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Preliminary Investigation of Impulsively Blocked Pipe Flow

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Abstract

A two-tank flow facility has been designed and tested for the study of sudden blockage in pipe flow. Preliminary experiments have been conducted to test the performance of the system. Acoustic Doppler Velocimetry was used to calibrate the flow facility and investigate the mean and fluctuating velocity components of the flow system in the absence of a blockage. Hydrogen bubble visualisation was used to visualise the velocity profile at a distance of 2 pipe diameters upstream of the pipe exit. In the absence of a blockage, a parabolic velocity profile was observed indicating fully-developed laminar pipe flow. When the flow in the pipe was suddenly blocked, the flow near the inside walls of the pipe was observed to reverse direction. Dye visualisation showed a stopping vortex near the pipe blockage. Vardi and Hwang [4], amongst others, have identified similar flow features in their studies of sudden pipe closure. The broader context of this work is to compare experimental results to the already published numerical simulations of project collaborators.

Introduction

Sudden blockage of pipe flow is a common occurrence of an unsteady flow. Vardi and Hwang [4] identified three major features associated with suddenly blocked pipe flow. Figure 1, reproduced from Vardi and Hwang [4], is a schematic of the flow behaviour before and after pipe blockage caused by valve closure.

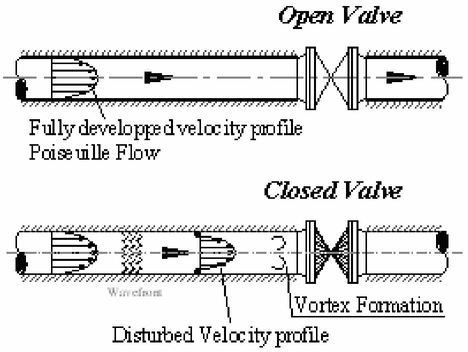


Figure 1. Typical behaviour of a pipe flow following a rapid valve closure. Reproduced and modified from Vardi and Hwang [4].

Induced waves, flow reversal and vortex formation are three significant features that occur after a sudden pipe blockage. The induced waves have been studied extensively in the past due to the significant effects they create such as water hammer. Changes in the flow velocity profile in a pipe contribute to the increased friction in such flows. These concerns are especially relevant in the case of rapidly accelerating or decelerating flow, such as occurs in a suddenly blocked pipe flow.

Furthermore, the valve closure problem is being numerically simulated by researchers at the School of Mathematical Sciences at the University of Adelaide. Our objective is to conduct experiments at similar flow conditions to their numerical studies. Results of experiments will be compared to those of the numerical modelling.

Equipment

A two-tank flow facility has been designed and tested for the study of sudden blockage in pipe flow. The closed loop system consists of a supply tank that delivers fluid at a constant pressure to an open receiver tank via a 25mm inner diameter clear acrylic pipe. Pipe blockage experiments are conducted at the downstream end of this pipe inside the receiver tank. The supply tank is made from 10mm thick PVC plate and the receiver tank from 10mm clear acrylic to allow visualisation of the flow inside. A 2 hp 240 V Onga pump transports fluid from the receiver tank, through a flow meter and back into the supply tank. The pump is driven by a variable frequency controller. In order to prevent the pump from stalling after pipe blockage, a bypass line was put in place. This bypass line allows the flow to keep circulating even when the pipe is blocked. Figure 2 is a schematic diagram of the flow facility.

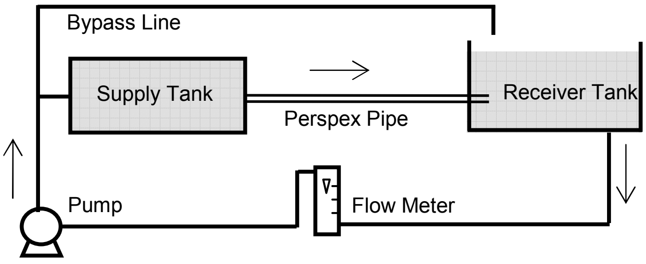


Figure 2 Schematic diagram of the flow facility.

Flow conditioning

The supply tank was designed to provide a low turbulence flow with uniform velocity distribution. This was achieved using a carefully designed flow distributor at the inlet, followed by perforated plates and flow screens, discharging into a large settling chamber. The flow entered the pipe through a contoured inlet, designed according to guidelines provided in Wallis [5].

The length of the Perspex pipe was set long enough to allow the flow to have a long development length of approximately 70 pipe diameters, sufficient to achieve fully developed laminar flow at the desired Reynolds numbers.

Figure 3 shows a photograph of the supply tank with the top removed, showing the flow conditioning features. When in use, the supply tank is pressurised. A 10mm thick PVC plate is affixed to the top of the supply tank by 30 bolts. A rubber seal is used to prevent leakage.

A Solarton-Morbrey 1½" (38.1mm) variable-area flow meter was used to measure the flow rate. Figure 4 shows the calibration of the pipe bulk velocity, U, and the pipe Reynolds number, $Re=UD/\nu$, against the pump frequency, f. The symbols denote actual measurements and the line denotes a curve of best fit. Although the pump could run at lower frequencies, the scale of the flow meter was unable to provide accurate measurements below 7 Hz. The figure shows linear relationship between the Reynolds number and the pump frequency.

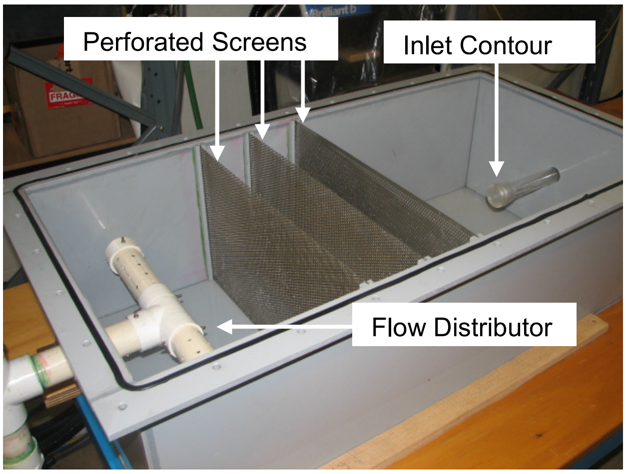


Figure 3. A photograph of the supply tank with the top removed, showing the flow conditioning features.

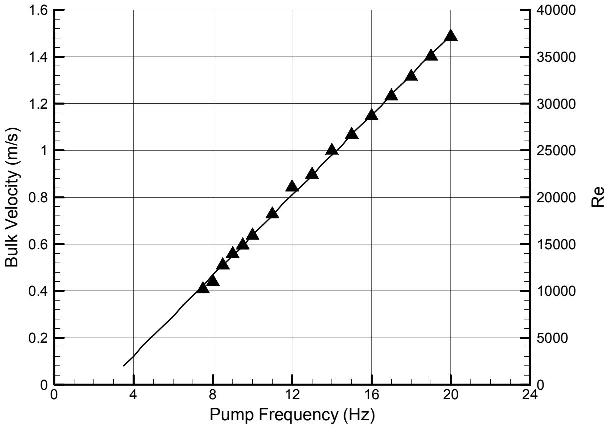


Figure 4. Calibration of the pipe bulk velocity and pipe Reynolds number against the pump frequency.

A Three-Component SonTek^{TM} Acoustic Doppler Velocimetery (ADV) was used to measure the pipe centreline velocity near the pipe exit. The sampling volume is approximately 0.25 cm^3 in size and is located 5 cm ahead of the transmitter. The flow was uniformly seeded with fine glass particles. The probe was aligned along the axis of the pipe so that the sampling volume was located on the pipe centreline and just upstream of the pipe exit. A number of tests were conducted to ensure that the pipe centreline velocity was constant for a fixed pump speed. These tests also allowed us to estimate the turbulence intensity in the pipe. Figure 5 shows a sample time trace of the measured centreline velocity and the corresponding correlation of that signal for a Reynolds number of approximately 8,000. The centreline velocity is observed to be relatively constant. An estimate of the turbulence intensity yields $u'/U \sim 2.6\%$. The correlation is observed to be consistently above 70% indicating an accurate signal. The error associated with velocity measurements using the ADV is quoted by the manufacturer at 1% of the measured value.

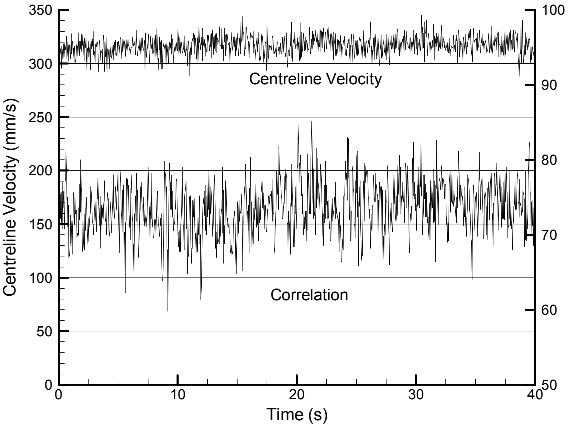


Figure 5. A time trace of the centreline velocity and correlation of the ADV signal for $Re \sim 8{,}000$.

Experimental Procedure

Hydrogen bubble visualisation was used to generate timelines for the purposes of investigating the development of the spatial velocity profile in the pipe. A straight hydrogen bubble wire was affixed diametrically across the pipe, 2D upstream of the exit. A variable voltage (0-120V) in-house built power supply with adjustable signal control was used to supply a small current through the wire. A cathode joined to the power supply was placed close to the pipe exit. The current signal was fully modulated to generate timelines. A bright light sheet was set up in the required plane to help illuminate the flow. A SONY Mini-DV video camera was used to digitally record the footage directly to a laptop computer for later analysis. Full details of the Hydrogen bubble visualization technique can be found in Smith *et al* [3].

Prior to any fluid flow, a small plastic target with a 5mm by 5mm square grid was inserted into the pipe and imaged. This image was then digitally superimposed over the Hydrogen bubble visualisations in post processing. At high velocity the quality of the flow visualisation was reduced. This limited the velocity range over which Hydrogen bubble visualisation was conducted.

Pipe flows both with and without a blockage were investigated. To facilitate pipe blockage a preliminary simple closure mechanism was used. It consisted of a hand driven slider that moves along the receiver tank walls in a direction co-axially with the pipe. It has a 3D x 3D rubber face that mates with the pipe exit. Although this mechanism does not provide instantaneous closure, it does allow fast enough closure for these preliminary experiments. The closure time is measured at approximately 300 milliseconds.

Dye visualisation was also used to investigate flow features near the pipe exit after pipe blockage. Neutrally buoyant dye was slowly introduced to the flow a short time after blockage. Dye was introduced from one of three 1.5 mm diameter dye ports located approximately 0.3D, 0.5D and 1D upstream of the pipe exit. When one dye port was in use the other two were sealed at the interface between the pipe and the dye port.

Results and Discussion

The velocity profile in the absence of any blockage was first investigated to test if the flow in the pipe was fully developed. Figure 6 shows the pipe exit region and the hydrogen bubbles. Superimposed over this figure are the target and symbols showing various locations of the Hydrogen bubbles. The bubble distribution shows a timeline of the simple pipe flow which is representative of the velocity profile. The line represents a parabolic curve fit to the shown points. This shows that the velocity profile is parabolic in shape representing fully developed pipe flow.

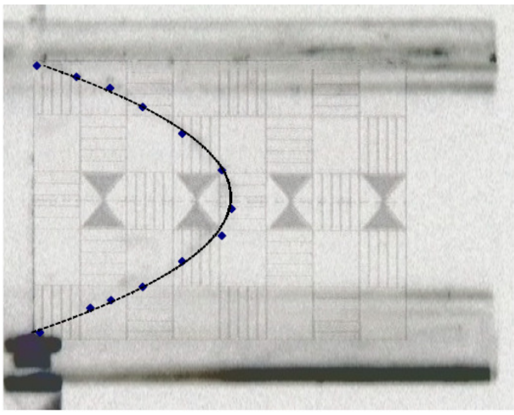


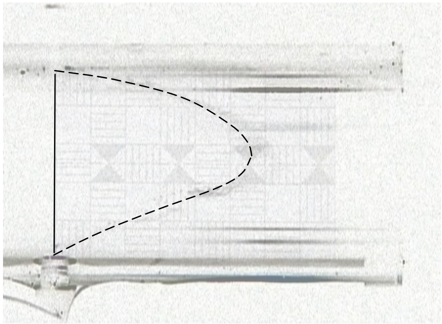
Figure 6 Hydrogen bubble visualisation of the pipe flow at Re=3,000. The solid line shows a parabolic curve fit to the selected data points.

Figure 7 shows the development of the velocity profile for a pipe flow before (a), during (b) and after (c &d) blockage of the flow. The time of the blockage is arbitrarily set to zero and the Reynolds number is approximately 2000.

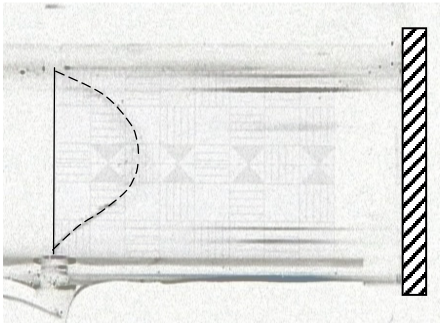
Figure 7 (a) shows the flow approximately 0.7 seconds before the blockage. A parabolic velocity profile is evident. Asymmetry in the velocity profile is due to the buoyancy effect of the bubbles downstream of the wire.

During the blockage, (figure 7 (b)), the face of the blockage mechanism can be seen at the exit of the pipe represented by the hatched rectangle. The velocity profile still appears parabolic.

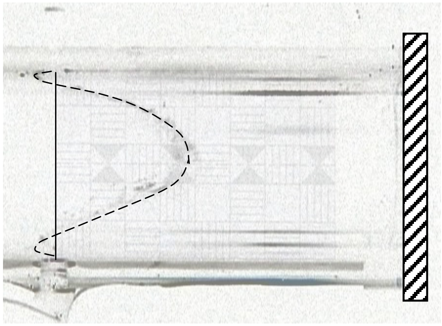
A short time after the blockage the velocity profile in the pipe begins to undergo significant changes. The fluid near the inside walls of the pipe slows down and reverses direction. This flow reversal can be seen in figure 7 (c). This can also be seen in figure 8 which shows dye visualisation a short time after the pipe blockage. This feature has been observed in pipe blockage experiments by Vardi and Hwang [4] and the numerical investigation of Jewell and Denier [2].



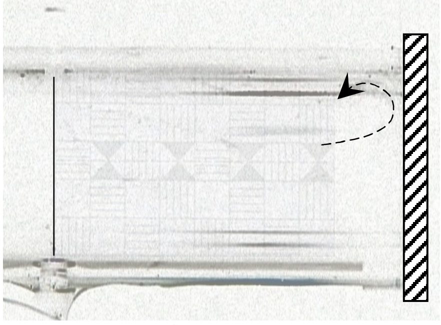
(a) t = -0.7 sec



(b) t = 0.0 sec (Blockage)



(c) t = 0.3 sec



(d) t = 2.1 sec

Figure 7. Hydrogen bubble visualisation of the pipe flow at Re=2,000 before (a), during (b) and after (c & d) the blockage. The time of blockage is arbitrarily set to zero. The dashed line shows the bubble distribution and the hatched rectangle represents the blocking surface.

This flow reversal near the walls represents a region of high velocity gradient.

Another flow feature of interest is the development of a stopping vortex near the pipe blockage. This feature is seen in figure 7 (d) near the top of the pipe and quite clearly in figure 8. This feature is similar to that predicted by Jewell and Denier [1].

Stream-wise velocity, u, in the pipe is estimated by tracking the displacement of timelines at particular radial positions. Figure 9 shows the relative stream-wise velocity before, during and after blockage at two radial locations. The uncertainty is approximately 0.3 u/U_{bulk}. The velocity along the pipe centreline (r = 0) is initially about twice the bulk velocity. This is consistent for fully developed laminar pipe flow. During the blockage the centreline velocity is seen to decrease but not to zero. The velocity at the radial location r = 10 mm (0.4D) is seen to decrease, attain a zero value and level off at a negative value. This is consistent with the flow reversal observed near the pipe wall in the flow visualisation. As the centreline velocity did not attain zero value, the flow reversal at the wall is necessary to satisfy continuity in the pipe.

Future work

The current preliminary experiments have only given a small amount of qualitative data over a small Reynolds number range. Further experimentation using quantitative techniques over a larger Reynolds number range is planned.

Particle image velocimetry experiments are planned to determine the development of the velocity profile before, during and after blockage at a number of locations near the pipe exit.

A more sophisticated blockage mechanism has been designed for improved consistency in the blockage process. This mechanism consists of a compressed air driven pneumatic cylinder that is regulated by a quick-response solenoid vale. This cylinder is aligned with the axis of the pipe. A 2D x 2D stiff rubber plate is fixed to the front face of the cylinder rod and closes the pipe when the solenoid engages the cylinder. The solenoid valve can be electronically activated. This is useful for synchronisation between the PIV laser, the PIV camera and the solenoid valve.

Conclusion

A two-tank flow facility has been designed and tested for the study of sudden blockage in pipe flow. Preliminary experiments have been conducted to test the validity of the system for generating fully developed pipe flow as well as simple blockage flows. In the absence of a blockage, fully developed pipe flow is observed. When the flow is blocked, flow features consistent with previous studies are observed.
Quantitative Laser based experiments with more consistent blockage techniques are planned.

Acknowledgment

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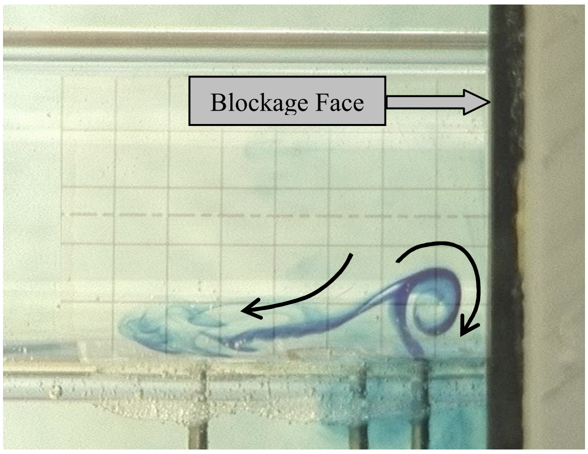

Figure 8. Dye Visualisation of blocked pipe flow 3.8 seconds after pipe blockage. The unblocked flow was at Re=2,000.

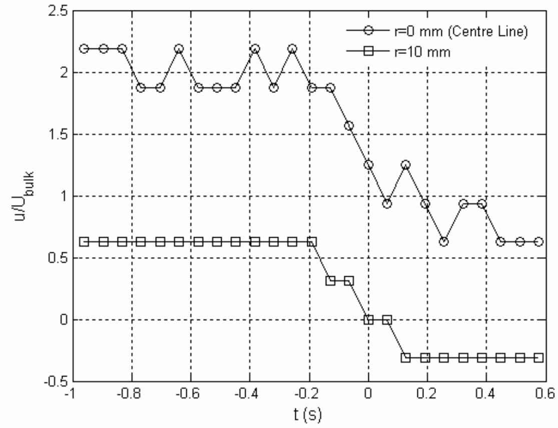

Figure 9. Relative stream-wise velocity during the blockage process. The time of blockage is arbitrarily set to t = 0 s.

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