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ScienceDirect
Applied Thermal Engineering 27 (2007) 1236–1247
APPLIED THERMAL ENGINEERING
www.elsevier.com/locate/apthermeng

Combined convection heat transfer for thermally developing aiding flow in an inclined circular cylinder with constant heat flux

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Received 22 September 2006; accepted 19 November 2006
Available online 3 January 2007

Abstract

Experiments have been conducted to study the local and average heat transfer by mixed convection for hydrodynamically fully developed, thermally developing and thermally fully developed laminar air flow in an inclined circular cylinder. The experimental setup consists of aluminum cylinder as test section with 30 mm inside diameter and 900 mm heated length ($L/D = 30$), is subjected to a constant wall heat flux boundary condition. The investigation covers Reynolds number range from 400 to 1600, heat flux is varied from 70 W/m^2 to 400 W/m^2 and cylinder angles of inclination including 30°, 45° and 60°. The hydrodynamically fully developed condition has been achieved by using aluminum entrance section pipes (calming sections) having the same inside diameter as test section pipe but with variable lengths. The entrance sections included two long calming sections, one with length of 180 cm ($L/D = 60$), another one with length of 240 cm ($L/D = 80$) and two short calming sections with lengths of 60 cm ($L/D = 20$), 120 cm ($L/D = 40$). The results present the surface temperature distribution along the cylinder length, the local and average Nusselt number distribution with the dimensionless axial distance Z^+. For all entrance sections, the results showed an increase in the Nusselt number values as the heat flux increases and as the angle of cylinder inclination moves from $\theta = 60°$ inclined cylinder to $\theta = 0°$ horizontal cylinder. The mixed convection regime has been bounded by the convenient selection of *Re* number range and the heat flux range, so that the obtained Richardson numbers (*Ri*) is varied approximately from 0.13 to 7.125. The average Nusselt numbers have been correlated with the (Rayleigh numbers/Reynolds numbers) in empirical correlations.

Keywords: Combined convection; Thermally developing aiding flow; Inclined circular cylinder; Constant heat flux

1. Introduction

Combined convection heat transfer exists when natural convection currents are the same order of magnitude as forced flow velocities. The term ‘mixed convection’ is also used, and the flows may be internal or external to a bounding surface. Forced flows may be horizontal, vertical or some angle between. The interactions of buoyancy-driven components of velocity and forced flow velocities can have a profound effect on the velocity profile and heat transfer coefficient. In aiding flows (heating in upflow or cooling in downflow), the velocities of forced flow and buoyancy forces are in the same direction, and laminar-like flow is preserved even if the Reynolds number based on forced flow average velocity is nominally in the turbulent region [1]. Hence aiding flow situations are amenable to laminar flow analysis, and that is the subject of the present work. Combined convection heat transfer in cylinders is encountered in a wide variety because of practical importance in engineering applications such as in heating or cooling of heat exchangers for viscous liquids, heat exchangers for gas flows, cooling of electronic equipment and cooling core of nuclear reactors [2]. Due to the practical significance of studying laminar convection heat transfer in the entrance region of circular cylinder, the entrance sections, which have been used in the present experimental work, included

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1359-4311/$ - see front matter
doi:10.1016/j.applthermaleng.2006.11.006

Nomenclature

A_s	cylinder surface area (m^2)
C_p	specific heat at constant pressure (J/kg °C)
D	cylinder diameter (m)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/m^2 °C)
I	heater current (ampere)
k	thermal conductivity (W/m °C)
L	cylinder length (m)
$\dot{m}$	mass flow rate (kg/s)
$Q_{cond.}$	conduction heat loss (W)
$q_{conv.}$	convection heat flux (W/m^2)
$Q_{conv.}$	convection heat loss (W)
Q_t	total heat input (W)
R	cylinder radius (m)
t	temperature (°C)
V	heater voltage (V)
x	axial distance (m)

Greek

θ	cylinder angle of inclination
β	thermal expansion coefficient, (1/K)
μ	dynamic viscosity (kg/m s)
v	kinematic viscosity (m^2/s)
ρ	air density (kg/m^3)

Dimensionless group

Gr	Grashof number $= g\beta D^3(t_s - t_a)/v^2$
Nu	Nusselt number $= h \cdot D/k$
Pe	Peclet number $= Re \cdot Pr$
Pr	Prandtl number $= \mu \cdot C_p/k$
Ra	Rayleigh number $= Gr \cdot Pr$
Re	Reynolds number $= \rho \cdot v \cdot D/\mu$
Ri	Richardson number $= Gr/Re^2$
Z^+	dimensionless axial distance $= x/D \cdot Re \cdot Pr$

Subscripts

a	air
b	bulk
calm.	calming
f	film
i	inlet
m	mean
s	surface
x	local

Superscript

–	average

four entrance sections (calming sections) with different lengths that in which the flow is hydrodynamically fully developed at entrance of the heat transfer pipe. From the following experimental and theoretical survey; very little investigators have dealt experimentally with thermally developing laminar flow mixed convection in an inclined circular cylinder with the influence of cylinder orientation on the heat transfer process with different entrance section lengths. The present work also has emphasized on the laminar range of Reynolds number and Grashof number since most of researchers have used the turbulent range rather than the laminar range, so that the mixed convection regime could be bounded by *Ri* range. In addition this work is a step toward broadening the scope of experimental investigations and fulfilling the existing gap in the experimental data for laminar range so that more empirical correlations for an inclined circular cylinder can be developed since these correlations are very limited and so sparse. Iqbal and Stachiewicz [3] studied theoretically upward fully developed laminar flow inside circular tube with constant pressure gradient and constant wall heat flux. The velocity, temperature fields and Nusselt number were calculated by perturbation analysis and expressed in terms of power series of Rayleigh number. It was concluded that as the tube inclination varies from horizontal, the Nusselt number increases up to maximum value which may occurs before the vertical position was reached. Cheng and Hong [4] presented a numerical solution using a combination of boundary vorticity method and line iterative relaxation method for fully developed upward laminar flow in tubes subjected to thermal boundary conditions of axially uniform wall heat flux and peripherally uniform wall temperature at any axial position. The results showed that in high Rayleigh number regime, the tube orientation effect had considerable influence on the results in the neighborhood of horizontal position. Sabbagh et al. [5] performed experimental study for simultaneously developing air flow in an inclined circular tube with uniform peripheral temperature and axial wall heat flux. The variation of the Nusselt number with tube angles of inclination has been compared with theoretical studies done by Iqbal and Stachiewicz [3] at low Rayleigh numbers and low Reynolds numbers. Barrozi et al. [6] reported experimental data of heat transfer for upward flow in inclined heated circular tubes for the range of $200 \leqslant Re \leqslant 2300$, $6 \times 10^3 \leqslant Gr \leqslant 7 \times 10^5$ and $10° \leqslant \alpha \leqslant 60°$. It was noted that the local Nusselt number first decreases along the heated length reaching a minimum and then increases to the fully developed value. Variation of Nusselt number with α was found to be very small, probably due to the small values of *Gr* number used in the study. Choudhury and Patankar [7] performed a numerical analysis of developing, laminar mixed convection with significant buoyancy effects in the entrance region of isothermal tubes. The results have revealed that the buoyancy effect had a considerable influence on the fluid flow and heat transfer characteristics of the development flow.