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The Impingement Heat Transfer Data of Inclined Jet in Cooling Applications: A Review

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Abstract: On the impingement heat transfer data, the experimental studies of air and liquid jets impingement to the flat surfaces were collected and critically reviewed. The oblique impingements of both single circular and planar slot jets were considered in particular. The review focused on the surface where the jet impingement cooling technique was utilized. The nozzle exit Reynolds numbers based on the hydraulic diameter varied in the range of 1,500–52,000. The oblique angles relative to the plane surface and the dimensionless jet-to-plate spacing vary in the range of 15°–90° and 2–12 respectively. The review suggested that the magnitude of maximum heat transfer shifted more for air jets compared with the liquid jets. The drop in the inclination angle and the jet-to-plate separation led to the increase in the asymmetry of heat transfer distribution. The displacement of maximum Nusselt number (heat transfer) locations was found to be sensitive to the inclination angle and the smaller jet-to-plate distance. Also, the Nusselt number correlations proposed by various researchers were discussed and compared with the results of the cited references.

Keywords: heat and fluid flow, jet impingement, Nusselt number, oblique angle

1. Introduction

A coordinated discharge of fluid on a target surface provides a controlled rate of heat transfer which is known as impinging jet. The high rate of heat/mass transfer between a fluid and surface is achieved by the impinging jets technique, and this technique is employed for heating, cooling and drying a surface. Impinging jets are used in a broad range of industrial and engineering applications like fabric drying [1], turbine blade cooling [2], furnace heating [3], tempering of glass and metal sheets [4], electronic chip cooling [5], etc. To improve the design of these systems, a comprehensive understanding of the parameters affecting the heat transfer characteristics is required. Studies on the jet impingement have been done by considering the cross-flow, confinement, pulse jet, offset jet, surface movement and many other cases. According to Zuckerman [6], the characteristic variables for defining the jets are the nozzle-to-plate separation and the nozzle size. Air is usually considered as the surrounding medium fluid, based on this condition the jet is categorized as the submerged and free surface jets. The jet enters into the surroundings with a same density is termed as submerged jet (e.g. air into air), where a jet of significantly higher density than the surroundings is called as the free surface jet (e.g. liquid into air). In addition, the impinging jets can be classified by their orientation of impinging, nozzle shape, and geometry of the target surface. Further, the jet is oriented vertically or obliquely with respect to the target surface where the

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Nomenclature

a,b	length and width of the cross-sectional dimensions of the nozzle	U_m	centerline velocity
D, W	hydraulic diameter of circular and slot nozzle	V_j	velocity of jet impingement
h	convective heat transfer coefficient	x	distance along the plate measured from the geometrical center
k	fluid thermal conductivity coefficient	**Greek symbols**	
L	geometric impingement distance	α	fluid thermal diffusivity coefficient
Nu	Nusselt number	ϑ	fluid kinematic viscosity coefficient
Pr	Prandtl number of fluid	ϕ	jet angle relative to the horizontal surface
q	heat flux	**Subscripts and superscripts**	
Re	Reynolds number	c	convective
S	displacement of stagnation point	p	perpendicular
T	temperature	ref	reference value
t	impingement surface thickness	w	wall

impingement surface is flat or curved, and the nozzle shape classifies the jets into circular or planar slot jets [7]. Several studies are available for normal impingement based on a variety of applications. The flow and heat transfer characteristics onto a flat horizontal surface under normal impingement have been well studied (Gardon [4]; McMurray et al. [8]; Beltaos & Rajaratnam [9]; Hrycak [10]; Beitelmal et al. [11]; Shi et al. [12]; Beaubert & Viazzo [13]; San & Shiao [14]; Kate et al. [15]; Sagot et al. [16], and Achari & Das [17]).

Gauntner et al. [18], Downs and James [19], Polat et al. [20], Jambunathan et al. [21], Weigand and Spring [22], Dewan et al. [23] and Carlomagno and Ianiro [24] have done an excellent review work associated with the vertical impingement of a jet to the flat surface. The inclined jets occur in many applications, and it is applied to the problem of non-uniform cooling or heating of impinging jets. For inclined jets, the free jet flow is turned and spread laterally onto the flat surface. This rate of turning and spreading of the jet is influenced by the impingement angle. It is essential to know the heat transfer data attributable to the asymmetric geometry. The flow field associated with the inclined jets has been reported in many studies. Beltaos [25] determined the shear stress and the wall pressure in the stagnation zone under the impingement of a circular jet at inclined angle. The jet Reynolds number (Re) and jet-to-plate separation were varied in the range of 35,000–1,00,000 and 15–47 respectively. The result presented a quasi-axisymmetric characteristic of the flow field. The shift of stagnation pressure points is directed toward the uphill side from the origin of plate. A few studies are available on the rate of heat transfer related to the inclined jets. Initially, the rate of heat transfer with inclined air jets was first determined by Perry [26]. Nevertheless, the shift of points of maximum heat transfer was first measured by Sparrow and Lovell [27]. The considered parameters varied were: the jet Reynolds numbers and jet-to-plate distances in the range of 2,500–10,000 and 7–15 respectively. It is noted that the distribution of local heat transfer coefficients over the test plate is non-uniform, and is diminishing more quickly on uphill side than that on the downhill side. Also, the point of maximum heat transfer was shifted from geometrical center point.

Goldstein and Franchett [28] measured the local heat transfer using the metallic foil heaters with the liquid crystals. The inclined jet was impinging through an opening like square-edged orifice. Their jet Reynolds numbers and jet-to-plate distances are varied in the range of 10,000–30,000 and 4–10 respectively. They developed the Nusselt number correlations from empirical data as a function of inclination and separation. Stevens and Webb [29] performed the experimental study to investigate the local heat transfer coefficients from a constant heat flux surface due to impingement of a circular liquid jet. The angle of inclinations and Reynolds numbers are varied in the range of 40°–90° and 6,600–52,000 respectively. In the results, the shift of the maximum heat transfer points is found to be extending in the range of 0.5 nozzle diameters. Ichimiya and Nasu [30] conducted an experimental study to measure the distribution of local heat transfer coefficients for a single small spacing (L/D=1). The confinement surface was kept parallel to the test plate; therefore the wall jet region is vanished after the jet impingement. Ma et al. [31] carried out an experimental study to determine the effect of jet angles (40°–90°) with Reynolds numbers in the range of 235–1,745. In the study, the free circular jet of transformer oil was impinging obliquely to the heated surface. Yan and Saniei [32] utilized the preheated wall transient liquid-crystal technique to estimate the rate of heat transfer for an impinging obliquely circular air jet to the flat surface. The investigated parameters varied were: the jet angles of 45°–90°, Reynolds numbers of 10,000–23,000 and the jet-to-surface spacing of 2–10. The results showed that the shift of peak heat transfer point is primarily influenced with a smaller jet-to-surface distance and a smaller jet angle.

In the study of Vipat et al. [33], the oblique impingement of a circular air jet to the flat plate has been done to recognize the flow and temperature fields. The considered Reynolds number, angles of impingement, and dimensionless distance are 8,200, 30°–90°, and 8 respectively. They performed both jet impingement cooling and heating technique for the same geometry. For cooling jet, the rise in inclination reduces the local effective temperature values, and in the case of heating jet, conversely increases the local surface temperature. Despite, the displacement of stagnation points toward the uphill side from the origin of the test plate is observed consistently in both cooling and heating cases. The effect of inclination on the rate of heat transfer under the impingement of a planar slot jet to the flat surface has been studied by the few authors (Beitelmal et al. [34]; Eren and Celik [35] and Akansu et al. [36]). Akansu et al. [36] examined the effect of inclination on the rate of heat transfer under the impingement of a slot jet to the flat plate. They conducted separate experiments for both wall pressure and heat transfer measurements. The parameters varied were: the Reynolds numbers, jet-to-plate distances and inclinations in the range of 2,500–7,500, 2–12 and 45°–90° respectively. In the results, the peak Nusselt number is steadily increasing with the lower impingement distances.

The aim of the present review work is to collect and evaluate the available experimental heat transfer data for an oblique impingement of a single jet to the flat surfaces. In the literature, there is no review paper available on the considered topic as per best of our knowledge. It is an effort to fill this gap in the literature. The considered parameters for the review work are varied as: the jet inclinations, Reynolds numbers, and jet-to-plate spacing in the range of 15°–90°, 1,500–52,000, and 2–12 respectively.

2. Jet Flow Characteristics

Fig. 1 illustrates the various regions of an impinging jet field for free surface and submerged jets. Following the pioneering studies of Gardon [4], Watson [37], Bieber et al. [7] and Carlomagno and Ianiro [24], it can be stated that the normal impinging jet flow fields are described by the following three main regions: First, the free jet region where the flow velocity is usually the same as that of nozzle exit velocity. Secondly, the impingement region leads to the large pressure gradient due to which the flow diverges in the radial direction. Lastly, in the wall-jet region the jet flow spans the ground surface. The free jet region is also identified with three more zones: the potential core region, the developing zone and the developed zone. The initial velocity and the turbulence at the nozzle exit affect the length of the potential core. As the turbulence and shear layer grow, the width of the potential core diminishes [38]. Livingood and Hrycak [39] concluded that the length of the potential core enlarges from the nozzle exit 6–7 orifice diameters for circular jets and 4.7–7.7 orifice widths for slot jets. The pattern of the free surface depends on pressure, gravitational forces

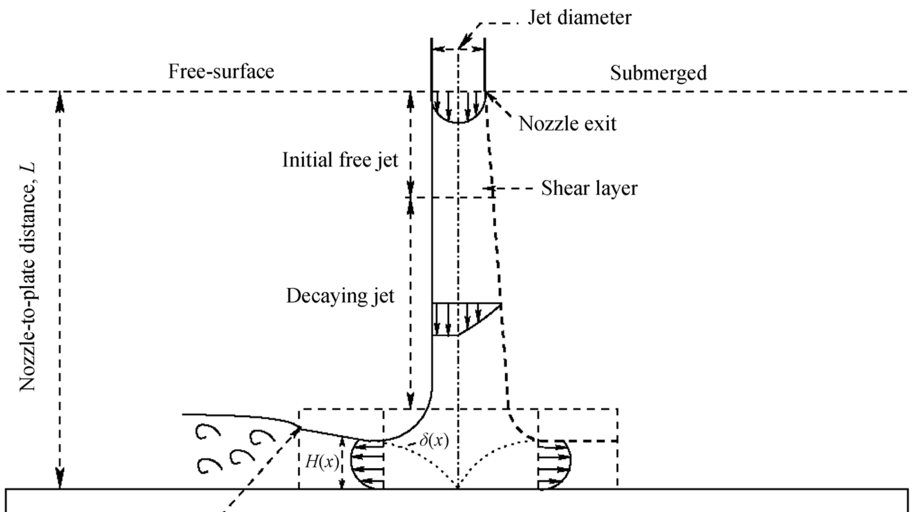


Fig. 1 Impingement regions for a free surface and submerged jets

and surface tension. The large shear stresses generate the turbulence at the jet boundary which initiates the reduction of axial velocity in the developing zone, and it leads to the dragging of additional fluid. After the developing zone, the velocity profile is fully developed.

Reichardt [40] has obtained a good correlation of the Gaussian velocity distribution with his practical data. The decay of axial velocity and widening of a jet alter linearly. In the stagnation region, the jet diverges into an accelerated horizontal component. Martin [41] pointed out that the thickness of the impingement zone boundary layer is relatively constant. Due to the lack of shearing with the low-density medium, a free-surface jet undergoes repose after exiting the outlet. Contrary to submerged jet, the free surface jet presents a hydraulic jump [24]. The slot width of a jet exhibits a wide thin two-dimensional profile. The single jet *Re* of about 2,500 will be considered to be laminar [20]. This value is generally accepted, although there is no direct proof determining a particular transitional *Re* for impinging jets. Further particularly, there are four characteristics regions for circular free jets: the dissipated laminar jet $Re<300$, a fully laminar jet $300<Re<1000$, a transition or semi-turbulent jet $1000<Re<3000$, and a fully turbulent jet $Re>3000$. According to Polat et al. [20], whether a laminar free jet is still laminar before impingement depends on many factors like the initial velocity profile, jet separation and confinement of a jet. All these variables affect the mixing at the exterior jet boundaries that generate a laminar jet into a turbulent jet.

Fig. 2 schematically describes an obliquely impinging jet to the flat surface at inclined angle ϕ. A single jet of diameter D (for circular jet) or W (for planar slot jet) is emanating from the nozzle exit with V_j as velocity of jet impingement. The terms a and b are the length and the width of the cross-sectional dimensions of the nozzle respectively. The geometric center point (0, 0) is also termed as the center of plate, where the jet axis intersects to the impingement surface.

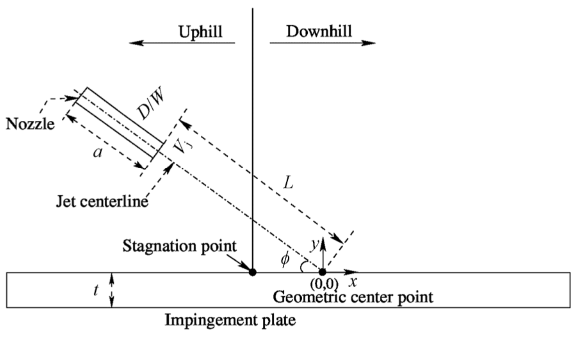


Fig. 2 A schematic diagram of an oblique impingement of a jet

The inclination between the jet axis and horizontal flat surface is termed as impingement angle ϕ. The notations L and t are the impingement distance and the plate thickness respectively. The inclined jet flow behaves the same as that of the behavior of orthogonal jet impingement with slight changes occuring in the following respects: (i) the axial symmetry remains only up to the free jet zone; (ii) the impingement zone, which is recognized to spread over the cross-section of the jet for an orthogonal impinging jet, is supposed to change in shape and size as the jet becomes obliquely inclined to the flat surface. Further, there is no more coincidence existing between the stagnation point and the geometric center point in the impingement zone. However, the distribution of radial flow over the impingement surface is irregular, the flux being the highest in the downhill side and the lowest in the uphill side. The shift of stagnation points toward the upstream of the surface from the geometric center point for impinging obliquely inclined jets has been reported in the studies of Beltaos [9], Stevens and Webb [29], Yan and Saniei [32], Ma et al. [31], Beitelmal et al. [34], Oztop et al. [42] and Attalla and Salem [43].

3. Non-Dimensional Groups and Definitions of Heat Transfer

The conduction and energy transfer rendered by the flowing fluid drives the convective heat transfer [44]. It is essential to measure the convective heat transfer coefficient h or convective heat flux q_c between a fluid and solid surface. Steady-state Newton's law perceives the relationship between these two terms:

$$q_c = h(T_w - T_{ref}) \tag{1}$$

where T_{ref} is a reference temperature and T_w is the surface temperature. The impingement surface is rendered within that of constant heat flux or constant wall temperature. The fluid film near the surface has the most significant impact on the amount of heat transported. The heat can only be transferred by conduction when the radiation mode of heat transfer is neglected. The convective heat flux is described by the Fourier's law:

$$q_c = -k\left(\frac{dT}{dy}\right)_{y=0} = -k\left(\frac{dT}{dz}\right)_w \tag{2}$$

Combining Eq. (1) and Eq. (2), the heat transfer coefficient is derived as:

$$h = -k\left(\frac{dT}{dy}\right)_w \Big/ \left(T_w - T_{ref}\right). \tag{3}$$

The convective heat transfer data obtained from theoretical or experimental results are usually determined using the non-dimensional number, Nusselt number (*Nu*).

$$Nu = \frac{hD}{k} \text{ or } Nu = \frac{hW}{k} \tag{4}$$

The *Nu* commonly depends on the fluid flow geometry and on the *Re* and, the *Re* is defined as:

$$Re = \frac{V_j D}{\vartheta} \text{ or } Re = \frac{V_j W}{\vartheta} \quad (5)$$

where V_j is the velocity of jet and ϑ is the kinematic viscosity coefficient of fluid. The Prandtl number of fluid is defined as:

$$Pr = \frac{\vartheta}{\alpha} \quad (6)$$

where α is the thermal diffusivity coefficient of fluid.

4. Heat Transfer Characteristics

The jet impingement heat transfer is a complex function of several variables like Reynolds number, Prandtl number, Nusselt number, dimensionless jet-to-surface spacing, and dimensionless displacement from the stagnation point. Sibulkin [45] reported the heat transfer at a stagnation point in laminar flow follows the equation $Nu \propto U_m^{1/2}$. It suggests that the Nusselt number (*Nu*) will remain roughly constant in the core region and reduce downstream of the core. The curves for local heat transfer distribution usually present the bell shape for the jet impingement. The asymmetry of heat transfer is pronounced more with fall in ϕ. In respect of maximum point, on the uphill direction the rate of heat transfer decreases rapidly because the jet does not have sufficient energy to raise the up-slope. But, in the downhill direction the high rate of heat transfer occurs because the initial momentum of the fluid. As compared to the vertical jet impingement, the oblique jet impingement shows the lower heat transfer rate in the uphill direction and the higher heat transfer rate in the downhill direction. As the inclination angle reduces, the maximum heat transfer point will be displaced towards the uphill side. Therefore, a significant amount of unevenness of cooling occurs on the two sides of the maximum point. Table 1 presents the selected configurations concerning literature sources. In the present review paper, the heat transfer data will be quantified by three parameters: the inclination angle relative to the horizontal flat surface, the Reynolds number, and the dimensionless jet-to-surface distance.

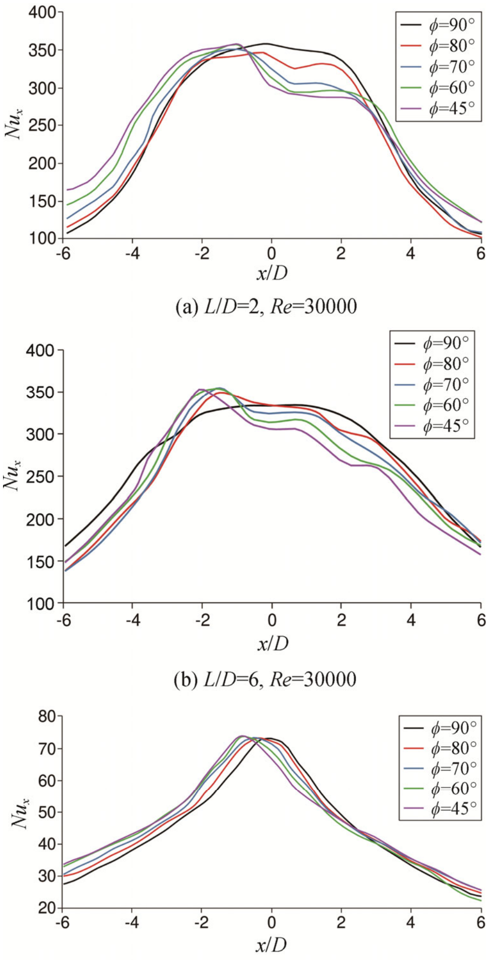
4.1 Effect of angle of jet inclinations

The position of the point at which the maximum pressure appears is being termed as the stagnation point/location, where the velocity of flow becomes zero. For the normal impingement, the position of stagnation location and geometric point are found at one place, because of the symmetric behavior of jet flow over the target surface. The stagnation zone shifts toward the inclination of the jet, due to early attachment of the shear layers with the impingement surface. In this context, the characterization of stagnation points are outlined from the previous experimental studies of Sparrow and Lovell [27], Goldstein and Franchett [28], Stevens and Webb [29], Beitelmal et al. [34], and Attalla and Salem [43]. Pressure measurements, temperature-sensitive surface, and liquid crystal techniques were employed to quantify the displacements of stagnation point or maximum heat transfer point. The jet inclination relative to the horizontal surface is varied in the range of 15°–90°, the

Table 1 The selected sources of heat transfer data of inclined jets

Authors	Year	Nozzle geometry	Nozzle diameter /mm	ϕ	*Re*	$\frac{L}{D}$ or $\frac{L}{W}$	Measurement technique
Martin	1977	Slot	4 and 23	90°–15°	1,500–1,20,000	2–10	Constant heat flux
Sparrow and Lovell	1980	Circular	0.0635	90°–30°	2,500–10,000	7–15	Naphthalene sublimation
Goldstein and Franchett	1988	Circular square orifice	28.4	90°–30°	10,000–35,000	4–10	Liquid crystal
Stevens and Webb	1991	Circular	4.6 and 9.3	90°–40°	6,600–52,000	1.6 and 3.2	Heat flux
Yan and Saniei	1997	Circular, Long pipe	0.205	90°–45°	10,000–23,000	2–10	Liquid crystal
Beitelmal et al.	2000	Slot	5.5	90°–40°	4,000–12,000	4–12	Heated plate
Eren and Celik	2006	Slot, long pipe	30	90°–30°	5,860–11,606	8	Heated plate
Akansu et al.	2008	Slot, long pipe	4	90°–45°	2,500–7,500	2–10	Preheated plate
*Vipat et al.	2009	Slot, long pipe	6.35	90°–30°	82,000	8	Constant heat flux
Beltaos	2010	Circular	1.59–19	90°–30°	35,000–1,00,000	15–47	Inductive approach
Attalla and Salem	2015	Circular	9.53	90°–45°	1,500–30,000	2–8	Infrared camera images
Ingole and Sundaram	2016	Circular	25	75°–15°	2,000–20,000	0.5–6.8	Heat flux

*Data not used in the present study



(a) L/D=2, Re=30000

(b) L/D=6, Re=30000

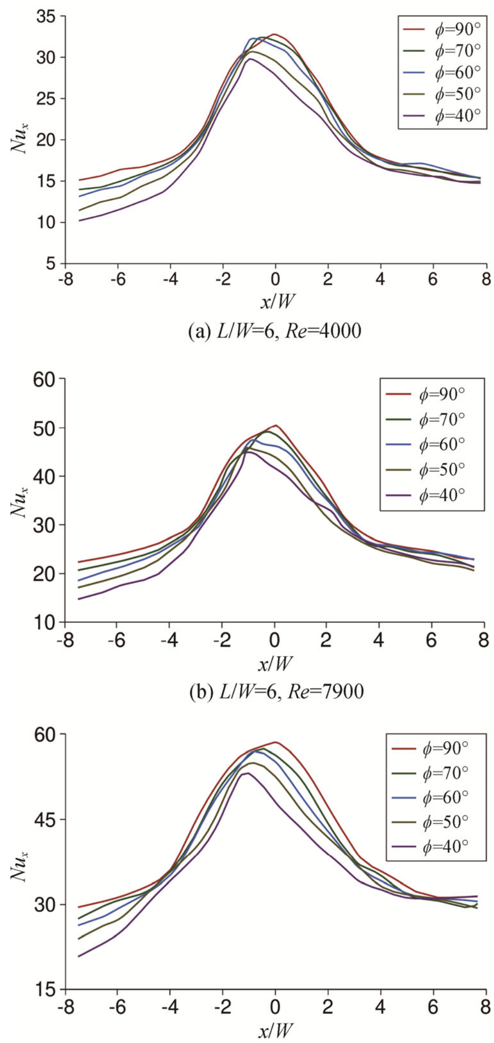
(c) L/D=6, Re=1500

Fig. 3 Variation in Nu_x for different values of ϕ [43]

condition ϕ=90° is being termed as the normal or orthogonal impingement. The effect of inclination on the rate of heat transfer data for circular and slot air jets have been well examined by Attalla and Salem [43] and Beitelmal et al. [34], respectively. They developed local Nusselt number correlations from the experimental data.

Attalla and Salem [43] conducted an experimental work to determine the influence of inclination (45°–90°) on the rate of heat transfer for an impinging circular air jet. This parametric study was examined for two impingement distances of 2 and 6. The variation of local *Nu* for the different inclinations is shown in Fig. 3. The distribution of heat transfer for ϕ=90° exhibits a symmetric behavior around the center of the plate. In the case of oblique jet the asymmetry increases as the inclination is decreased. The fall in ϕ leads to the shifting of maximum heat transfer (Nu_{max}) toward the upstream from the origin of the test plate. For the smaller jet-to-plate distances, the near peaks *Nu* are not affected by the initial drops in ϕ. They outlined that, for a smaller distance (L/D=2) the test surface is within the potential core of jet. The amount of increase in Nu_{max} decays gradually after a larger impingement distance of six. The creation of turbulence is intense in the transition region, and it begins the cause of second maxima of heat transfer. The coefficients on the downhill side matches the behavior of normal jet for same L/D with the second maxima extends within two jet diameters. For a given separation, the slope of Nu_x distribution on the uphill side (x/D<0) increases with a decrease in ϕ. Whereas on downhill side (x/D>0) slope decreases with a decline in ϕ.

The radial variation of x-axis profile changed with the decline in ϕ is found to be sensitive on smaller jet-to-plate spacing. In the results, the shift of Nu_{max} locations is appeared within 1.4D from the geometric point. In the study of Beitelmal et al. [34], the slot air jet at the same environment temperature was impinging obliquely to the uniformly heated flat plate. The Nu_x is plotted vs x/W for various ϕ is shown in Fig. 4. The maximum heat transfer point falls between 0 and 3W



(a) L/W=6, Re=4000

(b) L/W=6, Re=7900

(c) L/W=10, Re=12000

Fig. 4 Nu_x vs x/W for various ϕ [34]

from the geometric center point. The variation of Nu_x profile in the near-peak region is relatively independent of ϕ, where outside of the near-peak region, the Nu_x is greatly influenced by the jet inclination. The change of *Nu* in the near-peak region occurs meanwhile the jet is inclined.

According to Zumbrunnen et al. [46] and Stevens [47] the coefficients in a stagnation region is generally proportional to the spatial velocity gradient (du/dx). Entrainment has the impact of lowering the inflow velocity causing an increase in the impingement area of the jet at the target surface. The displacements of maximum heat transfer location will occur in this increased impingement area. With the decrease in the jet inclination angle for submerged jets, the maximum heat transfer point shifts toward uphill side and the jet flow increases in the downhill side. This type of behavior would yield the drop in the velocity gradient, and it provides the lower heat transfer. The entrainment and shear layer effects are negligible in the case of free liquid jet, where the asymmetry in the flow rises while lowering the ϕ. This would cause increase in the velocity gradient in the impingement region. Therefore, the higher *Nu* has noted in liquid jets where the significant lower *Nu* is found in the submerged jets.

4.2 Effect of Reynolds numbers

The selected Reynolds numbers (*Re*) based on the hydraulic diameter varied in the range of 1,500–52,000. Only a few studies showed the influence of Reynolds numbers on the heat transfer characteristics in oblique jet impingement. Goldstein et al. [28] presented the local Nusselt number profile in terms of $Nu/Re^{0.7}$ and stated that *Nu* profile (for circular jet) is found to be independent of Reynolds numbers. Stevens and Webb [29] examined the effect of *Re* (6,600–52,000) on the heat transfer coefficients from a constant heat flux surface under the impingement of a circular liquid jet. The results showed that the shifting maximum heat transfer points toward the uphill side of the surface occur within range of 0.5 nozzle diameter from the geometric center point. Beitelmal et al. [34] have determined the effect of Reynolds numbers on the heat transfer coefficients under the impingement of a slot jet to the constant heat flux surface. The *Re* varied in the range of 4,000–12,000. The effect of *Re* on the local Nusselt number distribution at constant value of L/W=6 is shown in Fig. 5. It is noted that Nu_x profile increases with increasing the *Re*. They concluded that the shifting of Nu_{max} location is independent of *Re*.

4.3 Effect of jet-to-plate spacing

For the oblique jet impingement, a few authors have investigated the influence of jet separation distances on the heat transfer coefficients from a flat surface. Beitelmal et al. [34] determined the influence of jet-to-surface distances on the rate of heat transfer under the impingement of a slot air jet. The separation distance varied in the range of L/W=4–12. The distribution of Nu_x over the test plate for various L/W is shown in Fig. 6. It is observed that the profiles of local *Nu* decreases monotonically with increase in the L/W. The *x*-axis distribution of the Nu_x is more dependent on the inclination for smaller separation distances (L/W=4 and 6). The *Nu* profiles of the same general characteristic shape would result in the *y*-axis distribution.

For the circular air jet impingement, Attalla and Salem [43] determined the influence of jet-to-surface spacing's (L/D) on the heat transfer coefficients from a impingement surface. The L/D varied in the range of 2–8. The variation of Nu_x over the flat surface for various L/D at two oblique angles ϕ=45° and ϕ=60° and a constant *Re*=23,000 is shown in Fig. 7. The total heat transfer decreases slowly as the jet-to-plate increased, and in the downhill direction the heat transfer became less rapid. The extent of asymmetry directs to decline with increase in the impingement distance.

The rate at which these Nu_x alter with the ϕ is dependent on the impingement distance. As the jet-to-plate distance increases, the decrease of heat transfer on the uphill side becomes less rapid. It

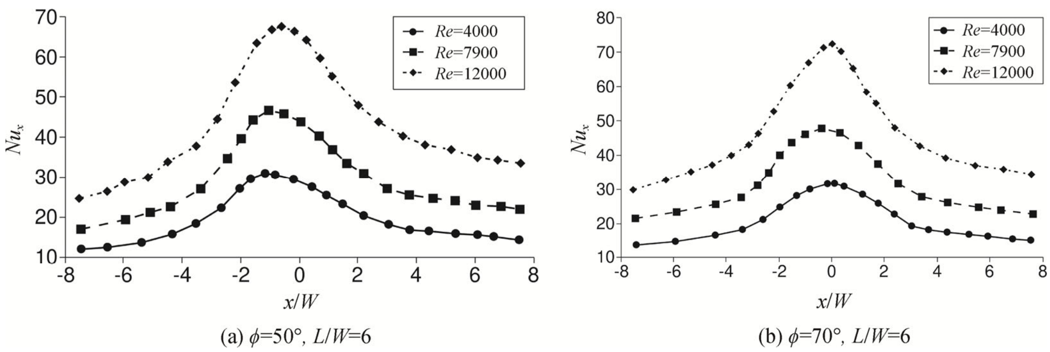


Fig. 5 Influence of *Re* on local Nusselt number [34]

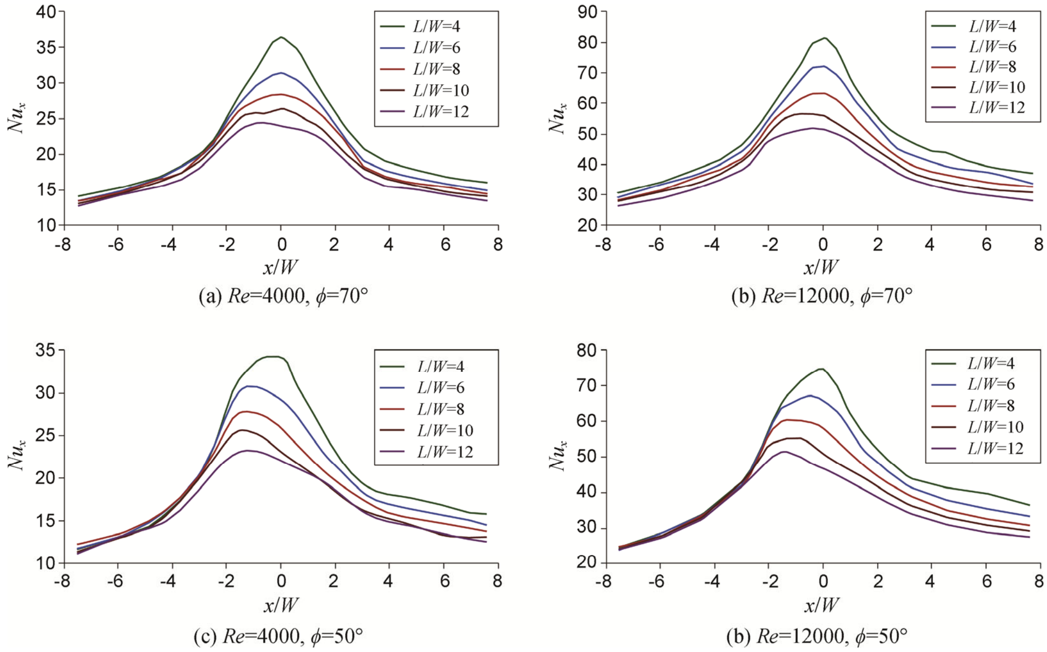


Fig. 6 Variation of Nu_x for different L/W [34]

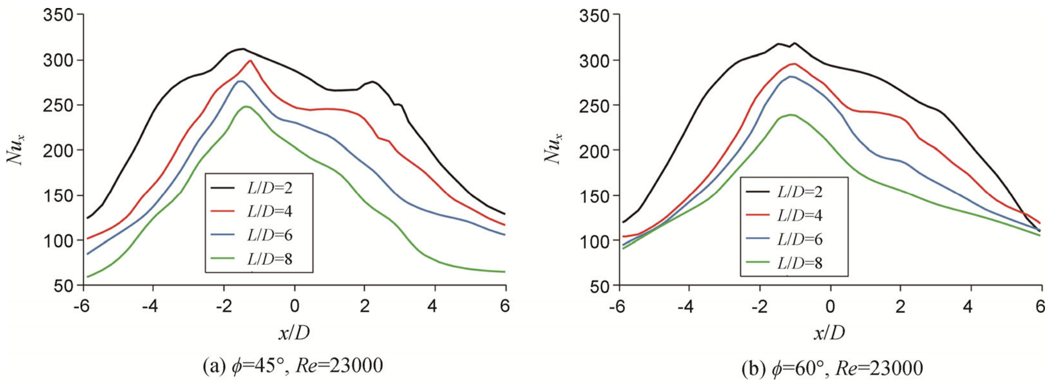


Fig. 7 Variation of local Nusselt number for different values of L/D [43]

represents that at the higher distances of impingement, the jet flow is thoroughly mixed and spread that the variation of heat transfer to the surface is less responsive to the jet separation. Overall, it concludes that the peak Nusselt numbers is not relatively influenced by variation in inclination till the 30° for all spacing (L/D=6). For circular liquid jet the local *Nu* on the downhill direction increases, and a decrease of *Nu* profile found on the uphill direction of the plate. The same general characteristics would occur for the circular liquid jets as that of circular air jets.

This effect is not unexpected because of the positive relationship of *Nu* on *Re* for both air and liquid jets. But, the amount of jet flow toward the downhill side increases rapidly with decrease in the jet angle for circular liquid jets. It provides a higher *Re* on the downhill side than on the uphill side.

Fig. 8 represents the displacement of maximum heat transfer location which is non-dimensionalized using the impingement distance. The influence of inclination angle on the movement of maximum heat transfer is found to be sensitive for the smaller spacing. At the larger separation spacings, the entrainment fluid is well mixed with the surrounding fluid; it leads to the uniform momentum before striking the target surface. The influence of ϕ is found to be less sensitive for the smaller separation distances where it affects more with the larger spacings. The scaled shift of maximum heat transfer points from different experimental studies is shown in Fig. 9. It concludes that the radial distribution of Nu_x is dependent on both the inclination and the separation. The profiles with a lower jet-to-plate distance and a lower jet angle have steeper profiles than the profiles with the higher separation and higher inclination.

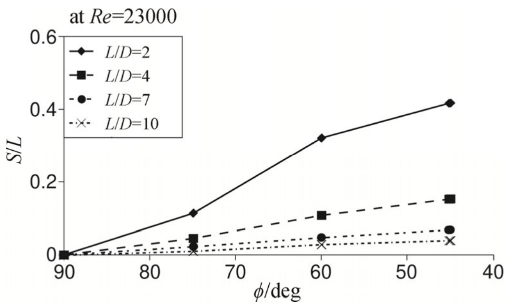


Fig. 8 Shift of points of maximum Nu [43]

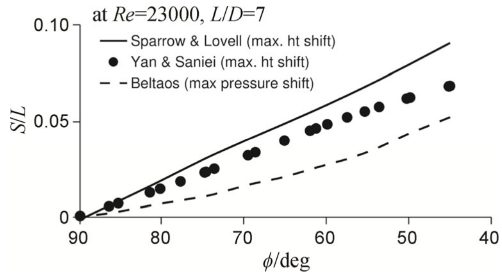


Fig. 9 Comparison of scaled displacement of maximum Nu locations with different experimental results [43]

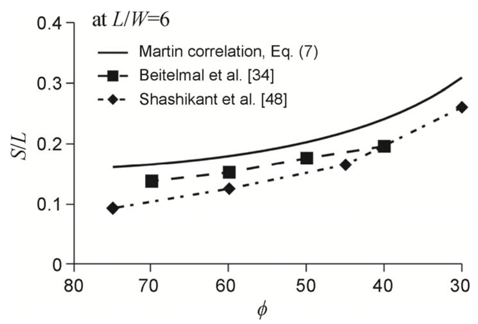


Fig. 10 Martin [41] correlation compared with the experimental and numerical study

5. Correlations for Nusselt number

A relationship for the shift of points of the maximum heat transfer was presented by Martin [41] for slot widths is:

$$S = 1.4\left(L + 0.11\frac{L}{\sin\varphi}\right) \tag{7}$$

The proposed Martin [41] correlation for the shifts of maximum heat transfer location is compared with the experimental and the numerical results of Beitelmal et al. [34] and shashikant et al. [48] shown in Fig. 10. For oblique impingement of a slot jet, the correlations for local Nusselt number (Nu_x) distribution over the flat plate was developed by Beitelmal et al. [34]. As it was difficult to express the bell shaped Nu_x profile in a single equation, individual correlations (as a function of L/W, x/W, ϕ and Re) were developed for different regions of the curve i.e. in the impingement region ($-1.5 \le X \le 1.5$), the uphill region ($-1.5 \le X \le -7.5$) and the downhill region ($1.5 \le X \le 7.5$). The inclination, jet separation from the plate and Re were varied in the limited ranges of 40°–90°, 4–12, and 4,000–12,000 respectively. The Nu_{max} values obtained from the empirical data were utilized to develop the correlations in the impingement region.

$$Nu_{max} = 0.09821Re^{0.7}\left(1.0 + 0.365\sin\phi\right) \times \left(1.0 - 0.0248\frac{L}{W}\right) \tag{8}$$

The above equation fits the experimental data to within 9%. For the uphill region, the experimental data was correlated with two equations, one for ϕ in the range of $40° \le \phi \le 60°$ and the second for $70° \le \phi \le 90°$.

$$Nu = 0.103Re^{0.697}\frac{\left(1.0 + 0.0633\sin\phi\right) \times \left(1.0 - 0.0248\frac{L}{W}\right)}{\left(\frac{x}{W}\right)^{0.558}} \tag{9}$$

$$Nu = 0.0538Re^{0.697}\frac{\left(1.0 + 0.94\sin\phi\right) \times \left(1.0 - 0.0174\frac{L}{W}\right)}{\left(\frac{x}{W}\right)^{0.388}} \tag{10}$$

The above Eq. (9) and Eq. (10) fits the experimental data to within 11.5% and 17% respectively. Further, these two correlations are compared with the results of Akansu et al. [36] at Re=5000, L/W=6 for different angles is shown in Fig. 11.

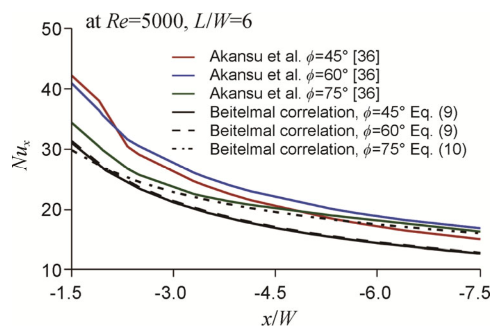


Fig. 11 Comparison of correlation with the experimental data in uphill side

For the downhill region, Eq. (11) fits the experimental data with a maximum deviation of 13%.

$$Nu = 0.0911Re^{0.68}\frac{(1.0 + 0.28\sin\phi) \times \left(1.0 - 0.0243\frac{L}{W}\right)}{(\frac{x}{W})^{0.303}} \tag{11}$$

The above correlation is compared with the results of Akansu et al. [36] at Re=5000, L/W=6 for different angles is shown in Fig. 12. Further, Beitelmal et al. [34]

correlation on the uphill side and downhill side is compared with the numerical results of Shashikant et al. [48] is presented in Fig. 13. Eren and Celik [35] performed the practical study to determine the effects of oblique angles (slot air jet) in the cooling of heated flat plate. The inclinations varied in the range of 30°–90°. They measured the local temperature profiles with respect to dimensionless length for Reynolds number of 5,860, 8,879 and 11,606, and developed the following temperature correlations as a function of Reynolds number (Re), dimensionless distance (L/W) and inclination angle (ϕ).

$$\frac{T_{\mathrm{w}}}{T_0} = cRe^d \left(\frac{L}{W}\right)^e \left(\sin\phi\right)^f \tag{12}$$

where the coefficients c, d, e, and f were relates to the ϕ.

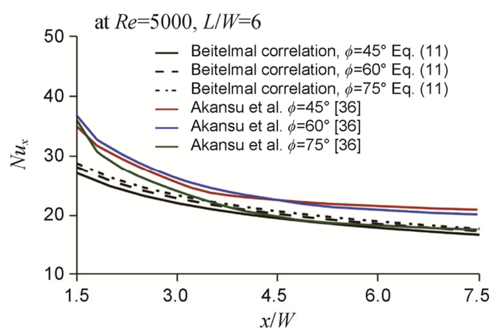


Fig. 12 Comparison of correlation with the experimental data in downhill side

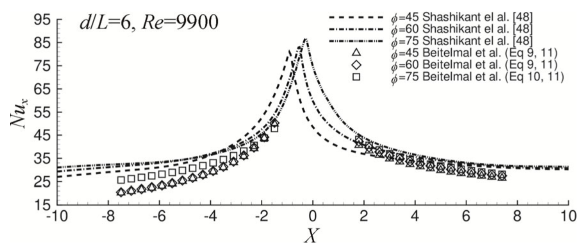


Fig. 13 Comparison of experimental correlations with the numerical results of Shashikant et al. [48]

For oblique inclined circular air jet, the Attalla and Salem [43] obtained the local Nu correlations in the same fashion as Beitelmal et al. [34] developed the correlations. Where, the local Nusselt number correlations were developed as a function of Re, ϕ, L/D, and x/D. The empirical correlations are as follows:

In the impingement region:

$$Nu_{\max} = 0.29Re^{0.69}Pr^{0.33}\left(\sin\phi\right)^{0.52} \times \left(\frac{L}{D}\right)^{-0.045}. \tag{13}$$

The above equation fits the experimental data to within 3.5%. For the uphill direction, the Nu_x was correlated with maximum deviation of 7.45%. The Nu_x results were correlated with equation:

$$Nu = 0.2977Re^{0.68}Pr^{0.33}\left(1+0.37\sin\phi\right)^{0.97} \times \left(\frac{L}{D}\right)^{-0.02} \times \left(\frac{x}{D}\right)^{-0.027} \tag{14}$$

For the downhill wall jet, the Nu_x was correlated with deviation of 6.32%. The Nu_x results were correlated with equation:

$$Nu = 0.345Re^{0.67}Pr^{0.33}\left(1.29\sin\phi\right)^{0.954} \times \left(\frac{L}{D}\right)^{-0.019} \times \left(\frac{x}{D}\right)^{-0.03} \tag{15}$$

Ingole and Sundaram [49] performed an investigation of average Nu characteristics with inclined circular jet impingement of air for cooling flat surface. The parameters ranges were the angle of jet inclination, Reynolds Number, and jet-to-plate distance of 15–75, 2,000–20,000, and 0.5–6.8 respectively. It was found the lower inclination angle leads to a smaller value of the average Nusselt number compared to other oblique angles. They developed the followed average Nusselt number correlation in terms of Reynolds number ($2000<Re<20{,}000$), angle ratio ($0<\phi/\phi_{\mathrm{p}}<1$), and jet-to-plate distance ($0.5<L/D<6.8$):

$$Nu_{\mathrm{avg}} = 0.0151Re^{0.908}\left(\frac{\phi}{\phi_{\mathrm{p}}}\right) \times \left(\frac{L}{D}\right)^{-0.181} \tag{16}$$

6. Conclusions

The experimental studies of air and liquid jets impingement to the flat surfaces have been critically reviewed. In particular, the oblique impingements of both single circular and planar slot jets have been considered. The majority of studies associated with the oblique jet impingement to the flat surfaces is having either constant temperature or constant heat flux surface boundary condition. The nozzle exit Reynolds numbers, the oblique inclination angles, and the jet-to-plate spacing are varied in the range of 1500–52,000, 15°–90°, and 2–12 respectively. The effect of nozzle diameter, confinement, and the turbulence on the heat transfer data has not been accounted. From the review of heat transfer characteristics on the parameters of jet inclinations, jet Reynolds numbers, and dimensionless jet-to-plate distances, the following remarks can be outlined:

- A commonly increasing trend in $Nu_{\max}$ is noted with increasing ϕ.
- The drop in the inclination and the jet-to-plate separation leads to the increase in the asymmetry of heat transfer distribution.
- The displacement of maximum Nusselt number (heat transfer) locations is found to be sensitive to

the inclination and the smaller jet-to-plate distance.
- The magnitude of shift of maximum heat transfer is more for air jets compared with the liquid jets.
- For lower inclination angles (<30°), the bulk of fluid disengages from the substrate during the flow reducing the average Nusselt number.
- In the case of oblique jet impingement, it is required to establish the relationship among the stagnation point, the point of maximum pressure and the point of maximum heat transfer.
- The experimental results compiled in this paper will serve as a benchmark to validate the numerical simulations for various parameter ranges.

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