CHAPTER V

ENHANCEMENT OF HEAT TRANSFER USING IMPINGEMENT OF MULTIPLE AIR JETS

Experiments were also conducted to study the heat transfer multiple air jet impingement on an electrically heated test surface. The following parameters on the heat transfer have been presented in this chapter:

- Effect of test parameters on heat transfer coefficient
- Dependence of heat transfer coefficient on heat flux
- Effect of Reynolds number on Nusselt number
- Development of correlation

5.1 EFFECT OF TEST PARAMETERS ON HEAT TRANSFER COEFFICIENT

Figs 5.1 and 5.2 show the variation of heat transfer coefficient as a function of temperature difference between the air at inlet ($\Delta t$) and test surface. The Reynolds number (Re) based on jet diameter and jet exit-to-test plate surface distances ($Z$) were varied. The study of horizontal and vertical positioning of the jets was carried out. Results have been plotted for the jet diameter of 0.25 and 0.5mm. For a given value of ($\Delta t$), the heat transfer coefficient increases with increase in
Reynolds number in all cases. Note that in addition to the variation of Reynolds number, heat flux is also varying along the constant temperature difference line ($\Delta t$).

Fig 5.1: Variation of heat transfer co-efficient with temperature difference for different flow rates at $Z=10\text{mm}$ and $d=0.50\text{mm}$ for vertical jets

Fig 5.2: Variation of heat transfer co-efficient with temperature difference for different flow rates at $Z=20\text{mm}$ and $d=0.50\text{mm}$ for vertical jets
Thus, the observed increase in heat transfer coefficient is due to the combined effect of the variation in the heat flux and the Reynolds number. Similar qualitative variations of (h) with (∆t) were also observed with the horizontal positioning of the jets.

The variations in the heat transfer coefficient with (∆t) for d=0.25mm are shown in Figs 5.3 and 5.4. Higher values of heat transfer coefficient are obtained with 0.25mm diameter jet compared to that obtained with 0.5mm diameter jet. The jet diameter of 0.25mm is found to be more effective in causing higher values of heat transfer coefficient, because smaller diameter jets have higher air jet velocity associated with them.

Fig 5.3: Variation of heat transfer co-efficient with temperature difference for different flow rates at Z=10mm and d=0.25mm for vertical jets
Fig 5.4: Variation of heat transfer co-efficient with temperature difference for different flow rates at $Z=20\text{mm}$ and $d=0.25\text{mm}$ for vertical jets

The slope of the $(h)$ versus $(\Delta t)$ curves is more for the jet diameter of $0.25\text{mm}$. It should be noted that $(\Delta t)$ values have decreased with a smaller diameter jet. There is a significant difference in the values of Reynolds number obtained with the two tested jet diameters. The results show that the effect of $(Z)$ and horizontal and vertical positioning of the jets is insignificant.

Figs 5.5 and 5.6 show the comparison of results obtained with different jet diameters. Significant effect of jet diameter has been noticed. Higher values of heat transfer coefficient are obtained with the lower diameter jets. This is possibly due to the reason that as the jet proceeds towards the impingement region, the thickness of boundary layer reduces, which causes higher heat transfer coefficients.
Fig 5.5: Variation of heat transfer co-efficient with temperature difference for different Reynolds numbers at Z=10mm for vertical jets

Fig 5.6: Variation of heat transfer co-efficient with temperature difference for different Reynolds numbers at Z=20mm for vertical jets

With the jet diameter of 0.25mm, lower values of (Δt) have been obtained. Although the tests have been carried out with different jet
diameters, the plots show consistent variations with Reynolds number.

5.2 DEPENDENCE OF HEAT TRANSFER COEFFICIENT ON HEAT FLUX

It should be noted that the heat flux is varied while conducting the experiments at constant Reynolds number. Large variations in heat transfer coefficient observed in Figs 5.1 to 5.6 are due to the combined effect of heat flux and the Reynolds number. The heat flux \( q \) is an independent parameter and \( \Delta t \) depends upon the heat flux in all the experiments conducted during this investigation. In order to isolate the effect of heat flux \( q \) and the Reynolds number on the heat transfer coefficient, the results are plotted with the heat flux as an independent parameter instead of \( \Delta t \) as shown in Figs 5.7 to 5.10.

Figs 5.7 and 5.8 show the heat transfer results for \( d=0.5\text{mm} \), \( Z=10 \) and 20mm for vertical positioning of the jets when plotted in \( h \) versus \( q \) coordinates. In all the cases, heat flux was varied from 25 to 200 \( \text{W/cm}^2 \). The heat transfer coefficient increases with heat flux. As the heat flux increases, the surface temperature also increases, which causes more turbulence in the impingement zone resulting in a higher heat transfer coefficient. The Reynolds number effect is insignificant and heat transfer coefficient increases slightly with increase in Reynolds number in the range of 1290 to 1816. The effect of \( Z \) on heat transfer coefficient is negligible.
Fig 5.7: Variation of heat transfer co-efficient with heat flux at $Z=10\text{mm}$ and $d=0.50\text{mm}$ for vertical jets

Fig 5.8: Variation of heat transfer co-efficient with heat flux at $Z=20\text{mm}$ and $d=0.50\text{mm}$ for vertical jets

Figs 5.9 and 5.10 show the heat transfer results obtained using $d=0.25\text{mm}$ with different Reynolds numbers, $Z=10$ and $20\text{mm}$ for vertical positioning of the jets.
Fig 5.9: Variation of heat transfer co-efficient with heat flux at \( Z=10\text{mm} \) and \( d=0.25\text{mm} \) for vertical jets

Fig 5.10: Variation of heat transfer co-efficient with heat flux at \( Z=20\text{mm} \) and \( d=0.25\text{mm} \) for vertical jets
Similar qualitative variation of heat transfer coefficient with heat flux as observed in the tests of d=0.5mm have been noticed in all cases; the effect of Reynolds number, (Z) and horizontal and vertical positioning of the jets are insignificant.

Figs 5.11 and 5.12 show the comparison of results obtained using d=0.5mm and d=0.25mm diameter jets.

It is evident that higher values of heat transfer coefficient are obtained with a 0.25mm diameter jet as compared to 0.50mm jet. Thus the smaller diameter jets are more effective in enhancing the heat transfer at a given Reynolds number.

Fig 5.11: Variation of heat transfer co-efficient with heat flux for different Reynolds numbers for vertical jets at Z=10mm
5.3 EFFECT OF REYNOLDS NUMBER ON NUSSELT NUMBER

Figs 5.13 to 5.16 show the variation of Nusselt number with Reynolds number for the heat flux range of 25 to 200 W/cm$^2$ for $d=0.25$ and $d=0.50$mm, $Z=10$ and 20mm for vertical positioning of the jets. As the heat flux is increased in the range of 25 to 200 W/cm$^2$, the plots of Nusselt number versus Reynolds number shift upwards. Although, slight variation with the Reynolds number has been noticed, the Nusselt number is found to be a strong function of heat flux. This is due to the thinning of the boundary layer surface and increased turbulence in the wall region. The effect of $(Z)$, the positioning of the jets (horizontal / vertical) and the Reynolds number seems to have insignificant effect on the Nusselt number versus Reynolds number variations. It can be concluded that the heat flux and jet diameter are
the dominating factors among all the test parameters in influencing the heat transfer coefficient.

**Fig 5.13:** Variation of Nusselt number with Reynolds number for different heat fluxes at Z=10mm and d=0.50mm for vertical jets

**Fig 5.14:** Variation of Nusselt number with Reynolds number for different heat fluxes at Z=20mm and d=0.50mm for vertical jets
Fig 5.15: Variation of Nusselt number with Reynolds number for different heat fluxes at Z=10mm and d=0.25mm for vertical jets

Fig 5.16: Variation of Nusselt number with Reynolds number for different heat fluxes at Z=20mm and d=0.25mm for vertical jets
Figs 5.17 and 5.18 show the variation of heat transfer coefficient with heat flux for different Reynolds numbers (Re=2573 and 4455) at Z=10 and 20mm and d=0.25mm for vertical positioning of the jets. It can be easily noticed that the effect of (Z) is negligible for both vertical and horizontal positioning of the jets.

Figs 5.19 and 5.20 show the variation of heat transfer coefficient with heat flux at Re=1570, d=0.50mm and Z=10 and 20mm for vertical and horizontal positioning of the jets. The heat transfer coefficient is slightly higher in vertical jets as compared to horizontal jets. The reason being, horizontal surface with vertical jets cools faster as compared to the vertical surface with horizontal jets due to the lower film thickness on the surface.

![Graph showing heat transfer coefficient variation](image)

Fig 5.17: Variation of heat transfer co-efficient with heat flux at Re=2573, d=0.25mm and Z=10 and 20mm for vertical jets
Fig 5.18: Variation of heat transfer co-efficient with heat flux at Re=4455, d=0.25mm and Z=10 and 20mm for vertical jets

Fig 5.19: Variation of heat transfer co-efficient with heat flux at Re=1570, d=0.50mm and Z=10 mm for both vertical and horizontal jets
Fig 5.20: Variation of heat transfer co-efficient with heat flux at $\text{Re}=1570$, $d=0.50\text{mm}$ and $Z=20\text{ mm}$ for both horizontal and vertical jets

### 5.4 DEVELOPMENT OF CORRELATION RELATING NUSSELT NUMBER WITH HEAT FLUX AND REYNOLDS NUMBER

Figs 5.21 and 5.22 show the heat transfer results obtained with jet diameter of 0.5mm plotted in $\ln(\text{Nu}_{\text{avg}}/\text{Re}^{0.25})$ versus $\ln(\text{q})$ coordinates for different Reynolds number, $Z=10$ and 20mm and for vertical positioning of the jets, the range of Reynolds number between 1290 to 1816. The plots of $\ln(\text{Nu}_{\text{avg}}/\text{Re}^{0.25})$ versus $\ln(\text{q})$ are fairly linear and the data obtained at different Reynolds number follow the similar relationships for both $Z=10$ and 20mm.
Fig 5.21: Variation of \((\frac{\text{Nu}_{\text{avg}}}{\text{Re}^{0.25}})\) with heat flux for various Reynolds numbers at \(Z=10\text{mm}\) and \(d=0.50\text{mm}\) for vertical jets.

Fig 5.22: Variation of \((\frac{\text{Nu}_{\text{avg}}}{\text{Re}^{0.25}})\) with heat flux for various Reynolds numbers at \(Z=20\text{mm}\) and \(d=0.50\text{mm}\) for vertical jets.

Figs 5.23 and 5.24 show the results obtained for jet diameter of 0.25mm. The variations of \(\ln(\frac{\text{Nu}_{\text{avg}}}{\text{Re}^{0.25}})\) versus \(\ln(q)\) are similar to
that obtained with 0.5mm diameter jet. Tests conducted at different Reynolds numbers also show similar variations.

Fig 5.23: Variation of \( \frac{\text{Nu}_{\text{avg}}}{Re^{0.25}} \) with heat flux for various Reynolds numbers at \( Z=10\text{mm} \) and \( d=0.25\text{mm} \) for vertical jets

Fig 5.24: Variation of \( \frac{\text{Nu}_{\text{avg}}}{Re^{0.25}} \) with heat flux for various Reynolds numbers at \( Z=20\text{mm} \) and \( d=0.25\text{mm} \) for vertical jets
Fig 5.25 shows the variation of \( \ln(\text{Nu}_{\text{avg}}/\text{Re}^{0.25}) \) versus \( \ln(q) \) for various values of heat flux between 25 to 200 W/cm\(^2\), jet Reynolds numbers in the range of 1200 to 1900, \( Z=10 \) and 20mm and for both horizontal and vertical positioning of the jets with the jet diameter of 0.50mm. The average experimental data follows the linear relationship

\[
\text{Nu}_{\text{avg}} = 0.75 \ q^{0.9} \text{Re}^{0.25}
\]  

(5.1)

The mean experimental data obtained with the jet diameter of 0.25mm with the same ranges of test parameters and the Reynolds number range of 2500 to 4500 is shown in Fig 5.26. Overall, the results follow the relationship

\[
\text{Nu}_{\text{avg}} = 0.69 \ q^{0.8} \text{Re}^{0.25}
\]  

(5.2)

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**Fig 5.25:** Variation of \( \text{Nu}_{\text{avg}}/\text{Re}^{0.25} \) with heat flux for different Reynolds numbers and \( Z \), \( d=0.50\text{mm} \), \( Z=10 \) and 20mm and Reynolds numbers range = 1200 to 1900 (Experimental data for both horizontal and vertical jets are included)
Fig 5.26: Variation of $\frac{Nu_{avg}}{Re^{0.25}}$ with heat flux for different Reynolds numbers and $(Z)$, $d=0.25\text{mm}$, $Z=10$ and $20\text{mm}$ and Reynolds numbers range = 2500 to 4500 (Experimental data for both horizontal and vertical jets are included)

It is interesting to note that although the multiple air jet cooling problem is complex, the heat transfer results can be correlated using the simple relationship developed in this research study. Slightly different correlations were obtained for the jet diameters of 0.5 and 0.25mm although the functional relationship is same in both cases. The effect of heat flux on the Nusselt number is significant and the effect of jet Reynolds number is small. The value of the exponent of jet Reynolds number is 0.25, which is same as value obtained for the multiple water jet experiment and agrees well with the value of 0.245 reported by Michna. G. J., Browne.E.A., Peles.Y., Jenson.M.K (66).

The correlation equations (5.1) and (5.2) were modified to include the effect of Prandtl number assuming $Pr=0.7$ for air. The
The exponent of Prandtl number is assumed as 0.4 based upon the studies of other investigators (19, 102).

\[
\text{Nu}_{\text{avg}} = 0.87q^{0.9}\text{Re}^{0.25}\text{Pr}^{0.4} \quad \text{for } d=0.5\text{mm} \quad (5.3)
\]

\[
\text{Nu}_{\text{avg}} = 0.80q^{0.8}\text{Re}^{0.25}\text{Pr}^{0.4} \quad \text{for } d=0.25\text{mm} \quad (5.4)
\]

Equations (5.3) and (5.4) are valid for heat flux up to 200 W/cm\(^2\), jet Reynolds number range of 1000 to 5000 and the pitch to jet diameter ratio range of 3 to 6.

These correlations show the effect of heat flux in addition to the effect of jet Reynolds number and Prandtl number on the Nusselt number. Even though the exponents and constants are slightly different, the same functional relationship is valid for both jet diameters.