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Velocity and temperature profiles, wall shear stress and heat transfer coefficient of turbulent impinging jets

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ABSTRACT

The purpose of this work is to present a set of empirical equations that can be used to predict the flow dynamics and the heat transfer properties of impinging jets over a wide range of Reynolds number, nozzle-to-plate spacing and radial position along the impingement plate. The parametrization scheme proposed by Loureiro and Silva Freire (Int. J. Heat Mass Transfer, 55 (2012), 6400–6409) is used here for the prediction of the mean flow field properties. In particular, the scaling for maximum velocity distribution along the impingement plate is extended to account for nozzle-to-plate distance and Reynolds number dependence. A new methodology for the calculation of the wall shear stress is also presented. The experimental data set of Guerra et al. (Int. J. Heat Mass Transfer, 48 (2005), 2829–2840) is used to propose a description of the full mean temperature profile for the wall jet region that follows a Weibull distribution. In all, eleven different experimental data sets are considered to propose working expressions that include a piecewise Nusselt number expression that furnishes a solution valid over the whole domain of the impingement plate, including the stagnation point and the wall jet region. New values are proposed for the power indexes and multiplicative parameters. The parametric analysis considers that the flow properties can be determined in terms of gross parameters like the free-jet momentum flux.

1. Introduction

Progress on the understanding of the fundamental physics of impinging jets is often troubled by the large number of parameters that are needed to define the problem. Very often authors limit their observations and theoretical analysis to the discussion of one or two aspects of specific interest. The inlet conditions (geometry and flow conditions), the nozzle-to-plate spacing, the effects of Reynolds number, the role of vortical structures, e.g., are a few of the many subjects of permanent interest.

The fragmented manner in which results are presented in literature naturally poses expected difficulties for the advancement of consolidated theories. For example, it is difficult to find a work where both the flow dynamics and the transfer of heat are discussed simultaneously. In particular, the experimental characterization of some parameters is notoriously difficult to find. The distributions of wall shear stress and local temperature profiles are typical examples.

The present work discusses both the velocity and temperature fields from the point of view of the theories introduced in Guerra et al. [1] and Loureiro and Silva Freire [2]. The parametrization scheme proposed by Loureiro and Silva Freire [2] for the maximum velocity distribution along the impingement plate is extended to account for nozzle-to-plate distance and Reynolds number dependence. The experimental results of Loureiro and Silva Freire [2] are used to validate a new methodology for the calculation of the wall shear stress. The turbulent impinging jet data set of Guerra et al. [1] is considered, to propose a description of the full mean temperature profile for the wall jet region that follows a Weibull distribution. The work also examines other nine different experimental data sets and ten different Nusselt number correlations to propose piecewise Nusselt number expressions, whose combination furnishes a solution that is valid over the whole domain of the impingement plate, including the stagnation point and the wall jet region. New values are proposed for the power indexes and multiplicative constants after a detailed analysis of eight different data sets is carried out.

The current new expressions are based on the data sets of Guerra et al. [1], Loureiro and Silva Freire [2], Poreh et al. [3], Fairweather and Hargrave [4], Fitzgerald and Garimella [5], Koseoglu and Baskayab [6], Huang and El-Genk [7], O'Donovan and Murray [8], Ozmen and Baydar [9], Katti and Prabhu [10] and Goldstein and Behbahani [11].

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Nomenclature

A, A_1, A_2	parameters in velocity law of the wall
a, b, c	parameters in Nusselt number expressions
B, B_1, B_2	parameters in temperature law of the wall
C_1, C_2	parameters in power-law expressions
c_p	specific heat
D	nozzle diameter
h	heat transfer coefficient
H	nozzle-to-plate distance
k	thermal conductivity
n_1 to n_5	parameters in the correlations for Nusselt number
m_1, m_2	parameters in power-law expressions
M_j	jet momentum flux ($=DU_j^2$)
N_u	Nusselt number ($=hD/k$)
P_r	Prandtl number ($=\nu/\alpha$)
q_w	wall heat flux
r	radial distance on the impingement plate
R_e	Reynolds number ($=(DM_j)^{1/2}/\nu$)
T_j	free-jet temperature
T_w	wall temperature
t_τ	friction temperature ($=q_w/(\rho c_p u_\tau)$)
U, u	longitudinal velocity component
U_j	jet bulk velocity
u_τ	friction velocity
r, y	flow cartesian coordinates located at the center of the impingement plate
$y_{0.5}$	position of the half-maximum value (for velocity and temperature distributions).

Greek symbols

α	thermal diffusivity ($=k/(\rho c_p)$)
$\beta, \gamma, \lambda, \sigma, \zeta$	parameters in Weibull distribution
Δ_1	shape factor for the velocity distribution in the wall jet region
$\varkappa$	von Karman's constant (=0.4)
$\varkappa_t$	von Karman's constant, temperature profile (=0.44)
μ	absolut viscosity
μ	mean value
ν	kinematic viscosity
ρ	density
σ	standard deviation
τ	shear stress.

Subscripts

min	local minimum
max	local maximum
w	wall condition

The use of analytical or empirical expressions for the description of complex problems offers obvious advantages in desired applications. The non-linear and multi-scale character of the Navier–Stokes equations for high-Reynolds number flows makes any attempt at resolving the smallest dynamically important scales an extremely difficult affair due to the very fine meshes and time steps that must be considered. Even numerical approaches that resort to averaged equations and closure modelling are very expensive. The objective implication is that methods which resort to local perturbation techniques, parametric analysis and experimental correlations can be very useful to introduce near wall solutions. These methods define simple working rules and predictive mathematical relations to describe the main characteristics of rapidly varying local solutions [12,13].

Many authors emphasize that one issue that needs to be adequately discussed is the high heat and mass transfer characteristics of impinging jets. The existing voluminous bibliography on the experimental, theoretical and numerical aspects of the problem has not, for instance, completely explained the appearance of distinct peaks in the radial distribution of the Nusselt number [14]. The adequacy of turbulence models and near-wall approaches is also a subject of considerable dispute as argued by Pulat et al. [15].

The analysis conducted in the present work follows the approach introduced by Narasimha et al. [13] and considers that the flow properties can be determined in terms of gross parameters like the jet momentum flux ($=DU_j^2$) and the wall heat flux (q_w). The existence of near wall logarithmic regions for the velocity and temperature fields is also considered as presumed by Özdemir and Whitelaw [16], Guerra et al. [1] and Loureiro and Silva Freire [2].

2. Impinging jet flow configuration

The complex configuration of the flow dynamics of an impinging jet has been illustrated in the visualization study of Popiel and Trass [17]. The existence of large-scale ordered structures is evident and determines much of the flow properties as discussed in the LES simulation results of Uddin et al. [14]. The evolution and breakdown of the jet ring vortices is further discussed in the LES investigation of Hadziabdi and Hanjalic [18].

A theoretical treatment of impinging jets is possible provided the flow domain is divided into regions where dominant physical effects can be singled out and local solutions found. One common procedure is to divide the flow into four regions. The four regions identified by Poreh et al. [3] are: the free-jet transition region, the free-jet region, the deflection zone and the radial wall jet (see Fig. 1). The classification of Phares et al. [19] divides the flow into the free jet region (consisting of near-field and far-field regions), the inviscid impingement region, the impingement boundary layer and the wall jet region (see Fig. 2). Of course, both pictures of the flow can be merged provided the deflection zone of Poreh et al. [3] is seen as a combination of the inviscid impingement region and the impingement boundary layer.

In their analytical approach to problem solution, Phares et al. [19] propose inviscid and boundary layer solutions to determine the wall shear stress in the small region of flow located just above

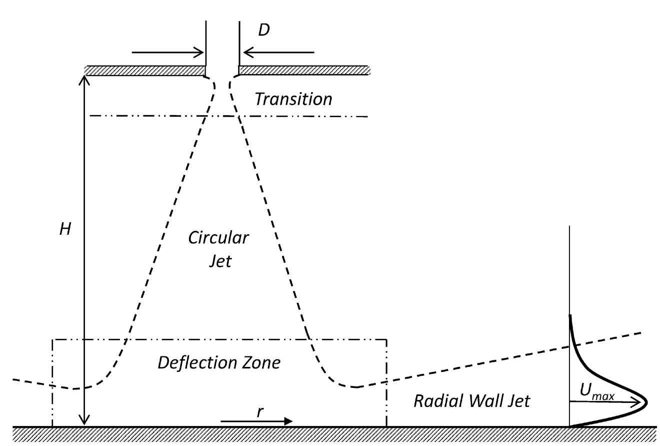

Fig. 1. Impinging jet flow configuration according to Poreh et al. [3].