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Review of Correlations on Jet Impingement Cooling

Sagar Chirade[1], Sunil Ingole[2], K. K. Sundaram[3]

[1]Research Scholar, Indira College of Engg and Management, Pune, 410506 India

[2] Research Scholar, Associate Professor, Indira College of Engg and Management, Pune, 410506 (India).

[3] Dean and Professor, Research and Development, Mechanical Engg, Vishwakarma Institute of Technology, Pune, 4 (India)

Abstract: ***Jet impingement study is of significant importance because of its numerous applications in various industries. Its fluid flow properties and heat transfer characteristics are giving interesting results by which its popularity increases .If also number of researchers worked till date there is scope for further work. Besides theoretical and experimental analysis number of equations developed .The Nusselt number generated because of use of jet is a function of jet diameter, Reynolds Number, Target to height spacing, jet inclination, and fluid properties in general. The paper reviews correlations related to varieties of jets and will be useful for further study in this area.***

Keywords: Cryogenic, heat, swirl, fluid

1. Introduction

An impingement jet is a jet of high velocity fluid which is made to strike against a target surface. An impinging jet can be classified as a) Submerged Jet or b) Free Jet. If the fluid issuing from the nozzle is of the same density and nature as that of the surrounding fluid then the jet is called a Submerged Jet. If the fluid issuing from the nozzle is of a different density and nature than that of the surrounding fluid then the jet is called a Free Jet. [1]

Further distinction between jets can be made as a) Confined and b) Un-confined jets. In the case of confined jets, the jet remains bounded between the two surfaces during its flow. There is very less entrainment of air from the atmosphere. Un-confined jets are free to expand after they impinge on the target surface.

Circular jets and slot jets are two basic jet configurations other arrangements are nozzle geometry of square edge (no chamfered) and with chamfered edge, inclined jet, axially symmetric air jet, elliptic jet arrays. Swirling Jet the impinging jet is forced to swirl when exiting the jet orifice/nozzle, providing a flow commonly known as the swirling jet.

The coolant fluids used in jet impingement are mainly air and water but some research has also been reported with kerosene, fluorocarbons (FC) and Freon etc.Jet impingement on smooth and non-smooth surfaces have been studied. The flow field jet impingement is characterized by a) Jet zone, b) Stagnation zone, and c) Wall jet zone. Applications of impinging jets include drying of textiles, film, and paper; cooling of gas turbine components and the outer wall of combustors; freezing of tissue in cryosurgery, cooling of electronic equipment, for the cooling of a grinding process. Various Parameters which are studied in Jet Impingement are Jet to plate spacing ,Reynolds No.,Jet Diameter, Prandtl number etc.[1-10]. Current paper deals with the Review on Correlations developed during the study of various arrangements of Jet Impingement.

2. Jet with Square Edge

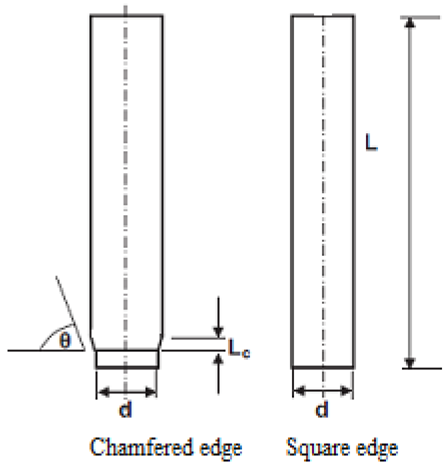

Figure 2.1: Square and chamfered edge nozzle.

Attalla et al investigated experimentally the effect of the nozzle geometry of square edge (nonchamfered) and with chamfered edge on local and average heat transfer distribution in free single circular air jet. Recorded Temperature using IR thermography camera. Experimental Reynolds number (Re) range of 6000< Re < 40,000 and plate surface spacing to nozzle diameter, H/d, in the range of 1<H/d <6 for single nozzle with square edge (non-chamfered) and chamfered nozzles both nozzles are of same diameter which is 5 mm. Lc is chamfered length which is varied from 1 mm to 3.65 mm with constant chamfered angle θ=60 and length to diameter ratio of 50. Developed the Correlations for the average Nusselt number and the nozzle Reynolds number as

For square edge

$$Nu \propto Re^{0.75} \left(\frac{H}{d}\right)^{-0.16} \quad (1)$$

For chamfered edge nozzles, the value of average Nusselt number is depend on jet Reynolds number, separation distance and chamfered length, Lc, For chamfered edge.

$$Nu \propto Re^{0.76} (H/d)^{(-0.15)} (Lc/d)^{(-0.01)} \quad (2)$$

It is found that when compared with other nozzle configurations square edge in nozzle gives the highest value of local and average Nusselt numbers. [2]

3. Jet with Sharp Edge Nozzle

Zhou Studied the flow structure and local heat transfer rate of an impinging rectangular slot jet issuing from sharp-edged rectangular nozzle. The parameters included were jet Reynolds number (Re = 2715–25,005) and nozzle-to-plate spacing (H/B = 1–30).

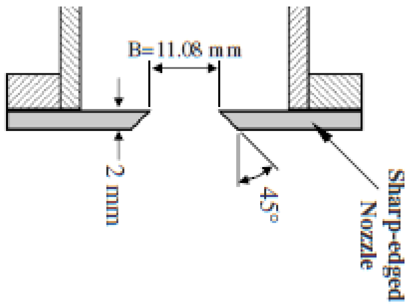

Figure 3.1: Sharp edge nozzle

The local Nu number and the free-stream turbulence intensity of impinging jets exhibit a relationship as follows:

$$\frac{Nu}{\sqrt{Re}} = 0.014Tu(\sqrt{Re}) + 0.517 \quad (3)$$

The corresponding average Nu number and turbulence intensity have a relationship as follows:

$$\frac{Nuavg}{\sqrt{Re}} = 0.014Tu(\sqrt{Re}) + 0.472 \quad (4)$$

Analysis of Heat transfer mechanics was done in terms of the turbulence intensity. The jet Reynolds number, the nozzle-to-plate spacing and the turbulence intensity have an important influence on the heat transfer of impinging rectangular jets, especially on the impingement region. [3]

4. Confined and Submerged Impinging Jets

Chin studied the parameter: orifice diameters of 1.59–12.7 mm, turbulent-flow Reynolds numbers of 4000–23 000, and orifice to heat-source spacing's of 1–5 jet diameters. De is the effective diameter of heat source. Experimentally investigated the influence of fluid thermophysical properties on the heat transfer from confined and submerged impinging jets. [4]

The correlations were given in the following forms:
For water

$$Nu=1.039Re^{0.515}Pr^{0.444}\left(\frac{l}{d}\right)^{(-0.058)}\left(\frac{De}{d}\right)^{(-0.246)} \quad (5)$$

For other fluids.

$$Nu=1.427Re^{0.496}Pr^{0.444}\left(\frac{1}{d}\right)^{-0.058}\left(\frac{De}{d}\right)^{-0.272} \quad (6)$$

Stagnation point Nusselt No. Correlation for Air

$$Nu = 1.671Re^{0.483}Pr^{0.444}\left(\frac{l}{d}\right)^{-0.058}\left(\frac{De}{d}\right)^{-0.226} \quad (7)$$

5. Inclined Jets

Kyosung choo studied the effect of inclination on heat transfer characteristics that is Nusselt number and dimensionless pumping power of an impinging slot air jet are studied. The Nozzle-to-plate spacing is equal to or less than one nozzle diameter (H/d< 1.0) are investigated. Parameter range from Reynolds numbers (5000 < Re <15,000), the inclination angles (0<θ<40) and nozzle-to-plate spacing (0.125 < H/d < 1).

The correlation of the pressure difference for the impinging jet has the following form:

$$\square P_{inclination} = 1+16exp\left\{\frac{-\left(H/d\right)}{0.2}\right\}\theta^{*} \quad (8)$$

Where a ratio of the pressure difference $\square P_{inclination}$ and the dimensionless inclination angle are

$\Delta P_{inclination}^{*} = \Delta P_{\theta}^{*} / \Delta P_{\theta=0}^{*}$ And $\theta^{*} = \theta / 90^{0}$, respectively.

$$Nu_{0,\theta}^{*} / Nu_{0,\theta=0}^{*} = \left\{1+16exp\left\{\frac{-\left(H/d\right)}{0.2}\right\}\theta^{*}\right\}^{0.18} \quad (9)$$

Where the Nusselt number for a horizontal plate is obtained from

$$Nu_{0,\theta=0}^{*} = 0.74Re^{0.54}\left(\frac{H}{d}\right)^{-0.18} \quad (10)$$

Effect of inclination on the average Nusselt number, a correlation was suggested as follows:

$$\left(Nu_{0,\theta}^{*}\right)avg / \left(Nu_{0,\theta=0}^{*}\right)avg = \left\{1+16exp\left\{\frac{-\left(H/d\right)}{0.2}\right\}\theta^{*}\right\}^{0.16} \quad (11)$$

The above correlation can be used for -6 ≤ H/d≤ 6. The results show that the heat transfer characteristics of small nozzle-to-plate spacing's are significantly different from those of large nozzle-to-plate spacing's. In the cases of fixed flow rate conditions, the impingement point and average Nusselt numbers at small nozzle-to-plate spacing (H/d< 1.0) increase as the inclination angle increases due to an increase in the pumping power, while the impingement point and average Nusselt numbers at large nozzle-to-plate spacing (H/d> 1.0) decrease as the inclination angle increases due to momentum loss of the wall jet. In the cases of fixed pumping power conditions, the impingement point and average Nusselt numbers at both of small and large nozzle-to-plate spacing's are independent of the inclination angle. Based on the experimental results, correlations for the impingement point and average Nusselt numbers of the impinging jet are suggested as a function of the pumping power alone. [5]

6. Round Jets

Sagot investigated experimentally the heat transfer configuration for a round air jet impinging on a circular flat plate and derived an average Nusselt number correlation. The experimental measurements results and the results of a numerical CFD modelling are compared which are found to be in are in good agreement. Simulations under constant wall heat flux conditions are compared to local Nusselt number distributions.

Parameters chosen were Re 10 000 $\leq$Re$\leq$ 30 000, the jet to plate spacing 2 $\leq$H/d $\leq$6 and radial spacing 3 $\leq$ R/d $\leq$10 , and the dimensionless viscosity ratio μj /μw (1.1 $\leq$ μj /μw $\leq$1.4).

An average Nusselt number correlation is proposed for jet impingement heat transfer calculations under constant wall temperature conditions, as a function of the jet Reynolds number [6]

A correlation by least squares method proposed in the form

$$(Nu)\,avg = 0.0623\,Re^{0.8}\left[1-0.168\left(\frac{R}{d}\right)+0.008\left(\frac{R}{d}\right)^{2}\right]\left(\frac{H}{d}\right)^{(-0.037)}\left(\frac{\mu j}{\mu\omega}\right)^{0.25} \quad (12)$$

7. Jet Array

In research work by Matt Goodro an array of impinging jets has been studied to see the effects of substantial, independent Mach number. Data were obtained when (i) at constant Reynolds number as the Mach number is varied, (ii) at constant Mach number as the Reynolds number is varied.

Parameters Chosen Mach numbers up to 0.74, and for Reynolds numbers up to 60,000. [7]

The correlation equation is given by

$$\frac{Nuavg}{Nu_{F}avg}=1.0+0.325Ma^{1.55} \quad (12)$$

The correlation equation is valid for Re = 60,000, 0.21 $\leq$ Ma $\leq$0.74, X/D = 8, Y/D = 8, Z/D = 3, and 20$\leq$X/D$\leq$60. Where X/D, Y/D, Z/D are dimensionless distances in X, Y, Z directions respectively. $Nu_{F}avg$ Is baseline average Nusselt Number.

8. Micro Scale Impinging Slot Jet

Kyo sung choo Developed correlations Based on the experimental results, for the stagnant and average Nusselt numbers as a function of Reynolds number and nozzle-to-plate spacing for macro-scale impinging slot jet. Parameters chosen were Reynolds numbers Re = 150–5000 and nozzle-to-plate spacing's H/d = 0.5–10.

At Reynolds numbers (Re < 2500 the heat transfer characteristics of the micro scale impinging slot jet are similar to those of the macro-scale impinging slot jet. However, at Reynolds numbers (Re>2500 the heat transfer characteristics of the micro-scale impinging slot jet are different from those of the macro-scale impinging slot jet.

The correlations of the stagnant Nusselt number for the micro-scale impinging jet have the following form:

At lower Reynolds numbers (150$\leq$Re < 2500),

$$Nu_{0} = 0.1Re^{0.74}\left(\frac{H}{d}\right)^{-0.15} \quad (13)$$

At higher Reynolds numbers (2500 $\leq$Re $\leq$5000)

$$Nu_{0}=2.11*10^{-4}Re^{m1}\left(\frac{H}{d}\right)^{3.6} \quad (14)$$

$$\text{Where } m1=1.618-0.236\left(\frac{H}{d}\right)+0.01144\left(\frac{H}{d}\right)^{2}$$

Correlations of the average Nusselt number for the micro-scale slot impinging jet have the following form:

At lower Reynolds numbers (150 $\leq$Re < 2500),

$$Nuavg = 0.078Re^{0.74}\left(\frac{H}{d}\right)^{-0.15} \quad (15)$$

At higher Reynolds numbers (2500$\leq$Re$\leq$5000)

$$Nu_{0}=1.075*10^{-5}Re^{m2}\left(\frac{H}{d}\right)^{4.5} \quad (16)$$

$$\text{Where } m2=2.015-0.294\left(\frac{H}{d}\right)+0.01144\left(\frac{H}{d}\right)^{2}$$

Also developed a heat transfer correlation to find a relation between Reynolds number and jet spacing to study the radius of the heat transfer area and jet spacing for maximizing the average Nusselt number. Parameters chosen Re from 6000 to 60,000, H/B from 1 to 12. [8]

$$Nuavg = Re^{0.76}Pr^{0.42}\left[a+b\left(\frac{H}{d}\right)+c\left(\frac{H}{d}\right)^{2}\right] \quad (17)$$

Where

$$a=(1X10^{(-4)})\left(506+13.3\left[\frac{r_{max}}{d}\right]-19.6\left[\frac{r_{max}}{d}\right]^{2}+2.41\left[\frac{r_{max}}{d}\right]^{3}-0.0904\left[\frac{r_{max}}{d}\right]^{4}\right)$$

$$b=(10^{(-4)})\left(32-24.3\left[\frac{r_{max}}{d}\right]+6.53\left[\frac{r_{max}}{d}\right]^{2}-0.694\left[\frac{r_{max}}{d}\right]^{3}+0.0257\left[\frac{r_{max}}{d}\right]^{4}\right)$$

$$c=(-3.85X10^{(-4)})\left(1.147+\left[\frac{r_{max}}{d}\right]\right)^{(-0.0904)}$$

9. Slot Jet

Roy Studied the heat transfer for eight different Reynolds numbers ranging from 500 to 20 000. The correlation between stagnation Nusselt number and Reynolds number is presented. Turbulent intensity þ and wall y distributions are the effect of jet impingement angle on local and average Nusselt number is studied. A correlation between the average Nusselt number, nozzle exit Reynolds number and the jet angle is given as. [9]

$$Nuavg = A\theta^2 + B\theta + C \quad (18)$$

Where

$A = -(0.0436Re^2 + 0.021Re + 0.0081)$

$B = (5.56Re^2 + 2.77Re + 2.45)$

$C = -(103.2Re^2 + 140.4Re - 130.8)$

10. Swirling Jet

Ortega studied the Numerical simulations of the impingement of a swirling jet against a heated solid wall The Swirling Jet is created by an experimental nozzle (whose exit diameter is d) and with the swirl given to the jet by moving swirl blades: different blade orientations give jets with different swirl intensities. Simulated numerically seven Reynolds numbers and three nozzle-to-wall distances. Proposed. Correlations of the area-weighted average Nusselt number and the stagnation point Nusselt number as a function of the dimensionless parameters. Used Parameters such as Reynolds number Re, jet swirl intensity Si, jet average turbulent intensity Iavg, and jet to wall spacing H/d as Re (7000 to 20 000), Si (0.015 to 0.45), Iavg (10 to 40%), and H/d (5, 10 and 30) respectively [10]

Proposed Correlation for Stagnation point Nusselt No.
When Si (0.015-0.1)

$$Nu_o = 0.772Re^{0.5644}Si^{0.0246}\left(\frac{H}{d}\right)^{-0.2770}(Iavg)^{-0.0230} \quad (19)$$

When Si (0.1-0.45)

$$Nu_o = 0.3246Re^{0.8598}Si^{0.2414}\left(\frac{H}{d}\right)^{-0.7079}(Iavg)^{-0.2844} \quad (20)$$

For Average Nusselt No Correlation is

$$Nuavg = 0.1805Re^{0.6313}Si^{0.0407}\left(\frac{H}{d}\right)^{-0.3780}(Iavg)^{-0.1132} \quad (21)$$

11. Conclusion

A review has been done on various types of jet impingement based on the correlations developed which include chamfered edge, slot, angular jet, swirl jet etc. Revealing the heat transfer Nusselt Number is function of Reynolds number, jet height to diameter ratio and parameter related to geometry of nozzle. Still a lot of scope for work in this area.

12. Nomenclature

I	Current from transformer [A]	V	Output voltage from transformer [V]
K	Thermal conductivity of air [$Wm^{-1}K^{-1}$ or Wm^{-1} $^{o}C^{-1}$]	h	Heat transfer coefficient [$Wm^{-2}K^{-1}$]
L	Length of the plate [m]	b	Width of the plate [m]
A	Surface area of the plate [m^2]	d	Diameter of nozzle [m]
Nu	Nusselt no. (Dimensionless Quantity) $Nu = h \times \frac{d}{K_{air}}$	Re	Reynolds no. (Dimensionless Quantity) $Re = \frac{\rho \times v \times d}{\mu}$
H	Nozzle tip to the plate surface distance [m]	Q	Heat power input to the plate [W]
Nuavg	Average Nusselt number (Dimensionless Quantity)	S/ Si	$S = \frac{2}{3}\left[\frac{1-(d/D)^3}{1-(d/D)^2}\right]\tan\theta$ Which is defined as axial flux of swirl momentum divided by axial flux of axial momentum, times the equivalent nozzle radius. Where D and d are nozzle and vane pack hub diameters and θ is swirling angle
H/d	Ratio of plate to nozzle tip distance to the diameter of nozzle (Dimensionless Quantity)	Ta	ambient temperature, K
Tp	Impinged plate temperature, K	μ	air viscosity, Kg/(m s)
v	Velocity of air jet [ms^{-1}]	$\overline{Tu}$	Average free steam turbulence intensity [Nm^{-2}]
Tu	Free steam turbulence intensity	ρ	Density of fluid,Kg/m^3
Pr	Prandtl Number	r	Radial distance on impinged plate
Iavg	Turbulent Intensity average	Ma	Mach Number

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Author Profile

Sagar U. Chirade earned his Bachelor of Engineering (Mechanical Engineering) from BDCE, Wardha (India) in 2011. Now, he is students of Master's in Mechanical Engineering – Heat Power from University of Pune (India).His mail id is chiradesagar@gmail.com.

Sunil Ingole. Born in Maharashtra – India (1975) and earned his Bachelor of Engineering (Mechanical Engineering) from JNEC, Aurangabad (India) in 1996. Next, he earned his Master's in Mechanical Engineering – Heat Power from University of Pune (India). He has sixteen years of experience in teaching, and presently working as Associate Professor in Indira College of Engineering and management, at Pune (India). His E-mail ID is: sbingole1@rediffmail.com. He published papers in national and international conferences. His major areas of interest are Heat transfer, Electronics cooling, Technical Education system, etc. Prof. Ingole is a life member of Indian Society for Technical Education (ISTE), and Indian Society of Heat and Mass Transfer (ISHMT).

K. K. Sundaram born in Nallur Village Tanjavur Dist. – India (1964) and earned his Bachelor of Engineering (Mechanical Engineering) from Birla Institute of Technology India in 1986, . Next, he earned his Master's in Mechanical Engineering from COE Pune (India) and then PhD from Florida International University USA in 2000. He is presently working as Professor and Dean(R & D) in Vishwakarma Institute of Technology, Pune (India). He can be contacted on: vit_sundaram@yahoo.com. He published number of papers in national and international conferences and Journals. His major areas of interest are Heat transfer, Electronics cooling, Biomedical engineering, and Foldable and Telescopic design technologies for Aerospace, Defense and automotive areas. He is specialist in space, redundancy and cost reduction in engineering design and has many inventions to his credit. Prof. (Dr.) K. K. Sundaram is a life member of Indian Society for Technical Education (ISTE), NIPM and holds membership of several technical boards and bodies.