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Numerical simulations of flow and heat transfer of rectangular impinging jets in rows

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ABSTRACT

Flow and heat transfer of rows of laminar rectangular impinging jets have been determined from the numerical solution of Navier-Stokes and energy-equations. The jets are in-line (ie. discharging axially) or radial (ie. discharging from the sides). Results show that depending on the Reynolds number and the geometry, the jet interaction can cause flow separation and vortices. With increasing Reynolds number the flow becomes periodic and eventually chaotic.

INTRODUCTION

Impinging jets are used for heating, cooling or drying of surfaces. They find applications in paper, glass or textile industries and electronic cooling. These jets discharge from round or rectangular slots. They can be axial or radial. An axial jet produces large transfer rates at the point of impinging. Away from the impinging point the transfer rate decreases rapidly.

A radial jet discharges from the side of the feed tube and reattaches on the impinging plate because of the Coanda effect. Here one obtains instead of a reattachment point a reattachment line in form of a closed curve. The transfer coefficient is moderately high on the reattachment line and decreases away from it. For a round feed tube the reattachment line is a circle and its radius depends on geometrical and flow parameters. The main advantage of a radial jet is that the moderately high heat or mass transfer can be distributed on a larger area than for the axial jet, the size and the location of this area as well as the flux density can be easily controlled by changing the geometrical parameters (e.g. h, distance between the jet and the impinging plate or ϑ the angle of inclination of the jet axis with respect to the impingement surface) or the Reynolds number at the jet discharge. For an axial jet these parameters can change essentially the flux density at the reattachment point.

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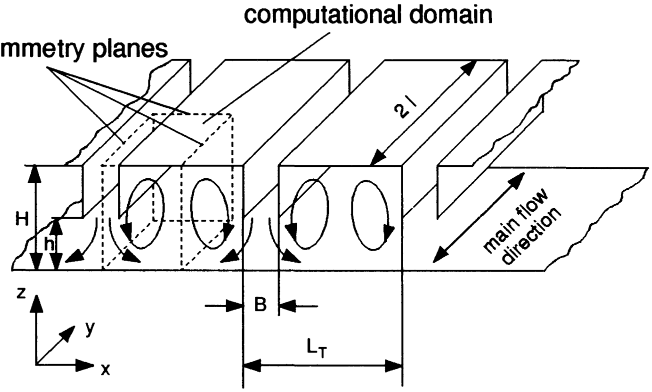

Fig. 1: Schematic of an axial slot nozzle bank

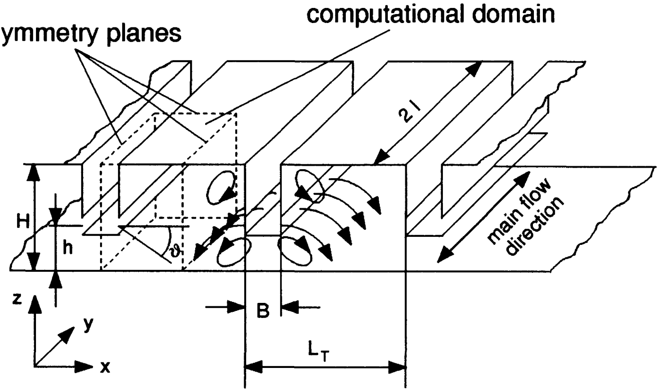

Fig. 2: Schematic of an radial slot nozzle bank

Martin [1], Viskanta [2] have summarized a large number of experimental studies of mass and heat transfer by impinging axial circular and rectangular jets. In practice these jets are generally turbulent or undergo transition before or after impinging on the products surface.

Numerical simulation of turbulent impinging jets by standard turbulence modes is inadequate because of the strong curvature effects and large deceleration and acceleration in the impingement area. A direct numerical simulation or at least large eddy simulation of the impinging jet, although requires large computer memory and time, is our final goal. As a first step we study in this work laminar impinging jets.

The flow structure of an impinging jet, especially that of an radial jet can be highly complex because of the separation, generation of vortices and flow entrainment. The flow develops like a wall jet after the impingement. But away from the impinging wall, there is a back flow and the ambient fluid flows in the opposite direction as the jet. Hence the complete flow field and heat transfer on the impingement plate can be simulated only from the solution of the full Navier-Stokes and energy equations. This is the purpose of the present work.

BASIC EQUATION AND METHOD OF SOLUTION

Figure 3 shows the computational domain for an axial jet. This consists of one element of the jet bank. The element is bounded by symmetry planes on three sides. These are the two midplanes of the slot nozzle and the boundary between two neighbouring nozzles.

The flow is described by non-steady three-dimensional continuity, momentum (Navier-Stokes) and energy equations for an incompressible fluid with constant properties.

In nondimensional index form these equations read as

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_i\, u_j)}{\partial x_i} + \frac{\partial p}{\partial x_i} = \frac{\nabla^2\, u_i}{Re}$$

$$\frac{\partial T}{\partial t} + \frac{\partial (u_i T)}{\partial x_i} = \frac{\nabla^2 T}{RePr}$$

Here u_i are cartesian velocity components non-dimensionalized by u_{av} which is the average velocity at the jet discharge. The lenghts have been nondimensionalized by 2B.

The height of the jet and the impingement plate is h. H is the height of the upper wall. The slot width is B, length is 21 and the distance between slots is L_T.

The temperature has been nondimensionalized by the difference of the jet exit and the impingement plate temperatures. The Reynolds number Re is $u_{av}2B/\nu$

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and the Prandtl number Pr = ν/a where ν and a are dynamic viscosity and the thermal diffusivity respectively.

At the jet exit the temperature is constant and the velocity is either uniform or corresponds to the fully developed channel flow, No-slip condition on the impingement plate and the symmetry conditions on the symmetry plane have been used. On the exit plane first derivatives of flow variables are set equal to zero.

The basic equations have been solved by a finite volume scheme based on the SIMPLE-C [3] technique. Certain modifications of the original SIMPLE-C have been done in order to permit back flow at the exit plane [4].

RESULTS AND DISCUSSION

Flow fields of impinging three dimensional laminar axial and "radial" jets issuing from a bank of rectangular feed tubes have been computed with 10300, 71400 and 530400 grid points. Only an element of the jet bank is the computational domain, see figs 3 for an axial jet. Results have been obtained for Re = 50, 100, 150, 250 and 500. For the jets the relative jet area $f = B/L_T$ (B = width of the feed tube, L_T = width of the impingement plate, see fig. 3) has been varied between 0.1 and 0.5. The distance between the jets is S = 2B and H/S = 1. Results show that a steady flow is obtained upto a Re of 650 ($Re = u_{av}2B/\nu$). For the Re = 700 the flow becomes periodic.

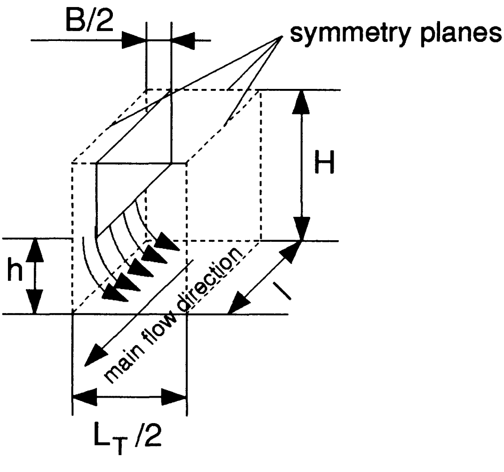

Fig. 3: Computational domain of one element of the jet bank (axial jet)

The structures of the steady flow for Re = 250 are shown with the help of streaklines in figs. 4, 5 and 6 for f = 0.125, 0.22 and 0.5 for axial jets.
The streaklines have been plotted with COMADI-graphic packet, Vollmers [5]. COMADI can search and plot areas where vortices appear. In the figures 7 to 9 dark-shaded areas indicate strong vortices. Because of the symmetry conditions on three sides the fluid after coming out of the tube may or may not hit the impingement plate, but moves up and then comes out of the computational domain. Through the upper part of the exit plane, ambient fluid moves into the computational domain. The flow structure is strongly dependent on f.

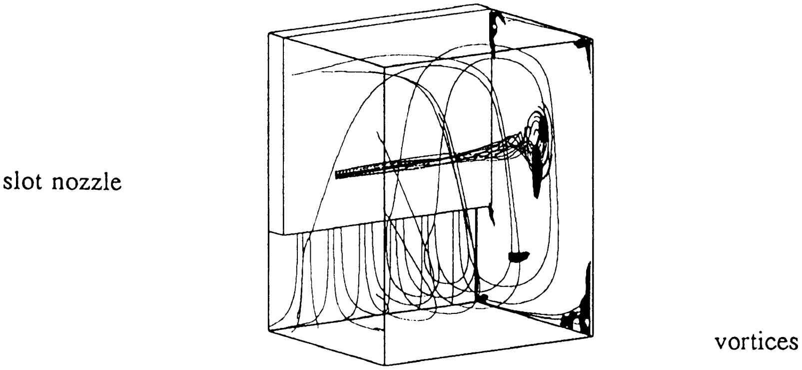

Fig. 4: Streaklines of an axial jet, f = 0,125 (f = B/L_T); Re = 250; steady solution

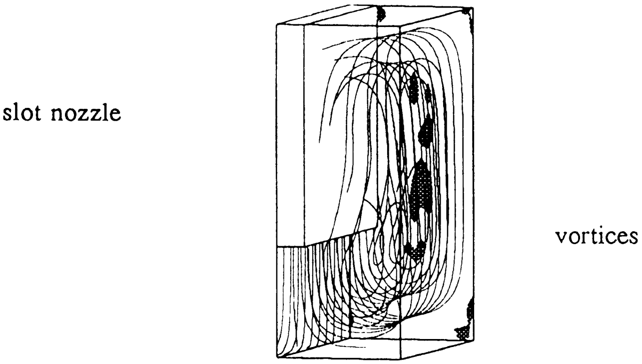

Fig. 5: Streaklines of an axial jet, f = 0,22 (f = B/L_T); Re = 250; steady solution

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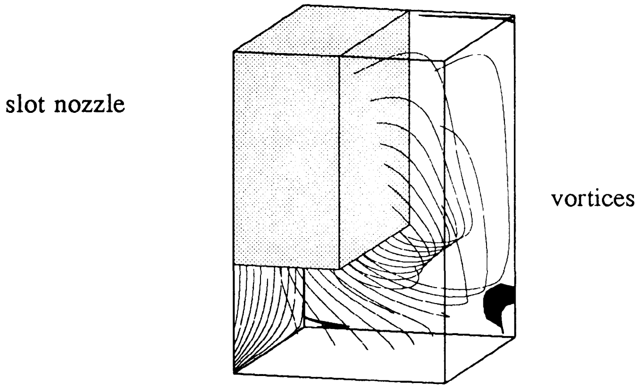

Fig. 6: Streaklines of an axial jet, f = 0,5 (f = B/L_T); Re = 250; steady solution

For turbulent jets Martin [1] found from experiments that the average Sherwood number Sh becomes maximum for an optimum value of f = 0.125 (for H/S = 1). Interestingly it was found from the computations that an optimum f exists also for laminar jets. The Nusselt number on the plate becomes maximum at an optimum f = 0.22.

Figure 7 shows $Nu_{av}/Re^{1/2}$ against f ($f=B/L_T$) for different H/S. Here Nu_{av} is the average impinging plate Nusselt number defined with the difference of the plate and the jet temperature. The optimum value of f increases with decreasing H/S. With H/S = 0.5 the optimum f becomes a plateau. This behavaior $Nu_{av}/Re^{1/2}$ vs. f for laminar jets agree qualitatively with the results of turbulent jets, see Martin [1].
Fig. 8 compares the average $Nu_{av}/Re^{0.76}$ vs. f ($f=B/L_T$) for radial jet and axial 3D jets for Re = 100, 200 and 500. We notice that for a radial jet an optimum f does not exist. In the log-log plot $Nu_{av}/Re^{0.76}$ increases almost linearly with f. Also surprising is Nu_{av} can be scaled by $Re^{0.76}$ in order to become Re-independent. For axisymmetric radial jets we found that with the increasing angle of jet inclination ϑ, the average Nu_{av} increases. For 3D jets we did similar computations.
Fig. 9 shows the average Nu_{av} vs. f for various angle of jet inclination. The Reynolds number is 250. With increasing f, the influence of ϑ on Nu_{av} becomes less prominent. For $\vartheta = 70°$ the effect of f on ϑ is weak and becomes negligible for f > 0.15.

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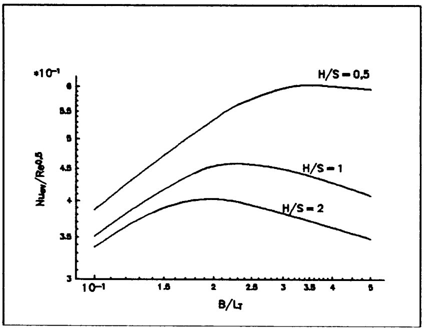

Fig. 7: the axial jet

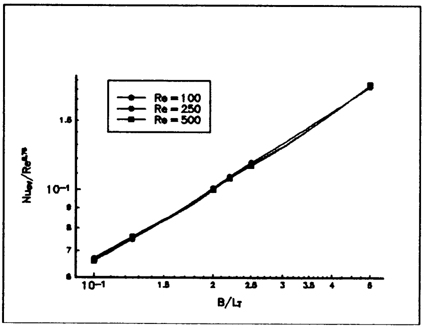

Fig. 8: Average Nusselt number for different B/L_T and Re ϑ for the 3D radial jet, Re = β = 0°

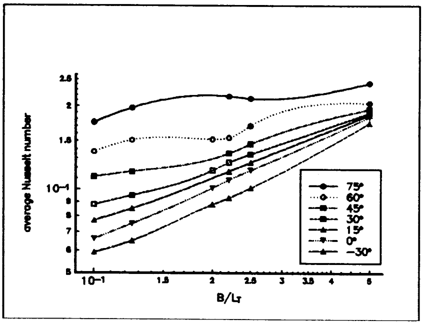

Fig. 9: Influence of B/L_T and ϑ on the average Nusselt number for the 3D radial jet, H/S = 1, Re = 250

CONCLUSION

Steady laminar impinging jet flows can be obtained at low Reynolds number which depends on the distance between the jets and the distance of the jet and the plate. If the jets are too close, the jet may not even impinge on the plate. An optimum value of the relative jet area giving the maximum Nusselt number on the plate can be determined.

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