International Journal of Heat and Mass Transfer 114 (2017) 981–991

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Transient heat transfer characteristics of small jet impingement on high-temperature flat plate

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ARTICLE INFO

Article history:
Received 7 April 2017
Received in revised form 14 June 2017
Accepted 24 June 2017

Keywords:
Glass tempering
Small jet impingement
Transient heat transfer
Velocity field

ABSTRACT

Numerical studies on the transient heat transfer characteristics of small-air-jet impingement under the condition of a large temperature difference between the nozzle and the plate are presented. The Reynolds number (*Re*) varied from 20,000 to 60,000 which is based on the hydraulic diameter of the circular jet. The nondimensional jet-to-plate distance (*H*/*D*) with nozzle diameter (*D*) of 5 mm is varied from 0.2 to 2. Variations in the stagnation point and boundary point Nusselt numbers with cooling times are discussed. It was found that with the decrease of jet-to-plate distance the heat transfer near stagnation point is enhanced, while it is decreased near boundary point. The velocity field is proposed as an explanation for the observed transient heat transfer.

1. Introduction

The thinning and miniaturization of components, such as liquid crystal display and solar cells have increased market demand for ultra-thin glass. In these application, the ultra-thin glass should be tempered to ensure the strength and safety of the final products. During the glass tempering process, glass is heated to its melting temperature and then exposed to a sudden cooling process, which can result in a sharp contraction of the glass surface, generating compressive stress in the outer regions of the glass while simultaneously slowing the formation of tensile stress in the inner regions [1]. Ultra-thin glass needs a shorter cooling time and faster surface cooling in the tempering process than ordinary 4–6-mm thick glass [2–5]. Jet impingement heat transfer is used for sudden cooling of thin glass during the glass tempering and is usually performed under conditions of high temperature difference and small jet-to-plate distance which is different from normal operating conditions.

Experimental studies and simulations on air-jet impingement heat transfer are mainly focused on the steady-state condition [6–11]. Few works [12–18] are on transient heat transfer characteristics, whose conditions are large jet-to-plate distances and small temperature differences between the nozzle inlet and the target plate. However, the transient heat transfer is very important in various engineering fields, especially in glass tempering, whose heat transfer during the cooling process is highly time dependent.

Most of the above mentioned studies have focused on steady-state condition and on a large jet-to-plate distances under the condition of small temperature differences between the inlet and plate. In this regard, we remark that very few studies have focused on transient-state condition under conditions of small jet-to-plate distances and high temperature differences between the inlet and plate. Several empirical correlations were suggested for air jet at large jet-to-plate distances, and while the transient heat transfer characteristics at small jet-to-plate distances is still limited. The purpose of this study is to ensure the tempering of the ultra-thin glass, it is helpful to investigate the transient heat transfer characteristics of air impinging jets under conditions of small jet-to-plate distances and high temperature differences between the inlet and plate. In an attempt to qualify the transient heat transfer of glass cooling, the surface-averaged temperature, stagnation point Nusselt number and the boundary point Nusselt number variation with the time obtained from the numerical studies are presented. The current simulation is conducted at a *Re* varied from 20,000 to 60,000 which is based on the hydraulic diameter of the circular jet [19], the nondimensional *H*/*D*is varied from 0.2 to 2. These data will be useful for understanding of the transient heat transfer characteristics at small jet-to-plate distances and designing of single jet impingement system have certain theoretical significance.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.06.112
0017-9310/

Nomenclature

D	nozzle diameter (mm)
h	heat transfer coefficient (W/m^2 K)
H	jet to impingement plate distance (mm)
I	enthalpy (J/kg)
N_u	Nusselt number
p	static pressure (Pa)
R_e	Reynolds number
T	temperature (K)
ΔT	temperature difference (K)
u	fluid velocity (m/s)
x	distance along impingement plate length (mm)
y	distance along impingement plate width (mm)
z	distance along impingement plate height (mm)

Greek symbols

ρ	density (kg/m^3)
λ	thermal conductivity (W/K · m)
$\overline{\tau}$	stress tensor
μ	dynamic viscosity (kg/m · s)

Subscripts

air	air
c	convection
boun	boundary point
s	surface
sta	stagnation point
t	total

2. Geometry and numerical analysis

2.1. Geometry

Fig. 1 shows the geometry of the computational domains. The air through a circular tube vertically impinging on a glass plate with length of 50 mm, width of 50 mm, and thickness of 2 mm. To obtain higher heat transfer efficiency, the shape of the jet inlet is circular (diameter is 5 mm and height of 6 mm). In the process of glass tempering, not only the dependence of surface temperature on time is nonlinear, but also material properties change significantly with the temperature. With the glass plate initial temperature set at 953 K, we consider the heat transfer characteristics by means of conjugate heat transfer between the fluid domain and the solid domain. In Fig. 1, the top part is considered as fluid domain and the bottom is solid domain whose constituent material is glass. In our study, the density of the glass is fixed at 2500 kg/m^3, while the other thermal characteristics vary with temperature. In addition, the thermal characteristics of the fluid flow vary with temperature as well.

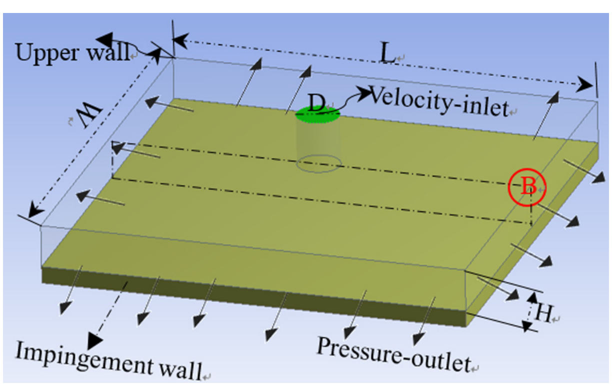

Fig. 1. Geometry of the computational domains.

The flow is assumed to be three-dimensional, incompressible turbulent flow. Due to the buoyancy effects depend on the Grashof number. In our simulations the Grashof number ($Gr = g\alpha_v \Delta t D^3/v^2$) is 6.24e3, which means the buoyancy force has little effect on heat transfer. And moreover, our study is mainly concerned with the convective heat transfer of air jet impinging [17], also shown that the natural convection and radiation have little effect on heat transfer. And therefore, the buoyancy and radiation heat transfer effects are neglected in our studies.

To improve the quality of the grid for capturing the near-wall flow phenomenon, a structural mesh was created for the whole domain using the O-blocking option with the ANSYS ICEM CFD 15.0 package. On the one hand, to capture the near wall flow phenomenon and improve the quality of the grid; on the other hand, the region nearby the target plate, where the flow and the temperature gradients were expected to be highest, the grid was refined near the target plate. An exemplary grid used in the circular nozzle with the jet to plate distance of $H = 2$ mm is shown in Fig. 2. And there are some other similar studies [10,20] use the same mesh resolution with ours.

2.2. Governing equations

The transient transport equations of mass, moment, and energy are:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{1}$$

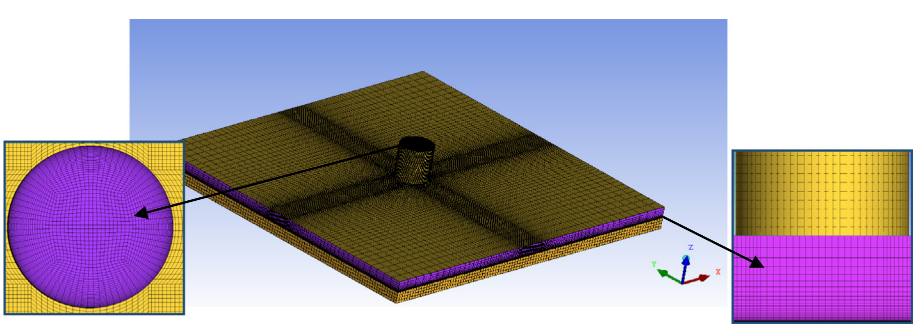

Fig. 2. Mesh of the computational domains.