and reattaching flow, numerically, by simulating the flow and heat transfer downstream of a backward-facing step. The effects of channel expansion ratio, Reynolds number and Prandtl number on heat transfer behavior were investigated. Erturk [6] investigated the characteristics of flow over a two dimensional BFS in a wide range of Reynolds numbers. The two-dimensional Navier–Stokes equations for incompressible steady flows were solved with a very efficient finite difference numerical method which proved to be highly stable even at very high Reynolds numbers. Abu-Nada [7–9] analyzed the convection flow over a backward facing step in a duct to investigate the amount of entropy generation in this type of flow. In those works, the set of governing equations were solved by the finite volume method and the distributions of entropy generation number, friction coefficient and Nusselt number on the duct walls were calculated. Moreover, the effect of suction and blowing on the entropy generation number and Bejan number were presented.

Although there are many research studies about BFS geometries, but the fluid flow with heat transfer over FFS received less attention. In a recent study, Bahrami and Gandjalikhan Nassab [10] analyzed the 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 convection flow over backward and forward facing steps was done by Abu-Mulaweh [11]. In that study, a comprehensive review of such flows, those have been reported in several studies in the open literature was presented. The purpose was to give a detailed summery of the effect of several parameters such as step height, Reynolds number, Prandtl number and the

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Nomenclature

A_x, A_y	areas of control volume's faces normal to the *x*- and *y*-directions, respectively (m^2)
C_p	specific heat ($J\ kg^{-1}\ K^{-1}$)
CR	contraction ratio
D_h	hydraulic diameter (m)
ER	expansion ratio
I	radiation intensity ($W\ m^{-2}$)
I^*	dimensionless radiation intensity
Nu_t	total Nusselt number
Nu_r	radiative Nusselt number
Nu_c	convective Nusselt number
q_t	total heat flux ($W\ m^{-2}$)
q_r	radiative heat flux ($W\ m^{-2}$)
q_c	convective heat flux ($W\ m^{-2}$)
Pe	Peclet number
Pr	Prandtl number
Re	Reynolds number
RC	radiation–conduction parameter
S	radiation source function
S^*	dimensionless radiation source function
T	temperature (K)
U_o	average velocity of the incoming flow at the inlet section (m/s)
x, *y*	horizontal and vertical distance, respectively (m)
X, *Y*	dimensionless horizontal and vertical coordinate, respectively
x_r	reattachment length (m)

Greek symbols

α	thermal diffusivity ($m^2\ s^{-1}$)
σ	Stefan Boatsman's constant = 5.67×10^{-8}, ($W\ m^{-2}\ K^{-4}$)
σ_a	absorbing coefficient (m^{-1})
σ_s	scattering coefficient (m^{-1})
ε	wall emissivity
ϕ	step inclination angle
κ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
μ	dynamic viscosity ($N\ s/m^2$)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
τ	optical thickness
Θ	dimensionless temperature
Θ_b	mean bulk temperature
θ_1, θ_2	dimensionless temperature parameters

Subscripts

c	convective
in	inlet section
r	radiative
t	total
w	wall

buoyancy force on the flow and temperature distributions downstream of the step. Also at different points of view, this geometry (FFS) was studied by several researchers [12,13].

There are many engineering applications, in which the forward or backward-facing step is inclined. Simulations of three-dimensional laminar forced convection adjacent to inclined backward-facing step in rectangular duct were presented by Chen et al. [14] to examine the effects of step inclination on flow and heat transfer distributions. Velocity, temperature, Nusselt number and friction coefficient distributions were presented in that study. The effects of step inclination angle on Nusselt number and friction coefficient distributions were showed by plotting many figures. In a recent study, Gandjalikhan Nassab et al. [15] studied the turbulent forced convection flow adjacent to inclined forward facing step in a duct. In that study, the Navier–Stokes and energy equations were solved in the computational domain by CFD method using conformal mapping technique and the effects of step inclination angle on flow and temperature distributions were determined.

In all of the mentioned studies, the effect of radiative heat transfer in fluid flow was not studied, such that the gas energy equation only contains the convection and conduction terms. In a forced 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. There are limited numbers of literatures about the radiative transfer problems in convection flows with complex 2-D and 3-D geometries.

Bouali and Mezrhab [16] studied heat transfer by laminar forced convection with considering surface radiation in a divided vertical channel with isotherm side walls. They found that the surface radiation has important effect on the Nusselt number in convective flow with high Reynolds numbers. Azad and Modest [17] investigated the problem of combined radiation and turbulent forced convection in absorbing, emitting and linearly anisotropic scattering gas particulate flow through a circular tube.

Two-dimensional forced convection laminar flow of radiating gas over a BFS in a duct was analyzed by Ansari and Gandjalikhan Nassab [18]. Effects of wall emissivity, Reynolds number and its interaction with the conduction–radiation parameter on heat transfer behavior of the system were investigated. Also, the same authors [19,20] studied the laminar forced convection flow of a radiating gas adjacent to two inclined backward and forward facing steps in a duct. The two-dimensional Cartesian coordinate system was used to simulate the inclined surfaces by considering the Blocked-off region in regular grid. The fluid was treated as a gray, absorbing, emitting and scattering medium. The effect of radiative properties on heat transfer behavior of fluid flow was investigated.

The study of mixed convection heat transfer in 3-D horizontal and inclined ducts with considering gas radiation effects has been numerically examined in detail by Chiu et al. [21,22]. Those works were primarily focused on the interaction of the thermal radiation with mixed convection for a gray fluid in rectangular ducts. The vorticity–velocity method was employed to solve the three-dimensional Navier–Stokes equations while the integro-differential radiative transfer equation was solved by the discrete ordinates method. Results revealed that radiation effects have a considerable impact on the heat transfer and would reduce the thermal buoyancy effects. Besides, it was revealed that the development of temperature was accelerated by the radiation effects.

Although there are limited studies about laminar forced convection flow of radiating gas over a BFS and FFS, but base on the author's knowledge, combined convection and radiation heat transfer over two inclined backward and forward facing steps, which provides a recess, is still not studied theoretically or experimentally. Since, this flow geometry has many engineering applications, therefore, the present research work deals the 2-D analysis of an incompressible laminar forced convection flow of a radiating gas over a recess in a horizontal duct, while the well known block-off method and DOM are employed to solve the fluid mechanic and radiation problems.