Effect of Nozzle Geometry

on Heat Transfer in Jet Impingement

Jet impingement has one of the highest modes of heat transfer. Its performance characteristics have been researched for a long time and numerous correlations has been developed for different situations. Jet impingement performance has been correlated as a function of various parameters, such as nozzle diameter, jet to target spacing, heat source area, Reynolds number, flow rate, etc. However, the shape of the nozzle has received less investigation. Therefore, in this article we will review a few papers that take up this focus.

Royne et al [1], investigated 4 different nozzle geometries shown in figure 1.



Figure 1. Schematic of Four Different Nozzle Geometries [1]

All the nozzles were 1.4 mm in diameter; the nozzle pitch to diameter ratio was 7.14; and nozzle to plate spacing to diameter was set at 3.57. The sharp edge and counter sink nozzles had a 30° angle with respect to the vertical line.

Figure 2 shows the pressure drop of different shape nozzles with respect to the volumetric flow rate. The figure shows that, at the same flow rate, the sharp-edged nozzle has the highest pressure drop, followed by short/straight, long/straight and countersink.



Figure 2. Pressure Drop as a Function of Volumetric Flow Rate for Different Nozzles [1]

The discharge coefficient C_d for the countersink nozzle is highest, which leads to the lowest pressure drop. The pressure drop across a nozzle can be approximately calculated as,

$$\Delta P = \frac{8\rho G^2}{N^2 \pi 2 C_d^2 d^4}$$

where,

 $\rho = \text{density} (\text{Kg/m}^3)$

- G = volumetric flow rate (m³/s)
- N = number of jets
- C_d = discharge coefficient
- d = nozzle diameter (m)

The discharge coefficients for different nozzles is shown in figure 3.

Nozzle configuration	$C_{\rm d}$	
Short/straight	0.582	
Long/straight	0.613	
Sharp-edged	0.520	
Countersunk	0.653	

Figure 3. Discharge Coefficient of Different Nozzles [1]

Royne et al [1] found out that, for a fixed volumetric flow rate, the sharp edged nozzle has the highest heat transfer coefficient and, similarly for a fixed pressure drop, the sharp-edged nozzle has the highest heat transfer coefficient. But, for a fixed pump, the characteristics curve of the sharpedged nozzles is the worst. This means that the determination of which nozzle is the best is really system dependent. They [1] also showed that, for a fixed pumping power, the countersunk and sharp-edged nozzles have the highest heat transfer coefficients. Figure 4 shows the heat transfer coefficients for different nozzle geometries.

Device	Maximum Q (mL s ⁻¹)	$\frac{\text{Maximum } h_{\text{avg}}}{(\text{Wm}^{-2} \text{ K}^{-1} \times 10^{-4})}$	
Short/straight	29.9 ± 1.5	3.1 ± 0.3	
Long/straight	31.7 ± 1.6	3.4 ± 0.3	
Sharp-edged	27.7 ± 1.4	3.5 ± 0.3	
Countersunk	33.3 ± 1.7	3.5 ± 0.3	

Figure 4. Heat Transfer Coefficients for Different Nozzle Geometries [1]

By looking at the data, one concludes that the sharp-edged nozzle has the comparable heat transfer coefficient with a countersunk nozzle at a significantly lower volumetric flow rate. But, these data are only for fixed pumping power. In a real application with a given pump, one has to find the operating point. From there, the volumetric flow rate and pressure drop of the system can be calculated, which will indicate which nozzle geometry yields the maximum heat transfer.

In another experiment, Whelan et al. [2] conducted an experiment on arrays of jets impinging on a surface using various nozzle shapes. They used 6 different nozzle geometries each, with an array of 45 jets of 1 mm diameter and a dimensionless jet spacing to nozzle diameter of 5 for submerged jets. The heated surface was made of copper, with a 31.5 mm diameter and heat input of 200 W. They conducted tests on both free surface jets and submerged confined jets. The jet to target spacing for the submerged jet was 2. They also tested 6 different geometries, as shown in figure 5.

Name	Configuration
Straight	
Contoured Inlet	
Contoured Inlet/Outlet	
Chamfered Inlet	
Chamfered Outlet	
Chamfered Inlet/Outlet	

Figure 5. Different Nozzle Geometries [2]

Figure 6 shows the experimental set up and the nozzle array.



Figure 6. Experimental Jet Impingement Setup [2]

Figure 7 shows the heat transfer coefficient ratio as a function of volumetric flow rate. The data has been normalized with respect to the straight nozzle. This figure shows that the chamfered inlet/

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Figure 7. Heat Transfer Coefficient as a Function of Volumetric Flow Rate [2]



Figure 8. Pressure Drop as a Function of Volumetric Flow Rate [2]



Figure 9. Heat Transfer Coefficient as a Function of Pumping Power [2]

outlet has the highest heat transfer coefficient for the same volumetric flow rate, but Figure 8 shows that at lower flow rates, less than 10 l/min, the chamfered outlet has the highest pressure drop, but for flows higher than 10 l/min, the chamfered inlet/ outlet has the highest pressure drop. At lower flow rates (less than 10 l/min), the pressure drop of the chamfered inlet/outlet looks reasonably small.

Figure 9 shows the heat transfer coefficient as a function of pumping power. The figure shows that for a given pumping power the contoured inlet and the chamfered inlet/outlet perform similarly, however, the chamfered inlet/outlet is preferred for ease of manufacturing.

The above results should be used carefully. One has to look at the overall system. The source of the pumping can have a variety of different forms, such as constant pressure, constant volume, constant power or simply a pump for which one needs to find the operating point.

The above arguments clearly demonstrate that for a jet impingement cooling, in addition to traditional variables such as jet diameter, jet to target spacing, and Reynolds number, the shape of the nozzle plays an important role in enhancing the heat transfer coefficient.

References:

- 1. Royne, A., Dey, C., "Effect of Nozzle Geometry on Pressure drop and Heat Transfer in Submerged Jet Arrays", International Journal Of Heat and Mass Transfer, June, 2005.
- 2. Whelan, B., Robinson, J., "Effect of Nozzle Geometry on Pressure Drop and Heat Transfer to Both Free-Surface and Submerged Liquid Jet Arrays", 5th European Thermal-Sciences Conference, The Netherlands, 2008.







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