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Simulation of turbulent impinging jet into a cylindrical chamber with and without a porous layer at the bottom

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ABSTRACT

Turbulent impinging jets on heated surfaces are widely used in industry to modify local heat transfer coefficients. The addition of a porous substrate covering the surface contributes to a better flow distribution, which favors many engineering applications. Motivated by this, this work shows numerical results for a turbulent impinging jet into a cylindrical enclosure with and without a porous layer at the bottom. The macroscopic time-averaged equations for mass and momentum are obtained based on a concept called double decomposition, which considers spatial deviations and temporal fluctuations of flow properties. Turbulence is handled with a macroscopic k–ε model, which uses the same set of equations for both the fluid layer and the porous matrix. The numerical technique employed is the control volume method in conjunction with a boundary-fitted coordinate system. One unique computational grid is used to compute the entire heterogeneous medium. The SIMPLE algorithm is applied to relax the system of algebraic equations. Results indicate that the permeability of the porous layer and the height of the fluid layer significantly affect the flow pattern. The effect of the porous layer thickness was less pronounced in affecting the flow behavior in the fluid layer.

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1. Introduction

Impinging jets are flow systems where an ejector is used to create a high-speed flow colliding against an obstacle. Near the stagnation point, velocity gradients tend to be high favoring localized mass and heat transfer mechanisms. As such, these jets are widely used in industry, mostly as devices to promote and control localized heat and mass transfer rates. Common industrial applications for impinging jets are cooling of metals in steel industry, glass tempering and ventilation of electrical components. Since the majority of applications uses air and water as the cooling fluid due to their relatively low viscosity, flow velocity tends to be high and the study of impinging jets in turbulent regime becomes necessary.

Most studies about turbulent impinging jets available in the literature refer to heat transfer obtained with a coolant flowing through a clear medium (non-porous), before reaching a surface. Two-dimensional jets in laminar regime are investigated in Law et al. [1], who made an extensive numerical analysis of the hydrodynamic characteristics of a 2D jet impinging normally against a flat plate. They found differences in the size of the recirculating bubble depending on the length of the confining plates. Baydar [2] experimentally evaluated the hydrodynamics characteristics of single and double jets colliding against a plate. Chalupa et al. [3] analyzed the mass transfer induced by a bidimensional turbulent jet and Park et al. [4] made a comparison between different numerical methods in flow resolution for both laminar and turbulent regimes.

The study of transport phenomena in porous media is relatively new. In the last decade, a number of analyses were published in the literature due to its great potential for innovative technological applications. For example, thermal performance of porous media was studied by Vafai et al. [5] evaluating the heat transfer of a hybrid medium. Huang and Vafai [6] investigated the heat transfer of a flat plate covered with a porous insert. Effects of the insertion of a porous medium in a fluid stream were evaluated by Hadim [7], who investigated the flow of a channel both fully and partially filled with a porous insert. In the recent years, a number of papers have been published covering a very wide range of problems involving flow and heat transfer in permeable media [8–17], including flows parallel to a layer of porous material [18] and across baffles made of permeable media [19,20].

Investigation on configurations concerning perpendicular jets into a porous core is much needed for optimization of heat sinks attached to solid surfaces. However, studies of porous medium under impinging jets are yet very scarce in the literature. Examples of this kind of work are in Prakash et al. [21,22], who presented an experimental and numerical study of turbulent jets impinging on a porous layer. Fu et al. [23] evaluated the thermal performance of different porous media under an impinging jet. Another example is of numerical simulations by Kim & Kuznetsov [24], who investigated optimal characteristics of impinging jets into heat sinks. Re-

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Nomenclature

Latin characters

c_1	Non-dimensional turbulence model constant
c_2	Non-dimensional turbulence model constant
c_F	Forchheimer coefficient
c_k	Non-dimensional turbulence model constant
c_μ	Non-dimensional turbulence model constant
D	Collision plate diameter
D_j	Jet nozzle diameter
H	Clear medium height
H_c	Height of main recirculating bubble
h_p	Porous layer height
K	Permeability of the porous medium
k	Turbulence kinetic energy per mass unit, $k = \overline{\mathbf{u}' \cdot \mathbf{u}'}/2$
$\langle k \rangle^i$	k intrinsic average
R	Radius of cylindrical chamber
R_c	Radius of main recirculating bubble
r/R	Dimensionless radial position
w	Exit flow ring length
z	Axial distance from collision plate
z/H	Dimensionless axial distance from collision plate

Greek characters

ε	Dissipation rate of k
$\langle \varepsilon \rangle^i$	Intrinsic average of ε
ϕ	$\phi = \Delta V_f/\Delta V$, Porosity
μ	Dynamic viscosity
$\mu_{t\phi}$	Macroscopic turbulent viscosity
ρ	Density
σ_k	Non-dimensional constant
σ_ε	Non-dimensional constant
σ_T	Non-dimensional constant
τ_w	Wall shear stress, $\tau_w = \mu \frac{du}{dy}$

Special characters

φ	General variable
$\bar{\varphi}$	Time average
φ'	Time fluctuation
$\langle \varphi \rangle^i$	Intrinsic average

cently, Saeld, N.H [25] presented computations for laminar flow of a jet entering a porous layer. He investigated the effect of cross flow on heat transfer characteristics.

This work uses the methodology proposed by Pedras and de Lemos [27,28], who developed a macroscopic two-equation model for turbulent flow in permeable matrices. The problem of turbulent flow parallel to a layer of porous material was later investigated by de Lemos [29] and de Lemos and Silva [30]. Recently, in an accompanying paper [31], laminar normally imping jets onto a flat layer of porous medium were studied, aiming at contributing to the understanding of flow structure in that configuration. Such flow cases, concerning perpendicular turbulent jets into a porous core, are much needed for optimization of heat sinks attached to solid surfaces. To this end, this contribution extends the work in [31], considering now turbulent flow regime simulated with the macroscopic k–ε model of [27,28].

2. Geometry and physical system

The problem considered is schematically presented in Fig. 1a, which shows the same geometry used by Prakash et al. [21,22]. The reason for choosing the same geometry as in the pioneering work of [21,22] was to be able to validate the computations herein with the experimental data provided by them. As shown in the figure, a fluid jet enters a cylindrical chamber through an aperture in an upper disk. An annular clearance between the cylinder lateral wall and the disc allows fluid to flow out of the enclosure. The incoming jet diameter, D_j, is 0.019 m and the inner cylinder diameter, D, is 0.39 m. The clearance between the cylinder and the disc holding the jet has a width, w, equal to 0.005 m. At the bottom of the chamber, a layer of porous material covers the surface and is hit by the incoming jet. Three different heights of fluid column above the porous substrate, H, namely 0.05 m, 0.1 m and 0.15 m, were used in the simulations. Two thicknesses of the porous layer, h_p, were considered, namely 0.05m and 0.1 m. The average velocity of the incoming jet was 1.6 m/s representing a Reynolds number of 30,000, which was based on the jet exit diameter. Different velocities were also used when evaluating the influence of Reynolds number on the main flow. The two other values 1.0 and 2.5 m/s corresponded to Re = 18,900 and 47,000, respectively. Turbulent results for streamfunction, velocity and turbulence kinetic energy profiles are compared here with those from Prakash et al. [21,22].

3. Mathematical model

Before continuing, a word about the class of turbulence model applied here seems timely. The mathematical framework for treating turbulent flow in porous media, used in this work, is based on a macroscopic version of the standard k–ε model of Jones and Launder (1972) [26]. It is well known in the literature, for nearly two decades, the shortcomings and limitations of the k–ε in predicting separation over curved surfaces, size of recirculation bubbles in sudden expansions/contractions and in flows subjected to strong normal strains, as in impinging jets onto solid surfaces. All of these examples, however, refer to free flows with no porous body embedded into the domain of calculation. Accordingly, the objective here was twofold. First, to simulate the flow in Fig. 1 with one unique set of equations, valid for both the porous substrate and the fluid layer. Secondly, to use a mathematical framework that has the characteristics of easy of programming in existing codes and the desirable advantages of numerical robustness and stability, which is obtained via the diffusion-like stress-strain relation inherent to the k–ε model. For these reasons, the two-equation model of [26], which was extended to hybrid media (free/porous regions) by [27], is used here. Also, further justification for using the k–ε level of closure in the flow of Fig. 1 is presented in Prakash et al. [21].

As mentioned, the mathematical model here used takes into account a systematic development presented in a series of papers already available in the open literature [27–30], where all equations and their mathematical derivations can be found. Therefore, these equations will be just reproduced here and details about their derivations can be obtained in the mentioned papers. In addition, the development in [27–30], has been extended to non-buoyant heat transfer under local thermal equilibrium [32,33], buoyant flows [34–41], mass transfer [42] and double diffusion [43], including applications to channel with porous inserts [44] and moving porous beds [45,46]. In that development, it was assumed that the porous matrix was homogeneous, rigid, steady and saturated by an incompressible fluid. Also, all physical properties were kept constant.

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