11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

10A-1

STUDY OF THE VORTEX CREATED AT THE HEAD OF A MOVING PISTON IN A CYLINDER

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Abstract

An experimental study is undertaken to examine the nature of the toroidal transient vortex formed at the head of a piston as it moves forward through a cylinder. Flow visualisation is used to show the development of this vortex. The effect of a variation in piston speed on the size and features of the vortex are examined and results are compared with previous empirical and analytical work.

Nomenclature

U_w= Wall velocity.
X = Distance travelled by cylinder wall.
A_v= Area of vortex.
A_b= Area of boundary layer.
ρ_w= Density of water.
μ_w= Absolute viscosity of water.
D = Piston diameter.
ν_w= Kinematic viscosity of water.

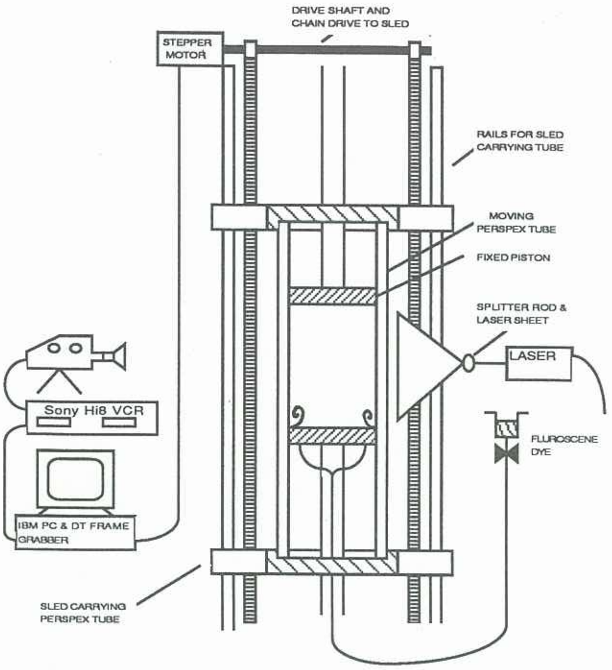
Introduction

An interesting fluid phenomenon is the vortex that is formed at the junction where one moving surface "scrapes" across a stationary surface. Little quantitative information exists regarding the topology of the flow in this region and the effect of the singularity on the flow field. A vortex forms as boundary layer material is scraped off one surface by the surface moving across it. This removed boundary layer material essentially forms a shear layer which rolls into the transient vortex seen near the surface junctions. This vortex was first observed experimentally by Tabaczynski et al. (1970) at the head of a circular piston moving through a cylinder. The vortex in this case was axi-symmetric and toroidal in shape which grew in size as the piston progressed across the cylinder surface. This vortex formation was also studied by Daneshyar et al. (1973) using a square piston of semi-infinite length which moved across a flat surface. The vortex formed in this case was two dimensional and not toroidal in nature. Although these experiments were conducted using water, they have obvious application to compressible situations, ie. the transient vortex formed in an engine cylinder when the piston moves through the exhaust and compression strokes. Researchers in the automotive field have observed a vortex forming at the head of a piston as it moves through a cylinder using schlieren photography, although little quantitative analysis exists as to the nature of this vortex, (see Ishikawa and Daily (1979) and Nazaman et al. (1980)). Analysis of the nature of the vortex was undertaken by Tabaczynski et al. (1970) who examined the vortex with respect to non-dimensional groups. They also derived an analytical relation to describe their non-dimensional groups. The work by Daneshyar et al. (1973) with a square piston rather than a circular one, used the same technique as Tabaczynski et al. (1970) in their analysis.

This paper outlines the formation of a toroidal vortex at the head of a circular piston moving through a cylinder. The effect of a variation of piston speed on the nature of the vortex is examined and compared with previous work in this field.

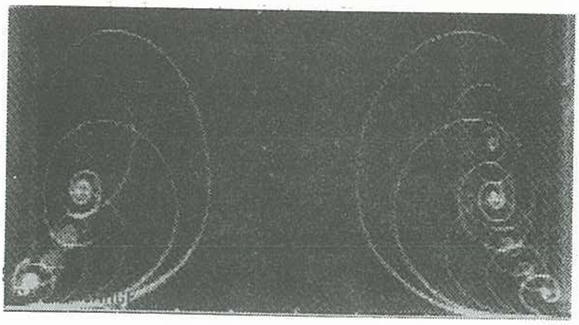
Experimental Apparatus

Figure (1) below shows a schematic diagram of the apparatus used to record the development of the vortex at a piston head. The experiment was conducted in a 138mm ID, 2m long vertical perspex tube. Water was used as the working medium. The pistons were held a fixed distance apart while the tube (simulating the cylinder walls) was moved. This enabled the cameras and video equipment to be held fixed while recording the development of the vortex at the piston head. A square viewing tank enclosed the working section of the experiment to prevent distortion of the image. The tube was held at its top and bottom to sleds that traversed vertically on a six metre rail system. The sleds were driven via a chain drive connected to a computer controlled stepping motor.



Fig(1) Schematic of experimental apparatus.

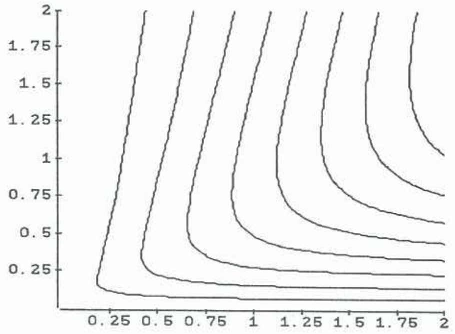
In this experiment the length scale used for Reynolds number is based on the distance traversed by the cylinder walls. The stepping motor speed could be accurately determined and hence enabled a determination of the wall speed to less than one percent error and hence an accurate determination of Reynolds number. Accurate control of the wall speed also ensured repeatable experimental results. This vertical apparatus is different from the previous experimental set-ups of Tabaczynski et al. (1970) and Daneshyar et al. (1973) who used horizontal apparatus. Dye was introduced through the piston very close to the piston/wall junction. The advantage of this was to enable the use of neutrally buoyant dye and hence the effects of buoyancy forces can be neglected. It also allows both sides of the cross-section of the toroidal vortex to be observed. The flow visualisation technique involved shining a laser sheet through an axi-symmetric vertical cross section of the tube. Fluorescein dye was leaked through 1mm diameter holes at two diametrically opposite edges. The laser sheet was set up to pass through these two points. The walls were started from rest and accelerated rapidly to a constant velocity, the tube reaching maximum speed in less the 0.2 second. Fig(2) below shows the the cross-section of the toroidal vortex for a number of discrete time intervals superimposed. The developing vortex was recorded onto a Sony Hi8 VCR. This allowed accurate time code insertion. The images were then subsequently digitised via a Data Translation frame grabber and printed.



Fig(2) Developing vortex for a wall speed of 2.15 cm/sec.

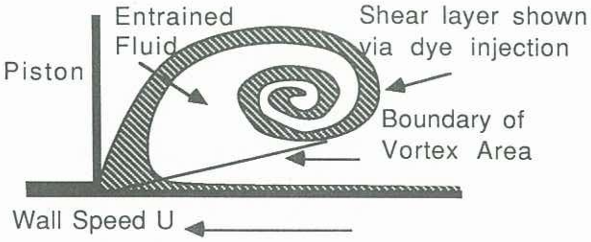
Analysis

A theoretical description of the flow field close to the junction of two surfaces scraping across one another was examined by Batchelor (1967). He neglected inertia terms and developed an analytical expression for the stream function shown in Fig(3). This describes the two-dimensional flow close to the surfaces junction. However this solution is based on the assumption that viscous forces are much larger than inertial forces and hence the region to which the result applies is very small, r<<0.025mm



Fig(3) Batchelor's solution for 2-D flow in a corner due to one rigid plane sliding over another

However experiments have shown that the boundary layer on the cylinder walls is removed at the corner junction and this shear layer rolls into a toroidal vortex of increasing size as time progresses. A dimensional analysis argument relating the area of the vortex, as defined in Fig(4) below, to the distance the piston has travelled was postulated by Tabaczynski et al. (1970).



Fig(4) Sketch of developing vortex.

In the analysis by Tabaczynski et al. (1970) the vortex area can be expressed as a function of the following independent variables.

$$A_v = \phi(U_w, X, \rho_w, \mu_w, D) \qquad (1)$$

A non-dimensional analysis yields the following relation.

$$A/X^2 = f(U_w X\, \rho_w/\mu_w, D/X) \qquad (2)$$

It is argued that if area of the vortex is small compared to the diameter of the piston then the area of the vortex is independent of the diameter of the piston. This gives the following non-dimensional relation involving two variables.

$$A/X^2 = f(U_w X\, \rho_w/\mu_w) \qquad (3)$$

Tabaczynski et al. (1970) conducted their experiments on the basis of these non-dimensional groups. Daneshyar et al. (1973) also attempted to collapse their data using similar non-dimensional groups. In both the analysis of Tabaczynski et al. (1970) and Daneshyar et al. (1973) the area of the vortex is assumed proportional to the area of the boundary layer being removed at the junction of the two surfaces. Equating this area of the boundary layer to the vortex area gives the following relation.

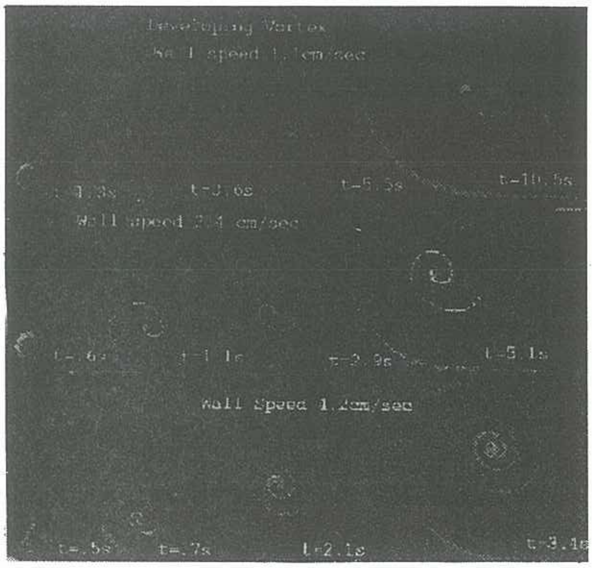
$$A_v/X^2 = C4/3.\pi^{-1/2}Re^{-1/2} \qquad (4)$$

This equation predicts the relationship between the non-dimensional groups where C is the constant of proportionality between the area of the boundary layer removed and the experimental area of the vortex. Hence a log/log plot of the experimentally determined non-dimensional groups should give a value for C and display a gradient of -1/2 in the region of collapse. The work by Tabaczynski et al. (1970) suggest that the constant C is equal to 1.35.
The aim of our dye experiment was to determine the range of collapse of these results and the validity of the above analysis as the data from Tabaczynski et al. (1970) was somewhat scattered.

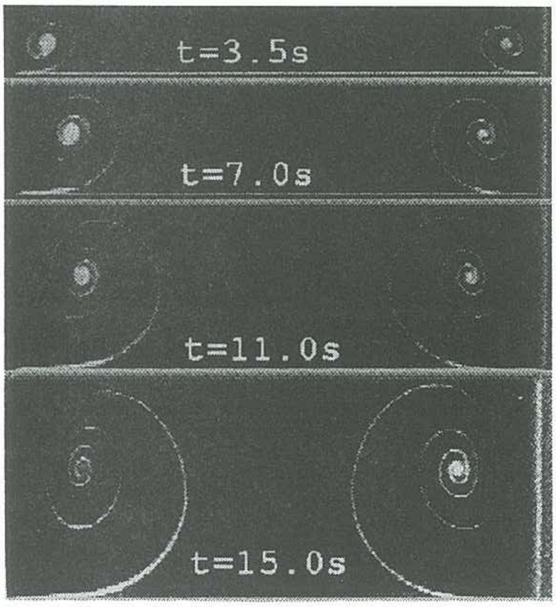
Results and Discussion

Figure (5) below shows typical pictures of the developing vortex for a range of wall speeds while the area of the vortex is still small in relation to the diameter of the piston. This typically means vortex diameter is less than one tenth of piston diameter.

Figure (6) below shows the continued development of the vortex when the diameter of the vortex is of the same order as the piston diameter.

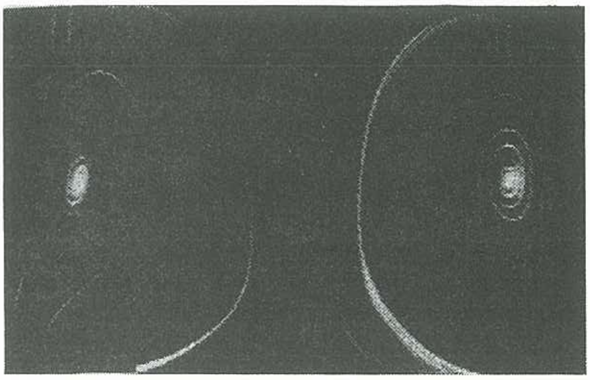


Fig(5) Developing vortex for a range of wall speeds.



Fig(6) Vortex development for wall speed of 2.4 cm/sec.

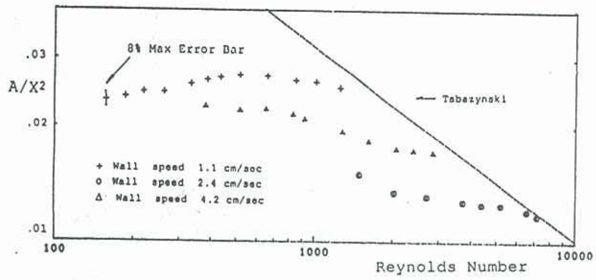
The structure holds its axi-symmetric nature until a Reynolds number of approximately 12,000. Figure(7) below shows the case when the flow has become three dimensional.



Fig(7) Non-symmetric vortex, wall speed 4.2 cm/sec, time 15 seconds from start.

Naziaman et al. (1980) noted that a lack of symmetry of the vortex could be influenced by the size and shape of the clearance between the piston and the cylinder wall.

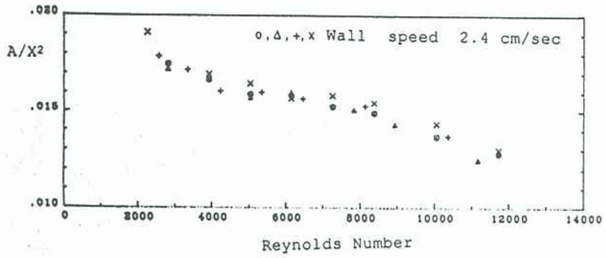
Figure (8) below shows a plot of *Experimental A_v / X^2* against *Reynolds number* for four different wall speeds. The maximum size of the vortex in these plots is 3cm². As can be seen the plots diverge from each other as the Reynolds number for each separate wall speed increases. The only possible region of collapse appears to be at very low Reynolds number and even in this section the -1/2 gradient law is not satisfied.



Fig(8) Plot of A/X^2 vs Reynolds Number, four different wall speeds.

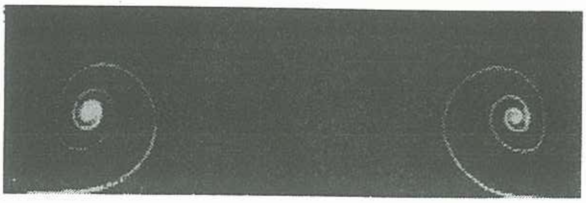
Random experimental error involved in the area calculation has been estimated as a maximum of 10% for the very low Reynolds number and less for the higher Reynolds number when the structure of the vortex is well defined.

A significant problem in previous work has been the experimental error involved in estimating the area of the vortex due to lack of clarity in the images obtained. Errors in determining the vortex area in the work of Tabaczynski et al. (1970) was estimated to be of the order of 25%. The errors involved in this work was less than 2% for Reynolds number and and less than 8% for the vortex area. Figure (9) below shows the area of the vortex at one wall speed as a function of Reynolds number for four different runs.



Fig(9) Plot of A/X^2 vs Reynolds Number, Wall speed 2.4cm/sec, four independent runs.

Figure (10) below shows the superposition of four different runs for identical time and speed.



Fig(10) Superposition of four independent experiments. Speed 2.4cm/sec, 9 seconds from start.

Both these results show the high degree of repeatability obtained with the experiments. and the relatively low random error.

Conclusions

The lack of collapse of results may be attributed to two major factors.
1) The area of the vortex, even at low Reynolds number (early development), is not insignificant compared to the piston diameter and hence the self induced effects of the toroidal vortex cannot be neglected.
2) The fact that the analytical solution was developed for 2D rather than an axi-symmetric cylindrical system means the compression of the vortex filaments as the vortex develops toward the centre of the cylinder is not accounted for.

Acknowledgments

The authors would like to thank ARC for their financial support.The authors also wish to acknowledge the assistance of Dr Julio Soria from C.S.I.R.O.

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