Distribution of effectiveness and Nusselt number over a corrugated surface impinged by a row of circular jets

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Abstract. The characteristics of effectiveness and heat transfer for a row of jets impinging on a corrugated surface were experimentally investigated. The Reynolds number, Re which was calculated based on the exit velocity and the hydraulic diameter of the nozzle, was 20000 and the jet-to-target spacing, L, was varied from 2 to 10 times the jet diameter, d. The spacing between adjacent jets, Sx, was kept constant at 4d. The actual angle of impingement and jet-to-target distance were different for different jets in the row due to the corrugated surface. This results in difference in the interaction of walljets of adjacent jets, which in turn influence the local distribution of effectiveness and Nusselt number

1. Introduction
Jet impingement gives high local heat transfer coefficient and can be used for the cooling of surfaces with severe thermal conditions. A row of jets can be used to reduce the drawback of sudden drop in heat transfer coefficient at locations far from the impingement region. Saripalli [1] studied flow visualization of impingement of two circular jet on a flat plate and observed a fountain due to the interaction of wall jets. Abrahams and Vedula [2] reported studies on impingement of column of circular jets on the convex surface with and reported that the distribution of Nusselt number for each jet is different due to the contact of the adjacent walljets. The flow behavior and heat transfer of obliquely impinging jets are different as more fluid diverts to the downhill side. Donovan and Murray [3] reported that the increase in the inclination decreases the turbulence generation in the downhill side.

The temperature of jet is needed to be different from the ambient for some applications and such jets are termed non-isothermal jets. The ambient gets entrained into the jet and changes the recovery temperature on the impinging surface from the jet temperature. This recovery temperature can be considered to be the adiabatic wall temperature, $T_{aw}$, and needed for the precise value of the heat transfer over the surface. Baughn et al. [4] and Goldstein et al. [5] studied on non-dimensional $T_{aw}$ data, termed as effectiveness, on a flat surface impinged with circular jet. Highest effectiveness observed at the impingement region and the variations were Reynolds number independent. Goldstein and Seol [6] studied row of jets on flat surface and observed maximum effectiveness at midway between jets at large stream wise direction. Abraham and Vedula [7] studied effectiveness for circular jets row impinging at different inclinations on a convex surface and observed that the interaction of walljets reduce the entrainment in the inner regions and shows high effectiveness. Abraham et al. [8] reported effectiveness data on convex surface for slot jet impinging at an angle. The effectiveness was decreasing on the uphill side and increasing on the downhill side as the inclination increased.
The present study is on jets arranged in a single row impinging on to corrugated surface for the application of cooling of after-burner of gas turbine engines. The corrugated liners of the afterburners must withstand very high temperatures and very effective cooling methods are required to keep the liner from failing. The studies on external cooling of a corrugated surface are very rare and are mainly restricted to film cooling. Funazaki et al. [9] reported cooling of a typical corrugated liner of an after-burner using film cooling method. The increase in the film cooling fluid velocity was observed to increase the penetration of the film into the primary flow. This causes the film to lift-off from the wall and causes reduction of film effectiveness. Present investigation reports the detailed effectiveness and Nusslet number distribution on a corrugated surface impinged with circular jets arranged in a single row.

2. Experimental setup and data reduction

2.1. Experimental setup

Figure 1 shows the layout of experimental setup. A compressor supplies air to a pressure vessel. The air was then supplied to a venturimeter by adjusting the control valves to the bypass and to the test setup. The pressure drop measured across the venturimeter gives the mass flow rate. The air was the heated above the ambient temperature for non-isothermal experiments by using heaters connected in series. Heaters were made by fixing high resistance electric rods with helical fins inside metal pipes. The air then entered the plenum chamber designed with to get a uniform flow at the exit by giving a divergence to the inlet section and then a constant area section. Plexiglass was used to fabricate the plenum chamber. The jet nozzle was fabricated with acrylic tubes and was attached to the plenum chamber. K-type thermocouples were used to measure the jet temperature.

Figure 1. Schematic of experimental test rig

Figure 2 shows the representative figure of the jet impingement on corrugated surface. The present corrugated surface consists of a convex portion at the middle and two concave parts at the sides. The radius of curvature for the convex and concave parts was kept as 100mm and the pitch as 160mm, giving an amplitude of 17mm. Corrugated cut of required dimensions were made on two Teflon sheets using CNC and the SS foil was fitted between the Teflon sheets. The foil was sandwiched between a pair of copper bars at both ends for support and for electric power connection.

The row of nozzles positioned along the corrugated surface. The diameter of the jet was 10mm, and was given a developing length of 25d. The spacing between the adjacent nozzles, Sx, was given as
4d and the jets were named as shown in the figure for the ease in discussion of the results. The middle jet, jet A impinged at the apex of the convex surface and jets C and $C'$ impinges at the centre of the concave portion. The jets B and $B'$ impinge at the merging position of the convex and concave surfaces, making the jets impinging at an inclination of $23^\circ$. The jet-to-target distance, $L/d$, is specified as the distance of the jet A from the apex of the convex portion, i.e. $r/d=0$ line. The distance along the height of the impinging surface is measured as $y/d$.

![Figure 2. Schematic of jets impinging on corrugated surface](image)

The actual jet-to-target distances for different jets vary due to the corrugated nature of the target and are shown in table 1. The spacing between the adjacent jets along the circumference ($r/d$ direction) is different from the $Sx/d$ value due to the curved nature of the impinging surface and is also included in Table 1.

| Jet          | Actual jet-to-target distance | $r/d$ position of impingement |
|--------------|-------------------------------|-------------------------------|
| Jet A        | $L$                           | 0                             |
| Jet B and $B'$ | $L_1=L+0.85d$                | -4.1 and +4.1                 |
| Jet C and $C'$ | $L_1=L+1.7d$                 | -8.2 and +8.2                 |

2.2. Data reduction
The data reduction methodology is reported in detail in [8] and is briefly discussed here. The impingement plate was made with 0.12 mm thick foil of Stainless steel. The plate surface opposite to the impinging surface was painted with black colour to take thermal image at steady state condition using a Infrared camera (Mikron make M7600PRO). Boundary condition as constant heat flux was obtained by applying Alternating Current to the foil. The total power given to the target surface (foil), $q_{total}$, was calculated from the measured values of current flowing through the foil and the voltage drop across it. A minor quantity of the heat supplied was lost to the ambient as one side of foil was open for thermal imaging. This loss in the heat, $q_{loss}$, was calculated with a no flow experiment and a curve between $q_{loss}$ and the temperature difference between the ambient and the foil was obtained. The difference in total heat flux supplied and the heat loss is the net heat flux, as in equation below.
The heat transfer coefficient was calculated based on the neat heat flux as shown in equation (2) for isothermal jet experiments (where jet temperature same as ambient). The jet diameter “d” was used as the characteristic length for the calculation of Nusselt number ‘Nu’ as shown in eq. (3).

\[ h_{iso} = \frac{q_w}{(T_w - T_b)} \]  
\[ Nu = \frac{h_{iso} d}{k} \]

The effectiveness was measured for non-isothermal jet experiments, and is defined as follows.

\[ \eta = \frac{T_{aw} - T_{amb}}{T_j - T_{amb}} \]

The method for calculating \( T_{aw} \) is as follows.

\[ q_w = h_b (T_w - T_{aw}) = h_b T_w - h_b T_{aw} \]

In the equation (5), \( h_b \) and \( T_{aw} \) are constants, and gives equation of straight line for the plot of \( q_w \) vs \( T_w \). The slope at each location gives \( h_b \) and the intercept on the temperature axis gives \( T_{aw} \). Each experiment was performed with different heat inputs and the plots were always linear. A typical case for slot jet on on a convex surface is shown in Figure 3 ([8]).

![Figure 3. q''w vs T_w for calculation of Taw on convex surface ([8])](image-url)
2.3. Uncertainty of the measured and calculated values
The uncertainties in the temperature measured using thermocouple and thermal camera were $\pm 0.3^\circ C$ and $\pm 1.1^\circ C$. The uncertainties of the calculated quantities were estimated using method mentioned in Coleman and Steele [10]. Minimum uncertainty for effectiveness and Nusslet number were calculated as 15% and 8% respectively.

3. Results and discussion
The studies were conducted for jets in a single row with spacing between adjacent jets equal to 4d impinging normally on the corrugated surface. Experiments were mainly conducted for a horizontal row impinging along the corrugated surface as shown in Figure 2. Few experiments were conducted with single jet impinging on the convex apex of the target surface to compare present results with literature. All the experiments were conducted for Re=20000.

3.1. Single jet

![Figure 4](image)

Figure 4. Comparison with literature for single jet (a) effectiveness (b) Nusselt number

Figure 4 (a) and (b) compares the effectiveness and Nusselt number variations for a single jet respectively on current corrugated and convex surfaces ([7] for effectiveness and [2] for Nusselt number) for the distance L/d=2. Data are provided at y/d=0, 2 and 4. At r/d=±4 the corrugated surface turns from convex to concave geometry, whereas for convex target the geometry is convex for the whole r/d range. The variations on convex surface are matching in the convex portion of the corrugated surface (± 4) for both Nusselt number and effectiveness, but the values differ in the concave portion of corrugated surface. However, the differences in values are within the uncertainty limit.

3.2. Row of jets along the corrugated surface

3.2.1. Effectiveness. Figure 5 (a) gives the effectiveness distribution on a corrugated surface impinged with the row of circular jets at jet to target distance L/d=2. The impinging location of various jets are shown as dotted lies in the figure. The data is symmetric about y/d=0 and the variations of effectiveness only along the +r/d portion of the target surface are discussed. The contours of constant effectiveness near jet A retain the circular shape of the jet till r/d=2, which is almost the midway between jets A and B. The impingement of jet B on the inclined portion causes a diversion of impinging air to the corresponding downhill side (r/d>4.1), making the contours near the impingement point depart from the round shape. The jet C, which impinges on the apex of concave surface, travels 1.7d distance more compared to jet A and 0.85d more to jet B before impinging on the target, is likely to be affected by the spent fluid from the other jets. The interaction of walljets of jets B and C results in the inclination of interaction zone towards concave portion and is characterized by high local effectiveness. The
effectiveness values in the convex portion at high $\pm y/d$ positions are noticed to drop faster compared to that in the concave part due to the increased flow towards the concave part by the jets A and B$^I$.

Figure 5 (b) show the effectiveness distribution on a corrugated surface at $L/d=8$. The general behavior of the effectiveness distribution are comparable to $L/d=2$. However, the values at $L/d=8$ are lower compared to values at a lower distance ($L/d=2$) because of the higher entrainment of stagnant surrounding air to the jets prior to the impingement.

Figure 6 (a) shows effectiveness data over corrugated surface at various $y/d$ locations at $L/d=2$. Even though the actual jet-to-target distances are different for different jets at $y/d=0$ (table 1), all are within the potential core length and therefore the peak effectiveness corresponds to all the jets are almost equal. The difference in the interactions of different pairs of adjacent jets results in the difference in drops of effectiveness between adjacent jets; with higher drop between jets A and B$^I$ compared to that between jets B$^I$ and C$^I$. The drop in effectiveness for jet B$^I$ is also noticed to be higher on the respective uphill side ($r/d<+4.1$), compared to the downhill side ($r/d>+4.1$). The high effectiveness with similar variations persists till $y/d=1$, after which the values drops. At $y/d=2$ the drop in effectiveness between the jets B$^I$ and C$^I$ is small due to the spread of jet B$^I$ on the concave surface due to the inclined nature of the jet. The $r/d$ position of the peak value appearing in the concave region increases with increase in $y/d$ due to the inclination of the interaction zone of walljets of the jets B$^I$ and C$^I$. The walljet momentum of jet B$^I$ is higher due to the inclination of jet B$^I$ towards the jet C$^I$ and results in the inclination of the interaction zone. The high effectiveness along the interaction zone is due to the weaker entrainment into the boundary layer at interaction zone as reported in [7].

Figure 6 (b) shows effectiveness variation at $L/d=8$. At $y/d=0$ the peak effectiveness value is shown at $r/d=0$ (the apex of the convex surface) and the values are lesser than $L/d=2$ because of the higher entrainment of the surrounding air before impingement. The actual jet-to-target distance of all the jets are outside the potential core region at this $L/d$ and therefore the effectiveness at the impinging point reduces progressively as $\pm r/d$ increase. The crossflows formed by the walljets of adjacent jets can be also influencing the effectiveness variations at large $|r/d|$ positions. The variation of effectiveness at various $y/d$ locations are comparable to that for $L/d=2$.

Experiments were also conducted for $L/d=4, 6$ and 10 and the effectiveness distribution at different $y/d$ locations relative to $y/d=0$ are similar to $L/d=2$ and 8. Figure 7 shows the effectiveness data for all the jet-to-target distances investigated, but only at $y/d=0$. The peak effectiveness values for all the jets are almost equal to unity at $L/d=2$. As the distance of target from jet exit ($L$) increases, the highest effectiveness values decreases and the drop is greater for $L/d>6$, which is roughly the length of
potential core. The drop in effectiveness values can be observed to be higher for the jets at higher |r/d| positions because of the larger jet-to-target distance.

Figure 6. Effectiveness variation at different y/d (a) L/d=2 (b) L/d=8

Figure 7. Effectiveness variation at y/d=0 for different L/d

3.2.2. Nusselt number. Figure 8 (a) show the distribution of Nusselt number for Re=20000 at L/d=2. The peak values of jets A and C\textsuperscript{0} occurs at the impinging region, whereas the peak values of jet B\textsuperscript{1} occurs at the corresponding uphill side. At low y/d positions the interaction of walljets by jets A and B\textsuperscript{1} has been observed to have minimum effect, whereas the interaction of walljets of jets B\textsuperscript{1} and C\textsuperscript{1} causes a local disturbance in variation of Nusselt number. The contours of high Nusselt number at the location near to the jet C\textsuperscript{1} are deviated from the circular shape of the impinging jet due to the influence of the walljets from the upstream position. Figure 8 (b) shows the distribution of Nusselt number at L/d=8 for Re=20000. The Nusselt number variations due to the interaction of jets are lesser than L/d=2.
Figure 8. Detailed distribution of Nusselt number (a) L/d=2 (b) L/d=8

Figure 9 (a) describes the Nusselt number data at several y/d positions at Re=20000. The peak Nusselt number of jets A and C occurs at the impinging point, whereas the peak of jet B shifts to the corresponding uphill side. The drop in Nusselt number along r/d after the peak values are similar to a normally impinging jet for jets A and C and similar to an obliquely impinging jet for jet B. The gradient of Nusselt number along y/d is also different at different jet impinging locations. At r/d=0 the Nusselt number drops rapidly along y/d direction till y/d=1.5, after which a local peak is noticed. The y/d=2 position gives higher Nusselt number than y/d=1.5 as the walljet transforms turbulent flow, after which the values drops again. At other jet impingement positions (r/d=4.1 and r/d=8.2) the values drop monotonically along y/d, however, at different rate. The difference in the peak values of Nusselt number for different jets maybe due to the difference in interference of adjacent jets. However, any physical interpretation cannot be given with certainty as the difference of the peak values are within the uncertainty limit. Figure 9 (b) reports the Nusselt number data at L/d=8. The drop in Nusselt number along y/d is monotonic as the significance of walljet transition to turbulence is minimum or nil at this high L/d position.
Experiments were conducted for L/d = 4, 6, and 10 also. Nusselt number behaviour for all configurations are similar to that explained for Re=20000 at L/d=2 and 8. Therefore for the other configurations the Nusselt number variations along only y/d=0 line are discussed. Figure 10 show the variation of Nusselt number for y/d=0 line for all jet-to-plate distances studied. The maximum Nusselt number at stagnation region are observed for L/d=4.

![Figure 10. Nusselt number variation along r/d at y/d=0 for differnet L/d](image)

The Nusselt number at the stagnation point can be observed to be increasing as |r/d| position of jet increases. This might be due to the deviation f spent fluid from jets ar r/d=0 and ± 4 towards the concave portion and its interaction with the impinging jets. The peak Nusselt number values can be observed to be decreasing drastically for L/d > 6. The drop in Nusselt number between the adjacent jets are monotonic at high L/d values due to the decrease in the momentum of interaction caused by higher entrainment of ambient.

4. Summary and conclusion
An experimental investigation on the detailed profile of Nusselt number and effectiveness for circular jets in a single row impinging on corrugated surface was conducted. The row of jets was oriented along the corrugated surface. Studies were done at and jet-to-plate distances (L/d) equal to 2, 4, 6, 8 and 10, and Reynolds number equal to 20000.

The actual inclination and jet-to-target distances of jets at different positions are different due to the geometry of target, which affects the Nusselt number and effectiveness variations. The effectiveness values in the convex part at high ±y/d positions are noticed to drop faster compared to that in the concave part. As jet-to-plate distance increases the peak effectiveness values decreases and drop is greater for L/d>6. The drop in effectiveness values can be observed to be higher for the jets at higher |r/d| positions caused by the larger jet-to-target distance. The difference in the impingement angle of different jets causes difference in the Nusselt number distribution between adjacent jets. The stagnation point Nusselt number is noticed to be increasing as |r/d| position of jet increases for L/d>2.

References
[1] Saripalli K.R., 1983, *AIAA Journal*, 21, 483–484.
[2] Abraham S., Vedula R.P., 2019, *Int. J. Heat and Mass Trans.*., 137, 751-764.
[3] O’Donovan T. S., Murray D.B., 2008, *Int. J. Heat and Mass Trans.*., 51, 6169–6179.
[4] Baughn J.W., Hechanova A.E., Yan X., 1991, *J. Heat Transfer*, 113, 1023–1025.
[5] Goldstein R.J., Sobolik K.A., Seol W.S., 1990, *J. Heat Transfer*, 112, 608–611.
[6] Goldstein R.J., Seol W.S., 1991, *Int. J. Heat and Mass Trans.*, 34, 2133–2147.
[7] Abraham S., Vedula R.P., 2018, *Int. J. Heat and Fluid Flow* 69, 210–223.
[8] Abraham S., Kakade A.B., Vedula R.P., *Pro. World Congress on Engineering 2015 Vol II*, July 1 - 3, 2015, London, U.K., 1273–1278.
[9] Funazaki K.S. K., Igarashi T., Koide Y., 2001, *Proc. ASME turbo expo*, June 4-7, 2001, New Orleans, USA, 1–8.
[10] Coleman H. W., Steele W.G., 1989, John Wiley, New York