Experimental Analysis of Natural Convection Heat Transfer from Smooth and Rough Surfaces

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ABSTRACT

The objective of the present work is experimental analysis of natural convection heat transfer from smooth and rough surfaces by designing and fabricating experimental set up. In first case both the upper and lower surfaces are smooth while in second case upper surface is smooth and lower surface is made rough by applying adhesive and sprinkling sand. The plate inclinations were chosen to be 0°, 30°, 45°, 60° and measured with respect to horizontal position. Experiments were performed for various power inputs and inclination; the results were comparison and analysis for smooth and rough surfaces and find out the correlations.

Keywords— Natural convection heat transfer, inclination, power input, correlations.

I. INTRODUCTION

Free convection heat transfer from smooth and rough surfaces of considerable interest to engineers because of its application to extended fins, heat exchangers, film cooling and solar energy. Rough surfaces also play an important heat transfer role in engineering equipment’s. Correlations for smooth surfaces at different positions are mentioned by different authors like Frank P. Incropera, David P. Devitt[1].

A literature survey indicated that there has been relatively scare information on the free convection heat transfer from rough surfaces. This paper concerned with experimentally studied natural convection heat transfer from smooth and rough surfaces at different inclinations. The objective of the present work is experimental analysis of natural convection heat transfer from smooth and rough surfaces by designing and fabricating experimental set up to study the effect of inclination and roughness. The experiments were performed in air.

II. EXPERIMENTAL SET UP & EXPERIMENTATIONS

Use To study the free convection from inclined smooth and rough surfaces, an experimental set up designed and fabricated which is shown in the figure 1. Also, cross sectional view of plate also shown in figure 2. It consist of two steel plates of dimensions are 305mm length, 305mm width and 5mm thickness held with adjustable gap between them. They are embedded with electric heater and designed to produce uniform temperature on it’s surface. The steel plate was used to dissipate heat to the surrounding air. The dimension of the heating element was 300 mm length, 300mm width and 1mm thickness and it could withstand a temperature of 800-900°C. In order to make a heater capacity of 400W, it is made of 30 gauge nichrome wire about 11.25m in length. Thickness of wire is 0.55mm, which was measured by using dial thickness gauge. Resistance of the nichrome wire was 59 Ω. We can supply maximum current of 2.6A and 153.6V. This nichrome laid mica sheet was sandwiched between two steel plates of size 305mm x305mm sides with another mica sheet in between to prevent short circuiting. The steel plates, mica sheet covers and heating element are bolted together.

Thermocouples are mounted on the lower and upper plates to measure temperatures at different locations. Thermocouples were soldered on the plate with tip of 0.5mm in order to provide good thermal contact between steel plates. These thermocouples were calibrated between the ice and maximum temperature attained by water. The temperature indicator is showing the temperature at different locations on the lower and upper plates. The temperature indicator is connected to the thermocouples through a selected switch, which can select thermocouple
whose temperature is to be measured. A copper tube is fixed around the edges of plate through which water is circulated and calculate heat losses from the sides. Copper tube is insulated with carbon to reduce heat losses. The entire assembly is bolted with nuts and mounted on the table. The plate is made adjustable using a screw by the help of which their respective position can be altered. The plate was fixed 17cm above the base for all inclinations.

Thermocouples are mounted on the lower and upper plates to measure temperatures at different locations. The power supply to the plate through dimmer stat, which is used to control the voltage applied. When the power is supplied through the dimmer stat to the heating element, the electrical energy supplied to the heating element was converted to thermal energy and large portion of this thermal energy conducted through both plates and lost as convection and radiation from the plates. After one hour to one and half hour a stage is reached when there is no further deflection shown by temperature indicating device, this stage is called as steady state.

Since the heater is identical, the amount of heat transfer to upper and lower plate is same in case of smooth surfaces. Consider heat losses i.e. heat carried away by water (QW) and heat lost by radiation. Heat carried away by water was calculated by using the mass flow rate and rise in temperature of the water. The net radiation heat transfer from the upper and lower steel plate surface was calculated using average plate temperature, ambient temperature. The remaining energy conducted through the steel plates was removed by convection.

In this experimental work, results were taken from smooth and rough surfaces. In first case both the upper and lower surfaces were smooth, in second case upper surface is smooth and lower surface making rough by applying adhesive and sprinkling sand particles size of 0.5mm to 0.85mm. Sand particle size measured by profile projector. Results were taken after the surface became dry.

III. DATA REDUCTION

The objectives of the data reduction were to determine the Nusselt and Rayleigh numbers for the smooth and rough surfaces. Dimensional analysis indicates that natural convection heat transfer from smooth and rough inclined surfaces depends on the Nusselt number, Nu, the Rayleigh number, Ra. For these reasons the data are presented in the form of

\[ \text{Nu} = f(\text{Ra}) \]

Here \( \text{Ra} = \frac{g \beta (T_s - T_a) L^3}{\nu^2 \cdot \text{Pr}} \) ; \( \text{Nu} = \frac{h L}{k} \)

Where \( \beta \) is the coefficient of thermal expansion, \( T_s \) is the average surface temperature, \( T_a \) is the ambient air temperature, \( \nu \) is the kinematic viscosity of air, \( \text{Pr} \) is the Prandtl number, \( g \) is the acceleration of gravity, \( k \) is thermal conductivity of air, \( L \) is characteristic length and his the heat transfer coefficient. The thermo physical properties on the Nusselt and Rayleigh numbers were all evaluated at the mean film temperature \( \frac{(T_a + T_s)}{2} \)

The heat transfer coefficient \( h \) is defined by the relation

For smooth surfaces

\( (P-Q_w-Q_{rad})/2 = h A (T_s - T_a) \)  \hspace{1cm} Eq. (1)

For rough surfaces

\( (P-Q_w-Q_{rad} - Q_u) = h A (T_s - T_a) \)  \hspace{1cm} Eq. (2)

Where \( P (=VI) \) is the power input, \( Q_w \) & \( Q_{rad} \) are the heat losses by water and radiation, \( A \) is the surface area of the steel plate. \( Q_u \) is the amount of heat is transferred to the upper smooth surface.

\( Q_w = (\rho v/t) C_p . \Delta T \)  \hspace{1cm} Eq. (3)

\( Q_{rad} = \varepsilon . \sigma A (T_s^4 - T_a^4) \)  \hspace{1cm} Eq. (4)
Where $\varepsilon$ = emissivity of the surface
for steel (0.8), sand(0.75)

$Q_u$ for rough surfaces calculated from the graph
temperature difference and amount of heat transfer to
upper plate. Data were collected at two different power
inputs. The unit inclination was measured from horizontal
positions and the inclinations angles were chosen as $0^\circ$, $30^\circ$, $45^\circ$, and $60^\circ$. Then the system was allowed to reach
thermal equilibrium.

IV. RESULTS AND DISCUSSIONS

Experiments were performed on smooth and
rough surfaces at different power inputs and different
inclinations. Following results came at different power
inputs and inclinations.

<table>
<thead>
<tr>
<th>$\Theta$ (degrees)</th>
<th>Smooth surface</th>
<th>Power input (W)</th>
<th>$h$ (W/m$^2$K)</th>
<th>$Nu$</th>
<th>$Ra \times 10^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>165</td>
<td>9.95</td>
<td>27.30</td>
<td>8.365</td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>11.21</td>
<td>30.14</td>
<td>8.175</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>164.6</td>
<td>11.17</td>
<td>30.50</td>
<td>7.304</td>
<td></td>
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<tr>
<td></td>
<td>216</td>
<td>11.92</td>
<td>32.3</td>
<td>8.931</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>165.5</td>
<td>9.10</td>
<td>24.70</td>
<td>6.254</td>
<td></td>
</tr>
<tr>
<td></td>
<td>216</td>
<td>11.50</td>
<td>30.34</td>
<td>9.317</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>163.66</td>
<td>10.38</td>
<td>27.30</td>
<td>6.378</td>
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</tr>
<tr>
<td></td>
<td>219</td>
<td>11.54</td>
<td>31.22</td>
<td>8.421</td>
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</tr>
</tbody>
</table>

Table 1: Readings for smooth surfaces

<table>
<thead>
<tr>
<th>$\Theta$ (degrees)</th>
<th>Rough surface</th>
<th>Power input (W)</th>
<th>$h$ (W/m$^2$K)</th>
<th>$Nu$</th>
<th>$Ra \times 10^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>166</td>
<td>9.45</td>
<td>25.73</td>
<td>6.984</td>
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<tr>
<td></td>
<td>216</td>
<td>11.50</td>
<td>31.31</td>
<td>8.960</td>
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<td>30</td>
<td>166.6</td>
<td>11.25</td>
<td>31.0</td>
<td>8.207</td>
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<tr>
<td></td>
<td>219.5</td>
<td>12.03</td>
<td>32.96</td>
<td>10.400</td>
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</tr>
<tr>
<td>45</td>
<td>166.6</td>
<td>10.36</td>
<td>28.32</td>
<td>7.189</td>
<td></td>
</tr>
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<td></td>
<td>222.7</td>
<td>12.2</td>
<td>33.22</td>
<td>9.358</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>166.6</td>
<td>9.75</td>
<td>26.95</td>
<td>8.260</td>
<td></td>
</tr>
<tr>
<td></td>
<td>221</td>
<td>11.7</td>
<td>31.88</td>
<td>9.454</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Readings for rough surfaces

The effect of roughness and inclination on natural
convection heat transfer from lower plate was investigated
for $00$, $300$, $450$ and $600$ with respect to horizontal. The
experiment was performed in air. In all cases, the heated
plate was maintained isothermal.

Heat transfer coefficient ($h$) depends on ambient
temperature, average surface temperature and area of the
plate. From the results the value of the heat transfer
coefficient slightly increased with increasing the power
input for all inclinations.

For same power input (164-166W & 216-222W),
the heat transfer coefficient ($h$) for smooth surfaces slightly
increased till $30^0$ and went on decreasing. It reached
minimum value at $45^0$ and started increasing from there on.
For rough surfaces, the values trend was also equal or sometimes greater than smooth surfaces.

![Fig 5: Temperature difference Vs Heat Transfer](image)

Dimensionless Nusselt number depends on the heat transfer coefficient, properties of air and characteristic length. For same power input the values of Nu slightly higher for rough surfaces.

Above graph shows amount of heat was transfer from the upper smooth surface for different inclinations for temperature difference.

![Fig 6: Variations of Nu and Ra Number for smooth and rough surfaces](image)

In case of smooth and rough surfaces the Ra value lies between $6.3 \times 10^5 \leq Ra \leq 9.0 \times 10^5$ for all inclinations when power input $164-166.6W$. In case of smooth and rough surfaces the Ra value lies between $8.1 \times 10^5 \leq Ra \leq 1.1 \times 10^6$ for all inclinations when power input $216-222W$.

**Dimensionless Correlation for Rough Surfaces**

a) Procedure for calculating $C, m$

i) Nusselt number is a function of Rayleigh number i.e., $Nu = C \times Ra^m$

ii) Plot a graph $\ln(Ra)$ vs $\ln(Nu)$.

iii) Draw a straight line through two points.

iv) The value of the $C = e^x$ where ‘x’ is the distance away from origin –ve Y-axis

v) $m = \text{slope of the line } i.e. (dy/dx)$

vi) After substituting values of C, m for different inclinations which were obtained from graph.

$Nu = 0.47 Ra^{0.30}$ for horizontal Eq.(5)
$Nu = 0.51 Ra^{0.30}$ for $30^\circ$ from horizontal Eq.(6)
$Nu = 0.37 Ra^{0.32}$ for $45^\circ$ from horizontal Eq.(7)
$Nu = 0.46 Ra^{0.30}$ for $60^\circ$ from horizontal Eq.(8)

![Fig 7: Graph for $ln(Ra)$ vs $ln(Nu)$](image)

**V. CONCLUSION**

Heat transfer coefficient ($h$) depends on ambient temperature, average surface temperature and surface area. From the results the value of the ‘$h$’ slightly increased with increasing power input for all inclinations. In case of smooth surfaces, for same power input, the value of the heat transfer coefficient slightly increases with increasing inclination and the minimum value at $450$ from horizontal and the values of heat transfer coefficient for rough surfaces are slightly increased or sometimes equal to the values of smooth surfaces.

For same power input, the value of $Nu$ for rough surfaces is slightly higher or sometimes equal to the values
of smooth surfaces. The correlations are almost equal for smooth and rough surfaces.

REFERENCES