POLİTEKNİK DERGİSİ

JOURNAL of POLYTECHNIC

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)
URL: http://dergipark.org.tr/politeknik

Flow and heat transfer characteristics of inclined jet impingement on a flat plate

Düz yüzey üzerine çarpan eğik jetin akış ve ısı transfer karakteristikleri

***Yazar(lar) (Author(s))**: Amir LAK[1], Tamer ÇALIŞIR[2], Şenol BAŞKAYA[3]*

ORCID[1]: 0000-0002-1840-2433

ORCID[2]: 0000-0002-0721-0444

ORCID[3]: 0000-0001-9676-4387

Bu makaleye şu şekilde atıfta bulunabilirsiniz(To cite to this article): Lak A., Çalışır T. and Başkaya Ş., "Flow and heat transfer characteristics of inclined jet impingement on a flat plate", ***Politeknik Dergisi***, 23(3): 697-706, (2020).

Erişim linki (To link to this article): http://dergipark.org.tr/politeknik/archive

DOI: 10.2339/politeknik.543267

Flow and Heat Transfer Characteristics of Inclined Jet Impingement on a Flat Plate

Highlights

- *Investigation of flow field and heat transfer using a turbulent inclined impinging jet.*
- *Numerical investigation using PHOENICS CFD software.*
- *By decreasing the jet inclination angle decrease in the maximum heat transfer occurs.*

Graphical Abstract

The effects of turbulent inclined jet impingement were investigated numerically with respect to flow field and heat transfer characteristics. The effects of jet-to-plate distances, inclination angles of the jet and Reynolds number were investigated.

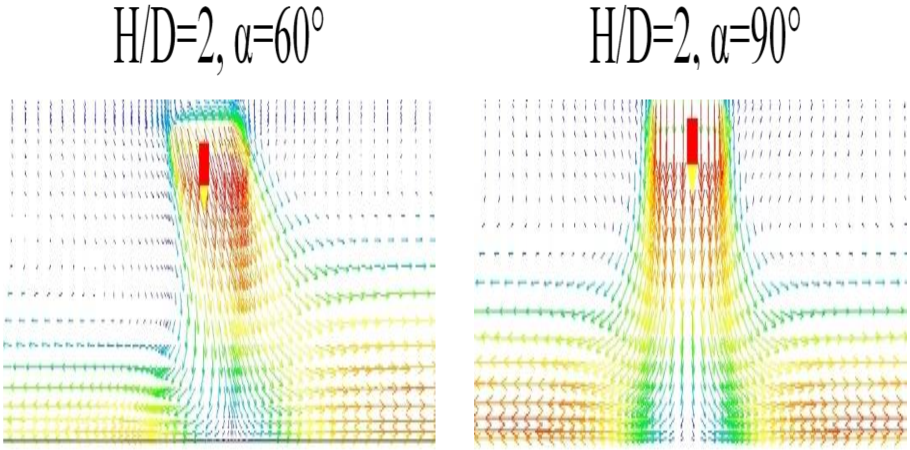


Figure. Velocity vectors for different inclination angles at H/D=2 and Re=30000.

Aim

Aim of the study was to show the effects of inclined impingement on flow characteristics.

Design & Methodology

The investigation was done numerically for a two-dimensional computational domain. Different jet inclination angles, nozzle-to-plate distances and Reynolds numbers were investigated.

Originality

Investigation of the effect of jet inclination on the flow field and heat transfer using a single inclined jet by applying numerical techniques.

Findings

Results have shown that heat transfer magnitudes for low jet angles are lower than for higher angles.

Conclusion

The flow field and heat transfer is directly influenced by the inclination angle as well as Re number and jet-to-plate distance.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Flow and Heat Transfer Characteristics of Inclined Jet Impingement on a Flat Plate

Araştırma Makalesi / Research Article

Amir LAK, Tamer ÇALIŞIR*, Şenol BAŞKAYA

Gazi University, Faculty of Engineering, Mechanical Engineering Department, Ankara, Turkey

(Geliş/Received : 22.03.2019 ; Kabul/Accepted : 25.07.2019)

ABSTRACT

The effects of a turbulent inclined jet impinging on a horizontal flat surface were investigated numerically with respect to the flow field and heat transfer characteristics. Main purpose of the study was to show the effects of inclined jet impingement on flow characteristics, which affects the heat transfer on a surface with a constant heat flux. Simulations were performed for different dimensionless jet-to-plate distances ($2 < H/D < 8$), inclination angle of the jet ($45° < \alpha < 90°$), and Reynolds number ($1500 < Re < 30000$). The heat transfer and fluid flow characteristics have been discussed using temperature contours and velocity vectors. Initial simulation results have been validated with experimental data from the literature, and a fairly good agreement has been achieved. Results showed that by decreasing the inclination angle, a decrease in the maximum heat transfer occurs. The ratio of the maximum Nusselt number to the stagnation Nusselt number increases as the jet angle is increased.

Keywords: Heat transfer, inclined impinging jet, turbulence, Computational Fluid Dynamics (CFD).

Düz Yüzey Üzerine Çarpan Eğik Jetin Akış ve Isı Transferi Karakteristikleri

ÖZ

Yatay düz bir yüzeye çarpan türbülanslı eğik jetlerin etkileri, akış alanı ve ısı transferi özellikleri bakımından sayısal olarak incelenmiştir. Çalışmada, sabit ısı akısına sahip bir yüzeyde ısı transferini etkileyen eğik jet çarpmasının akış karakteristiklerine etkisinin gösterilmesi amaçlanmıştır. Farklı boyutsuz jet-plaka mesafeleri ($2 < H/D < 8$), jet eğim açıları ($45° < \alpha < 90°$) ve Reynolds sayıları ($1500 < Re < 30000$) için simülasyonlar gerçekleştirilmiştir. Isı transferi ve akış karakteristikleri, sıcaklık konturları ve hız vektörleri kullanılarak irdelenmiştir. Simülasyon sonuçları literatürde yer alan deneysel veriler ile doğrulanmış ve oldukça iyi bir uyum sağlanmıştır. Jet eğim açısının azaltılması ile birlikte maksimum ısı transferinde azalmanın olduğu sonuçlardan görülmüştür. Maksimum Nusselt sayısının durma noktası Nusselt sayısına oranı jet eğim açısının artması ile birlikte artmaktadır.

Anahtar Kelimeler: Isı transferi, eğik çarpan jet, türbülans, Hesaplamalı akışkanlar dinamiği (HAD).

1. INTRODUCTION

Inclined impinging jets are used to elevate cooling, heating and drying performances, and hence, is one of the most favorite techniques used to increase the heat transfer. Impinging jets are used in a wide range of applications. Examples are gas turbine cooling, metal annealing, electronic equipment cooling, textile drying and cooling of grinding processes [1]. There have been many studies performed for the heat transfer and flow characteristics on flat surfaces using impinging jets in the past decades [2-6]. The heat transfer performance and flow field of impinging jets are affected by many parameters like jet Re number, jet-to-plate distance, angle of impingement surface and/or the jet, characteristics of impingement surface, turbulence intensity, etc. [7-9].

One of the main application areas of impinging jets are the thermal management of electronics. In recent years the power load of these electronic devices is increasing, whereas the area/volume is becoming smaller. Hence, the use of inclined jets could be an alternative. However, the effect of inclination angle of the jet on heat transfer is not studied enough and blind spots still exists.

The difficult nature of a turbulent impinging jet flow, a jet issuing out of a pipe or nozzle and then impinging on a target surface with change of flow direction upon impingement, makes it hard to rely on analytical solutions to analyze the heat transfer process between the jet and the target plate [10-11]. A number of studies narrate about the examination of inclined impinging air jet and a flat surface in the literature [12-17]. Beitelmal et al. [12] have made an investigation to study the influence of the inclination angle of an impinging two-dimensional air jet on the heat transfer from a uniformly heated flat surface. Yan and Saniei [13] considered the heat transfer for an obliquely impinging circular air jet to a flat plate using a preheated wall transient liquid crystal technique. Muthukannan et al. [18] investigated numerically the flow characteristics of two-dimensional laminar incompressible slot jet flow for a vertical slot jet on a block at the bottom wall. They investigated the reattachment length, detachment length, vortex center and the coefficient of friction for different types of flow

*Sorumlu Yazar (Corresponding Author)
e-posta : tamercalisir@gazi.edu.tr

patterns. Goldstein and Franchett [19] conducted a study about the heat transfer for an inclined impinging jet, and they measured the local heat transfer coefficients. The results showed that the stagnation point and average Nusselt numbers decrease as the inclination angle increases. Lamont et al. [20] investigated flows due to under-expanded axisymmetric jet impinging on flat plates at different inclination angles. Rubel [21] formulated an inviscid, rotational flow model for the impingement of fully developed round jets upon a plane wall at different inclination angles. Sparrow and Lovell [22] investigated the heat transfer characteristics of an obliquely impinging circular air jet on a flat plate. Ward et al. [23] measured the heat transfer rate between an air jet impinging onto a uniform cross flow of air over a flat plate coated with naphthalene along with the Chilton–Colburn analogy, and they achieved local heat transfer profiles.

There exist some studies dealing with impingement heat transfer at different inclination angles of the jet. However, there are still many blind spots. There are almost no studies, dealing with the flow field, which directly effects the heat transfer of inclined impinging jets. Hence, the main purpose of this study was the examination of the effect of jet inclination on the flow field and heat transfer on impingement jet heat transfer using a single inclined air jet by applying numerical techniques. In this sense, the effect of different jet angels (α), the Reynolds number (Re), the dimensionless jet-to-plate distance (H/D) was examined. The flow field was investigated, and correspondingly the heat transfer was examined and interpreted using these findings.

2. MATHEMATICAL FORMULATION AND NUMERICAL METHOD

In this part of the study, the mathematical formulation, solution technique, computational domain, boundary conditions, data reduction and validation of the numerical model is explained in detail.

2.1. Problem Description

The fluid flow and heat transfer characteristics on a flat surface under an inclined impinging air jet were investigated using the PHOENICS CFD code. The study was performed for jet inclination angles of α=45°- 90°, Re=1500-30000 and dimensionless jet-to-plate distance of H/D=2-8. A constant surface heat flux (q" = 1000 W/m^2) was used as boundary condition for the impingement plate, and the nozzle was fixed on the center of the geometry above the plate. The nozzle width was modelled as D=9.53 mm. Fig. 1 shows a schematic of the 2-D computational domain of the inclined impinging jet configuration. Boundary conditions are also displayed on the figure. The impinging plate has a length of A=425 mm, and the computational domain has a height of W=85.77 mm.

2.2. Turbulence Model Selection and Mathematical Formulation

Isman et al. [24] performed a numerical analysis to realize heat transfer characteristics of single slot jet impingement cooling with a constant heat flux plate, by using five different two-equation turbulence models. Also, Wang et al. [25] analyzed the effects of jets on the heat transfer characteristics of an impinging jet cooling system, and they recommended the k-ε turbulence model for predicting the fluid flow and heat transfer characteristics of impinging jets. They reported that the k-ε turbulence model is more effective than other eddy viscosity models, and thus precisely predicts the near-wall turbulence that plays an essential role in the accurate prediction of turbulent heat transfer. Zuckerman and Lior [26] and Chang-geng and Jie-min [27] indicated in their studies, that the flow becomes turbulent for Re>1000 in impinging jets. Hence, in this study the flow has to be considered as turbulent, and investigations are conducted with a turbulence model.

In this numerical investigation various turbulence models were tested, and it was observed that the k-ε model fits best with the experimental results. In addition, the k-ε turbulence model is the most common turbulence model used in Computational Fluid Dynamics (CFD), to simulate flow characteristics for turbulent flow conditions. The continuity, Reynolds averaged momentum and time averaged energy equations governing 2-dimensional steady flow of air with constant properties can be written in the cartesian coordinate system as follows:

Continuity equation:

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

Momentum equation:

$$\rho U_i \frac{\partial U_j}{\partial x_i} = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \rho\overline{u_i' u_j'}\right] \tag{2}$$

Energy equation:

$$\rho c_p U_i \frac{\partial T}{\partial x_i} = \frac{\partial}{\partial x_i}\left[k\frac{\partial T}{\partial x_i} - \rho c_p \overline{u_i' T'}\right] \tag{3}$$

The transport equations of the standard k-ε model are adapted in the code in the present study. The transport equations of the model are as follows:

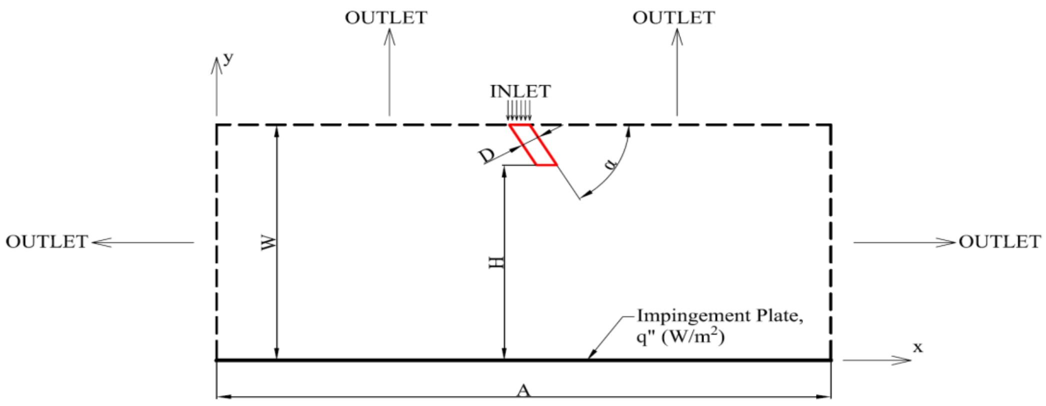


Figure 1. Computational Domain

$$\rho U_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + \mu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j} - \rho\varepsilon \tag{4}$$

$$\rho U_i \frac{\partial \varepsilon}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_1\mu_t \frac{\varepsilon}{k}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j} - C_2\rho\frac{\varepsilon^2}{k} \tag{5}$$

The turbulent kinetic viscosity is expressed as:

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \tag{6}$$

C_μ, $C_{1\varepsilon}$, $C_{2\varepsilon}$ are empirical constants of the model and σ_k and σ_ε are turbulent Prandtl number for k and ε, respectively. The values of these constants are given below.

$$\sigma_k = 1.00; \quad \sigma_\varepsilon = 1.314; \quad C_1 = 1.44; \quad C_2 = 1.92; \quad C_\mu = 0.09 \tag{7}$$

2.3. Solution Technique

A two-dimensional steady state problem was investigated in this study, and the Navier-Stokes equations were solved in Cartesian coordinates. The CFD code solves the equations in grid points, using appropriate boundary conditions. A grid independency test has been performed to verify that the solution is grid-independent.

The continuity, momentum and energy equations for an incompressible turbulent flow has been solved using appropriate boundary conditions. For the pressure correction process along with the solution procedure for the hydrodynamic equations the code employs the SIMPLEST algorithm. A staggered grid arrangement was used, and for the discretization of convective-diffusive transport, the hybrid scheme is the default scheme within the code.

2.4. Boundary Conditions

The boundary conditions of this study are shown on Table 1. Inlet section at the top of the geometry is a single slot impinging air jet. At the inlet section, velocity in the y-direction and temperature were implemented. All side walls as well as the immediate vicinity of the nozzle were used as outlet boundary conditions. Constant wall heat flux was applied on the impingement surface. No-slip wall condition was applied to solid walls, hence on wall surfaces velocities were taken as zero. The standard k-ε turbulence model uses wall functions, hence the boundary conditions on the wall surfaces for k and ε are as shown on Table 1. Radiation and natural convection heat transfer effects were not considered.

Table 1. Boundary Conditions

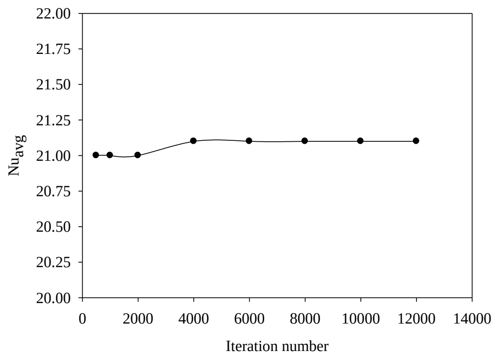
	U	**V**	**T**	**k**	**ε**
Inlet	$U = 0$	$V = v_j$	$T = T_j$	$\left(I_j v_j\right)^2$	$C_\mu^{3/4}\frac{k^{3/2}}{L}$
Wall	$U = 0$	$V = 0$	$q'' = \text{specified}$	$u_\tau^2 / \sqrt{C_\mu}$	$u_\tau^3 / \kappa y$
Outlet (x)	$\partial U/\partial x = 0$	$\partial V/\partial x = 0$	$\partial T/\partial x = 0$	$\partial k/\partial x = 0$	$\partial \varepsilon/\partial x = 0$
Outlet (y)	$\partial U/\partial y = 0$	$\partial V/\partial y = 0$	$\partial T/\partial y = 0$	$\partial k/\partial y = 0$	$\partial \varepsilon/\partial y = 0$

Constant surface heat flux was practical under the impingement plate. Impinging jet inlet fluid was selected as air, and the jet inlet temperature was modeled as 23°C. All outlet boundary conditions were considered to the atmosphere.

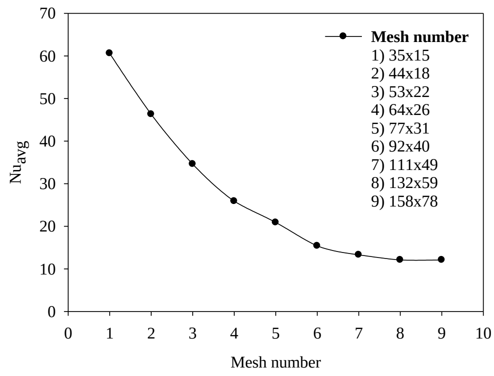
2.5. Validation of Numerical Results

In order to obtain reliable results from the numerical study, an iteration and mesh independency study has been performed. Afterwards, the results have been validated with results from the literature.

Linear algebraic equations resulting from the finite volume discretization procedure are solved iteratively. Due to the iterative process, convergence was considered as being achieved when these residuals become less than 10^{-7}, which was the case for most of the dependent variables. In addition, checks for final results were made based on the conservation of momentum, mass and energy. Results were obtained for iteration and mesh independency checks. As shown on Fig. 2, after 4000 iterations, there is little change in the average Nusselt number (Nu_{avg}). Hence, the suitable iteration number was selected as 10000. On the other hand, from a systematic grid independency study the suitable mesh number was obtained. In Fig. 2.(b) the change in the average Nusselt number becomes almost independent of the mesh for mesh numbers of 111 and 49 in the x and y directions, respectively. According to these observations the suitable mesh number in the x-y plane was selected as 158-78.



(a)



(b)

Figure 2. (a) Independency check of iteration, (b) Independency check of mesh

The suitable mesh distribution in the x-y plane is displayed on Fig. 3. It can be seen that the mesh structure is denser at the impingement wall and the nozzle outlet. So, it was possible to solve the impingement flow and heat transfer and all occurring circulations in the correct way. In addition, the y^+ distribution occuring on the the impingement plate has been shown on Fig. 3. As can be seen the the y^+ value has been obtained in the range of $3.5 \leq y^+ \leq 4.0$. This value is below the laminar sublayer ($y^+<5.0$), which shows that the used mesh is appropriate for the investigation.

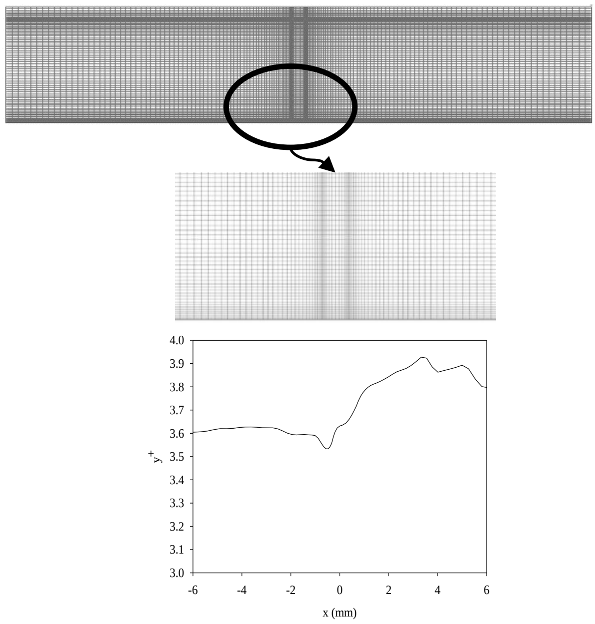


Figure 3. Mesh structure used in the study

Afterwards the grid and iteration independency study, the results were validated with experimental results of Attala and Salem [28], for the Reynolds number of 23000 and T_j=23°C and H/D=4. The local Nusselt number distributions were compared in Fig. 4, and it was observed that the results are in agreement with the experimental results. The position zero is the position where the jet inlet is located. To the left a negative sign and to the right a positive sign has been chosen. It could be said that the results are in agreement with the experimental values and are reliable.

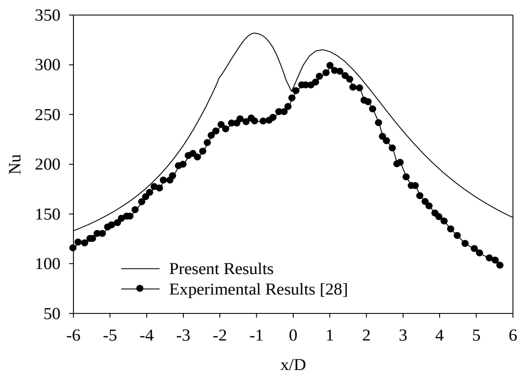


Figure 4. Comparison of numerical results with experimental measurements of Attalla and Salem [28]

2.6. Data Reduction

In the present study, the average as well as local heat transfer characteristics, and flow field results of inclined impinging jets have been obtained. The impingement plate surface temperature was obtained during the study. Using these temperature values the local and average Nusselt number values on the impingement plate have been calculated as follows;

$$Nu = \frac{h.D}{k_{air}} \tag{8}$$

$$Nu_{avg} = \frac{\int Nu.dx}{A} \tag{9}$$

Where, h is the heat transfer coefficient ($W/m^2.K$), D is the width of the inclined jet hole, k is the thermal conductivity of air and A is the length of the impingement plate (Fig. 1.).

The heat transfer coefficient used in the above equation was calculated as given below;

$$h = \frac{q''}{T_s - T_j} \tag{10}$$

Where, q" is the constant heat flux of the impingement surface, T_s and T_j are local surface temperature and jet inlet temperature, respectively.

A wide range of Reynolds numbers have been investigated. The Reynolds number values have been obtained as follows;

$$Re = \frac{v_j.D}{\nu} \tag{11}$$

Where, v_j shows the air jet inlet velocity and ν displays the kinematic viscosity of air.

3. RESULTS AND DISCUSSION

In this section, the effects of Reynolds number and jet-to-plate distances have been investigated, regarding changes in inclination of the inlet jet on heat transfer and flow characteristics. Investigations have been performed for $1500 \leq Re \leq 30000$, $2 \leq H/D \leq 8$, and a jet inclination angle of $45° \leq \alpha \leq 90°$. As one can see from Fig. 1 the inclination angle of 90° shows perpendicular impingement of the jet on the plate.

The effect of inclination angle of the jet for different jet-to-plate spacing on the vertical velocity component has been shown on Fig. 5. The normalized vertical velocity component distributions along the height of the channel for different H/D values and inclination angels at Re=10000 are shown on the figure.

The velocity values have been obtained at the mid of the geometry, where the jet inlet is located (x/D=0). At low jet-to-plate distance the velocity values are very close for inclination angles of α=90° - 60°. For all H/D values, except H/D=2, the highest vertical velocities were obtained for α=90°. The velocity profile for α=90° (perpendicular jet impingement) is almost the same for all jet-to-plate distances. In addition, for α=90° and in the range of $4 \leq y/D \leq 8$ it was observed that the velocity is almost constant at the jet outlet velocity until the jet reaches y/D=2 (except H/D=2). This shows that for a vertical impinging jet the vertical velocity is nearly unaffected until y/D=2, and after that height the radial velocity decreases immediately, which is due to the deflection of the jet near the impingement plate. With the increase in H/D, and decrease in inclination angle the vertical velocity component of the jet becomes almost zero at higher y/D locations.

Flow fields for different inclination angles and jet-to-plate distances have been shown in Fig. 6 for a Re number of 30000. The results are in agreement with Fig. 5. It can be seen that, with the decrease of the inclination angle the velocity before impingement decreases. For α=90°, the velocity decreases immediately before the impingement, and there is almost a symmetrical flow distribution around the centerline of the jet. This is not the case for α≠90°, where the flow is directed at an inclined angle to the impingement plate. In addition, for inclined jets the horizontal velocity component (wall jet) becomes dominant.

The findings of the flow field will guide in the interpretation of the findings for heat transfer. Fig. 7 displays the local Nusselt number distributions for inclination angles of α=90° - 45° for Re=23000 at different jet-to-plate distances. In the case of inclination angle of α=90°, the jet impinges perpendicularly on the surface, and the local heat transfer was symmetrical around x/D=0. However, with the decrease of the jet inclination, the shift in the stagnation point moves in the positive x/D direction. The decrease in the jet inclination decreases the heat transfer on the impinging plate. This is due to the velocity and momentum which decreases, as it was observed in Fig. 6. It was observed that the velocity before impingement decreases with the decrease in inclination angle and jet-to-plate distance. In addition, this has also a negative effect on the velocity of the wall jet, hence heat transfer on the plate due to the wall jet. Hence, the heat transfer is affected in a negative way with the decrease of momentum. As can be seen from Fig. 7 the maximum heat transfer occurs around the stagnation point, where two maximum heat transfer peaks occur. At the stagnation point a local minimum occurs (except H/D=2), and the stagnation points shift towards the positive x/D direction, where the jets are directed to. The results are in agreement with the results of Donovan and Murray [7]. They measured the flow field and heat transfer from an inclined jet impinging on a flat plate. They showed that the velocity stagnation point shifted to the upflow side of the impinging jet with decreasing jet inclination angle. The Nusselt number at the stagnation point shows considerable changes, especially between α=50° and 60°. The value of the Nusselt number sharply decreases with a reduction in the inclination angle. It was observed that with the decrease in inclination angle the secondary peaks in the Nu number distributions are less distinct for H/D=2. At higher H/D values no secondary peaks were formed, this was interpreted due to the long distances to the impingement plate at larger jet-to-plate distances.

It was well probed by Goldstein et al. [29], Baughn and Shimizu [30], Beitelmal et al. [12] and Rubel [31] that for small jet-to-plate distances, secondary peaks in the Nusselt number distributions occur at a radial location of approximately 1–3 diameter from the geometric center for a normally impinging jet. Hence, it could be said that the results are in agreement with the literature.

The effect of Reynolds number on the average Nusselt number for different inclination angles is presented in Fig. 8. The results are shown for H/D=2 and H/D=6. As can be seen from the figures the average heat transfer increase almost linearly with increase in the Reynolds number for all inclination angles. For 1500≤Re≤10000 and H/D=2 the inclination angle has almost no effect on the average Nu number. Potential core lengths are generally between 4 and 6 nozzle diameters. The length of the potential core is dependent on the turbulence intensity at the nozzle exit and the initial velocity profile [32]. Hence, for H/D=2 (Figure 5 (a)) it can be seen that the flow is in the potential core region in the range of 1500≤Re≤10000, and is not affected by the inclination angle of the jet. It was also observed that the average Nu number values are lower for H/D=6 compared to H/D=2. This is due to the fact that the entrainment into the jet decreases the momentum of the jet, which has a detrimental effect on heat transfer.

The effects of the jet-to-plate distance on the average heat transfer have been presented for different values of 2<H/D<8, and for Re=23000 and Re=30000 at different inclination angles of the jet. The results are shown in Fig. 9. The findings are in agreement with Fig. 7, where it was observed that with an increase in H/D the local Nu number decreases. For all H/D values the highest and lowest heat transfer rates were obtained for α=90° and α=45°, respectively. In the range of 70°≤α≤90° there is a slight decrease in heat transfer. However, for α<70° the decrease is occurring faster. This shows that the decrease in the y-component of velocity is more effective for the range of 45°≤α≤70°.

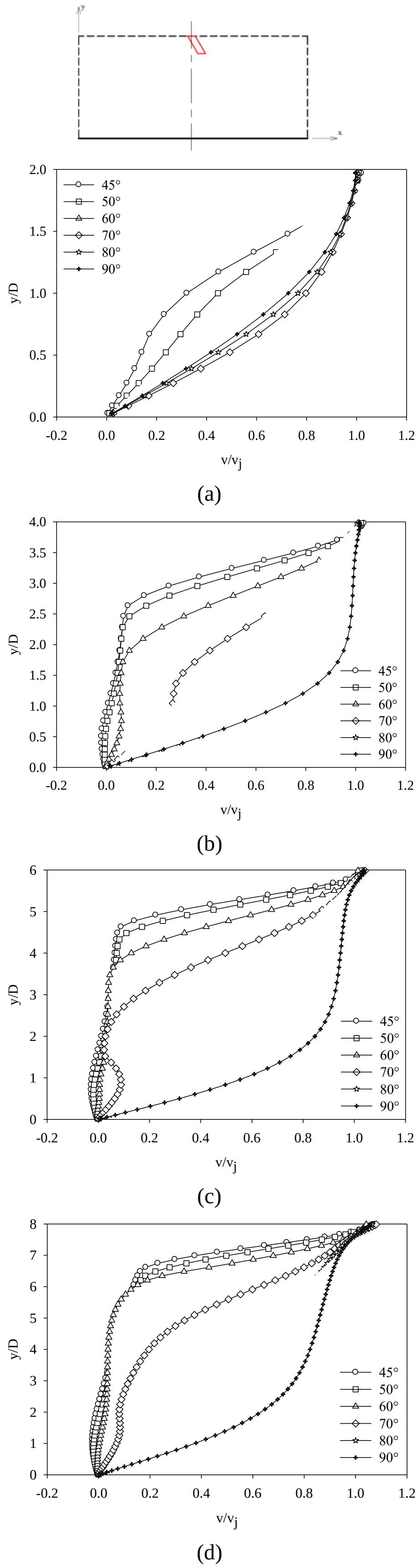


Figure 5. Vertical velocity distributions for Re=10000 at different inclination angles, (a) H/D=2, (b) H/D=4, (c), H/D=6, (d) H/D=8

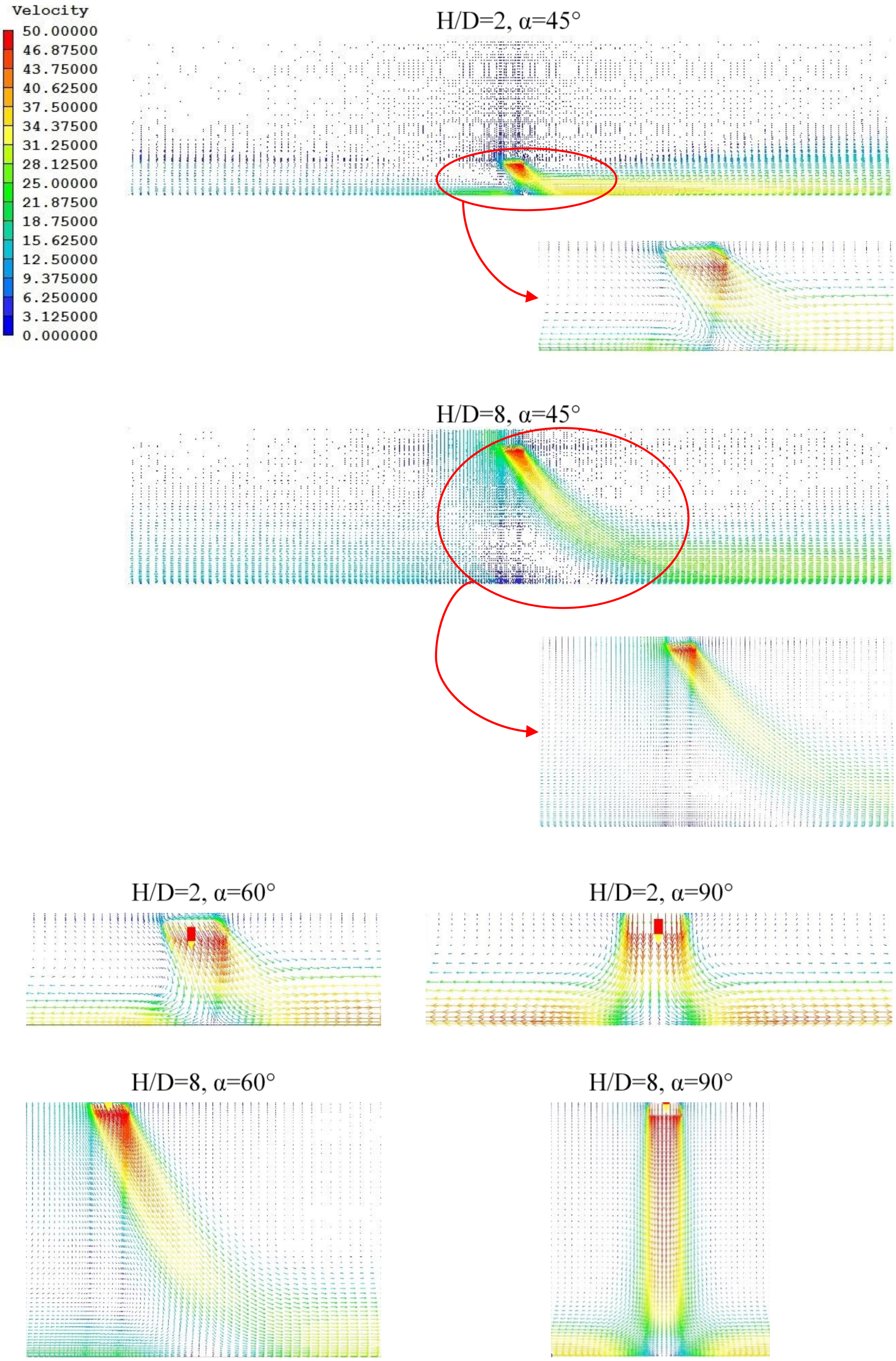
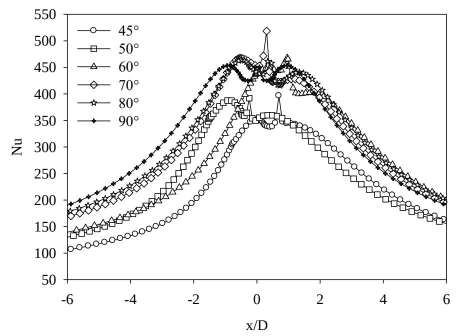
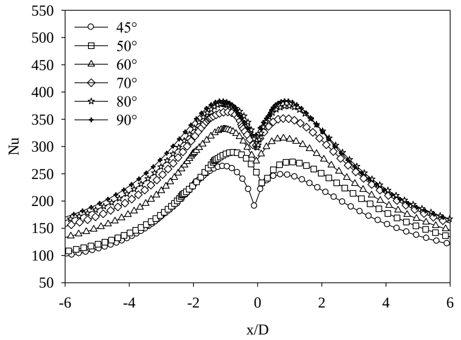


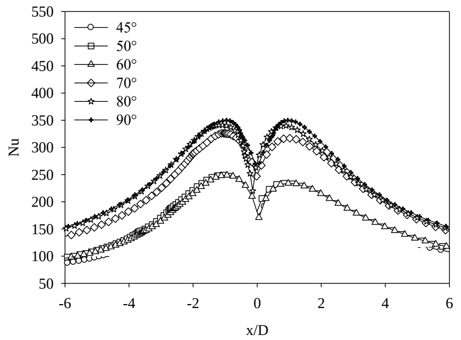
Figure 6. Velocity vectors for Re=30000



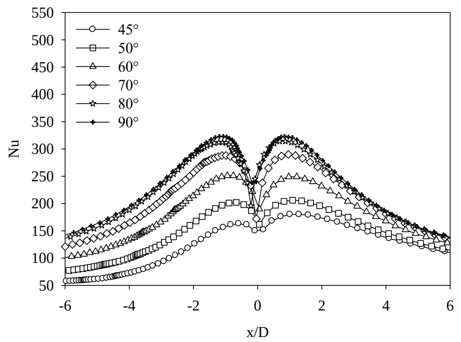
(a) H/D=2



(b) H/D=4



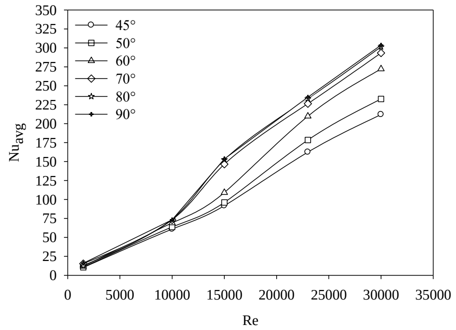
(c) H/D=6



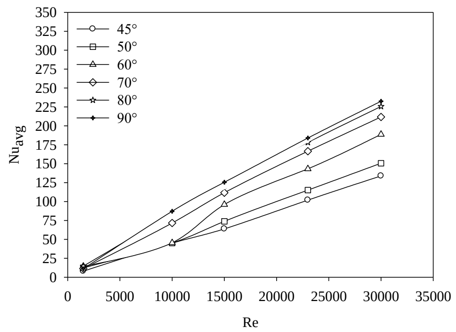
(d) H/D=8

Figure 7. Variation of local Nusselt number for Re=23000 with different values of the inclination angle

A correlation was obtained using the findings of the parametric study. The area-averaged Nusselt numbers were obtained as a function of Reynolds number (1500≤Re≤30000), impinging jet angle (45°≤α≤90°) and jet-to-plate distance (2≤H/D≤8). A nonlinear estimation was taken into consideration. The correlation derived for the inclined jet impingement on a flat surface is given in Eq. 12. The numerically observed and predicted values of the line-averaged Nusselt numbers for the flat surface, and different situation are shown in Fig. 10. It can be seen that the regression fits well with the observed values.

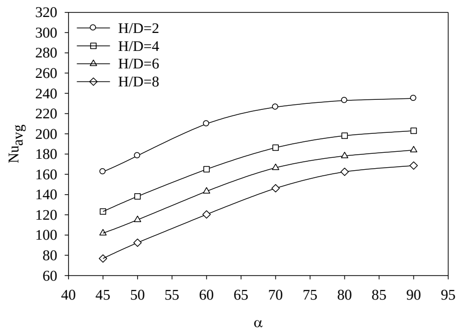


(a) H/D=2

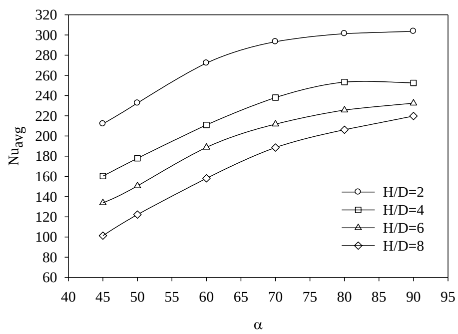


(b) H/D=6

Figure 8. Effect of Re number and inclination angle on the average Nusselt number



(a) Re=23000



(b) Re=30000

Figure 9. Variation of average Nusselt number with jet inclination angle

$$Nu_o = 0.000318.(Re)^{1.05}.(H/D)^{-0.298}(\alpha)^{-0.722} \quad (12)$$

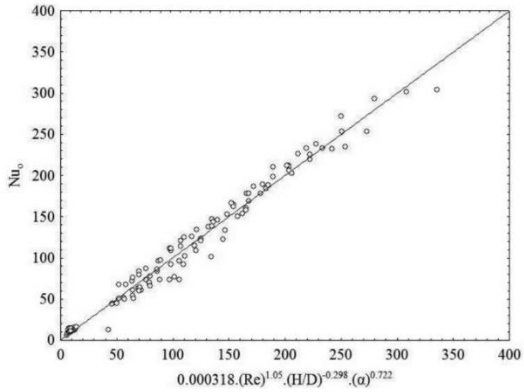


Figure 10. Correlation of the area-averaged Nusselt number for 1500≤Re≤30000, 2≤H/D≤8 and impinging jet angle 45°≤α≤90°

4. CONCLUSIONS

A parametric study of an impinging inclined jet on a flat surface was performed numerically. The results of the numerical analysis with the standard k-ε turbulence model displayed good agreement with experimental data from the literature. The effects of the inclination angle of the jet (α), the dimensionless jet-to-plate distance (H/D) and Re number on the flow field as well as local and average heat transfer were investigated. Some conclusions may be drawn from the findings of this study.

The results showed that the position of the stagnation point shifts away from the center of the impingement point, when the inclination angle is reduced. In addition, a more non-symmetrical local Nu number distribution has been observed with the decrease in the inclination angle. In general the highest heat transfer values were obtained around the stagnation point (except for low H/D and vertical impingement cases).

It was found that the heat transfer characteristics for low nozzle-to-plate spacing were considerably different from higher nozzle-to-plate spacing. On the other hand, results have shown that heat transfer magnitudes for low jet angles are lower than for higher angles. The average Nusselt numbers at a small nozzle-to-plate spacing (H/D=2) increased as the inclination angle was increased. Maximum heat transfer coefficient was obtained far from the stagnation point when the tilt angle increases (angle of jet is decreased), or the distance between the nozzle and impinging surface reduces. The average Nusselt number increases with an increase in jet Reynolds number, and a decrease in inclination angle.

From the findings of this study, it was observed that the flow field is directly influenced by the inclination angle as well as Re number and jet-to-plate distance. Hence, the heat transfer is directly affected from the flow field of the mpinging as well as wall jet of the inclined impinging jets.

REFERENCES

[1] O'Donovan T.S., Murray D.B., Torrance, A.A., "Jet heat transfer in the vicinity of a rotating grinding wheel", ***Proc. ImechE Part C: J. Mechanical Engineering Science***, 220: 1-11, (2006).

[2] Martin H., "Heat and Mass Transfer between Impinging Gas Jets and Solid Surfaces", ***Advances in Heat Transfer***, 13: 1-60, (1977).

[3] Viskanta R., "Heat transfer to impinging isothermal gas and flame jets", ***Experimental Thermal and Fluid Science***, 6(2): 111-134, (1993).

[4] Polat S., Huang B., Mujumdar A.S., Douglas W.J.M., "Numerical Flow and Heat Transfer under Impinging Jets: A Review", ***Annual Review of Heat Transfer***, 2: 157-197, (1989).

[5] Lytle D., Webb B.W., "Air jet impingement heat transfer at low nozzle-plate spacings", ***International Journal of Heat and Mass Transfer***, 37(12): 1687-1697, (1994).

[6] Choo K.S., Kim S.J., "Heat transfer characteristics of impinging air jets under a fixed pumping power condition", ***International Journal of Heat and Mass Transfer***, 53(1-3): 320-326, (2010).

[7] O'Donovan T.S., Murray D.B., "Fluctuating fluid flow and heat transfer of an obliquely impinging air jet", ***International Journal of Heat and Mass Transfer***, 51(25-26): 6169-6179, (2008).

[8] Kilic M., Calisir T., Baskaya S., "Experimental and numerical study of heat transfer from a heated flat plate in a rectangular channel with an impinging air jet", ***Journal of the Brazilian Society of Mechanical Sciences and Engineering***, 39(1): 329-344, (2017).

[9] Kilic M., Calisir T., Baskaya S., "Experimental and numerical investigation of vortex promoter effects on heat transfer from heated electronic components in a rectangular channel with an impinging jet", ***Heat Transfer Research***, 48(5): 435-463, (2017).

[10] Schueren S., Hoefler F., von Wolfersdorf J., Naik S., "Heat Transfer in an Oblique Jet Impingement Configuration with Varying Jet Geometries", ***Journal of Turbomachinery***, 135(2): 021010, (2012).

[11] Dogruoz M.B., "Experimental and Numerical Investigation of Turbulent Heat Transfer due to Rectangular Impinging Jets", ***Phd. Thesis***, University of Arizona, (2005).

[12] Beitelmal A.H., Saad M.A., Patel C.D., "The effect of inclination on the heat transfer between a flat surface and an impinging two-dimensional air jet", ***International Journal of Heat and Fluid Flow***, 21(2): 156-163, (2000).

[13] Yan X., Saniei N., "Heat transfer from an obliquely impinging circular, air jet to a flat plate", ***International Journal of Heat and Fluid Flow***, 18(6): 591-599, (1977).

[14] Akansu, Y. E., Sarioglu, M., Kuvvet, K., Yavuz, T., "Flow field and heat transfer characteristics in an oblique slot jet impinging on a flat plate", ***International Communications in Heat and Mass Transfer***, 35(7): 873-880, (2008).

[15] Abdel-Fattah A., "Numerical and experimental study of turbulent impinging twin-jet flow", ***Experimental Thermal and Fluid Science***, 31(8): 1061-1072, (2007).

[16] Al-Hadhrami L.M., "Study of Heat Transfer Distribution in a Channel with Inclined Target Surface Cooled by a

Single Array of Staggered Impinging Jets", ***Heat Transfer Engineering***, 31(3): 234-242, (2010).

[17] Al-Mubarak A.A., Shaahid S.M., Al-Hadhrami L.M., "Impact of Jet Reynolds Number and Feed Channel Geometry on Heat Transfer in a Channel with Inclined Target Surface Cooled by Single Array of Centered Impinging Jets with Outflow in Both Directions", ***Proceedings of the World Congress on Engineering 3***, London, U.K., (2011).

[18] Muthukannan M., Kannan P.R., Bajpai A., Jeyakumar S., "Numerical Investigation on the Fluid Flow Characteristics of a Laminar Slot Jet on Solid Block Mounted on a Horizontal Surface", ***Arabian Journal for Science and Engineering***, 39(11): 8077-8098, (2014).

[19] Goldstein R.J., Behbahani A.I., Heppelmann K.K., "Streamwise distribution of the recovery factor and the local heat transfer coefficient to an impinging circular air jet", ***International Journal of Heat and Mass Transfer***, 29(8): 1227-1235, (1986).

[20] Lamont P.J., Hunt B.L., "The impingement of underexpanded, axisymmetric jets on perpendicular and inclined flat plates", ***Journal of Fluid Mechanics***, 100(3): 471-511, (1980).

[21] Rubel A., "Computations of the Oblique Impingement of Round Jets upon a Plane Wall", ***AIAA Journal***, 19(7): 863-871, (1981).

[22] Sparrow E.M., Lovell B.J., "Heat Transfer Characteristics of an Obliquely Impinging Circular Jet", ***Journal of Heat Transfer***, 102(2): 202-209, (1980).

[23] Ward J., Oladiran M.T., Hammond G.P., "Effect of nozzle inclination on jet impingement heat transfer in a confined cross flow", ***ASME 91-HTD***, 181: 25-31, (1991).

[24] Isman M.K., Pulat E., Etemoglu A.B., Can M., "Numerical Investigation of Turbulent Impinging Jet Cooling of a Constant Heat Flux Surface", ***Numerical Heat Transfer, Part A: Applications***, 53(10): 1109-1132, (2008).

[25] Wang T., Lin M., Bunker R.S., "Flow and heat transfer of confined impingement jets cooling using a 3-D transient liquid crystal scheme", ***International Journal of Heat and Mass Transfer***, 48(23-24): 4887-4903, (2005).

[26] Zuckerman N., Lior N., "Jet Impingement Heat Transfer: Physics, Correlations, and Numerical Modeling", ***Advances in Heat Transfer***, 39: 565-631, (2006).

[27] Chang-geng L., Jie-min Z., "Experimental and Numerical Simulation Study of Heat Transfer Due to Confined Impinging Circular Jet", ***Chemical Engineering Technology***, 30(10): 1355-1361, (2007).

[28] Attalla M., Salem M., "Heat transfer from a flat surface to an inclined impinging jet", ***Heat and Mass Transfer***, 50(7): 915-922, (2014).

[29] Goldstein R.J., Franchett M.E., "Heat Transfer from a Flat Surface to an Oblique Impinging Jet", ***Journal of Heat Transfer***, 110(1): 84-90, (1988).

[30] Baughn J.W., Shimizu S., "Heat Transfer Measurements from a Surface with Uniform Heat Flux and an Impinging Jet", ***Journal of Heat Transfer***, 111: 1096-1098, (1989).

[31] Rubel A., "Oblique impingement of a round jet on a plane surface", ***AIAA Journal***, 20: 1756-1758, (1982).

[32] Geers L.F.G., "Multiple impinging jet arrays: an experimental study on flow and heat transfer", ***PhD Thesis***, Technical University Delft, (2004).