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CFD MODELLING OF AF12 PRODUCT FILLING VALVE FOR LIQUID PACKAGING MACHINES

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ABSTRACT

A full-scale computational fluid dynamics (CFD) model has been developed to investigate the complex flows in AF12 filling valve that is used for packaging liquid products. Detailed investigations of flow parameters like pressure, velocity etc. were made for finding areas of improvement of existing valve design. Formation of reverse flow was observed at the outlet and comparatively low shear stresses were observed at the wall regions, causing reduction in filling rate and poor cleaning in place (CIP) performance of the valve. Cavitation occurs in two regions, within the flow domain, causing an objectionable sound level of the device and a reduction in filling efficiency. To overcome these problems, several possible modifications have been identified, which will enhance the product quality, reduce the operating cost, and improve the performance of the valve through better CIP performance.

Keywords: Cleaning in Place (CIP); Product fill valve; Cavitation; Filling Time; Turbulence Intensity; Wall Shear Stress.

1. INTRODUCTION

A filling machine is a sophisticated piece of equipment and used for packaging a vast array of liquid products, from catering products such as ketchup and mayonnaise through soft drink post mixes, wine and even motor oil. In the constant quest for faster filling speeds the product valve has been identified as one of the components in the system that currently limits packaging speed. In this study a product valve, used to fill bags in wineries is analysed to determine if recent developments in materials, processes, modelling and manufacture could produce an assembly with a significantly improved flow rate while retaining all of the benefits of the existing device.

In the re-design of this piece of equipment emphasis was placed on improving the CIP ability, reducing cavitations and increasing filling speed. In addition, the sound level produced by the valve was investigated. CIP brings several significant benefits to the equipment. These include improved product quality, longer shelf life, lower labor cost and increased production capacity. By the middle of the last century it was thought that fluid velocity was the influential factor in CIP design, and at that time it was determined that a minimum flow rate equivalent to five feet per second in the largest tube diameter of the system was necessary for thorough cleaning [1,2]. Later research has shown that wall shear stress and turbulence are the important parameters for effective cleaning [3]. Several European researchers have attempted to add to this early research on the subject by trying to quantify wall shear stress required for the practical cleaning of food processing equipment. Testing the CIP performance of process equipments' prototype are very time consuming and expensive. This encourages the use of validated CFD models during equipment design, saving manufacturers considerable resources. Several researchers [4-6] used CFD to evaluate the CIP design and to yield guidelines for hygienic design of components on a qualitative level. The work of Lelievre [5] is of particular interest as it deals with the effect of the shape of the fluid conductor on the wall shear stress and turbulence. This study found that the fluctuation in the value of the wall shear stress was of major importance. Some shapes produced large fluctuations in the measured stresses and were found to be more reliably cleaned than areas of higher shear stresses but lower fluctuation rates. These results were verified by actual measurement of the shear stresses involved and showed that surfaces are cleanable with wall shear stress as low as 0.15 Pa, if the fluctuation rate is high.

Experiments performed by Fris and Jensen [7] also identified the possibility that cleaning could not be highly effective in complex geometries in areas where the critical wall shear stress had not been reached. Jensen and Fris [8-10] used CFD to predict the critical wall shear stress required to clean components to the level required by European Hygienic Engineering and Design Group (EHEDG). Their suggested critical wall shear stress of 3 Pa has formed a basis for further research by themselves and others. Several other works [11,12] on valve design using CFD are also available in the literature. However, like Jensen et al.[8,9], most of these works are based on simplified two- dimensional models that are not adequate for predicting fluctuations in wall shear stress, an important parameter for investigating CIP performance of the valve. Therefore, a full three dimensional analysis is required for this purpose.

The wall shear stresses in areas of low turbulence intensity are of major interest, as at lower turbulence intensity, cleanablilty of the valve will be reduced. If the turbulence intensity can be critically evaluated in the light of the results of Lelievre et al. [5] and effectively applied, then valuable likely in-place cleanability can be gained. Therefore, in this study, a full scale, three dimensional model of the current AF12 valve design used in wine filling has been modeled to investigate the fluid velocity, wall shear stress and cavitation properties to evaluate the key operating parameters such as, CIP performance and filling rate. The results obtained from this research will demonstrate the capability of CFD analysis as a valuable aid in designing the product fill valve and will provide guidance for future experimental work.

2. PRODUCT VALVE: CFD Modelling

The product valve is the interface between the filling machine and the package. It has been used to dispense product on varied equipments in many applications around the globe. These include filling machines in wineries, dairies, and industrial product plants. A drawing of the product valve commonly used in winery is shown in Fig. 1. Using the dimensions from the engineering drawings of the product valve a computational model of the fluid flow domain of the valve was developed using Gambit, the modeller associated with FLUENT 6.0. Figure 2 shows the computational grid used for the calculations on the standard valve. The model was tested with a range of coarse and fine meshes to achieve grid independence. The final geometry contains 45,029 tetrahedral hybrid cells.

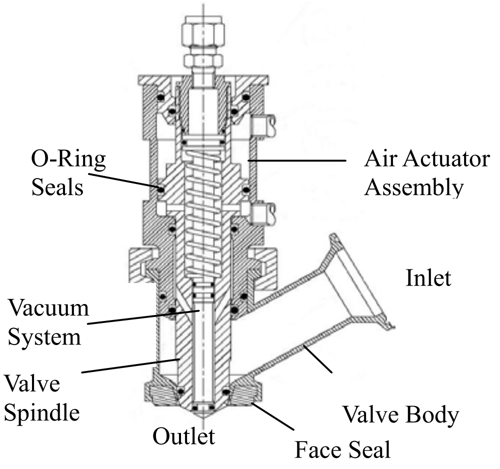

Fig 1: Schematic diagram of AF12 product fill valve

Comprehensive study on the applications of this particular valve indicates that it is mainly used for a range of beverages that have similar properties to water. In Australia, the valve is generally used for wine industry. One user of the equipment, a winery, reported the viscosity of their product as 1.002 N·s/m^2, equal to the viscosity of water, and the specific gravity as 0.991. From this study, some basic parameters were set and were used for the computational model. In summary these are: all fluid properties are those of water at a temperature of 20 degrees Celsius, the operating environment is the ISO Standard Atmosphere, with a pressure of 101.325 kPa, and the fluid supply pressure at the valve inlet is set at 200 kPa.

The Standard two equation Reynolds Averaged Navier Stokes k-ε turbulence has been used in this model. The Standard k-ε is robust and reasonably accurate if not used on models with strong separation. It may not give accurate results in cases of large pressure gradients and highly curved streamlines. The product valve does not have significant problems in these areas, and hence advantages in computational cost were achieved through the use of the simplest two-equation turbulence model.

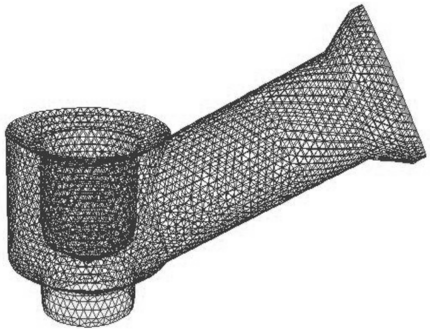

Fig 2: Computational Mesh

In this simulation, pressure boundary conditions were used for both inlet and outlet of the valve. The inlet pressure was set at 2 bar and the outlet pressure was set at atmospheric pressure (101325 pa). All solid boundaries were represented by wall and enhanced wall treatment was used for near wall treatment. The flow was assumed to be in steady state with water as a Newtonian incompressible fluid. The results of the FLUENT analysis of the existing geometry are presented in this study. Of interest for this analysis are the inlet and outlet contour charts of velocity, turbulence intensity in near wall region and wall shear stress distribution of the valve. Contours of these parameters at selected viewing planes in the valve interior and walls are presented to aid in looking into the details of CIP performance in the complex regions.

3. RESULTS AND DISCUSSION

Figure 3 shows the contour plots of fluid velocity at the inlet and outlet of the AF12 fill valve. The velocity of fluid flowing through the inlet plane shows a uniform velocity distribution and is in good agreement with the core-annular nature of the pipe flows. The velocity varies from zero at the valve wall up to a maximum of 9 m/s in the centre. However, the contours of velocity at the outlet are of interest due to their non-symmetrical nature. Unlike the usual pipe flow, position of the highest velocity shifted from the centre. This unexpected distribution is a result of the internal shape of the valve, which can be improved through the use of alternate design. The observed maximum velocity at the outlet was 17 m/s.

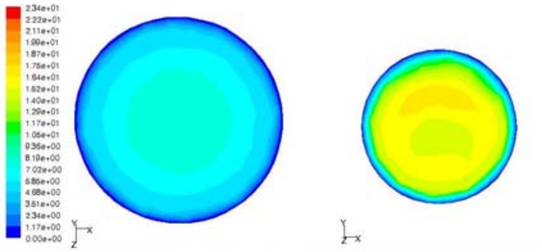

Fig 3: Fluid velocity at inlet and outlet of AF12 product fill valve (m/s)

In this research, as a trial, the geometry of the valve was modified by raising the valve stem 10 mm further than its usual opening position to investigate the effect of shape changes on the valve's performance. The inlet and outlet boundary conditions along with other fluid flow parameters (like viscosity, density etc.) were kept similar to the previous study for comparison purposes. Results of this analysis indicate significant improvement in velocity distribution as can be seen in Fig. 4.

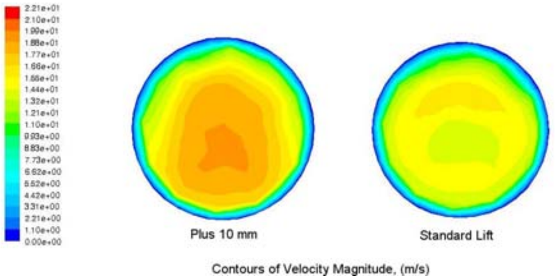

Fig 4: Comparison of velocity contours at the outlet with standard lift and plus 10 mm lift

Figure 5, the midplane velocity plot, shows a velocity contours through valve assembly in fully open position. The flow is fully developed with a mass flow of approximately 5.1 kg/s,, which is very close to the manufacturer's rated product-filling rate of 5.0 kg/s, and provides the validation of this model. However, analysis of this result reveals some concerns that reduces the valve's efficiency. For example, a rapid increase in velocity was observed at area 1 (Fig. 5), where the flow turns through 60 degrees. The high velocity in this area causes a local pressure drop that is severe enough to cause cavitation of the fluid. This cavitation is responsible for the backflow, developed at the outlet, as observed in Fig. 6, resulting in a loss in filling efficiency.

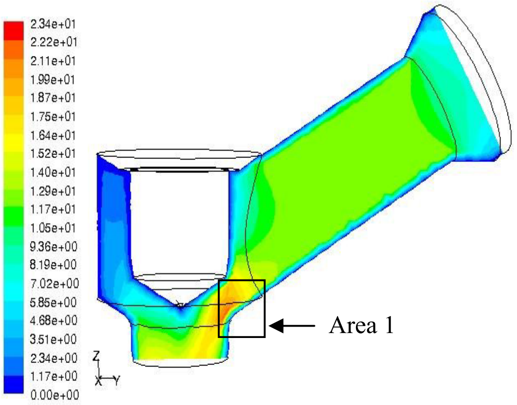

Fig 5: Velocity (m/s) distribution along the midplane of AF12 product valve

Furthermore, very low velocity was observed in most of the near wall region of the valve, associated with low turbulence intensity. This certainly decreases the CIP performance of the valve Therefore, several alternate geometries can be generated by varying the inlet pipe angle relative to the valve body, the length and shape of the outlet tube, the entry position of the inlet pipe and the shape of the valve body to enhance the CIP performance as well as increase the filling speed without any change in operating pressure.

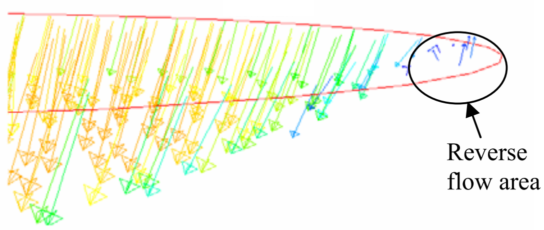

Fig 6: Areas of reverse flow at the outlet.

The plot of wall shear stresses is of interest as CIP performance of the valve depends on adequate wall shear stresses to remove soils [4]. The wall shear stress is velocity dependant, so theoretically almost any shape could be cleaned if adequate pressure and therefore velocity are available. In practice it is preferable to keep CIP pressures as low as feasible for many practical reasons, piping and fitting pressure ratings, pump and holding vessel sizes, equipment size and cost, and operator safety among them. Previous research outcomes have shown that very low wall shear stress results in objectionably poor CIP performance in most circumstances.

Wall shear stress distribution of this valve has been presented in Fig. 7. It can be observed from Fig. 7 that much of the internal walls of the valve were subjected to very low wall shear stress, which may not be sufficient

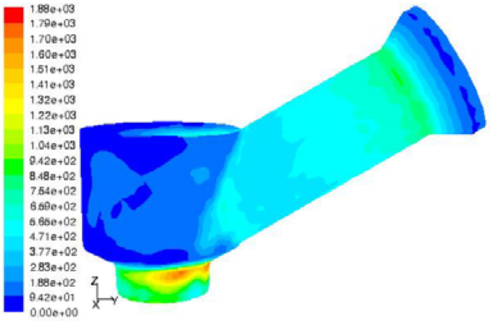

Fig 7: Wall shear stress (pa) distribution at valve wall

enough for cleaning, leading to poor CIP performance. However, as mentioned earlier in this paper, even at low shear stress, good cleanablity can be achieved if sufficient fluctuation in shear stress is present. Therefore, investigation on shear stress fluctuations in lower shear stress regions is vital, in evaluating the cleanability of the valve.

Earlier in this paper, references were made to the idea of using the intensity of turbulence as an indicator of wall shear stress fluctuation. Therefore the plot of turbulence intensity at the same operating conditions is important for the interpretation of the wall shear stress plot. The contour plot of turbulence intensity at the valve wall is shown in Fig 8. If the relationship suggested by Jensen et al (2005) is used then a level of 15 percent fluctuation in turbulence intensity corresponds to approximately a 10 percent wall shear stress fluctuation. In experiments conducted by Lelièvre a fluctuation level of 10 percent was not sufficient to significantly improve cleanability. Using this work as a guideline it can be strongly suspected that the areas of Fig 8 that are coloured dark blue will be difficult to clean in place as they coincide with areas of very low wall shear stress.

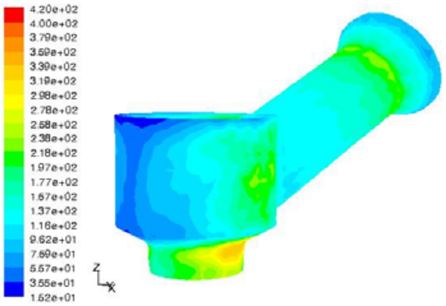

Fig 8: Turbulence intensity distribution at valve wall (%)

Use of alternate design, as suggested in the previous sections may results in better fluid circulation and hence greater turbulence intensity in the valve body, resulting in improved CIP performance.

The treatment of the product that passes through the valve has received greater interest in recent years from many of the end users. Conditions that might alter some delicate product qualities such as taste or aroma, and which may depend upon gases dissolved in the product, require further consideration. High fluid velocities and the adverse pressure drops that accompany them can have a negative impact on these qualities. If the pressures are low enough to reach the vapour pressures of the filling liquid, evaporation of the liquid will take place within the fluid domain, causing cavitation. In addition, at low pressure the dissolved gasses will start to come out of solution, lowering product quality and reducing filling efficiency.

Figure 9 shows the static pressure distribution in two planes. The first is on the symmetry plane and the second is on the plane parallel to the outlet plane at a point 7.5 mm inside the valve exit.

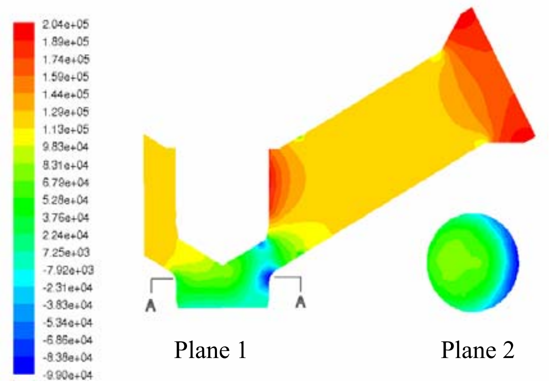

Fig 9: Static pressure (gage) distribution in plane 1 and plane 2

In this plot, the area of reduced pressure and its extent has been clearly illustrated. Extreme low-pressure regions were predicted within the flow domain. The predicted pressures are far below the water vapour pressure, causing the water to evaporate resulting in cavitation.

Elimination of these low-pressure regions through better design will help to maintain product quality as well as improve the efficiency of the valve.

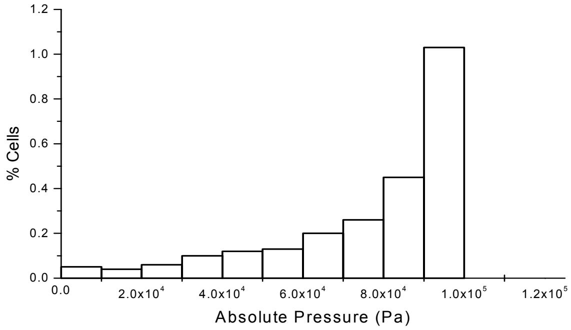

Fig 10: Distribution of low-pressure cells

Histogram analysis indicated that only about 2.6 percent of the 45,029 cells that constitute the fluid path of the model are subject to pressures lower than ambient atmospheric pressure. The majority of the low-pressure cells have pressure drops of 100 kPa or less, but a small percentage of cells reaches very low pressures. The pressure histogram, Figure 10, shows the distribution of the low-pressure cells. As cavitation is dependent on the vapour pressure of the fluid, described by Miller [13], in the case of water, only small portion of cells at the left side of the graph are of concern. In the case of wine or compounds like ethanol, which have vapour pressure higher than water, more cells will be involved. Of perhaps greater importance is the air and carbon dioxide that is in solution in the fluid. This forms gas bubbles in the diffusing section, which restrict the fluid flow, resulting in lower filling speed.

4. CONCLUSIONS

CFD investigation of a product fill valve used for filling bags in wine industry reveals several areas, where the flow pattern can be improved to increase the valve's performance and product quality. The current design shows some cavitation in areas where the fluid flows through 60 degrees bend which are responsible for backflow and loss in filling efficiency. Thus, the CFD analysis is found to be effective for this type of flow in filling machines. However, more investigation should be carried out with alternate designs for a range of fluids ranging from wine to ketchup ensuring no cavitation under conditions of changed fluid density and viscosity. Furthermore, CFD analysis has also identified areas with very low turbulence intensity, which in turn indicates the poor CIP performance of this valve. Again, with the aid of CFD analysis, alternative design of this valve can be achieved with no cavitation and better CIP performance and that will bring several remarkable benefits, which includes gentler product treatment, improved filling rate and less labour cost.

5. REFERENCES

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