The Effect of Nozzle Height on Cooling Heat Transfer from a Hot Steel Plate by an Impinging Liquid Jet

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The effect of nozzle height on heat transfer of a hot steel plate cooled by an impinging liquid jet is not well understood. Previous studies have been based on the dimensionless parameter $z/d$. To test the validity of this dimensionless parameter, and to investigate gravitational effects on the jet, velocity measurements were made in a liquid jet with a stagnation point, and heat transfer from a hot steel plate was investigated. Also, the critical instability point of a laminar liquid jet was examined over a range of flow rates.

The experimental velocity data for the liquid jet were well correlated with the dimensionless number $1/\text{Fr}^2$ based on height. It was thought that the $z/d$ parameter was not valid for heat transfer to an impinging liquid jet under gravitational forces; unsteady cooling experiments showed that the heat transfer was independent of $z$ when $1/\text{Fr}^2<0.187$. A finite enhancement of heat transfer was observed when $1/\text{Fr}^2=0.523$. The discrepancy between these results and previous research is likely due to the instability of laminar liquid jets.

KEY WORDS: impinging liquid jet; hot steel plate; inverse heat conduction; Weber number; Froude number; gravitational force.

1. Introduction

Many industrial applications use free impinging jets, because of the high rates of heat transfer that can be obtained using relatively simple equipment. Generally impinging circular liquid jets are used as a rapid cooling system for hot steel plates. Previous studies indicate that cooling by impinging jets is 10–30% more efficient than cooling by spray jets at high pressure.1–3) The high heat transfer rate at the impingement point is caused by the stagnation mass that impacts on the hot surface at high speeds. Impinging liquid jet streams can contact a hot strip surface without splashing and suppress the formation of a vapor film.

Many researchers have studied the variables that affect heat transfer rates, such as an impinging jet's velocity, the shape and size of the nozzle, the speed at which the plate moves, the nozzle height, the temperature of the liquid, and the liquid's thermal properties such as density and surface roughness. Vader et al.6) conceived a method to measure the steady state heat transfer to an impinging liquid jet, and Zumbrunnen et al.7) developed a method and an apparatus to measure local heat transfer rates on moving and stationary plates.8) They observed the relation between the heat transfer and plate velocity. Oliphant et al.9) compared the characteristics of heat transfer in the non-boiling region between a liquid jet and a spray.10) Storr and Behnia11) studied the breakup mechanisms of liquid jets that impact with a liquid pool.12)

However, the effect of nozzle height from the heat transfer surface is not clear, especially in the case of an impinging liquid jet. Hatta et al.13) performed a cooling experiment with a hot steel plate, in which the nozzle height ($z$) from the plate was varied from 0.1 to 0.5 m under flow rates from 1 to 7 L/min.14) They used a pipe nozzle with a 10-mm diameter and concluded that the nozzle height had negligible effects on the heat transfer rate. However, the measured cooling rate for $z=0.1$ m appeared to be slightly larger than when $z=0.5$ m. Oh and Lee performed similar measurements with a flow rate of 1.14–2.27 L/min and nozzle heights of 0.1, 0.3 and 0.5 m.9) Using a 10-mm diameter pipe nozzle they showed that the maximum cooling efficiency was obtained with $z=0.3$ m. Stevens and Webb examined the surface velocity of a pre-impinging free liquid jet between the nozzle exit and $z/d=6$ for Reynolds numbers of $Re=32 600$, 46 600 and 47 500.10) They found that the liquid jet flow was almost fully developed at $z/d=0.2–0.3$ and after that, at $z/d=4$, instability occurred. Elison and Webb performed heat transfer experiments with $z/d=0–50$ under non-boiling conditions.11) The range of $Re$ was between 920 and 5 000. They concluded that the stagnation Nusselt number $Nu$ was independent of variations in $Re$ and $z/d$. The acceleration of a free liquid jet due to gravity was measured by Di Marco et al., who concluded that the heat transfer in the non-boiling regime was dependent on $z$.12) They proposed a theoretical model for the relation between the heat transfer and the height from heat transfer plate.
The above literature review clearly shows that the effect of \( z \) on the rate of heat transfer is not well understood. Therefore, the present study examined the validity of the dimensionless parameter \( z/d \) that was used in previous studies and variation of the heat transfer with \( z \).

2. Experimental Apparatus and Methods

A schematic diagram of the experimental apparatus used to measure the stagnation pressure at the point of impingement and the temperature of the hot steel plate is shown in Fig. 1. The experiments were performed in a 1\( \times 1\times 1\)-m\(^3\) air chamber. This system was designed to maintain the air and water jet temperatures at 30°C, within \( \pm 0.2^\circ \text{C} \). The relative humidity of the air was 55–56% at the start of each experiment. The nozzle height, \( z \), was 0.04, 0.07, 0.16 and 0.45 m. The flow rate of the liquid jet was fixed at 3 L/min and measured using a flow meter with an error of \( \pm 10 \text{ mL/min} \).

The nozzle for the liquid jet consisted of a sharp-edged orifice, shown in Fig. 2. The diameter of the nozzle was 6 mm. Two fine mesh layers were used to prevent a vortex from forming in the water chamber and to maintain a laminar liquid jet. The average jet velocity at the nozzle discharge \( U_\text{e} \) was calculated by considering the vena contracta effect. The contraction coefficient was 0.61. In this experiment, \( U_\text{e} = 2.89 \text{ m/s} \) and \( Re = 21,600 \). The stagnation pressure was measured on the plate to determine the effect of \( z \) on the impingement velocity. A 0.6-mm diameter pressure tap, located at the stagnation point, was connected to a 1-m water column. The velocity of the impinging jet \( (U_\text{stag}) \) at the stagnation point was calculated from the height of the water column by Eq. (1).

\[
U_\text{stag} = \sqrt{(2gh_w)} \tag{1}
\]

A water valve system was used at the top of the water chamber to produce an immediately abrupt jet at the nozzle.

An SUS304 plate was used to prevent oxide scale and phase transformation during the cooling process. The plate was 200 mm in length and 10 mm thick. The temperature history of the plate during the cooling process was measured with three thermocouples installed on the side opposite to the jet’s impingement. The 1.5-mm diameter K-type sheath thermocouples were located at \( x=0, 0.03 \) and 0.06 m from the impingement point. The plate surface was cleaned with ethanol and heated to 900°C in a furnace. Once the temperature reached 900°C, it was kept in the furnace for 30 more minutes so that the inner part of the plate would also be heated uniformly to 900°C. Then the hot plate was withdrawn from the furnace by a transport system, cooled to 800°C by natural convection, and placed in the chamber. When the plate temperature reached 750°C, the impinging water jet was started.

In this study, it was assumed that the differences in previous heat transfer results were due to the instability of the liquid jet. Thus, the point at which instability was initiated in the jet was measured as a function of \( z/d \) for various Weber numbers, \( W_e \). The position of the first wave on the liquid jet’s surface was considered to be the point at which the jet became unstable. This was illuminated with two tungsten lights and recorded with photographs.

3. Inverse Heat Conduction Analysis

An inverse heat conduction package, developed by Trujillo at Trucomp Co.,\(^{13} \) was used to calculate the heat flux on the impinging surface from the measured hot plate temperatures. Table 1 shows the thermo-physical properties that are dependent on the temperature for this calculation.\(^{14} \) For boundary conditions, the impingement axis was assumed axi-symmetric and an adiabatic condition was used on the three sides of the plate without impingement, since the radiative and free convective heat transfer quantities on those surfaces are much less than the boiling heat transfer quantity on the impinging side. The numerical domain is shown in Fig. 3. Four regions are defined with uniform heat flux in each region. The temperature for region 2 was interpolated from the data measured at \( x/d = 0 \) and \( x/d = 5 \).

![Fig. 1. Schematic diagram of the experimental apparatus.](image1)

![Fig. 2. Geometric shape of the sharp-edged nozzle.](image2)

### Table 1. Thermo-physical properties.

| \( T(\circ \text{C}) \) | \( C_p(\text{kJ/kg°C}) \) | \( \rho(\text{kg/m}^3) \) | \( h(\text{W/m}^2\text{°C}) \) |
|----------------|----------------|-------------|----------------|
| 20             | 543.7          | 8000        | 17.09          |
| 407            | 697.1          | 8000        | 26.90          |
| 605            | 748.5          | 8000        | 31.29          |
| 700            | 757.3          | 8000        | 33.01          |
| 799            | 761.0          | 8000        | 34.01          |
| 885            | 781.6          | 8000        | 35.91          |
4. Results and Discussion

4.1. Liquid Jet Velocity Measurements for a Parameter Study

Figure 4 shows the height of the water column measured from the stagnation pressure tap and the stagnation impinging velocity ($U_{stag.}$) calculated from Eq. (1). Values of $U_{stag.}$ for a liquid jet passing through a sharp-edged orifice nozzle without viscosity effects are also plotted, 

$$U_{stag.} = \sqrt{U_{jet}^2 + 2gh_w} \quad \text{(2)}$$

The difference between $U_{stag.}$ with the vena contracta and $U_{stag.}$ derived from the height of the water column is 2.5%. Therefore, it is appropriate to consider the vena contracta when calculating $U_{stag.}$ in this study.

The relation between the nondimensional $z/d$ and $U_{stag.}/U_{jet}$ is plotted in Fig. 5 to observe the effect of gravity on the velocity of the liquid jet. The value of $U_{stag.}/U_{jet}$ indicates the increase in the velocity of the impinging jet. In this figure, data shown from previous studies were induced from given experimental conditions. The value of $U_{stag.}/U_{jet}$ was obtained from Eq. (2). The figure shows that the changes of $U_{stag.}/U_{jet}$ due to variations in $z$ were negligible in the experiments of Stevens and Webb\textsuperscript{10} and Elison and Webb.\textsuperscript{11} However, $z$ does affect $U_{stag.}/U_{jet}$ in other experiments over the same range of $z/d$. The relation between $z/d$ and $U_{stag.}/U_{jet}$ appears to be random and irregular. Therefore, $z/d$ is not an adequate dimensionless number to express changes in the impinging velocity due to gravity. It may also not be appropriate to consider the effect of $z/d$ on heat transfer.

Figure 6 shows the relation between $U_{stag.}/U_{jet}$ and $Fr_z^2$, which is used as a dimensionless number for nozzle height. Equation (2) is modified to

$$U_{stag.}/U_{jet} = \sqrt{1 + 2/Fr_z^2} \quad \text{(3)}$$

Using Eq. (3), the values of $U_{stag.}/U_{jet}$ for all of the experiments collapse onto a single curve. Changes in the velocity of a liquid jet due to gravity are negligible when $Fr_z^2$ is above 100. However, when $Fr_z^2$ is below 1, the gravitational effects are significant. This shows that the experimental conditions in the previous studies differed from each other. The critical range was investigated in this study, in which $U_{jet}$ accelerated with decreasing $Fr_z$ (or increasing $z$). From these facts, $1/Fr_z^2$ is proposed as an appropriate dimensionless number to indicate the change in a liquid jet's velocity and heat transfer with the nozzle height from the heat transfer plate. The nozzle height, $z$ and the related dimensionless numbers considered in this study are summarized in Table 2.

4.2. The Instability of a Liquid Jet

To investigate instability in a liquid jet issuing from a sharp-edged orifice nozzle, and its effect on heat transfer...
from a hot plate, the starting position of the instability was examined to identify its relation with flow rates. Figure 7 shows the development of the instability when \( \text{We}_d = 348 \). In this case, instability was first observed at \( z = 0.6 \) m. Comparisons of the points at which instability was first observed and jet flow rates are summarized in Fig. 8 as functions of \( \text{We}_d \) and \( 1/\text{Fr}_z^2 \). The results of previous experimental studies in terms of these dimensionless parameters are also reported. The flow conditions of the previous studies can be classified into two groups according to \( \text{We}_d \) and \( 1/\text{Fr}_z^2 \), which might be expected from the results shown in Fig. 6. The starting point of the flow instability as a function of the flow rate is correlated according to

\[
1/\text{Fr}_z^2 = 5.1 \exp(-0.0021 \cdot \text{We}_d) \quad \text{..................(4)}
\]

Using the data reported by Hatta et al.\(^8\) and Oh and Lee,\(^9\) \( \text{We}_d = 56.96 \) and 32.61, respectively. From Eq. (4), \( 1/\text{Fr}_z^2 = 4.54 \) and 4.77, respectively, when \( z = 0.1 \) m. However, the values of \( 1/\text{Fr}_z^2 \) when \( z = 0.5 \) m are 12.04 and 21.07, which are greater than the curve indicated by Eq. (4). Thus, the experimental conditions for these flows were in the unstable regime. This may have affected the reported heat transfer from the plate.

4.3. Heat Transfer to an Impinging Liquid Jet

Unsteady cooling experiments of a hot plate at various \( 1/\text{Fr}_z^2 \) conditions were performed to investigate the characteristics of heat transfer. Figure 9 shows successive stages during the cooling process with \( 1/\text{Fr}_z^2 = 0.186 \). Immediately after the cooling process started, a water vapor film that resembled a small white circle formed near the center of impingement. As the circle disappeared, a circular single-phase forced-convection area developed. During the cooling process, sputtering of small water droplets, caused by boiling, was observed on the circular boundary of the forced convection area. Because the boiling intensity decreases as cooling progresses, the size of the sputtering water droplets increases and the intensity of the sputtering decreases.

The temperature of the plate is plotted in Fig. 10. The

| \( z \) (m) | \( z/d \) | \( \text{Fr}_z \) | \( \text{Fr}_z^2 \) | \( 1/\text{Fr}_z^2 \) |
|---------|---------|---------|---------|---------|
| 0.04    | 6.7     | 4.628   | 21.42   | 0.047   |
| 0.07    | 11.7    | 3.498   | 12.24   | 0.082   |
| 0.16    | 26.7    | 2.315   | 5.36    | 0.186   |
| 0.45    | 75      | 1.378   | 1.9     | 0.52    |

Table 2. \( z \) and normalized \( z \) parameters used in this study.
The temperature history is nearly independent of $1/Fr_z^2$ at the stagnation point $x/d=0$. As $x/d$ increases, the temperature history is similar, provided $1/Fr_z^2$ is between 0.047 and 0.186. However, the cooling progress increases rapidly when $1/Fr_z^2 > 0.52$. Comparing this with the results shown in Fig. 6, the heat transfer rate increases with the velocity of the liquid jet for some $1/Fr_z^2$ regimes.

Figure 11 shows a comparison of the temperature distribution history, as indicated by isothermal lines. The isothermal contours of the inner temperatures extend in the radial direction as the size of the pure forced convection region increases after impingement. The temperatures on the impinged and inner surfaces rapidly decrease when $1/Fr_z^2 > 0.52$, compared with those measured when $1/Fr_z^2 = 0.047$.

The heat flux history obtained from an analysis of the inverse heat conduction is shown in Fig. 12. The heat flux history at region 1, the point of the jet’s impingement, is almost independent of $1/Fr_z^2$. However, the differences between the heat flux histories increase with $x/d$ in regions 2 to 4. This indicates that the amount of initial cooling increases as the pure forced convection region develops. After the heat fluxes reach a maximum, the difference between the heat flux histories decreases. In region 4, in which pure forced convection does not develop until later in the experiment, the difference between the heat fluxes dur-
ing the initial cooling process is small; this value increases after a period of cooling.

To examine the energy extracted from the plate by the cooling process, the energy for each jet condition is calculated for the period extending 27 s from the onset of cooling, which is when the heat flux at region 4 reaches a maximum for $1/Pr^2 = 0.047$. This time period was chosen because the energy difference becomes negligible over an infinite amount of time. The difference in the amount of energy extracted from the plate between the two different flow conditions is nearly 11%.

From the results of this study and the conclusion of Di Marco et al.,\textsuperscript{12) it appears that the $Nu$ is independent of $1/Pr^2$ when $1/Pr^2$ is below 0.25, regardless of whether boiling occurs. When $1/Pr^2 = 0.523$, a 4.8% increase in the $Nu$ is obtained from the relation given by Di Marco et al.;\textsuperscript{12} thus 4.8% more energy is extracted by the impinging jet. In the present study, 11% more energy was extracted under this condition, which seems reasonable, because the experiment was performed in the film boiling regime and the error range in the study by Di Marco et al.\textsuperscript{12) was 10% when $1/Pr^2 > 0.25$.

The results from the measurements and calculations in this study are different from those reported previously when $1/Pr^2 < 1$. This difference is likely due to the instabilities in liquid jets. In the experiments of Stevens and Webb\textsuperscript{10) and Elison and Webb,\textsuperscript{11) the stagnation $Nu$ was independent of $z/d$ because $1/Pr^2 < 0.01$. Therefore, $z/d$ does not indicate the effect of nozzle height on the heat transfer. Rather, heat transfer is enhanced with increasing $1/Pr^2$ over a critical value of $1/Pr^2$; below the critical value, the jet flow remains stable.

5. Conclusion

The effect of nozzle height on the impingement velocity of the liquid jet and the heat transfer from the plate were investigated. The stagnation velocity measurements for the jet indicate that the ratio of $U_{stag}$ to $U_{jet}$ correlates better with $1/Pr^2$ than with $z/d$. Also, the critical instability point of a circular liquid jet was examined for differing flow rates, and a correlation for the point at which instability first occurs was suggested. This correlation indicates that flow instabilities might have been present in some previous studies.

A cooling experiment was performed. The difference in the rate of heat transfer for impinging jets in which $1/Pr^2 < 0.187$ was negligible. However, heat transfer was enhanced by 11% when $1/Pr^2 = 0.523$. This was compared with the results of Di Marco et al.\textsuperscript{12) The deviation of the amount of heat transfer from that reported in previous studies over some flow regions in which $O(1/Pr^2) > 1$ is caused by the onset of instability in the liquid jet. Therefore, $1/Pr^2$ seems to be an appropriate dimensionless parameter to relate the nozzle height with variations in the impingement liquid jet velocities and heat transfer rates.

\section*{Nomenclature}

- $C_p$: Specific heat of test plate for cooling experiment (J/kg °C)
- $d$: Nozzle diameter (m)
- $Fr_z$: Froude number of the jet, $U_{jet}/(g)^{1/2}$
- $g$: Gravitational force (m/s\(^2\))
- $h_o$: Height of the water column (m)
- $Re$: Reynolds number of the jet ($U_{jet}d/\nu$)
- $T$: Temperature of test plate for cooling experiment (°C)
- $U_{stag}$: Impinging velocity of the liquid jet (m/s)
- $U_{jet}$: Average velocity of the liquid jet at the nozzle exit (m/s)
- $We_z$: Weber number of the jet, $\rho_d(U_{jet}^2)/\sigma$
- $x$: Radial distance from the point of impingement (m)
- $z$: Nozzle height from the target cooling plate (m)
- $z/d$: Dimensionless $z$ parameter used in previous studies
- $1/Pr^2$: Dimensionless parameter used in this study, $gz/U_{jet}^2$

\section*{Greek symbols}

- $T$: Thermal conductivity of test plate for cooling experiment (W/m °C)
- $\rho$: Density of test plate for cooling experiment (kg/m\(^3\))
- $\rho_d$: Density of water (kg/m\(^3\))
- $\nu$: Kinematic viscosity (m/s\(^2\))
- $\sigma$: Surface tension (N/m)

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