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論　文

FLUENT MODELLING OF CAVITATION IN POPPET VALVES

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포펫트밸브내에서의 캐비테이션에 관한 FLUENT 모델링

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〈목　차〉

Abstract

The aim of this paper was to expand on work already carried out on the modelling of the flow through a poppet valve using CFD software FLUENT V4.22. Several different models were run on FLUENT for various lifts of the poppet cone and various back pressures. The results for pressure and velocity obtained were interpreted.

The results revealed the presence of cavitation downstream of the orifice around the cone tip, and the presence of a high velocity jet stream along the centre line. These results confirm what has been found to happen in practice.

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1. INTRODUCTION

A great deal of research has been published on the flow characteristics of hydraulic valves [1-3]. This serves to indicate that valve flow can be a highly complex process which is strongly dependent on the details of the valve geometry, the fluid properties and the operating conditions. Recently fluid power is widely used in a variety of ways. It is used throughout industry, where a fluid under pressure is used for the control and transmission of power. Fluid power devices can be pneumatic of hydraulic, using compressed air or liquid. Hydraulic systems are used where high power, precision speed control or high forces are required.

In hydraulic systems valves are used to control the direction of flow, the pressure of the fluid and the flow rate. There is a wide range of valves available designed to perform specific tasks within hydraulic systems. These can be actuated by manual, mechanical or electrical means in order to control the system. This paper is concerned only with the poppet valve which is a directional flow control valve. Poppet valves allow flow only in one direction and prevent it in the reverse direction as shown in Figure 1. The flow indicated by the arrows in Figure 1 is in the normal direction.

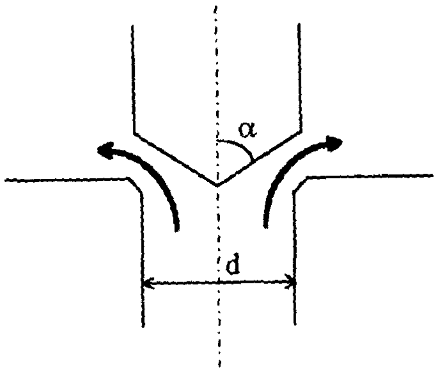

Fig. 1 Flow in the normal direction in a poppet valve

The flow modelled here is in the reverse direction where cavitation has been found to occur. The geometry used that of actual valves and was drawn from engineering drawings supplied by the industrial collaborator. Figure 2 shows close-up view of seat and poppet of them.

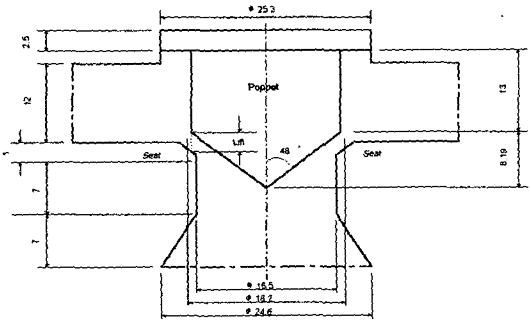

Fig. 2 Close-up view of seat and poppet

The objective of this paper is to expand on previous work studying the flow through a poppet valve in the reverse direction using a computational fluid dynamics package (FLUENT V4.22). The work[4] that has already been carried out on this subject has shown qualitatively that such a reverse flow leads to cavitation and damage to the valve. The aim of this paper is to develop the work already done to get a quantitative representation of the flow, and if possible to redesign the valve in order to avoid the problem of cavitation all together.

2. CAVITATION IN THE FLUID POWER[5-8]

Cavitation occurs when a liquid is exposed to low pressures equal to, or less than, vapour pressure. Any nuclei like small gas bubbles or voids present in the liquid, that enter an area where local pressure is equal to that of vapour pressure, form cavities. These cavities will continue to grow rapidly as long as the local pressure remains at vapour pressure. If the surrounding pressure is above vapour pressure, or the cavity moves to an area of higher pressure, then it will collapse.

As the fluid approaches the orifice in the poppet valve, it accelerates through the smaller cross section, and there is a fall in static pressure as potential energy is converted into kinetic energy. If the local pressure falls below vapour pressure, vapour filled cavities will form. As the jet of fluid slows downstream of the orifice, where the flow area increases again, then the pressure recovers to levels above that of vapour pressure. At this point the cavities collapse. Whenever there is a substantial pressure drop across a valve, there is the possibility of cavitation effects occurring downstream of the valve.

Cavitation can be damaging to a system in a number of ways. The collapse of cavities within a liquid can cause problems with noise. Noise can be a legal problem as well as a physiological problem with increasingly stringent legislation on noise levels. The type and intensity of noise depends mainly on the physical attributes of the system involved and can range from hissing or light crackling to a sound more reminiscent of a dynamite explosion.

Another of the problems associated with cavitation is that of vibrations within a system. Collapsing cavities generate shock waves which produce pressure fluctuations causing the system to vibrate. The magnitude of vibrations increases with the cavitation and heavy levels of cavitations can loosen bolts, break tie-downs and may lead to structural failure.

Large vapour cavities forming in advanced stages of cavitation can change the hydro dynamics of the flow thus reducing the efficiency of the system. Efficiency is reduced in the form of reduced power output from turbines, reduced head production from pumps and valves no longer passing the predicted flow.

The main problem due to cavitation that is examined in this paper is that of erosion damage to fluid power components, in particular the poppet valve. As cavities collapse near a wall or boundary within the system this results in erosion damage to the surface. Research has indicated that collapse of cavities must occur approximately one bubble diameter from the boundary to cause erosion damage. This indicates that only bubbles very near or on the boundary will cause damage since the bubbles are very small. There are two mechanisms which are generally held to explain how erosion damage occurs at boundaries. The first is that the collapse of the cavities produces high pressure shock waves which are capable of damaging any material. The second is known as a microjet. As a bubble collapses near a boundary the pressure distribution around it is asymmetric due to the boundary. The bubble therefore collapses inward since the side of the bubble away from the wall achieves a higher velocity. A jet is produced, shooting through the centre of the bubble, which creates a local pit when it impacts with the boundary. The level of damage due to erosion increases rapidly with the velocity of the system. The rate of erosion has been found to be proportional to V^n where n varies between 4 and 7 depending on the system.

Another aspect of erosion damage due to

cavitation is corrosion. The top resistant layer of metal is removed due to the erosive properties of collapsing cavities. Fresh metal is then exposed and is then subject to the corrosive properties of the fluid itself. Cavitation can also accelerate erosion damage caused by the abrasive action of sediment in the fluid.

3. COMPUTATIONAL FLUID DYNAMICS USING FLUENT V4.22

3.1 The structure of the FLUENT package

FLUENT Version 4.22[9)] is a computational fluid dynamics(CFD) program which enables to analyse a variety of complex flow problems. It is an interactive, menu driven, program able to solve a wide range of fluid dynamics problems.

FLUENT V4.22 consists of two parts ; a pre-processor, PreBFC and the main module, FLUENT. In the PreBFC module the geometry of the system to be modelled is set up and the grid defined. This is then stored in a grid file and transferred to the main FLUENT module. In the main module the physical constants of the system are defined along with the boundary conditions. This information is then stored in a case file. The calculations are then performed within FLUENT and the data obtained is stored in a data file. From the data file, along with the relevant case file, the results can be displayed and examined graphically and alphanumerically.

3.2 The pre-processor and the main module

The geometry for the body fitted grid is created in the pre-processor PreBFC. The geometry is defined in terms of points and curves. The grid for the geometry is then defined. This is done in several steps. Figure 3 shows the computational domain for the poppet valve, The first step in setting up the computational domain is to set the number of grid points. In the case of the poppet valve 50 x 30 grid was used. The areas that are shaded, in this problem, must first be defined as dead. This is done by mapping the interior regions. The lines lying on the boundaries of these regions are mapped. The same is then done for the exterior region until the computational domain is complete.

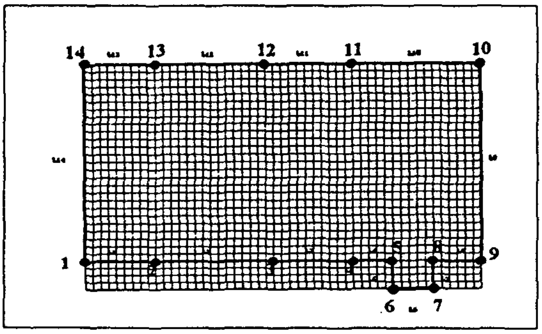

Fig. 3 Computational Domain of FLUENT preBFC Grid

Once the computational domain has been defined the grid is created by interpolation. The geometry is divided into five regions for this model, and each of these regions is interpolated individually. The grid for the poppet valve can be seen in Figure 5. From this figure it can be seen that the grid at the vena contracta is finer than elsewhere.

Once the grid has been stored in a grid file it is then loaded into the main module of FLUENT V4.22. Here the operating conditions of the model are defined as follows (incompressible flow using Shell Oil Tellus 37 with a dynamic viscosity of 0.02 Ns/m^2, density of the fluid is 860 kg/m^3 and does not change with temperature, fixed pressure boundaries at inlet (350 bar) and outlet (50 - 150 bar), steady state model used, very small fixed pressure boundary chamfer seat set at atmospheric pressure).

In order to set the outlet at a fixed pressure it was necessary to redefine the outlet cells as inlet cells. This is because FLUENT does not allow fixed pressure outlets. These cells, however, behave in the same way as an outlet since the pressure was set much lower than at the actual inlet. The pressure at the outlet was set at various levels to determine the effect of a change in back pressure on cavitation.

It has shown that FLUENT gives large negative pressures for small areas within the vena contracta. This is obviously impossible and so steps were taken to prevent its occurrence. It was decided that by setting one or two cells in the critical area to atmospheric pressure, this would prevent the pressure falling below absolute zero in the area of the vena contracta.

3.3 The models

Several models of the poppet valve were set up as described above. As already mentioned several models with different back pressures (i.e. pressure at the outlet) were set up to determine the effect of such change. The back pressures were 50, 75, 100 and 150 bar. Also models were set up with the lift of the poppet set to different levels, i.e. 0.5, 1.0 and 1.5 mm. In total twelve different models were set up and results obtained for each. Figure 4 shows an outline of the flow area that was modelled with the inlets and outlets marked.

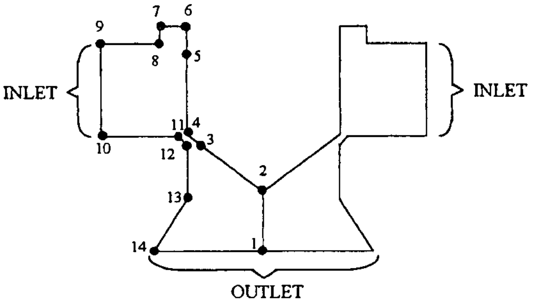

Fig. 4 Flow area modelled in FLUENT

4. RESULTS AND DISCUSSION

4.1 The poppet valve.

The results obtained for the model of the poppet valve are shown by the figures No.5 to 7. Tables 1,2,3 show specific values of interest for each of the models. The results will be discussed in three sections. The first section will discuss the general pattern of results obtained. The second section will discuss the effects of changing the back pressure, and the effects of changing the lift will be discussed in the third of the three sections. All pressure

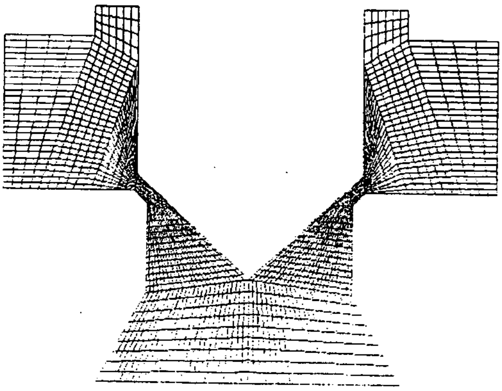

Fig. 5 Finite difference grid for poppet valve

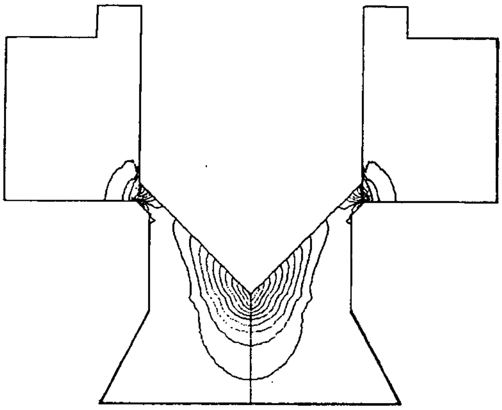

Fig. 6 Pressure contours 1.5mm lift, 50bar outlet pressure

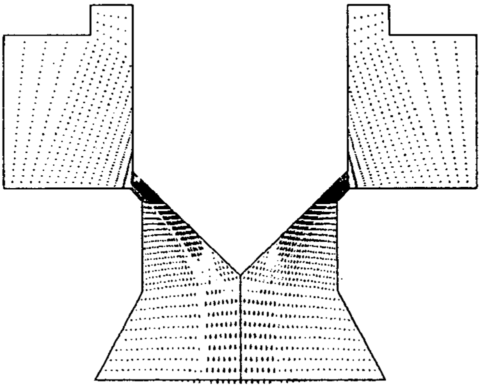

Fig. 7 Velocity vectors 1.5mm lift, 50bar outlet pressure

values are relative to atmospheric pressure, -1 bar being absolute zero.

4.2 The general pattern of flow.

All the results obtained follow the same basic pattern. Figure 6 shows the filled pressure contours obtained for a 1.5 mm lift with a 50 bar outlet pressure. The flow starts off at the inlet at very high pressure. As the fluid approaches the vena contracta the pressure increases slightly at the entrance. As the fluid passes through the vena contracta the pressure drops dramatically down to its lowest levels. When the fluid has passed through the small gap between the poppet and the seat the pressure begins to rise again. Areas of high pressure are found around the tip of the cone, before the pressure falls again at the outlet. This pattern is the same for all the models.

Figure 7 shows the velocity vectors obtained for a 1.5 mm lift with a 50 bar outlet pressure. At the inlet the fluid moves at its slowest velocity. The magnitude of the velocity increases at the fluid approaches the vena contracta. The fluid then accelerates through the vena contracta and is at its highest velocity along the edge of the poppet cone. At the tip of the cone the magnitude of the velocity decreases slightly. The fluid then speeds up toward the outlet in a stream in line with the cone tip. Along the wall of the valve below the vena contracta the fluid moves very slowly in an upwards direction towards the vena contracta.

4.3 Effects of changing the back pressure.

The back pressure, or outlet pressure, on the poppet valve was set at four different levels, 150bar, 100bar, 75bar and 50bar. The effects of this change are examined at each of the three lifts.

4.3.1 1.5mm Lift.

As the back pressure is increased the

following effects on the flow within the poppet valve are observed. The maximum pressure was found to decrease as the back pressure was increased(see Figure 8), whereas the minimum pressure was found to increase (see table 1). As the back pressure was increased the maximum velocity of the fluid within the valve decreases (Table 2 and Figure 9). Table 3 shows that in each case the pressure difference between the vena contracta and the outlet is approximately equal to the back pressure. This is to be expected since the minimum pressure is found at the vena contracta and these values are very close to zero. The pressure difference between the vena contracta and the cone tip varies slightly around a figure of 250 bar but does not follow any noticeable pattern. The area of low pressure at the vena contracta decreases in size as the back pressure is increased. The area of

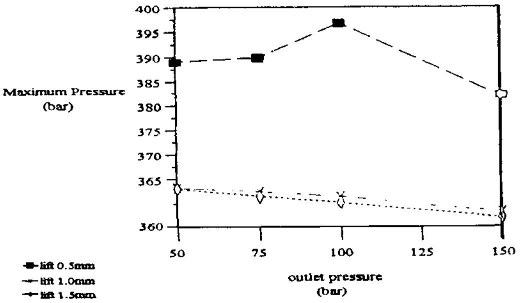

Fig. 8 Variation of maximum pressure with outlet pressure at 0.5, 1.0 and 1.5mm lift

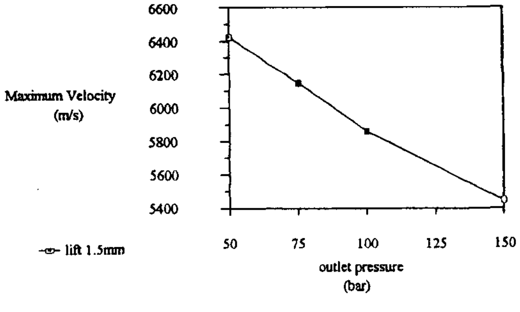

Fig. 9 Variation of maximum velocity with back pressure

Table 1

Lift (mm)	Outlet Pressure (bar)	Maximum Pressure (bar)	Minimum Pressure (bar)
0.5	50	389.0	-6.1
0.5	75	389.9	-2.2
0.5	100	396.8	-2.7
0.5	150	382.1	-5.0
1.0	50	364.1	-2.6
1.0	75	363.7	-0.9
1.0	100	363.1	-0.4
1.0	150	361.6	-0.2
1.5	50	364.0	-3.9
1.5	75	363.2	-0.4
1.5	100	362.6	-0.1
1.5	150	361.0	0.7

Table 2

Lift (mm)	Outlet Pressure (bar)	Maximum Velocity (m/s)
0.5	50	264.1
0.5	75	266.1
0.5	100	255.8
0.5	150	256.8
1.0	50	252.8
1.0	75	2425
1.0	100	231.3
1.0	150	215.8
1.5	50	6425
1.5	75	6150
1.5	100	5861
1.5	150	5446

Table 3

Lift (mm)	Outlet Pressure (bar)	Pressure difference between vena contrcta and cone tip (bar)	Pressure difference between vena contracta and outlet (bar)
0.5	50	125.1	56.2
0.5	75	144.2	77.2
0.5	100	146.7	102.7
0.5	150	204.0	155.0
1.0	50	212.6	52.6
1.0	75	229.9	75.9
1.0	100	229.6	99.6
1.0	150	209.2	150.2
1.5	50	251.9	53.9
1.5	75	248.4	75.4
1.5	100	248.1	100.1
1.5	150	265.3	149.3

high pressure around the cone tip is very large for the 50 bar back pressure, but remains approximately the same size for the other three outlet pressures.

4.3.2 1.0mm Lift

Similar patterns emerge for the poppet valve pressure and velocity for the 1 mm lift as for the 1.5 mm lift. Again the maximum pressure decreases as the back pressure increases and a straight line correlation can be seen in Figure 8. Figure 10 shows the relationship between the back pressure and the minimum pressure. There is no strict correlation between the two but there is a general increases of minimum pressure with back pressure. The maximum velocity of the flow decreases as the back pressure is increased and appears to behave linearly. The pressure difference between the vena contracta and the cone tip is fairly constant and fluctuates about 225 bar. Again the pressure difference between the vena contracta and the outlet is approximately equal to the outlet pressure. The area of low pressure on the seat at the vena contracta decreases in size as the back pressure increases. The area of high pressure on the cone tip is very large for the 50 bar outlet pressure model but approximately the same size for all the other models.

4.3.3 0.5mm Lift

When the lift of the poppet was set at 0.5mm, the results obtained were more erratic than those found for the other two lifts. There was no discernible pattern for the effect of back pressure on the maximum or the minimum pressures(Figures 8 and 10 and Table 1). The maximum velocity again seems to follow no pattern with regards to outlet pressure (see Figure 11). The pressure difference between the vena contracta and the cone tip is also rather erratic and fluctuates between 125 and 200 bar. The pressure difference between the vena contracta and the outlet is again approximately equal to the outlet pressure, although it varies more than in the other models. The area of low pressure at the vena contracta decreases as the outlet pressure is increased. The pattern of pressure within the valve, however, is slightly different to the other models in that as the outlet pressure is increased the area of high pressure at the cone tip decreases, and have much fewer contours than the other models.

4.4 The effects of changing the lift.

The lift of the cone was set at three different levels, 1.5mm, 1.0mm and 0.5mm. The effects of

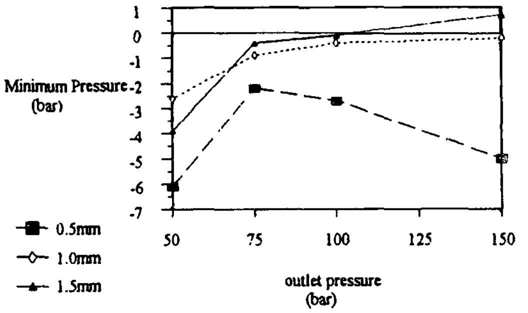

Fig. 10 Variation of maximum pressure with back pressure for 0.5, 1.0 and 1.5mm lift

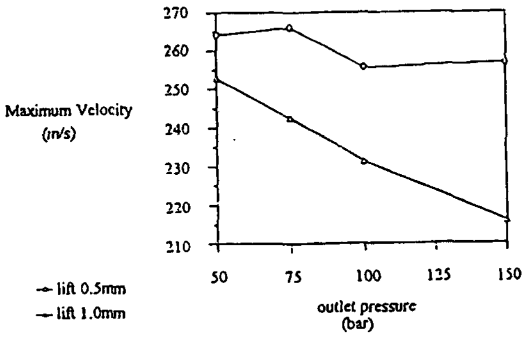

Fig. 11 Variation of maximum velocity with back pressure for 0.5, 1.0mm lift

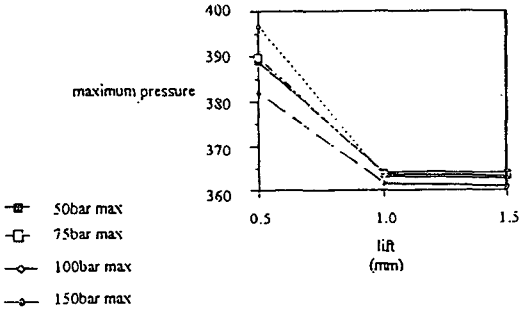

Fig. 12 Variation of maximum pressure with lift, for all back pressure

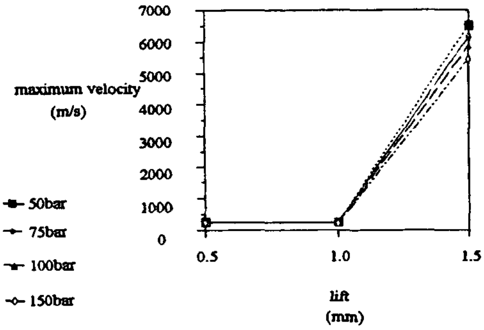

Fig. 13 Variation of maximum velocity with lift, for all back pressure

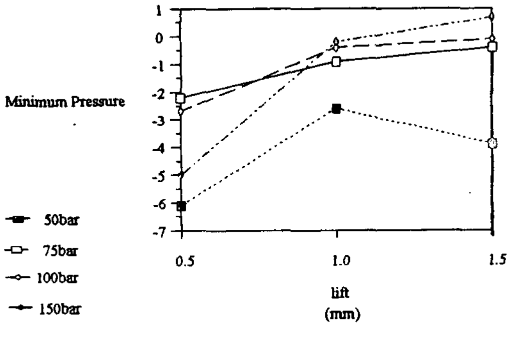

Fig. 14 Variation of minimum pressure with lift, for all back pressure

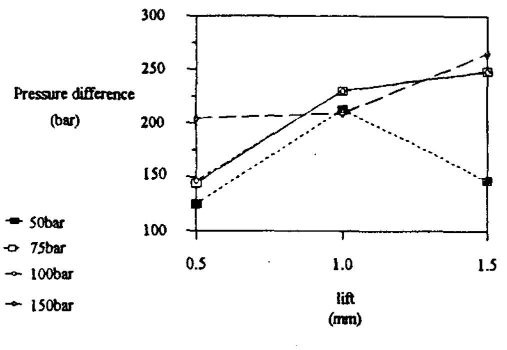

Fig. 15 Pressure difference between vena contracta and tip, for all back pressure

this change are examined at each of the four back pressures. The same patterns emerged for each of the four back pressures with regards to maximum pressure and maximum velocity. These patterns can be seen in Figures 12 and 13. The maximum pressure in each case is at its highest for the 0.5mm lift. There is little variation between the 1.0 and 1.5mm lift with maximum pressures between 360 and 365 bar. Maximum velocities vary between 200 and 270 m/s for both the 0.5 and 1.0mm lift. At a lift of 1.5mm, however, there is a massive increase in maximum velocity, as it varies between 5400 and 6400 m/s.

The variation of minimum pressure with lift is shown in Figure 14. It can be shown that all of the models follow approximately the same pattern, although it is noticeable that the 50bar model produced much lower pressures than the other models. The pressure difference between the vena contracta and the cone tip varies as shown in Figure 15. From this figure it can be seen that the pressure differences for 75 and 100 bar vary in the same pattern. There is a general increase, but it is non-linear. There is also a general increase for pressure difference for the 150bar model. The values for 50bar, however, follow no noticeable pattern.

4.5 Discussion of FLUENT V4.22 results.

It was found that some of the minimum pressures found were below absolute zero (i.e. below -1bar in figures and tables). This is because FLUENT V4.22 is unable to model cavitation. When cavitation occurs the fluid no longer has the same uniform density. The introduction of small pockets of vapour require the introduction of a new species at a certain pressure. The actual density of the fluid at the points of low pressure is actually lower than the 860 kg/m^3 specified in the set-up of the model. The pressures at these points, therefore, would not be as low as FLUENT calculated them to be. This change in pressure caused by the cavitation can be taken account of by using a 'user subroutine'. This would involve the introduction of a new species when the pressure falls to or below vapour pressure.

5. CONCLUSION

The results given by FLUENT V4.22 for the various models of the poppet valve give the following points from which conclusions can be drawn : -

1. An area of very low pressure at the vena contracta and an area of high pressure around the cone tip were observed.
2. A high velocity jet stream was found to develop in line with, and below, the cone tip.
3. When the lift was reduced to 0.5mm the results obtained were erratic and inconsistent with the results obtained for the other two lifts. The maximum pressure is the highest and the minimum pressure is the lowest when the lift is 0.5mm.
4. When the back pressure was reduced to 50bar the area of low pressure both increased in size and decreased in magnitude. This would lead to an increase in cavitation.
5. With a lift of 1.5mm the magnitude of the fluid velocity increased massively by a factor of about 25. This is not desirable.
6. The area of low pressure at the vena contracta increases as the lift decreases and decreases as the back pressure is increased.
7. The area of high pressure around the cone

tip increases as the lift is increased. The number of contours in this area also increases with the lift.

From these points it can be concluded that the best configuration for the poppet valve would be a 1.0mm lift. The back pressure that would be most desirable in practice is 75bar. FLUENT V4.22 suggests that 150bar would be better, although this is unrealistic in practice.

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