International Journal of Heat and Mass Transfer 118 (2018) 235–246

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Transient flows on an evenly heated wall with a fin

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ARTICLE INFO

Article history:
Received 9 August 2017
Received in revised form 29 October 2017
Accepted 29 October 2017

Keywords:
Transient flows
Evenly heated wall
Fin
Scaling analysis

ABSTRACT

Transient natural convection flows on an evenly heated wall with a fin are common in industrial systems. In this paper, transient flows around the fin are investigated using scaling analysis and numerical simulation. The dynamics and heat transfer of transient flows are discussed. The scaling analysis shows that there are four flow scenarios for the intrusion but three for the plume bypassing the fin, which are dependent on the Rayleigh number and the Prandtl number. In a typical flow scenario, the intrusion could travel under different regimes such as an unsteady viscous conduction regime, an unsteady inertial conduction regime, an unsteady inertial convection regime, a steady inertial convection regime, a steady inertial conduction regime or a steady viscous conduction regime, but the starting plume could ascend under an unsteady and a steady inertial conduction regime or under a steady viscous conduction regime. Further, the scaling laws of the intrusion and the plume under different regimes are obtained. Numerical simulation is employed to validate the scaling laws of the velocity and the thickness of transient flows. The scaling predictions are consistent with numerical results.

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1. Introduction

Natural convection on a heated vertical wall is a fundamental model of fluid mechanics and heat transfer [1–4]. Accordingly, the quest for the thermal boundary layer on the vertical wall motivated a great number of studies owing to its fundamental and practical significance [5–8].

When a vertical wall is heated, the fluid adjacent to the vertical wall is in turn heated and moves up due to the effect of buoyancy. As a result, a thermal boundary layer flow forms. It has been demonstrated that the thermal boundary layer flow on a length-limited vertical wall suddenly heated is firstly characterized by the leading edge effect (LEE) involving an overshoot and traveling waves [9–12]. In fact, the development of the thermal boundary layer flow on the vertical wall suddenly heated can be described by different stages: a conduction stage, a transitional stage and a fully developed stage [13–15]. The scaling analysis has been employed to investigate the dynamics and heat transfer of the thermal boundary layer flow [13]. Studies by Lin and co-authors [16–18] have demonstrated that the thermal boundary layer flow is usually determined by the Rayleigh number (*Ra*) and the Prandtl number (*Pr*). Further, the scaling laws of the thermal boundary layer flow on a vertical wall in a linearly stratified fluid have been obtained [19]. It is worth noting that the abovementioned studies [13,16–19] focused on only the thermal boundary layer flow on an isothermal wall. Thus, the thermal boundary layer flow on an evenly heated wall has also been paid attention and the corresponding scaling laws have been presented in [20–22]. Additionally, the scaling analysis has been used to discuss the thermal boundary layer flow on the vertical wall with time-dependent heating and the corresponding scaling laws have been obtained in [23–25].

The thermal boundary layer flow could be laminar, transitional or even turbulent, which determines heat transfer near and through the vertical wall [26,27]. Therefore, instability of the thermal boundary layer flow has received attention [28]. Traveling waves in the thermal boundary layer flow have been observed and analyzed using direct numerical simulation and linear stability analysis [29,30]. The asymptotic form of the growth rate and phase speed of disturbances in the thermal boundary layer has been obtained using the quasi-steady approximation [31,32].

Since a thermal vertical wall is widely present in industrial systems such as heat exchanger, it is important to control the heat transfer through the wall. It has been known that one of good ways is to place a fin on a vertical wall (namely finned wall) in order to enhance or depress the heat transfer through the wall [33–35]. The fin can be conductive or adiabatic. The conductive fin can increase the conducting surface, which in turn enhances heat transfer [36].

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https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.117
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Nomenclature

A	aspect ratio of the cavity ($A = H/L$)
g	acceleration due to gravity (m/s^2)
h	position of the fin (m)
H	height of the cavity (m)
k	thermal conductivity (W/(m K))
L	length of the cavity (m)
p	pressure (N/m^2)
P	dimensionless pressure
Pr	Prandtl number
q	heat flux (W/m^2)
Q	volumetric flow rate (m^3/s)
Ra	Rayleigh number
Ra_f	Local Rayleigh number
t	time (s)
t_g	time for the transition of the intrusion between steady inertial and viscous regimes (s)
t_{gc}	time for the transition of the intrusion between unsteady inertial convection and conduction regimes (s)
t_{gcs}	time for the transition of the intrusion between steady inertial convection and conduction regimes (s)
t_{Pgc}	time for the transition of the plume between steady inertial convection and conduction regimes (s)
t_{Pvc}	time for the transition of the plume between steady viscous convection and conduction regimes (s)
t_{Pvs}	time for the transition of the plume between steady inertial and viscous regimes (s)
t_s	time when the thermal boundary layer becomes steady (s)
t_v	time for the transition of the intrusion between unsteady inertial and viscous regimes (s)
t_{vc}	time for the transition of the intrusion between unsteady viscous convection and conduction regimes (s)
t_{vcs}	time for the transition of the intrusion between steady viscous convection and conduction regimes (s)
T	temperature (K)
T_0	initial temperature of the ambient fluid (K)
ΔT	temperature difference between the wall and the ambient fluid (K)
u	x-velocity (m/s)
u_I	velocity of the intrusion (m/s)
u_{Ig}	velocity of the intrusion under an unsteady inertial regime (m/s)
u_{Igs}	velocity of the intrusion under a steady inertial regime (m/s)
u_{Iv}	velocity of the intrusion under an unsteady viscous regime (m/s)
u_{Ivs}	velocity of the intrusion under a steady viscous regime (m/s)
U	dimensionless x-velocity
U_{Ig}	dimensionless velocity of the intrusion under an unsteady inertial regime
U_{Igs}	dimensionless velocity of the intrusion under a steady inertial regime
U_{Iv}	dimensionless velocity of the intrusion under an unsteady viscous regime
v	y-velocity (m/s)
v_P	velocity of the plume (m/s)
v_{Pg}	velocity of the plume under an unsteady inertial regime (m/s)
v_{Pgs}	velocity of the plume under a steady inertial regime (m/s)
v_{Pv}	velocity of the plume under an unsteady viscous regime (m/s)
v_{Pvs}	velocity of the plume under a steady viscous regime (m/s)
v_T	velocity of the thermal boundary layer (m/s)
v_{Ts}	velocity of the thermal boundary layer at a steady state (m/s)
V	dimensionless y-velocity
V_{Pgs}	dimensionless velocity of the plume under a steady inertial regime
V_{Pvs}	dimensionless velocity of the plume under a steady viscous regime
x, y	horizontal and vertical coordinates (m)
X, Y	dimensionless horizontal and vertical coordinates
α	the time power of the volumetric flow rate of the starting plume
β	coefficient of thermal expansion (1/K)
δ_I	thickness of the intrusion (m)
δ_{Ig}	thickness of the intrusion under an unsteady inertial regime (m)
δ_{Igs}	thickness of the intrusion under a steady inertial regime (m)
δ_{Iv}	thickness of the intrusion under an unsteady viscous regime (m)
δ_{Ivs}	thickness of the intrusion under a steady viscous regime (m)
δ_P	thickness of the plume (m)
δ_{Pg}	thickness of the plume under an unsteady inertial regime (m)
δ_{Pgs}	thickness of the plume under a steady inertial regime (m)
δ_{Pv}	thickness of the plume under an unsteady viscous regime (m)
δ_{Pvs}	thickness of the plume under a steady viscous regime (m)
δ_T	thickness of the thermal boundary layer (m)
δ_{Ts}	thickness of the thermal boundary layer at a steady state (m)
Δ_{Ig}	dimensionless thickness of the intrusion under an unsteady inertial regime
Δ_{Igs}	dimensionless thickness of the intrusion under a steady inertial regime
Δ_{Iv}	dimensionless thickness of the intrusion under an unsteady viscous regime
Δ_{Pgs}	dimensionless thickness of the plume under a steady inertial regime
Θ	dimensionless temperature
κ	thermal diffusivity (m^2/s)
ν	kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
τ	dimensionless time
τ_g	dimensionless time for the transition of the intrusion between steady inertial and viscous regimes
τ_{Pvs}	dimensionless time for the transition of the plume between steady inertial and viscous regimes
τ_s	dimensionless time when the thermal boundary layer becomes steady
τ_v	dimensionless time for the transition of the intrusion between unsteady inertial and viscous regimes
$\Delta\tau$	dimensionless time step

In addition, the fin including the adiabatic fin can induce the transition of a thermal boundary layer flow to a periodic flow or even a turbulent flow, which improves convective flows and heat transfer [37,38]. Further, studies indicate that the length, thickness and number of the fin can also influence convective flows near the wall [35,39,40].

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