The Review of Studies on Heat Transfer in Impinging Jet

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ABSTRACT: In this paper, recent research trend on heat transfer in impinging jet is reviewed. We focused on submerged jet that air issued into air or liquid issued into liquid. To control and enhance the heat transfer in single jet, researchers have performed a lot of experiments by considering the nozzle geometry, impinging surface and active method such as jet vibration, secondary injection and suction flow. The studies on multiple jet have been mainly focused on finding out the optimum condition and on investigating many different factors concerned with application condition (crossflow, rotation and geometry etc.) and combined techniques (rib turbulator, pin fin, dimple and effusion hole etc.). All most experiments showed the detailed heat transfer data by using liquid crystal method, infrared camera technique and naphthalene sublimation method. Many numerical calculations have been performed to investigate the flow and heat transfer characteristics in laminar jet region. Various turbulence models such as $k-\varepsilon-\overline{v^2}$, modified $k-\varepsilon-f_\mu$ were applied to the calculation for turbulent jet and the predicted results showed a good agreement with the experimental data. Although a lot of studies on impinging jet have performed consistently up to recently, further studies are still required to understand the flow and heat transfer characteristics more accurately, and to give a guideline for optimum impinging jet design in various applications.

Nomenclature

- AR : aspect ratio of elliptic jet nozzle
- D : diameter of round nozzle (orifice)
- H : nozzle-to-surface spacing
- Nu : Nusselt number
- Re : Reynolds number
- S : jet-to-jet spacing
- W : width of slot nozzle

1. Introduction

Heat transfer under an impinging jet is generally superior to that achieved with a typical convective heat transfer method. With an impinging jet, it is easy to adjust the location of interest and to remove a large amount of heat on the impingement surface. For these reasons, the impinging jet cooling/heating technique has been widely used in many industrial systems such as cooling of high temperature gas turbines, drying of paper or textiles, and processing of steel or glass. In recent years, it has been applied to cool high-density electrical and electronic equipment.

There have been numerous experimental and numerical investigations on flow and heat transfer characteristics of impinging jet. Since Martin[1] reported his review on heat and mass transfer of impinging jet, several additional literature reviews have published.[2-4] Until now, a lot of studies on impinging jet are performed

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consistently.

In this paper, recent research trend on impinging jet is reviewed. We have focused on the submerged jet that air issued into air or liquid issued into liquid.

2. Single jet

Experimental studies on the single jet are classified into three group; nozzle geometry, impinging surface and active control. Table 1 is summary of the studies on the single jet.

2.1 Nozzle geometry

To control heat transfer in impinging jet, many researchers change the nozzle shape or install additional structure on the nozzle as passive method.

Lee and Lee[5] considered the shape of the nozzle — from circular to elliptical shape. For smaller nozzle-to-surface spacing ($H/D<4$), as the nozzle aspect ratio AR of elliptic jet increases, the heat transfer rate was larger than that for the axisymmetric jet ($AR=1$) in the stagnation region. They concluded that the elliptic impinging jet can be used as an effective passive control technique for heat transfer enhancement for engineering applications having small nozzle-to-surface spacing less than the potential core length. Lee et al.[6] investigated heat transfer by using a swirling round impinging jet. For small nozzle-to-surface distance, $H/D=2$, the average Nusselt numbers of the swirling jet flows were larger than with non-swirling flow for all swirl numbers. However, for large nozzle-to-surface distance $H/D>10$, the effect of the swirling jet flows was rarely seen. Wen and Jang[7] reported the difference about the round jets with/without swirling insert. Choi et al.[8] installed a twisted tape swirl generator in the nozzle and examined the

Table 1 Summary of experimental flow and heat transfer studies on single jet

Reference	D(mm)	H/D	Re_D or Re_W	Jet type	Comments
Lee and Lee[5]	25	2~10	10,000	Round jet	Elliptic nozzle shape
Lee et al.[6]	3.4	2~10	23,000	Round jet	Swirl jet
Wen and Jang[7]	7	3~16	500~27,000	Round jet	Swirl jet
Choi et al.[8]	17	1~7	8,700~26,500	Round jet	Swirl jet and block surface
Zhou and Lee[9]	2.5	0.2~10	15,000	Round jet	Mesh screen installed on nozzle
Gao et al.[10]	12.7	1~10	23,000	Round jet	Triangular tap installed on nozzle
Beitelmal et al.[11]	5.5	4~12*	4,000~12,000*	Slot jet	Inclined surface
Song et al.[12]	25	2.5~10	53,200	Slot jet	Inclined surface
Chan et al.[13]	6.25	2~10	5,600~13,200	Slot jet	Curvature surface
Choi et al.[14]	5	0.2~14	1,780~7,100*	Slot jet	Curvature surface
Lim et al.[15]	30	2~10	11,000~50,000	Round jet	Curvature surface with inclined jet
Cornaro et al.[16]	72.6	1~4	6,000~20,000	Round jet	Curvature surface
Gau and Lee[17]	3.5~20	2~16	2,500~11,000	Slot jet	Triangular rib-roughen surface
Pyo et al.[18]	50	2~14	6,500~58,500	Slot jet	Hybrid rod in front of surface
Yim et al.[19]	2	1~4	2,400~7,400*	Slot jet	Roughen surface
Hwang et al.[21]	20	1	1,615~5,672	Round jet	Aluminum foam heat sink
Camci and Herr[22]	5	24~60	7,500~14,000	Slot jet	Oscillating jet
Hwang et al.[23-24]	24.6	2~16	34,000	Round jet	Acoustic excitation/secondary flow
Mladin et al.[25]	5	3~10	1,000~11,000	Slot jet	Pulsating jet

*Based on hydraulic diameter.

effect of swirl jet. Zhou and Lee[9] installed the mesh screen in front of the jet nozzle and performed the experiment with varying the solidity of the mesh screen. The result showed that for nozzle-to-surface spacings of $H/D<4$, the turbulence intensity was increased with mesh solidity, causing an increase in the local heat transfer rate. Gau et al.[10] added arrays of triangular tabs to the exit of turbulent round impinging jet issuing from a long pipe. They found that the local heat transfer was increased more than 25% in a series of distinct regions surrounding the impingement region at small nozzle-to-surface distances.

At smaller nozzle-to-surface distance, enhanced heat transfer result is obtained but as the nozzle-to-surface distance becomes large, it is shown that the effect of nozzle geometry or additional structure on nozzle reduce.

2.2 Impinging surface

To apply impinging jet to various engineering applications, experimental studies have been performed on various impinging surface conditions not simple flat surface.

Beitelmal et al.[11] investigated the effect of inclined flat surface. They showed that the region of maximum heat transfer shifted towards the uphill side of the plate and the maximum Nusselt number decreased with decreasing the inclination angle. The location of the maximum heat transfer region was found to be insensitive to the Reynolds number in the range used in their study. Song et al.[12] reported the Oblique Wall Attaching Offset Jet (OWAOJ) which is a two-dimensional slot jet issued into quiescent surroundings above an inclined plate.

Heat transfer characteristics of a heated slot jet impinging on a semicircular convex surface been investigated by Chan et al.[13] Meanwhile, Choi et al.[14] studied the flow and heat transfer characteristics of a slot jet impinging on a semicircular concave surface. They laid emphasis on interpreting the heat transfer data in association with the measured mean velocity and velocity fluctuations of impinging and evolving wall jet region along the concave surface, particularly. Lim et al.[15] investigated the heat transfer characteristics on concave surface and changed the surface angle between impinging jet and concave surface from 0° to 40°. They reported that the displacement of the maximum Nusselt number from the stagnation point increased with increasing surface angle or decreasing nozzle-to-surface distance.

Cornaro et al.[16] investigated impinging jet on both concave and convex surface by using smoke wire flow visualization. They showed that flow over a concave surface was more unsteady than flow over a convex surface as the flow upstream of the concave surface was strongly affected by the flow exiting the surface into recirculation. This exhaust flow became entrained in the primary jet flow, reducing the likelihood of stable ring vortices.

Gau and Lee[17] performed the experiments on slot air jet impingement cooling along triangular rib-roughened walls. The geometric shape of the triangular ribs was more effective in rebounding the wall jet away form the wall than in the case with rectangular ribs. Pyo et al.[18] examined impinging jet on a flat surface which had a set of hybrid rod with a half of circular cross section. They reported that the installed hybrid rod enhanced the heat transfer in the whole surface. Yim et al.[19] studied the effect of surface roughness in water jet with boiling.

McDaniel and Webb[20] investigated a slot jet impinging on a circular cylinders. They also considered both the sharp-edged nozzle and contoured nozzle. The average Nusselt number on circular cylinder showed stronger Reynolds number dependence for the sharp-edged nozzle than for the contoured nozzle. Hwang et al.[21] performed the experiment of impinging jet on aluminum foam heat sink. They compared the confined jet with the unconfined jet and investigated the effect of Reynolds number and the pore density of the aluminum foam.

2.3 Active control

The studies of active method such as jet vibration, secondary injection and suction flow have been published.

Adding two communication ports at the throat section, Camci and Herr[22] converted a stationary impinging cooling jet into a self-oscillating impinging jet. It was shown that a self-oscillating impinging jet configuration is extremely beneficial in enhancing the heat removal performance of a conventional (stationary) impinging jet. Significant heat transfer coefficient enhancements ranging from 20 percent to 70 percent over the stationary jet values existed because of the oscillation motion of the impinging jet. Hwang and Cho[23-24] investigated the characteristics of excited circular impinging jet by the control of the vortex pairing; secondary flow and acoustics excitation. Also, they tested two different acoustic excitation methods based on the locations of the actuator; main jet excitation and shear layer excitation. Mladin et al.[25] reported the study of flow pulsation on the characteristics of planar jet. Result indicated that the forcing Strouhal number was an influential parameter that controlled the large scale structure formation (i.e., structure size and frequency) and interaction (i.e., passage frequency and localized merging point), as well as the downstream penetration distance (i.e., propagation wavelength) of the initial perturbation.

3. Multiple jet

Since multiple jet covers heating or cooling in large areas, the key factors of multiple jet are both high average heat transfer coefficient and uniformity of heat transfer over target surface. Therefore, studies on multiple jet have been mainly focused on finding out the optimum multiple jet condition by considering interactions among the jets. Recently, the majority of these studies are related to the complicated effect instead of simple multiple jet; application condition (crossflow, rotation and geometry etc.) or combined techniques (rib turbulator, pin fin, dimple and effusion hole etc.).

San and Lai[26] investigated the effects of jet-to-jet spacing on the local Nusselt number for confined circular air jets. They suggested optimum jet to jet spacing (S/D) for Re in the range of 10,000~30,000 from their result of experiment. Brevet et al.[27] studied optimization in the case the impingement was confined by the test section and spent air was constrained to exit in only one direction. The heated-thin-foil technique was used jointly with infrared thermography. Ekkad and Kontrovitz[28] obtained the detailed heat transfer distributions on a jet impingement target surface with dimples. Result showed that the presence of dimples on the target surface, in-line or staggered with respect to jet location, produced lower heat transfer coefficients than the non-dimpled target surface. They reported that the bursting phenomena associated with flow over dimples produces disturbances of the impingement jet structures resulting in lower levels of heat transfer coefficients on the target surface. Kanokjaruvijit and Martinez-botas[29] performed the experiment about array jet onto a staggered array of dimples at Reynolds number 11,500. Two dimple geometries of hemispherical and cusped elliptical were examined. Moreover, the effect of crossflow scheme on heat transfer was investigated: one-way, two-way and four-way spent air exits. Nakabe et al.[30] studied the interactions of longitudinal vortices made by two inclined impinging jets in in-line and staggered arrays by using thermochromic liquid crystal, fluorescence dyes and PIV.

Son et al.[31] presented the detailed heat transfer coefficient distributions measured on both

Table 2 Summary of experimental flow and heat transfer studies on multiple jet

Reference	D(mm)	H/D	Re_D	S/D	Comments
San and Lai[26]	3	2~5	10,000~30,000	4~16	Optimum jet-to-jet spacing
Brevet et al.[27]	10	1~10	3,000~20,000	2~10	Optimum jet-to-jet spacing
Ekkad and Kontrovitz[28]	6.35	3	4,800~14,800	4	Dimple surface
Kanokjaruvijit and Martinez-botas[29]	10	2~8	11,500	4	Dimple surface
Nakabe et al.[30]	6		5,000	10	Inclined jet
Son et al.[31]	NA	1.875~3	15,000~40,000	3~6	Non-uniform nozzle size
Gao et al.[32]	3.17~6.35	1~5	2,000~10,000	3~6	Non-uniform nozzle size
Taslim et al.[33]	8.2	4.3~6.2	15,000~40,000	4	Roughen surface
Rhee et al.[34]	10	1~6	10,000	6	With effusion hole
Hong et al.[35]	10	2	10,000	6	With pin fin and effusion hole
Iacovides et al.[36]	11.2	3.125	15,000	4	Rotating curved surface
Hwang and Cheng[37]	5	6	12,000~42,000	3	Triangular duct with crossflow
Yan et al.[38]	10	3	1,500~4,500	1.5~3	Elliptic nozzle shape
Haiping et al.[39]	NA	1.5~5	7,000~20,000	5~15	Rib-roughen surface

NA: Not Available.

surfaces of the impingement plate. It was found that the average heat transfer coefficient on the impingement downstream surface is about 50% of the average target surface heat transfer coefficient. Gao et al.[32] tested impingement heat transfer for linearly stretched arrays of holes. Two different arrays are investigated with uniform diameter holes through the array for one case and varying diameter holes at every row location for another case. Taslim et al.[33] measured the heat transfer coefficient of impingement for different target wall roughness geometries on curved surface: a smooth wall, a wall with high surface roughness, a wall roughened with conical bumps, and a wall roughened with tapered radial ribs. Rhee et al.[34] investigated the effects of spent air flows with and without effusion holes. Result showed that for a multiple jet without effusion holes, the spent air of the injected jets forms a crossflow within the confined space and affects significantly the downstream jet flow. But, uniform distributions and enhancements of heat transfer coefficients were obtained by installing the effusion holes. Hong et al.[35] studied a combined multiple jet with pin fins and effusion holes. They reported that installed pin fins reduced the adverse effect of crossflow to impinging jet and enhanced the heat transfer.

Iacovides et al.[36] reported an experimental study of impingement cooling in a rotating passage of semi-cylindrical cross section. Local Nusselt number measurements showed that under stationary conditions a high Nusselt number region developed around each impingement point, with secondary peaks half-way between impingement points. Rotation reduced heat transfer, leading to the disappearance of all secondary peaks and also, surprisingly, of some of the primary peaks. Hwang and Chang[37] studied the heat transfer and pressure drop characteristics in a triangular duct cooled by an array of jets. The outflow orientation affects significantly the local heat transfer characteristics through influencing the jet flow together with the crossflow in the triangular duct. The triangular duct with two openings was recommended since it had the highest wall averaged heat transfer and the moderate loss coefficient among the three outflow orientations investigated. Yan et al.[38] obtained the detailed heat transfer characteristics under elliptic multiple jet by a transient liquid crystal technique. The elliptic jet holes of five different aspect ratios, $AR=4$, 2, 1, 0.5 and 0.25, jet Reynolds numbers Re= 1500, 3000 and 4500, and three exit flow conditions were considered. Result showed that effects of the aspect ratio and crossflow had significant influences on the axial shift of the impingement/touchdown locations. Haiping et al.[39] studied the heat transfer on rib roughened surface with arrays of circular jets and suggested the correlation equation.

4. Numerical simulation

A lot of numerical simulation have been carried out on both laminar impinging jet and turbulent impinging jet to understand flow and heat transfer characteristics more accurately and to validate various turbulence models.

4.1 Laminar impinging jet

Chatterjee and Deviprasath[40] showed heat transfer in confined laminar axisymmetric impinging jet at small nozzle-to-surface distances, presenting the role of upstream vorticity diffusion. Ichimiya et al.[41] estimated the impingement heat transfer and flow in the radial and circumferential directions by a single circular laminar jet in a flow passage with a confined insulated wall. Miranda and Campos[42] performed numerical simulation of mass transfer from soluble plate to an impinging liquid jet confined by a conical wall at short nozzle-to-surface distance. Aldabbagh and Sezai[43] investigated the flow and heat transfer characteristics of impinging laminar multiple square jets for Re in the range of 100~500. Fu et al.[44] studied the effect of moving block on heat transfer of a heat plate under a slot jet. They used modified Arbitrary Lagrangian Eulerian (ALE) method to simulate moving block. The result showed moving block destroy thermal boundary, leading to high enhancement of heat transfer.

Bula et al.[45] studied the conjugate heat transfer due to the impingement of a high Prandtl number fluid in impinging surface with discrete heat source. The position of the discrete heat sources played a very important role in determining the temperature and the heat transfer rate. Chung et al.[46] used the direct numerical simulations of an unsteady impinging jet to study momentum and heat transfer characteristics. The unsteady compressible Navier-Stokes equations were solved using a high-order finite difference method with non-reflecting boundary conditions. It was found that the impingement heat transfer was very unsteady and oscillatory in time. At the stagnation point, the amplitude of the oscillation was as high as 20% of the time-mean value.

4.2 Turbulent impinging jet

Behnia et al.[47] compared $k-\varepsilon-\overline{v^2}$ model and $k-\varepsilon$ model for prediction of heat transfer in an axisymmetric turbulent jet. They showed the heat transfer predictions by $k-\varepsilon-\overline{v^2}$ model are in excellent agreement with the experiments, whereas the $k-\varepsilon$ model did not properly resolve the flow features, greatly over-predicts the rate of heat transfer and yields physically unrealistic behaviors. Thielen et al.[48] used $k-\varepsilon-\overline{v^2}$ model for the effect of nozzle arrangement on the heat transfer of multiple impinging jet. They also compared $k-\varepsilon-\overline{v^2}$ model with standard $k-\varepsilon$ model. Park and Sung[49] applied a modified $k-\varepsilon-f_\mu$ model to an impinging jet flow. It was shown that modified $k-\varepsilon-f_\mu$ model get a good agreement with experimental data in the stagnation region.

Chattopadhyay et al.[50] predicted turbulent flow field and heat transfer in an array of slot jets impinging on a moving surface using Large Eddy Simulations. Numerical predictions of turbulent plane discharged normal to a weak or moderate cross-stream were proposed by Kalita et al.[51] The Reynolds-averaged Navier Stokes equations along with a standard $k-\varepsilon$ turbulence model have been used to formulate the flow problem. For application of impinging jet, Olsson et al.[52] predicted the heat transfer from a slot air jet impinging on a cylinder shaped food product placed on a solid surface in a semi-confined area. They used Shear Stress Transport (SST) model. The result showed that the local Nusselt numbers had little dependency on jet-to-cylinder distance.

5. Conclusions

Recent study trend on heat transfer in submerged impinging jet is reviewed. The experimental and numerical studies on single jet and multiple jet are briefly described.

To control and enhance heat transfer in single jet, researchers have investigated the effect of the nozzle geometry, impinging surface and active method such as jet vibration, secondary injection and suction flow.

For the applications ranging from gas turbine to electrical equipments, it becomes important to find out the optimum design condition and enhance the cooling performance. Therefore, the majority of recent multiple jet studies deal with the many different factors; application condition (crossflow, rotation and geometry etc.) or combined techniques (rib turbulator, pin fin, dimple and effusion hole etc.).

All most experiments suggested the detailed heat transfer data by using liquid crystal method, infrared camera technique and naphthalene sublimation method.

Many numerical calculations have been performed to investigate the flow and heat transfer characteristics in both laminar jet region and turbulent jet region. Various turbulence models such as $k-\varepsilon-\overline{v^2}$, modified $k-\varepsilon-f_\mu$ were applied to the calculation for turbulent jet and the predicted results showed a good agreement with the experimental data.

Although a lot of papers on impinging jet have published consistently up to recently, further studies are still required to understand flow and heat transfer characteristics more accurately, and to give a guideline for optimum impinging jet design in various applications.

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