International Journal of Heat and Mass Transfer 127 (2018) 413–425

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Transient heat transfer characteristics of array-jet impingement on high-temperature flat plate at low jet-to-plate distances

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ARTICLE INFO

Article history:
Received 7 November 2017
Received in revised form 8 June 2018
Accepted 19 July 2018

Keywords:
Transient heat transfer
Glass tempering
Array jet impingement
Low jet-to-plate distances

ABSTRACT

Numerical studies on the transient heat transfer characteristics of air-array-jet impingement, for small jet-to-plate distances and a large temperature difference between the nozzle and plate, are presented. The total mass flow rate of the jets ($\dot{m}$) is constant at 30.34 kg/h. The nondimensional jet-to-plate distance (H/D) for a nozzle diameter (D) of 5 mm is varied from 0.2 to 1. The nondimensional hole-to-hole spacing is $S/D = 5$, 7, and 10, respectively. The variations in the transient heat transfer characteristics and flow velocity at different values of H/D and S/D, as a function of the cooling time, are discussed. It is found that there exists a turning point $H/D = 0.4$ in the effect of the transient heat transfer. As H/D is decreased, the quenching time shrinks quickly. The velocity field is proposed as an explanation for the observed transient heat transfer. In addition, an appropriate proposal is presented for designing equipments of tempering ultra-thin glass.

1. Introduction

The thinning and miniaturization of components, such as liquid-crystal displays and solar cells, have increased the market demand for ultra-thin glass. The glass tempering process is based on a sudden cooling process using air jets, in which the glass is heated close to its melting temperature, strengthening the glass [1,2]. Ultra-thin glass needs a shorter cooling time and faster surface cooling compared to ordinary 4–6-mm-thick glass [3–6].

Jet-impingement heat transfer is used for the sudden cooling of thin glass, during the glass tempering process. From the resent literature, a single jet [7–14] is generally used for the local cooling of a small surface area. Choo et al. [11,12] investigated the heat transfer characteristics of impinging jets at low nozzle-to-plate distances ($H/D = 0.125$–1.0). They found that the Nusselt number is independent of H/D at a fixed pumping power. In addition, Kuraan et al. [10] studied the heat transfer and hydrodynamics of free water jet impingement at low nozzle-to-plate spacing ($H/D = 0.08$–1.0). They showed that the normalized Nusselt number, pressure, and hydraulic jump diameter are divided into two regions over the entire H/D range. With respect to array-jet impingement, while a certain amount of experimental [15–23] and numerical [24–28] studies on the multiple impinging air-jets have been done, few works [29–36] focused on the transient heat transfer characteristics. Glass tempering is performed at a large temperature difference between the inlet and glass plate with a small jet-to-plate distances (H), which is very different from the normal operating conditions. However, most of the above mentioned studies concentrated on steady-state conditions and large jet-to-plate distances. Several empirical correlations were suggested for air jet at a large H/D for single and array-jet impingement, but the transient heat transfer characteristics at small H/D are still limited. An investigation of the transient heat transfer characteristics for air-jet impingement is necessary to ensure the tempering quality of large ultra-thin glass plates. More importantly, the differences in the transient heat transfer characteristics from the normal conditions should be elucidated.

The purpose of this study is to investigate the transient heat transfer characteristics of air-array impinging jets for a small H/D and a large temperature difference at a constant total mass flow rate ($\dot{m}$) for air jets. A simulation is conducted with an $\dot{m}$ value of 30.34 kg/h and the results are compared and discussed in detailed for the different nondimensional H/D varied from 0.2 to 1, the different nondimensional hole-to-hole spacing ($S/D = 5$, 7, and 10), respectively. The results will be useful for understanding the transient heat transfer characteristics a under a confined space,

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.099
0017-9310/

Nomenclature

D	nozzle diameter (mm)
D_ω	cross-diffusion term
G_j	mass flow rate of coolant per unit area ($kg/m^2 \cdot s$)
H	jet to impingement plate distance (mm)
h_c	convection heat transfer coefficient
h_{ext}	external heat transfer coefficient
I	Enthalpy (J/kg)
L	the length of impingement plate (mm)
$\dot{m}$	total mass flow rate of jets (kg/h)
N	number of jet nozzle
P	static pressure (Pa)
P_{amb}	ambient pressure
R_e	Reynolds number
S	jet to jet spacing (mm)
S_k	user-defined source term
S_ω	user-defined source term
T	temperature (K)
ΔT	temperature difference (K)
u	fluid velocity (m/s)
W	the width of the impingement plate (mm)

Greek symbols

ρ	density (kg/m^3)
λ	thermal conductivity ($W/K \cdot m$)
$\bar{\tau}$	stress tensor
μ	dynamic viscosity ($kg/m \cdot s$)
v	kinematic viscosity (m^2/s)
ζ	quenching times reduction ratio
η	temperature difference enlargement ratio

Subscripts

j	Jet
p	target plate
air	air
ext	external

and for designing an array-jet impingement system with certain theoretical significance.

2. Geometry and numerical analysis

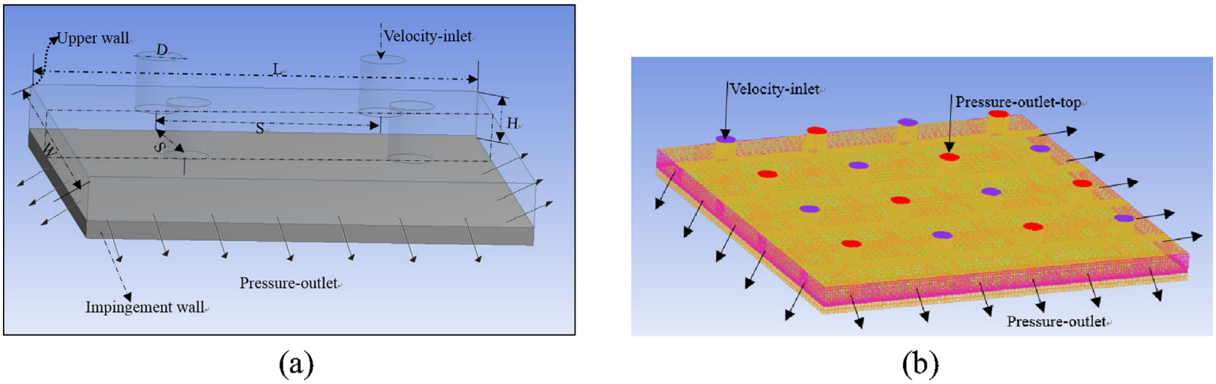
2.1. Geometry

Fig. 1 shows the basic geometry of the computational domain. Air through circular tubes vertically impinges on a glass plate with a length of 100 mm, width of 100 mm, and thickness of 2 mm. The circular jet diameter, D, is constant at 5 mm. The origin of the coordinate system is at the center of upper surface of the impingent plate. The distance between the nozzle and glass plate (H) is varied from 1 to 5 mm. For $S/D = 5$, 7 and 10, respectively, the jet nozzle plates are all velocity-inlet nozzles. Only for the case of $S/D = 5$, 8 nozzles with reversed flow are used, and the number of the jet nozzles are the same as that for $S/D = 5$; for the jet nozzle plate, the velocity-inlet nozzles and pressure-outlet nozzles are arranged in a staggered manner. The position of the jet is symmetrical at the center of the target plate. For the case of $S/D = 10$, the two rows of jet nozzles are psitioned at $y = \pm 25$ mm, respectively. When $S/D = 7$, the jet position is located at $y = \pm 17.5$ mm, respectively. When $S/D = 5$, the four rows of jet nozzles are positioned at $y = \pm 12.5$ mm and $y = \pm 37.5$ mm, respectively.

The jet inlet velocity is varied to set the total mass flow rate, $\dot{m} = 30.34$ kg/h, which corresponds to jet-inlet Reynold numbers of 30,000 for the four inlet nozzles, respectively. The distance between the nozzles (S) is varied to set the nondimensional hole-to-hole spacing, $S/D = 5$, 7 and 10, respectively. The detailed array-jet impingement nozzle arrangements are depicted in Fig. 2. The parameters used for different array-jet arrangements are listed in Table 1.

In the process of glass tempering, not only is the dependence of the surface temperature on time nonlinear, but the material properties also change significantly with temperature. In our study, the density of glass is fixed at 2500 kg/m^3, while the other thermal characteristics vary with the temperature. Moreover, the thermal characteristics of the fluid flow also vary with temperature. The initial temperature of glass plate is set at 953 K, and we consider the heat-transfer characteristics through conjugate heat transfer between the fluid and solid domains. In Fig. 1, the top part is considered as the fluid domain, whereas the bottom is the solid domain, in which the material is glass.

The flow is assumed to be a three-dimensional, incompressible turbulent flow. A structural mesh was created for the entire domain using the O-block option, with the ANSYS ICEM CFD 15.0 package. In order to improve the grid quality for capturing the near-wall flow phenomenon, and the region near the target plate,



(a) (b)

Fig. 1. (a) Basic geometry and (b) the genmetry of array-impingement-jet with reversed flow.