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Experimental Investigation on Natural Convection over a Flat Plate: Implications of Heat Interaction with an External Heat Sink

Chhaya Warathe[1], **Shivanshu Chalotra**[2], **Deeksha Chalotra**[3] **and Vinayak Malhotra**[4]

[1,4]*Department of Aerospace Engineering, SRM University, Chennai, India*
[2]*Department of Mechanical Engineering, SDDIET, Panchkula, India*
[3]*Department of ECE, SMVDU, Katra, India*
E-mail: [1]chhayawarathe@gmail.com, [2]shivanshuchalotra@gmail.comm,
[3]blueskydotmail@gmail.com, [4]vinn99@gmail.com

Abstract—*Transfer of heat through natural convection within a confined passage on a flat plate is investigated in interaction with an external heat sink. Experimentation relates the role of heat transfer coefficient with heat absorbed by the sink. The optimal position of heated plate and sink for wide-ranging applications are predicted. Secondary heat transfer is the primary reason for affecting the heat transferred from the pilot source. Results indicate that small diameter mesh is effective for additional heat transfer whereas, at large orientations wider diameter mesh will be more productive. Intermediate diameter mesh play vital role in energy conservation and can be used for heat transportation in conjunction with varying diameter meshes. Smoother surfaces will are useful in conservation of heat and with the use of varying diameter heat sinks, are more effective in transfer of heat.*

1. INTRODUCTION

Convective transfer of heat is a phenomenon of practical and functional importance with wide range of scientific and engineering applications. The conventional heat transfer theory directs to predict the energy transfer that takes place between hot body and the surrounding fluid. This transfer of energy in aid of temperature difference governs the most of actuated systems whether natural or manmade around us. The transfer of heat by natural mode refers to fluid motion by buoyant forces arising due to density gradients as a result of temperature gradients.

The free mode of convection is prominent in nature with applications ranging from the need of cooling to heating under different surroundings. Some of the articulated examples includes, cooling of electronic devices, reactor cores, high voltage power transformers and heating of houses, heat transfer through chimneys, energy storage systems, in aircrafts coolant flow path to service direction. Generally, the transfer of heat is studied by investigation of vital parameters viz., heat transfer coefficient, power input, flow velocity (forced convection), nusselt number. Whereas, to simplify the subject, the convective heat transfer over a flat plate is probed extensively under diverse conditions. The results have dictated simplified understanding of the operating physics which resulted in wider scope for applications. An interesting aspect in this domain is interaction of the natural convective heat transfer with an external heat influence viz., a heat source or a heat sink. This concern with the secondary heat transfer owing to external influence and related influence on convective transfer of heat. The phenomenon is widely encountered and has necessitated active research efforts to fundamentally understand the mechanisms controlling the compound heat transfer. There is heavy requirement under various conditions which instruct this issue to be addressed however, the issue is *yet to be comprehensively addressed.* The convolution of the problem deals with uneven heat and mass interactions and thus had prevented a complete understanding.

The present work attempts to explore the natural convection over a flat square plate influenced by the presence of an external heat sink (here metallic wire mesh). Here, efforts are directed to understand heat transfer behavior over a square flat plate in the free convection configuration bounded by enclosures. The interest in this class of problems is primarily driven by the need to have better understanding of convective heat transfer.

Following the classical work of [1] over laminar free convection on plates, in the last five decades research works have contributed significantly to the improvement in the understanding of the convective heat transfer. The contributions have been reported in several reviews like [2]-[8]. The works provide an excellent review on the developments up to the end of the century.

Acharya and Tsang [9] showed that the average heat transfer from the enclosure is relatively insensitive to the inclination angle. However, the local values do exhibit a significant dependence on the inclination of the enclosure. Rasoul and prinos [10] studied the effect of the inclination angle on steady natural convection in a square enclosure. They reported that when the hot wall approach the top position (inclination angles greater than 90°), fluid from the hot or cold wall returns back to the same wall and an almost horizontal flow is observed in the central part of the enclosure. Lakhal et al., [11] numerically studied natural convection in an inclined rectangular enclosure with perfectly conducting fins attached to the heated wall. They work stated that the heat losses through the cold wall can be reduced considerably by using fins attached on the heated wall. This phenomenon becomes more pronounced when the enclosure inclination angle from the vertical is increased.

Islam et al., [12] investigated natural convection in a tilted square enclosure containing internal energy sources. They noted that the diffusion heat transfer is prominent for the lower value of internal heat generation whereas the convection outweighs the diffusion for the higher value of internal energy. Furthermore, the work stated that the convective currents always prevail at the bottom part of the cavity whatever its magnitude is. Abu-Nada et al., [13] explored the influence of inclination angle for a square enclosure. Inclination angle of the enclosure was proposed a control parameter for fluid flow and heat transfer. Recently, Tiwari and Malhotra [14] showed that the convective heat transfer rate for laminar flow over a flat plate exhibits a monotonically decreasing behavior with increment in plate orientation for a square plate enclosed from two sides.

While, there is plentiful literature available addressing varied issues to enhance understanding but, the complexity of the problem had prevented a complete understanding due to interaction between flow, heat and mass transfer. In most of the convection problems, the heat transfer characteristics are explored on entities (here square plate) open to atmosphere. The presence of an external heat sink (i.e. metallic wire mesh) partially acts as a heat sink and as an enclosure to the flow. The heat sink take a part of heat transferred from the square plate along with obstructing and thus redirecting the flow to affect the primary heat transfer. The heat transfer characteristics are expected to be altered with varying orientation. *This aspect of convective heat transfer is yet to be explored.* Hence, a systematic study is needed to understand mechanisms controlling the convective heat transfer under effect of heat sinks. In the light of above mentioned works, the present work focuses on variation of convective heat transfer coefficient for varying plate orientation due to existence of an external heat sink under. The specific objectives of the present study are to.

a) Investigate influence of an external heat sink (metallic wire mesh) on convective heat transfer coefficient of a square plate and thus reasoning the optimal heat transfer conditions.
b) Analyze the role of key controlling parameters.

2. EXPERIMENTAL SETUP AND SOLUTION METHODOLOGY

A simple natural convection apparatus (Fig. 1(a & b)) was adapted for this study. The apparatus comprised of base made of mild steel plates which supports the assembly. The glass sheets confine the square plate assembly along the sides except from top and bottom ends which are open to atmosphere. The square plate (15 cm x 15 cm) is made up of aluminum (Fig. 1(c)) with two surfaces viz., smooth and rough and a coil sandwiched in between to ensure required heat power supply. The plate temperature is ascertained with utility of Thermocouples (5 in numbers) embedded in plate (Fig. 1(c)) and located equidistance to embark average plate temperature.

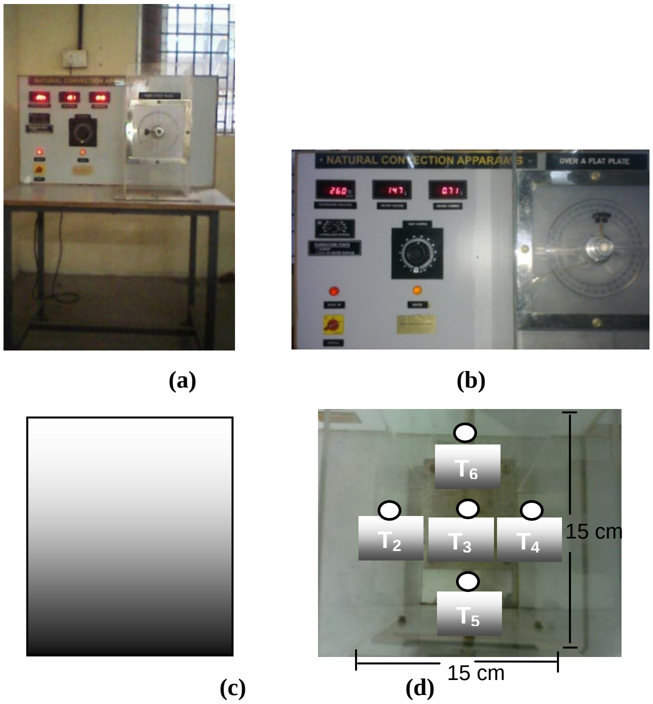
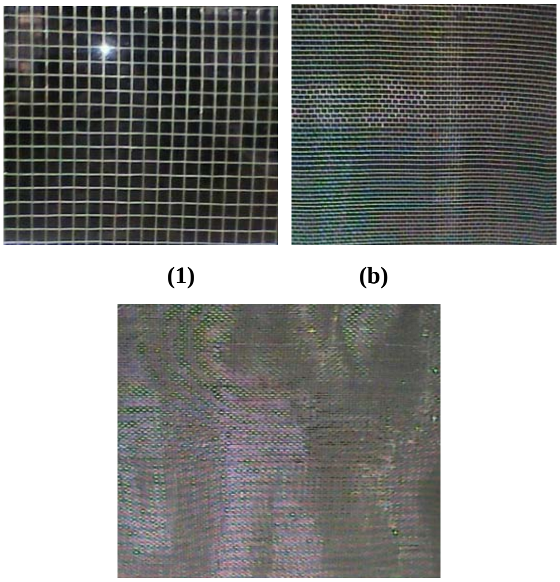


Fig. 1: Pictorial view of the apparatus (a) Experimental setup (b) digital system (c) Top view of square plate (d) schematic of square plate with location of embedded equidistant thermocouples (shown by circles).

In order to facilitate the heat transfer at different orientations, the entire plate assembly can be adjusted with the help of a handle and an attached protractor.

Prior to the experimentation, the plate is heated using electrical power at desired rate for 2 hours. The rate of heating the plate can be adjusted with the help of a handhold and a digital display.



(1) (b)

(c)

Fig. 2: Pictorial view of the external heat sinks (a) Large diameter wire mesh (b) Intermediate diameter wire mesh (c) Small diameter wire mesh.

The experiments were carried out on three mild steel varying diameters and number of wires per unit length meshes (Please see fig. 2). The employed external heat sinks are large diameter mesh (wire diameter = 0.80 mm), intermediate diameter mesh (wire diameter = 0.50 mm) and small diameter mesh (wire diameter = 0.25 mm) respectively. Geometrically, the meshes are in square shape of dimensions 25 cm x 25 cm each. The convective heat transfer coefficient is determined as heat power lost due to convection is equated to the electrical power supplied.

$$h A \Delta T = V I$$

Where

$$h = \frac{V \times I}{A \times \Delta T}$$

$$\Delta T = (T_{av} - T_1)$$

$$T_{av} = \left(\frac{T_2 + T_3 + T_4 + T_5 + T_6}{5}\right)$$

h = Heat transfer coefficient (W/m^2-K)

V = Voltage supplied (Volt)

T_{av} = Average thermocouples temperature (K)

T_1 = Ambient temperature (K)

θ = Surface orientation (Degrees)

I = Current intensity (Ampere)

A = Area of square plate (m^2)

The work primarily focuses on the implications of external heat sink on transfer of natural convective heat transfer from the square plate. It must be noted that all the readings presented here represent the repeatability of results obtained.

3. RESULTS

An experimental exploration was carried out to study the effect on transfer of heat from a confined heated flat plate when enclosed by external heat sinks. The resulting heat transfer is primarily looked upon by its implications on buoyancy and convection currents governing convective heat transfer on square plate. The effect of controlling variables viz., surface roughness, heat sink placement, sink dimensions and heat source input, reflected in heat transfer coefficient at different plate orientations. Prior to the main study, the predictions of the experimental setup were validated with the bench mark heat transfer theory. Fig. 1 shows the variation of heat transfer coefficient with plate orientation extending from horizontal to vertical for the cases of rough and smooth surface of plate facing upward.

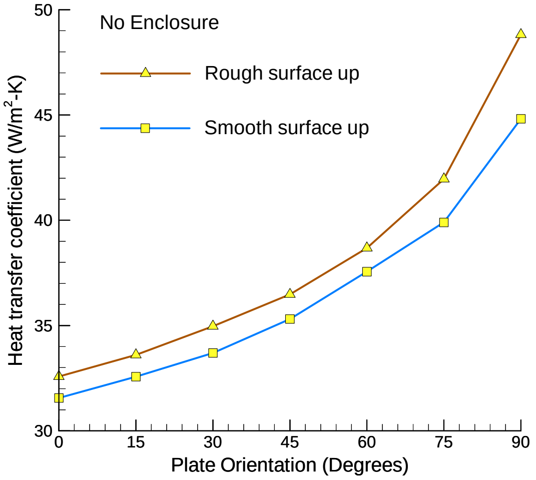


Fig. 3: Effect of surface roughness on convective heat transfer for case of no enclosure.

The study was carried out for electric input of 100 Volt and 0.45 Ampere without any enclosure. Experiments showed that the heat transfer rate exhibits a monotonically increasing behavior with increment in plate orientation. Highest rate were noted for the case of plate kept vertical. The surface roughness effect is well observed with additional heat transfer at all orientations. The above mentioned results conform reasonably well to the heat transfer theory which states supplementary heat transfer for plates kept vertical due to thick boundary layer formation. This decrease overall linear temperature resulting in reduced average plate temperature. Maximum cooling effect comes when the objects are in horizontal orientation whereas, in applications requiring enhanced heating effect, vertical orientation can be more suitable. The experimental setup predictions matches reasonably well so it is expected to provide better physical insight to the present explorations.

First, we look at the effect of external heat sink on heat transfer rate. Fig. 4 shows variation of heat transfer coefficient with plate orientation for three different types of meshes selected in comparison to the case of no mesh. The experiments were conducted with top end closed and smooth surface of plate facing upward.

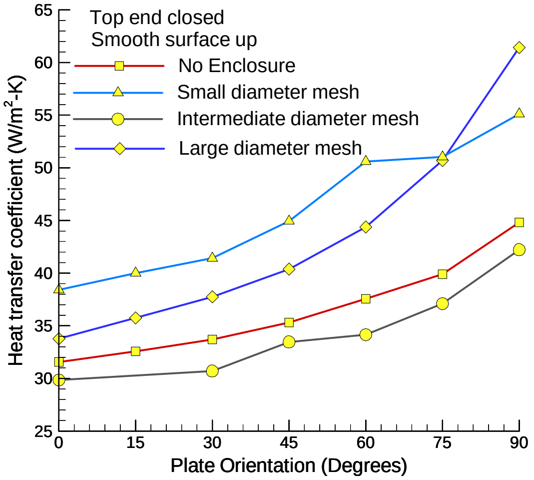


Fig. 4: Effect of variable diameter mesh on convective heat transfer.

Looking at the plot, one can note that the presence of an external heat sink affects the transfer rate as is reflected in varying heat transfer coefficient values. Trend similar to no enclosure is observed of heat transfer coefficient variation with plate orientation. It was noted that the rate of heat transfer increases with decrease in wire mesh diameter. Small diameter mesh allows more heat transfer from the plate followed by the large diameter mesh. However, with intermediate diameter mesh the heat transfer rates shells below no sink case. This signifies that a critical limit exists below which and above which only, mesh are effective for heat transfer. It is interesting to note that, at higher plate orientations (above 75^o) transfer of heat is more with large diameter mesh. The reason for these changes may be attributed to, as hot flow (carrying convective heat) interacts with the mesh placed at top. The mesh takes considerable amount of heat and thus reduces the flow temperature which causes the motion downwards. The small diameter meshes covers more area on the end and so obstructs a larger part of flow and take more heat. The more quantity of cold flow starts coming down to interact with the heated plate again to carry more heat. Large diameter meshes obstructs less but absorb more heat from hot fluid and become increasingly effective at higher plate orientations. At higher orientations, the blockage to flow increases with increased secondary heat transfer owing to more contact surface. This cold fluid coming down heavily and significant reduction in average plate temperature is probably the reason for boosted transfer of heat. However, the intermediate diameter mesh behave saturated and proportionally allow mixing of two fluids (hot coming up from plate surface and cold coming from mesh to plate) reasonably well. They are expected to affect the heat transfer drastically by formation of thermal vortices to offset the transfer to heat to a very low value. The result signifies that heat sinks are equally effective for both cases of heat transfer and heat conservation. For enhanced cooling effects, the small diameter mesh is effective as secondary heat transfer is more. However, for conservation purposes, an intermediate diameter mesh can yield desired results. It is important to note that, for all applications seeking enhanced heating effect, operations at vertical orientation will have increased effect. The secondary heat transfer affecting the primary heat transfer severely is established. As the phenomenon is buoyancy and convection current oriented, next we look at the role of mesh placement in transfer of heat.

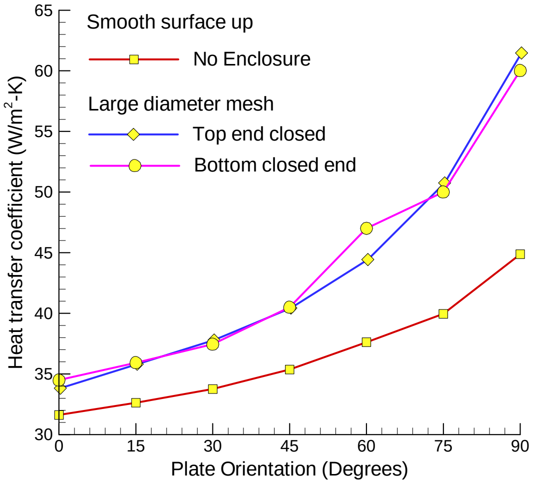


Fig. 5: Effect of mesh placement on convective heat transfer.

Fig. 5 shows the effect of mesh placement on primary convective heat transfer. Large diameter mesh was selected and both ends were closed systematically and results compared to the case with no mesh. The plate was kept in position of smooth surface facing upward and rough bottom surface facing downward open to atmosphere. First, the results confirm the effect of external heat sink and secondary heat transfer with increased heat transfer coefficient values. It was noted that the heat transfer effect is insensitive to mesh placement at top or bottom of the selected system.

As both ends are open, a localized temperature field is setup with the continuous heating of the plate. This localized temperature field disturbs the atmosphere in immediate vicinity. When mesh is placed at bottom, the temperature gradient increases heat transfer as hot fluid keeps moving upward and mass conservation is observed. The variation of heat transfer effect mostly shows crossovers with mesh placed at top and bottom. At plate orientation of 60^o mesh placed at bottom yields sudden increase in heat transfer. Precisely, for the requirement of more and fast heat transfer, a small diameter mesh at either top or bottom end will produce same effect. Heat sinks and their interaction with flow carrying heat can increase or reduce transfer of heat from the pilot source (square plate).

To explore deeper, next we see the effect of power input to the system in presence of an external heat sink on transfer of heat. Convective heat transfer is directly proportional to the power input. Fig. 6 shows the effect of power input on convective heat transfer rate. It is well-known that the maximum heat transfer rate is achievable when the plate orientation is kept vertical so, the experimentation was carried out for vertical plate orientation with an intermediate diameter mesh and smooth surface facing upward. The voltage was varied systematically to note the variation of heat transfer rate.

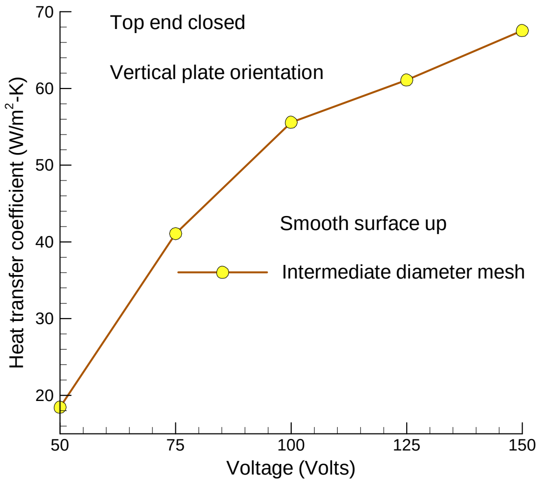


Fig. 6: Effect of power input on convective heat transfer in presence of an external heat sink.

Looking at the plot one can note that, heat transfer coefficient variation with voltage follows trend similar to plate orientation. The heat transfer rate increases monotonically with increase in power input. The rate of increase however comes down with increase in voltage beyond a limit owing to material properties. Mesh is expected to affect the transfer of heat drastically. More power supply results more heat transfer which will dictate more secondary heat transfer for a fixed mesh and will be reflected in enhanced heat transfer coefficient value.

Next, the work attempts to verify the combination of mesh for optimal heat transfer conditions. Meshes are noted to have significant effects on heat transfer. Also it was noted that the heat transfer effect is insensitive of placement. Two varying diameter mesh were selected and placed at odd ends viz., intermediate diameter mesh at top and large diameter mesh at bottom to determine the effect on heat transfer rate with smooth surface facing upward. The results were compared to the simple case of no enclosure.

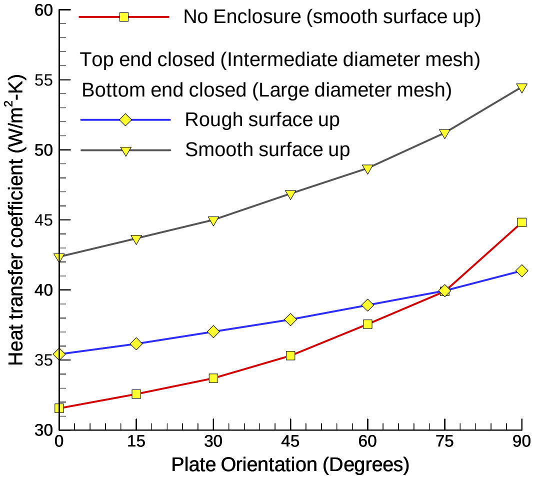


Fig. 7: Effect of multiple sink types on confined convective heat transfer.

The variation of heat transfer coefficient with plate orientation follows same increasing trend qualitatively but quantitatively differs. In case of multiple meshes in a confined system, the configuration with smooth plate surface facing up yields increment in transfer of heat. However, the same configuration with rough surface up behaves in an unusual way and results in drop of heat transfer. The rate of increase in heat transfer coefficient is very low and at higher orientations of the plate it falls below the one without any external heat sink. The transfer of heat is seen more in case of intermediate diameter mesh in conjunction with another mesh than just intermediate mesh alone for the same case.

It is worthwhile to note that the effectiveness of intermediate diameter meshes increases when used in collaboration with another sink. Both the cases yielding heat transfer values more than no enclosure case further supports the heat sink effect. As more heat transfer seen in the form of more heat transfer coefficient is a result of more secondary heat transfer. The presence of mesh at bottom obstructs the flow to the plate. With the smooth surface up, the drastic increase in heat transfer coefficient is owing to enhanced secondary heat transfer. The flow interacting with bottom surfaced (rough) gets tapped and limited proportion comes up which carries heat from smooth surface and moves up owing to buoyancy. Post carrying heat from the plate, fluid moves smoothly upward and interacts with the mesh and loses more heat to direct itself downward and carry additional heat. However, in case of rough surface upward, the flow smoothly carries heat from the bottom surface and interacts with the plate surface (rough) facing upward. It carries additional heat and buoyant upward to the mesh. The heat loss or transfer to the mesh is low so limited flow redirects downward. This further keeps reducing resulting in lower heat transfer rates.

We notice such confined systems and need of heat transfer in our ambience, most of engineering devices like propulsive systems (heat engines), space craft structure, electronic systems. The work proposes the use of external heat sinks (wire meshes) as an effective and productive method for emergent heat transfer and conservation.

4. CONCLUSIONS

Experimental were carried out to investigate effectiveness of external heat sink on heat transfer coefficient under diverse conditions. Based on results obtained following conclusions may be drawn:

a) Convection heat transfer is more effective in vertical orientation due to stronger buoyant forces leading to better cooling applications. Rough surfaces interacting with flow results additional heat transfer.
b) Presence of external heat sink (wire mesh) drastically affects the transfer of heat. Small diameter meshes are more effective in fast heat transfer, large one become effective when operated at higher orientation and intermediate one are significant in conservation of heat.
c) The heat transfer coefficient increases with heater input but it results in diminishing returns beyond a critical value and thus indicates that a critical power input is adequate to remove sufficient heat and further increase may be redundant.
d) A critical limit exists of mesh wire diameter below and above which only meshes are effective.
e) The secondary heat transfer is insensitive to the placement of wire mesh (top or bottom) in a confined system.
f) Intermediate diameter meshes perform better in conjunction with other meshes placed at selected distance. Two varying diameter meshes with smooth surfaces facing upward are more effective in better cooling applications.
g) The predictions of the experimental setup were validated with the benchmark heat transfer theory and matches reasonably well.

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