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EXPERIMENTAL INVESTIGATION OF TRANSIENT TEMPERATURE DISTRIBUTION AND HEAT TRANSFER BY JET IMPINGEMENT IN GLASS TEMPERING PROCESSING*

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Abstract– Heating and sudden cooling are among the most important processes affecting temper quality in the production period of tempered auto glass. In this study, heat transfer characteristics and cooling times during the sudden cooling process of tempered glass production have been experimentally investigated. Flat glass with dimensions of 50x50x4 mm has been heated up to 680 ºC in the furnace and was then exposed to sudden cooling process until its surface temperature dropped to 70 ºC. In the cooling process two mutually placed 8 cm long air jet nozzles with an internal diameter of 8 mm have been used. Experiments have been conducted for Reynolds numbers in the range of ($20000 \leq Re \leq 40000$) and for dimensionless jet to plate distances in the range of ($1 \leq H/D \leq 10$). Based on the above parameters cooling periods, local (Nu_x), average (Nu_{aver}) and stagnation point (Nu_{stag}) Nusselt numbers have been experimentally determined.

Keywords– Auto glass tempering, heat transfer, impinging air jet, Nusselt number

1. INTRODUCTION

Tempered glass has crucial importance in the automotive industry. Their production process mainly consists of a heating process near to glass melting temperature (approximately 700 ºC) which is followed by a sudden cooling process that increases mechanical strength of glass four or five times. At the beginning of the cooling process, glass surface cools much more rapidly than the inside which causes high temperature difference between the surface and interior of the glass. As a result, compression stresses on the surface and tensile stresses in the interior surfaces become effective [1-3].

Temper quality highly depends on heating and sudden cooling periods. Among the parameters which determine the length of heating time are chemical composition of the glass, mass, desired surface temperature and capacity of the furnace. On the other hand, cooling period depends more likely on the parameters like H/D, S/D, Reynolds number, nozzle arrangement type (in-line or staggered), initial and desired final temperatures of the glass, etc.

In the present study, impinging air jets are used for the cooling process of glass tempering. Impinging jets are widely used for localized heating and cooling processes in the industry and they were also the subject of many previous scientific studies. Some of the related literature on the impinging jets is summarized below.

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Monneyer and Lochegnies (2008) experimentally and numerically investigated glass tempering process with impinging air jets. In an industrial facility, in order to determine convective heat transfer characteristics they modeled tempering of a glass sample with the dimensions 300x300x6 mm. For four different Reynolds number (11000, 22000, 33000, 44000), they observed the common power law relationship between Nusselt and Reynolds numbers [3]. In their studies with impinging jets, Jambunathan et al (1992), Martin (1997) and Garimella. (2000) determined local, average and stagnation point Nusselt numbers as a function of Reynolds number, Pr number, and dimensionless jet to plate distance (H/D) [4-6].

Katti et al. (2011) experimentally investigated the effect of dimensionless jet to plate distance (H/D) and Reynolds number on local Nusselt number distributions on a flat plate. Reynolds numbers were in the range of 500-8000 and H/D ratios were between 0.5 and 8. For high Reynolds numbers, maximum stagnation point Nusselt numbers were obtained at a value of H/D=6 [7]. Bilen conducted a parametric study on heat transfer characteristics on a heated plate by perpendicularly and obliquely impinging jets. Among the parameters investigated are Reynolds number (10000≤Re≤40000), dimensionless jet to plate spacing (6≤H/D≤14), and oblique angle (45≤Ø≤90). It is determined that stagnation point Nusselt number decreases with decreasing oblique angle where 90 represents the perpendicular jet [8].

Local heat transfer characteristics on a flat plate by single impinging air jets approaching at a Mach number of M=0.2, 0.4, 0.6, 0.8, 1 have been investigated by Limaye et al. Dimensionless jet to plate distance (H/D) values was between 1 and 12. For Mach≤0.4, maximum stagnation point Nusselt number obtained at H/D=6. On the other hand, for Mach≥0.6 it was obtained at H/D=8 [9]. Yazıcı et al. (2011a), Yazıcı et al. (2011b) and Akcay et al. (2011) constructed a prototype automobile glass tempering unit in their laboratory and used mutually placed impinging jets for the cooling process. In their research Reynolds number was kept constant at 30000 and the effect of H/D values on cooling times, local and average Nusselt numbers were investigated [10-12].

The effect of velocity components on heat transfer and fluid flow has been investigated by O’Donovan and Murray [13, 14]. They determined the second maximum in the wall jet region and showed that it is closely related to turbulence intensity. In addition, they concluded that magnitude of the vortex in the wall jet region is also effective on the heat transfer [13-14]. In an experimental study by Sözbir and Yao (2004), the effect of water mist on the energy consumption of cooling process in the glass tempering procedure has been investigated. They determined that addition of water mist to the impinging air stream greatly reduced energy consumption in the process [15]. Cirillo and Isopi (2009) conducted a research to evaluate process parameter values and jet dimensions in glass tempering process. They developed a mathematical model for average heat transfer coefficient calculation based on design of experiments matrix of CFD simulations. In their simulation plate temperature has been set to 640 ºC [16].

In Golcu et al. (2012), heat transfer characteristics of heated glass plates during their cooling with mutually placed circular air jets have been experimentally investigated. According to the results the highest average Nusselt number has been achieved for S/D=2 and H/D=4 with a value 123.3 and the lowest average Nusselt number was obtained for S/D=10 and H/D=10 with a value 58.6 [17]. In an experimental study by Akcay et al. (2014), variation of cooling time and particle number have been investigated according to different heating and cooling temperatures. According to the study, while higher heating temperature of the glass resulted in higher cooling time and particle number, higher cooling temperature resulted in lower cooling time and particle number [18].

Yazici (2013) conducted a study on identifying the configuration of the optimum rapid cooling unit for different Reynolds numbers using square and triangle arrayed multiple nozzles for 4 mm thick flat glass in auto glass tempering. The study was conducted using the values of Re=15000-40000, and the rates of S/D=2, 4, 6, 8 and H/D=2, 4, 6, 8, 10. The particle numbers and impact strength energies of the tempered glass were identified. It was found that the optimum tempering conditions were obtained in triangle arrayed nozzle system and the rapid cooling process conducted [19].

Glass tempering is one of the many application areas of impinging jets. Due to the difficulties arising from dealing with high temperature glass and transient nature of tempering process only very limited amount of experimental work has been cited on the subject. Current study on a prototype tempering facility under real operating conditions with two mutually placed impinging jets for tempering small scale glasses aims to fill some of this gap.

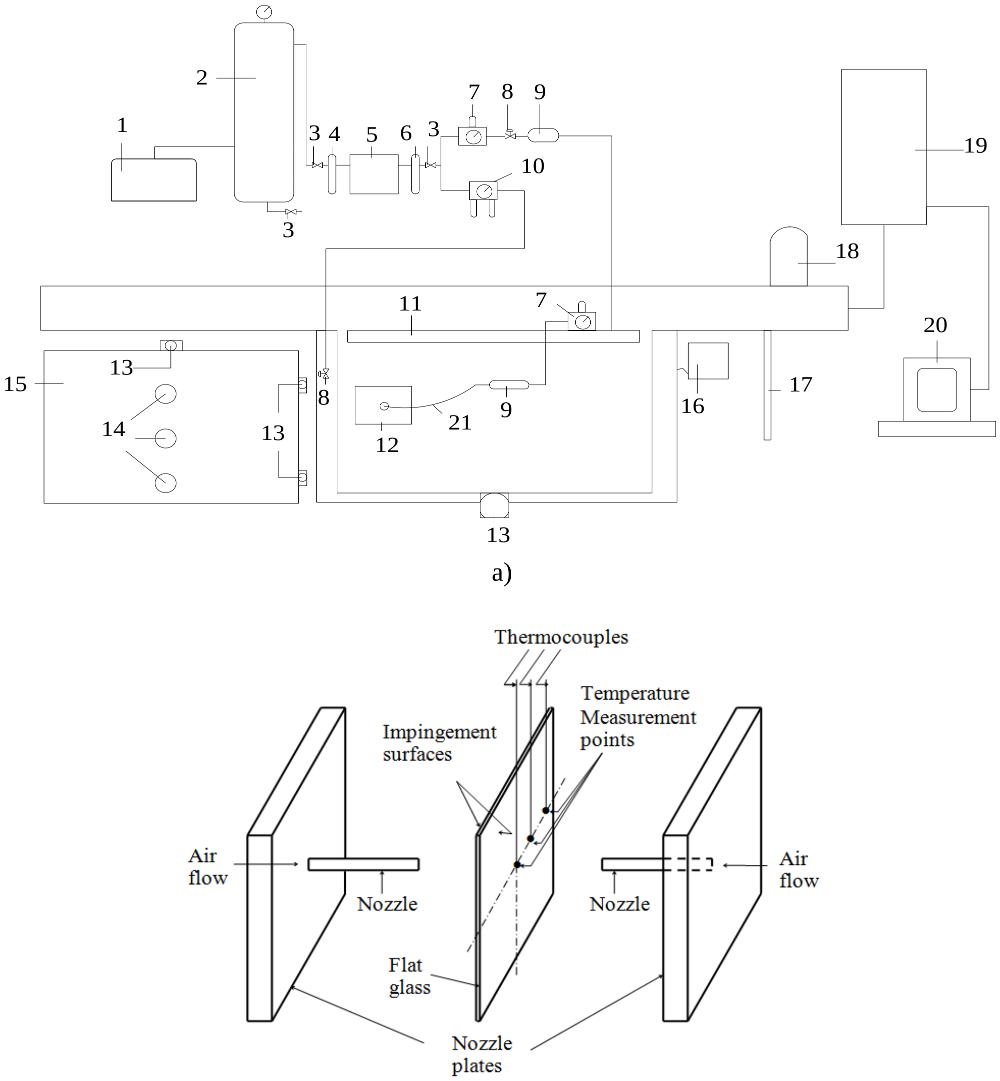
Heat transfer during the cooling process of glass tempering is highly time dependent. Due to mentioned time dependency and high temperatures on the glass, the process needs to be examined very carefully. In this experimental study, mutually placed two impinging air jet nozzles with an internal diameter of 8 mm have been used for the cooling process. Glass samples used in the experiments have dimensions of 50x50x4 mm. Local, average, stagnation point Nusselt numbers and cooling times have been determined for Reynolds numbers between 20000 and 400000 and for H/D values in the range of $1 \leq H/D \leq 10$.

2. GLASS TEMPERING UNIT

Two main processes in automotive glass tempering are heating and sudden cooling processes. For the heating process of the glass near its melting temperature, a furnace with a 10 kW power and 0.38 m^3 internal volume has been designed and manufactured. For the automatic input and the output of the glass, furnace walls were equipped with pneumatic pistons which allow automatic opening and closing of the furnace. Furnace walls were insulated with 17 cm thick ceramic boards which can endure 1100 ºC temperature. 11 cm thick fire stones have been used on the bottom surface of the furnace. To measure the temperature, inside of the furnace is equipped with 3 high temperature NiCr-Ni thermocouples.

In the experimental facility, high velocity impinging air jets are used to cool the glass samples which were initially heated up to their melting temperatures. Desired amount of air is supplied with an air compressor connected to an air tank with auxiliary components like air dryer, inlet, outlet filters, regulator and solenoid valves. Power input of the screw compressor was 30 kW and it supplies 5.1 m^3/min of air at a working pressure of 7 bars. Air tank has been used to damp the pressure fluctuations from the compressor. Detailed schematic view of the experimental set up is given in Fig. 1. Air volumetric flow rates in the main line and in a single nozzle on the cooling unit are measured with DN40 Testo 6443 and DN15 Testo 6441 respectively. Transient temperatures on the glass surfaces are measured with fiber glass coated K type flexible thermocouples of 0.81 mm thick. Thermocouples are fixed to the glass surface by using heat conductive high temperature cement (Omega® CC High Temperature Cement).

Automobile glass tempering unit consists of many independently operating parts. Their control is important to correctly determine the effect of parameters on the temper quality of the glass. To serve this purpose, an automation system has been built to control opening and closing times of the furnace, furnace internal temperature, pneumatic pistons, and transient glass surface temperatures, cooling period, air flow rate and temperatures. PLC has been used for the automation of the system. In addition, all experimental data during the tempering process has been collected and sent to computer simultaneously by using SCADA program.



b)

1) Compressor, 2) Air tank, 3) Ball valve, 4) Entrance filter, 5) Dryer, 6) Exit filter, 7) Regulator, 8) Solenoid valve, 9) Flow meter, 10) Conditioner, 11) Pressurized air chamber, 12) Nozzle plate, 13) Pneumatic piston, 14) NiCr-Ni thermocouples, 15) Furnace, 16) Control panel, 17) Glass carrier, 18) Servo motor, 19) PLC and automation panel, 20) Computer, 21) Air hose

Fig. 1. a) Schematic view of tempering unit and b) Schematic view of cooling unit

a) Experimental uncertainty

An uncertainty analysis was conducted on measured and calculated quantities to determine the reliability of experimental results. The sensitivity of NiCr-Ni K type thermocouples (NEL Electronics) used for measuring furnace temperatures were ±2.5 ^{o}C for the measurement range 40-333 ^{o}C and ±0.75% for the measurement range 333-1100 ^{o}C. K type flexible thermocouples (Cole Parmer KH-08541-23, 20 gauge) which are used for glass surface temperature measurements are accurate, ±2.2 ^{o}C in the range between (-200) – (+285) ^{o}C and ±0.75% in the range 285–1250 ^{o}C. Flow meter (Testo 6441 DIN 15) is accurate ±3% and pitot tube (Delta OHM HD2134P.1) is accurate ±2% in the measurement range. Uncertainty in length measurement was ±0.2 mm. Uncertainty analysis has been made according to the principles mentioned in Koseoglu [20] and Holman [21]. Results of the uncertainty analysis are given in Table 1.

Table 1. Results of the uncertainty analysis

Variable	**Uncertainty (%)**
Area	0.21
Temperature Difference	2.66
Mass	0.21
Reynolds number	2.36
Nusselt number	3.07

3. HEAT TRANSFER ON THE GLASS SURFACE

Local temperature measurement locations and surface areas which are used in the calculation of local Nusselt numbers are shown in Fig. 2. Three thermocouples have been mounted on the glass surface with equal distances of 8 mm from the geometrical center of the glass and readings from these thermocouples were used in the calculation of local Nusselt numbers. In Fig. 2, x/D=0, 1 and 2 represents measurement points and $T_{s,0}$, $T_{s,1}$ and $T_{s,2}$ represents corresponding temperature values at these locations.

In the present study heat transfer calculations have been made for 30 different cases depending on Reynolds number and H/D values. For all the experiments furnace temperature has been set to 750 °C. Sample glass is heated in the furnace until its surface temperature reaches to 680 °C and then it is cooled with impinging jets in the cooling unit until its surface temperature drops to 70 °C. During the cooling stage of glass tempering process, glass surface temperature (T_s) is a transient variable. In addition, heat transfer is also time dependent. So there is no constant surface temperature and there is no constant heat flux boundary condition. As a result, it is difficult to determine Nusselt number variations which highly deviate from empirical correlations obtained under certain conditions in the literature [22-24].

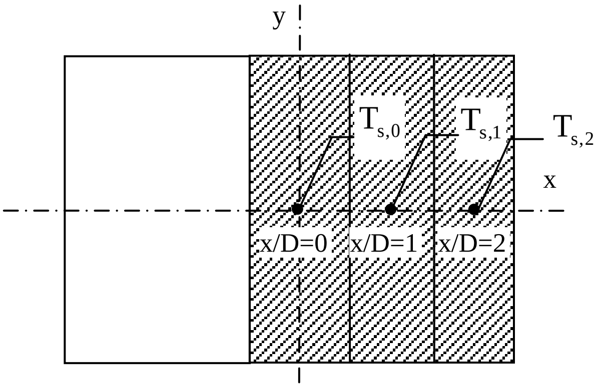


Fig. 2. Temperature measurement locations for local Nusselt number calculations

In this experimental study, glass surface temperatures were recorded for every 0.5 seconds during the cooling period and time averaged Nusselt numbers have been calculated with the following procedure:

Depending on the air flow rate average jet velocity is calculated from equation 1 as follows.

$$\overline{U}_j = \frac{Q}{A} \tag{1}$$

Reynolds number is obtained by using kinematic viscosity at 25 ºC and nozzle diameter 8 mm:

$$\mathrm{Re} = \frac{\overline{U}_j D}{\nu} \tag{2}$$

In the impinging jet studies target surface temperatures are generally measured with thermal cameras, thermocouples [9, 23] or thermo chromic liquid crystals. For the current study, due to physical structure of the system and high temperatures, flexible thermocouples are used for temperature measurement. Temperature measure points were drilled 0.5, 1, 1.5 and 2 mm depths of the glass plate and the temperature measurement was then taken. However, at each depth, all glass plates used in the experiment fractured or exploded in furnace (especially for temperatures up 500 ºC). During glass heating in the furnace, it was thought that micro-cracks caused fracture or explode on surfaces in the drill hole. It was not possible to measure temperature at the glass plate surface with an instrument other than thermocouple in the furnace up to the value of 750 ºC. Therefore, temperature changes were not measured at different depths and could only be measured at the glass plate surface. So, heat transfer coefficient was calculated using Eq. (3).

$$m_x C_x \left(dT_{s_x}/dt\right) = h_x 2A_x \left(T_{s_x} - T_j\right) + \varepsilon\sigma 2A_x \left(T_{s_x}^4 - T_a^4\right) \tag{3}$$

where m_x and A_x represent local mass and surface areas of the sample glass. Air jets are mutually placed on both sides of the glass for cooling so surface areas are multiplied by two. T_j is the nozzle exit temperature of the air jet, kept at 25 °C. Emissivity (ε) of the glass was measured to be 0.9, σ is Stephan–Boltzman constant, T_{s_x} is local surface temperature and T_a is the ambient temperature, kept at 30 °C. C_x is the temperature dependent specific heat of the glass.

Specific heat of the glass is highly temperature dependent and is calculated for every temperature recorded at 0.5 second intervals. Mass is also calculated accordingly;

$$m_x = \rho V_x \tag{4}$$

According to Leidenfrost temperature (T_g=824.4 K) specific heat values can be obtained from,

$$T_{s_x} < T_g \Rightarrow C_{p_x} = 893 + 0.4T_{s_x} - \frac{1.8x10^7}{T_{s_x}^2} \tag{5}$$

$$T_{s_x} > T_g \Rightarrow C_{p_x} = 1443 + 6.5x10^{-3} T_{s_x} \tag{6}$$

Local heat transfer coefficients obtained from equation (3) are used to calculate time averaged local Nusselt numbers for every x position in Fig. 2 as follows:

$$Nu_x = \frac{h_x D}{k} \tag{7}$$

where D is nozzle diameter and k is the thermal conductivity of air. Average Nusselt number is calculated from arithmetic average of time averaged local Nusselt numbers.

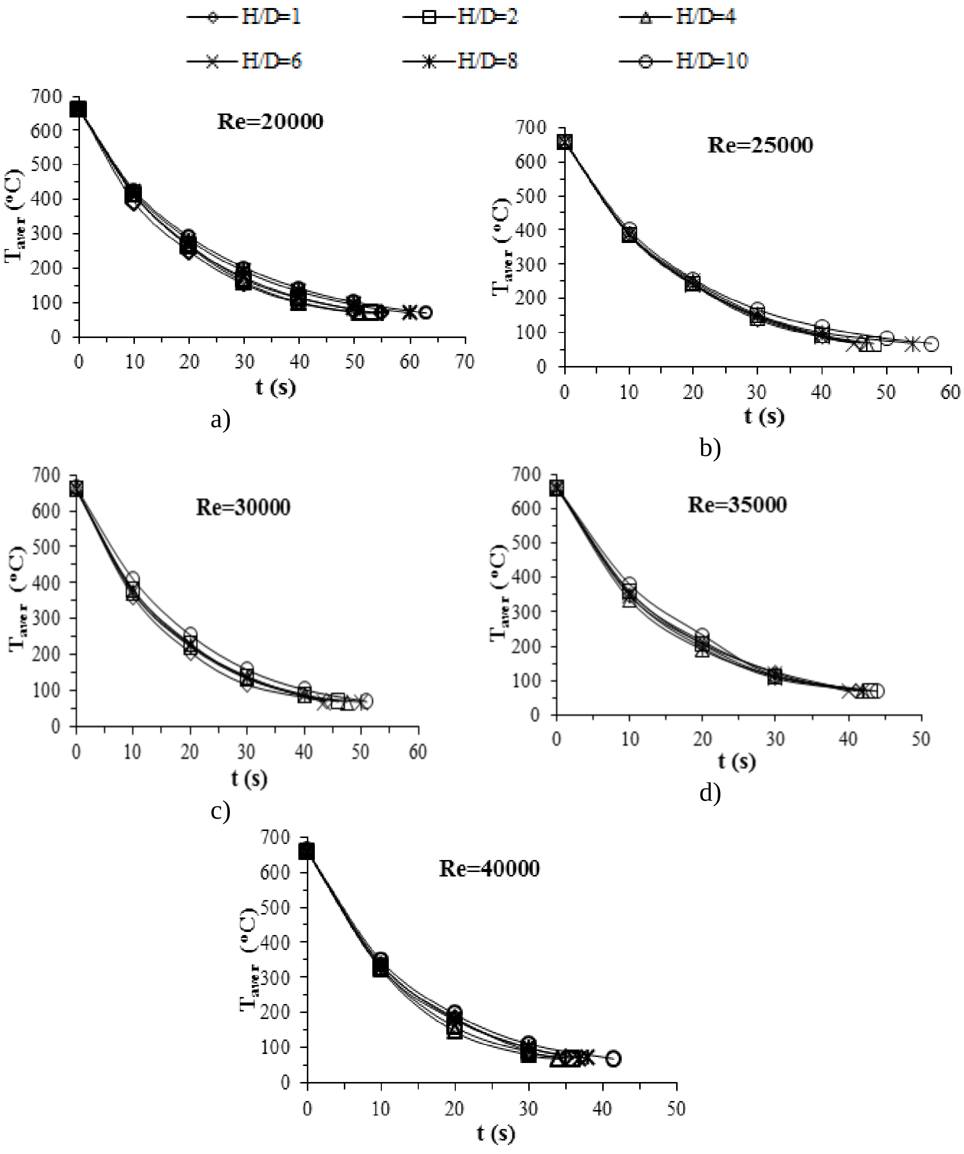
4. RESULT AND DISCUSSION

Cooling times, local and average heat transfer results of the present study conducted with two mutually impinging jets are summarized below.

a) Cooling times

Sample glass has been sent to the furnace at 750 °C and it has been heated up to 680 °C. Glass leaving the furnace at the mentioned temperature is exposed to sudden cooling process by impinging air jets until its surface temperature reaches 70 °C. Cooling process has been repeated for different H/D (H/D=1, 2, 4, 6, 8, 10) and Reynolds numbers (Re=20000, 25000, 30000, 35000, 40000). Transient surface temperature changes and cooling times for every case have been recorded.

Figure 3 shows the effect of H/D values on cooling times and transient surface temperature for different Reynolds numbers. As expected with increasing Reynolds number cooling process ends in shorter times. For every Reynolds number tested, maximum and minimum cooling times and corresponding H/D values are presented in Table 2. Among the cases investigated the shortest cooling time is obtained at Re=40000 for H/D=6 with a value of 34.5 s and the longest cooling time was 63 s at Re=20000 and H/D=10.



a)

b)

c)

d)

e)

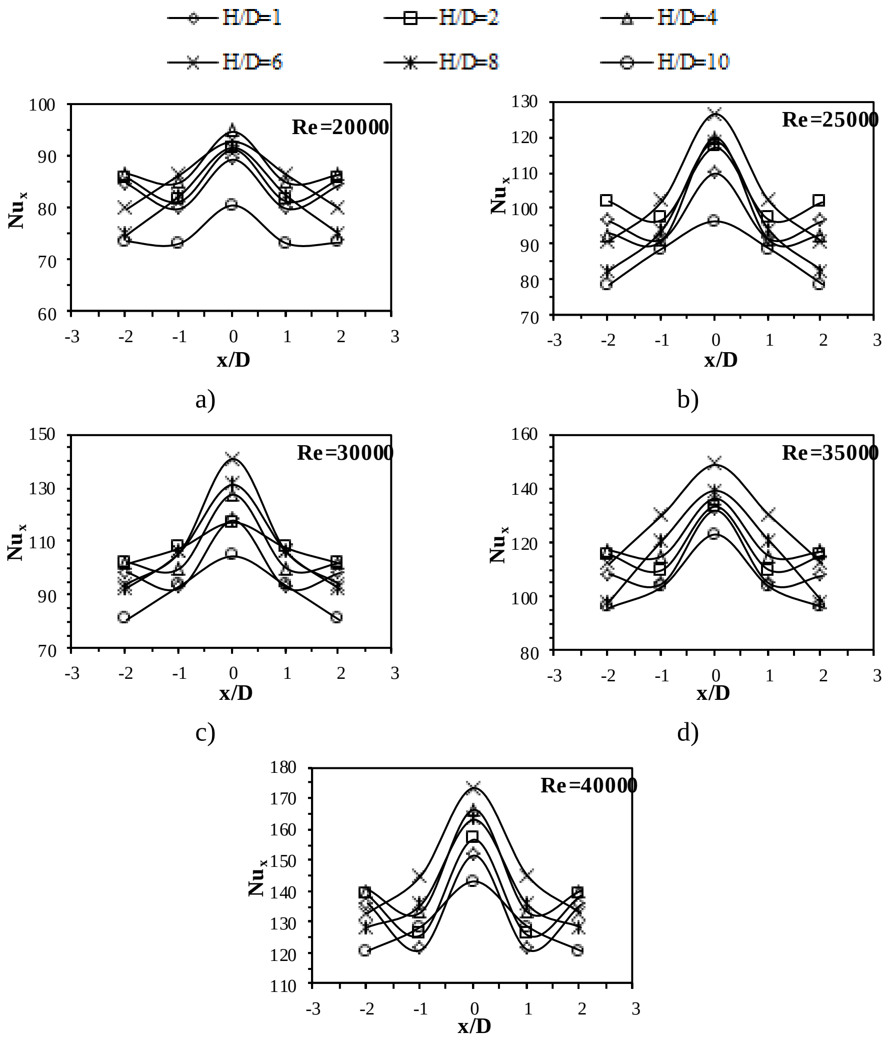
Fig. 3. Temperature variation as a function of cooling times for different H/D and Reynolds numbers

Table 2. Maximum and minimum cooling times and corresponding H/D values

Re	H/D	Min. cooling times, (s)	H/D	Max. cooling times, (s)
20000	4	51	10	63
25000	6	45	10	57
30000	6	43.5	10	51
35000	6	40	10	44
40000	6	34.5	10	41.5

b) Heat transfer results

By using the above mentioned data reduction methodology time averaged local, average and stagnation point Nusselt numbers have been calculated for the cases considered.



a) b)

c) d)

e)

Fig. 4. The effect of H/D ration on the local Nusselt number distribution

i. Local Nusselt number

Local Nusselt number variations for every Reynolds number at different H/D values are presented in Fig. 4. From the figure it can be concluded that local Nusselt number is directly proportional to Reynolds number and also for all the cases considered, maximum Nusselt number has been obtained at the stagnation point.

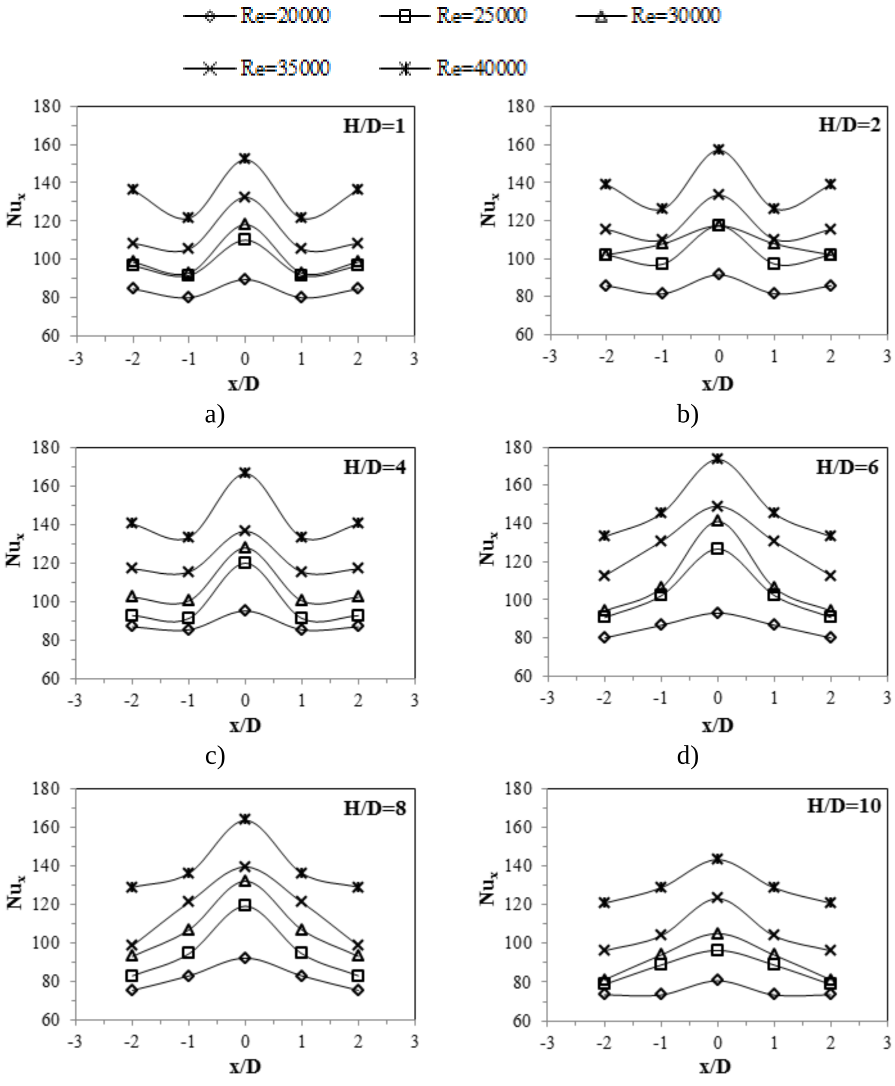
The highest stagnation point Nusselt number for the case of Re=20000 was obtained at H/D=4 with a value of $Nu_{stag}=95.0$ but for all other Reynolds numbers (Re=25000, 30000, 35000 and 40000), it was obtained at H/D=6 with corresponding values $Nu_{stag}=126.7$, 141.1, 149.1 and 172.6. For every Reynolds number considered the minimum local Nusselt number has been obtained at H/D=10 and x/D=2.

Local Nusselt number variations with x/D for different Reynolds numbers are shown in Fig. 5. For every H/D ratio the highest value of local Nusselt number has been obtained at x/D=0. Similar results have been obtained in the literature with impinging jets, in which the highest Nusselt number is at the stagnation point [13, 25, 26]. At relatively small values of H/D<6 (Figs. 5a, 5b and 5c) the minimum value of local Nusselt number has been obtained at x/D=1 and then an increase has been observed. This situation has been explained with radial flow acceleration in that region [14].

For H/D≥6 ratios the second maximum is not observed and local Nusselt number continuously decreases with increasing radial distance from the stagnation point (Figs. 5d, 5e and 5f). Limaye et al.

(2010) and Zhou and Lee (2007) observed similar heat transfer characteristics in their studies with impinging jets [9, 22].

The values of the second maximum Nusselt number are close to stagnation point values at smaller H/D and high Reynolds numbers. For instance at Re=40000 and H/D=1, second maximum value is 89.5% of stagnation point value.



a) b)

c) d)

e) f)

Fig. 5. The effect of Reynolds number on local Nusselt number distribution

ii. Stagnation point Nusselt number

Stagnation point Nusselt numbers as a function of H/D for different Reynolds numbers are presented in Fig. 6. As expected, the value of stagnation point Nusselt number is a strong function of Reynolds number.

The highest value of stagnation point Nusselt number was obtained at the H/D=4 and Re =20000. For all other Reynolds numbers it was obtained at H/D=6. Similar results have been observed by Limaye et al. and Katti and Prabhu [9, 23]. Potential core length of the impinging jets was the subject of many studies, obtained maximum values at H/D=4 and 6 support the findings that maximum heat transfer is obtained at H/D values near potential core length which is also a function of Reynolds number [13,14].

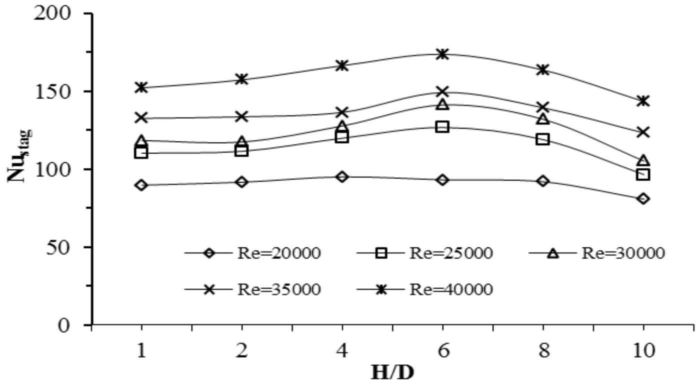


Fig. 6. The effect of H/D on stagnation point Nusselt numbers at different Reynolds numbers

iii. Average Nusselt number

Average Nusselt numbers during the cooling period have been obtained by calculating the arithmetic mean of time averaged local Nusselt numbers which were obtained by using temperature measurements on the glass surface with the previously mentioned procedure. Variation of average Nusselt number with H/D for different Reynolds numbers is given in Fig. 7.

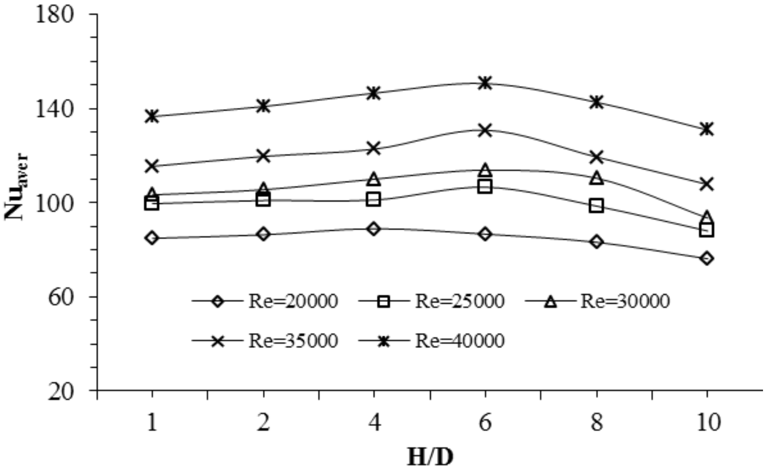


Fig. 7. Variation of average Nusselt number as a function of H/D for different Reynolds numbers

For all the Reynolds numbers under investigation, the lowest average Nusselt number was obtained at H/D=10. On the other hand, the highest value of average Nusselt number was at H/D=6 for all Reynolds numbers except Re=20000 at which it was obtained for H/D=4. Numerical values of the highest Nusselt numbers for Re=20000, 25000, 30000, 35000 and 40000 are Nu_{aver}=89, 106.6, 113.9, 130.8 and 150.6. Similarly, corresponding minimum average Nusselt numbers are Nu_{aver}=76.2, 88, 93.4, 107.7 and 130.8 in the same order. It was observed that the average Nusselt number increases with the Reynolds number.

Cooling time is a stronger function of Reynolds number compared to H/D and it is inversely proportional with Reynolds number as expected. For H/D<4, stagnation point Nusselt number is almost independent of H/D ratio. This behavior was also observed by Limaya et al. (2010) and explained with almost constant stagnation region velocity gradient at H/D values smaller than 4 [9].

5. CONCLUSION

Extensive prior research has been conducted on flow and heat transfer characteristics of impinging jets. Most of these studies examined impinging jet characteristics under constant surface heat flux or constant surface temperature conditions. Dealing with high temperature variations, continuously changing surface temperature and heat flux are important points in the present study.

In addition to the transient characteristics mentioned above, many other parameters including cooling time period, geometry and configuration of the nozzles, distance between the target plate and the jet, Reynolds number determine the temper quality of automobile glasses cooled with impinging jets. In the present study, for the tempering process two mutually placed 8 mm nozzles have been used.

The effect of Reynolds number and H/D ratio on transient temperature and heat transfer characteristics on the glass has been determined. Results of the study can be summarized as stated below:

- For constant H/D, glass sample can be cooled to desired temperature in a shorter time with increasing Reynolds number. Among all the cases investigated, the shortest cooling time was obtained at Re=40000 and H/D=6 with 34.5 s. On the other hand, 63 s was the longest cooling time period which was obtained at Re=20000 and H/D=10.
- Maximum local Nusselt number has been obtained at the stagnation point for all Reynolds numbers and H/D ratios investigated.
- As expected, local Nusselt number is directly proportional with Reynolds number for each H/D ratio.
- The highest stagnation point and average Nusselt number has been obtained at H/D=6 for all Reynolds numbers investigated except Re =20000. At Re=20000, they reached their maximum values at H/D=4.
- Besides stagnation value, a second maximum in local Nusselt number has been observed for H/D≤4 values and it is more pronounced at high Reynolds numbers and low H/D values at x/D=2.
- For the future work, to determine the temper quality standard mechanical tests of tempered glasses which are obtained from the current study will be done. The effect of parameters that determine heat transfer characteristics on temper quality will be examined.

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NOMENCLATURES

A	surface area for glass surface (m^2)
C	specific heat of air at constant pressure, (kJ/kgK)
D	diameter of nozzle exit (m)
H	glass-nozzle spacing (m)
h	heat transfer coefficient (W/m^2K)
k	thermal conductivity of air (W/mK)
m	glass mass (kg)
Nu	nusselt number (hD/k)
x	radial distance from the stagnation point (m)
Re	Reynolds number ($\overline{U}_j D / \nu$)
T	temperature (ºC)
T_g	Leidenfrost temperature (ºC)
$\overline{U}_j$	jet exit average air velocity (m/s)
Q	volumetric flow rate (m^3/s)
V	glass volume (m^3)

Greek symbols

ν	kinematic viscosity, (m^2/s)
μ	dynamic viscosity, (kg/ms)
ρ	density, (kg/m^3)
σ	stefan-Boltzmann constant, (W/m^2K^4)
ε	emissivity

Subscripts

Aver	average
a	ambient
J	jet
s	surface
stag	stagnation
x	local

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