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NUMERICAL SIMULATION OF HEAT EXCHANGE FOR JET IMPINGEMENT

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1. INTRODUCTION

Jet technology is developed for many applications e.g. for jet cutting, jet drying systems, jet cooling, VTOL aircraft.... Experiments indicate that the heat exchange between the jet and the impinged wall near stagnation point is more intensive than in the parallel part of the flow.

Numerical simulation of the jet impingement problem without heat transfer is considered in [1, 2, 3]. The analogous problem with heat exchange between a two-dimensional slot jet and the wall is numerically conducted in [4, 5]. Some experimental works are also carried out in [6, 7, 8].

We consider a gas jet of axial symmetry impinging upon a flat wall. There are two possible cases: first, the temperature of the jet is higher than that of the wall (the jet heating case), and second, the jet is cooler than the wall (the jet cooling case). The main aim of our numerical simulation is the heat exchange near the stagnation point. For the sake of simplicity we assume that the flow is laminar and incompressible (as indicated in [4] this regime of motion may be realized if $d/H \ll 1$, the jet temperature is high enough and this temperature not much differs from that of the impinged wall).

2. PROBLEM FORMULATION

Suppose that a gas jet issuing from a nozzle of diameter 2d impinging upon a wall at the distance H from the nozzle orifice (fig. 1).

Let $T_w = \text{const}$ be the temperature of the wall. The governing equations of the problem then consist of the Navier-Stokes equations, the equation of continuity and the energy equation with variable properties of the medium:

$$\rho\Big(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + v\frac{\partial u}{\partial z}\Big) = -\frac{\partial p}{\partial r} + \frac{\partial}{\partial r}\Big(2\mu\frac{\partial u}{\partial r}\Big) + 2\mu\frac{\partial}{\partial r}\Big(\frac{u}{r}\Big) + \frac{\partial}{\partial z}\Big[\mu\Big(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r}\Big)\Big] \tag{2.1}$$

$$\rho\Big(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial r} + v\frac{\partial v}{\partial z}\Big) = -\frac{\partial p}{\partial z} + \frac{\partial}{\partial z}\Big(2\mu\frac{\partial v}{\partial z}\Big) + \frac{1}{r}\frac{\partial}{\partial r}\Big[r\mu\Big(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r}\Big)\Big] \tag{2.2}$$

$$\frac{\partial u}{\partial r} + \frac{u}{r} + \frac{\partial v}{\partial z} = 0 \tag{2.3}$$

$$\rho c\Big(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial r} + v\frac{\partial T}{\partial z}\Big) = \frac{1}{r}\frac{\partial}{\partial r}\Big(\lambda r\frac{\partial T}{\partial r}\Big) + \frac{\partial}{\partial z}\Big(\lambda\frac{\partial T}{\partial z}\Big) +$$
$$+ \mu\Big\{2\Big[\Big(\frac{\partial u}{\partial r}\Big)^2 + \Big(\frac{u}{r}\Big)^2 + \Big(\frac{\partial v}{\partial z}\Big)^2\Big] + \Big(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r}\Big)^2\Big\} = 0 \tag{2.4}$$

Now let V, L, $\Delta T = T_{\max} - T_w$, $\tau = L/V$ be the characteristic values for the gas motion (How to choose them will be mentioned latter). Using these values we reduce (2.1) - (2.4) to the following nondimensional form (for simplicity we use the former denotations for r, z, u, v, p, t):

$$\frac{\partial u}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(ru^2) + \frac{\partial}{\partial z}(uv) - \frac{2}{Re}\Big[\frac{\partial}{\partial r}\Big(f\frac{\partial u}{\partial r}\Big) + f\frac{\partial}{\partial r}\Big(\frac{u}{r}\Big)\Big] - \frac{1}{Re}\frac{\partial}{\partial z}\Big(f\frac{\partial u}{\partial z}\Big) =$$
$$= \frac{1}{Re}\frac{\partial}{\partial z}\Big(f\frac{\partial v}{\partial r}\Big) - \frac{\partial p}{\partial r} \tag{2.5}$$
$$\frac{\partial v}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(ruv) + \frac{\partial}{\partial z}(v^2) - \frac{1}{Re}\frac{1}{r}\frac{\partial}{\partial r}\Big(rf\frac{\partial v}{\partial r}\Big) - \frac{2}{Re}\frac{\partial}{\partial z}\Big(f\frac{\partial v}{\partial z}\Big) =$$
$$= \frac{1}{Re}\frac{1}{r}\frac{\partial}{\partial r}\Big(rf\frac{\partial u}{\partial z}\Big) - \frac{\partial p}{\partial z} \tag{2.6}$$
$$\frac{1}{r}\frac{\partial}{\partial r}(ru) + \frac{\partial v}{\partial z} = 0 \tag{2.7}$$
$$s\Big[\frac{\partial \theta}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(ru\theta) + \frac{\partial}{\partial z}(v\theta)\Big] - \alpha\Big[\frac{1}{r}\frac{\partial}{\partial r}\Big(rg\frac{\partial \theta}{\partial r}\Big) + \frac{\partial}{\partial z}\Big(g\frac{\partial \theta}{\partial z}\Big)\Big] =$$
$$\beta f\Big\{2\Big[\Big(\frac{\partial u}{\partial r}\Big)^2 + \Big(\frac{u}{r}\Big)^2 + \Big(\frac{\partial v}{\partial z}\Big)^2\Big] + \Big(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r}\Big)^2\Big\} \tag{2.8}$$

This form of the equations is convernient for later using the Hybrid scheme for numerical calculation of (2.5) - (2.8). Here we use the following denotations:

$$\alpha = \frac{\lambda_0}{LV\rho C_0} = \frac{1}{Pr}\frac{1}{Re}, \quad Pr = \frac{\mu_0 C_0}{\lambda_0} \quad \text{Prandtl number}$$

$$\beta = \frac{\mu_0 V}{L\rho C_0 \Delta T} = \frac{Ec}{Re}, \quad Ec = \frac{V^2}{C_0 \Delta T} \quad \text{Eckert number}$$

$$\mu = \mu_0 f(\theta); \quad \lambda = \lambda_0 g(\theta); \quad C = C_0 s(\theta); \quad \theta = \frac{T - T_w}{\Delta T}$$

where μ_0, λ_0, C_0 are viscosity, heat conductivity and specified heat of the gas at the certain temperature, hence functions $f(\theta)$, $g(\theta)$, $s(\theta)$ experess the dependence of these properties on temperature.

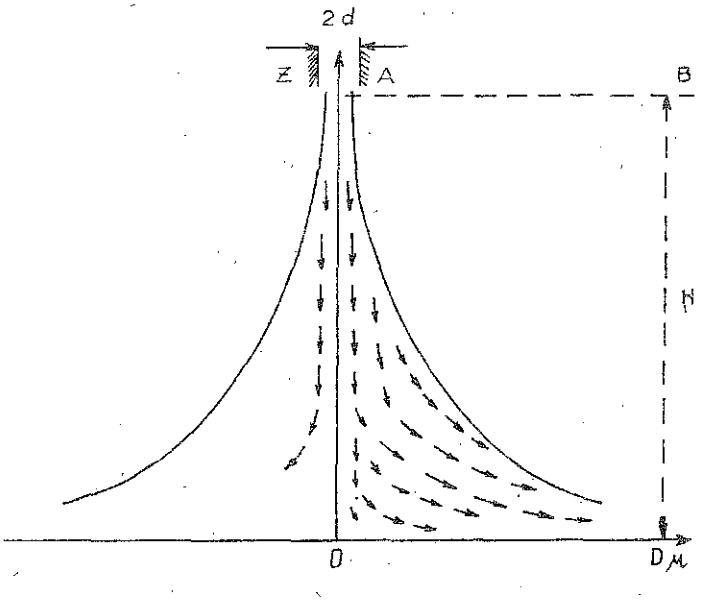

Fig. 1

By virtue of the symmetry of the jet the boundary conditions to (2.5)-(2.8) are set as follows:

on AB (inflow) [12]:

$$v = v(r); \quad u = 0; \quad \theta = \theta(r); \quad p = p_a \tag{2.9}$$

where p_a is the pressure of the circumstances.

on AO (jet axis):

$$u = 0; \qquad \frac{\partial v}{\partial r} = \frac{\partial p}{\partial r} = \frac{\partial \theta}{\partial r} = 0 \tag{2.10}$$

on BD (outflow) [9]:

$$\frac{\partial u}{\partial r} = \frac{\partial v}{\partial r} = \frac{\partial p}{\partial r} = \frac{\partial \theta}{\partial r} = 0 \tag{2.11}$$

on OD (wall) [9]:

$$u = v = \theta = 0; \quad \frac{\partial p}{\partial n} = -\frac{1}{Re}\frac{\partial \varsigma}{\partial r} \tag{2.12}$$

where $\varsigma = \dfrac{\partial u}{\partial z} - \dfrac{\partial v}{\partial r}$

3. NUMERICAL SIMULATION

In [3] the authors have calculated the velocity and pressure fields using the vorticity and streamfunction variables. This method requires a special manipulation of the boundary condition for the vorticity especially on rigid surfaces. In this paper we use the so called SIMPLES METHOD described in [9] to solve the above posed problem in physical variables: u, v, p, T. It is necessary to note that at large Reynold numbers all physical parameters of the motion vary very strongly near the wall. To overcome this difficutly we have to use there a sufficiently fine gride. The computational practice shows also that the central finite difference scheme losses stability when a strongly irregular gride is used, especially at large Reynold numbers. Here for approximating both the dynamical and heat transfer equations we apply the hybrid scheme in the combination with the alternating directions implicit method [10]. In the hybrid approximation central differences are used when the magnitude of the convective term is smaller than the corresponding diffusion term and in the opposite case the "upwind" scheme is applied. For the numerical procedure the Thomas's algorithm [9] is used also to solve the obtained system of the difference equations.

4. NUMERICAL RESULTS

In this paper for the jet substance we choose steam. For the inflow condition for the velocity we use the parabolic form given in [3]:

$$v(r) = -(1 + C_2 r^2)^{-2}, \quad C_2 = \sqrt{2} - 1$$

and for the temperature we take the following profile [11]:

$\theta(r) = v(r)^{Pr}$ where Pr is Prandtl number and for steam we take $Pr = 1$. All calculations in this paper are conducted for steam at 100°C. The Reynold number is arranged between 1000 and 1000000 and the difference between the jet temperature and that of the wall is accepted to be 5°C. At large Re ($10^5 \div 10^6$) the grid near the wall is taken in three hundred times finer than that near the jet exit and the grid near the jet axis is in ten times finer than that in the uniform part of the flow. The profiles of the u - component, v - component of the gas velocity, pressure and temperature at some distances from the wall are shown in Fig. 2, 3, 4, 5 respectively. Fig. 6, 7 respresent isolines for the pressure and temperature and their distribution in (r,z) coordinate is shown in fig. 8, 9 respectively. The heat transfer at the wall is represented in the fig. 10. The result shows an intensive heat exchange near the stagnation point. Far from the jet axis the heat exchange rate coincides with that of the parallel flow [12].

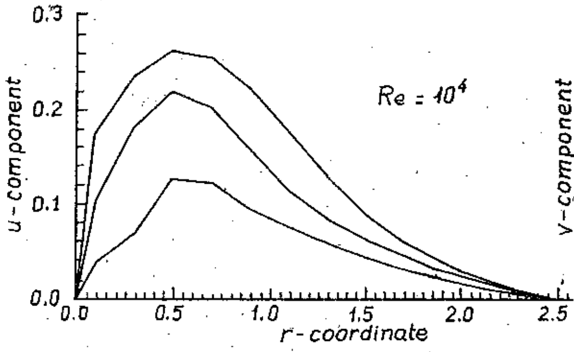

Fig. 2

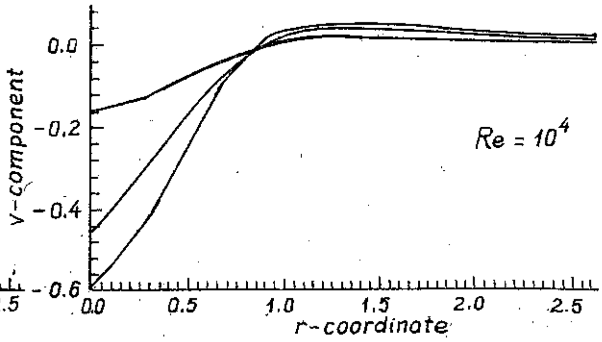

Fig. 3

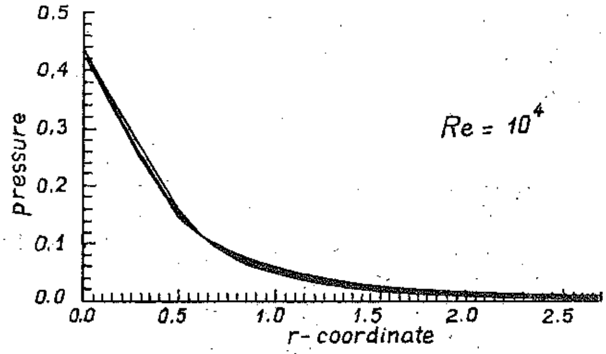

Fig. 4

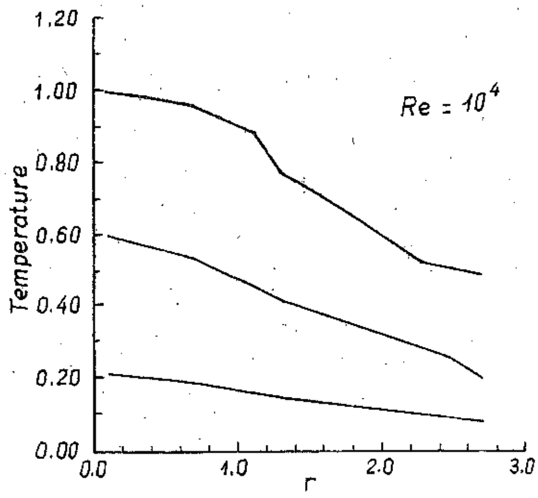

Fig. 5

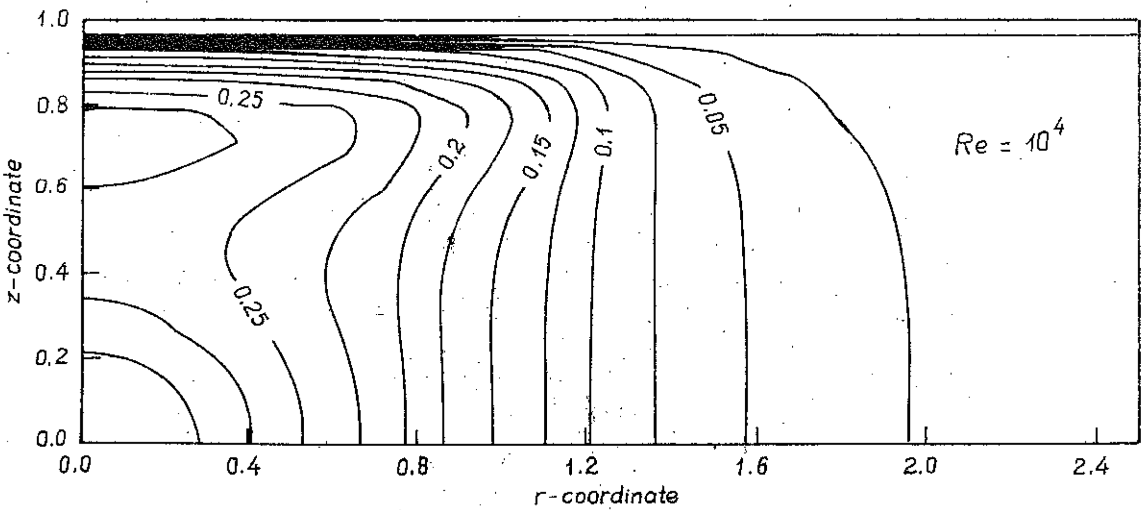

Fig. 6. P - izoline

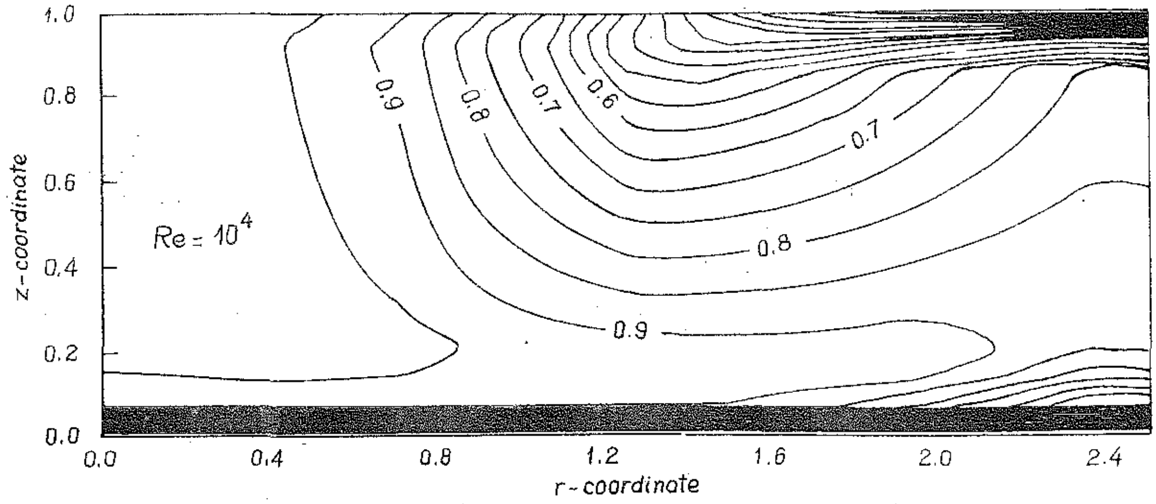

Fig. 7. T - izoline

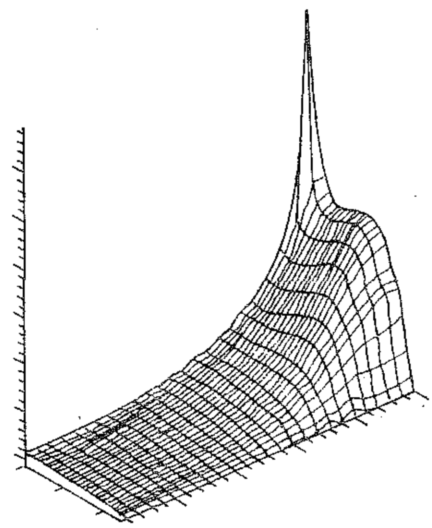

Fig. 8

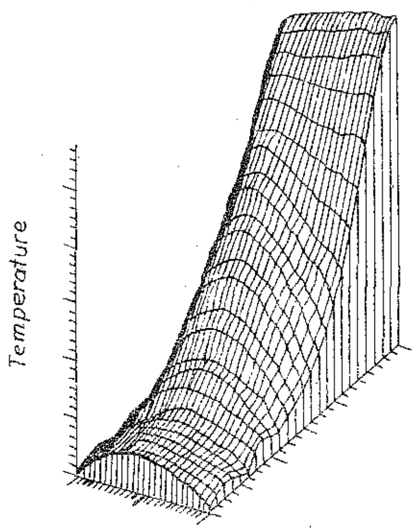

Fig. 9

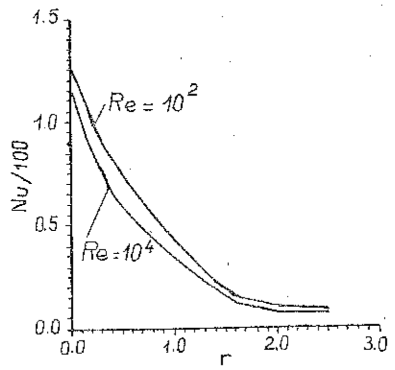

Fig. 10

5. CONCLUSION

In accordance with experimental data the obtained results show that jet impingement is a very good way for heat exchange between a gas flow and a solid surface. It is especially effective when the local heating or cooling is needed. In the former case when the temperature difference between the jet and the wall is sufficiently large the condensation on the surface of the wall may be realized. This very complicated phenomenon will be discussed in a separated paper.

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MÔ PHỎNG SỐ TRAO ĐỔI NHIỆT GIỮA DÒNG TIA VA ĐẬP VÀ THÀNH CỨNG

Dòng tia va đập được dùng nhiều trong thực tế, ví dụ như để cắt vật cứng, trong kỹ thuật làm lạnh hay nung nóng, trong kỹ nghệ sấy, trong công nghệ chế tạo các máy bay cất cánh thẳng đứng ... Trong bài báo này quá trình trao đổi nhiệt giữa dòng tia và thành cứng bị va đập được mô phỏng bằng phương pháp số. Các kết quả nhận được cho thấy hiệu xuất rất cao của dòng tia va đập so với dòng chảy song song.