International Journal of Thermal Sciences 79 (2014) 90–102

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Numerical study of turbulent flow in heated circular tube using transitional shear stress transport turbulence model

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ARTICLE INFO

Article history:
Received 5 June 2013
Received in revised form
11 January 2014
Accepted 14 January 2014
Available online 14 February 2014

Keywords:
Low Reynolds number
Turbulent forced convection
Variable properties
High heating rates
Laminarization
Transitional SST turbulence model

ABSTRACT

Low Reynolds number turbulent air flow moving upward in a vertical circular tube subjected to high heating rates was simulated using the transitional shear stress transport (SST) model for an inlet Reynolds number range of $4000 \leq Re_{in} \leq 10{,}000$ and a non-dimensional heating rate range of $0.001 \leq q_w^+ \leq 0.005$. The transitional SST model was validated by comparing pressure drop, Stanton number, and local velocity and temperature profiles with available experimental data and DNS results. The good agreement obtained between the transitional SST turbulence model predictions and the experimental data and DNS results shows that the transitional SST turbulence model is able to predict laminarization accurately. Parametric calculations using the validated transitional SST model were performed to obtain Nusselt number and pressure drop correlations. In addition, a laminarization criterion that is based on the attenuation of Reynolds shear stress due to flow laminarization is proposed. The laminarization criterion predicts a reduction in the Nusselt number as compared to the constant property results, ranging from as much as 62% reduction for $Re_{in} = 4000$–23% reduction for $Re_{in} = 10{,}000$.

1. Introduction

Gas coolants are used in heat exchanger applications for fission and fusion nuclear reactors as they provide safety, chemical inertness, and high thermal efficiency benefits. For such applications, to provide higher outlet temperature the gas coolant flow rate is kept low. As a result, the flow regime for such applications involves low Reynolds number turbulent flow which is subjected to high heating rates leading to significant variations in thermo-physical properties. For example, the Reynolds number at the exit of the High Temperature Engineering Test Reactor (HTTR) cooling channel in Japan is around 3500 [1]. For low Reynolds number turbulent flow subjected to high heating rates, the flow field may change to a laminar-like state due to wall variables approaching laminar values at local Reynolds number representing turbulent flow [2]. This transition from turbulent to a laminar-like flow regime is referred to as laminarization [3,4]. Laminarization leads to degradation of heat transfer due to thickening of the thermal boundary layer and may result in a heat transfer rate as low as 40% of those in the corresponding turbulent forced convection case [5]. Thus, an understanding of flow and thermal behavior for laminarized flow is required to predict the thermo-hydraulic performance for design, optimization, and operation of such heat exchangers.

Laminarization of flow caused by heating is due to acceleration, buoyancy, and/or thermo-physical property variation effects. As the gas is heated, the reduction in density causes the bulk flow to accelerate which reduces the turbulent bursting rate near the wall. The reduced turbulent bursting reduces the momentum exchange leading to a reduction in heat transfer. Similarly, the variation in fluid density caused by heating leads to buoyancy effect that reduces the generation of turbulence within the boundary layer causing a reduction in heat transfer. On further heating of the fluid, the buoyancy effects starts dominating and the heat transfer levels are enhanced due to increased mixing caused by the buoyancy driven currents.

Based on similarity with external boundary layer flow, previous investigators [6–10] have used an acceleration parameter, defined as $k_v = (v_b/w_b^2)/(dw_b/dz) = 4q_w^+/Re_{in}$, for constant wall heat flux cases to characterize the laminarization caused by acceleration and to develop one or more criterion for predicting laminarization. The flow was found to laminarize with deterioration in heat transfer observed for $k_v > 2.5 \times 10^{-6}$ [9,10]. The effect of buoyancy on laminarization of flow has been studied extensively [5,11–13]. A buoyancy parameter defined as $Bo = Gr/(Re^{3.425}Pr^{0.8})$ has been proposed [11] to assess the impact of buoyancy on heat transfer. Deterioration in heat transfer due to buoyancy effects was found to occur for $Bo > 6 \times 10^{-7}$ [9,10].

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http://dx.doi.org/10.1016/j.ijthermalsci.2014.01.011

Nomenclature

A_c	tube cross-sectional area
Bo	buoyancy number [$=\mathrm{Gr}/(\mathrm{Re}^{3.425}\mathrm{Pr}^{0.8})$]
c_p	specific heat at constant pressure
D	tube diameter
F_1, F_2	blending functions in transition SST model
g	gravitational acceleration ($=9.81$ m/s^2)
G	mass flux [$=\dot{m}/A_c$]
Gr	Grashof number based on heat flux [$=gD^4q_w/(\upsilon_b^2\lambda_bT_b)$]
h	heat transfer coefficient [$=q_w/(T_w-T_b)$]
k	turbulence kinetic energy [$=1.5\langle u_i'u_i'\rangle$]
k_v	local acceleration parameter [$=(\nu_b^2/w_b^2)\mathrm{d}w_b/\mathrm{d}z$]
$\dot{m}$	mass flow rate
Nu	Nusselt number [$=hD/\lambda$]
p	pressure field
P_k, P_γ, $P_{\theta t}$	production term in transport equation for turbulence kinetic energy, intermittency, and transition momentum thickness Reynolds number, respectively.
P^+	non-dimensional pressure drop [$=\rho_{\mathrm{in}}(p_{\mathrm{in}}-p)/G^2$]
q_w	heat flux at wall
q_w^+	non-dimensional heat flux [$=q_w/(Gc_{p,\mathrm{in}}T_{\mathrm{in}})$]
r, z	spatial coordinates in radial and axial direction, respectively
R	tube radius
Re	Reynolds number [$=\rho wD/\mu$]
$\mathrm{Re}_{\theta t}$	transition momentum thickness Reynolds number [$=\rho w\theta_t/\mu$]
St	Stanton number [$=\mathrm{Nu}/(\mathrm{RePr})$]
T	temperature
v, w	velocity components in radial and axial direction, respectively
w^+	non-dimensional axial velocity in wall coordinates [$=w/w_\tau$]
w_τ	friction velocity [$=\sqrt{\tau_w/\rho_w}$]
$\langle w'v'\rangle$	Reynolds shear stress
W	non-dimensional axial velocity [$=w/w_b$]
y^+	distance from wall in wall coordinates [$=(R-r)\nu_w/w_\tau$]

Greek symbols

α, β_1, β_2	constants in transition SST model
ε	turbulence dissipation [$=\nu\langle(\partial u_i'/\partial x_i)(\partial u_i'/\partial x_i)\rangle$]
γ	turbulence intermittency
λ	thermal conductivity
μ	dynamic viscosity
ν	kinematic viscosity
Θ	non-dimensional temperature [$=(T_w-T)/(T_w-T_b)$]
Θ^+	non-dimensional temperature in wall coordinates [$=(T_w-T)\rho_wc_{p,w}w_\tau/q_w$]
ρ	fluid density
σ	turbulent Prandtl number
τ_w	viscous wall shear stress
ω	turbulence specific dissipation rate [$=\varepsilon/k$]
$\langle\phi\rangle$	Reynolds-averaged value of variable ϕ

Subscripts

b	evaluated at bulk condition
in	evaluated at inlet
w	evaluated at wall

Superscripts

+	evaluated in wall coordinates

Abbreviations

DNS	direct numerical simulation
LES	large eddy simulation
RANS	Reynolds averaged Navier Stoke equations
SST	shear stress transport

Laminarization in air flowing vertically upwards through a tube and subjected to high heating rates has been a subject of numerous experimental and numerical investigations. The majority of the experimental investigations focused on the integral quantities such as heat transfer rate and pressure drop and not on the local velocity and temperature profile measurements. Exceptions to this are the experimental investigations [14–16] where velocity profile, temperature profile, pressure drop, and Nusselt number distributions were measured for heated air flow through a vertical circular tube with flow regime ranging from fully turbulent flow to laminarized flow.

Numerical simulation of laminarized flow of air through vertical tubes using LES and DNS methods have been conducted by Xu et al. [17], Satake et al. [18], and by Bae et al. [19]. The LES and the DNS studies revealed detailed flow and thermal structures as well as turbulence statistics for laminarized flow; however, these simulations are computationally expensive for practical applications. There have been a number of studies which used low Reynolds number eddy-viscosity based turbulence models as well as higher order Reynolds stress turbulence models [20–26] to simulate laminarized flow through vertical tubes. Many of these studies were specific to the conditions used in the experiments of Shehata and McEligot [15,16] and thus, the knowledge base available outside the conditions used in Shehata and McEligot experiments is limited. An assessment of the performance of a variety of turbulence models in simulating buoyancy-aided turbulent mixed convection in vertical pipes has been conducted [27]. The assessment identified the turbulence models which are able to capture the main features of buoyancy-influenced heat transfer.

Recently, local correlation based turbulence models [28] have been developed to simulate transitional flows. These models rely on coupling of fully turbulent flow models with empirical transition correlations and solve additional transport equations of intermittency (γ) and transition momentum thickness Reynolds number ($\mathrm{Re}_{\theta t}$) to include the transitional flow effects. These models have been used to predict internal flow and heat transfer in tubes, channels, and conical diffusers undergoing transition from fully laminar to fully turbulent flow [29–35] as well as for external flow over airfoils, wing-flaps, and turbo-machinery blades [36,37]. The $\gamma-\mathrm{Re}_{\theta t}$ transition model has been validated against experimental data for both internal flows [30–32] and for external flows [36,37].

The objectives of this paper are three-fold. The first objective is to assess the performance of the transitional $\gamma-\mathrm{Re}_{\theta t}$ SST model [28] which belongs to this class of local correlation based turbulence model for low Reynolds number turbulent flow of air moving upward in a vertical tube subjected to high heating rates leading to flow laminarization. This problem setup was chosen as it represents a test case for which detailed experimental results are available [15,16] against which the predictions of the transitional $\gamma-\mathrm{Re}_{\theta t}$ SST model can be compared and validated. To the best of the author's knowledge this would be the first instance where the transitional $\gamma-\mathrm{Re}_{\theta t}$ SST turbulence model has been applied to a low Reynolds turbulent flow subjected to high heating rates leading to flow laminarization. The second objective is to use the validated