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FLOW ANALYSIS IN SUDDEN AND GRADUAL CONTRACTION AND EXPANSION PIPES

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Abstract— This project aims to study the fluid flow characteristics of sudden and gradual contraction and expansion pipes. Recent study has revealed that the flow behavior in sudden contraction and expansion pipes can be quite complicated with vortices, eddies, and other flow phenomena affecting the pressure and velocity distribution. This understanding is important to design more efficient and reliable piping systems that can reduce energy consumption, improve system performance, and minimize failure risk. In this study, the length of larger diameter for sudden and gradual contraction and

Sudden Expansion and Sudden Contraction	expansion pipes is 0.040 m. Next, the length of the smaller diameter for gradual is 0.050 m and 0.060 m for sudden. The sudden and gradual contraction and expansion pipes are designed using the SolidWorks software and ANSYS Fluent simulation software was used to plot the contour of velocity magnitude and static pressure of the pipes in which water is a media. In a sudden contraction pipe, the velocity flow shows a large separation at the edge of the upstream region before entering the contraction region which creates vortices and eddies. In a sudden expansion pipe, the pressure is unstable and fluctuates in the wider section. In a gradual expansion, the pressure pattern near the wall of the upstream section increases gradually and steadily. It proves that the flow pattern in the gradual expansion and gradual contraction creates less separation and disturbance of flow compared to the sudden expansion and sudden contraction pipes.

I. Introduction

Fluid flow through a channel or a pipe where there is a sudden contraction or sudden expansion section has become an evolving area in engineering study. In recent years, there have been significant advancements in understanding the behavior of fluid flow in sudden reduction and enlargement in pipes, which has led to the development of new methods and technologies for optimizing system performance [1-13].

When a fluid flows through a pipe and encounters a sudden reduction in diameter, the fluid must either accelerate or decelerate to accommodate the reduced cross-sectional area, depending on the flow direction. The flow behavior in a reduction can be highly complex and may involve vortices, eddies, and other flow phenomena that affect the pressure and velocity distribution. To understand and predict such flow behavior, researchers have employed a variety of techniques, including numerical simulations, experimental measurements, and analytical models. These methods have enabled engineers to design more efficient and reliable piping systems that minimize energy losses, reduce wear and tear, and improve system safety. For example, Computational Fluid Dynamics (CFD) is used to simulate the flow behavior in a sudden reduction. The findings show that the flow separation and reattachment were influenced by the Reynolds number and the geometry of the reduction [14]. Other than that, Particle Image Velocimetry (PIV) is used to measure the flow behavior in an axisymmetric sudden expansion and found that the recirculation eddy strength which has a non-linear dependence on Reynolds number (Re) becomes weaker as Re is increased [15].

Similarly, when a fluid flows through a pipe and encounters a sudden enlargement in diameter, the fluid must decelerate to accommodate the increased cross-sectional area. Recent researcher has revealed that the flow behavior in an enlargement can be even more complex than in a reduction, involving separation, reattachment, and recirculation zones that can significantly affect the pressure and velocity distribution [16]. To overcome these challenges, researchers have developed advanced numerical models, such as Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS), which can obtain the excellent feature of the flow behavior in a sudden enlargement pipe.

For instance, the researcher used DNS method to investigate the flow behavior in a sudden enlargement. They found that the recirculation zone was influenced by the Reynolds number and the aspect ratio of the enlargement [17]. Similarly, LES is used to simulate the flow behavior in a sudden enlargement. The findings show that the pressure recovery and recirculation zone were affected by the shape of the enlargement and the turbulence intensity [18].

Therefore, this research is conducted to analyse the flow in sudden contraction and expansion pipes due to the recent research which revealed that the flow behavior in an enlargement can be even more complex than in a reduction, which involving separation, reattachment, and recirculation zones that can significantly affect the pressure and velocity distribution.

II. Manuscript Preparation

A. Geometry setup

The dimensions of sudden expansion, sudden contraction, gradual expansion and gradual contraction were shown in Figure 1. The dimension is based on previous researchers [8]. The sudden expansion and contraction geometry consists of a cylindrical duct of larger diameter of pipe, *D* is 40 mm. with length, *L* of 40 mm.

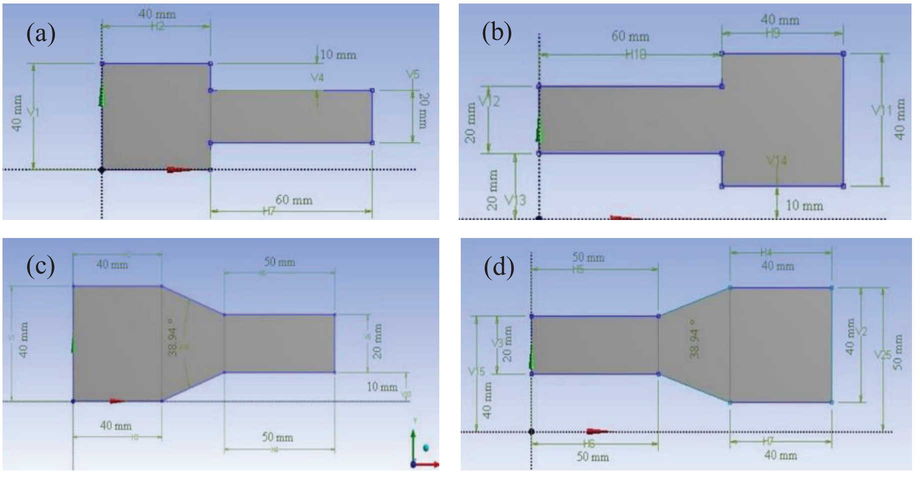

Figure 1: Dimension of pipes (a) sudden contraction (b) sudden expansion (c) gradual contraction (d) gradual expansion

For the smaller pipe, the diameter, d is 20 mm, and the length, l is 60 mm with angle of 90°. Next, for the geometry gradual expansion and contraction pipes, they have the same diameter and length which are both 40 mm. For smaller pipes, the geometry is 20 mm in diameter by 50 mm in length with an angle of 38.94°.

Both sudden and gradual expansion pipes in Figure 1 (b) and (d) are mainly used in diffusers in gas turbines to reduce the velocity and increase the gas pressure. This is crucial for the efficient operation of gas turbines. Meanwhile, sudden and gradual contraction pipes in Figure 1 (a) and (c) are used in spray nozzles and injectors to increase the fluid velocity and create fine sprays. This principle is used in applications such as agricultural sprayers and fuel injectors in engines.

B. Simulation using ANSYS Fluent software

In this project, the main fluid used from the inlet throughout the outlet diameter was water with a 998.2 kg/m^3 density. The simulation procedure can be simplified in terms of drawing geometry, mesh modification, boundary condition setup such as initial value, result, and solver parameter setting. In this study, the type of mesh that will be used is the 2D Prism (Quadrilateral). This is because quadrilateral mesh yields a more accurate solution compared to triangular mesh [19, 20]. Next, it is important to create a named selection for each surface of the pipe body. This is because the properties of boundary conditions can be determined and adjusted. In this project, the sudden and gradual expansion and contraction pipe will be discretization into elements and meshing. Three meshing strategies were applied in this computational analysis domain: face meshing, edge sizing and name selection. After named selections, the meshing starts by generating the mesh in ANSYS Fluent for the enclosure.

In the meshing process, the process discretization of the domain was divided into elements and forming the base block which the boundary conditions and external effects are specified. The face meshing was applied to the domain face. The case free (unstructured mesh) are transformed into mapped face meshing (structured meshes) with orthogonal quadrilateral elements (2D).

Besides, the local mesh method (edge sizing) is applied to the pipe boundary layer to capture the boundary layer effects. The edge sizing was applied on the pipe is to focus the meshing point around the pipe. Edge sizing giving the ability to set a local growth rate for the target cell on the edge and control the apply number of divisions with bias function for obtaining a proper wall boundary. Next, this is for creating the thin elements or finer mesh for high-density mesh in specific areas such as pipe throat. As a result, the greater the number of divisions the more accurate the boundary layer effects.

Furthermore, the spacing ratio of node on an edge can be adjustable by using bias type where it is controlled by bias factor called bias function. Bias function makes the nodes be more clustered on an edge or more concentrated in a particular region. The example results of sudden contraction and gradual contraction pipe after experiencing structure meshing, edge sizing and bias function were shown in Figure 2.

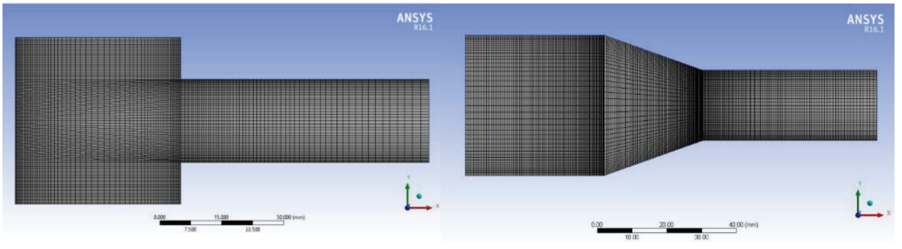

Figure 2: Sample of sudden contraction and gradual contraction pipe after experiencing structure mesh, edge sizing and bias function process

Figure 3 shows an example of boundary conditions for a sudden contraction pipe. The section where the fluid enters the pipe is referred as the inlet, and the area where the fluid exits the pipe is referred as the outlet. While the fluid flow passing through the surface area of pipe boundary is referred as walls.

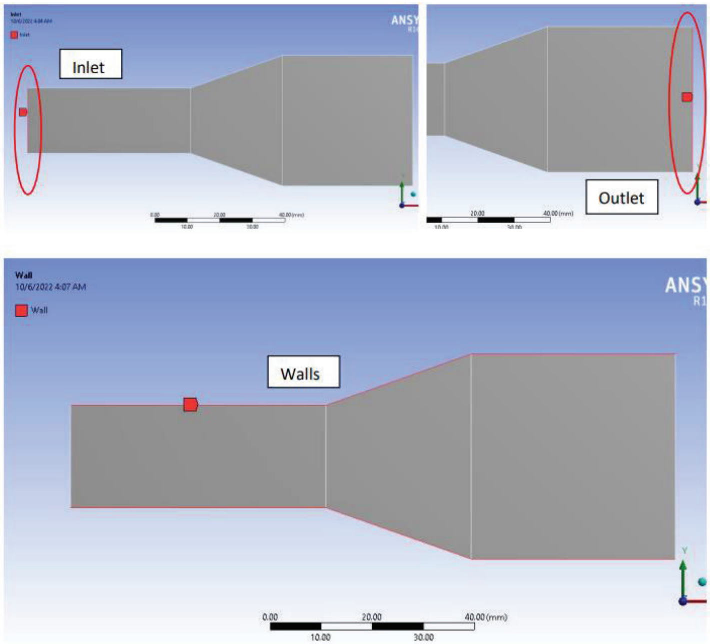

Figure 3: Boundary conditions for sudden contraction pipe

The viscous model setting used in this setup process is a standard k-epsilon model with standard wall functions. This is based on the previous research [8] to compare their results for validation purposes. The cell zone conditions have set the fluid material to flow throughout the pipe during simulation is water which has a density of 998.2 kg/m^3 and viscosity of 0.001003 kg/ms.

The Reynold number applied in this project simulation is turbulent and the velocity magnitude at the inlet for boundary condition is 5 m/s and the outlet pressure is zero initial gauge pressure which is based on the literature review [8]. The grid independence test was also carried out to find suitable mesh elements with accurate simulation results and less computation time.

III. Results

A. Grid Independent Test

Grid independent test was conducted for gradual expansion case for example in this paper. According to the Figure 4, the optimal mesh grid for this simulation solution was considered in 65461 nodes and 64800 elements of mesh with a velocity magnitude obtained is 6.078347 m/s. From the observation, the mesh 1, 2, 3, 4, and 5 have particular uniform velocities where the difference between their velocity is very small. It is seen that the greater the mesh, the difference between the two velocity values is approximately constant and considered uniform. It is because of the smaller error increase in the mesh size on the geometry. The mesh 9 was selected as the optimal mesh for this simulation as the next velocity has a higher difference value. As a result, the 65461 nodes and 64800 mesh elements with a velocity magnitude of 6.078347 m/s show it has sufficient mesh for the simulation and the obtained result is more accurate.

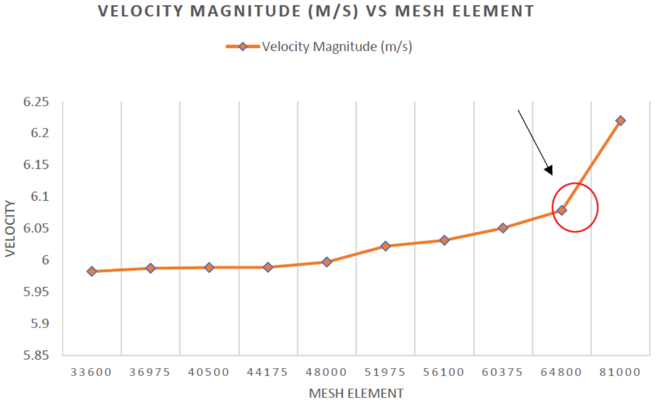

Figure 4: Grid independent test for gradual expansion

B. Velocity Magnitude

The velocity contours obtained from the simulation are shown in Figure 5. In a sudden contraction pipe as shown in Figure 5 (a), the velocity contours typically show an increase in fluid velocity as the flow passes through the contraction region. The maximum velocity about 13 m/s occurs at the vena contracta, which is the narrowest point of the pipe. The velocity flow shows a large separation at the edge of the upstream region before entering the contraction region which creates vortices and eddies. Other than that, the velocity contours near the vena contracta also separate from the walls before reattaching downstream of the pipe. While, in a gradual contraction pipe as show in Figure 5 (b), the velocity contours show a more gradual increase in fluid velocity as the flow passes through the contraction region, with no separation occurring in vena contracta than in a sudden contraction pipe. The result proves that the gradual contraction pipe has lower head loss compared to the sudden contraction pipe.

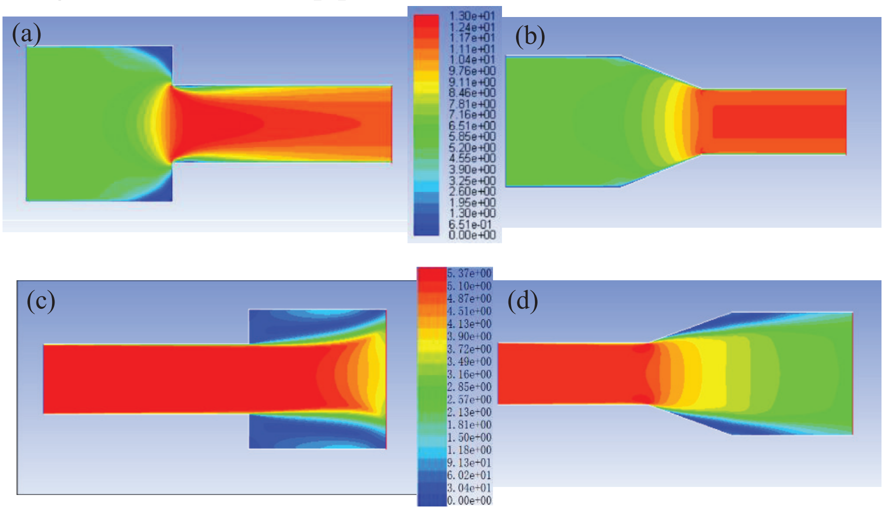

Figure 5: Contour of velocity magnitude (a) sudden contraction (b) gradual contraction (c) sudden expansion (d) gradual expansion

In a sudden expansion pipe as shown in Figure 5 (c), the velocity contours show a gradual decrease in fluid velocity downstream of the expansion region. However, the velocity contours downstream of the pipe show a large area of separation forming turbulence eddies. In a gradual expansion pipe as shown in Figure 5 (d), the velocity contours show a more gradual decrease in fluid velocity as the flow passes through the expansion region with a smaller area of separation than in a sudden expansion pipe. The result proves that the gradual expansion pipe has lower head loss compared to the sudden expansion pipe.

C. Static Pressure

The static pressure contours obtained from the simulation are shown in Figure 6. In a sudden contraction pipe as shown in Figure 6 (a), the pressure typically shows an abrupt pressure drop due to the rapid increase in fluid velocity. The pressure fluctuation near the wall of the upstream section is larger and unstable. The flow experiences an adverse pressure gradient causing the flow to separate near vena contracta by forming eddies and vortices. Flow separation increases turbulent kinetic energy resulting in higher head loss.

While in a gradual contraction pipe as shown in Figure 6 (b), the pressure drop is typically more gradual than in a sudden contraction. The pressure fluctuation near the wall of the upstream section decreases slowly and steadily compared to the sudden contraction. In a gradual contraction, the gradual change in flow area help to minimize adverse pressure gradient. Reduced adverse pressure gradient means that the flow is less likely to separate, resulting in lower level of energy losses compared to sudden contraction.

Due to viscous effect, the shear stress is distributed more evenly along the narrowing length, resulting in less head loss than in a sudden contraction. Other than that, the flow pattern in the gradual contraction may cause less damage to the pipe compared to the sudden contraction.

In a sudden expansion pipe as shown in Figure 6 (c), the pressure is unstable and fluctuates in the wider section. While the pressure in a gradual pipe increases gradually from the upstream section to the downstream section as shown in Figure 6 (d).

The pressure pattern near the wall of the upstream section increases gradually and steadily compared to the sudden expansion. It proves that the flow pattern in the gradual expansion may cause less damage to the pipe compared to the sudden expansion.

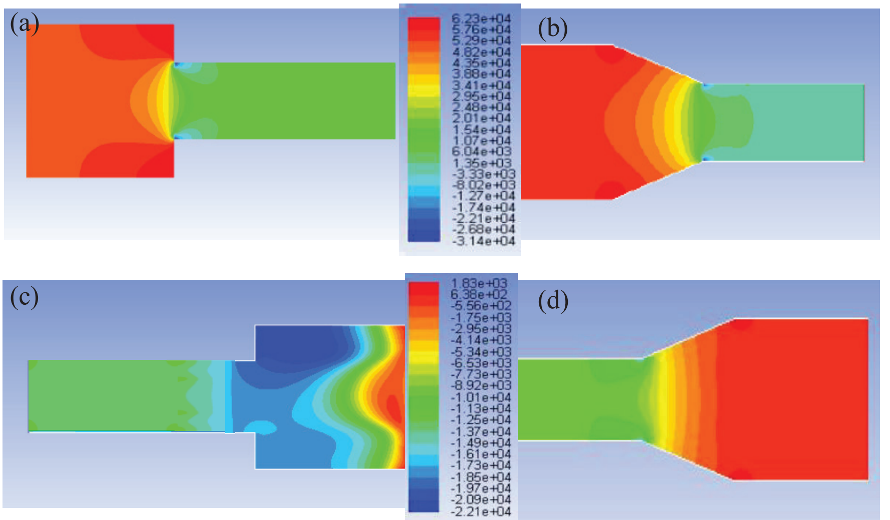

Figure 6: Contour of static pressure (a) sudden contraction (b) gradual contraction (c) sudden expansion (d) gradual expansion

D. Head Loss

The head loss, h of all types of pipes were calculated as shown in Table 1 [21]. The head loss value is obtained based on the inlet velocity v_1, inlet cross-sectional area A_1, outlet velocity v_2, outlet cross-sectional area A_2, pipe coefficient C_C and gravitational effect g.

Sudden contraction loss is obtained from Equation (1), sudden expansion loss is obtained from Equation (2) and gradual expansion and contraction losses are obtained from Equation (3).

$$h = (1/C_C - 1)\, {v_2}^2/2g \qquad (1)$$

$$h = {v_2}^2/2g\, (A_2/A_1 - 1)^2 \qquad (2)$$

$$h = C_C (v_1 - v_2)^2/2g \qquad (3)$$

The pipe coefficient depends on the ratio of the cross-sectional area and the angle of the pipe. The results in Table 1 support the result in Figure 5 and Figure 6. From Table 1, the gradual contraction pipe has lower head loss than in a sudden contraction pipe. While the gradual expansion pipe has a lower head loss compared to the sudden expansion pipe.

Table 1: Head Loss, *h*

Pipe Types	Sudden contraction	Gradual contraction	Sudden expansion	Gradual expansion
Head loss (m)	1.23	0.215	0.746	0.220

IV. Conclusion

In conclusion, the gradual contraction pipe has lower head loss compared to the sudden contraction pipe. While the gradual expansion pipe has a lower head loss compared to the sudden expansion pipe. This is proven in the velocity contour and static pressure contour outcomes. For example, in a gradual expansion pipe, the velocity contours show a more gradual decrease in fluid velocity as the flow passes through the expansion region with a smaller area of separation than in a sudden expansion pipe.

For a gradual contraction pipe, the velocity contours show a more gradual increase in fluid velocity as the flow passes through the contraction region, with no separation occurring in vena contracta than in a sudden contraction pipe. In gradual contraction, the pressure fluctuation near the wall of the upstream section decreases slowly and steadily compared to the sudden contraction. While the pressure in a gradual pipe increases gradually from the upstream section to the downstream section. The pressure pattern near the wall of the upstream section increases gradually and steadily compared to the sudden expansion. It proves that the flow pattern in the gradual expansion and gradual contraction creates less separation and disturbance of flow compared to the sudden expansion and sudden contraction pipes.

The future direction of this study is likely to focus on the experimental works using high-speed imaging techniques and particle image velocimetry (PIV) to obtain detailed flow fields and compare them to simulation works.

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