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Inverse determination of convective heat transfer between an impinging jet and a continuously moving flat surface

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ABSTRACT

In this study an inverse method is developed to determine the heat flux distribution on a moving plane wall. The method uses a thin layer of material (the measurement medium) glued on the conveyor belt. The heat flux distribution on the moving wall is then determined by an inverse method based on the temperature measurement by infrared thermography on the upper surface of the measurement medium. A finite element based inverse algorithm of a steady state heat conduction advection in the Eulerian frame is performed. The algorithm entails the use of the Tikhonov regularization method, along with the L-curve method to select an optimal regularization parameter. Both the direct solution of moving boundary problem and the inverse design formulation are presented. The accuracy of the inverse method is examined by simulating the exact and noisy data with four different values of the surface-to-jet velocity ratio, and two different materials (PVC and Aluminum) for the measurement medium. The results show a greater sensitivity to the convective heat flux allowing a better estimation of heat flux distribution for the PVC layer. An alternative underdetermined inverse scheme is also studied. This configuration allows a different extend between the retrieval heat flux surface and the measurement temperature surface.

1. Introduction

Impinging jets are extensively used in numerous applications due to the high heat transfer enhancement mechanism occurring in the vicinity of impingement zone. Industrial processes include the tempering of glass, the cooling of metal sheet, cooling of electronic components and several food processing operations. In many applications, the impinging jet is directed to a moving surface. Jet impingement is an active domain of research. Numerous studies have been conducted in order to analyze the highly complex flow structure that contains laminar, transitional and turbulent regions and to determine the heat transfer characteristics (Cziesla et al., 2001; Chattopadhyay and Saha, 2003). When the impingement surface is moving, the flow structure can be highly modified depending on the normalized surface velocity (normalized by the jet exit velocity) also called the surface-to-jet velocity ratio by some authors (Senter and Solliec, 2007). Relatively few studies have been conducted on this more complex configuration. Cziesla et al. (2001) have used large eddy simulation to simulate the flow field of an impinging jet emanating from a rectangular slot nozzle. The velocity of the impingement surface has been varied up to two times the jet velocity at the nozzle exit. It was shown that the surface velocity has a profound effect on the production rate of turbulence and heat transfer. The results of Chattopadhyay and Saha (2003) have shown that the local distribution of heat transfer coefficient is varied with the surface-to-jet velocity ratio. The peak value at the impingement point decreases with increasing surface velocity. Globally the averaged Nusselt number is dependent of surface velocity with a first increase and then a decrease for high surface-to-jet velocity ratio. These results are in qualitative agreement with the preceding experimental investigation of Raju and Schlunder (1977) concerning a moving flat surface impinged by a turbulent slot air jet. However the experimentation of Raju and Schlunder gives only the averaged value of heat transfer coefficient preventing a good understanding of the physical phenomenon. Senter and Solliec (2007) have used PIV system to investigate the flow field topology of a confined turbulent slot air jet impinging normally on a moving flat surface. The detailed analysis has allowed a better understanding of the physical phenomenon and has shown the main influence of the surface to jet velocity ratio on the flow field topology. More recently Sharif and Banerjee

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Nomenclature

c	specific heat (J kg^{-1} K^{-1})
e	material thickness (m)
H^1	Hilbert space
J	objective function (functional)
n	unit normal vector
$N^{nd}_{\Omega_i}$	number of finite element nodes in Ω_i
$N^{nd}_{\partial\Omega_u}$	number of spatial components of flux
N_Γ	number of contact interfaces
$N^{el}_{\Omega_i}$	number of finite triangular element in Ω_i
R	thermal contact resistance (m^2 K W^{-1})
R_{sj}	surface-to-jet velocity ratio
Re	Reynolds number
R_{reg}	regularisation matrix
S	sensitivity matrix
T	temperature (K)
V	velocity vector of impingement surface
V_j	mean velocity of jet centerline (m s^{-1})
X, Y	coordinates (m)

Greek symbols

ρ	density (kg m^{-3})
λ	thermal conductivity (W m^{-1} K^{-1})
ϕ	unknown boundary heat flux (W m^{-2})
Ω	computation domain
$\partial\Omega$	boundary of the computational domain
Γ	contact interface
∇	gradient operator
υ	test function
$\Im$	triangulation
Λ	finite dimensional subspace
ψ	basis function
α	regularization parameter
σ	standard deviation
ω	random vector
τ	specified positive number

Subscripts

eq	equilibrium
b	bottom boundary of Ω
i, j	index of computational domains
l	left boundary of Ω
p, q	index of finite element nodes in Ω_i
r	right boundary of Ω
s	surface
u	upper boundary of Ω

Superscripts

$\star$	simulated values
$\wedge$	estimated values
el	elements
nd	nodes
T	transpose symbol

Abbreviations

Al	aluminum material
Adv	advective
Cond	conductive
Cplg	coupling
div	divergence
ER	average error (%)
PVC	PVC material

(2009) have investigated using RANS simulations the convective heat transfer due to confined slot-jet impingement. The study aimed at giving a qualitative understanding of the effect of impingement plate motion on the resulting global and local heat transfer processes and quantitative effects of the variation of Nusselt number for a wide range of flow and geometric parameters. Nevertheless the authors pointed out that RANS turbulence models cannot predict heat transfer accurately. Moreover the authors noticed that the specification of the boundary conditions at the left and right open boundary of the calculation domain is problematic. The rightward movement of the bottom plate involves shear driven backflow into the calculation domain with unknown values of temperature and turbulence.

From the above bibliography it is clear that a need exists for experimental local data on heat transfer between a continuously moving flat surface and a jet impinging on it. Inverse heat conduction techniques can be implemented for estimating heat flux on the external surface of a conductive medium through the use of experimental temperature measurements within or on the surface of the body. In inverse heat conduction problem (IHCP) a surface heat flux is looked for at a boundary of the system, from temperature measurement made somewhere in the medium. Several authors used quantitative infrared thermography which is a very powerful technique for temperature measurements (Vintrou et al., 2013; Bougeard, 2007; Fenot et al., 2005). In the case of infrared thermography the temperature measurements are made on a surface of the conduction system. Gradeck et al. (2012) determined using a two-dimensional inverse heat conduction problem the convective heat flux due to a water jet impingement on a disk. The temperature field on the rear face (opposite face of impingement) of the disk is measured by infrared thermography. The implemented method allows the transient cooling heat flux estimation from experimental rear face thermogramm. Ryfa and Bialecki (2011) used also an inverse technique for the determination of the heat transfer coefficient in an application of hot air jet impinging on a disk. Temperatures on the rear face of the disk are measured by infrared thermography. The inverse technique is aimed at retrieving, space dependant and constant in time, distribution of heat transfer coefficient from the measured temporal variation of temperature at selected points.

To the best of our knowledge there is no experimental work in the literature concerning the determination of heat flux spatial distribution at the air jet flow impingement on a moving surface. Such an experimental determination is difficult because of the convective and advective nature of the problem. The movement of the plate generates advective heat flux in the material when we are placed in a steady state Eulerian frame. The final goal of present work is to design an experimental method with an inverse technique allowing the determination of convective heat flux due to jet impingement on a moving conducting wall, using IR temperature measurement on the face of impingement. The experimental apparatus is the same as the slot jet experiment configuration on a moving surface presented in (Senter and Solliec, 2007). This experimental configuration and the experimental procedure are presented in the next section. In this article, we will focus on the inverse method for analyzing in details its strengths and weaknesses. Hence, in the present work, the inverse developed technique is validated against simulated measurements (and no real measurements) as if they were coming from physical sensors. The simulated measurements are obtained using CFD results as explained in Section 4.1. The objectives are to illustrate the effectiveness of the inversion process in assessing the accuracy and

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