1992

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Tramschek, A. B. and Nasr, A., "CFD and LDA Studies of Flow Through a Plate Valve" (1992). *International Compressor Engineering Conference.* Paper 917.
https://docs.lib.purdue.edu/icec/917

CFD AND LDA STUDIES OF FLOW THROUGH A PLATE VALVE.

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ABSTRACT

For many years compressor designers have utilised the results gained from steady state tests on valve assemblies to assist in compressor design processes and have employed various analytical models derived from experimental programmes. The present paper reports a continuation of this process, in that results derived from computational studies involving the PHOENICS computational fluid dynamics (CFD) code were able to be compared with experimental results based on conventional pressure measurements and Laser Doppler Anemometry (LDA) velocity measurements.

Computer analyses and experimental measurements were undertaken for a rotationally symmetric plate valve system with air as the working fluid. The working fluid was treated as an ideal gas with a simple relationship between its pressure, density and temperature. Calculations and measurements were performed for valve lift/valve port diameters in the range $0 < h/d < 0.2$, and valve plate diameter/valve port diameter ratios in the range $0 < D/d < 2.8$. The valve port diameter used throughout the tests was 25mm. Flow upstream of the valve was essentially a stagnation flow and overall system pressure ratios were in the range $1.0 > Pd/Pu > 0.75$, where Pd was generally the prevailing atmospheric pressure. Velocity and pressure distributions were obtained and used to demonstrate the degree of agreement between calculated and measured quantities and also to reveal the extent of the separation zone formed immediately downstream of the valve port exit plane.

Pressure distributions were measured using 30 or more pressure tappings distributed over the wall surfaces bounding the flow. Laser Doppler Anemometry techniques were used to measure radial components of fluid velocity in the gap between the valve plate and the adjacent fixed wall.

CFD calculations were made using various energy dissipation mechanisms. Flows were analysed on the basis of constant laminar viscosity, constant eddy kinematic viscosity and ultimately the $\kappa-\epsilon$ turbulent energy creation and dissipation model.

A comparison of calculated and measured velocity distributions and the extent of the resulting separation zone revealed that the calculated results appeared to suppress circulation and perhaps implied that a false diffusion mechanism was playing too significant a role in the calculations.

Attempts were made to mitigate this effect by modifications to the calculational schemes and the present paper shows the degree to which these attempts have been successful.

INTRODUCTION

Compressor designers have long recognised the crucial role that valves play in the operation of many positive displacement compressors and as a result there is available a wealth of literature (1) showing the important criteria that designers must consider when selecting reliable, efficient, economic to manufacture valve systems for use in compressors. The literature draws together the experiences of those who have designed, manufactured and operated compression machinery as well as those who have modelled either analytically or experimentally partial or complete compressor systems. Those familiar with the field will know of the diversity of contributions - models ranging from the most rudimentary to those using state of the art computational techniques - experiments ranging from those using the simplest of tools to those employing the latest developments in sensors and signal processing. This present paper fits into this pattern in that it brings together computational and experimental work on a simple plate valve arrangement. It reports on the use of a highly developed fluid dynamics code PHOENICS (2) in association with a Laser Doppler Anemometry investigation of the flow through an axially symmetric disc valve. As a result, it has been possible to compare calculated and experimentally derived velocity and pressure distributions at various locations throughout the valve system. The study was performed for a series of steady state operating conditions as the resulting data can be employed in a quasi steady fashion when modelling the dynamic behaviour of compressor systems.

VALVE GEOMETRY

An extremely simple geometry was chosen for the study in that the valve comprised a single circular disc placed directly over a circular hole in a valve plate. The gap between the disc and the valve plate could be varied in a precise manner. The complete valve assembly formed the upper surface of a cylindrical chamber which was connected via a diffuser, pipework system, orifice meter and regulating valves to a compressed air supply. Air passing through the valve was discharged directly to the atmosphere. Details of the system are shown in Figure 1.

The diameter d of the hole (valve port) in the valve plate was 25 mm and a series of valve discs of different diameter D was manufactured such that D/d values in the range $1.04 \leq D/d \leq 2.8$ could be provided. Work reported in this paper relates to the use of a D/d value of 2.4. A gap adjusting mechanism allowed the gap (valve lift) h between the valve disc and the valve plate to be set at fixed values in the range $0.04 \leq h/d \leq 0.16$.

Some 30 pressure tappings were incorporated into the apparatus via a series of small holes in the valve disc and valve plate surfaces in the vicinity of the valve port. Details of the pressure tapping points are shown in Figures 2a, 2b, and 3.

WORKING FLUID AND OPERATING CONDITIONS

Experiments were performed in a laboratory having a compressed air supply capable of delivering air at 15 bar (gauge) pressure to the regulating and control valves upstream of the valve flow rig. The air supply temperature was typically in the range 10 to 20°C.

Control valves allowed the pressure in the cylindrical chamber upstream of the valve assembly to be held steady at pressures in the range $0 \leq P_{chamber} \leq 2$ bar gauge.

For calculational purposes air was treated as an ideal gas having the simple equation of state $P=\rho RT$. Values for the transport properties Cp, μ, k were taken from standard tables at the corresponding pressure and temperature conditions. Flow through the valve was assumed to be adiabatic.

EXPERIMENTAL TECHNIQUES

Pressure Measurements

Pressure measurements were made using a water filled multi tube manometer whose tubes were individually connected to the pressure tappings distributed throughout the apparatus. By photographing the manometer it was possible to get an instantaneous picture of the fluid levels in some 30 manometer tubes and thereby obtain pressure distributions in the valve assembly and the orifice flow metering system. The use of the photographic technique enabled slight variations in the valve plenum chamber pressure during a test run to be accommodated. Details of the pressure tapping locations are shown in Figures 2 and 3. Pressure tappings were made in the lower surface of the valve disc, the upper surface of the valve plate and in the valve port. The flow was assumed to be rotationally symmetric and the tapping points on the valve disc and valve plate were located at different radii on a spiral path in order to facilitate connections and eliminate interference.

An attempt was made to ensure that an adequate number of closely spaced holes would exist in regions where significant pressure gradients were expected with the number and location of the holes being guided by the preliminary predictions of the PHOENICS computer code.

Pressure measurements were made for a number of flow rates determined by the relative values of the plenum chamber and atmospheric pressure levels and a combination of both D/d and h/d values. The monitored values for the plenum chamber pressure and the lowest pressure indicated by one of the tapping points would indicate that the flow had not choked.

Velocity Measurements

A commercially available Laser Doppler Anemometer system was used to measure the radial component of fluid velocity at different locations in the gap between the valve disc and the valve plate. Laser anemometry is a non intrusive technique and the presence of beams of laser light does not disturb the basic flow pattern. The technique does however require the mounting of an appropriate laser beam and photomultiplier system with a facility to traverse the focus of the laser beams to desired locations. Since the technique relies on the scattering of light from flow borne particles it was necessary to seed the flow with a supply of oil particles of less than 5 micron diameter.

The valve flow rig exhibits rotational symmetry and hence by choosing to traverse the laser beam probe parallel to a given diametral line a complete range of radial locations could be covered. By adjusting the vertical location of the traverse plane, measurements could be effected for different points in the gap between the valve disc and the valve plate.

Figures 4 and 5 show details of the probe mounting and traversing system. In the system employed, two laser beams lying in a plane parallel to that of the valve disc intersect to produce interference fringes on the measuring diameter. Seeding particles moving with the flow cross the interference fringes and bursts of scattered light can be detected by a photomultiplier system thereby allowing the radial component of the flow velocity to be measured.

EXPERIMENTAL RESULTS

Velocity Measurements

Velocity measurements were made at radial locations corresponding to important regions of the pressure profiles. Thus three distributions were obtained for the central region of the flow directly above the valve port, see Figures 6a,6b,6c.

Six further locations were used to illustrate significant features of the flow in the valve disc - valve plate gap, see Figures 7a,7b,7c. Results from these locations illustrate, flow separation, flow reattachment and flow recirculation and their disposition relative to the position at which minimum pressures are recorded. Such results provide useful information about the shape, extent and strength of the resulting recirculating flow regions and provide valuable evidence by which to judge the validity of results calculated by computer codes such as PHOENICS.

Pressure Measurements

Figure 8 shows a typical radial pressure variation for the gap region. Results taken from the tappings on the valve disc show high pressure values in the centre of the disc. The pressure remains reasonably constant until a radius corresponding to the valve plate port hole radius is reached. For further outward radial movement the pressure decreases rapidly to a minimum value before recovering to attain the prevailing atmospheric pressure value at the edge of the disc. Results taken from tappings on the valve plate show corresponding behaviour where disc and plate results co-exist. The valve plate results lie slightly below the valve disc results in the central part of the system but converge with the disc results at the outer region of the disc.

For a given gap (h/d ratio) the radial pressure profile is preserved for a range of flow rates corresponding to a succession of upstream plenum pressures. The maximum pressure values recorded in the centre of the disc rise whilst the minimum value in the gap decreases further as the flow rate is increased. The location of the point of minimum pressure does not appear to move. Figure 8 illustrates these points. There is general agreement between the trends shown by pressure and velocity measurements and simple predictions based on the application of Bernoulli's equation for flow along a given streamline. At the centre of the flow the velocity is essentially axial in direction and the pressure on the disc surface corresponds to the stagnation pressure for the flow. At the edge of the valve port the flow has taken on more of a radial characteristic, local velocities have increased and the pressure has fallen. At slightly greater values of radius increased radial velocities are associated with further reductions in pressure. As the edge of the valve disc is approached a diffusion process associated with increasing flow area results in reduced velocity and increasing pressure levels.

CALCULATED RESULTS

The PHOENICS computer code is a generalised CFD code which solves the discretized form of the governing fluid dynamic equations see Patankar (3).The PHOENICS computer code was used to obtain calculated results for a series of cases for which corresponding experimental evidence had been collected. Thus set values of d, D/d, h/d were employed together with known values of downstream pressure, upstream pressure, upstream temperature and system flow rate. Density variations in the flow were accommodated by a simple ideal gas representation of the equation of state i.e. $P=\rho RT$. A constant value of 1×10^{-5} kg/ms was adopted for the viscosity of air.

PHOENICS gives users the facility to activate a variety of turbulent kinetic energy production and dissipation models as part of the calculational process and this paper presents the results of the exercise of two such models. The first set of calculations employed only a constant value laminar viscosity (μ) approach. The second set of calculations employed the full blown $\kappa-\epsilon$ turbulent kinetic energy creation and dissipation terms in addition to normal viscous dissipation effects. Results for the constant laminar viscosity case show a recirculation region which lies well downstream of the corner of the valve port and which has a different location, shape and size to those revealed by the corresponding experimental pressure and velocity measurements – see Figure 9 (calculated) and Figure 8 (measured).

The calculated radial pressure profile does not exhibit the same degree of pressure reduction in some parts of the flow as was observed in practice.

Similar comments apply to the calculated velocity values. The inbuilt solution techniques ensure that the calculated pressure and velocity values are consistent. However the agreement between measured and calculated velocities varies according to which region of the flow is being considered. Calculated and measured radial velocity components agree in central region of the valve port where the flow is contracting and no significant energy dissipation is occurring, see Figures 6a, 6b, 6c.

Similar comments apply to pressure and velocity components calculated using the $\kappa-\epsilon$ routines within PHOENICS.

Neither the simple constant viscosity treatment nor the $\kappa-\epsilon$ turbulent kinetic energy process adequately predicted the pressure and velocity fields in the gap region where separation, reattachment and recirculation occurs. The $\kappa-\epsilon$ calculations caused the centre of the recirculation zone to move upstream towards the port corner but reduced its size considerably. The inclusion of turbulent kinetic energy consideration (into the calculations) had made the flow appear to be more viscous than it really is. Figure 10 illustrates these effects.

Careful examination of the experimental and calculated results prompted the authors to question whether a false diffusion mechanism associated with the form of the PHOENICS calculations was responsible for the discrepancies.

False diffusion effects, Raithby (4), are known to occur with many difference schemes in flow fields where the resultant velocity vector at particular points in a flow field is inclined at 45° to the directional axes of the calculational grid. The effect is amplified as the fluid velocity increases. The valve geometry currently being studied contains all the ingredients where false diffusion effects associated with the calculational schemes embodied in the PHOENICS code might be expected to be present. A 90° change in the direction of the main flow field inevitably means that in parts of the flow field the velocity vectors will be inclined at 45° to the principal grid directions. Small gaps between the valve disc and the valve plate are associated with significant fluid velocities. False diffusion effects are less noticeable with low velocity flows. Figure 12 shows results for a two dimensional plane geometry at a greatly reduced flow rate. In this case the centre of the predicted recirculation zone has moved upstream and is closer to the port corner.

The PHOENICS computer code contains a facility which permits the user to introduce user developed routines (2) into parts of the code thereby allowing alternative schemes to be deployed.

In its standard form the PHOENICS code uses equations linking cell variables with the corresponding values in neighbouring cells via the components of fluid velocity normal to the cell surfaces. The upwind difference formulation employed is known to introduce false diffusion effects for flows inclined at 45° to the principal grid orientations. To overcome this effect a modification was introduced which allows greater account to be taken of the variable values in cells lying in a direction along which the fluid has travelled.

At the time of writing this paper coding modifications had been effected for the plane cartesian X-Y coordinate system and further coding changes were being put in train to handle the axi-symmetric R-Z system.

The efficacy of the modifications was tested by undertaking a comparison of modified and unmodified PHOENICS calculated results with experimental results obtained by Duggins (5), (6) in a 2 dimensional large scale model of a plate valve employing water as the fluid medium.

The unmodified PHOENICS results show generally good agreement with Duggins experimental results. This is partially attributable to the low velocity throughout the flow field and the viscosity of the fluid medium (water), Figure 11.

The modified calculations have raised the upstream pressure level slightly and caused a further reduction in pressure immediately downstream of the corner of the flow. This is precisely the form of change needed to bring about a better match between the calculated and measured results for the rotationally symmetric system being studied by the authors.

CONCLUSIONS

Whilst very considerable advances have been made in the development of calculational and experimental techniques used to study fluid flows, it must however be recognised that difficulties can still arise when computer codes employing difference schemes are applied to geometries where very sudden changes in flow direction are involved. Research workers performing fluid dynamic calculations on the types of flow and geometrical arrangements found in compressor valve systems would be well advised to pay attention to the effects of "false diffusion" which may be present in any calculational scheme that they might employ.

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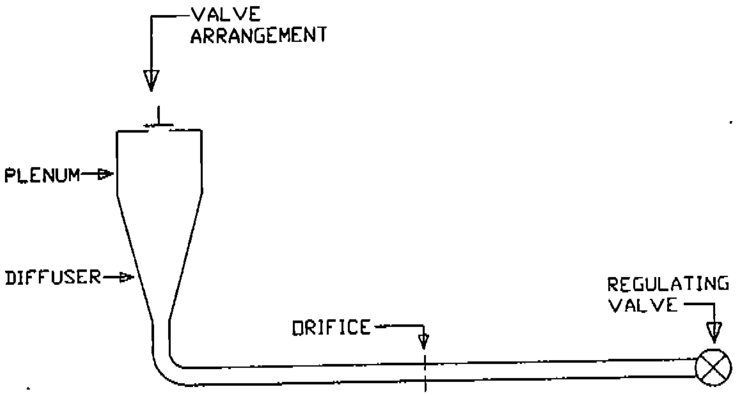
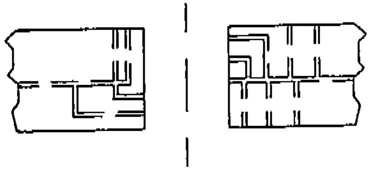
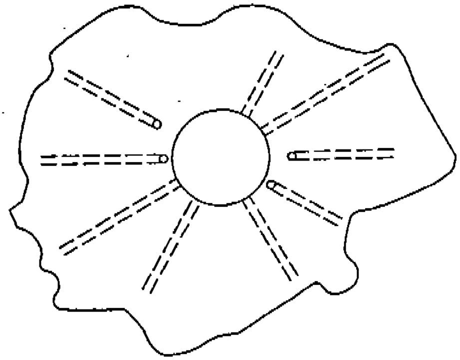


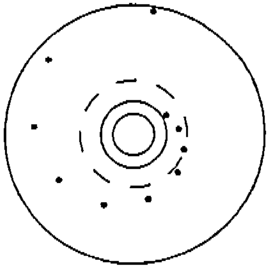
(FIG. 1) LAYOUT OF THE TEST RIG.



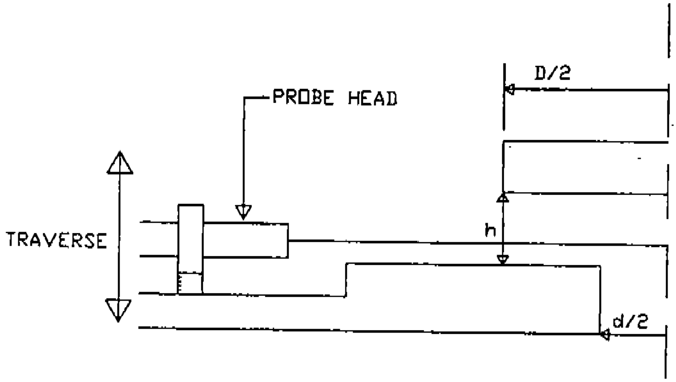
(FIG. 2A) PRESSURE TAPPINGS IN THE PORT AREA.



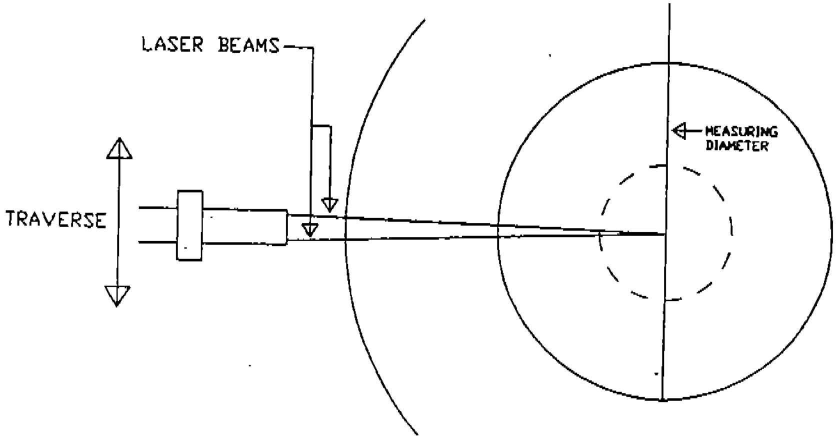
(FIG. 2B) PLAN VIEW FOR THE PRESSURE TAPPPINGS IN PORT.



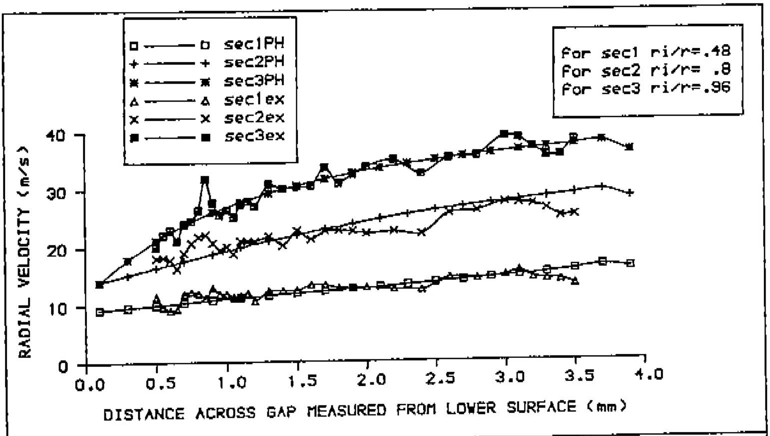
(FIG. 3)PRESSURE TAPPINGS IN THE VALVE DISC.



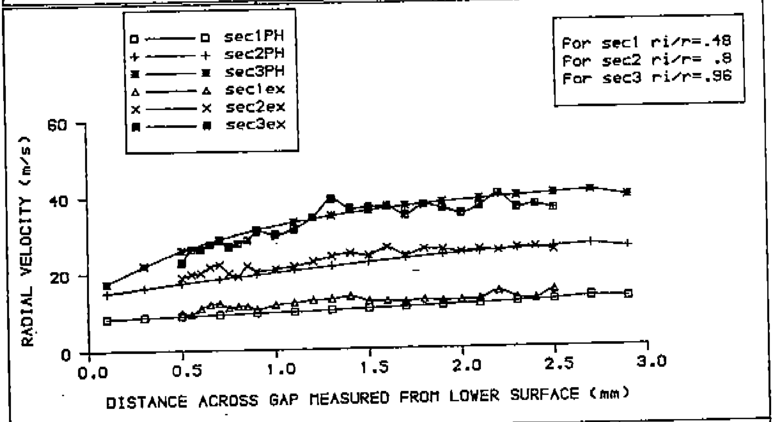
(FIG. 4)



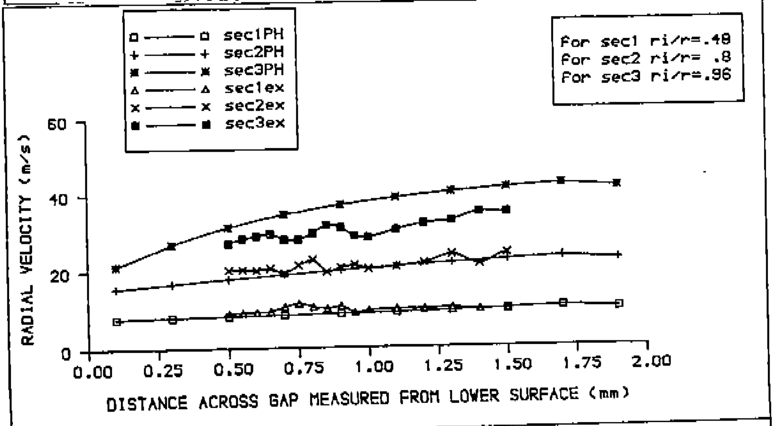
(FIG. 5)LASER DOPPLER VELOCITY MEASUREMENTS.



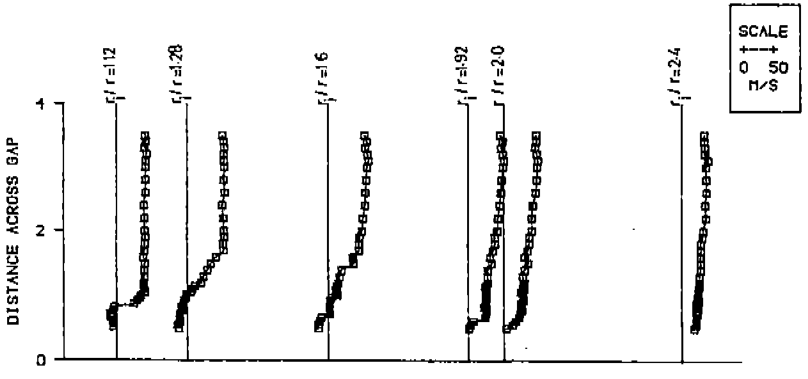
(FIG.6A) COMPARISON OF MEASURED AND CALCULATED RADIAL VELOCITY FOR 4 mm GAP



(FIG.6B) COMPARISON OF MEASURED AND CALCULATED RADIAL VELOCITY FOR 3 mm GAP



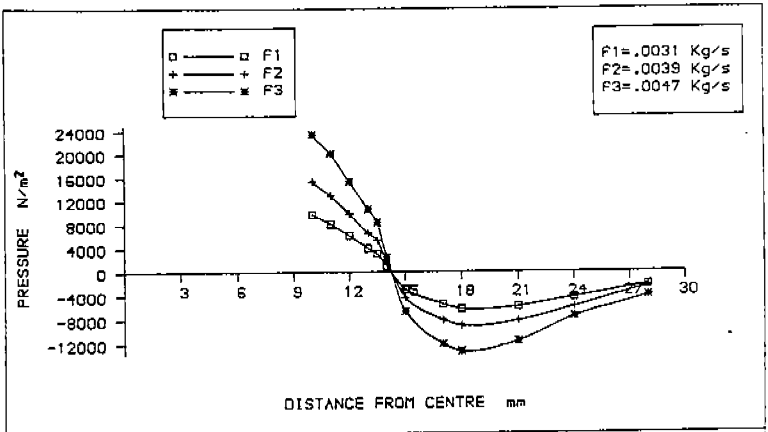
(FIG.6C) COMPARISON OF MEASURED AND CALCULATED RADIAL VELOCITY FOR 2 mm GAP



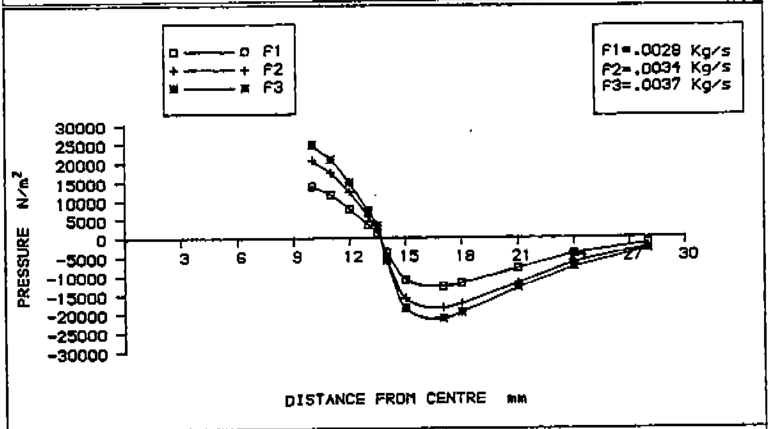
(FIG.7A)RADIAL VELOCITY PROFILE DEVELOPMENT ALONG 4 mm GAP

(FIG.7B)RADIAL VELOCITY PROFILE DEVELOPMENT ALONG 3 mm GAP

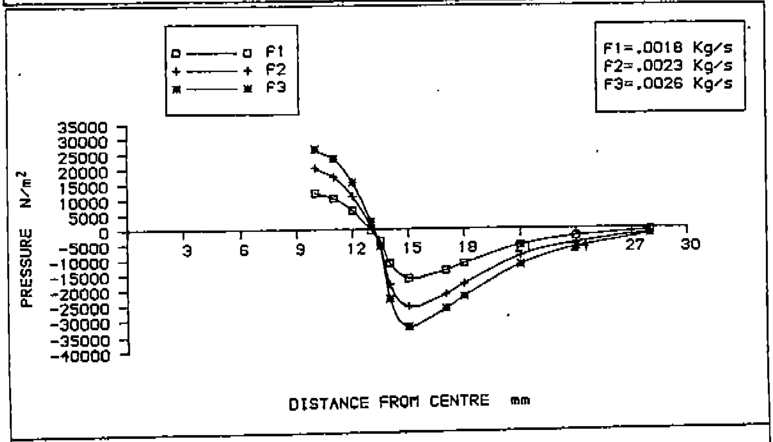
(FIG.7C)RADIAL VELOCITY PROFILE DEVELOPMENT ALONG 2 mm GAP



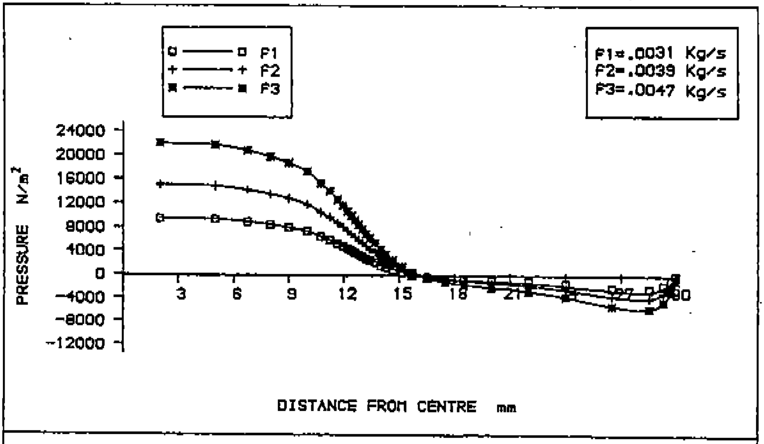
(FIG.8A)EXPERIMENTAL PRESSURE DISTRIBUTION OVER DISK D/d =2.4,h=4 mm



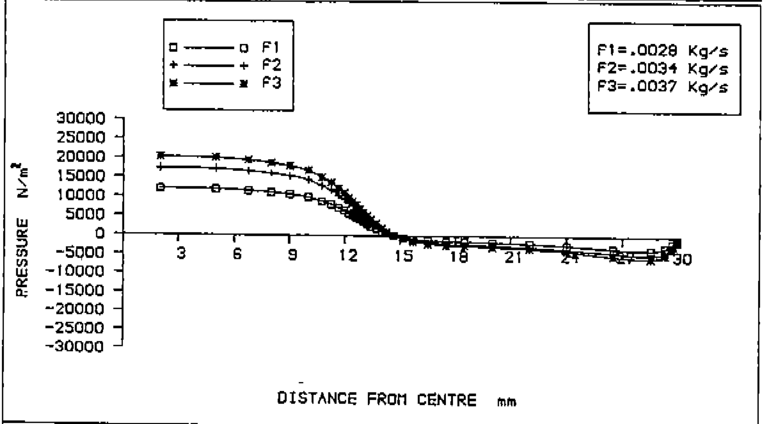
(FIG.8B)EXPERIMENTAL PRESSURE DISTRIBUTION OVER DISK D/d =2.4,h=3 mm



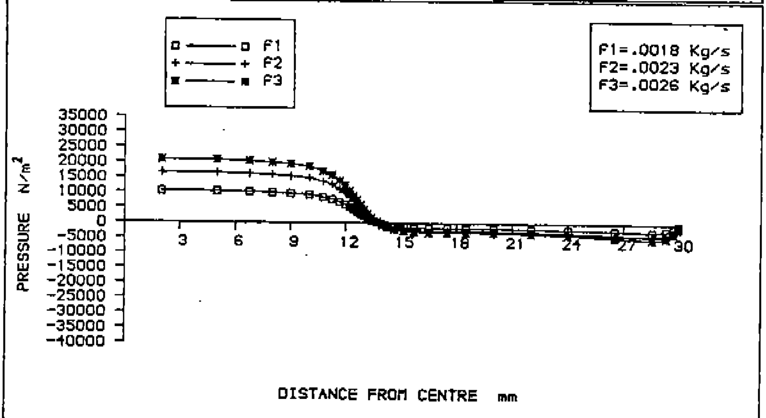
(FIG.8C)EXPERIMENTAL PRESSURE DISTRIBUTION OVER DISK D/d =2.4,h=2 mm



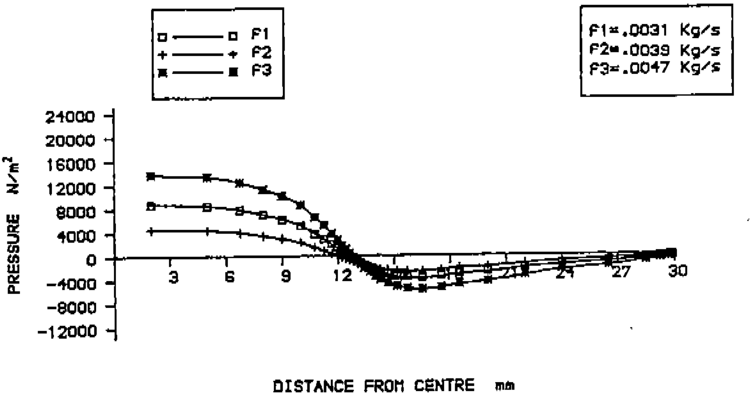
(FIG.9A)CALCULATED PRESSURE DISTRIBUTION OVER DISK,LAMINAR, D/d =2.4,h=4 mm



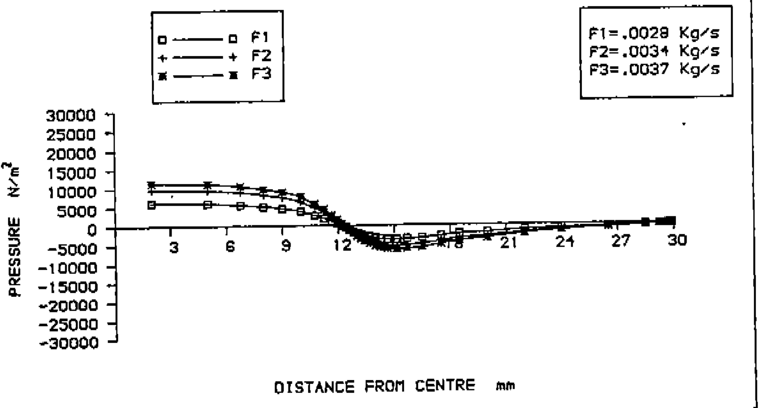
(FIG.9B)CALCULATED PRESSURE DISTRIBUTION OVER DISK,LAMINAR, D/d =2.4,h=3 mm



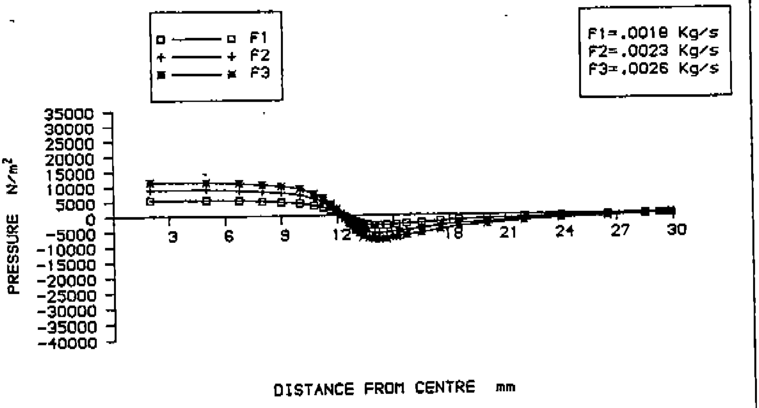
(FIG.9C)CALCULATED PRESSURE DISTRIBUTION OVER DISK,LAMINAR, D/d =2.4,h=2 mm



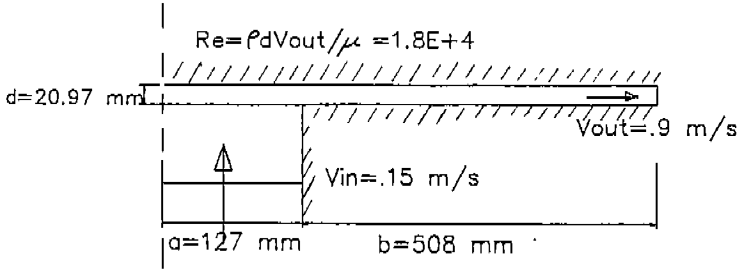
(FIG.10A)CALCULATED PRESSURE DISTRIBUTION OVER DISK,K-E, D/d =2.4,h=4 mm



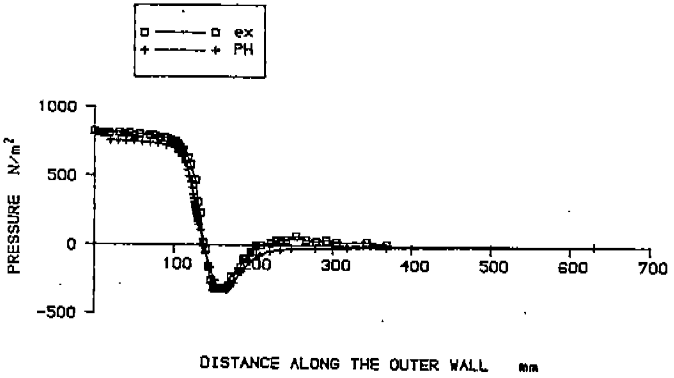
(FIG.10B)CALCULATED PRESSURE DISTRIBUTION OVER DISK,K-E, D/d =2.4,h=3 mm



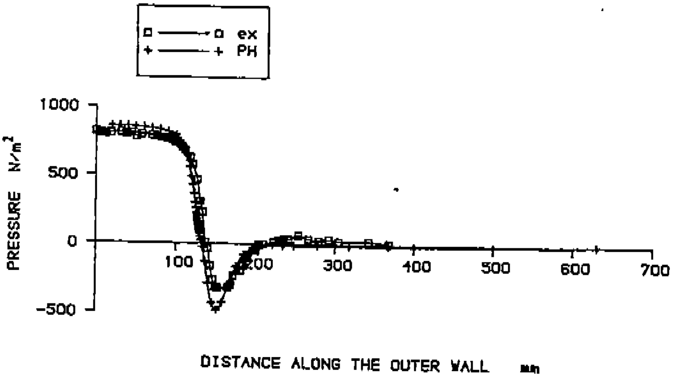
(FIG.10C)CALCULATED PRESSURE DISTRIBUTION OVER DISK,K-E, D/d =2.4,h=2 mm



(FIG.11) PRINCIPAL DIMENSIONS OF TWO DIMENSION WATER FLOW MODEL.



(FIG.12A)COMPARISON BETWEEN EXPERIMENT AND STANDARD PHOENICS



(FIG.12B)COMPARISON BETWEEN EXPERIMENT AND MODIFIED PHOENICS