Numerical Simulation of Minimum Distance Jet Impingement Heat Transfer

Aman Agarwal, and Georg Klepp

***Abstract*—**Impinging jets are used in various industrial areas as a cooling and drying technique. The current research is concerned with the means of improving the heat transfer for configurations with a minimum distance of the nozzle to the impingement surface. The impingement heat transfer is described using numerical methods over a wide range of parameters for an array of planar jets. These parameters include varying jet flow speed, width of nozzle, distance of nozzle, angle of the jet flow, velocity and geometry of the impingement surface. Normal pressure and shear stress are computed as additional parameters. Using dimensionless characteristic numbers the parameters and the results are correlated to gain generalized equations. The results demonstrate the effect of the investigated parameters on the flow.

***Keywords*—**Heat Transfer Coefficient, Minimum distance jet impingement, Numerical simulation, Dimensionless coefficients.

I. Introduction

THE investigation of flow and heat transfer characteristics using experimental and numerical methods is a very dynamic research area. Due to the high heat transfer coefficient which can be achieved through forced convection, jet impingement is taken as a highly effective cooling or drying technology. It is used in thermal management of electronic devices on small scale and in various industrial applications: Impinging jets are used in heating and drying process for production of paper, textile, glass, annealing of metal sheets as well as the cooling of turbine blades.

Due to the importance, a wide range of investigations may be found in the literature [1] – [9]: There are measurements, numerical investigations and correlation equations of various sets of data. These days in addition to elaborate measurements, numerical methods are used to study the jet impingement on flat plates using computation fluid dynamics (CFD) techniques to achieve precise numeric results.

The published results are mostly for single jets and simple geometric configuration. Thus a wide range of parameters, as encountered in industrial applications, is not fully addressed.

The focus of this investigation is on minimum distance jet impingement: The distance of the impingement surface is very small, concretely smaller than the nozzle width. The influence of parameters in a range relevant for industries processing sheets will be analyzed. The method used is CFD simulation of the flow, because an experimental analysis of complex geometries and boundary conditions like nozzle arrays, moving or curved surface is more expensive to realize.

The flow field is generally characterized by three different regions, [9]: free jet region, impingement region and wall jet region, shown in Fig. 1. For the heat transfer coefficient, the shear stress and the normal pressure on the wall the wall jet region and the stagnation region are of importance. For minimum distance jet impingement the free jet region is not relevant, as the nozzle exit lies within the stagnation region.

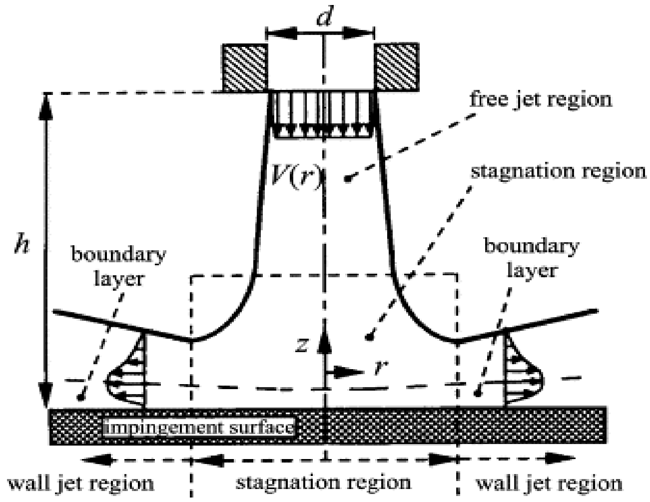

Fig. 1 Three different region of flow in jet impingement on a wall, nozzle diameter d and distance h [9]

The target is to increase the heat transfer coefficient, which can be done by increasing the number of jets, reducing jet distance from the impingement surface and increasing the outlet jet velocity. Shih et al [3] experimentally investigated the two conflicting effects of the heights on the heat transfer with ongoing impinging jet flow. They also explained the increase of the heat transfer by increasing the amount percentage of (cooling) air reaching the (heated) surface.

Impinging jet has been widely studied with various flow configurations. Knowles and Myszko [5] examined the effects of the nozzles heights on the thickness of wall jet after the impingement region rent regions.

Modeling the turbulent flow is the challenging task in predicting the heat transfer coefficient of impinging jet and until now no single model has been accepted to be superior for all class of problems [5].

Our primary objective is to analyze for minimum distance jet impingment, the heat transfer coefficient of a planar jet array on the impingement surface with varying nozzle size,

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spacing between the nozzles and distance of nozzle from surface and jet velocity.

In a second step the effect of different jet angles, impingement surface velocities and impingement surface curvatures is analyzed.

In addition to the heat transfer coefficient, also the pressure force and the shear force acting on the surface are computed, as they are important design parameters for industrial applications.

The investigation was performed for air, so no analysis of the influence of the Prandtl Number on the results was performed.

As the mass transfer can be deducted from the heat transfer [10], so only the heat transfer was computed.

The aim of this investigation is not an in depth analysis of all the relevant physical phenomena occurring with minimum distance jet impingement, but a comparison of the different parameters in order to make an assessment of the qualitative impact on the heat transfer and the forces acting on the surface. Thus the focus will be on the integral heat transfer, the total pressure force and the total friction force acting on the plate.

In order to get a general equation the results and the parameters are expressed as dimensionless numbers and correlated.

II. Problem Details

In Fig. 2 there is a sketch of the problem with the appropriate boundary conditions and the variables used: *s* - nozzle width, *d* - distance between two nozzles, *a* - distance between nozzle and surface. The fluid leaving the nozzle is air at 100° C and ambient pressure, the temperature of the plate is 20° C and constant. As the computation is done for an infinite array of nozzles, there is a symmetry boundary (at the axis of symmetry of the nozzle) respectively a periodic boundary (at the centerline between two nozzles) on the left and the right side of the computational domain. The range of parameters used for the computations is summarized in Table I. The dimensionless velocities is given in terms of the Reynolds-number, the length are scaled by the nozzle width.

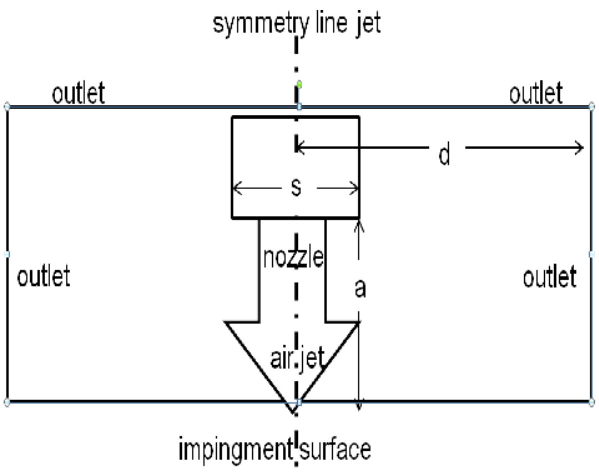

Fig. 2 Model Geometry

III. Numerical Approach

The computation was done using a commercial solver (ANSYS CFX). The velocity was defined at the nozzle inlet. Only the domain for one nozzle was computed as a two-dimensional model with symmetry and periodic boundary conditions accordingly to account for the nozzle array. End effects were neglected.

TABLE I
Variation of Dimensionless Parameters

Parameter	Dimensionless number	Value Range
Reynolds -number	*Re*	179000 to 679000
distance adjacent nozzle	*d/s*	1.3 to 5.3
distance nozzle surface	*a/s*	0.070 to 0.28
surface velocity	$V_{surface}/v$	0.035 to 1.4
jet angle	Θ	15° to 60°
wall curvature	ω	1.1 to 1.5

A. Heat Transfer Model

Here we use the total energy model because this includes kinetic energy effects. As the Mach number is more than 0.2 this heat transfer model is always preferable as viscous heating effects raise the boundary layers, and kinetic energy effects become significant.

B. Turbulence Model

For the computation two different turbulence models were compared, the standard K-ε model and the Shear stress transport model (SST). The models are described in detail in the literature [11]. Chougle N. K [5] shows the comparison of four different turbulence models for jet impingement applications. His results indicate that the SST model provides very good prediction of flow and heat transfer phenomenon at a moderate computational cost.

This coincides with the results of a preliminary investigation [12] for the case of minimum distance jet impingement analyzed here. The results with the SST model were more accurate and the computation was more stable.

C. Discretization and Grid Independence

The partial uniform discretization of the computational domain was done using hexahedral elements. The grid independent solution was assessed as follows.

A 100% model was defined with approximate 500,000 grid elements. The discretization was done on the basis of number of division of the edges of the model. A mesh refinement is placed near to the impingement surface and the stagnation region. We define 6 different models at coarser meshes (at 25%, 50%, 65%, 75%, 80% , 85%) to evaluate the mesh independent solution. The mesh is refined enough near the solid wall to keep the Y^+ value as low as possible, [11].

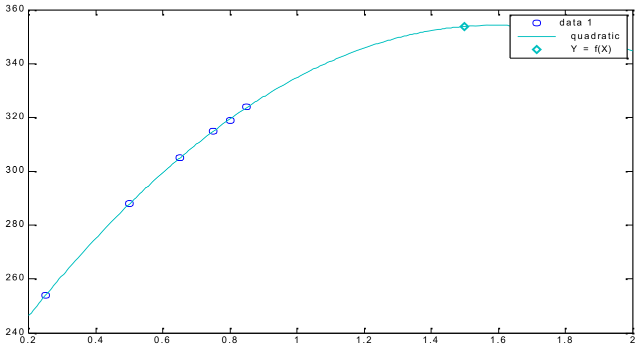

Fig. 3 Value of heat transfer coefficient for different mesh sizes

The computed values of the heat transfer coefficient with the percentage level of meshing are plotted and fitted with a polynomial curve using MATLAB, Fig. 3. The grid independent solution would be at 150% of the mesh size. The heat transfer coefficient at the 150% mesh leads to the reference value. For the computation of this investigation we take the 85% grid. This leads to an estimated error of 8%. This is acceptable (as it is comparable to the data scatter in the literature) and the computational cost is not so restrictive.

The errors for the computed shear stress and normal forces are of similar magnitude.

IV. Dimensionless Representation

The computation were performed for the range of parameters shown in Table I. Using the computed velocity field, pressure field and temperature field, the local heat transfer coefficient, the pressure distribution on the plate surface and the local wall shear stress were computed. The values were integrated and used to compute characteristic dimensionless numbers:

The Nusselt-number

$$Nu = \frac{\alpha \cdot s}{\lambda} \tag{1}$$

is a dimensionless heat transfer coefficient with the average heat transfer coefficient α, the width of the nozzle *s* and the thermal conductivity λ .

The pressure coefficient

$$CP = \frac{2 \cdot p}{\rho \cdot v^2} \tag{2}$$

is a dimensionless normal pressure number which is the ratio of the normal pressure force to the inertial force of the jet with the average (normal) pressure *p* on the plate and the velocity *v* and density ρ of the fluid at the nozzle exit.

The drag coefficient

$$CD = \frac{2 \cdot \tau}{\rho \cdot v^2} \tag{3}$$

is the ratio of the shear stress to the inertial force with the average shear stress τ on the plate and the velocity *v* and density ρ of the fluid at the nozzle exit.

In order to correlate these results a set of dimensionless parameters is used:

The Reynolds-number

$$Re = \frac{\rho \cdot v \cdot s}{\mu} \tag{4}$$

is a dimensionless velocity, with the jet velocity *v*, nozzle width *s*, density ρ and dynamic viscosity μ at the nozzle exit.

There are two geometric parameters: the scaled distance *a/s* between nozzle and surface and the scaled distance *d/s* between two adjacent nozzles

The characteristic dimensionless numbers are correlated as an exponential function of the dimensionless parameters.

A variety of different functions and correlations are available in the literature. Some have a physical background; others try to fit the data most accurately leading to complex formulae. For the simplicity of the representation as well as the possibility to easily assess the different influences, the dimensionless numbers are represented as exponential functions of the dimensionless parameters. The bigger the exponent computed by the correlation, the bigger the influence of the dimensionless parameter. The exponents computed are constants, thus restricting the possibility to extrapolate these correlation equations. The fitting procedures were performed using MATLAB.

V. Minimum Distance Jet Impingement for Various Jet Nozzle Configurations

Results in the parameter range used for these investigations are scarcely available in the literature, due to the very small distance between nozzle and surface.

With *Re* > 3000 the flow is fully turbulent. In this investigation we analyze the results for very small distance between nozzle exit and impinging surface *a/s* < 0.3.

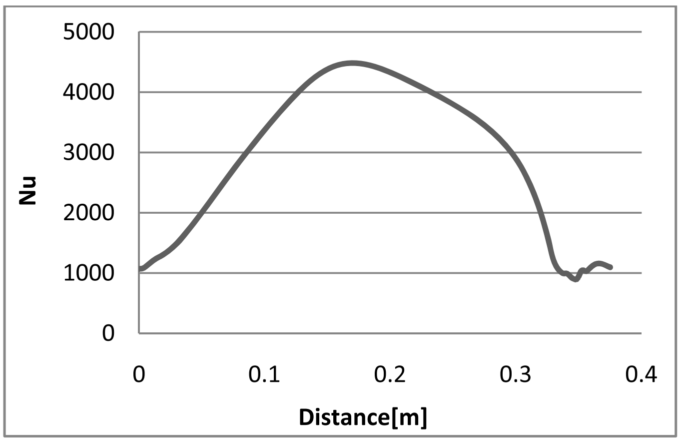

Fig. 4 Dimensionless heat transfer coefficient Nu – local variation

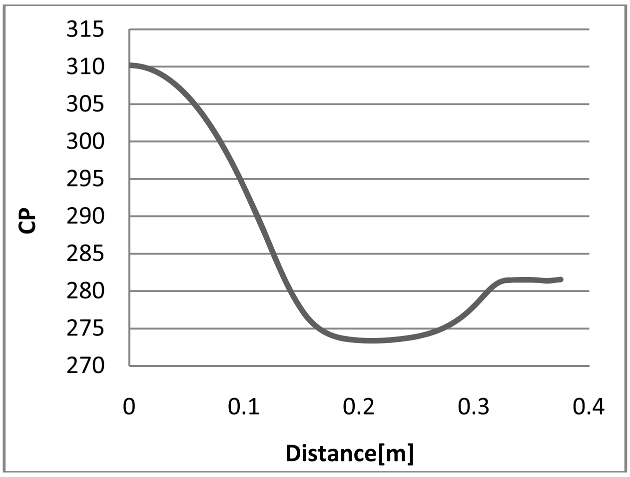

Fig. 5 Dimensionless normal pressure CP – local distribution

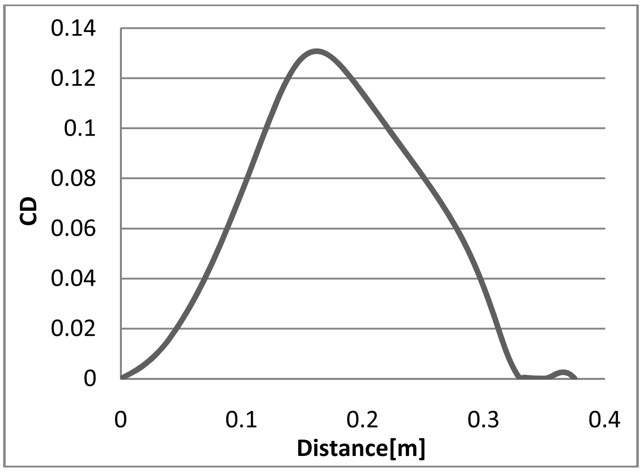

Fig. 6 Dimensionless shear stress CD – local distribution

Using the correlation procedure the Nusselt-number was correlated with the Reynolds-number and the two dimensionless geometric parameters (*a/s*) and (*d/s*).

$$Nu = 0.0216\, Re^{0.7334}\, (d/s)^{0.1262} (a/s)^{-1.204} \quad (5)$$

The heat transfer increases with decreasing distance. This is the reason, why minimum distance heat ransfer is of great industrial significance.

The values of the Nu-numbers are similar to the data in the literature [9].

As in all cases of jet impingement heat transfer the distance between surface and nozzle exit *(a/s)* has the strongest influence.

In the case that a free jet region, exists, the results from the literature [3], [7], [8] indicate, that the decreasing nozzle distance would increase the total heat transfer coefficient as most of the fluid will flow over the boundary layer in the wall jet region. With minimum distance jet impingement, the physical mechanism is different. As the distance is smaller than the nozzle width, the flow is choked in the impingement zone, leading to an increase in the flow velocity in the region between impingement zone and boundary layer zone. This flow characteristic seems to be of significant importance to the heat transfer, normal pressure and shear stress distribution.

The Reynolds-number has a significant influence, the bigger the velocity, the better the heat transfer. The exponent of the Reynolds-number in the correlation is comparable to the data found in the literature [9].

The distance between two adjacent nozzles is of minor importance. Here the distance is of similar magnitude as the nozzle width: The area of the impingement zone, with the maximum heat transfer is of the same magnitude as the wall jet region. Thus the average values are mainly influenced by the values in the impingement zone which is independent of the nozzle distance.

For the normal pressure coefficient the resulting correlation is.

$$CP = 1.84\ 10^{13} Re^{-1.98} (a/s)^{-0.1491} (d/s)^{-0.06} \quad (6)$$

The strongest influence is due to the velocity at the nozzle exit, and the resulting pressure in the impingement zone. Viscous effects are negligible.

For the shear stress coefficient the resulting correlation is

$$CD = 1.41\ 10^{-3}\, Re^{-0.125} (a/s)^{-2.552} (d/s)^{0.3445} \quad (7)$$

The shear stress is mainly determined by the boundary layer region, which correlates with the nozzle distance. For minimum distance jet impingment one additional influence is the velocity peak between boundary layer region and impingement region due to the choked flow: with decreasing distance and increasing exit velocity the velocity gradient and thus the shear stress are increasing. As can be seen in the local distribution the normal pressure is determined in the stagnation region. Heat transfer and shear are influenced by the choked flow regime and the wall jet region.

VI. Moving Impingment Surface

In many cooling and drying applications, the impingement surface is not stationary, the surface is moving with a certain velocity. In these simulations we define the impingement surface with a velocity $V_{surface}$ to see the effect of it on the heat transfer coefficient, the normal pressure force and the shear force. The wall velocity will influence mainly the phenomena in the wall jet region.

An additional dimensionless number is introduced, describing the ratio of the velocity at the nozzle exit to the plate velocity ($v/V_{surface}$). The parameter range in this investigation is from 0.036 to 1.67.

As the plate moves from right to left, the relative velocity on the left side is bigger than on the right side and hence the heat transfer coefficient on the left side is higher than on the right side. The difference between the two sides is even stronger for the shear stress but negligible for the normal pressure.

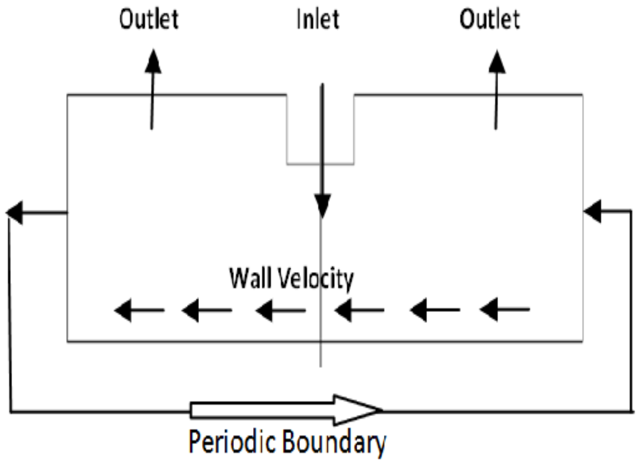

Fig. 7 Model with moving surface

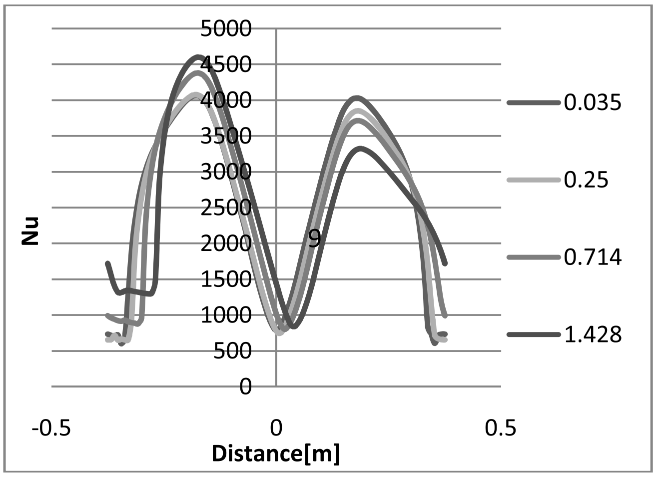

Fig. 8 Dimensionless Heat transfer coefficient Nu for four different impingement wall velocities - local distribution

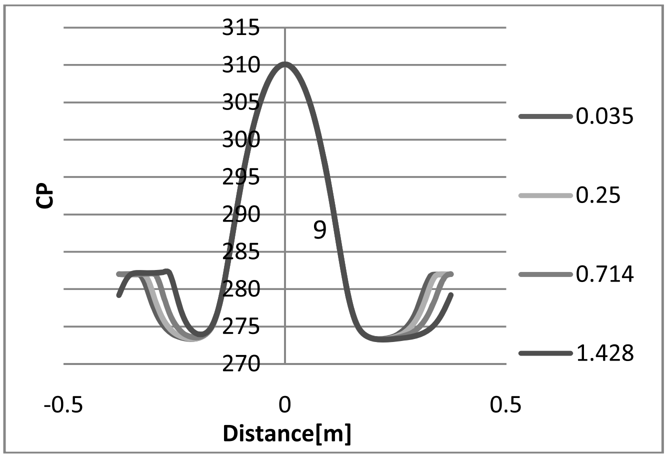

Fig. 9 Dimensionless normal pressure CP- for four different impingement wall velocities-local distribution

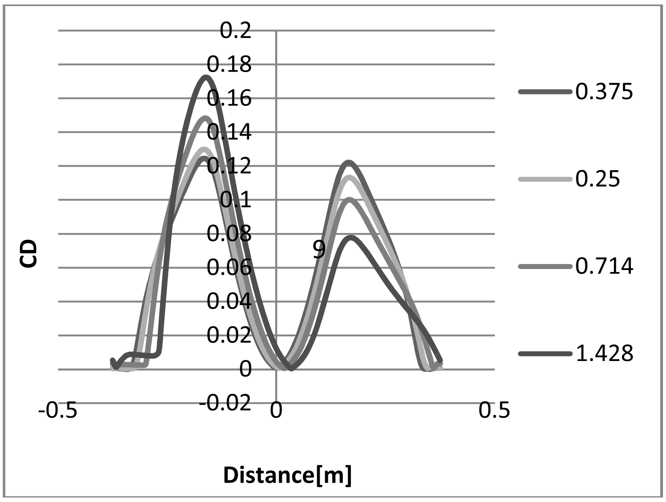

Fig. 10 Dimensionless shear stress CD, for four different impingement wall velocities-local distributions

Nevertheless the average heat transfer coefficient for the analyzed range of parameters differs only slightly from the values for the stationary surface. Thus the influence of the moving surface might be ignored, if only the average heat transfer coefficient is of importance, as it is for many industrial applications.

This coincides with our assumption: the wall velocity decreases heat transfer and friction in the wall jet region on one side and increases heat transfer and friction in the wall jet region on the wall jet region on the other side. As increase and decrease have the same magnitude, the average value stays approximately independent of the wall velocity. Here the effect of possible enhancement of turbulence due to the moving wall seems not to be significant: the increase in heat transfer and friction due to an increase I turbulence is not substantial for the velocity ranged in this investigation.

VII. Velocity at Different Angle

As a further parameter the influence of the jet angle was studied to analyze the contribution of both components of velocity on heat transfer coefficient, shear stress and normal pressure. In most academic studies the flow direction of the jet is perpendicular to the impingement plate; in many industrial applications the situation is different.

For minimum distance heat transfer, there are two different flow regimes: quasi-symmetric flow and asymmetric flow. For small and medium angles the flow is mostly influenced by the choked flow and the distribution of heat transfer coefficient, normal pressure and shear stress is almost symmetric. As the distance between nozzle exit and surface is very low, the deflection of the jet has little effect. For larger angles the distribution is asymmetric, with higher heat transfer coefficient, shear stress and normal pressure on the side where the jet impingement occurs. For the case of (*a/s*) =0.14 and (*d/s*)=2.63 the threshold lies at approximately 60°. Here only the quasi-symmetric regime is taken into account.

The change in the angle influences both the wall boundary region as well as the stagnation region. The normal pressure is mainly influenced by the vertical component; heat transfer and shear are correlated with the total volume flow of the jet.

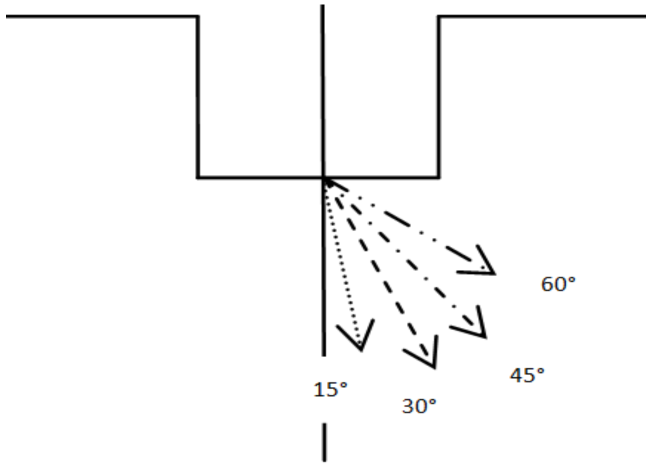

Fig. 11 Model with varying jet angle

The dimensionless parameter describing the angle is $A = \cos\alpha$, where α is the angle of the jet with the perpendicular.

These correlations show the influence of the angle: the ratio of the dimensionless numbers at different angles to the dimensionless numbers of the perpendicular jet is related to the dimensionless angle ⍰.

$$Nu / Nu_{perp} = A^{0.434} \quad (8)$$

$$CP / CP_{perp} = A^{0.0436} \quad (9)$$

$$CD / CD_{perp} = A^{1.882} \quad (10)$$

The angle mostly affects the shear stress and to a lesser extent the heat transfer. With increasing angle the shear stress and the heat transfer decreases. There is also a slight change in the normal pressure but not significantly.

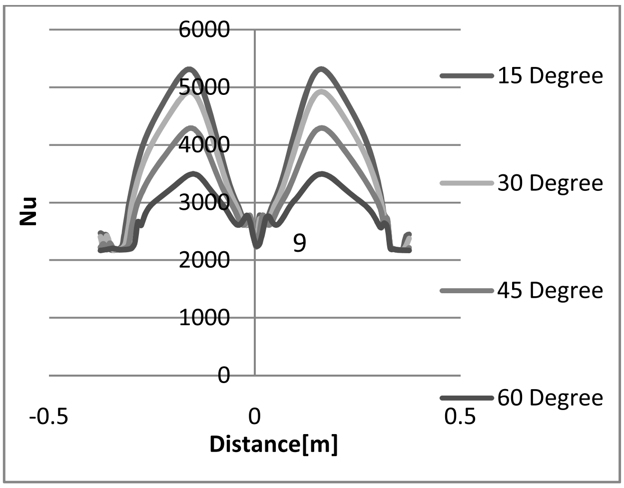

Fig. 12 Dimensionless heat transfer coefficient Nu for four different nozzle angles – local distribution

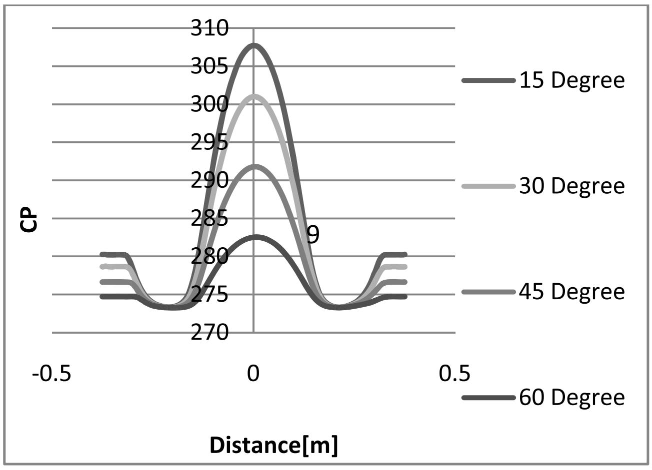

Fig. 13 Dimensionless normal pressure CP for four different nozzle angle – local distribution

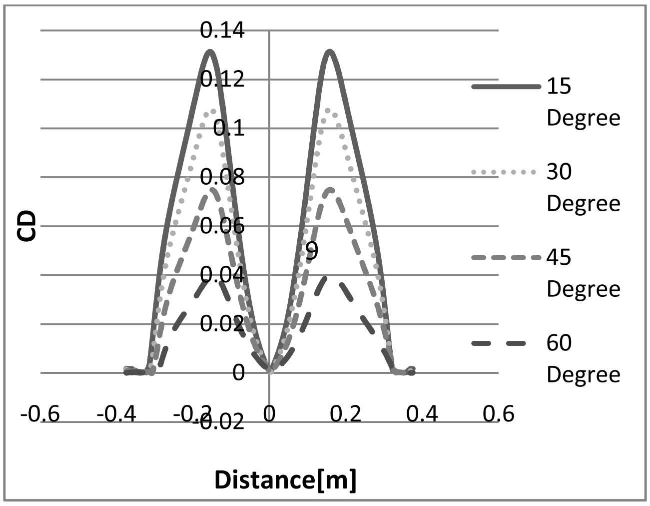

Fig. 14 Dimensionless shear stress CD, for four different nozzle angle – local distribution

VIII. Impingement Surface with Curved Profile

Finally the influence of the curvature of the impingement surface on heat transfer, normal force and shear force is analyzed. For the simulation three configurations were chosen with the amplitude of the curvature of 10%, 20% and 50% of the reference distance of the nozzle from the impingement surface. The shape of the curvature follows a cosine–function, see Fig.15

The curvature influences the phenomena in the stagnation region as well as in the wall jet region. The heat transfer, normal pressure and shear stress values are scaled by the values of the flat surface and correlated with ω, which is ratio of the total distance (reference distance plus amplitude) to the reference distance between nozzle and surface, see Fig. 15.

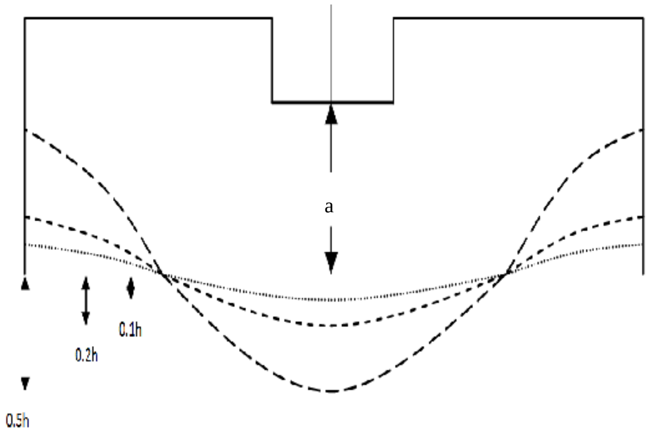

Fig. 15 Geometry of curved surface

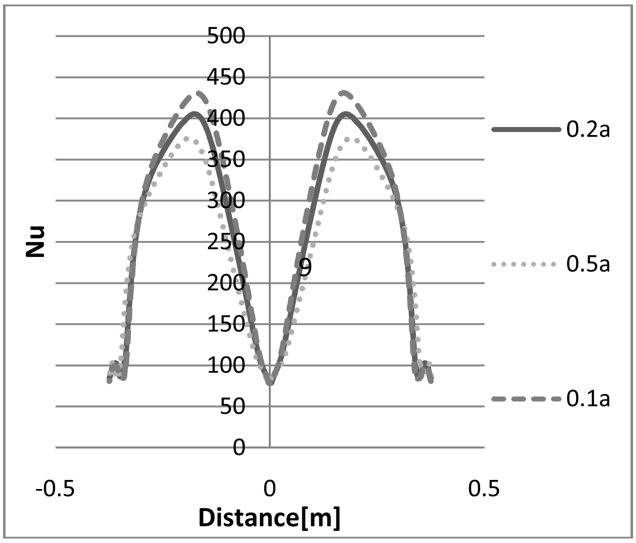

Fig. 16 Dimensionless shear stress CD, for three different curved profiles – local distribution

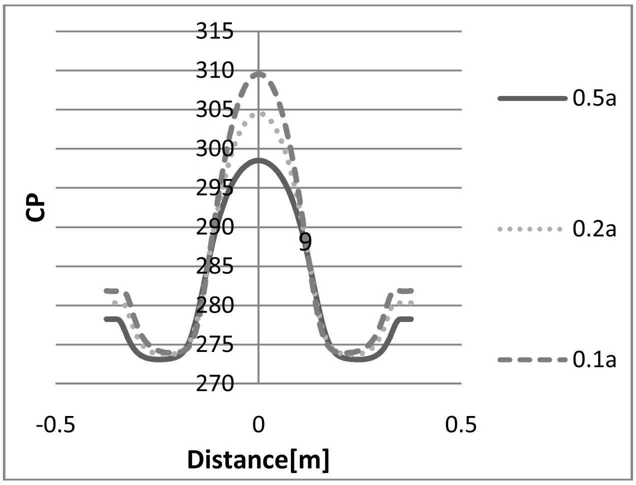

Fig. 17 Dimensionless normal pressure CP, for three different curved profiles – local distribution

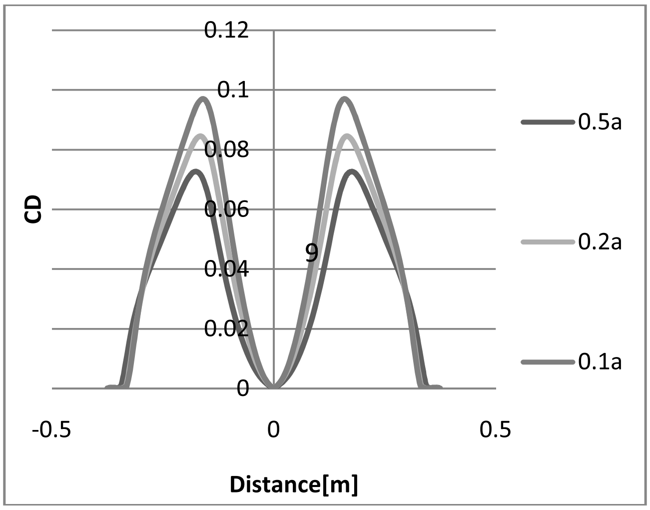

Fig. 18 Dimensionless shear stress CD, for three different curved profiles – local distribution

$$Nu/Nu_{flat} = \omega^{-0.705} \tag{11}$$

$$CP/CP_{flat} = \omega^{-0.0257} \tag{12}$$

$$CD/CD_{flat} = \omega^{-1.575} \tag{13}$$

The curvature mostly affects the shear stress and to a lesser extent the heat transfer. With increased distance from the nozzle exit the shear stress and the heat transfer decreases. There is also a slight change in the normal pressure but not significantly.

IX. General Correlation

All the results were correlated together to get a single function for the average heat transfer coefficient, average normal pressure coefficient and average Shear force coefficient.

Combining all the results yields this set of equations

$$Nu = 0.0216\, Re^{0.7334}\, (d/s)^{0.1262} (a/s)^{-1.204} \omega^{-0.705} A^{0.434} \tag{14}$$

$$CP = 1.84\ 10^{13} Re^{-1.98} (a/s)^{-0.1491} (d/s)^{-0.06}\, \omega^{-0.0257} .A^{0.0436} \tag{15}$$

$$CD = 1.41\ 10^{-3}\, Re^{-0.125} (a/s)^{-2.552} (d/s)^{0.3445}\, \omega^{-1.575} .A^{1.882} \tag{16}$$

As the analysis was performed only for air, the dependence on the Prandtl-number is not included. These correlation equations can be readily used for design purposes or for an optimization of an appropriate process.

X. Conclusion

A numerical investigation was performed to analyze heat transfer, normal pressure and shear force in arrays of planar air jets with a minimum distance between the nozzle exit and the impingement surface. In addition to the surface distance, the jet velocity and the nozzle distance, the influence of the jet angle, the wall velocity and the wall curvature were examined. The parameters used were described in terms of dimensionless numbers and the results were correlated to equations which are easy to use.

Due to the minimum distance (the distance form nozzle to surface is smaller than the nozzle width) specific flow patterns occur, which strongly influence heat transfer, normal pressure force and shear stress force. The resulting correlations are only partially similar to the results shown in the literature for "normal" distance jet impingement. Additional work, with more elaborate computational models and flow measurements is required to get a deeper insight into the phenomena taking place for nozzles with minimum distance jet impingement.

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