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Experimental study of onset of laminar–turbulent transition in mixed convection in a vertical heated tube

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ABSTRACT

Unsteady phenomena were observed in the case of airflows approaching transition inside a uniformly heated vertical tube. An analysis of the experimental data at three Reynolds numbers ($Re = 1000$, 1300 and 1600) allowed to establish that: (i) A flow instability onsets at different Grashof numbers (Gr) when the condition $Gr/Re > 1500$ is achieved. (ii) The FFT of the temperature signal shows a peak at a frequency f_D (0.45 Hz) when $Gr/Re > 1500$. (iii) This instability is associated to a thermal buoyant instability rather than to a thermal shear instability. (iv) This instability forms in the buffer region and then propagates towards the whole section of the tube as the Grashof number is increased.

1. Introduction

Experimental evidence compiled by Metais and Eckert [1] indicates that airflows inside a vertical tube with uniform heat flux can undergo transition from laminar to turbulent regimes for Reynolds numbers (Re) as low as 1000. For a given Reynolds number, the route to turbulence is one in which a radial temperature gradient destabilizes the otherwise laminar flow by accelerating the fluid close to the tube wall and causing a point of inflexion in the velocity profile (Lord Rayleigh's 1st Theorem). Scheel and Hanratty [2] studied experimentally the stability of flow in a vertical tube under mixed convection heat transfer by detecting temperature fluctuations in the effluent. They showed that the stability depends primarily on the shape of the velocity profile and only secondarily on the value of the Reynolds number. They found that the flow, when buoyancy assisted, first becomes unstable as the velocity profiles develop points of inflexion. They also mentioned that the temperature fluctuations, for low values of Re, are low frequency small scale oscillations. At larger values of Re, the initially regular fluctuations distort and grow in amplitude until fluctuations characteristic of turbulence such as a large scale periodicity appear. Yao [3] suggested that a buoyancy assisted flow is highly unstable and that its instability is supercritical. Except for a narrow range of Reynolds numbers, the disturbed flow has a double-spiral structure. Moreover, he showed that some of the unstable flows observed by Scheel and Hanratty [2] occurred in the developing region instead of in the fully developed region.

The importance of the Prandtl number in mixed convection stability was studied by Yao and Rogers [4]. They showed that thermal shear perturbations occurring in low Prandtl number fluids as the Rayleigh number is increased, initiate a linear instability that distorts the velocity profiles sufficiently to destabilize the flow. In larger Prandtl number fluids, however, the flow becomes unstable to the thermal buoyant perturbations induced locally by the temperature fluctuations: this local disruption of the buoyant force in turn causes a distortion of the velocity field by a transfer of kinetic energy from the fluctuating buoyant potential. Chen and Chung [5] investigated the linear stability of mixed convection flow in a vertical channel. The flow, when buoyancy assisted, is dominated by two dimensional disturbances and its stability is strongly dependent on the Prandtl number. They showed that the instability characteristics for some case of channel flow are significantly different from the results for heated annulus and pipe flows. Su and Chung [6] analyzed the linear stability of mixed convection in a vertical tube. They showed that the flow can become unstable at low Reynolds number and Rayleigh number irrespective of the Prandtl number. Their results show that the Prandtl number plays an active role in buoyancy assisted flow and is an indication of the viability of kinematic or thermal disturbances. They also showed that for assisted flow with $Pr < 0.3$ the thermal shear instability is dominant while for $Pr > 0.3$, the assisted–thermal buoyant instability becomes responsible. If the Grashof number (or the heat flow at the wall) is sufficiently increased, the velocity gradient produces a shear from which originates a periodic or wavy structure. The visualization of the flow field in a vertical tube subjected to a uniform wall heat flux carried out by Bernier and Baliga [7] points to this route leading to the laminar–turbulent transition. Behzadmehr

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Nomenclature

A	tube cross sectional area
C_p	specific heat
D	internal tube diameter
ES	thermal shear production, $-\langle U_{\mathrm{sd}} U_{\mathrm{sd}} \frac{\mathrm{d}U}{\mathrm{d}r} \rangle$
EB	thermal buoyant turbulent production, $\frac{Gr}{4Re^2} \langle U_{\mathrm{sd}} T_{\mathrm{sd}} \rangle$
f	frequency
g	acceleration of gravity
Gr	Grashof number, $g\beta D^4 q_w / \lambda\nu^2$
L	length of test section
$\dot{m}$	mass flow rate
Nu	Nusselt number
P	pressure
Pr	Prandtl number
q_w	uniform heat flux at the solid–fluid interface
r	radial coordinates
Re	Reynolds number, $U_b D/\nu$
Ri	Richardson number, Gr/Re^2
T, T'	time averaged and fluctuating temperature
U, U'	time averaged and fluctuating velocity indicator
Z	axial coordinates

Greek letters

β	volumetric expansion coefficient
λ	thermal conductivity
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density

Subscripts

0	inlet condition
b	bulk
c	centreline
L	tube outlet
sd	standard deviation
w	wall

et al. [8,9] implemented a numerical procedure that models laminar as well as turbulent flow to study mixed convection of air flowing through a vertical tube with uniform wall heat flux. The results of their numerical simulations indicate two laminar–turbulent transitions at Reynolds number as low as 1000. The effects of inlet turbulent intensity on the axial evolution of the hydrodynamic and thermal fields as well as on the developed velocity and temperature profiles are presented by Behzadmehr et al. [10]. They found that the flow regime is influenced by the inlet turbulence intensity and by the Grashof number. For a given Pr and Re, increasing inlet turbulent intensity (inlet disturbances) decreases the Gr for which flow regime changes from laminar to turbulent. However, for higher value of the inlet turbulent intensity, the same Re and Pr, higher value of the Gr is needed for which flow regime change back to laminar (re-laminarization).

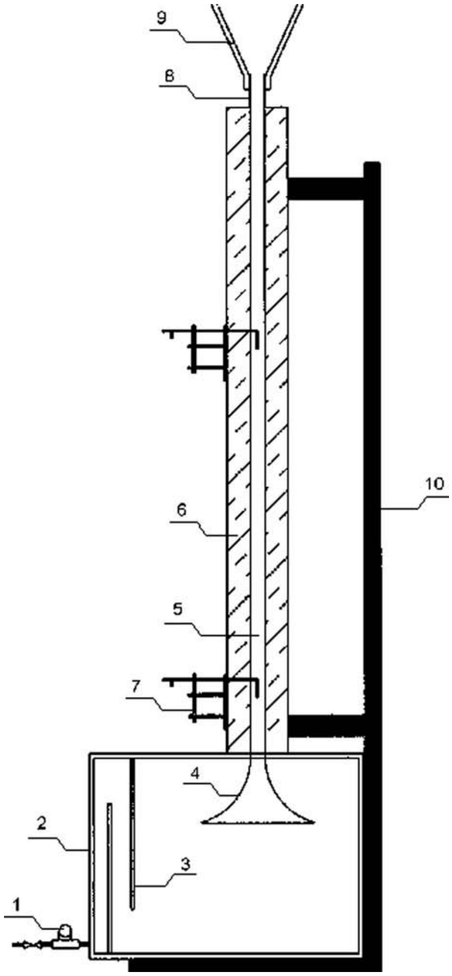

Fig. 1. Sketch of experimental apparatus.

Table 1
Estimated uncertainties

Item	Uncertainties
Mass flow meter	±2% of reading value
Temperature	±0.05 °C
Thermocouple location	±1.2 mm
Pitot tube location	±2.2 mm
Radial position of Pitot tube	±0.03 mm
Pressure transducer	±0.024 Pa
Manometer	±0.024 Pa

In the case of airflows undergoing transition, the temperature and velocity fluctuations have not been studied in detail neither experimentally nor numerically. An experimental apparatus was therefore designed in order to examine the characteristics of these fluctuations as transition onsets in the case of low Reynolds numbers. Since the Prandtl number for air is of the order of unity, a correlation should exist between the temperature fluctuations and the velocity fluctuations: the signal of the fluctuating temperature should give some insight on the flow transition [11]. This article deals with an analysis of the nature of the temperature and velocity fluctuations using experimental data obtained at $Re = 1000$, 1300 and 1600 over a wide range of the Grashof numbers. A signal analysis is presented to show the details that could characterize onset of laminar–turbulent transition.

2. Experimental set-up and procedure

2.1. Experimental apparatus

Fig. 1 shows a schematic view of the experimental set-up. It consists of two principal components: a settling chamber used to