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Heat & mass transfer characteristics of natural convective flow in ducts – An application to solar water heating system

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ABSTRACT

The present work deals with experimental studies on heat transfer and flow characteristic for buoyancy induced flow through inclined tubes. The parameters varied during the experimentation are; tube inclination and heat supply. It was found that mass flow rate and heat transfer coefficient increases with increase in heat flux supplied. The flow rate decreases for increase in tube inclination.

Introduction

Heat transfer by natural convection inside a duct (circular or square) has large number of application in industries. These include solar water heating system; cooling of gas turbine blades, heat exchanger etc. The heat transfer and flow characteristics with respect to various parameters plays a vital role for design of such systems .The present work is carried out a specific application in mind, i.e. domestic solar water heating system.

Presently most of the dimensions of solar water heater are standardized from some other commercial consideration and not necessarily giving the best thermo-siphon results. Very little information is available in the literature on the heat transfer characteristics for buoyancy-induced flow through inclined tubes [1, 2, 3, and 4]. The present work aims to study the effect of tube inclination, and heat flux on heat transfer and flow characteristics for buoyancy induced flow through inclined tube and to develop an experimental model. Hence this work is undertaken.

Nomenclature

a = Side of the square duct (m)
h= Heat transfer coefficient (W/m2 oC)
q = Heat flux (W/m2)
m = Mass flow rate (ml/min)
g = Acceleration due to gravity (m/sec2)
T = Temperature, (oC)
K = Thermal conductivity (W/moC)
Cp = Specific heat of constant pressure, (KJ / kg K)

Dimensionless Number

Gr = Grashof Number (β g ΔT a^3 / ν^2)
Nu_u = Nusselt Number (h a / k)
Pr = Prandtl Number (μ C_p / k)
Ra = Rayleigh Number (Gr Pr)
Re =Reynolds Number (4 m / ($\prod$aμ)

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Greek Symbols

θ = Angle of Inclination (degree)
β = Coefficient of Thermal Expansion, K^{-1}
ν = Kinematic Viscosity, (m^2 / sec)
μ = Dynamic Viscosity, (N-s /m^2)

Experimental set-up

A schematic of the test set up & photograph is shown in Figure 1.It consists of a long aluminium tube. The tube is wound uniformly with a 90-gauge Nichrome wire to provide a uniform heat flux condition on the tube surface. The power supplied is measured directly with the help of pre-calibrated digital wattmeter. The tube will be fully insulated to reduce the external heat loss. The tube is connected to a constant headwater tank and flow is measured with the help of a calibrated measuring jar. Thermocouples were used to measure the wall and water inlet and outlet temperatures. The arrangement and methodology suggested by Thombre and Prayagi [4], was adopted for this purpose. About four thermocouples were used to measure the wall temperature.

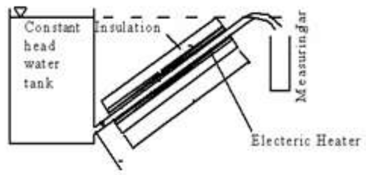

Fig 1. Experimental set-up

Two thermocouples were used to measure inlet and outlet temperature of water flowing through the pipe. A linear temperature variation was assumed from inlet to the exit of the flowing water. It is well justified since the boundary condition created at the pipe surface is a uniform heat flux boundary condition. The dimensional details of the experimental set-up and the parameters varied during the experimentation are given in table -1

Table 1. Details of the experimental set-up

Sr.No.	Parameter	*Range*
1	Length of the tube	1.5m
2	Side of the square duct	0.012 m
3	Inclination of the tube (θ)	$20^0, 30^0, 45^0$ and 60^0
4	Heat flux supplied (q)	200 W/m^2 to 7000 W/m^2
5	Type of insulation used	Asbestos
6	Fluid used	Water

Results

The steady state data generated on the experimental set-up for different values of tube inclination and heat flux where correlated for heat transfer and flow characteristic as described below.

Heat transfer characteristics:-

The increase in the heat transfer coefficient for different values of tube inclination with respect to heat flux in shown in figure 2. It represents the effect of heat supplied on the fully developed heat transfer coefficient for the test section of 20 degree-12mm side of square duct and 1.5 m in length.

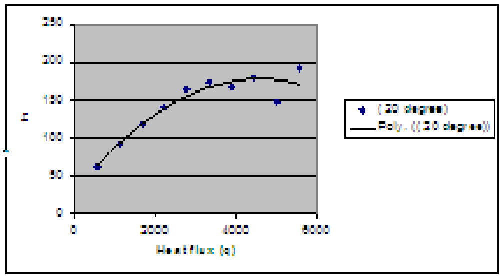

Figure 2 Heat transfer characteristics

It can be seen from the figure that with increase in the value of heat supplied the heat transfer coefficient tends to increase. This is due to the fact that with increase in heat supplied the buoyancy force tends to increase. The net effect of this is to increase in mass flow rate of liquid through the tube. The same trend was observed for the other configurations.

Conventionally the heat supplied (the main driving force) is represented by Rayleigh number, where as the heat transfer coefficient is represented by the Nusselt number. Hence in the present study the heat transfer characteristics are obtained by correlating the Nusselt number with the Rayleigh number.

Figure 3 shows the plot between the Nusselt number and the Rayleigh number for the entire configuration investigated.

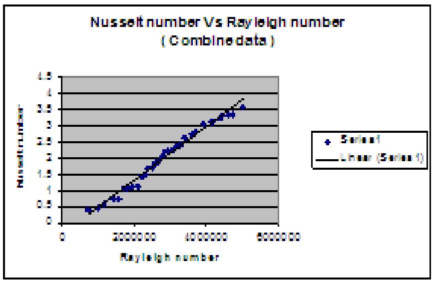

Figure 3 Nusselt number versus Rayleigh no.

Figure 3 Nusselt number versus Rayleigh no.

It can be seen from this figure that Nusselt number increases with increase in the Rayleigh number.This is an expected result. Since increase in Rayleigh number, increases the buoyancy force and hence the flow rate and the Nusselt number. Typically for increase in Rayleigh number by about 50 %, the increase in the Nusselt number is around 30 %.This is attributed to the fact that if heat supplied is increased, the corresponding system equilibrium temperature will also increase there by leading to more heat loss from the system. Further the increase in heat loss depends upon the heat capacity of the liquid Higher the heat capacity, lower will be the heat loss and vice versa. The correlation (best fit curve) obtained from the above figure is as follows.

$$Nu=1*10^{-9}Ra^{1.442}$$

This equation is valid for Rayleigh number ranging from 7 x 10^5 to 5 x 10^6 and Reynolds number ranging from 36.58 to 473.6.

Flow characteristics:-

Figure 4 represents the effect of heat flux on the flow rate for test section 30 degree-12 mm sides of square duct and 1.5m in length. The following observations were made:

a. The induced flow rate increases with the heat supplied and the variation is nearly parabolic. This is in accordance with the mathematical results derived from the equation.
b. The same trend was also observed for other configurations investigated. The same trend was also observed for other configurations investigated.

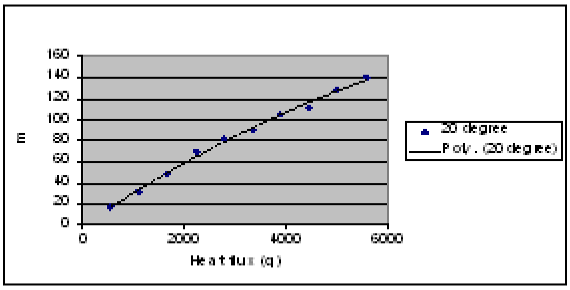

Figure 4 Flow characteristics

Conventionally the heat supplied for the buoyancy force is represented by the Rayleigh number where as the induced flow rate established is represented by Reynolds number. Hence to obtain Mass flow characteristics, the Reynolds number is correlated with Rayleigh number. The relevant data is plotted in the figure 5

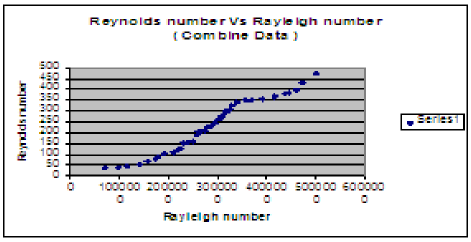

Figure 5 Reynolds number versus Rayleigh number

It can be seen from the figure 5 that, the Reynolds number increases with increase in the value of Rayleigh number. Typically it was observed that for increase in Rayleigh number to from 3 x 10^5 to 4 x 10^5, the percentage increase in the value of Reynolds number was around (30-35 %). This is an expected variation as increase in Rayleigh number, increases the buoyancy force which results in higher mass flow rate. Thus from the above analysis it can be concluded that Reynolds number is dependent upon Rayleigh number.

The correlation (best fit curve) obtained from the figure 6 is as follows.

$$Nu = 0.029 * Re^{0.7864}$$

Validation of experimental set-up

Experiment is validated against the laminar forced convection which is available in the literature i.e.

Nu = h a / k = 3.64.

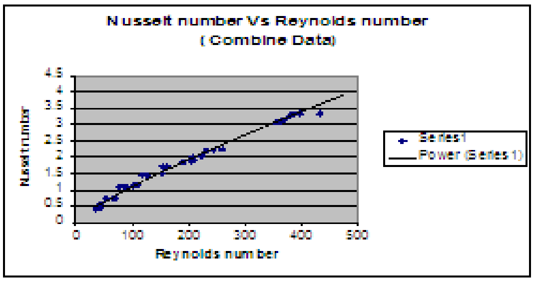

Figure 6 Reynolds number versus Rayleigh number

Conclusions

Experiment were performed to study heat transfer and flow characteristic for buoyancy induced flow through inclined tube of square duct with different inclinations and various heat flux. The following observations were made.

Heat transfer characteristics

- The heat transfer coefficient is strongly influenced by heat flux.
- Increase in heat flux, the heat transfer coefficient is also increases.
- The heat transfer coefficient is found to be weak function of the tube inclination.

The correlation obtained is as follows:

$Nu = 1 * 10^{-9} Ra^{1.442}$

Mass Flow characteristics

- The mass flow rate increases with the heat supplied and the variation is parabolic.
- The mass flow rate is strongly influenced by heat flux.
- The mass flow rate is found to be practically independent of the tube inclination and tube length.

The correlation obtained is as follows:

$Nu = 0.029 * Re^{0.7864}$

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