Experimental Investigation of the Transient Cooling Characteristics of an Industrial Glass Tempering Unit

Hilmi Yazici, Mehmet Akcay, Mustafa Golcu, Mehmet F. Koseoglu, and Yakup Sekmen

***Abstract*—**Energy consumption rate during the cooling process of industrial glass tempering process is considerably high. In this experimental study the effect of dimensionless jet to jet distance (S/D) and jet to plate distance (H/D) on the cooling time have been investigated. In the experiments 4 mm thick glass samples have been used. Cooling unit consists of 16 mutually placed seamless aluminum nozzles of 8 mm in diameter and 80 mm in length. Nozzles were in staggered arrangement. Experiments were conducted with circular jets for H/D values between 1 and 10, and for S/D values between 2 and 10. During the experiments Reynolds number has been kept constant at 30000. Experimental results showed that the longest cooling time with 87 seconds has been observed in the experiments for S/D=10 and H/D=10 values, while the shortest cooling time with 42.5 seconds has been measured in the experiments for S/D=2 and H/D=4 values.

***Keywords*—**Glass tempering, cooling, Reynolds number, nozzle

I. INTRODUCTION

TEMPERED glass is used as safety glass in many field changing from automotive industry to architectural applications [1,2]. During the tempering process, glass is heated to near its melting temperature (700 ^{o}C) in the furnaces and then it is exposed to sudden cooling process with fluid jets [3-5]. Due to non-uniform cooling during this process, surface of the glass cools faster which cause contraction on the surface and it becomes tougher, on the other hand central region of the glass stays relatively hot. As a result glass faces compression stress on the surfaces and tensile stress in the center region [1,4,6,7]. Strength of the glass increases proportionally with pre compression stress [6-8].Ordinary glasses gain four or more times strength during tempering process [4,8,9]. They are difficult break and when they break, they break into small parts without sharp edges [7]. Temper quality depends on many factors including heating time, sudden cooling time, H/D and S/D ratios and Re number. Here, H represents the distance between nozzle exit and the target plate; D nozzle diameter and S is the jet to jet spacing.

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Sudden cooling during the tempering process has been achieved with impinging jets. In the literature, there is wide variety of studies with impinging jets covering many different applications. Some of the literature related to the subject of this study has been summarized below.

In their numerical study [6] modeled heating and cooling processes during tempering under mixed boundary conditions. In the study by using the method of single flux, radiation source term of the glass plate has been calculated and energy equation has been solved with finite difference method. By using the program written in FORTRAN center line temperature change of the 6.1, 14, and 20 mm thick glasses has been calculated.

In an attempt to reduce the pressurized air consumption and save energy, [2] conducted an experimental study and they added water paper to cooling air jets. They reported that the addition of water paper reduced the pressurized air amount necessary for cooling process.

[10], in his study controlled and observed the tempering furnace by using PLC and SCADA program. He conducted experiments with 3 mm thick glass cooker lids. In the experiments heating periods of 100, 105, 110, and 120 seconds and cooling periods of 4,10,15,20 seconds have been tested. Safety criteria's have been checked by applying fracture tests to tempered glass samples.

[11] 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 (Re) number (11000, 22000, 33000, 44000), they observed the common power law relationship between Nu and Re numbers.

In an experimental study with confined circular air jets of 3 mm in diameter, [12] investigated the effect of jet to jet spacing on Nusselt number. Experiments have been conducted for a flat plate under fixed heat flux value of 1500 W/m^2. In the experiments Re number was in the range of $10000 \leq Re \leq 30000$ and S/D ratio was between 4 and 16.

In the present study, transient change of glass surface temperature during auto glass tempering process has been experimentally investigated. In the experiments 4 mm thick glass samples of different dimensions for each S/D= 2, 4, 6,8,10 values were tested. Cooling unit consists of mutually placed nozzle arrays in staggered arrangement. Totally, 16 nozzles of 8 mm in diameter and 80 mm in length made of seamless aluminum pipes have been used. For a Reynolds number of 30000, H/D values 1≤H/D≤10 and S/D values 2≤S/D≤10 were tested and compared.

II. Experimental Study

A. Experimental Set Up

Schematic diagram of the tempering facility is shown in Fig. 1.

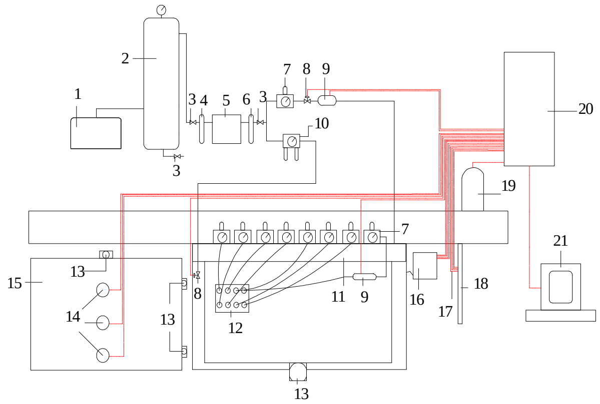

Fig. 1 Schematic diagram of the tempering facility
1)Compressor,2)Air tank,3)Vane, 4)Inlet filter,5)Dryer, 6)Exit filter,7)Regulator, 8)Solenoid valve, 9)Flow meter, 10)Conditioner,11)Pressurized air chamber,12)Nozzle plate,13)Pneumatic piston,14)Thermocouples,15)Furnace, 16)Control panel, 17)Flexible thermocouples, 18)Traverse, 19)Motor,20)Plc automation panel, 21)Computer

During the tempering process, glass first needs to be heated near its melting temperature (700 ^{o}C) in the furnaces, and then heated glass is transferred to cooling unit. In authors' previous studies [13], detailed explanation of the experimental facility used for glass tempering is given.

B. Measurement and Data Reduction

In order to measure transient temperature changes on the surface, glass surface has been equipped with 0.81 mm thick type K thermocouples. Thermocouples are fixed to the glass surface along the centerline at different x/D values. CC High Temperature Cement with high thermal conductivity has been used to fix thermocouples to the surface.

Table I shows the details of glass dimensions corresponding to different S/D values. Temperature measurement points (X0, X1 and X2) and corresponding temperature values (Ts_1, Ts_2 and Ts_3) are shown in Fig. 2.

TABLE I
Glass Dimensions For S/D Values

S/D	Length (mm)	Width (mm)
2	41,5	48
4	83,1	96
6	124,7	144
8	166,3	192
10	208	240

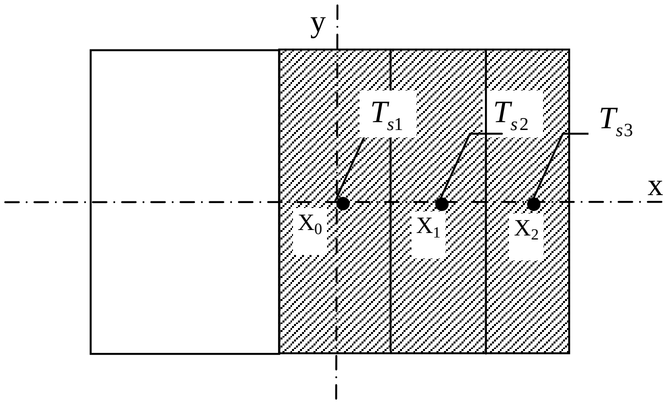

Fig. 2 Temperature measurement points and areas used in the calculation of local Nu number

Glass is heated in an oven at 750 ^{o}C until average surface temperature reaches to 680 ^{o}C and then it is sent to sudden cooling unit to be cooled to an average temperature 70 ^{o}C. In all experiments above mentioned temperatures are kept constant and applied to glass samples.

Fig. 3 Cooling nozzle arrays in staggered arrangement

Fig. 3 shows the staggered nozzle arrays used in the experiments. Heated glass in the oven is transferred to cooling unit by traverse like mechanism and symmetrically placed in between nozzle arrays. Nozzle plates are kept in constant position throughout the cooling period. Totally, 16 nozzles of 8 mm in diameter and 80 mm in length made of seamless aluminum pipes have been used. 30 different configurations for a Reynolds number of 30000, H/D values 1≤H/D≤10 and S/D values 2≤S/D≤10 were tested and compared.

III. Result And Discussion

- *Temperature Change*

Glass is heated in an oven at 750 ^{o}C until average surface temperature reaches to 680 ^{o}C and then it is sent to sudden cooling unit to be cooled to an average temperature 70 ^{o}C. In all experiments above mentioned temperatures are kept constant and applied to glass samples. In the experiments, cooling times have been observed for different S/D and H/D values at constant Reynolds numbers.

During the transfer period from the oven to the cooling unit, temperature of the heated glass decreases from 680 ^oC to 660 ^oC. Approximately 20 ^oC temperature drop has been observed for all the S/D values investigated. Cooling process is ended when the average surface temperature of the glass reached to 70 ^oC. Average surface temperature (T_{ave}) has been calculated as the arithmetic averages of the local temperatures.

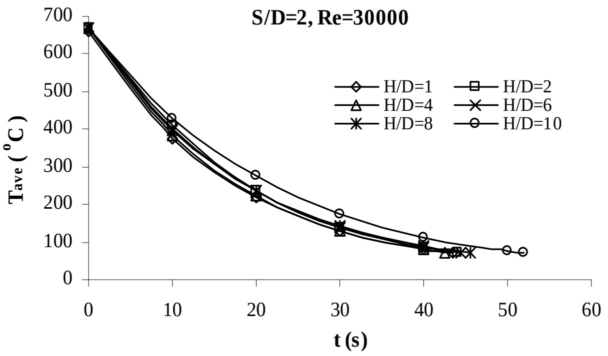

Fig. 4 Transient change of average glass temperature during the cooling period for different H/D values (S/D=2)

Transient change of average glass surface temperatures at S/D=2 value for different H/D values are presented in Fig. 4. For these set of experiments the shortest cooling time was 42.5 seconds and it is obtained at H/D=4 value. 18,2% reduction in the cooling period were observed compared to the value of 52 seconds at H/D=10.

Fig. 5 shows, transient change of average glass surface temperatures at S/D=4 value for different H/D values. For these set of experiments the shortest cooling time was obtained in H/D=1 case with 48 seconds and the longest cooling time was 60 seconds in H/D=10. When the shortest cooling times were compared for S/D=2 and S/D=4 configurations, 12.9% increase in S/D=4 was observed.

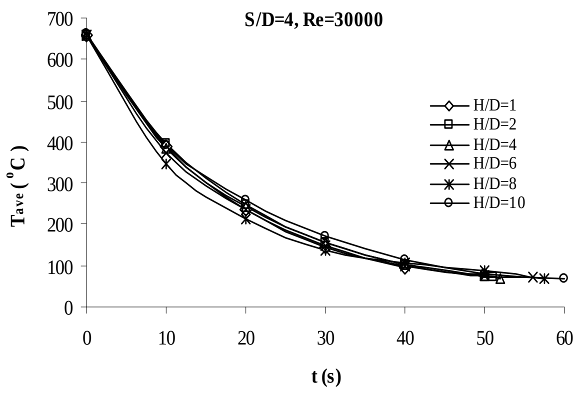

Fig. 5 Transient change of average glass temperature during the cooling period for different H/D values, (S/D=4)

For constant S/D value of 6, time dependent change of average glass surface temperatures are given in Fig. 6 for different H/D values. Cooling time of 52.5 seconds was the shortest obtained with H/D=1 which is %16 lower than the value in H/D=10. 62.5 seconds was the longest time obtained in H/D=10 configuration. When the shortest cooling time of S/D=6 compared with S/D=2 and 4, it has been observed an increase of 23% and 9.3% compared to S/D=2 and S/D=4 respectively.

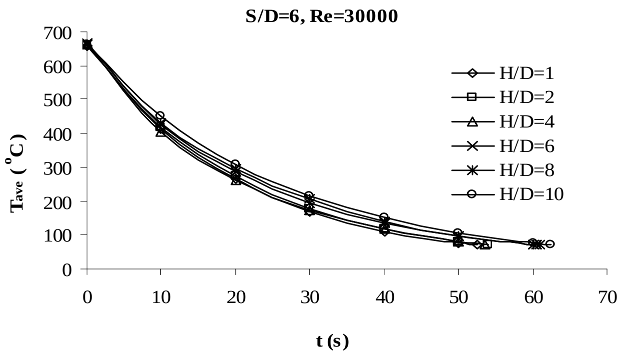

Fig. 6 Transient change of average glass temperature during the cooling period for different H/D values (S/D=6)

Fig. 7 shows, transient change of average glass surface temperatures at S/D=8 value for different H/D values. For these set of experiments the shortest cooling time was obtained in H/D=1 case with 62 seconds and the longest cooling time was 75 seconds in H/D=10.Cooling time was 17.3% lower in H/D=1 compared to H/D=10. When the shortest cooling time of S/D=8 compared with S/D=2, 4 and 6, it has been observed an increase of 45.8%, 29.1% and 18% compared to S/D=2, S/D=4 and S/D=6 respectively.

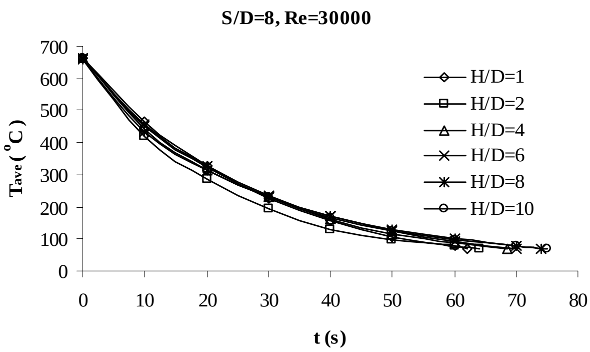

Fig. 7 Transient change of average glass temperature during the cooling period for different H/D values (S/D=8)

For constant S/D value of 10, time dependent change of average glass surface temperatures are given in Fig. 8 for different H/D values. Cooling time of 72 seconds was the shortest obtained with H/D=1 which is %17.2 lower then the value in H/D=10. 87 seconds was the longest time obtained in H/D=10 configuration. When the shortest cooling time of S/D=10 compared with S/D=2,4,6 and 8, it has been observed an increase of 69.4%, 50%, 37.1% and 16.1% compared to S/D=2, S/D=4, S/D=6 and S/D=8 respectively.

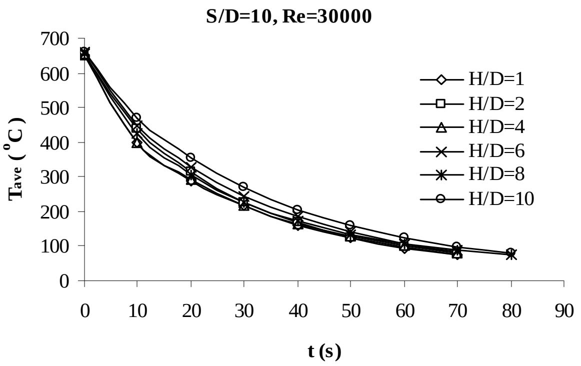

Fig. 8 Transient change of average glass temperature during the cooling period for different H/D values (S/D=10)

Table II gives cooling time durations necessary to reach final average surface temperature of 70 ^oC for all the configurations investigated at different H/D and S/D values. According to the values in the table, the shortest cooling time was obtained in S/D=2 and H/D=4 with a value of 42.5 seconds. S/D=10 and H/D=10 gives the longest cooling time of 87 seconds. S/D=2 stands as an exception, for all S/D values investigated, the shortest cooling time was obtained in H/D=1.

TABLE II
COOLING TIME DURATIONS TO REACH AN AVERAGE SURFACE TEMPERATURE OF 70 OC AS A FUNCTION OF S/D AND H/D

S/D	H/D	Time (s)
2	1	43,5
	2	44
	4	42,5
	6	44,5
	8	45,5
	10	52
4	1	48
	2	51
	4	52
	6	56
	8	57,5
	10	60
6	1	52,5
	2	54
	4	57
	6	60,5
	8	61
	10	62,5
8	1	62
	2	64
	4	68,5
	6	70
	8	74
	10	75
10	1	72
	2	75
	4	78
	6	80
	8	83
	10	87

Table II summarizes minimum and maximum times for cooling process that covers the time period necessary to drop initial glass temperature of 660 ^oC to 70 ^oC.

TABLE III
MAXIMUM AND MINIMUM COOLING TIMES AS A FUNCTION OF S/D AND H/D

S/D	H/D	Min. cooling times, (s)	S/D	H/D	Max. cooling times, (s)
2	4	42.5	2	10	52
4	1	48	4	10	60
6	1	52.5	6	10	62.5
8	1	62	8	10	75
10	1	72	10	10	87

IV. CONCLUSION

In this study, transient cooling process for tempering of glass samples has been experimentally investigated for different S/D and H/D ratios.

Glass is heated in an oven at 750 ^oC until average surface temperature reaches to 680 ^oC and then it is sent to sudden cooling unit to be cooled to an average temperature 70 ^oC. In all experiments above mentioned temperatures are kept constant and applied to glass samples for different H/D ratios.

Oven doors are opened when glass reaches the desired temperature of approximately 680 ^oC and glass is transferred to cooling unit by means of a traverse like mechanism. It takes about 4 seconds to reach the cooling unit. During that time, approximately 20 ^oC drops in the glass temperature is observed. Cooling process starts at 660 ^oC and continues until average surface temperature of glass drops to 70 ^oC. For every S/D and H/D values examined, mentioned starting and ending temperatures are fixed. According to the results, the longest cooling time of 87 seconds has been measured during the tests with H/D=10 and S/D=10. The shortest cooling time observed in the experiments with H/D=4 and S/D=2 configuration and it was 42.5 seconds.

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