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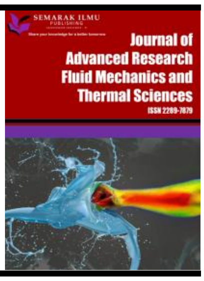

Experimental Investigation of Local Nusselt Profile Dissemination to Augment Heat Transfer under Air Jet Infringements for Industrial Applications

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ABSTRACT

An experimental study is presented in this paper to evaluate the enhancement of heat transfer characteristics. This includes the study of a steady air jet impinging on a planar aluminum plate with constant heat flux. Extensive industrial applications of heat transfer include electronic heat sinks, the food industry, automobiles, and heat exchangers. The magnitude of the local Nusselt number along the streamwise direction is determined through detailed experimental computation using the infrared radiometry technique. The range of Reynolds number was selected between $6500 \leq Re \leq 15000$ and the air jet outlet-to-target surface spacing $2 \leq Y/D \leq 6$. The objective is to develop a semi-empirical correlation that can be used to determine the distribution of local Nusselt numbers over a flat plate. Considering the objective function of the spacing between the air jet outlet and target surface spacing (Y/D), Reynolds number (Re), and non-dimensional number from stagnation point in the radial direction of the plate (r'/D), it was observed that the heat transfer rates are higher for the configuration Y/D = 4 for varying Reynolds numbers, a 5 percent increase was observed. The stagnation Nusselt number shows an increasing trend up to Y/D = 4, for Reynolds numbers 10,000 and 12,000 respectively, the corresponding stagnation Nusselt numbers are 110 and 115. In comparison to the stagnation Nusselt number, which is the same Reynolds number corresponds to, the transition field Nusselt number had heat transfer values that were 12% lower.

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1. Introduction

Jet infringement has many practical and varied applications. It is used in many quenching applications to cool heated billets, in the cooling of electronic miniature devices, in the food industry for drying food products, de-icing aircraft, and many other applications. Currently, considerable research attention has been given to heat transfer augmentation using air jet infringement as reported by Lytle and Webb [1], the study focuses on the effect of symmetrical infringing air jets with a nozzle-target length $\frac{z}{d}$ less than one. They found that the stagnation Nusselt number N_{us} increased by 60% as z/d was reduced from 1.0 to 0.1. Lee and Lee [2] examined heat flow aspects of jet infringement in the stagnation region, considering the spacing between nozzle-to-plate $l/d = 2, 4, 6{,}10$ and Reynolds number $5000 \leq Re \leq 30000$.

The local first elevation in the Nusselt profile is attributed to the augmented flow aspect resulting from the transition from, laminar to a turbulent boundary layer and noted as $L/d = 4$.

Gao and Ewing [3] examined the effect of an enclosing plate on the heat transfer phenomenon with nozzle-to-target spacing $0.25 < z/d < 6$. It was found that the presence of the enclosing plate does not have any influence on enhancing heat flow characteristics with infringing jets $H/d \geq 1$ in stagnation as well as transition regions. Further study of confining jets in two directions was carried out by San and Shiao [4] to investigate heat transfer phenomena related to surface-to-jet distance H/d, jet-to-plate width W/d, and jet-to-plate length L/d. Results show that there was a decrease in the Stagnation Nusselt number Nu_0, with an increase in W/d, L/d, and H/d, mainly attributed to the recirculation of flow that occurs due to confinement. O'Donovan and Murray [5] studied the variation in the local Nusselt number Nu at very low nozzle-plate spacing $H/d \leq 2$. The combined effect of increased local momentum and significant temperature differences within the plate and its surroundings leads to the highest Nusselt number at the stagnation region. Gulhane and Siddique [6], Umair *et al.,* [7], and Ansari *et al.,* [8] presented comprehensive results on the location of the first local elevation in Nusselt number. A local increase in the Nusselt number was observed due to a local first elevation curve of Nu, occurring over stagnation and transition regions. The magnitude of this increase is attributed to the jet-infringing Reynolds number (Re). Illyas *et al.,* [9] carried out a comparative study of swirling jet and circular jet and reported that the presence of an axial recirculation zone for the triple helicoid significantly affects the efficiency of heat transfer.

Katti and Prabhu [10] derived the conclusion that the Nusselt number increases with an increase in the Reynolds number, and the first local elevation is absent at a low Reynolds number of 12,000-16,000. Similar observations were recorded by Anwarullah *et al.,* [11] about Nusselt number profiles for different jet Reynolds number Re $5{,}500 - 28500$ and jet-to-target spacing $H/d = 2 - 10$. They showed that augmentation in Re, augments Nu at all radial positions, including that the stagnation point Nu is a strong function of Re. Gillespie *et al.,* [12] examined the effect of H/d ratio on the heat transfer characteristics of an infringing jet experimentally, and it was indicated that the highest heat release occurs at $4 \leq H/d \leq 11$. The results show that SST combined with the transition model accurately predicts the flow conditions that vary from laminar to turbulent transitions due to infringing jets in the wall jet region [13]. A recent conducted by study Shamitha *et al.,* [14] examined the surface pressure of a wedge at a hypersonic Mach number. The study reported that the dimensionless static pressure at the nose of the wedge only undergoes minimal changes for smaller wedge angles and Mach numbers. These findings are considered significant for designing aerospace vehicles because wind tunnel testing is expensive.

Sagot *et al.,* [15] studied jet infringement at a constant wall temperature. They analyzed the local Nusselt number at a constant wall temperature, Nut, and compared it with the local Nusselt number at constant heat flux Nuϕ. The Nusselt number at constant heat flux was always greater than Nut and the difference between these two fluxes was more significant at r/d ≥ 3. The research further revealed that the use of a target surface consisting of square and rectangular grooves with specified dimensions [16]. The average Nusselt number Ňut for a constant wall temperature was experimentally compared between a smooth plate and a grooved surface. The results showed an increase in the mean Nusselt number up to 80% compared to the smooth plate. Furthermore, in a study conducted by Gau and Lee [17], it was that the presence of triangular channels significantly enhances the distribution of the Nusselt profile in stagnant regions. A novel study conducted by Shaikh *et al.,* [18,19] showed that the diffuser angle needs to be set at an ideal value to ensure uniform flow and minimize pressure drop. An inlet cone angle of 52.3° is reported to result in improved pressure drop characteristics. Umair and Gulhane [20] proposed a critical edge grid size using ANSYS CFX. The Nusselt profile becomes independent of the grid size 500×350 at the edges of the jet-target spacing and the base plate. Siddique *et al.,* [21] studied a technique to increase the base pressure at the nozzle exit and found that the pitch circle diameter of the control jet played a significant role in increasing the base pressure at the nozzle exit.

Pathan *et al.,* [22] and Zhou and Lee [23] studied the characteristics of forced convection heat transfer by examining the infringement of a rectangular jet infringement with dimensions of 44.2 mm × 11.08 mm. They reported an increase in average momentum and swirl augmentation with an increase in the jet outlet Reynolds number Re. Further study on rectangular slot jets was carried out by Zhou and Lee [24], and an accurate correlation of the Nusselt number based on the hydraulic diameter for the wall jet region was proposed. Beitelmal *et al.,* [25] studied the impingement of a liquid jet on a circular cavity heat sink and reported that the heat transfer efficiency improved by 11.8% compared to a flat plate. Tang *et al.,* [26] examined the characteristics of the Nusselt number (Nu) profile and effectiveness curves of infringement jets at temperatures ranging from atmospheric to 414 K. They concluded that the radial distribution of Nu and effectiveness was not dependent on the jet exit temperature. Fénot *et al.,* [27] explained that as the nozzle pressure ratio increases, the base pressure decreases while the Mach number (M) and area ratio (AR) increase. Mach number, area ratio, and nozzle pressure ratio all increase with an increase in thrust. By increasing the L/D ratio from 2 to 5, the base pressure decreases. From a L/D ratio of two to five, the thrust increases. NPR (Nozzle Pressure Ratio), M, AR, and L/D ratio are parameters that can be taken into consideration for the study of abruptly expanded flows based on the obtained results. Continuing their research work, Pathan *et al.,* [28] showed that the nozzle flow decreases as the NPR (Nozzle pressure ratio) increases. This leads to a reduction in over-expansion and eventually results in properly expanded jets that subsequently become under-expanded. We can conclude that, for all values of NPR and study parameters, there is a tendency for the base pressure to decrease as NPR increases. We can therefore conclude that both the base pressure and the reattachment length increase with increasing Mach numbers. Various analytical and experimental studies related to the flow from the nozzle were found in the literature [29-43].

The study mentioned above, conducted by most researchers, is based on the average Nusselt number. This approach provides limited accuracy when plotting heat dissipation curves for engineering purposes. However, with an exemption of Katti and Prabhu [10] a technique to evaluate the heat transfer rate from stainless steel foil. In the present study, the research focuses on aluminium, which is a widely used industrial application material i.e. Most of the studies found in the literature have been carried out in the stagnation region. The present study will serve as a benchmark for evaluating heat transfer rates in various practical applications, such as the automobile industry and billet manufacturing. Several research works have been dedicated to stagnation regions only. However, there is a lack of studies on the transition and wall jet regions, which requires attention. Therefore, the objective of the current study is to investigate the distribution of the local Nusselt profile distribution and to generate a comprehensive report by utilizing the infrared thermal imaging technique. This will result in more precise and dependable data. The objective of the present study is to

i. To conduct experimental research work to assess the local Nusselt profile by measuring temperatures along the radial direction on the target surface plate using an infrared thermal imaging technique.
ii. Investigate the effect of various parameters, such as Reynolds number and nozzle-to-target spacing, on the local Nusselt number Nu_l distribution profile.
iii. The objective of this study is to develop an empirical correlation for the local Nusselt number Nu_l distribution profile over a flat plate. This correlation will be a function of the spacing between the air jet outlet and the target surface, the Reynolds number, and a non-dimensional number representing the distance from the stagnation point in the radial direction of the plate.

2. Methodology

The experimental system used in the present research work is shown in Figure 1. The inlet blower runs at full speed, providing an airflow of 200 m^3/hr. The airflow can be varied. A heat sink heater has been provided. The power supplied to this heater can be varied using the dimmer stat provided on the door panel.

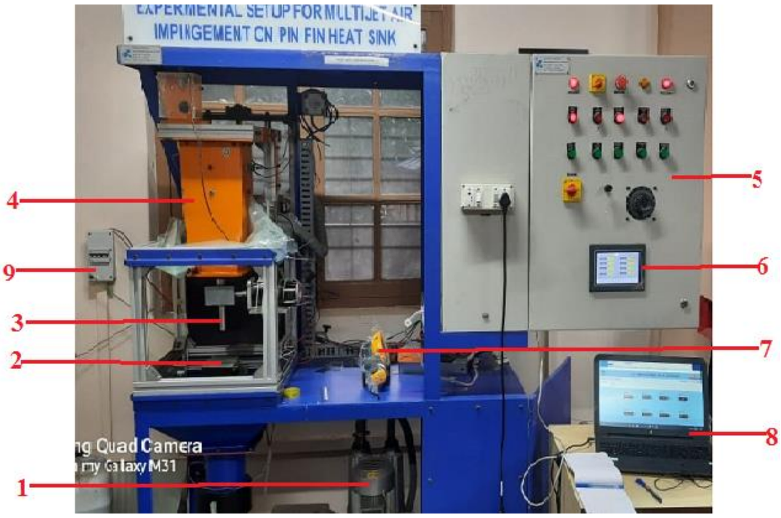

Fig. 1. Experimental system for analysis of steady-state air jet infringement on a heated aluminum plate: 1. inlet blower, 2. target plate assembly, 3. Nozzle, 4. Phelum, 5. control panel, 6. HMI, 7. Thermal infrared camera, 8. DAQ system, 9. Mains Supply

An air jet issues from the nozzle with an inner diameter of D = 15 mm (measured with a digital Vernier caliper) and a length of 105 mm. The target plate measures 100 mm × 100 mm and is 3 mm thick. Infrared images are obtained by positioning the camera onto the surface plate surface of the target. Calibration of the surface emissivity is carried out using the standard procedure as mentioned in Katti and Prabhu [10]. The average emissivity is calculated to be 0.98. The thermal imaging technique, also known as infrared imaging, is used to measure the local temperature of a target surface plate with a constant heat flux input. This method provides a more accurate spatial resolution of temperature compared to using a thermocouple. The 'Fluke' TiS75+ infrared camera is used to capture the local temperature distribution with a resolution of approximately 0.2 mm per pixel. Jet exit temperature is measured by the 'Testo' vane anemometer 410i with an accuracy of ±0.3 m/s.

2.1 Data Minimization

Digitization of thermal data for radial temperature distribution on the surface plate of the target is performed using 'Fluke Connect software, version 1.1.550.0. Temperature distribution over the target plate is obtained by averaging five infrared images for each experimental setting, once steady state conditions are achieved. The local Nusselt number is obtained by calculating the Nusselt number at a specific point or location.

$$Nu_l = \frac{hD}{k_{am}} \tag{1}$$

where, h is Convective heat transfer coefficient $W/m^2{}^\circ C$, D is Diameter of nozzle m, k_{am} is Thermal conductivity of air $W/m\ {}^\circ C$.

$$h = \frac{q''_{Conv}}{T_s - T_{surr}} \tag{2}$$

$$R_e = \frac{\rho v D}{\mu} \tag{3}$$

where, ρ is the density of air in kg/m^3, υ is the average velocity of jet exit fluid m/s, D is the diameter of nozzle m, μ is the Dynamic viscosity of air Pa.

Uncertainties in the present case experimentation in Nusselt number, heat supplied, and Reynolds number were evaluated using the standard procedure mentioned in Brown *et al.,* [44]. The 95% confidence intervals for the heat supplied, Nusselt number, and Reynolds number are approximately 12.3%, 10.5%, and 7%, respectively. This is consistent with data recorded by Sagot *et al.,* [15].

3. Results and Discussion

3.1 Validation of Present Results Published in Previous Literature

As shown in Figure 2, the ongoing experimental methodology is validated by comparing the local Nusselt number distribution to the experimental results reported by Sagot *et al.,* [15].

The maximum variation between the current experimental results and the experimental results of Sagot *et al.,* [15] is 12%. Therefore, we can conclude that the current experimental procedure is validated. The experiments were carried out using a different configuration of Reynolds number $6500 \leq Re \leq 15000$ and nozzle-to-surface plate spacing $2 \leq Y/D \leq 6$.

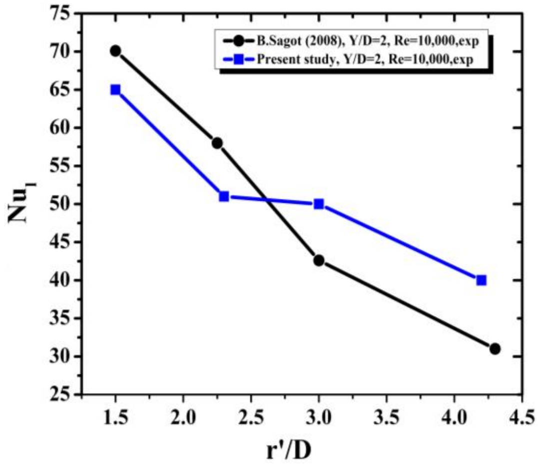

Fig. 2. Comparison of the results with preceding literature for the local Nusselt number dissemination

3.2 Effect of Reynolds Number on Nusselt Number Dissemination

Figure 3 shows the distribution of the Nusselt profile in the radial direction of the target plate. It can be observed that the Nusselt number increases with an increase in the Reynolds number. This is attributed to the increased impulse of air resulting from the higher velocity. Furthermore, a localized peak is observed in the local Nusselt profile at 0.5 ≤ Y/D ≤ 1, indicating a 14% increase in the maximum Nusselt number. The trends are similar for Figure 4. At $r'/D = 5$, corresponding to $Re = 10000$, there is an increase in Nusselt number. This can be attributed to the air jet striking the surface, which experiences more turbulence due to the formation of eddies caused by the partial recirculation of air combined with the air jet.

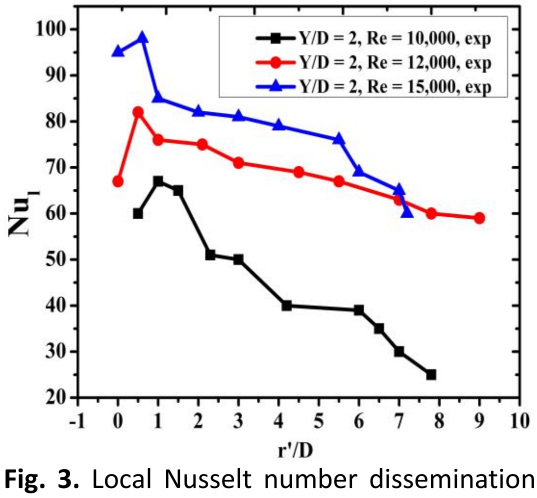

Fig. 3. Local Nusselt number dissemination for steady state normal air jet infringement at Y/D=2, and different Reynolds number

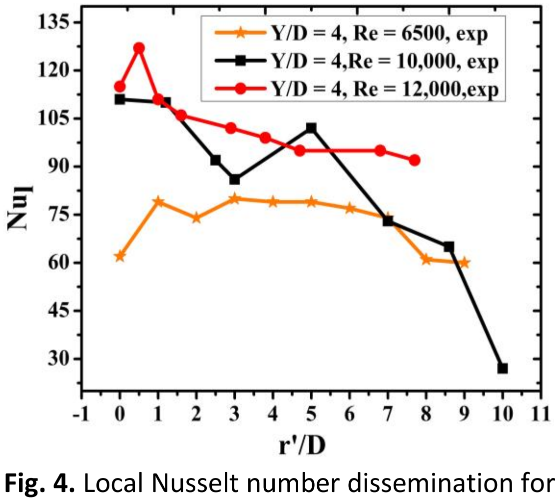

Fig. 4. Local Nusselt number dissemination for steady state normal air jet infringement at Y/D=4 and different Reynolds number

Figure 5 shows the result of augmentation in jet exit Reynolds number, revealing an increase in the shear layer velocity gradient. The stagnation local Nusselt number, Nu_0 is maximum at $r'/D = 0$ at the center of the jet striking the target surface. The combination of high local velocities and maximum temperature differences, results in a high heat transfer rate at the stagnation region. The Nusselt profile distribution curve has a steep, slope as shown in Figure 5. This suggests that heat transfer rates decrease relatively quickly compared to Y/D = 2,4. It is also observed that up to the stagnation region, i.e., $0 \leq r'/D \leq 1.0$, the heat transfer rate increases, and there is a decrease in heat transfer rates along the streamwise direction of the target surface plate, as reported by Umair and Gulhane [20]. The presence of a first local peak at $Y/D = 2$, 4 is due to the higher turbulence in the boundary layer, which originates from the extreme shear between the radial outgoing wall-jet and the inactive surrounding, as Y/D diminishes. The secondary peaks are more noticeable for jet-to-plate spacing, $2 \leq Y/D \leq 4$ which is a new finding from the Figure 3 and Figure 4. This observation had not been highlighted in previous literature. At, $Y/D = 6$ the local first peak diminishes.

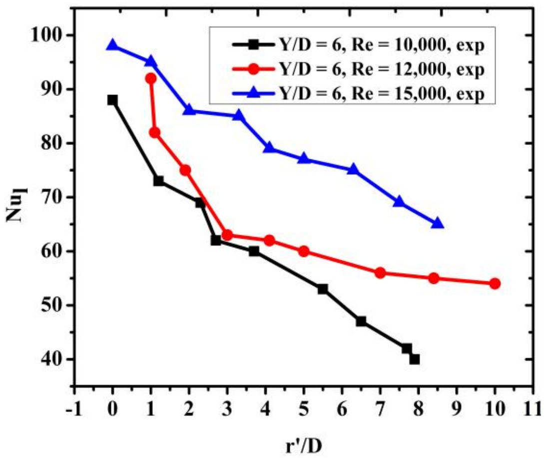

Fig. 5. Local Nusselt number dissemination for steady state normal air jet infringement at Y/D=6 and different Reynolds numbers

3.3 Effect of Jet-to-Target Plate Spacing on Nusselt Number Dissemination

Figure 6 shows an initial increasing trend of stagnant Nusselt numbers until Y/D = 4 with corresponding stagnant Nusselt numbers of 110 and 115 for Reynolds numbers 10,000 and 12,000, respectively. As Y/D continues to increase, the spread of the Nusselt number decreases. Furthermore, it is observed from Figure 6 and Figure 7 that at higher values of Y/D i.e. $4 \leq Y/D \leq 6$ large space between the jet-to plate allows the shear layer to, enter into a stagnation field. The nozzle air jet has a longer distance to travel before reaching the surface target plate, allowing it to blend with the recirculation flow. As a result of this phenomenon, the velocity of the air jet decreases when it strikes the surface plate due to increased turbulence intensity and decreased heat. Furthermore, a trend reversal can be observed in the Nusselt number distribution, with Re = 15000 showing a different pattern than Re = 10000 and 12000. The above parameter initially decreases until Y/D = 4, after which it increases. The stagnation Nusselt number peaks occur at Y/D = 4, corresponding to Re = 10000, 12000.

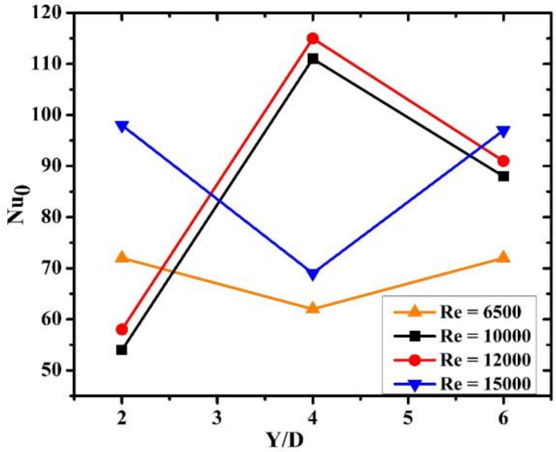

Fig. 6. Stagnation Local Nusselt number (0 ≤ r'/D ≤ 1) dissemination for steady state normal air jet infringement at different Reynolds number

From Figure 7, it can be concluded that the Nusselt number in the transition field exhibits similar trends to the corresponding Nusselt number in the stagnation field. Compared to the corresponding stagnation field Nusselt profile spread, the transition field Nusselt profile spread had 12% lower values. The results of the present study are consistent with the findings presented in San and Shiao [4], however, while their study focused solely on the Nusselt number at the stagnation point, our study also includes an analysis of the transition and wall-jet regions.

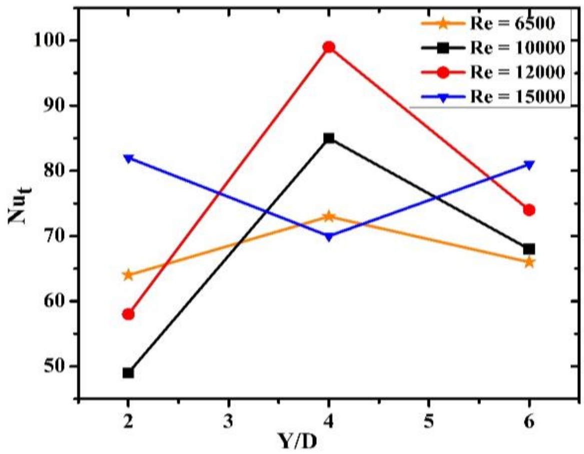

Fig. 7. Transition Local Nusselt number (1 ≤ r'/D ≤ 4) dissemination for steady state normal air jet infringement at different Reynolds number

The distribution of the Nusselt profile for wall-jet fields is shown in Figure 8, which exhibits a trend similar to that of stagnation and transition fields. In the wall-jet field, the Nusselt number was 10% lower than the corresponding values in the stagnation and transition fields.

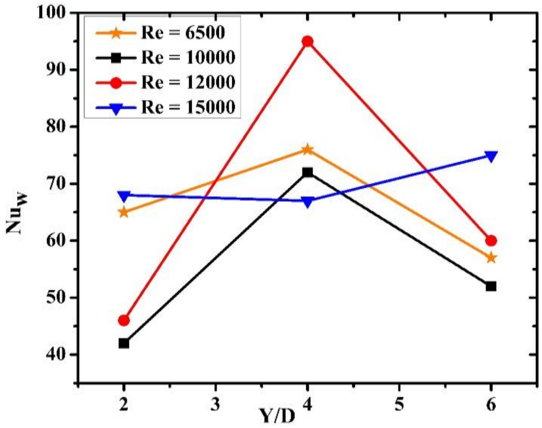

Fig. 8. Wall jet Local Nusselt number (r'/D ≥ 4) dissemination for steady state normal air jet infringement at different Reynolds number

4. Semi-Empirical Correlations

Three distinct fields as suggested by Yogi *et al.,* [45] have been highlighted in sec 4.1 and utilized for further studies in the local Nusselt number dissemination to develop the correlation between $Nu = f\{Re, r'/D, Y/D, Pr\}$. We propose a new generalized correlation for field-wise local Nusselt numbers that can be very well conveyed as:

$$N_u = C \times R_e^m \left[\frac{r'}{D}\right]^n \times \left[\frac{Y}{D}\right]^p \times p_r^q \quad (4)$$

where the normal Prandtl number exponent of 0.33 is utilized as recommended by Zhou and Lee [23,24]. The coefficients C and exponents m, n, p, and q were evaluated by least-square techniques. The least values of standard deviations represent a good accord existence between the present results and the correlations as presented in Table 1.

Table 1
Field-wise correlation of the local Nusselt number

Field	C	m	n	p	Standard Deviation
Stagnation field ($0 \le r'/D \le 1$)	3.08	0.141	0.084	-0.070	M = 0.16, n = 0.68, p = 0.43
Transition field ($1 \le r'/D \le 4$)	0.798	0.349	-0.073	0.214	M = 0.16, n = 0.18, p = 0.45
Wall jet field ($r'/D \ge 4$)	0.838	0.338	0.207	0.11	M = 0.16, n = 0.15, p = 0.45

4.1 Field A ($0 \le r'/D \le 1$ Stagnation Field)

The pressure ramp declines swiftly with streamwise direction from the stagnation field, this is evident by the exponent of the jet Reynolds number which augments moderately. The smaller values of exponent Y/D indicate, less dependency of Nusselt number on the jet-to-plate spacing.

4.2 Field B ($1 \leq r'/D \leq 4$ Transition Field)

The flow from the stagnation field to the wall jet field is continuous by the transition field. Towards the borderline of the stagnation field, the stream converts into a sensitive stream because of the existence of irregular turbulent variations. From the exponent n in the transition field, it is concluded that the Nusselt number decreases with r'/D.

4.3 Field C ($r'/D \geq 4$ Wall Jet Field)

The interpreter m here decreases conservatively, this shows that at a length ahead of $r'/D \geq 4$, the interpreter m, has a feeble confidence on the air stream. This expresses a perfect wall jet field. The local Nusselt numbers with stream-wise direction decrease very rapidly as the interpreter n is at higher values compared to its previous field.

5. Conclusion

The evolution of the Reynolds number at the air jet exit and the jet-to-plate distance, based on the local Nusselt number, was evaluated to determine the best framework for increasing heat transfer. The Reynolds numbers selected were 6500, 10000, 12000, and 15000. The Distance between the nozzle and the target surface plate was kept at Y/D=2, 4, and 6. Present experimental results show that the Reynolds number at the jet exit has a profound influence on increasing heat transfer. An increasing trend in the stagnation Nusselt number is found until Y/D = 4, with corresponding stagnation Nusselt numbers of 110 and 115 for Reynolds numbers 10,000 and 12,000, respectively. The Nusselt number in the transition region exhibited a 12% decrease in heat transfer values compared to the Nusselt profile in the stagnation region, despite having the same Reynolds number. The experiments confirm that the first peak in the local Nusselt number spread is more pronounced at lower values of $Y/D \leq 1$ due to the increased turbulence in the stagnation field. However, this first peak diminishes at higher values of $Y/D \geq 6$. The heat transfer rates are higher for the configuration Y/D = 4. An increase of 5% was observed for various Reynolds numbers compared to the corresponding values of Y/D = 2 and 6. Semi-empirical correlations for local Nusselt spreading rates are developed for $0 \leq Y/D \leq 6$. For most practical purposes, a wide range of Reynolds numbers from $6500 \leq Re \leq 15000$ is applied. At Y/D=4, Re=10,000, and r'/D=5, there is a local increase in the Nusselt number. This increase is attributed to the formation of vortices caused by the partial mixing of the circulating air with the air jet. The turbulence intensity increases when the air jet impinges on the surface, resulting in an elevated local Nusselt number.

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