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Transverse recirculations in low Reynolds number mixed convective gas flow over a model heated substrate

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Abstract

Combined flow visualization and temperature measurement are conducted to investigate the structure of the buoyancy driven transverse vortex rolls (T-rolls) at low Reynolds number mixed convective gas flow through a horizontal flat duct with a 0.3 m (12-in.) heated circular plate embedded in the bottom of the duct for the Rayleigh number ranging from 3506 to 23,485. The results suggest that the regular transverse vortices prevail in the duct core only in a certain range of Rayleigh number with very low Reynolds number ($Re \leqslant 12.1$) and the vortex flow is characterized by the moving T-rolls over the heated plate enclosed by an incomplete circular roll. More specifically, the regular transverse vortex rolls are curved at the early stage of their initiation and deformed to some degree due to the presence of the incomplete circular roll around the upstream edge of the heated plate. But in the exit half of the duct the T-rolls are nearly straight and they are almost spanwisely symmetric with respect to the vertical central plane. Besides, the transverse rolls get stronger and bigger during the downstream moving and they do not travel downstream at a constant speed. The data from the transient temperature measurement reveal that the flow oscillation of the T-rolls driven by the circular heated plate is slightly space dependent for given *Ra* and *Re*. Moreover, the frequency of the flow oscillation decays substantially with the decrease in the Reynolds number. Furthermore, the amplitude of the temperature oscillation can be reduced for a raise of *Ra*. These characteristics are very different from the transverse vortex rolls induced in a duct with a uniformly heated bottom plate.

Keywords: Convection; Fluid flows; Metalorganic chemical vapor deposition

1. Introduction

The buoyancy induced vortex flow and thermal characteristics in a low Reynolds number ($Re \leqslant 50$) mixed convective gas flow through a horizontal flat duct uniformly heated from below and cooled from above have been intensively investigated recently because of the important roles they play in the vapor-phase growth of thin crystal film for microelectronic fabrication [1]. Various vortex flow patterns such as longitudinal, transverse, mixed longitudinal and transverse flow recirculations, and others were identified and examined in detail [2–4]. In the practical microelectronic fabrication, the crystal films are normally grown on heated circular silicon wafers. The vortex flow patterns appear on these circular wafers are expected to be somewhat different from those driven by the uniformly heated duct bottom since the buoyancy induced flow is known to be very sensitive to the geometry of the heated surface. However, the buoyancy induced vortex flow structures in a mixed convective flow over a heated circular surface remain poorly understood. In the present study, combined flow visualization and temperature measurement are conducted to delineate transverse vortex flow pattern and associated thermal characteristics in a mixed convective gas flow over an isothermally heated circular plate embedded in the bottom of a horizontal flat duct. Attention is focused on how the geometry of the heated surface affects the

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Nomenclature

A	aspect ratio (b/d)
a	wave number of vortex rolls (m^{-1})
b, d	channel width and height (m)
F	dimensionless frequency ($F = f/(\alpha/d^2)$)
f	dimensional frequency (Hz)
g	gravitational acceleration (m/s^2)
Gr	Grashof number ($g\beta d^3\Delta T/\nu^2$)
l	length of test section (m)
Pr	Prandtl number (ν/α)
Ra	Rayleigh number ($g\beta d^3\Delta T/\alpha\nu$)
Ra_c^L	critical Rayleigh number corresponding to the onset of longitudinal rolls
Ra_c^T	critical Rayleigh number corresponding to the onset of transverse rolls
Ra_{tu}	Rayleigh number corresponding to the upper bound for the appearance of the regular transverse rolls
Ra_{tl}	Rayleigh number corresponding to the lower bound for the appearance of the regular transverse rolls
Re	Reynolds number ($W_m \times d/\nu$)
T	temperature (K)
T_{in}, T_{cp}	temperature at inlet of the test section and the circular copper plate (K)
ΔT	$T_{cp} - T_{in}$ (K)
t	time (s)
t_p	oscillation period (s)
W, W_m	velocity and average velocity components in z direction (m/s)
W_r	wave speed of the transverse rolls (m/s)
X, Y, Z	dimensional Cartesian coordinates (m)
x, y, z	dimensionless Cartesian coordinates scaled with b, d, l
α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
θ	dimensionless temperature $(T - T_{in})/\Delta T$
ν	kinematic viscosity (m^2/s)
λ	dimensional wavelength of transverse rolls (m)
$\bar{\lambda}$	dimensionless wavelength of transverse rolls ($\bar{\lambda} = \lambda/d$)

transverse vortex flow characteristics in the duct by comparing the present results with those reported in the literature for a duct with a uniformly heated bottom.

The relevant literature mainly on the transverse recirculations induced in a mixed convective flow through a bottom heated horizontal flat duct is briefly reviewed here. In a mixed convective flow through a horizontal plane channel with the bottom plate at a higher uniform temperature than the top one, the critical Rayleigh number for the onset of the secondary flow due to thermal instability Ra_c^L is 1708 [5,6]. Beyond this critical Rayleigh number, steady longitudinal vortex rolls with spanwise symmetry prevail and the roll diameter is nearly equal to the duct height. At high buoyancy, the induced longitudinal vortex flow loses its steadiness and can become asymmetric with the presence of the roll splitting and merging [7]. The existence of the transverse thermoconvective vortex rolls (T-rolls) in mixed convective flow through a horizontal bottom heated rectangular duct was proved by Luijkx and Platten [8] with silicone oil ($Pr \approx 450$) as the working fluid at extremely low Reynolds number with $0.001 \leqslant Re \leqslant 0.01$. The critical Rayleigh number corresponding to the onset of the transverse rolls Ra_c^T was found to be a function of the aspect ratio and Prandtl number. It is well known that Ra_c^L is unaffected by the Reynolds number Re. But the critical Rayleigh number for the onset of the transverse rolls Ra_c^T increases with the Reynolds number Re [8,9]. Ouazzani et al. [10–12] experimentally disclosed the appearance of transverse rolls in low Reynolds number mixed convective air flow with $1 < Re < 9$ and $2000 < Ra < 12{,}000$. They noted that the regular transverse rolls all had the same diameter which was nearly equal to the duct height and the effects of the Reynolds and Rayleigh numbers on the roll size are relatively mild. Besides, the generated transverse vortex rolls travel downstream at the same speed. But this speed is nearly proportional to the mean speed of the flow forced into the channel. They further used Laser Doppler Anemometry to investigate the mixed convective flow of water [12] and proposed a particular flow regime in which only irregular and intermittent flow structure prevailed.

To disclose various vortex patterns in a horizontal plane channel with a uniformly heated bottom, direct flow visualization was performed in several experimental studies covering wide ranges of the governing parameters. Particularly, Chiu and Rosenberger [13] proposed a flow regime map for nitrogen ($A = 10$) locating the boundaries among the flow with no rolls, steady and unsteady L-rolls. Later, Ouazzani et al. [10] included both the longitudinal and transverse rolls in their map for air in a wider duct ($A = 19.5$). Recently, Chang and Lin and their colleagues [2,3,7,14–16] conducted combined flow visualization and temperature measurement to explore the mixed convective air flow and several vortex flow patterns were identified. More specifically, depending on the competition between the buoyancy and inertia forces the flow can consist of the mixed longitudinal and transverse rolls, U-rolls, nonperodic transverse waves and longitudinal rolls, and inlet stationary transverse rolls along with downstream longitudinal rolls, in addition, to the regular and irregular longitudinal and transverse rolls. The characteristics of longitudinal vortex rolls in mixed convective air flow driven by a circular heated plate embedded in the bottom of a horizontal plane channel were recently investigated by