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Original Research Article

Experimental Investigation on Natural Convection in Cylindrical Enclosure Having Different Orientations

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Abstract

Natural convection in water inside an enclosure between two concentric cylinders has been investigated experimentally during heating and cooling process. This is made by the flowing of water as heat transfer fluid through the inner tube of the test section. The temperature distribution of water filled in the enclosure is established during heating and cooling process. As the natural convection phenomenon majorly depends on the heat source and orientation of the test section, the effect of mass flow rate and inlet temperature of heat transfer fluid on temperature distribution and heat transfer rate is investigated, first. Afterward, the effect of inclination of the test section on the temperature distribution is also established. The test section is inclined at 45^o, 75^o and 90^o with the horizontal. The results obtained with different angle oriented test section are compared with the horizontal test section. It is found, convection heat transfer is dominant in heating process while in cooling process conduction mode of heat transfer dominated over convection. It is also observed that during the heating process, heat transfer rate is higher for vertical test section as compared with the other inclinations.

Keywords: Heat Transfer, Natural Convection, Enclosure, Orientation.

INTRODUCTION

Heat transfer and fluid flow in annulus are important phenomena in engineering systems because of their technological applications in heat exchangers, nuclear reactors, thermal storage systems, cooling of electronic devices, gas-cooled electrical cables, thermal insulation etc. Other than this, inclined type enclosures often find application in solar collectors, that is, heat transfer in the space between the glass cover and the absorber plates. The inclination angle significantly affects the rate of heat transfer. Several investigations have been carried out in this domain. The natural convection heat transfer phenomenon in vertical and horizontal rectangular enclosures has been studied by various researchers. The simplest configuration of natural convection within an enclosure is based on the presence of a single heat source. The effect of localized heating in rectangular channels was studied by Chu *et al.* [1]. They obtained results by solving the partial differential equations numerically for the conservation of mass, momentum and energy using an unsteady formulation and the alternating-direction-implicit method. It was concluded that the relationship between the circulation pattern and the rate of heat transfer was quite complex. Chao *et al.*, [2] studied the effects of inclination angle in a partially heated rectangular cavity and they showed that the inclination angle has much significance as control parameter. Despite differences in the Prandtl and Rayleigh numbers, the observed and predicted patterns of circulation were in good agreement, and the measured and predicted rates of heat were in qualitative agreement. Ho and Chang [3] investigated natural convection heat transfer inside a vertical rectangular enclosure using four two-dimensional discrete flush-mounted heaters. They carried out numerical and experimental analysis to unveil primarily the influence of aspect ratio of the enclosure. Numerical results revealed that the increase of the aspect ratio leads to substantial degradation of convective dissipation from the discrete heaters. Frederick and Quiroz [4] studied the natural convection inside a cubic cavity for the Rayleigh number range between 10^3 and 10^7. They concluded that, for the Rayleigh numbers higher than $10^5$the convection heat transfer mechanism dominates the conduction heat transfer. Saeid *et al.*, [5] numerically investigated the natural convection in two-dimensional porous cavity by considering the horizontal walls as uniform hot and cold sources while the vertical walls were adiabatic. The bottom wall was heated under spatial sinusoidal temperature variation around a constant mean value. The author studied the effect of heat source length and amplitude of bottom wall temperature for Rayleigh number ranging from20 to 500. They reported that the average Nusselt number increases with the length and the amplitude of the heat source. It was also observed that the heat transfer per unit area of the heat source decreased by increasing the length of the heated segment. Varol *et al.,* [6] studied numerically the heat transfer of Newtonian fluid due to natural convection in a right triangle enclosure with flush mounted heater on the wall. It was shown that the heater position can control the heat transfer within the enclosure. The highest enhancement was achieved when the heater is positioned at the top of the vertical wall because of the intersection between the heat and cold zones. Cheikh *et al.,* [7] examined the effect of boundary conditions on free convection heat transfer in a cavity filled with air. The bottom wall was partially under a constant heat flux while other sections of the cavity were kept in a cold temperature or had been insulated. In this work, the Rayleigh number changed between 10^3 and 10^7 while the length of heated portion can be varied. The maximum Nusselt number was dependent upon the size of the heated section and the value of Rayleigh number. Alam *et al.,* [8] carried out a comprehensive numerical investigation on the natural convection in a rectangular enclosure using the finite element method. They observed that the local heat transfer is increased as the aspect ratio increases with maximum heat transfer occurring in square enclosures. The numerical experiments show that increasing of Rayleigh number implies the enhancement of thermal buoyancy force, which in turn increased the thermal convection in the cavity. Heris *et al.,* [9] investigated experimentally the effects of inclination angle on the natural convection of nanofluids inside a cubic cavity with the side size of 10 cm. One of the surfaces of the cavity was kept in cold temperature and another one (opposite side) in hot temperature while the other four surfaces were insulated. The mixtures of three different types of nanoparticles including Al_2O_3, TiO_2, and CuO within turbine oil (TO) were used as the heat transfer fluid. The heat transfer in the cavity was investigated in three inclination angles with respect to the horizontal position including 0°, 45° and 90°.The weight fractions of nanoparticles were 0.2%, 0.5%, and 0.8%. It was found that at the inclination angle of 90°, and the weight fraction 0.2%, the application of TiO_2 particles resulted in the maximum Nusselt number while for weight fraction of 0.8%, the maximum Nusselt number was associated with the CuO Nano powders. From the literature it is found that natural convection phenomenon in a rectangular enclosure filled with air has been widely investigated. However, rare literatures are found where effect of inclination of enclosure on natural convection of water/air is established. Thus the objective of the present work is to investigate the thermal performance of water filled in single shell and tube heat exchanger at different fluid inlet temperature and mass flow rate of heat transfer fluid. The effect of inclination of the test setup on temperature distribution of water is also going to be established.

EXPERIMENTAL SETUP

The line diagram of experimental setup is shown in Figure-1 along with the actual setup in Figure-2. The setup mainly consists of single shell and tube heat exchanger (test section) and water circuits. The test section consists of two concentric cylinders of length 0.6m each. Inner one is made of brass with inside diameter 0.033 m. Outer tube is made of stainless steel with inside diameter of 0.128 m. The outer cylinder is thermally insulated well with cerawool to avoid heat loss to the surroundings. The annulus space between the inner and the outer tube is filled with water. Water as HTF is circulated through the inner tube for heating and cooling process. The flow of HTF is operated through manually operated valves. The hot bath and the hot water circuit are insulated in order to prevent any heat loss to the surroundings.

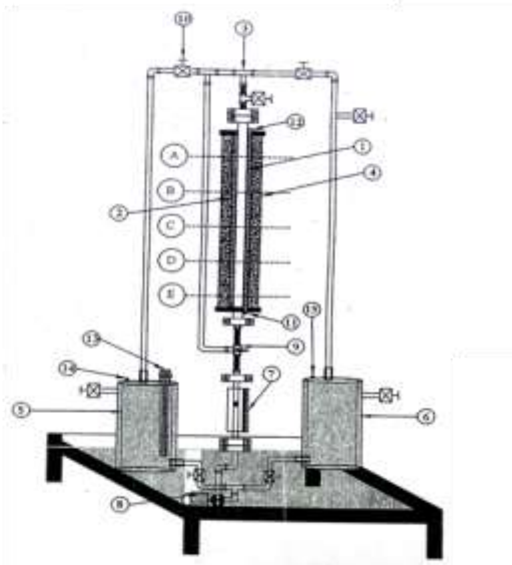

Fig-1: Line diagram of experimental setup

Fig-2: Actual experimental setup

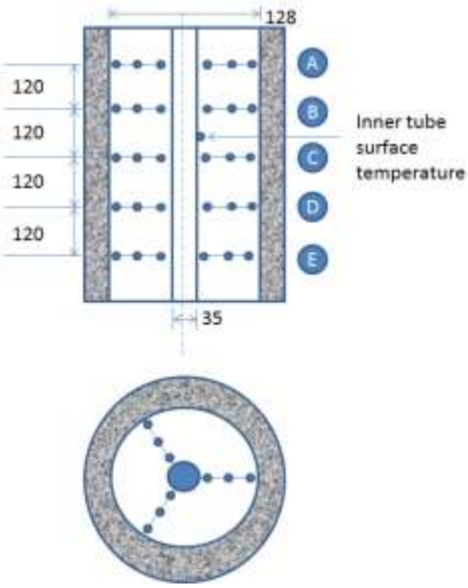

Fig-3: Thermocouples locations (numeric figures are in mm)

Total forty-five thermocouples (K-type) are used to measure temperature distribution of shell side water in radial and axial direction. Three thermocouples are fixed at the same junction, i.e., near the HTF pipe (1 mm away from HTF pipe), at the centre (24 mm away from HTF pipe) and near outer shell (46 mm away from HTF pipe) for radial measurement. These three temperature probes are also installed at 120 degrees of angular interval in the same radial plane. Thus, in one radial plane, nine thermocouple probes are used. These nine probes are installed at five different axial planes, (A, B, C, D and E) at equal axial distance. Two thermocouples are placed at the upstream and downstream of the HTF pipe to measure the HTF inlet and outlet temperatures. One more thermocouple is placed on the outer surface of HTF pipe. All temperature probes (K type thermocouples) are calibrated according to immersion probe temperature sensor. The positions of different thermocouples in the test set up are shown in Figure-3.

RESULTS AND DISCUSSIONS

Temperature distribution of the shell side water with time is established for different mass flow rates and fluid inlet temperature of HTF for heating and cooling process. The effect of inclination of test section on non-dimensional term of heat transfer i.e., heat fraction is also investigated. After ensuring the leakproofness of the system, reliability and calibration of the instruments, the experiment was performed for vertical, horizontal and inclined test section ($45^o, 75^o$). Uncertainty analysis was also carried out to establish the uncertainty in the heat transfer evaluation based on the errors associated with temperature and flow measurement, it was found the heat transfer uncertainty not to be above 5%.

Heating Process

Figure 4(a) & (b) show the axial temperature distributions of vertical test section with HTF flow rate of 5 kg/min and 1 kg/min respectively. TA4, TB4, TC4, TD4 and TE4 are the thermocouples located at the mid-section of planes A, B, C, D and E. It is observed from figure 4(a) that the temperature of the various planes increases with time. Also, initially the rate at which the temperature rises is higher up to15 minas initially the temperature gradient available for the heat transfer is more. As time passes the temperature gradient reduces, consequently the rate of temperature rise gradually decreases. Finally, the steady state is reached after 28 min. Further it is noticed that the temperature is maximum at the top plane A and minimum at the bottom plane E. This is for the obvious reason of natural convection heat transfer in which heated portion is accumulated at the upper regions or spaces. Thus temperature of water at the top is higher than the same at the bottom even though hot water passes from the bottom.

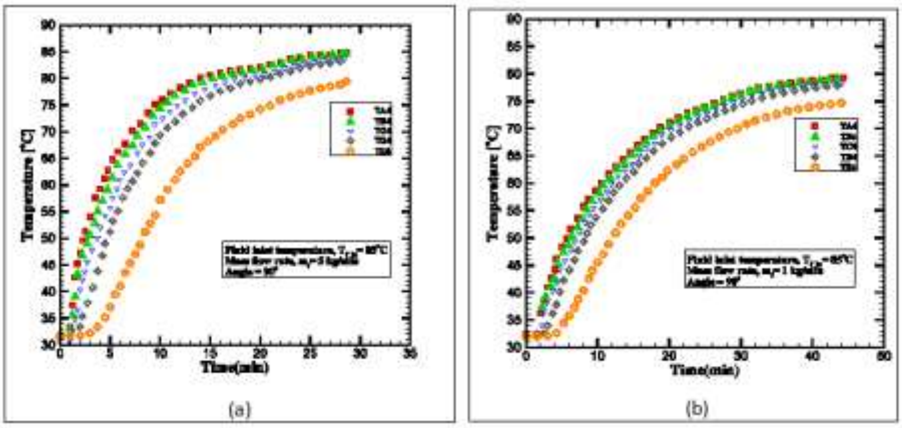

Fig-4: Variations of water temperature with time at mid-surface when (a) $m_f = 5\ kg/min$, and (b) $m_f = 1\ kg/min$

The same way, it is noticed from the figure 4(b) that the rate of temperature rise is higher-up to20 min thereafter it approaches steady state and the rate reduces. The nature of both the figures is same with some quantitative difference. From figures 4(a) and (b), it is observed that the steady state is reached 13 min earlier for mass flow rate of 5 kg/min than 1 kg/min mass flow rate. This is because at higher mass flow rate turbulence occurs which enhances the heat transfer; also due to this very reason maximum attainable temperature in Figure 4(b) is not reaching 85^{0}C, i.e., fluid inlet temperature.

Further it is also noted from the figures that the temperature deviation at different planes at the same time is higher for mass flow rate of 5 kg/min than that of 1 kg/min. This reflects that the effect of natural convection is higher in case (a). While in case (b), heat transfer from HTF tube to water is almost uniform, this indicates lesser effect of natural convection phenomenon.

Figure 5 shows the temporal variation of temperature at different sections (inner, mid and outer section) at the two planes A and D with the HTF flow rate of 5 kg/min and fluid inlet temperature of 85^oC.

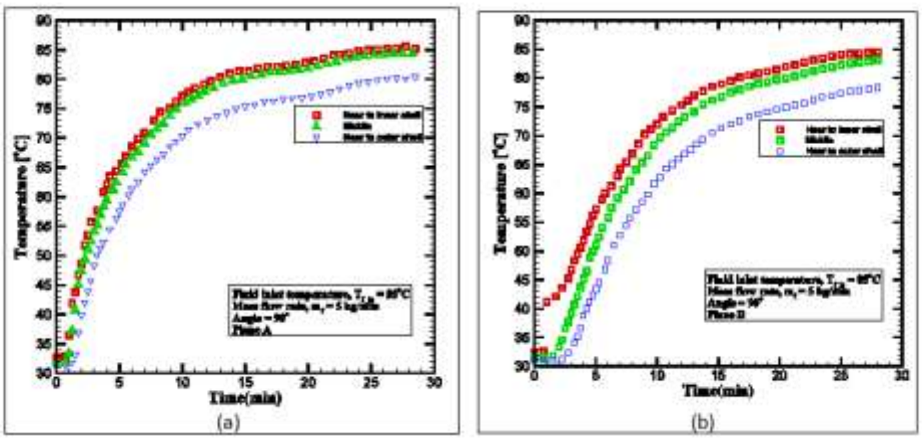

Fig-5: Radial temperature variation of water with time during heating process, at (a) Plane A, and (b) Plane D

Figure 5(a) shows that the temperature of water at plane A increases with time. As temperature of water near outer shell is far from HTF tube, its temperature is lower compared to temperature near inner shell and middle. Figure 5(b) shows the same temperature distribution at plane D for fluid inlet temperature of 85^oC and mass flow rate of 5 kg/min. Here, in this figure it is noticed that temperature gradient between two section is significant than that in case (a). Thus it may be concluded that the effect of natural convection is higher at the top of the test section rather than at the bottom. As the heat transfer due to natural convection is higher at the top, temperature gradient is smaller between the radial planes at the top. In short it is concluded that heat transfer in the water takes place from top to bottom along the radial direction for heating process.

Cooling Process

Figure-6 shows the temporal variation of temperature of mid-section at different planes during cooling process with the water flow rate at 5 kg/min and fluid inlet temperature is 35^oC.It is noticed from the figure that the rate of cooling is higher up to 15 min thereafter it decreases.

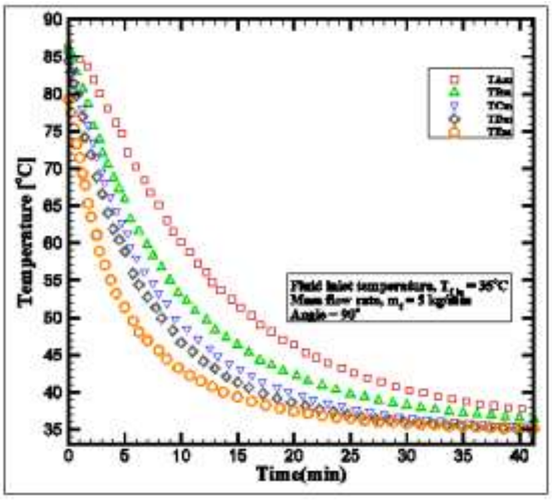

Fig-6: Variation of water temperature with time at axial planes A, B, C, D, E at mid surface during cooling

It is also observed from figure that during cooling process plane E cools down at the fastest rate while plane A has the lowest cooling rate. As cold water flows from bottom to the top, temperature of water at E cools faster due to higher temperature gradient. However, during cooling process, more time is required to get steady state than process.

Figure-7 shows the variation of temperature with time at axial plane A at different radial distance (inner, mid and outer sections) during the cooling process. From the figure it is seen that temperature of water at near to inner shell, middle and near to outer shell is almost equal. This indicates heat transfer from inner shell to outer shell is faster and uniform due to conduction. Thus it is concluded that during cooling process, heat transfer takes place from bottom to top along radial direction. While during heating process heat transfer takes place from top to bottom due to natural convection induced by buoyancy forces due to temperature difference.

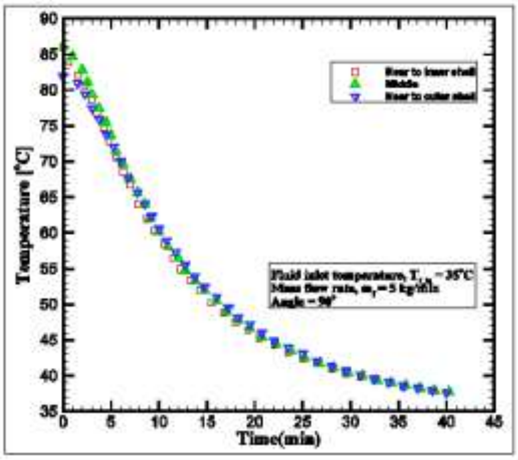

Fig-7: Variation of water temperature with time at axial plane A at different radial distance during cooling

Effect of mass flow rate

Figure-8 shows the effect of different mass flow rate of HTF on temperature of the water contained in the shell side of the test section during heating process. The inlet temperature of the HTF is being at 85^oC and the test section remaining at 90^o angle.It is noted from the figure 8 that initially the rate of temperature rise is higher and nearly same for the HTF flow rate 3 kg/min and 4 kg/min up to 10 min thereafter the temperature rises at faster rate for HTF flow rate of 4 kg/min (Re= 7860) followed by 3 kg/min (Re= 5821), 2 kg/min (Re= 3777) and 1 kg/min (Re= 1857). Thus it can be said from the figure 8 as mass flow rate increases from 1 kg/min to 4 kg/min in steps of 1 kg/min, the time taken to get steady state increases by 11%, 37% and 66% respectively. Further it is also noticed that temperature difference of water at flow rate 3 kg/min and 4 kg/min is smaller because for these mass flow rates the flow becomes turbulent. This enhances the heat transfer. The temperature gradient at the mass flow rate of 2 kg/min and 1 kg/min is higher because flow is laminar which reduces the heat transfer. In short, as the mass flow rate increases from 1 kg/min to 4 kg/min the time taken by the process to reach steady state reduces.

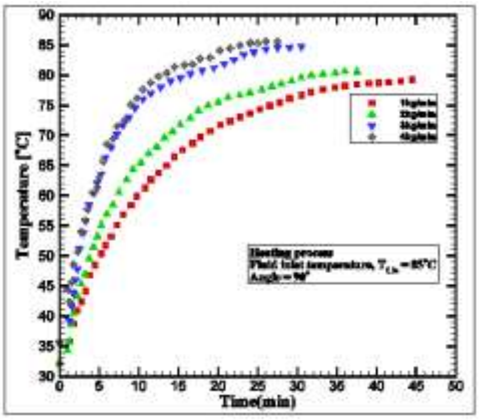

Fig-8: Effect of different mass flow rate of HTF on temperature of water with time at fluid inlet temperature of 85^oC

The effect of mass flow rate on heat transfer rate is also established. The total heat storage capacity of a fluid depends on operating parameters and physical parameters of the experiment and the fluid used. A non-dimensional heat fraction (Q^+) during the heating process may be defined as the ratio of energy input to the fluid up to a particular instant of time to the total energy input up to the steady state attainment of the fluid. This parameter indicates the relative contribution of experimental parameters. The amount of total heat storage is calculated as [10]:

$$Q_{tot} = \int_0^{t_1} qdt + \int_1^{t_1} qdt + \cdots + \int_{n-1}^{t_n} qdt \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

So, heat fraction is calculated as follows:

$$Q^+ = \frac{\int_0^t qdt}{Q_{tot}} \ldots\ldots\ldots\ldots\ldots (2)$$

Figure-9 shows the variation of heat fraction with time for HTF mass flow rate of 1 kg/min, 3 kg/min and 5 kg/min. The fluid inlet temperature is kept at 85^oC keeping the test section vertical. The heat fraction approaches to 1 as time passes.

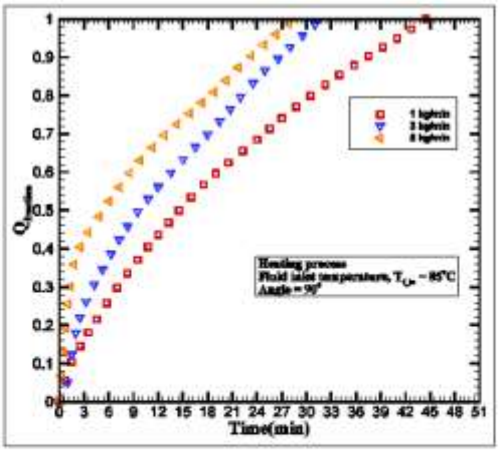

Fig-9: Effect of mass flow rate of HTF on heat fraction during heating process

It is noticed from the figure that initially the heat gaining rate of shell side water is maximum for the HTF flow rate of 5 kg/min and it is minimum for the HTF flow rate of 1 kg/min. Consequently, the time taken to reach heat fraction equal to one is 44 min, 30 min and 22 min for the mass flow rate of 1 kg/min, 3 kg/min and 5 kg/min respectively. That means if the HTF mass flow rate is increased from 1 kg/min to 5 kg/min the time taken by the heat fraction to reach the value 1 is reduced by 50 %.

Effect of Fluid Inlet Temperature

The figure-10 shows the variation of temperature with time at the plane A, for different fluid inlet temperature. The test section is kept at 90^o angle with respect to the horizontal, the HTF mass flow rate is kept constant at 5 kg/min. The fluid inlet temperature varies from 75^oC to 85^oC in the step of 5^oC (i.e.75^oC, 80^oC and 85^oC).

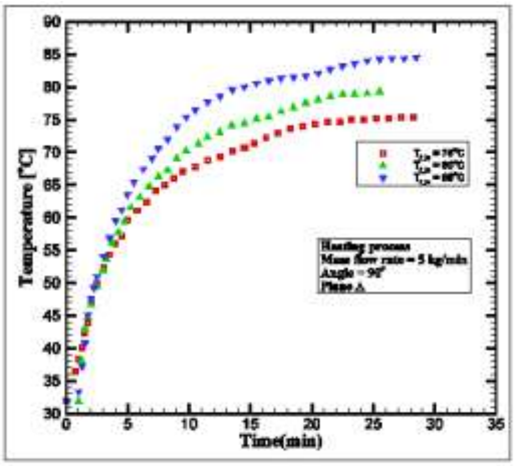

Fig-10: Temporal variation of temperature of plane A with different inlet temperature

As the fluid inlet temperature increases the heat transfer rate increases due to increase in temperature gradient for the heat transfer to take place. Thus the rate of temperature rise is higher for fluid inlet temperature of 85^oC and it decreases asfluid inlet temperature decreases from 85^oC to 80^oC and then to75^oC. As the HTF inlet temperature increases from 75^oC to 85^oC the water temperature at plane A increases by 29 % at around 20 min after starting of heating process.

Figure-11 shows the effect of fluid inlet temperature on heat fraction with time for mass flow rate 2 kg/min during heating process of water. It is clear from the figure that as fluid inlet temperature is decreased from 85^oC to 80^oC , system takes approximately 6 min more to reach heat fraction of 1. While it takes approximately 11 min more to reach heat fraction of 1 for fluid inlet temperature of 75^oC. Thus the time required to reach heat fraction of 1 increases by 19 % and 28 % when fluid inlet temperature is decreased from 85^oC to 80^oC and then to 75^oC respectively. This is because higher temperature difference between HTF and shell side water. This enhances the heat transfer in the system. The linear variation of heat fraction observed, indicates uniformity in the rate of heat transfer.

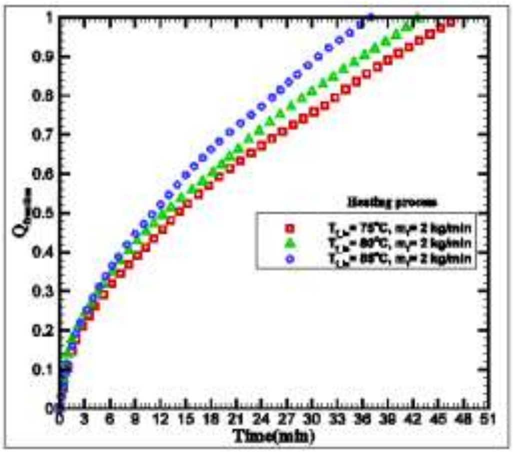

Fig-11: Effect of fluid inlet temperature on heat fraction during heating with (a) $T_{f\_In} = 75^oC$, (b)$T_{f\_In} = 80^oC$, and (c) $T_{f\_In} = 85^oC$

Effect of inclination of test section

After the successful experimentation carried out on vertical test section, the effect of inclined test section on natural convection is also carried out experimentally. The provision is made in the test rig that test section can be rotated from vertical to horizontal with the inclination angle of 15^{o}. Thus the test section can be rotated for 0^{o} to 90^{o} with the successive difference of 15^{o}. First, the test section is kept in horizontal position, that is, at an angle of 0^{o} .Figure 12 shows the temperature variation of water with time for horizontal and vertical test section. The mass flow rate and inlet temperature of fluid is 5 kg/min and 85^{o}C respectively. The temperature profiles are plotted at TA6, TB6, TC6, TD6 and TE6.

The thermocouples TA6, TB6, TC6, TD6 and TE6 are located in the middle surface inside shell at different planes. In case of horizontal test section, these thermocouples are above the HTF tube. Thus, it is observed from figure 12(a) that temperatures of water are almost same for all thermocouples. This is because of all temperature probes are at the same height with respect to the HTF pipe in case of horizontal test section. Thus temperatures are same. Temperature of water at TA6 is slightly lesser than others because this temperature probe is at the exit of the HTF tube. HTF flows in the direction of TE6 to TA6. At the exit, at TA6, HTF outlet temperature is slightly reduced. This may be the reason of having less temperature at TA6 than others.

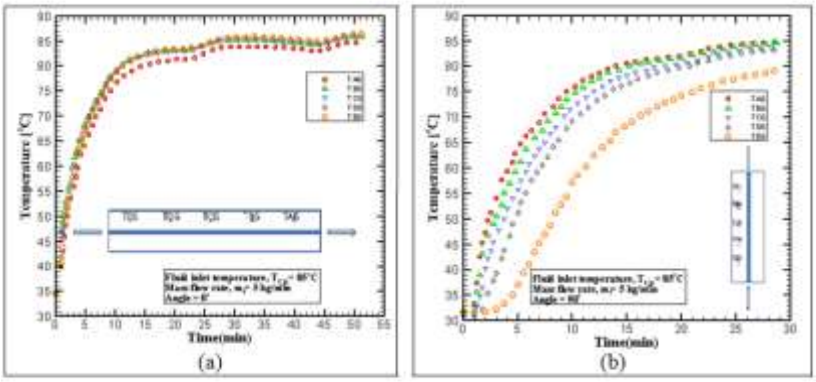

Fig-12: Variations of water temperature with time at axial planes at the centre; 24 mm away from HTF pipe during heating when test section is (a) horizontal, and (b) vertical

However, significant temperature difference is observed at TA6, TB6, TC6, TD6 and TE6 in the case of vertical test section. This is because these temperature probes are at the different heights from horizontal. Due to natural convection, hot fluid raises to the top due to density difference induced by buoyancy forces. Thus, maximum temperature is observed at the top, i.e. TA6. Afterwards the temperature is decreased gradually as one can go from TA6 to TE6, i.e. from the top to the bottom, at particular time.

The figure-13 shows the variation of water temperature at the middle of the annulus of the test section at different orientation during heating at junctions A6 and E4 respectively. The inlet temperature and mass flow rate of HTF is kept constant at 85^{o}C and 5 kg/min respectively. The junction TA6 is at the top position in the test section irrespective of orientation angle. From the figure 13(a), it is observed that temperature of the water for horizontal test section i.e. 0^{o} angle increases rapidly than the others with time. This is because in the case of horizontal test section, the travel distance for natural circulation is less as compared to the other orientated test section.

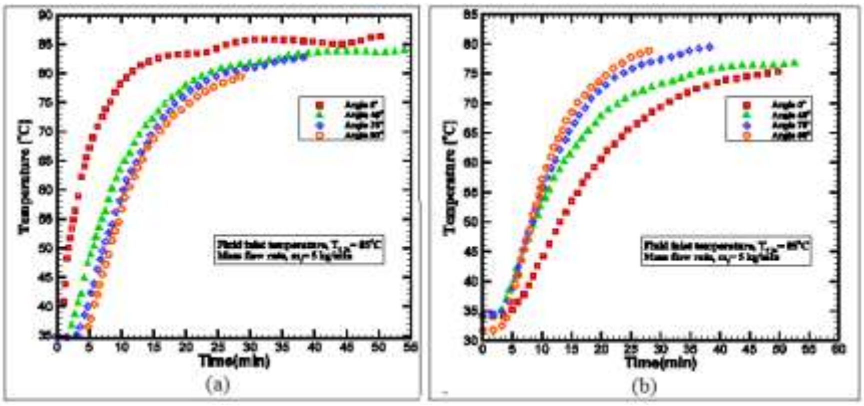

Fig-13: Variation of water temperature with time at axial mid-section during heating at (a) junction TA6, and (b) junction TE4

This may be the reason that the temperature of the water increases rapidly with time in case of horizontal test section. As the angle increases, travel distance for natural circulation is increased. Thus, the temperature is less at a particular instant as the inclination increases from the horizontal. Figure 13(b) shows the temperature variation of water at middle of the annulus of the test section at TE4. From the figure 13(b), it is observed that the temperature of water at TE4 is higher for the vertical test section (i.e., angle 90^{o}) and lowest for the horizontal test section (i.e., angle 0^{o}). This is completely reversed as shown in figure 13(a). In the case of horizontal test section, TE4 is below the HTF pipe. As the HTF pipe is at the top of theTE4, the heat transfer is only due to conduction mode of heat transfer. As the inclination increases from the horizontal, the junction TE4 will be near to the HTF pipe. Thus, in the case of vertical test section, TE4 is at the side of HTF pipe. Thus, due to natural convection in vertical test section, the temperature of water is at TE4 is higher as compared to others. However, these two figures cannot indicate in which type of orientations, the overall rate of heat transfer is more. Thus, the effect of the same on heat fraction is established and which is shown in Figure-14.

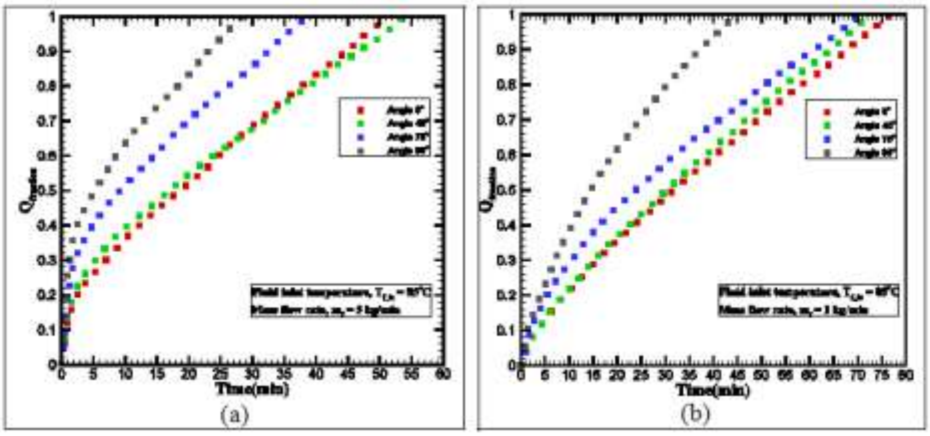

Fig-14: Variation of heat fraction with time when HTF mass flow rate (a) 5 kg/min, and (b) 1 kg/min

The Figure-14 shows the variation of heat fraction with time. It is observed from the Figure-14, that heat fraction reaches its value as one, for vertical arrangement of heat exchanger, earlier as compared to the other inclinations. Figure 14(a) shows the effect of inclination on heat fraction for mass flow rate of 5 kg/min. As the inclination angle is decreased from 90^{o} to 75^{o} the time taken to reach steady state is increased from 27 min to 37 min, which is approximately 37 % increase. When the inclination angle is further decreased beyond 75^{o} to 45^{o}, the time taken to reach steady state increased, that is, approximately 46 % increase. If the angle is again decreased from 45^{o} to 0^{o}, a very little change is observed. Figure 14(b) shows the same profile for the mass flow rate of 1 kg/min. From Figure 14(b), it is noted that it takes 43 min for a vertical test section to reach steady state. When the angle of inclination is decreased from 90^{o} to 75^{o} the time taken to reach steady state is increased approximately by 63 %. After further decrease of inclination angle beyond 75^{o}, no significant change in the time, taken to reach steady state, is observed.

CONCLUSION

The following are the conclusions derived from the experimental study:

- During cooling process, heat transfer takes place from bottom to top along radial direction. While during heating process heat transfer takes place from top to bottom due to natural convection induced by buoyancy forces due to temperature difference.
- If the HTF mass flow rate is increased from 1 kg/min to 5 kg/min the time taken by the heat fraction to reach the value 1 is reduced by 50 %.
- The time required to reach heat fraction of 1 increases by 19 % and 28 % when fluid inlet temperature is decreased from $85^{o}C$ to $80^{o}C$ and then to $75^{o}C$ respectively.
- When the angle of inclination is decreased from 90^{o} to 75^{o} the time taken to reach steady state is increased approximately by 63 %. After further decrease of inclination angle beyond 75^{o}, no significant change in the time, taken to reach steady state, is observed. Thus, in vertical test section heat transfer is observed faster than other orientations.

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