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OSCILLATIONS OF SUBMERGED JETS CONFINED IN A NARROW DEEP RECTANGULAR CAVITY

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ABSTRACT

A jet flowing into a rectangular cavity in a two dimensional model produced a stable pattern of whole cavity oscillation over ranges of inlet flow rate. The frequency of oscillation was a function of flow rate, cavity size and jet orifice size. This confined jet oscillation was simulated using the computational package FLOW3D. The simulation showed that the oscillation results from a dynamic balance between the pressure difference across the jet and the momentum of the recirculating entrained flows. Oscillation frequency scaled on cavity space velocity for a range of experimental and industrial steel caster geometries.

INTRODUCTION

The two dimensional flow pattern of a jet into a blind cavity, where a steady input flow into a fixed geometry gave rise to a pulsatile exit flow, has been described previously (Molloy 1969, 1970). This investigation of flow in a narrow deep rectangular tank fed by a confined submerged jet is industrially significant as it typifies the flow domain of a thin slab steel casting machine (Honeyands 1994).

PHYSICAL MODEL

Measurements were made in a series of cavities constructed simply of a gasket between two polymethacrylate sheets, with a longitudinal slit delivering a water jet at the open top of the cavity. Figures 1 (a) and (b) are photo sequences of the oscillation pattern while Figure 4 indicates diagramatically the essential elements. The "top" of the cavity was defined by the transverse line through the jet exit. The outflows passed either side of the entry jet duct. The flow pattern consisted of vortices formed alternately on each side of the jet, switching to and fro within the confines of the cavity. Variations to define the controlling elements of the geometry included extending the side walls parallel to the nozzle body producing two separate exit flows, introducing the nozzle through the back wall to eliminate the jet duct as a geometric element, and running with the cavity in both vertical and horizontal positions. None of these changes appeared to affect the oscillatory behaviour of the system. The frequency of oscillation of the flow within the cavity was a function of the flow rate, the size of the cavity and the size of the jet orifice. The three dimensions of cavity depth, cavity width and nozzle width were varied within the range possible with the model. The experimental variables were jet flow rate and oscillation period whose relationship is illustrated in Figure 2, and can be summarised as:

1. oscillation occurs within a range of flow rates as a function of cavity size (given in metres in the legend)
2. oscillation period decreases with increasing jet flow rate
3. for a given flow rate, in a region of oscillation, the period generally increases with increasing cavity width and depth

By considering the jet flow as a pendulum a similarity relation for the oscillatory flow may be derived:

$$N_{St} = fn\left(\frac{L}{D}, N_{\mathrm{Re}}\right)$$

where N_{St} is the Strouhal number for the cavity based on a cavity dimension. Figure 3 plots Strouhal No (fL/u) versus jet Reynolds number. For a given cavity size the Strouhal number is essentially constant, within experimental error. The oscillation falls in two distinct bands when plotted on this basis.

MATHEMATICAL MODEL

The experimental difficulty of manipulating model size and flow rate to extend the oscillation range made the development of a numerical simulation desirable, using the experimental data available for calibration. The simulation used the FLOW3D package with finite volume formulation to solve the Navier-Stokes equations.

A cavity 230 mm wide and 900 mm deep with a 7 mm slot nozzle was chosen for simulation. The model geometry was two dimensional implying that the cavity was infinitely thick and that the cavity cross-section was constant throughout the thickness. This approximation was acceptable as the nozzle occupied the entire transverse thickness of the pseudo-two dimensional cavity. The physical model cavity was 17 mm thick and the front and back walls would have some frictional effects on the flow, however this was not simulated. The entire two dimensional flow field was modeled without truncation on lines of symmetry. The necessity for this has been demonstrated experimentally in the thin slab caster geometry (Honeyands 1994), where artificially imposing symmetry on the flow prevented flow oscillation. The model fluid was water in both physical and numerical models. No body force was included in the simulation as experimental work indicated that flow oscillation was the same whether the model was horizontal or vertical.

A finer grid was used in the centre of the cavity in the vicinity of the nozzle. The flow was turbulent with jet Reynolds numbers between 35000 to 45000. A two equation k-ε turbulence model was used. The use of this turbulence model was not essential in modelling the oscillating flow, but did improve the accuracy of the simulation.

The internal flow in the nozzle prior to its exit to form the oscillating jet was simulated to give developed flow at the orifice. This was necessary for a sustained oscillation of the jet; if the velocity components were instead specified at the nozzle exit then the simulation yielded only a dampened oscillation. Figure 5 shows the horizontal and vertical components of velocity at the centreline of the cavity for 10 seconds of simulation time. This plot indicates a period of 2.8 seconds which is similar to the experimental result - see Table 1. Oscillation only initiated with an initial asymmetry or perturbation in the flow, eg starting the simulation with the jet displaced from the centrally symmetric position. If the model started with centreline symmetry of the jet then no oscillation developed.

Table 1 compares the physical and numerical results. Both show similar trends eg, the period increases with decreasing velocity in both cases. This simple oscillating system is compared with other geometries in Figure 6, including data from water model cavities at different scales and operating steel casters. Similarity is based on the relation between cavity space velocity and oscillation frequency.

The mathematical model results were then examined in detail to elucidate the mechanism of oscillation. It was found that the jet flow oscillated in response to a dynamic balance between pressure gradient and the momentum of the recirculating entrained flow shown schematically in Figure 7. The initial displacement of the jet caused a pressure gradient to form across the cavity due to the asymmetric entrainment pattern. The jet moved toward the cavity side wall in response to this pressure gradient, however the momentum of the entrained flow on that side of the cavity simultaneously increased. Eventually a point was reached where the flow momentum exceeded the pressure gradient and the jet movement reversed.

CONCLUSIONS

The cavity flow was strongly oscillatory for steady flow and symmetric geometry. The period of oscillation was a function of flow rate, cavity dimensions and nozzle design.

The oscillation is caused by the jet flow and the consequent pattern of a pair of recirculating eddies forming the entrainment field of the jet in the confined volume. Mathematical simulation indicates that confined jet oscillation is produced by a dynamic balance between the pressure difference across the jet and the momentum of the recirculating flows.

The frequency of oscillation is directly proportional to the average space velocity for fluid in the cavity. This was found to be valid for water models at two scales, the mathematical model and for operating steel casters.

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SYMBOLS

D= nozzle width [m]
f = frequency [s^{-1}]
L = depth of cavity [m]
P = pressure [kPa]
u = jet velocity [m s^{-1}]
W = cavity width [m]
ν = kinematic viscosity [m^2s^{-1}]
N_{St} = Strouhal number (fL/u) [nondimensional]
N_{Re} = Reynolds number (Du/ν) [nondimensional]

TABLE 1. COMPARISON OF PERIOD OF OSCILLATION

Inlet Velocity (m/s)	Reynolds Number	Period (s) Numerical model	Period (s) Physical model
5.04	35,780	2.77	2.47
6.30	44,100	2.21	1.80

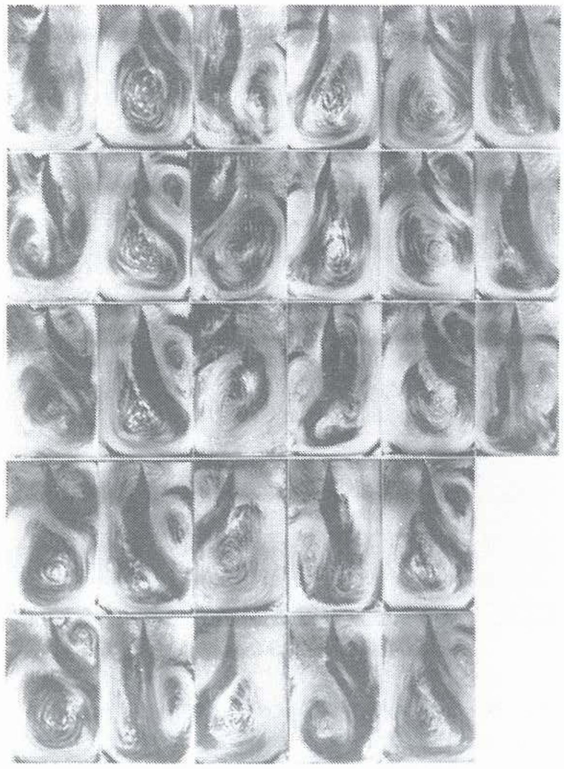

Figure 1(a) Horizontal flow table sequence; 1 s exposures at 1.5 s intervals; reads top to bottom left to right. Jet Re 170000.

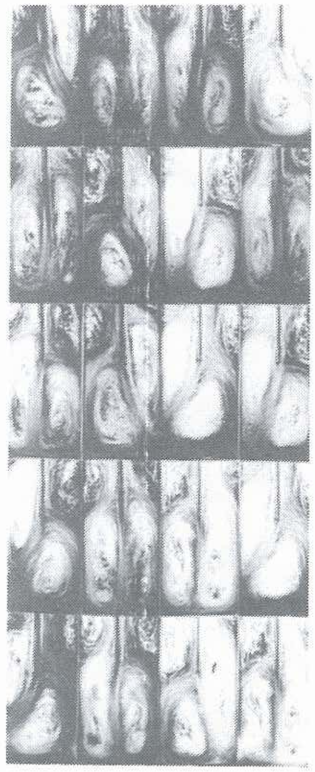

Figure 1(b). Vertical cavity flow sequence. 0.5s exposures at 1s intervals. Jet Re 57000.

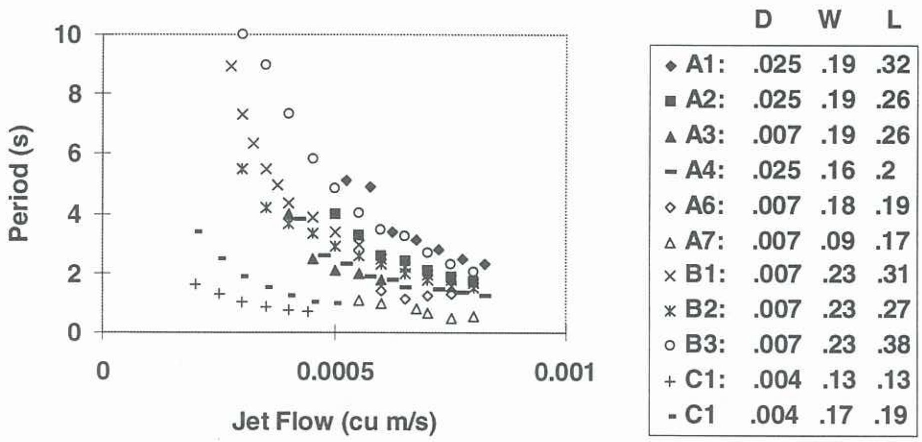

Figure 2. Period of oscillation (seconds) vs. flow rate (cubic metres per second)

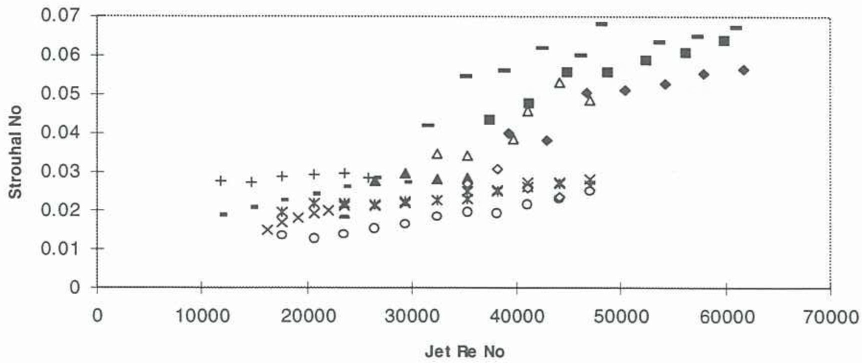

Figure 3. Strouhal number (fL/u) vs jet Reynolds number (Du/v)

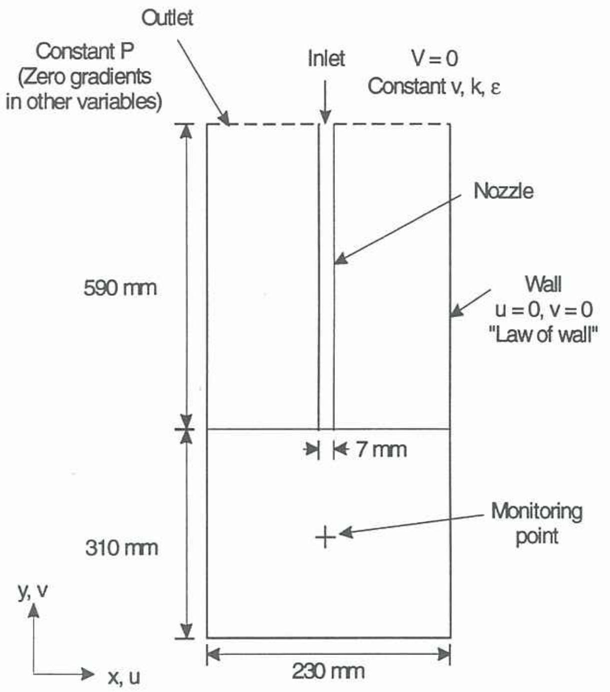

Figure 4. Confined jet simulation flow domain.

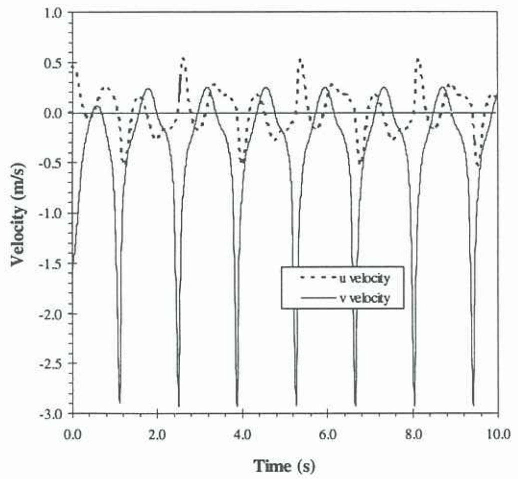

Figure 5. Velocities at monitoring point on cavity centreline for simulation with inlet velocity of 5.04m/s.

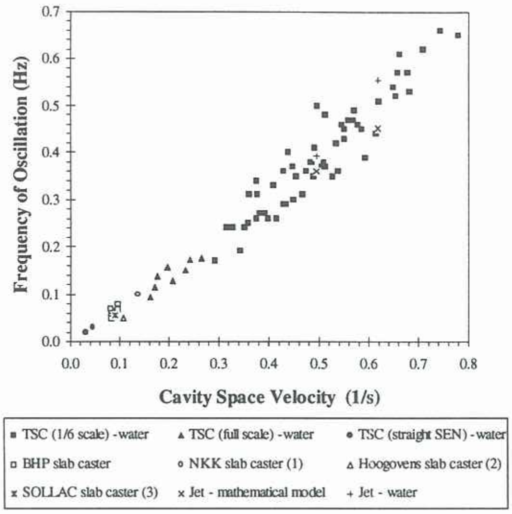

Figure 6 Frequency of oscillation vs cavity space velocity - inverse residence time for fluid in the recirculating region (References: (1) Kubota et al 1991, (2) Cornelissen et al 1991, (3) Birat et al 1991).

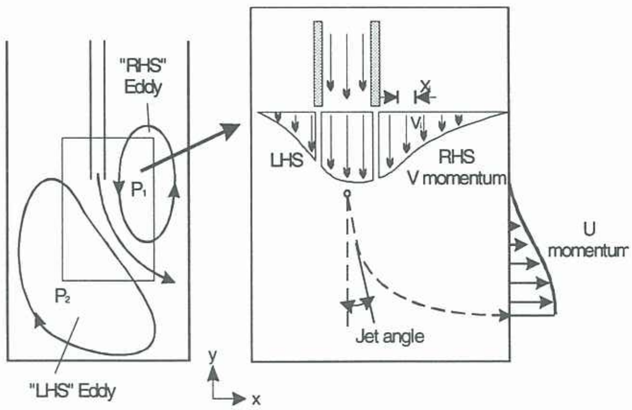

Figure 7. Schematic diagram of flows in the confined jet model.