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# DESIGNING A BUTTERFLY VALVE

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## 1. Abstract

Throughout this report the different features and calculations that surround a butterfly valve will be discussed. The first task within this report touches on the Reynolds number and Bernoulli's equation to determine what type of flow is within the valve.

Following this, the report then moves on to deliberate boundary flow looking at the layer separation and the different pressures flowing through the butterfly valve, along with how rivets connecting the disk plate to the body has an effect on the fixing and flow type.

Moving on to task three, which reviews the use of the butterfly valve within industries and outlines the advances that have been made over the years. As is clearly shown within this report, the use of these valves has greatly increased in a positive way assisting the industries and helping them work more efficiently. This is aided with new materials being used such as glass fibre reinforced plastic.

Task 4 discussed the use of computational fluid dynamics modelling software along with the advantages and disadvantages of these methods.

Finally, task 5 will discuss how a prototype butterfly valve is tested within a laboratory environment and how the data from these trials are obtained and how they can be compared to CFD modelling as discussed in task 4.

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## 5. Introduction

This report will be used to help understand the fluid flow properties of petroleum when a glass fibre reinforced plastic butterfly valve is used. The flow type will be determined by Reynolds number to characterise the flow being laminar or turbulent. Bernoulli's equation is relevant to calculating the Reynolds number as the velocity of the fluid needs to be found. The boundary conditions will be understood and discuss how the rivets have an implication of the separation and turbulence around the valve. Rivets are commonly used in multiple industries due to their ease of use. However, it is critical that the rivets won't be affected by the pressure through the valve especially as the water hammer phenomenon occurs. This report will discuss how butterfly valves have been developed over the years throughout industry and how they will continue to develop in the future. It is important that valves comply to the necessary British guidelines to ensure the safe operation in all industries, especially BS EN 558:2017 This regulation states the maximum pressure the valve must comply to along with several other key parameters. With the enhancement of computerised technology, Computational Fluid Dynamics (CFD) is used more often than full laboratory testing. The different methods of this technology will be discussed to see how it can be used to simulate the petroleum following through this valve. The data from the trial can be obtained by using pressure, flow and temperature sensors for live results being displayed and logged on a computer. As this technology is forever growing, the expectation of CFD analysis is forever growing. The results from the CFD and laboratory testing will be compared to see how much difference there is between the two methods.

## 6. Task One

Reynolds number, often referred to as  $Re$  is a dimensionless value which foresees a pattern within a fluid's behaviour (Rehm, et al., 2008) (Rapp, 2017) (Menon, 2015). The  $Re$  number is used to determine whether the flow of a liquid is laminar or turbulent (Simscale, 2021) (Rehm, et al., 2008). This is important because Laminar flow is characterised by smooth or in regular paths of particles of the fluid. Thus, laminar flow is referred to as "streamline flow" (ToolBox, 2021) (Menon, 2015) as there is no disruption between the layers. This flow pattern is common within low velocities as the fluid tends to flow without lateral mixing and adjacent layers flow past one another.

In contrast to laminar flow, turbulent flow is characterised by the irregular movement of particles of the fluid. The turbulent fluid does not flow in parallel layers with the lateral mixing being very high and there is a disruption between the layers (Simscale, 2021) (Rapp, 2017). This allows viscous losses to increase and parameters such as velocity and pressure to have a contribution to turbulent flow (ToolBox, 2021) (Simscale, 2021). Affectively the flow doesn't travel in layers which makes the flow inefficient due to the mixing within the tube.

The general equation for Reynolds number is:

$$Re = \frac{\rho V D}{\mu}$$

Where:

$\rho$  = density of the fluid (kg/m<sup>3</sup>)

$V$  = the velocity of the fluid (m/s)

$D$  = the pipe diameter (m)

$\mu$  = the dynamic viscosity of the fluid (kg/m.s) (Rehm, et al., 2008) (Rapp, 2017) (Menon, 2015)

As Reynold equation requires velocity to be expressed, Bernoulli's equation can be used with the known data to find the velocity flowing out of the tank.

$$P_1 + \rho g h_1 + \frac{1}{2} v_1^2 = P_2 + \rho g h_2 + \frac{1}{2} \rho v_2^2$$

$$v_2 = 9.9 \text{ m/s}$$

*Equation 1 Summarised Bernoulli's Equation*

*The full equation can be seen in appendix A (Nasa, 2016) (KhanAcademy, 2016)*

However, it has been assumed that there are no external forces acting on the fluid resulting in kinematic viscosity being used instead of dynamic viscosity. As there is a direct link between density and kinematic & dynamic viscosity (Gatenby, 2020), the equation for Reynolds number can be rearranged below.

$$\mu = v\rho$$

$$Re = \frac{\rho VD}{v\rho}$$

$$Re = \frac{VD}{v}$$

Where  $v$  is kinematic viscosity ( $m^2/s$ ) =  $0.000031 m^2/s$  supplied by (Toolbox, 2017)

$$Re = \frac{VD}{v}$$

$$Re = \frac{9.9 \times 0.194}{0.000031}$$

$$Re = 61,955$$

*Equation 2 Reynold Number*

The results from the above calculation will determine what flow is contrasted through the pipe. For laminar flow  $Re < 2000$  and for turbulent flow  $Re > 4000$  (Rapp, 2017), which from the calculation above the flow has been determined to be turbulent flow.

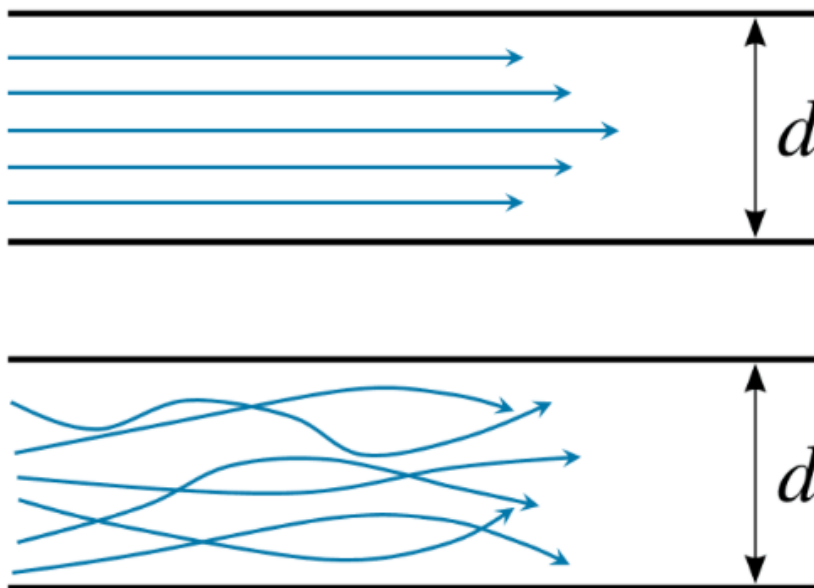


*Figure 1 Laminar and turbulent flow (Simscale, 2021)*

## 7. Task Two

Boundary flow is the contact of the petroleum against the inner wall of the butterfly valve. This fluid is subjected to shearing forces as a mixture of velocities exist within the boundary layer (Britannica, 2020). Figure one shows a velocity profile of fluid flowing through a pipe, where the profile gradually builds up from the surface to become fully formed. The thickness of the boundary layer is determined as the distance from the surface to where the velocity is 99% of free stream velocity (Britannica, 2020) (Leeds, 2018). Once the boundary layer has reached the centre line of the pipe, it is determined as fully developed, which results in all the fluid being affected by boundary friction. Boundary layer separation is dependent on the Reynolds number and flow rate. The lower these values, the less pressure difference occurs whereas when the Reynolds numbers is greater than 70, the flow pattern separates into vortices known as 'Karman vortex trials' (Leeds, 2018) (Britannica, 2020).

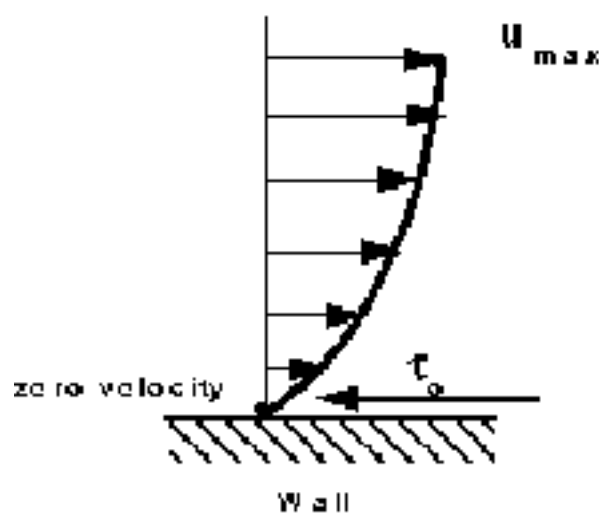


Figure 2 Boundary flow diagram (Leeds, 2018)

As the flow velocity changes this also changes the pressures flowing through the valve. According to Bernoulli's principle, the change in kinetic energy is directly linked to the change in static pressure. As petroleum flows across the rivets there is an increase of kinetic energy at the expense of pressure. As the flow slows the static pressure rises until atmospheric pressure is reached (KhanAcademy, 2016). During separation adverse pressure is seen when the pressure acts against the flow direction. This results in a backflow area where the laminar flow is detached and a turbulent wake forms behind the body.

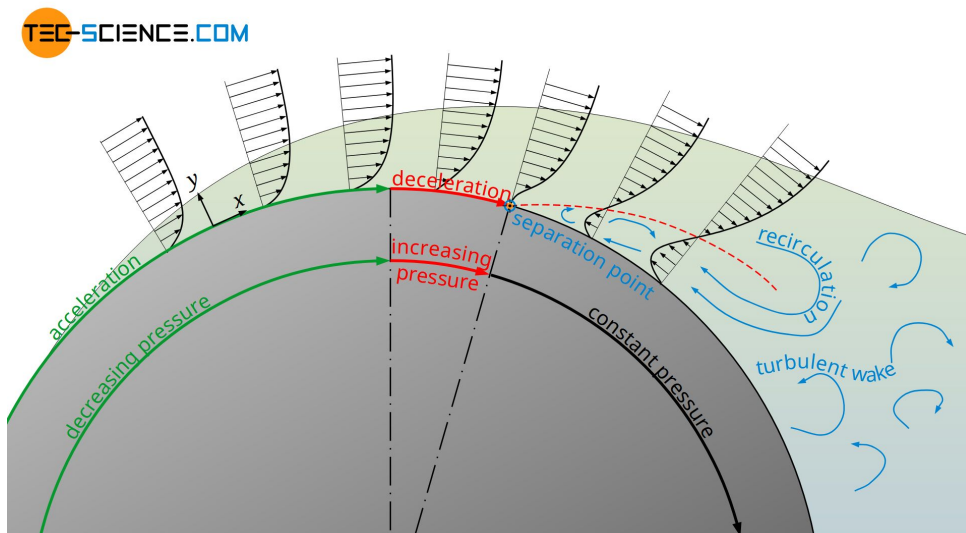


Figure 3 Velocity distribution around a cylinder (Tec-Science, 2020)

The use of rivets for this butterfly valve has numerous benefits. The first being the elimination of dissimilar metals which allows rivets to be used with any material. Riveting is also a fast and clean installation method (Weldarc, 2018) (Mecholic, 2019). A limitation of using rivets in this design is due to the affects that occur on the fluid flow due to the protruding head. Which from figure 2 shows how wake turbulence occurs in the boundary separation point. Additionally, rivets don't have as much structural integrity compared to welding or bolted connection as they are unable to withstand the same amount of force (Technical, 2019). For the use in the butterfly valve, this would likely cause issues when the valve is required to close quickly and suddenly and will have to deal with the amount of force which may cause the water hammer affect, shown in figure 4. Where this affect will send shock waves through the fluid to the valve where the valve will be subjected to high amounts of pressure (Walsh, 2019).

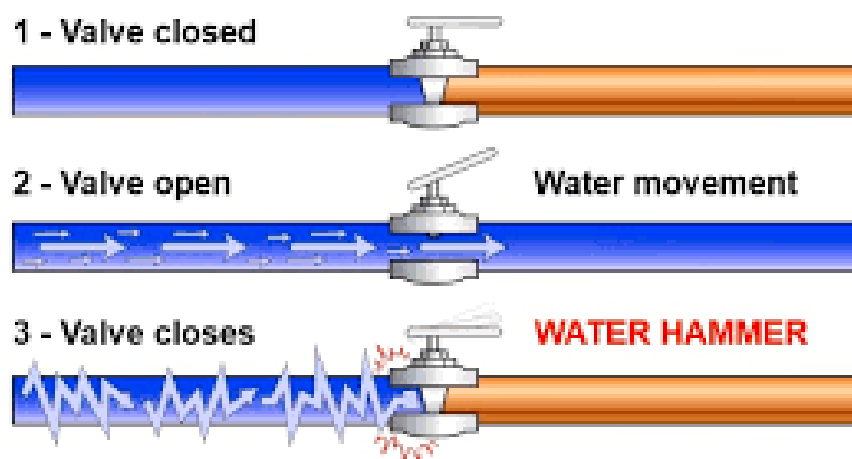


Figure 4 Water hammer effect (Walsh, 2019)

## 8. Task Three

The use of butterfly valves in the petroleum industry must be able to withstand the harsh chemical and mechanical properties that are associated with petroleum. The UK government has changed the standard grade of petroleum from E5 to E10. Which means there will be more bioethanol in the petrol, meaning this grade is more corrosive and historic components are likely to corrode faster compared to the previous grade which will reduce the ergonomics of the valve (RAC, 2021) (Berg, 2020). Additionally, in other petroleum industries, temperature can exceed 816°C and be exposed to pressures of 25,000 psig (Industry, 2018). From BS EN 558:2017 the minimum pressure required from the valves is “150psi to 1500psi and PN6 to PN40” which the standards minimum pressure is low compared to the extreme pressure seen within the industry.

The first butterfly valve was manufactured back in the 1930's to replace gate valves in low-pressure and low-temperature environments (Brandt, et al., 2017) (Lunsford, 2020). The disc could only open and close from 0 to 90 degrees. As the industry developed, valves became “*more compact and lighter in weight to help comeback emissions and safety challenges*” (Ajan & Lemes, 2006). Initially the valve body was manufactured from cast iron due to the limited forces being applied to the body. Only in 1982 did butterfly valves have a standardise design for use globally (Lunsford, 2020) (Rao, et al., 2015).

Due to the advancement in steels, it has allowed butterfly valves to be manufactured lighter allowing valves to cope admirably with high-pressure and low-pressure drops (Conover, 2015). The current expectation is for the valve to deliver a high degree of reliability and durability to ensure minimal maintenance and long-life service in this industry. For use in current industries, the valve must comply to multiple standards which includes ‘BS EN 593:2017 Industrial valves. Metallic butterfly valves for general purposes’ where this standard sets the regulations the valve needs to conform to. As well as ‘BS EN 558:2017’ which has dimensional requirements the valve needs to achieve. The Petroleum (Consolidation) Regulation 2014 (PCR) which was effective from 1<sup>st</sup> October 2014 applies to storage tanks where petroleum is present which is regulated by the Petroleum Enforcement Authorities (PEAs). Due to the nature of petroleum, it falls within ‘The Dangerous Substances and Explosive Atmospheres Regulations 2002’ (DSEAR).

Carbon steel is most common for the disc plate and valve body. Carbon steel is available from several different grades and is manufactured to ‘ASTM A216’. These valves are now fitted with seals to reduce the rate of corrosion and to improve the sealing efficiency (Carbin, 2016).

In corrosive application, austenitic and duplex stainless steel are used as they have better corrosion resistant properties compared to carbon steel due to the high chromium content (LANGÁRD & COSTA, 2007).

Glass Fibre Reinforced Plastic (GFRP) is very comparable to steel as there is very limited differences between the strength properties. Due to the fibreglass grating being greater in flexibility, GFRP is able to withstand a greater impact than steel as steel is very rigid offering very limited flexibility. This is due to the elastic modulus being ten times smaller than steel

allowing deformation to occur more in GFRP (Jones, 2012) (Ratnayaka, et al., 2009). However, GFRP has a far greater life expectancy over steel as it is resilient to corrosion. The material cost for steel is cheaper than what it is for GFRP. However, as steel is a “tenth heavier” (Jabbar & Farid, 2018) than GFRP further costs for installation are required where additional powered tools are required during installation for steel valves.

Although GFRP has great advantages, the material technology is still relatively new, resulting in limited experience with GFRP within industries along with lack of design standards, codes of practice and performance history compared to the use of steel (Technicala, 2019). A major implication is the materials poor high temperature resistance. The strength of GFRP decreases above 300°C and in some petroleum applications the operating temperature can exceed 800°C due to the autoignition temperature being 280°C. These temperatures will cause the material to creep causing leaks from the valve (Jones, 2012).

With the ever-growing understanding of materials, all valves will need to adapt to the ever-changing requirements. Valves will get smarter by the use of technology to integrate with the current industrial revolution as well as the next in generations to come. These valves will have to become more environmentally friendly as the steel manufacturing industry will adapt to reduce its carbon footprint. The performance of GFRP will continue to improve with further material understanding along with an increase service life.

## 9. Task Four

One way to simulate fluid through a butterfly valve is to use Computational Fluid Dynamics (CFD). Prior to computer technology, fluid flow was calculated by hand using the Navier-Stokes equations (NSE) and lengthy experiments. This technology currently uses the NSE with different algorithms (Sjodin, 2016) (Simscale, 2017). The importance of CFD analyses will continue to increase with the industry going through its fourth revolution (Tschirschnitz & Sabrowski, 2020) (ITOH, 2001) (Zhang, et al., 2017).

As part of CFD, there are two classifications Eulerian method and Lagrangian method. The Eulerian method utilises a mesh to describe the fluid domain. If the mesh is not changed, these cells and their neighbours stay the same throughout the simulation. Then Lagrangian method does not use a mesh but use points which move around freely in space. As these points often carry mass and volume, they are called particles (Tschirschnitz & Sabrowski, 2020).

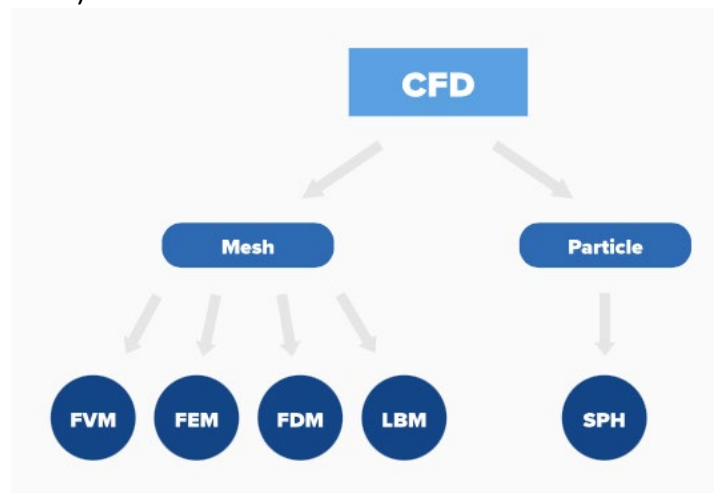


Figure 5 CFD Variants (Tschirschnitz & Sabrowski, 2020)

The first Eulerian CFD method is Finite Difference Method (FDM). FDM discretises the NSE on a set of points that hold the physical variables on the fluid e.g. pressure and velocity. FDM is limited by its dependence on structure grids making it difficult to use this method for problems involving complex boundaries. However, FDM can be used effectively as a regular grid can be utilised and can be used more effectively than FEM or FVM (Peritus, 2019) (Tschirschnitz & Sabrowski, 2020).

Finite Volume Method (FVM) is most commonly used for CFD simulations due to the partial differential equations that are required to be solved are conservation laws. This method only needs to carry out flux evaluations for cell boundaries which makes the method more powerful for handling conservation laws in fluid problems. Compared to FEM and FDM this method can only approximate the solution and cannot be easily made of the higher order (Sjodin, 2016).

The third mesh CFD method is Finite Element Method (FEM). "FEM can be used to discretise any partial differential equation, including NSE" (Tschirschnitz & Sabrowski, 2020). This allows FEM to be actively used to solve fluid flow problems. This method has the ability to combine formulations which is straightforward to use in this method but near impossible in

other methods. However, mathematical expertise is required as the mathematics is very advanced. In some aspects a solver is required and this is challenging for FEM compared to FDM and FVM (Zhang, et al., 2017).

Lattice Boltzmann Method (LBM) is the final Eulerian method. This method offers an alternative to traditional CFD approaches. The Boltzman equation is used to approximate macroscopic fluid phenomena as mesoscopic shock events of fictitious particles. This allows a very efficient analysis as there are multiple LBM codes which have a far greater performance compared to traditional methods (Peritus, 2019). However, LBM is still a new method with many aspects yet to be exploited. The algorithm used shows certain conditions to the Boltzman equation which is related to a second order discretisation of NSE. This has led to criticism as it is not wholly based on the NSE. Many engineers do not trust the results from this method (Tschirschnitz & Sabrowski, 2020).

The Lagrangina CFD method is Smoothed Particle Hydrodynamics (SPH). Similarly to the methods discussed above, SPH method discretises the NSE to simulate fluid flow. This method uses a particle-based discretisation scheme compared to a mesh being used in the other methods. SPH is especially well suited to deal with moving boundaries which allows the SPH method to conduct never seen before simulations. However, SPH is less efficient than mesh-based approaches due to the costly neighbour-search process (Peritus, 2019) (Tschirschnitz & Sabrowski, 2020) (Sjodin, 2016). There still needs to be further developments as the discretisation error is hard to formulate since the particle distribution is always changing.

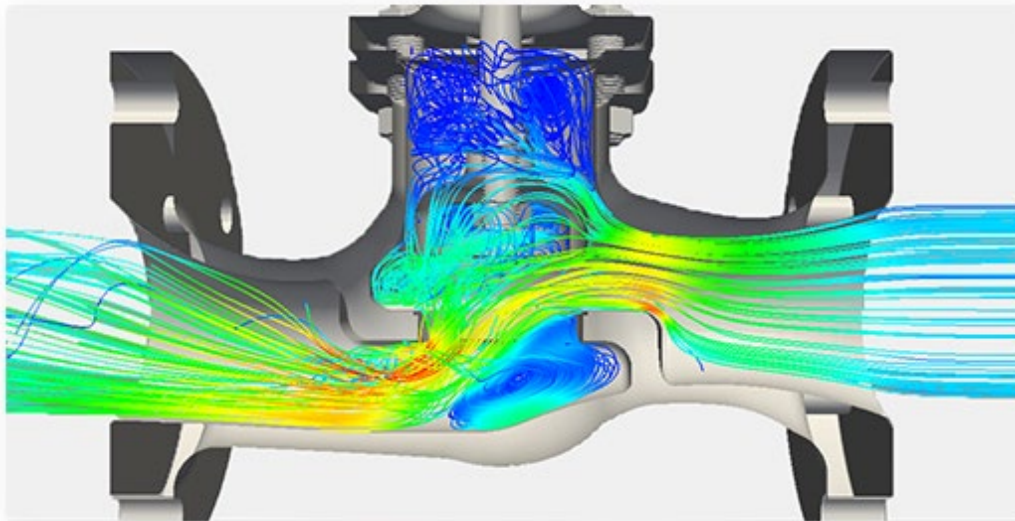


Figure 6 Example of CFD of fluid flow through a valve (Simscale, 2017)

## 10. Task Five

Before carrying out experiments the risks of the environment should be considered. As petroleum is being used, the fluid must be contained as it passes through the valve, where an Intermediate Bulk Container (IBC) can be used to allow the petroleum to empty into. Careful considerations should be made for personal protective equipment to ensure the safe conduction of trials. Finally, in the case of a failure of the prototype valve, there should be containment precautions to avoid the petroleum reacting with other surfaces. It is recommended a secondary valve is used for an emergency shut off upstream.

The importance of carrying out prototype testing is to ensure the valve is free from cracks, loose pores, and slag as these all affect the strength properties of the valve (Testing, 2020). Butterfly valves require strength tests as the turbulent flow increases the force of the fluid flowing through the valve because of the resultant increased velocity. To test the sealing performance on the butterfly valve, the petroleum should be introduced from the test tank with the valve fully open. The valve should be plugged downstream initially so the pressure holds within the valve then once leak checks have been conducted, the plug can then be removed. The maximum pressure should be used to test the limits of the valve. This will allow for leak checks to occur during operation. Lastly, the valve plate should be closed to ensure no fluid can pass the plate and no leaks occur. There should then be a final visual inspection before issuing a conformity certificate which will include the tests performed and the material details (Lab, 2015). Once gathering the maximum allowable pressure, the certification for maximum operation the valve should be 20% lower than the laboratory test as a factor of safety.

To obtain accurate data from these trials, pressure transducers and flow sensors are used to log real-time data which is fed back by an electrical source to a main computer. Using the latest software this data can be automatically turned into visualisation, normally in the form of graphs. By using these digital sensors, it has a direct impact with Industry 4.0 as this can lead to prevention before any significant failures can occur by operating within set parameters.

To pump fluid through the valve a variable speed pump can be used to gradually increase the flow and pressure to all comparison of the results from different flow rates. The positioning of the sensors are critical to ensure the correct data is being recorded. There should be a pressure and flow sensor for the fluid incoming to the valve, a set of sensors just before and just after the valve, with a final set of sensors downstream of the valve. The spacing of the sensors are very important as the two sets of sensors on the valve should be equally spaced from each other as well as the upstream and downstream sensors should be equispaced from the centre of the valve (Said & AbdelMeguid, 2014). This allows for fair testing to occur for a good comparison for how the fluid behaves before and after the butterfly valve. However, these sensors can be expensive, and a good alternative are analogue pressure gauges with a flow meter. Temperature sensors or gauges can also be used to identify how temperature impacts the performance of the valve and highlight the affects, if any, on the physical properties of the material. It is also possible to use dye within

the fluid to compare the flow before and after the valve to determine laminar or turbulent flow.

After the data has been gathered the CFD results can be compared to the lab results. From the information on CFD in task 4, FEM should be used to conduct simulation as it is the preferred method for fluid flow. The results should be represented in the form of a line graph with clear label indicators to identify each parameter, as seen below in figure 7.

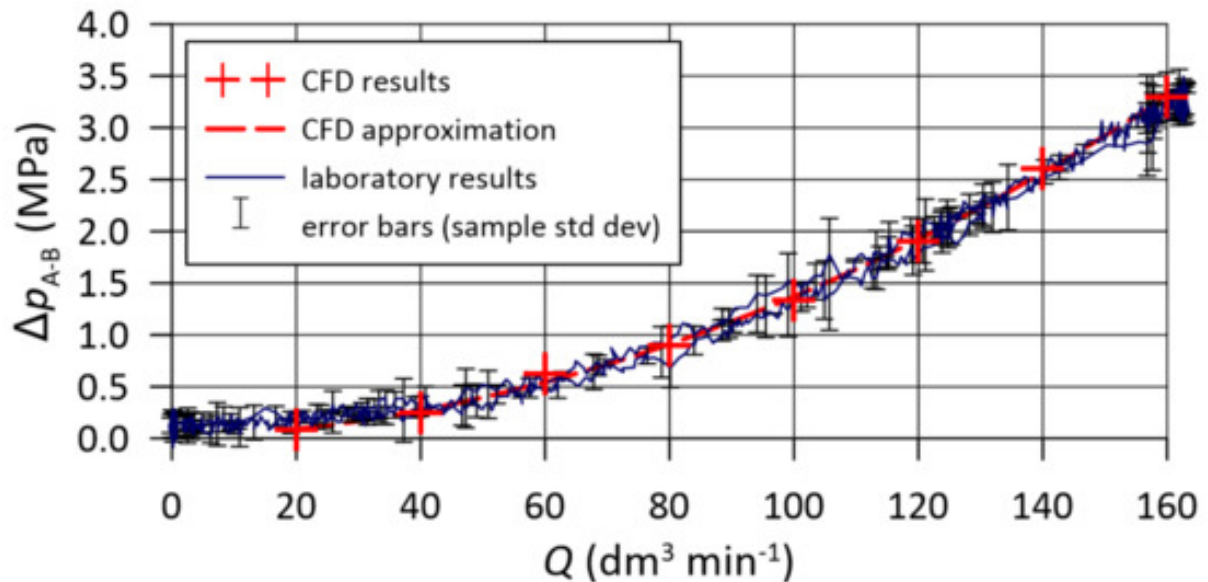


Figure 7 Example of data comparison from CFD to laboratory testing (Filo, et al., 2021)

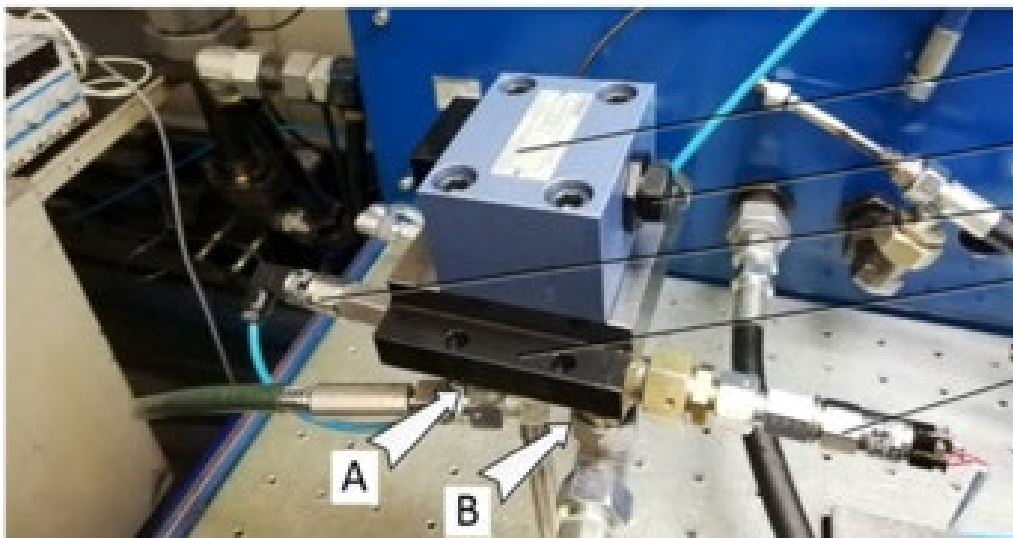


Figure 8 Example of sensors connected to a valve during laboratory testing (Filo, et al., 2021)

## 11. Conclusion

From the discussion within this report, it is clear to see that glass fibre reinforced plastic will lead the future industry due to its superior properties compared to steel. However, there is still further understanding needed to allow this material to be used at high temperatures. It is also important to design the butterfly valve, so it allows as much laminar flow as possible, so the pressure drop is low and is able to stay at a minimum before the flow changes to turbulent flow. The Reynolds number is important to determine whether the flow is laminar or turbulent as well as incorporating other theories such as Bernoulli's principle. The importance of testing valves before being implemented into normal operating environments is crucial. This is to ensure the valve conforms to necessary standards and regulations to ensure the safe operation of the valve. The fixing method is critical to the design as the disk plate may be subjected to large amounts of forces if the valve needs to be instantly shut. The water hammer phenomena is likely to occur if this happens where extreme forces will collide with the disk plate. This means the fixing point between the valve body and the disk plate needs to be able to absorb this force without leaking petroleum. The preferred fixing method would be using welding or a bolted connection instead of rivets as they deal with higher forces better. Because of the rivets protruding head this also causes additional boundary separation to occur. The importance of CFD allows the valve to be designed correctly before the manufacture by predicting how the fluid flows through the valve. Finally, the importance of data analysis and control is critical especially in industry 4.0 as this allows for greater control and prevention of failure due to the live data being recorded.

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## 13. Appendices

### A) Bernoulli's Equation

$$\begin{aligned}
 P_1 + \rho g h_1 + \frac{1}{2} v_1^2 &= P_2 + \rho g h_2 + \frac{1}{2} \rho v_2^2 \\
 P_1 &= P_2 = P_{ATM} \\
 \cancel{P_{ATM}} + \rho g h_1 + \frac{1}{2} \cancel{(0)}_1^2 &= \cancel{P_{ATM}} + \cancel{\rho g (0)} + \frac{1}{2} \rho v_2^2 \\
 \cancel{\rho g h_1} &= \frac{1}{2} \cancel{\rho} v_2^2 \\
 2 g h_1 &= v_2^2 \\
 v_2^2 &= 2 g h_1 \\
 v_2 &= \sqrt{2 g h_1} \\
 v_2 &= \sqrt{2 \times 9.81 \times 5} \\
 v_2 &= 9.9 \text{ m/s}
 \end{aligned}$$