International Journal of Heat and Mass Transfer 82 (2015) 325–334

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Natural convection from horizontal heated cylinder with and without horizontal confinement

Geo Sebastian, S.R. Shine *

Department of Aerospace Engineering, Indian Institute of Space Science and Technology, Thiruvananthapuram 695547, India

ARTICLE INFO

Article history:
Received 26 August 2014
Received in revised form 13 October 2014
Accepted 18 November 2014
Available online 6 December 2014

Keywords:
CFD
Natural convection
Horizontal cylinder
Top and bottom confinement

ABSTRACT

Laminar natural convection flow around horizontal heated cylinder with and without confinement is numerically studied. Confinement is done above or below the cylinder at various vertical positions. Two-dimensional computational models using finite volume formulation have been developed and validated against experimental data. Local heat transfer predictions are correlated for an unconfined single cylinder. The significance of confinement on the top and bottom side of the cylinder is clearly demonstrated for a wide range of *Ra*, and spacing between the cylinder and the confinement. In case of top confinement, the increase in Nu_θ at the upper portion of the cylinder depends on the position of the wall. The confinement below the cylinder caused a reduction in $\overline{Nu}$ at the bottom half of the cylinder as compared to the top half. For both cases, the effect of confinement can be neglected at high H/D ratios.

1. Introduction

Natural convective flows around heated horizontal cylinders are relevant to many applications. The nature of the flow around the cylinder can be affected when the flowing medium around the cylinder is vertically or horizontally confined. With the case of combined horizontal and vertical confinement (rectangular enclosure), the interactions between the finite fluid and the enclosure walls can still be different. In this paper, numerical analyses are performed for natural convection from a single horizontal heated cylinder with and without horizontal confinement to distinguish the effects when the confinement is above or below the cylinder.

Studies on natural convection around a horizontal cylinder stretch way back into the days of Nusselt. Ackerman [1] under the supervision of Nusselt carried out experiments on a horizontal cylinder to verify Nusselt's theory. Survey of current literature shows extensive studies for horizontal, isothermal cylinder with and without adiabatic or conductive ceiling in various arrangements such as horizontal, vertical and rectangular. The more famous work in this area is that of Morgan [2] and Churchill and Chu [3]. Morgan compared large number of experimental data and found major discrepancies between different data. It was found that the wide dispersion in experimental data was due to various factors associated with the experiments. He proposed a time and area-averaged Nusselt number correlation for range of *Ra* varying from 10E−10 to 10E + 12 and Chu [3] proposed a time and area-averaged Nusselt number correlation valid for all *Pr* and *Ra*. Many researchers including Hermann [4], Sako et al. [5], Chen and Yoon [6] and Farinas and Garon [7] have theoretically predicted the temperature distributions in space around heated cylinders. Nakai and Okazaki [8] studied natural convection around horizontal wires of small diameter for uniform temperatures. Similarity solution obtained were compared with experimental results. De Socio [9] and Herrez and Belda [10] used holographic interferometry to study the corresponding temperature fields. Herrez and Belda [10] proposed equations for surrounding temperature fields, local and average heat transfer coefficients. Morgan [11] conducted a review of analytical, experimental and numerical results available for the prediction of $\overline{Nu}$ around horizontal heated cylinders. It was concluded that the $\overline{Nu}$ predicted by analytical and numerical methods was in agreement within 4% of the experimental values for *Ra* of the order of 10^4. At *Ra* of the order of 10^5, the experimental values were higher by around 8%, and at $Ra \approx 10^7$ the experimental values were higher by 11%. Kitamura's [12] experimental investigations showed higher local heat transfer coefficients in the regions with transitional (laminar-turbulent transition) behaviour. Numerical investigations by Kuehn and Goldstein [13] showed a decrease in boundary layer thickness with an increase in *Ra*. Their experimental results obtained using a copper cylinder and Mach–Zehnder interferometer compared fairly well with the numerical data and experimental data from other researchers. The buoyant plume generated above the heated

* Corresponding author. Tel.: +91 471 2568427; fax: +91 471 2568406.
E-mail address: shine@iist.ac.in (S.R. Shine).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.11.063
0017-9310/

Nomenclature

c_p	specific heat, J kg^{-1} K^{-1}
D	diameter of the cylinder, m
g	gravitational acceleration, m s^{-2}
H	cylinder-to-ceiling distance from the tip of the cylinder, m
h	convective heat transfer coefficient, W m^{-2} K^{-1}
k	thermal conductivity of the surrounding media, W m^{-1} K^{-1}
Nu_θ	local Nusselt number, $h_\theta D/k$
$\overline{Nu}$	average Nusselt number
$\overline{\overline{Nu}}$	normalised local Nusselt number given by Eq. (5)
Pr	Prandtl number, ν/α
q	heat flux, W m^{-2}
Ra	Rayleigh number, $g\beta(T_w - T_\infty)D^3/\alpha\nu$
Ra^*	modified Rayleigh number, $g\beta q_w D^4/k\alpha\nu$
T	temperature, K
v	velocity in the radial direction, m s^{-1}

Greek letters

α	thermal diffusivity, m^2 s^{-1}
β	volumetric expansion coefficient, K^{-1}
δ	boundary layer thickness, m
θ	angle from the bottom of the cylinder, °
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}

Subscripts

max	maximum
w	at the cylinder surface
∞	ambient condition

cylinder was experimentally investigated by Grafsrnningen et al. [14]. The flow exhibited non-laminar behaviour at a height above the cylinder. It was also observed that with the increases of Ra, flow becomes transition and the starting point of the separation moves along the cylinder to the bottom.

It can be noted that investigations over the years have mainly concentrated on improving the empirical correlations for the time and area-averaged Nusselt numbers at different Ra. The absence of a simple correlation for the prediction of local natural convection heat transfer coefficients around the horizontal cylinders at various conditions defined one of the objectives of the present study.

1.1. Effect of horizontal confinement

Many investigations have reported the effect of horizontal confinement on a horizontal cylinder with various spacing to cylinder diameter ratios. Model geometry of this type is shown in Fig. 1. Saito et al. [15] noted that overall convection heat transfer from the cylinder was minimum compared to a cylinder in an infinite medium at a $H/D \approx 0.12$. Koizumi and Hosokawa [16] observed unsteady three-dimensional flow at higher Ra below the isothermal ceiling. The flow patterns depended mainly on Ra and the H/D ratio. Karim and Farouk [17] showed that the effect of confinement becomes negligible at higher Ra. Lawrence et al.'s [18] experiments showed that when $H/D > 1$, the ceiling has almost negligible influence on heat transfer. Correa et al.'s [19] numerical results demonstrated that the ceiling has no effect on heat transfer rate for $H/D > 2$. Flow visualisation studies by Ashjaee et al. [20] confirmed the above findings and reported the following. (i) Adiabatic ceiling had no influence on free convection heat transfer for $H/D \geqslant 1.5$. (ii) Considerable decrease in Nu between H/D ratios from 1.5 to 0.5. (iii) For close spacing of $H/D < 0.5$, increase in Nu due to the vortex formation below the ceiling. Atmanne et al. [21] studied natural convection flow above a heated horizontal cylinder immersed in water and confined by the water free surface. It was noted that variation in separation distance between the cylinder and fluid boundary resulted in higher Nu on the upper part of the cylinder. Large scale fluctuations of the thermal plume were noticed when the distance between the free surface and the cylinder is roughly equal to diameter of the cylinder. Optimal spacing between horizontal cylinders placed in an array of fixed volume for maximum heat transfer was determined by Bejan et al. [22]. They proposed correlations for optimal spacing and heat transfer rates. It was observed that the spacing is relatively insensitive to the cylinder conditions such as isothermal and uniform heat flux. Sparrow and Ansari [23] investigated heat transfer due to all participating modes for a heated cylinder with a horizontal wall beneath the cylinder. It was found that the bottom wall caused reduction in heat transfer rates in about 5% more than those due to the side wall. The degradation in heat transfer was negligible as the cylinder to wall distance increased. Ashjaee et al. [24] studied similar configurations at various wall spacing and at Ra ranging from 100 to 10^5. He proposed correlations for $\overline{Nu}$ of the cylinder as a function of Ra and H/D ratio.

It is noted that when the cylinder is confined, studies done so far confirm a reduction in $\overline{Nu}$ for lower H/D ratios. However there is no consensus among researchers regarding the optimum spacing between the cylinder and the confinement beyond which the effect of confinement can be neglected. Atmane et al. [21] reported an increase in Nu_θ at the top half of the cylinder for lower H/D ratios. The possibility of transient flow phenomena cannot be ruled out for such a case. It is also noted that the effect of bottom confinement at various conditions is not studied in detail. The objective of the present study is to address the above mentioned deficiencies in

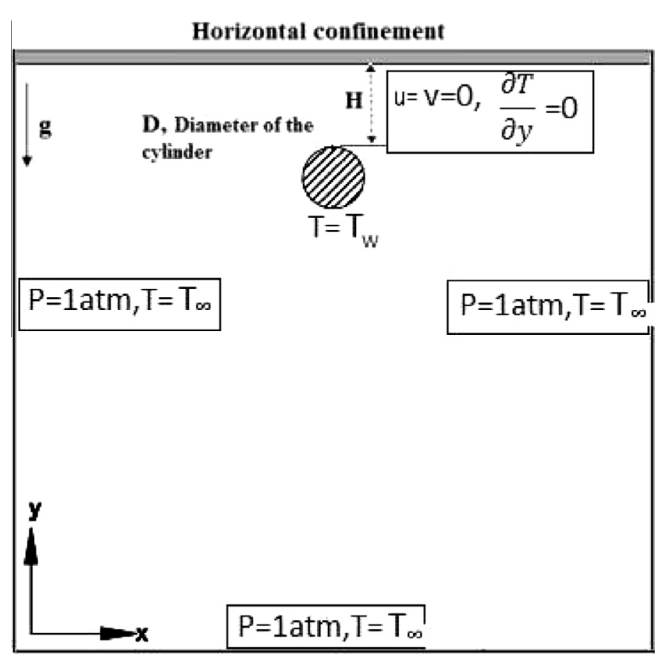

Fig. 1. Model geometry showing boundary conditions.