Applied Mathematics and Computation 299 (2017) 153–164

Contents lists available at ScienceDirect

Applied Mathematics and Computation

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

Radiation effect on the turbulent compressible boundary layer flow with adverse pressure gradient

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ARTICLE INFO

Keywords:
Compressible boundary layer
Turbulent flow
Thermal radiation
Localized suction
Adverse pressure gradient

ABSTRACT

The effects of thermal radiation and localized suction on the steady turbulent compressible boundary layer flow with adverse pressure gradient are numerically studied. The compressible flow is subjected to a constant localized suction velocity and the fluid is considered as a radiative optically thin gray fluid. The plate is adiabatic and the flow is subjected to adverse pressure gradient.

The Reynolds Averaged Boundary Layer (RABL) equations with appropriate boundary conditions are transformed using the compressible Falkner Skan transformation. The resulting nonlinear, coupled system of partial differential equations (PDEs) is solved using the Keller box method. For the eddy kinematic viscosity, the turbulent models of Cebeci Smith and Baldwin Lomax are employed. For the turbulent Prandtl number, the extended Kays Crawford model is used. The obtained results are validated with previously published computational results and with experimentally based correlations, showing a good agreement.

The results show that the flow is influenced by the combined effect of radiation and localized suction. The coupled effect moves the separation point downstream, towards the plate's end, and increases total drag. Radiation alters the thermal boundary layer above the plate by cooling the fluid at plate's vicinity and by slightly increasing the boundary layer maximum temperature.

1. Introduction

Thermal radiation has significant effects on the flow field, especially at high temperatures. These effects have important applications in many areas of engineering and there has been substantial research on the effects of radiation on fluid flow. Free convective laminar flow in the presence of radiation has been studied by Ali et al. [1], Raptis and Toki [2] and Raptis and Perdikis [3]. Thermal radiation of an optically thin gray fluid has been studied in several incompressible flow configurations [4,5]. Others have studied radiation effects on flow past a stretching plate with temperature dependent viscosity [6]. The interaction of thermal radiation on a vertical oscillating plate and the effect of radiation on a moving vertical plate have been studied by Muthucumaraswamy [7] and Muthucumaraswamy and Chandrakala [8].

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http://dx.doi.org/10.1016/j.amc.2016.11.024
0096-3003/

Nomenclature

$\bar{u},\ \bar{v},\ u',\ v'$	mean values and fluctuating parts of the dimensional velocity components
$\bar{p}, p'$	mean value and fluctuating part of pressure
$\bar{T},\ T'$	mean value and fluctuating part of temperature
x, y	dimensional Cartesian coordinates
L	length of the plate
k	thermal conductivity
c_p	specific heat under constant pressure
$H = c_pT + u^2/2$	total enthalpy
e	subscript refers to the condition at the boundary layer edge
u_e, H_e, T_e	velocity component, enthalpy and temperature at the boundary layer edge
w	subscript refers to the condition at the wall
v_w, H_w, T_w	mass transfer velocity component, enthalpy and temperature on the wall
$\mathrm{Pr} = \frac{\mu c_p}{k}$, Pr_t	Prandtl number, turbulent Prandtl number
Pe_t	turbulent Péclet number
$f(x, \eta)$	dimensionless stream function
$S = H/H_e$	dimensionless total energy ratio
$S_w,\ S'_w$	dimensionless total energy ratio and heat transfer parameter on the plate (wall)
$R_x = \frac{u_e(x)x}{v_e(x)}$	local Reynolds number
$m_1,\ m_2$	pressure gradient parameters
$R = \frac{16\alpha^*\sigma T_e^3 x}{\rho u_e c_p}$	Radiation parameter
$c = \frac{\rho_e}{\rho}$	density ratio
$C = \frac{\rho\mu}{\rho_e\mu_e}$	density and viscosity ratio
M	Mach number
C_{f_x}	skin friction coefficient
D	total drag of the plate per unit length
f''_w	dimensionless wall shear parameter

Greek symbols

α^*	absorption coefficient
$\bar{\rho},\ \rho'$	mean value and fluctuating part of density
$\mu,\ \nu$	dynamic and kinematic viscosities
σ	Stefan–Boltzman constant
δ	distance sufficiently away from the wall
$\varepsilon_m,\ \varepsilon_m^+$	eddy kinematic viscosity, eddy kinem. viscosity over kinem. viscosity
$\psi(x, y)$	dimensional stream function
$\eta(x, y)$	dimensionless y-coordinate

However, the study of compressible and turbulent boundary layer flow under the influence of thermal radiation has received little attention. This is an interesting area that needs to be further explored. Anghaie and Chen, present a computational model for convective and radiative heat transfer in high temperature gas cooled and gaseous fuel nuclear reactors. Their model considers the turbulent and compressible flow under the effect of radiation in a very large range of temperatures [9]. Their results are compared with experimentally based correlations, showing a good agreement. Duan et al. have studied the emission turbulence–radiation interaction in hypersonic boundary layer flows [10,11]. In this study, when emission is coupled to the flow, the temperature is drastically decreased in the turbulent layer. Miroshnichenko et al. have performed a detailed and comprehensive numerical analysis of complex heat transfer (turbulent natural convection, conduction and surface thermal radiation) in a rectangular enclosure [12,13]. They applied an iterative implicit finite-difference scheme for the solution of the governing equations using the dimensionless stream function, vorticity and temperature variables. The effects of Rayleigh number, thermal conductivity ratio, as well as internal surface emissivity on the fluid flow and heat transfer have been extensively studied [13]. In their analysis they concluded that the effect of thermal radiation leads to heat transfer enhancement. An essential cooling of the internal volume was found with an increase in the thermal conductivity ratio [13]. Kim and Baek, in their study for the compressible turbulent flow over a backward facing step, show that thermal behavior is influenced by radiation and the fluid is heated faster. Furthermore, the reattachment length of the recirculation area at the backward step is shrunk due to reduced adverse pressure gradient. Overall, the radiative heat flux was found to play a role in the recirculating zone [14].

Prevention of flow separation is a challenging task, applicable to several aerospace engineering problems. Many passive and active techniques have been developed for the prevention of flow separation [15]. In the last decades considerable research exists on the use of riblets for viscous drag reduction [16,17]. Rathnasigham and Breuer experimentally studied