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Jet impingement onto kerf: Effect of kerf wedge angle on heat transfer rates and skin friction

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ABSTRACT

Jet impingement onto a kerf is considered in relation to laser cutting process. Flow and temperature fields are predicted using the three-dimensional modeling. In the simulations influence of kerf wall wedge angle on the Nusselt number and the skin friction at the surface of the kerf wall is examined. The RNG $k-\varepsilon$ model is incorporated to account for the turbulence. A control volume approach is introduced to discretize the governing flow equations. It is found that the kerf wall wedge angle has considerable influence on the Nusselt number and the skin friction.

1. Introduction

Jet impingement onto surfaces finds applications in industry. One of the applications is laser cutting process. In this case, impinging jet is used to assist the laser cutting process. The assisting gas protects the cutting section from high temperatures involved during the laser cutting process, thus reducing thermal deformation of processed material. The assisting gas usually emerges from the conical nozzle and impinges onto the laser produced kerf. The kerf walls remain at almost melting temperature of the substrate material and the impinging jet has threefold effects: (i) preventing high temperature oxidation reactions; (ii) convective cooling of the kerf wall surfaces; and (iii) exerting the drag force on the molten layer around the kerf wall surfaces. Therefore, the cooling and frictional drag effects of the assisting gas need to be examined in detail. Moreover, the kerf wall surfaces are not exactly parallel, but form wedges with small angles whose effects must also be taken into consideration.

Considerable studies were carried out to examine gas jet impingement onto heated surfaces. The jet impingement onto concave surfaces was investigated by Yang et al. [1]. They indicated that the average heat transfer rates for impingement on the concave surface were more enhanced than the flat plate. Experimental study on round jet impingement onto a convex surface was carried out by Lim et al. [2]. They showed that the ratio of the maximum Nusselt number to the stagnation Nusselt number increased as the jet angle increased. The heat transfer due to unsteadily impinging jets was investigated by Herwig et al. [3]. They indicated that slight increase in heat transfer performance was observed, which was due to vortex shedding within the jet. The slot jet impingement onto a constant heat flux surface was examined by Sahoo and Sharif [4]. They observed that the average Nusselt number at the heat flux surface increased with increasing jet exit Reynolds number; however, the average Nusselt number did not change significantly with Richardson number. The jet impingement heat transfer for varying flow characteristics was investigated by Patel and Roy [5]. They compared the Nusselt number and turbulent intensity with closed and open boundary conditions on three specified lines located on the inclined surface. Jet impingement onto the laser irradiated surfaces in relation to laser machining was considered by Chen et al. [6]. They indicated that fluctuations of pressure gradient and shear force at the machining front resulted in poor surface finish. Jet impinging on a flat plate and flowing into an axisymmetric cavity was examined by Amano and Brandt [7]. They indicated that the use of $k-\varepsilon$ turbulence model resulted in good predictions of velocity, pressure, and skin friction distributions in the surface vicinity of the axisymmetric cavity. The effects of nozzle-inlet chamfering on pressure drop and heat transfer in air jet impingement were studied by Brignoni and Garimella [8]. They showed that the ratio of average heat transfer coefficient to pressure drop was enhanced by as much as 30% as a result of chamfering the nozzle and that narrow chamfering provided the better performance. The off-axial was designed and tested in relation to laser cutting process by Ilavarasan and Molian [9]. They indicated that the off-axial nozzle provided straight and non-turbulent flow to the cutting erosion front thereby improving the quality of the cut. The influence of high pressure assisting-gas flow on high power CO_2 laser cutting

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Nomenclature

a	speed of sound
A_ε	constant for turbulence length scale
c_l	constant for turbulence length scale
c_p	constant pressure specific heat (kJ/kg K)
c_v	constant volume specific heat (kJ/kg K)
$C_{1\varepsilon}, C_{2\varepsilon}$	RNG turbulence model constants
$C^*_{2\varepsilon}$	RNG turbulence model modified constant
C_ν, C_μ	turbulent viscosity modeling constants
G_k	generation of turbulence kinetic energy (kg/ms^3)
k	turbulence kinetic energy (m^2/s^2)
k_{eff}	effective thermal conductivity (W/mK)
l_μ	length scale
M_t	turbulent Mach number
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
R	gas constant (kJ/kg K)
RNG	renormalization group
Re	Reynolds number
Re_y	wall-distance based Reynolds number
S	strain rate (s^{-1})
S_{ij}	mean rate of strain tensor (s^{-1})
t	time (s)
T	temperature (K)
U_i, U_j	arbitrary mean velocity component (m/s)
U	velocity in the x-direction (m/s)
V	velocity in the y-direction (m/s)
W	velocity in the z-direction (m/s)
$u_i^{'}, u_j^{'}$	arbitrary fluctuating velocity component (m/s)
u'	fluctuating velocity in the x-direction (m/s)
v'	fluctuating velocity in the y-direction (m/s)
w'	fluctuating velocity in the z-direction (m/s)
x_i, x_j	arbitrary direction
x	distance along x-axis (m)
y	distance along y-axis (m)
y^+	non-dimensional wall coordinate
z	distance along z-axis (m)

Greek symbols

α	inverse effective Prandtl number
α_k, α_ε	inverse effective Prandtl numbers for k and ε respectively
δ_{ij}	Kronecker delta
ε	turbulence kinetic energy dissipation (m^2/s^3)
γ	specific heat ratio (c_p/c_v)
Γ	blending function for velocity laws-of-the-wall
κ	von Karman constant (=0.4187)
λ	thermal conductivity (W/m K)
Π	blending function for temperature laws-of-the-wall
μ	dynamic viscosity (kg/m s)
μ_t	turbulent (eddy) viscosity (kg/m s)
μ_{eff}	effective viscosity (μ+μ_t) (kg/m s)
ν	kinematic viscosity (m^2/s)
$\hat{v}$	ratio of effective to dynamic viscosity
Φ	arbitrary scalar quantity
φ'	fluctuating component of arbitrary scalar quantity
ρ	density (kg/m^3)
τ	shear stress (Pa)
τ_{ij}	arbitrary Reynolds stress (Pa)
θ'	fluctuating component of temperature (K)

Subscripts

eff	effective
ε	turbulence kinetic energy dissipation
i, j	arbitrary direction
j	jet
k	turbulence kinetic energy
t	turbulent
M	momentum
Φ	arbitrary scalar quantity
T	temperature
W	wall
under-bar	vector quantity

Superscripts

$^-$ over-bar	time-averaged variable
$\sim$ tilde	density-weighted or Favre-averaged variable
y	wall distance (m)

process was examined by Chen [10]. He indicated that for inert gas cutting dross formation at the cut edges was observed for most of the cutting conditions considered in the study. The dynamic characteristics of gas flow inside a laser cut kerf due to high assisting gas pressure were examined by Man et al. [11]. They indicated that for supersonic operation stand-off distance and the workpiece thickness were important for the quality cutting. The analysis of heat transfer and fluid flow in laser drilling was carried out by Batteh et al. [12]. The semi-quantitative analysis introduced yielded quasi-steady estimates for the laser drilling characteristics such as the penetration velocity and the melt layer thickness. The optimization study on off-axis nozzle laser cutting was carried out by Quintero et al. [13]. They indicated that the oblique shock wave which impinges on the cutting front provokes reversal of the pressure gradient, which leads to the detachment of the boundary layer. Jet impingement onto heat transferring surfaces was carried out previously [14–20]. However, most of the previous studies [14–16] were limited to two-dimensional axisymmetric heating situations. Since the laser cutting process is involved with jet impingement onto a rectangular slot, the consideration of two-dimensional axisymmetric heating situation fails to cover the geometric configuration of the process. Therefore, consideration of three-dimensional flow and heating situations is necessary in the model study.

In the light of the previous studies [14–16], three-dimensional modeling of jet impingement onto a kerf in relation to laser cutting process is carried out. It should be noted that the jet impingement onto a surface can be considered as an axisymmetric and the problem may reduce to two-dimensional case such as laser drilling of circular holes. However, the jet impingement onto a kerf, in relation to cutting, cannot be reduced to two-dimensional case, since the slot has a rectangular geometry rather than the circular geometry. Therefore, consideration of the axisymmetric heating is not possible in relation to the laser cutting process and the problem remains as a three-dimensional heating problem. The surface temperature of the kerf wall is kept at 1500 K to resemble the laser produced kerf. The flow equations are solved using the control volume approach and the RNG $k-\varepsilon$ model is