Mist Cooling for Thermal Tempering of Glass*

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This paper presents a feasibility study of glass tempering using mist cooling. First, transient tests of mist cooling were conducted to investigate the effects of the thermal properties of a cooling surface. To do this, test plates made of silver, nickel, stainless steel (SUS 304), and fused quartz were used. The experimental conditions of mist flow were as follows: the air velocity was $V_a=20 \text{ m/s}$, the temperature of the water droplets was $T_i=21^\circ\text{C}$, and the volumetric droplet flow rate was $D=0.000 \, 3\sim0.01 \text{ m}^3/\text{m}^2 \cdot \text{s}$. The experimental data show that both the plate temperature corresponding to the minimum heat flux ($T_\nu$) and the heat transfer coefficients at wall temperatures above $T_\nu$ increase as the thermal conductance of the surface material decreases. Second, tempering tests of soda-lime glass plates of 2.95 and 3.90 mm thicknesses were conducted using mist cooling. The initial temperature of the glass plates was about 690°C. The plates were cooled only from one side. The test results indicate that thin and low-cost tempered glass plates can be made by mist cooling without fracture.

Key Words: Thermal Engineering, Heat Transfer, Mist Cooling, Thermal Tempering, Tempered Glass, Fracture

1. Introduction

Glass is strong in compression but weak in tension. Thus, the tempering process freezes the stress distribution, thereby raising its usable strength by permanently prestressing the surface in compression. The current method of thermal tempering used in the flat glass industry is by conventional air-jet cooling.

With the increasing popularity of tempered glass, a demand has also arisen for thin and low-cost glass products. To temper a thin glass plate by the current process, it is necessary to increase the air-jet velocity. However, the increase in air velocity produces an undesirable effect on the flatness of the glass plates. As well, the electrical costs for air compression are high. Therefore, novel methods realizing high cooling rates sufficient to temper a thin glass plate at a low cost are needed. The present paper, thus, recommends the use of the mist-cooling tempering technique.

Mist cooling has been currently used in the steel industry. It is known that cooling rates of mist flow atomized by slightly pressurized air are higher than those of air-jet cooling with highly pressurized air.$^{[3]}$ In regard to this new technique, the following problems must be examined. The first is the heat transfer characteristics of mist cooling on glass plates. There are a number of reports on mist-cooling heat transfer for metal objects. However, it is doubtful whether these experimental results can be applied to mist cooling of poor thermal conductors such as glass because boiling heat transfer is sensitive to thermal conductance of the surface material. In particular, it is known that the Leidenfrost temperature is higher for poorer thermal conductors.$^{[9]}$ The second problem is that of the fracture of glass plates during mist cooling. The main temperature region in which the stress distribution in glass plates is generated and frozen is between $500\sim700^\circ\text{C}$. Since this temperature region is located near the Leidenfrost temperature on glass.$^{[8]}$ there is some possibility that direct liquid-solid contacts cause the fracture of glass during the tempering process. In this study, these two problems were examined.

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2. Experimental Apparatus and Procedure

2.1 Heat transfer experiments

In the heat transfer experiments, a full cone pneumatic atomizing nozzle (Fuso-Seiki, Lumina φ1.5) was used to produce the mist flow from a water-air mixture.

A schematic diagram of the experimental apparatus is shown in Fig. 1. Compressed air needed to atomize the liquid jet was supplied from a compressor ① to the nozzle ⑦ through a regulator ②, a flowmeter ③ and an air-temperature controller ④. The test liquid was deionized and sufficiently deaerated water which was stored at a regulated temperature of 20～25°C in a tank ⑤. The test liquid was supplied to the nozzle ⑦ by a centrifugal pump ⑥ through a flowmeter ③ and a heater ④. The mist flow formed by the nozzle impinged on a vertical heat transfer plate ⑩ located at a distance of 200 mm from the nozzle. The temperature of the experimental vessel was regulated by a heater ④ with a blower ⑪.

A detailed drawing of the heat transfer plate is shown in Fig. 2. The test plates were made of silver, nickel, stainless-steel (SUS 304), and fused quartz. Dimensions of the test plates are shown in Table 1. To minimize the effect of surface oxidation, the initial plate temperature was set below 750°C. The plates were ceramic bonded to a pyrophyllite holder. To measure the temperature-time data of test plates during mist cooling, two CA thermocouples 0.1 mm in diameter were attached to the back side of the plates. They were spot-welded directly to the nickel and stainless-steel plates, but were inserted tightly into slits on the back side of the silver and fused quartz plates and ceramic bonded in place. The thermocouple locations are shown in Fig. 2 as points A and B.

The test plate was heated to a fixed initial temperature by an infrared heater ②, and then mist cooling was started after the shutter ⑧ was opened. All metal plates were mirror-finished with grit, and cleaned with acetone before each test.

Surface heat fluxes and temperatures were calculated from the temperature-time data as follows. In the cases of silver and nickel plates, the heat flux $q_w$ and the superheat $\Delta T_{so}$, were calculated by the lumped heat-capacity approximation. The error which resulted from this approximation was estimated to be a few percent because the Biot number of such plates is smaller than 0.05 in the high-temperature region. In the case of stainless-steel and fused quartz plates, the heat transfer characteristics were calculated by the inverse method proposed by Beck. Thermal properties cited in reference were used.

2.2 Glass tempering and fracture tests

The experimental apparatus used in the glass tempering and fracture experiments was the same as that used in the heat transfer experiments, except for the nozzle and plate holder. The atomizing nozzle used in these experiments was equipped with a needle.

<table>
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<th>Table 1 Dimensions of heat transfer plates</th>
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Fig. 1 Schematic diagram of experimental apparatus (Top view)

Fig. 2 Structure of heat transfer plate
valve controlled by compressed air. Using this nozzle, it became possible to switch from mist cooling to air-jet cooling at any time during the cooling process. The test plates used in these experiments were soda-lime glass plates of dimensions \( a = 30 \text{ mm} \), \( b = 32 \text{ mm} \), and \( t = 1.0, 1.5, 2.95, 3.9 \text{ mm} \). A surface stress meter (Toshiba FSM-30) was used for nondestructive measurements of residual compressive stresses at the plate surface \(^{(15)}\). Thermal properties of soda-lime glass cited in reference \(^{(16)}\) were used.

3. Results of Heat Transfer Experiments and Fracture Tests

3.1 Measurements of hydrodynamic aspects of mist flow

Before the heat transfer experiments, the hydrodynamic properties of mist flow were obtained. These properties were measured at a distance of 200 mm from the nozzle.

First, the approaching velocity of impinging air jet \( V_a \) was determined as follows. In the conventional process of glass tempering by air-jets, \( V_a \) is about 100 m/s. However, from the viewpoint of making low-cost tempered glass plates, the approaching velocity should be decreased so as to reduce electric fee. Thus, in the present work, the approaching velocity was chosen as 20 m/s.

Second, the velocity distribution of the approaching air jet without water supply was measured by a Pitot tube. The experimental results showed that the distribution of air velocity in the area of the heat transfer surface was negligible.

Third, the distributions of the volumetric droplet flow rate \( D(r) \) were measured by using 13 collecting-glass-tubes of 3.35 mm inner diameter arrayed in the area of the heat transfer surface. Its half-width decreased upon increasing the water flow rate. In this study, the value of \( D \) at the stagnation point was chosen as the representative one because the experimental results of mist-cooling heat transfer in the high-temperature region were not affected by the size of the plates, as shown in Fig. 4.

Finally, the temperature of the water droplets was measured for supplied water of 30°C. The results showed that the temperature of the water collected by an insulated hole 24 mm in diameter and 23 mm in depth on the area of the heat transfer surface was about 21°C for any value of \( D \).

3.2 Results of heat transfer experiments

The experimentally obtained heat transfer coefficients in the high-temperature region (\( h_f \)) are shown in Fig. 3 for a silver plate (open symbols), along with the existing data (solid symbols) for a silver plate \(^{(10)}\). In this figure, the solid lines are given by \( h_f = \text{const} \cdot \Delta T_{sat}^{-1/3} \) \( (1) \). The present results show that values of \( h_f \) are not very strongly dependent on surface superheat \( \Delta T_{sat} \). This fact is supported also by the data for other surface materials.

As mentioned previously, the main temperature region for glass tempering is between 500~700°C. Thus, in the present work, the heat transfer coefficient at \( \Delta T_{sat} = 500 \text{ K}(h_f[500]) \) was chosen as the characteristic value of \( h_f \) in the high-temperature region. In Fig. 4, the present data of \( h_f[500] \) are plotted against volumetric droplet flow rate \( D \) along with the existing data \(^{(11) - (13)}\). The data shown in the figure indicate that the dimensions of a test plate do not have a strong effect on \( h_f \), and the effect of \( D \) on \( h_f[500] \) is expressed by the following equation:

\[
h_f[500] = \text{const} \cdot D^{0.6}
\]

(2)

This relation is similar to the result obtained by Mitsuzuka \(^{(7)}\).

On the other hand, the data plotted in Fig. 4 indicate that the value of \( h_f[500] \) for a given \( D \) increases with decreasing thermal conductance of surface material. Based on this fact, the following equation was developed to treat the present data of \( h_f[500] \) for \( D = 0.001 \text{ m}^3/\text{m}^2/\text{s} \), and is written here as \( h_f[500, 0.001] \).

\[
h_f[500, 0.001] = 455 + 0.126 \times a_w^{-0.585}, \text{ [W/(m}^2\text{.K}]} \]

(3)

In Eq. (3), \( a_w = (k/\rho C)_w \), where \( k, \rho, \) and \( C \) denote the thermal conductivity, the density, and the specific heat, respectively, and the subscript \( w \) denotes the surface material. Combining Eqs. (2) and (3), the final correlating equations for mist-
cooling heat transfer in the high-temperature region are given as
\[ h_f[500] = 2.87 \times 10^4 (1 + 2.77 \times 10^{-4} \times a_w^{-0.58})D^{0.6} \quad [W/(m^2\cdot K)] \]  
(4)
If the representative property is chosen as the thermal inertia \( \beta \) instead of \( a_w \), the above equation is rewritten as
\[ h_f[500] = 2.87 \times 10^4 (1 + 1.69 \times \beta)D^{0.6} \quad [W/(m^2\cdot K)] \]  
(5)
In Eq. (5), \( \beta = [(\rho C_p)_{l}/(\rho C_p)_{w}]^{1/4} \), where the subscript \( l \) denotes the liquid. In the derivation of Eqs. (4) and (5), it was assumed that the controlling macroscopic factor on mist cooling was \( D \), because experimental data of Ishigai et al. \(^{(3)} \) indicated that the effect of \( V_a \) on mist-cooling heat transfer is not strong for values of \( V_a \) below 20 m/s. The comparison between the predictions from Eq. (4) and the experimental data is shown in Fig. 5. From this figure, it is found that the uncertainty of Eq. (4) is within \( \pm \) 30\%. Similar results were also obtained by using Eq. (5).

The experimental results of the plate temperature corresponding to minimum heat flux \( T_m \) are plotted against the volumetric droplet flow rate \( D \) in Fig. 6. The solid lines denote the existing data\(^{(2,3)} \). The present data for stainless-steel plates are similar to those of Ishigai et al. \(^{(3)} \). The present data show that the minimum temperature remains constant for \( D<0.001 \text{ m}^3/(\text{m}^2\cdot \text{s}) \) but that it increases with increasing \( D \) for \( D>0.001 \text{ m}^3/(\text{m}^2\cdot \text{s}) \). Further, they show that the minimum temperature for a given \( D \) is higher with decreasing thermal diffusivity of the surface material. This tendency is similar to the experimental results of the Leidenfrost temperatures\(^{(9)-(10)} \).

### 3.3 Tests for fracture conditions

To investigate the fracture conditions of glass plates, the temperature-time data during mist cooling were measured using soda-lime glass plates. In this experiment, visual observation of the fracture process was enabled by using a video camera. From this observation, it was found that fracture occurred at the initiation of growth of the liquid film formed on the plate. Further, the temperature-time data on the back side of the soda-lime glass plate indicated that

![Fig. 5](image-url)  
**Fig. 5** Comparison between present correlation of heat transfer coefficient and experimental data

![Fig. 6](image-url)  
**Fig. 6** Dependence of minimum temperature of high-temperature region on volumetric droplet flow rate

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the temperatures at the moment of fracture were below about 500°C, except for the condition of \( t = 3.90 \) mm and \( D > 0.0013 \, \text{m}^3/(\text{m}^2 \cdot \text{s}) \). These results indicate that the tempering was finished before fracture occurred.

Therefore, in the present tempering tests of soda-lime glass plates, the cooldown process was divided into the following two stages. Namely, the stage of cooling from 690 to 500°C by mist cooling, and consequent slow cooling to room temperature by an air jet. As stated before, the tempering of the glass plates was expected to have finished during the first stage.

Heat transfer coefficients at \( \Delta T_{\text{fin}} = 500 \, \text{K} \) for soda-lime glass plates were roughly estimated from the obtained temperature-time data. The results were correlated by the following equation:

\[ h_{(500)} = 4.86 \times 10^4 D^{0.6} \quad [\text{W/(m}^2 \cdot \text{K})] \quad (6) \]

This equation is roughly equivalent to Eq. (5) for soda-lime glass.

### 3.4 Results of tempering tests

Finally, tempering tests of soda-lime glass plates were conducted. In this experiment, the plates were cooled only on one side, owing to experimental limitations which necessitate studying the estimation procedure of the degree of temper in asymmetric cooling.

Before tempering tests of soda-lime glass plates, the correlation between the residual stress and the Biot number is discussed. To analyze the residual stress distribution in tempered glass plates, several methods including Baricenev’s “instant freezing theory” have been proposed for symmetric cooling. For practical use, however, simple correlations to estimate the residual stress are necessary. Thus, at first, simple correlations for the residual stress in tempered glass plates were developed.

Bartenev(17) showed experimentally that the degree of temper depends strongly on both the initial temperature and the thickness of the glass \((T_i \text{ and } t)\). Gardon(24) reported that the degree of temper depends strongly on heat transfer coefficients during the tempering process. From these results, it is considered that the residual stress must be expressed by the following equation:

\[ \sigma = \text{func.} [T_i, B_i] \quad (7) \]

In Eq. (7), it is assumed that the Biot number defined as \( h \cdot t / 2k \) and \( k = 1.65 \, [\text{W/(m} \cdot \text{K})] \) denote the heat transfer coefficient and the thermal conductivity, respectively.

Using Eq. (7) and the logistic curve, the following equation based on Gardon’s data(24) was obtained for the residual midplane tensile stress \( \sigma_t \).

\[ \sigma_t = B \cdot \frac{S_{\text{max}} \cdot e^{n \tau_i}}{S_{\text{max}} + S_{\text{min}} (e^{n \tau_i} - 1)} \quad [\text{MPa}] \quad (8) \]

where

\[ B = 0.38(24) \times 0.998 \quad [\text{MPa/(nm/cm)}] \]

\[ S_{\text{min}} = 10^{-7} \quad [\text{nm/cm}] \]

\[ S_{\text{max}} = 226 \, 7B^{0.367} \quad [\text{nm/cm}] \]

\[ m = 0.0410 \, B^{0.024} \quad (0 < B_i < 0.61) \]

\[ m = 0.0405 \quad (0.61 \leq B_i) \]

As for the surface stress \( \sigma_s \), the following empirical equation (where \( R = \sigma_s / \sigma_t \)) was similarly obtained using Gardon’s data(24).

\[ \sigma_s = R \sigma_t = \left\{ \frac{R_{\text{max}} - R_{\text{min}} \cdot e^{n \tau_i}}{R_{\text{max}} + R_{\text{min}} (e^{n \tau_i} - 1)} + A \right\} \times \left\{ 0.0372 \frac{S_{\text{max}} - S_{\text{min}} \cdot e^{n \tau_i}}{S_{\text{max}} + S_{\text{min}} (e^{n \tau_i} - 1)} \right\} \quad [\text{MPa}] \quad (9) \]

where

\[ A = 1.59B^{0.009} \]

\[ n = 0.064 \, B_i - 0.0145 \]

\[ R_{\text{min}} = 10^{-18} \]

\[ R_{\text{max}} = 2.58B_i^{0.009} \quad - A \]

A comparison between the predictions (\( \sigma_s \)) from Eqs. (8) and (9), and experimental data (\( \sigma_s^{(24/26/29/27)} \)) for symmetric cooling by air jets are shown in Fig. 7. Equations (8) and (9) are in good agreement with all data except for those of Katayama et al.(16).

Next, it was examined whether Eqs. (8) and (9) could be applied to asymmetric cooling. In this case, the following two problems were examined. The first is the symmetry of stress distribution which was assumed in the derivation of Eqs. (8) and (9). The second is the definition of the Biot number. The analytical study by Woo(29) and the experimental study by Shabanov et al.(27) show that the frozen stress distribution is nearly symmetric, even in asymmetric cooling. Further, the stress distribution measured in this experiment showed that the residual compressive stresses on both surfaces are nearly equal, even for glass plates cooled on one side by mist cooling. From these results, it seems that Eqs. (8)
Fig. 8 Dependence of residual compressive stresses on mean Biot number

and (9) are applicable to asymmetric cooling as well. In Fig. 8, the predictions (solid lines) of Eq. (9) are compared with the experimental data for asymmetric mist cooling and the existing data for air-jet cooling\(^{27}\), where \(h_1/h_2\) is the ratio of the heat transfer coefficients on both sides for asymmetric cooling. In this plot, the Biot number based on the mean heat transfer coefficient of both surfaces for asymmetric cooling, and that based on the temperature difference between the plate and water for mist cooling have been used. While the data of Shabanov et al.\(^{27}\) for symmetric cooling (\(\square\)) and weakly asymmetric cooling (\(\blacktriangle\)) are located near the predicted curves, their data for asymmetric cooling fall well below the predicted curve for higher degrees of asymmetry (\(\blacktriangle\rightarrow \nabla \rightarrow \Box\)). That is, the values of residual surface compressive stress for highly asymmetric cooling are lower than the predictions obtained by Eq. (9). This tendency can be understood as a result of the deformation of glass plates due to asymmetric cooling.

As stated above, the residual stress cannot be estimated correctly by Eq. (9) for asymmetric cooling, but in the following discussion, we estimate the degree of temper in asymmetric cooling. From Ref. (25), for a glass plate to be fully tempered, a residual compressive stress higher than 98 MPa (1,000 kg/cm\(^2\)) is needed. Using this limiting value together with Eq. (9), it is found that the limiting value is 63.7 MPa (645 kg/cm\(^2\)) for asymmetric cooling from \(T_i=690^\circ C\), where \(T_i\) is the initial temperature of the glass plates. If the experimental data of residual compressive stress for asymmetric cooling are higher than this limiting value, the glass plates can be regarded as being fully tempered because the deformation of the glass plates results in a smaller value of stress.

The limiting values for symmetric and asymmetric cooling mentioned above are shown in Fig. 8 by horizontal chain-dot and chain-double-dot lines, respectively. From this figure, it is found that the present values are larger than the limiting value for asymmetric cooling.

Now, let us consider the tempering process by symmetric mist cooling. As mentioned before, the present correlation of \(\sigma_i\) is in good agreement with the data for symmetric air-jet cooling.

Since the Biot number is 0.455 for the glass plate of \(t=1.5\) mm tempered by symmetric mist cooling of \(D=0.00121\ m^3/(m^2\cdot s)\), Eq. (9) predicts the residual compressive stresses frozen at the glass surface as 129 MPa (the dotted line in Fig. 8). This dotted line is higher than the limiting value of symmetric cooling (98 MPa) for glass tempering; thus, it can be concluded that thin and low-cost tempered glass plates can be made by mist cooling without fracture.

4. Conclusions

(1) Correlating equations (4) and (5) were developed for the mist-cooling heat transfer in the high-temperature region by taking into account the volumetric droplet flow rate and thermal conductance of the cooling surface.

(2) Correlating equations (8) and (9) were developed for the residual stresses in a tempered glass plate.

(3) A new technique for the thermal tempering of glass using mist cooling was proposed. It was found that thin and low-cost tempered glass plates can be made without fracture by this method.

References


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