International Journal of Thermal Sciences 111 (2017) 321–329

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Transition to turbulent heat transfer in heated vertical channel - Experimental analysis

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ARTICLE INFO

Article history:
Received 27 April 2016
Received in revised form
25 August 2016
Accepted 6 September 2016

Keywords:
Natural convection
Turbulent heat transfer
Vertical open channel
Shear layer

ABSTRACT

This experimental study deals with natural convection flow in a water channel with a symmetrical isoflux wall heating. Wall temperature, velocity, bulk temperature and fluctuating quantities are measured for a modified Rayleigh number $Ra^*=6.7\times10^7$. The analysis of the mean values shows a change of behaviour at the two-third of the height of the channel. This change turns out to be a transition from a laminar heat transfer in the bottom part of the channel to a turbulent one in the upper part. Due to isoflux wall boundary conditions, shear layers develop and thicken in each half-channel. It is shown that the meeting of these layers at the centre of the channel triggers the transition from a laminar heat transfer to a turbulent one. This experimental study is followed by a scaling analysis [1].

1. Introduction

Natural convection in open-ended vertical channels has been investigated for decades thanks to its broad application fields (electronic, solar systems, buildings, …). With isoflux wall boundary conditions, the flow can be characterized by the modified Rayleigh number: $Ra^* = \frac{g\beta q_w b^5}{\lambda\nu\kappa H}$; where g is the gravitational acceleration, q_w the wall heat flux, b and H the width and height of the channel, and β, ν, λ, κ the isobaric thermal expansion coefficient, kinematic viscosity, thermal conductivity and thermal diffusivity of the fluid, respectively. The Rayleigh number compares buoyant effects that tend to lift the fluid upward with viscous dissipation and thermal diffusion that tend to counteract the buoyant effect. This definition is the most commonly used but there is no evidence showing that it is the only parameter that characterizes the flow behaviour. The natural convection flow at low Rayleigh number ($Ra^*<10^5$) has been fully investigated for years [2–5], and analytical solutions have been developed [6]. However, many applications such as photovoltaic double-skin façades [7], are characterized by higher Rayleigh number ($Ra^*\sim10^{10}$) where natural convection flow undergoes a transition to turbulence. Flows at these ranges of high Rayleigh numbers were much less investigated.

Miyamoto et al. [8] carried out one of the first experimental studies on turbulent natural convection flow in a 5 m high vertical air channel. One wall is heated with a constant heat flux, the other wall being adiabatic. They performed wall temperature measurements by using thermocouples and velocity measurements in the channel with a Laser Doppler Velocimetry (LDV) system for several aspect ratios (H/b=100,50 and 25). The wall temperature profile exhibits a maximum value located between 1 and 2 m from the channel inlet for three Rayleigh numbers Ra^* ranging from 7×10^3 to 2×10^7. They attributed this maximum to a transition from laminar to turbulent flow. Vertical velocity and temperature profiles are shown at three vertical positions in the channel for the three aspect ratios. The increase in the vertical velocity as the fluid rises along the heated wall is clearly seen for the experiment with the largest aspect ratio whereas the behaviour is not clear for the lower ones. Indeed, for the lowest aspect ratio, the velocity peak does not increase until the end of the channel, a decrease is seen in the upper part. This decrease comes with an increase in the temperature of the fluid in the whole section. Despite the difference in the experimental setups, this behaviour could be similar to the one described in this study.

Later, Webb and Hill [9] analysed heat transfer in a configuration close to Miyamoto's but adiabatic extensions have been added at the entry and the exit of the channel. The channel height is 15 cm. The 7.62 cm high heated zone is vertically centred on one wall. In

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http://dx.doi.org/10.1016/j.ijthermalsci.2016.09.004
1290-0729/

Nomenclature

b	Channel width (m)
g	Acceleration of gravity (m s^{-2})
H	Channel height (m)
l	Channel depth (m)
Nu_x	Local Nusselt number, Eq. (2)
Pr	Prandtl number
q_w	Wall heat flux (W m^{-2})
Ra^*	Modified Rayleigh number, $Ra^* = \frac{g\beta q_w b^5}{\lambda\nu\kappa H}$
Ra_x	Local Rayleigh number, Eq. (1)
Re	Reynolds number
$T(x,y)$	Mean temperature (K)
$T_c(x)$	Mean temperature at the channel centre (K)
T_{ref}	Reference temperature for the Boussinesq approximation (K)
T_{inlet}	Inlet temperature (K)
$T_{lw}(x)$	Mean temperature of the left wall (K)
U,V,W	Mean velocity component in the directions x,y,z, respectively (m s^{-1})
u',v',w'	Instantaneous velocity fluctuations in the directions x,y,z, respectively (m s^{-1})
U_{max}, U_{min}	Maximum and minimum of the mean vertical velocity profile, respectively (m s^{-1})
x	Distance from the inlet in the ascendant direction (m)
y	Distance from the left wall (m)
y_{uv}	Location of the maximum Reynolds stress at x (m)
y_{SL}	Right boundary location of the shear layer at x, Eq. (6), (m)
z	Distance from the front lateral wall (m)
β	Isobaric thermal expansion of water (K^{-1})
$\Gamma=H/b$	Aspect ratio
$\Delta U=U_{max}-U_{min}$	Mean vertical velocity difference at x (m s^{-1})
δ_ν	Viscous boundary layer thickness, Eq. (5), (m)
δ_T	Thermal boundary layer thickness, Eq. (3), (m)
$\delta_{T,0}$	Thermal boundary sublayer thickness, Eq. (4), (m)
θ'	Instantaneous temperature fluctuations (K)
κ	Thermal diffusivity of water (m^2 s^{-1})
λ	Thermal conductivity of water (W m^{-1} K^{-1})
ν	Cinematic viscosity of water (m^2 s^{-1})
$\sigma_u,\sigma_v,\sigma_w$	Root mean square of the velocity fluctuations u',v',w', respectively (m s^{-1})
σ_θ	Root mean square of the temperature fluctuations (K)
$< >$	Time average operator

the range $10^3 \leq Ra^* \leq 4\times 10^7$, no transition is observed. For the most efficient heat transfer, the Nusselt number based on the channel width is found to be proportional to the modified Rayleigh number raised to the power of 1/5 which means that heat transfer is independent of the channel width as in the case of the vertical flat plate ([10]).

More recently, Habib et al. [11–13] performed LDV and Particles Images Velocimetry (PIV) measurements on a 12.5 cm high channel with isothermal heating (symmetrical and asymmetrical heating). They presented several results on turbulent quantities with numerical validations. The comparisons focused on the influence of the width and no much information were given on the evolution along the channel.

Fossa et al. [14] as well as Brinkworth and Sandberg [7] have carried out experimental studies in vertical channels with isoflux heating on one wall, the other one being adiabatic. As Miyamoto did, they observed a maximum on the heated wall temperature profile. This maximum appears around the three-quarters of the height of the channel with a sharp decrease at the outlet. Sanvicente et al. [15] published a study completing the one of Fossa et al. [14] by using the same configuration with a 1.5 m high channel. A wall temperature decrease is also shown in the upper third of the channel height. They associated this maximum to a change in flow regime which is probably combined with the effect of radiative heat losses to the surrounding. This change is visualized by Particles Image Velocimetry (PIV) measurements that show an increase in the velocity fluctuations at the channel outlet.

Concerning numerical studies, Fedorov and Viskanta [16] were among the first to carry out simulations in this configuration in the same range of Rayleigh numbers. They analysed cases of both isoflux and isothermal heating on one wall, the other one being adiabatic. They used a k-ε low Reynolds number model and they addressed the problem of boundary conditions at the channel inlet. The influence of the inlet turbulent intensity was investigated and results were compared with Miyamoto's in the isoflux case. Finally, for an aspect ratio of H/b=50 and Ra^*=7×10^5, they showed that without considering inlet turbulence, the transition to turbulence occurs at x=3.8 m from the channel inlet whereas it occurs at x=1.8 m in the experimental study. The transition moves upstream as the Rayleigh number or the inlet turbulence intensity increases.

Cheng and Müller [17] studied turbulent natural convection numerically and experimentally. One wall was isothermally heated and the other was insulated. The simulations were performed with a k-ε turbulence model and took radiative heat transfer between walls into account, but the inlet conditions were not described in detail. Comparisons with a 8 m high experimental air channel showed a good agreement but the study was mainly focused on the thermal heat transfer and the turbulent characteristics of the flow were not investigated.

Yilmaz and Fraser [18] presented a numerical and experimental study on a 3 m high vertical channel with isothermal heating: one wall heated and the other adiabatic. They tested 3 different k-ε models and neglected radiative heat transfer. In the numerical study, they used the experimental turbulent intensity at the inlet as a boundary condition. However, the comparison with LDV measurements showed that numerical turbulent kinetic energy profiles did not match the experimental ones.

To investigate the impact of boundary conditions on numerical simulation of natural convection flow in a vertical open channel, benchmark solutions based on the configuration of Webb and Hill [9] were given by Desrayaud et al. [19]. It appears that the thermal field is weakly dependent on the inlet and and outlet conditions which is not the case for fluid flow quantities (mass flow rate and bulk temperature).

Most of the studies on natural convection in an open-ended channel are focused on asymmetrical heating. Studies on symmetrical configurations are limited to laminar flows ([20,21]). To investigate this configuration, an experimental apparatus has been set up in order to study turbulent natural convection in a vertical channel with symmetrical isoflux heating conditions. The set-up has already been presented by Daverat et al. [22]. The water is chosen as the working fluid to avoid radiative heat transfer between heated walls and their surroundings. A measuring system coupling LDV and a micro-thermocouple has been developed to