Experimental Thermal and Fluid Science 83 (2017) 260–270

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Experimental investigation of the relationship between heat transfer rate and number of broken glass particles in tempering process of glass plates

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ARTICLE INFO

Article history:
Received 21 June 2016
Received in revised form 10 January 2017
Accepted 17 January 2017
Available online 18 January 2017

Keywords:
Glass tempering
Impinging air jet
Nusselt number
Number of broken glass particles

ABSTRACT

Thermal glass tempering process is based on heating the glass in a furnace and suddenly cooling it down in a cooling unit. The quality of the glass obtained at the end largely depends on the heat transferred from the glass surface. In this study, the glass tempering process was conducted in a specially designed and manufactured glass tempering unit prototype, and the change in the local number of broken glass particles was examined based on the local heat transfer rate. A 6-mm-thick flat glass in 170 × 170 mm dimensions was used in the study. Two single nozzles, 13 mm in diameter and 300 mm in length that were placed against each other were used for the cooling process. The distance between the nozzle and the glass plate surface was taken as $1 \leqslant H/D \leqslant 10$, and the Reynolds number as $40{,}000 \leqslant Re \leqslant 60{,}000$. In the sudden cooling process conducted according to different H/D ratios and Reynold numbers, the cooling times, and the local, average and stagnation-point Nusselt numbers were obtained. Then, the tempered glasses produced under these conditions were broken apart, and the number of particles was determined. The results showed that the cooling time firstly decreased and then increased with H/D ratio generally, whereas it decreased as the Reynolds number increased. It was also observed that as the average Nusselt number increased, the number of particles also increased. Besides, as the air jet moved away from the stagnation point, the Nusselt number decreased, and concordantly, the number of particles also decreased. It was found that the number of particles was substantially proportional to the heat transfer rate.

1. Introduction

Glass, as a material that can be used in all branches of engineering [1], usually loses its functionality due to surface defects [2]. Fracture strength can be improved by creating residual compressive stresses on the glass surface. Such compressive stresses on glasses can be usually created through thermal tempering or ion exchange [3]. Glass tempering process basically consists of the steps of heating the glass over the transmission temperature, and then suddenly cooling it down to the ambient temperature [4,5]. When heated glass is rapidly cooled below its transition temperature, high temperature gradients occur across the glass thickness. While the surface layers tends to shrink by solidification that causes tension on the surface and compression in the mid plane with higher temperature and lower viscosity than surface. The rest of the process, while the glass cooled to room temperature, the mid plane continues to cool and shrink. The hardened surface layer forced to the shrink. This creates the compression on the surface and the tension in the mid plane. And as a result, residual stress profile with compression on the surface balanced by tension in the interior [6]. Those compressive stresses near the surface close crack development caused by scratches or surface defects [7,8]. Tempered glasses do not only become more resistant against cracking and breaking apart but also provide higher energy absorption when exposed to external high loads [9]. At the same time, when broken, they break apart to small, harmless pieces because of the strain energy it has with the tempering process [10], and decrease the risk of injury to a minimum [11].

In the glass tempering process, cooling is conducted with the air jet that comes out of the nozzle impinging on the hot glass surface [4]. The impinging jets are used to achieve very intensive heat and mass transfer in many engineering applications, such as the cooling of turbine blades, hot steel plates and electronic components, tempering of glass, drying of papers and textiles [12–17].

The schematic illustration for a single impinging jet is shown in Fig. 1. The jet issues from a round nozzle of diameter D and

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http://dx.doi.org/10.1016/j.expthermflusci.2017.01.013
0894-1777/

Nomenclature

A	glass surface area (m^2)
C	specific heat of glass ($J\,kg^{-1}\,K^{-1}$)
D	diameter of nozzle exit (m)
H	glass-nozzle spacing (m)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k	thermal conductivity of air ($W\,m^{-1}\,K^{-1}$)
m	glass mass (kg)
NP	number of particle (pcs)
Nu	Nusselt number
x	radial distance from the stagnation point (m)
Re	Reynolds number
T	temperature (°C)

Subscripts

aver	average
a	ambient
J	jet
T_g	Leidenfrost temperature (°C)
$\overline{U}_j$	jet exit average air velocity ($m\,s^{-1}$)
Q	volumetric flow rate ($m^3\,s^{-1}$)
V	glass volume (m^3)

Greek symbols

ν	kinematic viscosity ($m^2\,s^{-1}$)
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
σ	Stefan-Boltzmann constant ($W\,m^{-2}\,K^{-4}$)
ε	emissivity
s	surface
stag	stagnation
x	local

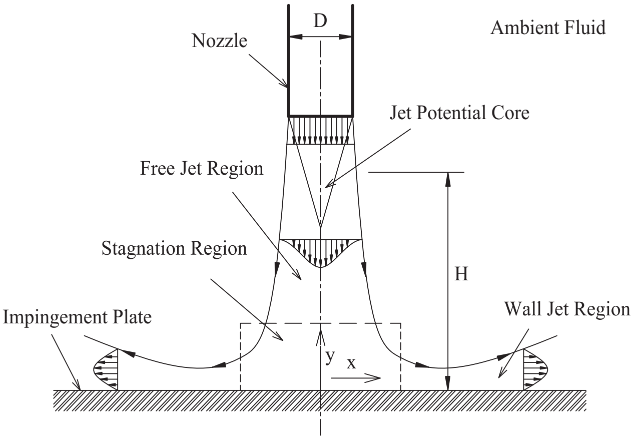

Fig. 1. Flow regions of an impinging jet.

impinges perpendicularly on a plate at a distance H from the nozzle. As can be seen in Fig. 1, generally it is possible to divide an impinging jet flow into three regions that are free jet region, impingement region (stagnation region) and wall jet region [12,18,19]. In free jet region, there are mass, momentum and energy transfer between the environment and the jet. The flow is not affected from the impact surface [20]. The flow in the stagnation (impingement region) does not have an exact direction and the flow in this region is affected by the target surface, slowing down in the vertical direction and speeding up in the parallel direction [21]. The stagnation point in which the velocities parallel and vertical to the surface are zero is also in this region. In the wall jet region, radial distance (x) increases on the plate, the velocity components parallel to the surface reach the highest values from zero, and then drop to zero. The fluid that leaves the impingement region now flows parallel to the surface and this is called wall or side jet [20,22].

In impinging jet applications, heat transfer rates are significantly affected by parameters such as Nusselt number, Reynolds number (Re), distance between jet and plate (H/D), distance between two jets (S/D), radial distance to stagnation point (x/D), Prandtl number, inclination of target plate, curvature and roughness of target plate, nozzle geometry, and turbulence intensity at the nozzle exit [23–28]. To the produce high-quality tempered glass with minimum energy consumption, these parameters should be optimized and the process should be controlled carefully.

The cooling process conducted using single air jets has been experimentally and numerically investigated by many researchers [28–33]. Martin [34], Jambunathan et al. [35] and Viskanta [36] reviewed jet impingement heat transfer from flat surfaces. Recently, Zuckerman and Lion [37] carried out detailed studies on identifying the heat transfer characteristics and physical behaviours of impinging jets.

Bu et al. [38] experimentally examined the heat transfer occurring on a variable-curvature concave surface on a turbine blade by using impinging air jets. The Reynolds number was taken as $51.021 \leqslant Re \leqslant 85.340$ and the H/D ratio as $1.736 \leqslant H/D \leqslant 19.76$. It was found that as the Reynolds number increased, the heat transfer also increased. The best heat transfer performance was obtained in nozzle diameter $D = 2$ mm, Reynolds number $Re = 51.021$ and $H/D = 4.5$ values. Katti et al. [39] investigated the effect of low Reynods number and H/D ratio on local Nusselt number by using air jets impinging on a smooth and flat surface. The Reynolds number in the nozzle outlet was taken as $500 \leqslant Re \leqslant 8000$ and the distance between the nozzle and the plate as $0.5 \leqslant H/D \leqslant 8$. It was revealed that in high Reynolds numbers, the highest stagnation point Nusselt number occurred around $H/D = 6$.

Limaye et al. [26] examined the local heat transfer occurring as a result of a single circular air jet vertically impinging on a plate. The Mach number was taken as 0.2, 0.4, 0.6, 0.8, 1 and H/D ratio defining the jet-plate distance as $1 \leqslant H/D \leqslant 12$. The heat transfer rate was observed to increase with the Mach number for each H/D distance. The highest stagnation point Nusselt number was obtained in $H/D = 6$ for Mach $\leqslant 0.4$, and in $H/D = 8$ for Mach $\geqslant 0.6$. Mostafa et al. [40] examined the turbulent flow structure of rectangle jet flow experimentally and numerically. The measurements were done using a hot wire anemometer having an x type probe. The calculations were revealed using a computer program run based on finite differences method. The average speed of the flow direction, turbulence kinetic energy and shear stress measured experimentally were compared to numerical results, and it was found that the experimental and the numerical results were compatible to each other.

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