Analysis of the Effect of Variations in Expansion Loop Shapes on Pressure Drops Occurring in the Flow of Crude Oil in Pipeline Using Computational Fluid Dynamics

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Abstract. Expansion loop is a solution to overcome the expansion of the pipe due to thermal loads. However, the installation of an expansion loop will increase the pressure drop. Consequently, the pump power will increase with the increasing pressure drop, and cause additional operating costs. In this study, 4 types expansion loop is compared. The length of the expansion loop designed is 10 m, the inner diameter is 336.55 mm, and the outer diameter is 355.6 mm. This study evaluate the effect of flow velocity, fluid density and viscosity on pressure drop. This report also presents the effect of pressure drop on pump power and additional costs due to expansion loop types. Computational fluid dynamic is used to obtain the pressure drops. The pressure drop that occurs in 4 types of expansion loops will be discussed and the type of expansion loop that causes the lowest pressure drop will be determined.

Keywords: Expansion loop, Pressure drop, Pump power, Operating costs, Computational fluid dynamics.

1 Introduction

There are 3 types of transportation that are commonly used to move oil and gas based on volume and distance. First, trucks to distribute oil or gas in small volumes and relatively short distances (usually within one country). Second, tankers to distribute in large volumes and over long distances (usually between countries). Lastly, a pipeline to distribute for large volumes over short distances. In addition, the use of pipelines to distribute oil and gas also has other advantages such as safer and more cost efficient [1].

The use of pipelines in distributing oil and gas must be designed properly by considering the economic, social, technological, and legal aspects. In this design, all aspects must be met so that the project can run. If one of them is lacking, the pipe procurement project cannot be carried out.

In the pipe installation process, there is one important thing to note, namely flexibility. This is done to prevent pipe or pedestal failure due to overstress/fatigue, prevent leakage at the connection and prevent distortion of the pipe or connection with other equipment such as pumps,

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vessels, and so on. This flexibility can be increased by changing the direction of the pipe such as elbows, loops, or offsets.

Fig. 1. Expansion loops in piping systems [2].

Figure 1 shows the use of expansion loops in the arctic. Due to the large temperature fluctuations between the summer and winter months in the arctic, thermal expansion must be carefully considered [2]. Therefore, the installation of an expansion loop is one solution.

The use of expansion loops for flexibility has a drawback, namely that it will increase the head loss in the flow. This increase in head loss will cause an increase in pressure drop and in the end the pump energy required to drain the fluid also increases. Therefore, the author made this study to identify the best type of expansion loop to use in terms of the resulting pressure drop.

2 Methodology

The research conducted is in the form of flow simulation on several types of expansion loops using the Solidworks application. Before doing the simulation, first do the design for the variation of the expansion loop shape. After making the design, the next step is to enter the simulation stage. The simulation is carried out using the flow simulation available in Solidworks. There are three variables used in this simulation, namely the fluid flow velocity variable, fluid density variable and fluid viscosity variable. Each variable will be simulated, and the resulting pressure drop is recorded. The pressure drop obtained will be used as a comparison in selecting the best type of expansion loop to use.

2.1 Expansion Loop Specification

The pipe data used include the following:

Tabel 1. 14” Diameter pipe data.

Material	*Commercial/Welded Pipe*
Diameter	14” (355.6 mm)
Schedule Number	30
Wall Thickness	0.35” (8.89 mm)
Surface Roughness	0.045 mm

Table 1. is a 14” diameter pipe data with Schedule Number 30 [2]. This data is needed to design expansion loop types in Solidworks applications.

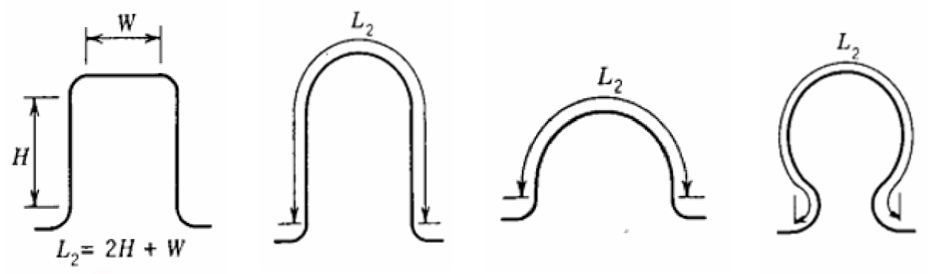
Tabel 2. Fluid data.

Fluid Type	*Crude Oil*
Mass Density	851.4 kg/m^3
Spesific heat	0.00169 J/(kgK)
Thermal Conductivity	0.12 W/(mK)

Table 2. is the fluid data that will be used in the simulation. Density data of crude oil is taken from data of one type of crude oil, namely Arabian Light [4]. The specific heat for the crude oil used comes from Sathivel et.al.[5]. As for the thermal conductivity used, it comes from Elam et.al.[6].

The first thing to do in this simulation is to design 4 types of expansion loops that will be simulated.

Tabel 3. Selected types of expansion loops.



Tipe I	Tipe II	Tipe III	Tipe IV

Table 3. shows the variation of the selected expansion loop shape for simulation. Variations in the form of the expansion loop are based on the nomogram. This nomogram is used to determine the length of the expansion loop. After the length of the loop is determined, then the next selection of the shape of the expansion loop is in accordance with the 4 shape that already exist in the nomogram. Therefore, this research was conducted to determine the most economically less cost type to use based on the additional costs incurred due to the expansion loop.

Before designing the model in Solidworks, first determine the size of the expansion loop to be studied. In this case, the size for the inside diameter is 336.55 mm and the outside diameter is 355.6 mm [3]. The length of the expansion loop is 10 meters. The geometry size for the selected expansion loop design is moderate so that the results obtained are not too small and not too large. Then for the elbow radius used is 500 mm [7].

2.2 Simulation Procedure

There are 3 variables used in this study, namely the variable flow velocity, fluid density, and fluid viscosity. Variable flow velocity using a flow velocity variation of 1-4.5 m/s [8]. The density variable uses a density of 851.4-1000 kg/m^3 [4]. Viscosity variable uses viscosity variations ranging from 0.001688-0.00911 Pa s [4]. For other data used in the simulation can be seen in Table 4.

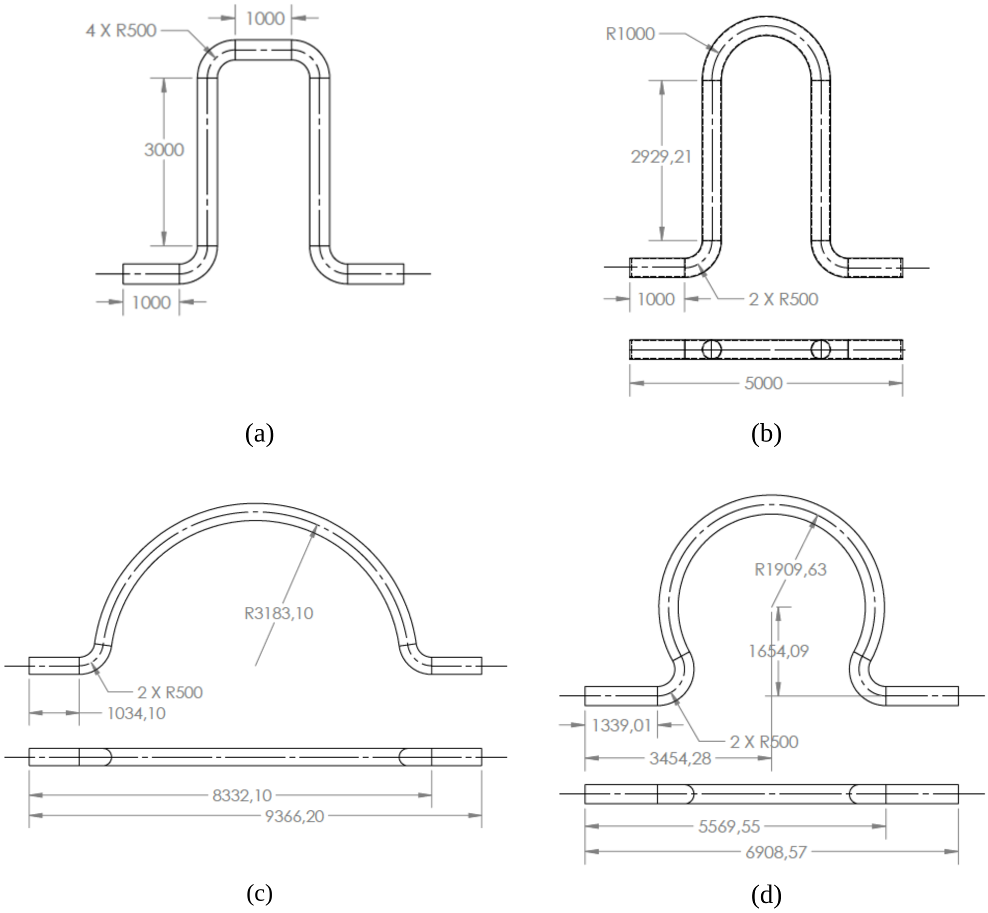


Fig. 2. Expansion loop design that has been made, (a) type I, (b) type II, (c) type II and (d) type IV in millimeters (mm).

Tabel 4. Simulation method.

	Simulation Method					
Variables	Inlet Velocity (m/s)	Fluid Densiy (kg/m^3)	Viscosity (Pas)	Outlet Pressure	Pipe Roughness (mm)	Pressure drop
Flow speed	1-4.5	851.4	0.00911	Ambient pressure	0.045	Total pressure inlet-total pressure outlet
Density	2.75	851.4-1000	0.00911	Ambient pressure	0.045	Total pressure inlet-total pressure outlet

Viscosity	2.75	851.4	0.001688-0.00911	Ambient pressure	0.045	Total pressure inlet-total pressure outlet

3 Result and Discussion

In this study, 3 types of simulations were carried out. The first is a simulation of 4 types of expansion loops using variations in flow velocity. The second simulation is a simulation of 4 types of expansion loops with variations in fluid density differences. The third simulation is a simulation of 4 types of expansion loops with variations in fluid viscosity. These three simulations have the same goal, namely, to determine the amount of pressure drop that occurs in each expansion loop and determine the best type of expansion loop to use based on the pressure drop value.

3.1 Simulation Results with Variation of Flow Velocity

One of the factors that affect the value of the pressure drop is the fluid flow velocity in the pipe. Therefore, this experiment was conducted to determine the effect of flow velocity on pressure drop. The following are the results of the simulations carried out on the four expansion loops with variations in flow velocity.

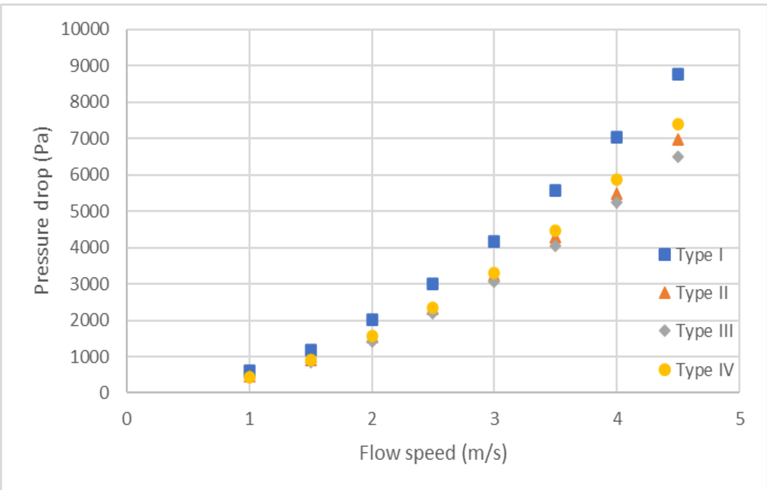


Fig. 3. The relationship between flow velocity and pressure drop for each type of expansion loop.

Figure 3 is the relationship between flow velocity and pressure drop. It can be seen in the graph that the greater the flow velocity, the greater the pressure drop that occurs. This is in line with the theory that pressure drop is directly proportional to head loss. Head loss is also directly proportional to speed.

In addition to the increased pressure drop due to an increase in flow velocity, **Figure 3** also shows the effect of the type of expansion loop on the magnitude of the pressure drop. In this simulation, there is an increase in the average pressure drop for every 1 m/s increase in flow velocity. Type I experienced an average increase of 2339.33 Pa, type II experienced an average increase of 1856.37 Pa, type III experienced an average increase of 1727.01 Pa and type IV experienced an average increase of 1983.58 Pa.

3.2 Simulation Results with Variations in Fluid Density

Another factor that affects the pressure drop is the size of the fluid density. Therefore, it is important to know its effect on pressure drop. The following are the results of the simulations carried out on the 4 expansion loops with variations in fluid density.

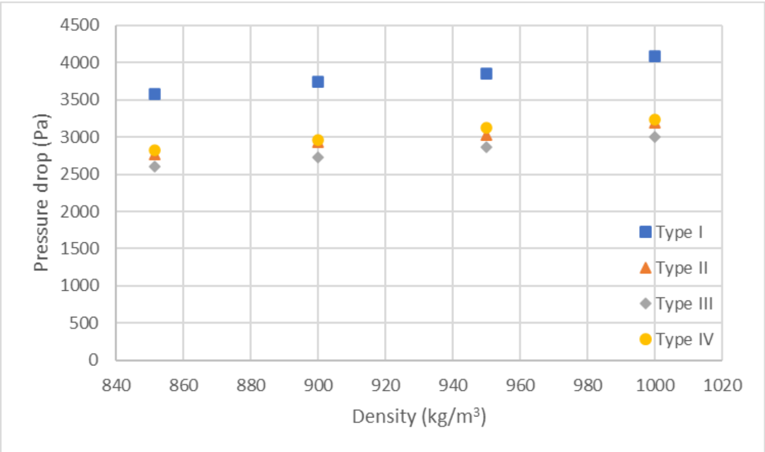


Fig. 4. The relationship between density and pressure drop for each type of expansion loop.

Figure 4 shows that the fluid density affects the pressure drop. Increasing fluid density will cause an increase in pressure drop. In this simulation, there is an increase in the average pressure drop for every 1 kg/m^3 increase in fluid density. Type I experienced an average increase of 3.466 Pa, type II experienced an average increase of 2.817 Pa, type III experienced an average increase of 2.637 Pa and type IV experienced an average increase of 2.83 Pa.

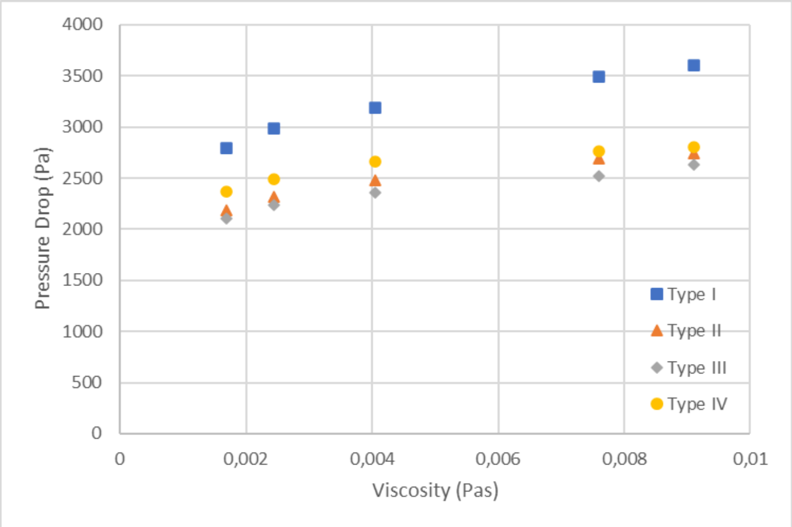


Fig. 5. The relationship between density and pressure drop for each type of expansion loop.

3.3 Simulation Results with Variations in Fluid Viscosity

In addition to flow velocity and fluid density, another factor that affects the pressure drop is the viscosity of the fluid. Therefore, this simulation aims to determine the effect of fluid viscosity on pressure drop. The following are the results of the simulations carried out on the four expansion loops with variations in fluid viscosity.

Figure 5 shows that the greater the viscosity, the greater the pressure drop that arises. In this simulation, there is an increase in the average pressure drop for each increase in fluid viscosity of 0.001 Pas. Type I experienced an average increase of 135.83 Pa, type II experienced an average increase of 91.22 Pa, type III experienced an average increase of 91.40 Pa and type IV experienced an average increase of 83.3 Pa.

3.4 Validation

Validation was carried out on an expansion loop type I for 3 variations of speed, namely flow rates of 1 m/s, 1.5 m/s and 2 m/s. Validation is done by calculating the major loss and minor loss. The major loss is calculated on a straight pipe whose total length is 9 m. The calculated minor loss is the minor loss that occurs at the elbow. Elbow in type I expansion loop consists of 4 pieces. After calculating the major loss and minor loss, the next step is to calculate the pressure drop that occurs. The last is to compare the pressure drop from the simulation results with the calculation results. The following is a comparison between the pressure drop from the simulation results and the calculation results along with the error.

Table 5. Comparison of pressure drop simulation results with theoretical calculations on expansion loop type I.

Flow speed (m/s)	Simulation pressure drops (Pa)	Theoretical pressure drops (Pa)	Eror (%)
1	598.26	561.644	6.519
1.5	1183.76	1212.387	2.361
2	2019.34	2100.622	3.869

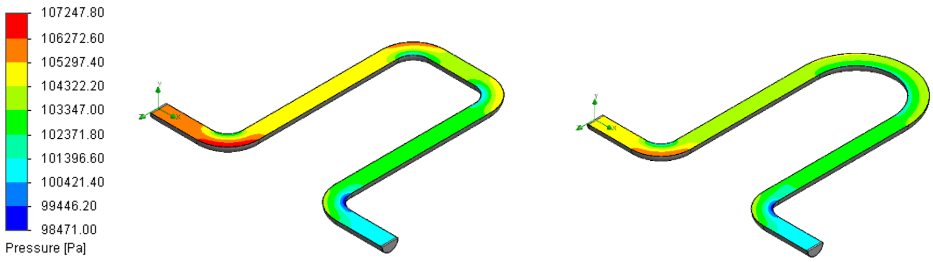
Based on Table 5, the percent error in the simulation is below 10%. According to Widodo et al., this simulation is quite valid because the percent error is <10% [9].

3.5 Pressure Contour

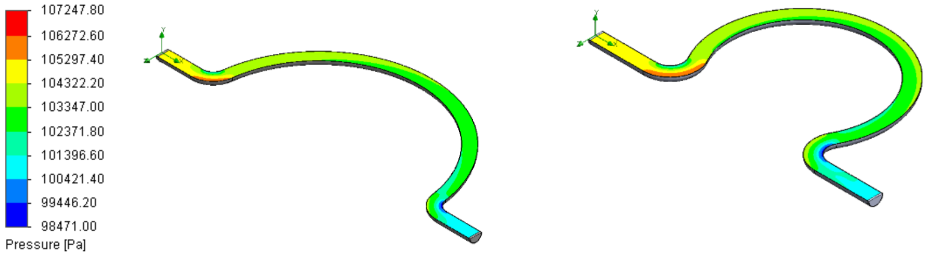
This contour retrieval is carried out to determine the effect of the expansion loop shape on the pressure drop that occurs. The contour taken in this simulation is the pressure contour. The following are the results of taking the contour in the simulation with variations in flow velocity, density and fluid viscosity.

Figure 6. is the simulated pressure contour at the variation of the flow velocity, which is 3 m/s. Based on the visuals seen in the four types of expansion loops, the pressure in the pipe is concentrated in the bends of the pipe. The pressure concentration that occurs makes the pressure at the inlet accumulate. Therefore, type I experiences more pressure accumulation at the inlet than other types so that the pressure drop that occurs is greater than the other types.

Figure 7 is the simulated pressure contour on the variation of fluid density, which is 950 kg/m^3. Based on the visuals seen in the four types of expansion loops, the pressure that occurs in the pipe is concentrated in the bends of the pipe. The concentration of pressure in the flow is the cause of the differences in the four types of expansion loops. Type III is the type with the lowest pressure concentration so that the pressure drop that occurs in type III is lower than other types.

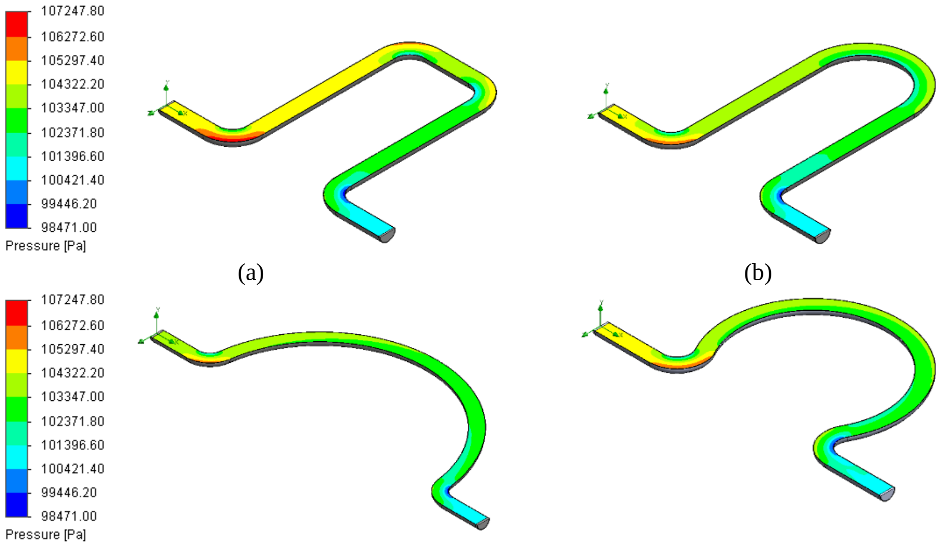


(a) (b)



(c) (d)

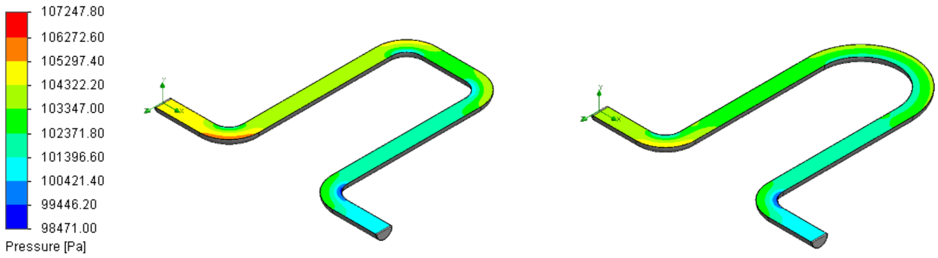
Fig. 6. Pressure contour on (a) type I, (b) type II, (c) type III, and (d) type IV in a simulation with a flow velocity of 3 m/s.



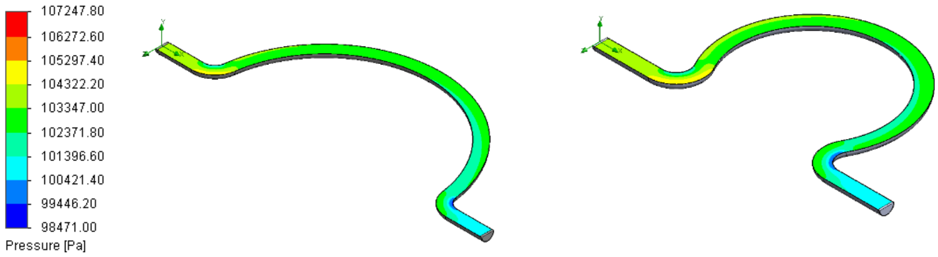
(a) (b)

(c) (d)

Fig. 7. Pressure contour on (a) type I, (b) type II, (c) type III, and (d) type IV in the simulation with a fluid density of 950 kg/m^3.



(a) (b)



(c) (d)

Fig. 8. Pressure contour on (a) type I, (b) type II, (c) type III, and (d) type IV in the simulation with a fluid viscosity of 0.004054 Pas.

Figure 8 is the simulated pressure contour for variations in fluid viscosity at 0.004054 Pas. Based on the visuals seen in the four types of expansion loops, the pressure is concentrated in the pipe bends. The pressure concentration in the simulation with this viscosity variation also shows that type I experiences the highest-pressure concentration and type III experiences the lowest pressure concentration. Therefore, the pressure drop in type I is the highest pressure drop and the pressure drop in type III is the lowest pressure drop.

Figures 6, 7 and **8** show that the pressure distribution that occurs in the flow in each type of expansion loop. The concentration of pressure at the bends of the pipe. Like the stress concentration that occurs in an object that has a change in geometry.

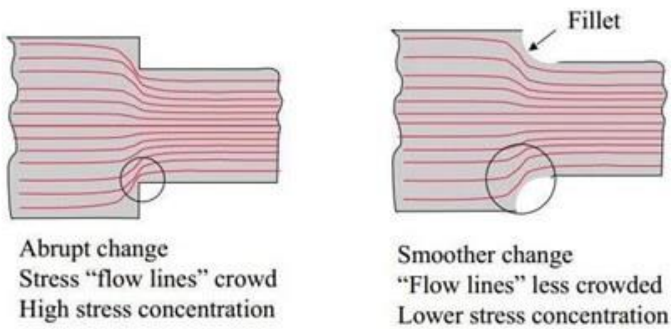


Fig. 9. Stress concentration due to changes in geometry [10].

Figure 9 shows the stress concentration that occurs in 2 types of objects that undergo geometric changes with different levels of fillet sharpness. Different fillet sharpness causes different concentrations. The sharper the fillet on an object, the greater the stress concentration. Likewise with the problem of flow in the piping. The sharper the bend in the pipe, the greater the concentration of pressure that occurs due to the collision of flow in the pipe. Therefore, the best expansion loop is based on how the expansion loop forms in following the fluid flow (streamline).

3.6 The Best Type of Expansion Loop in terms of Pressure Drop Generated

After performing simulations on three variables, namely the variable flow velocity, density, and viscosity of the fluid, it was found that type III is the type of expansion loop that causes the lowest pressure drop. This is of course a result of the shape of type III which has a semicircular shape.

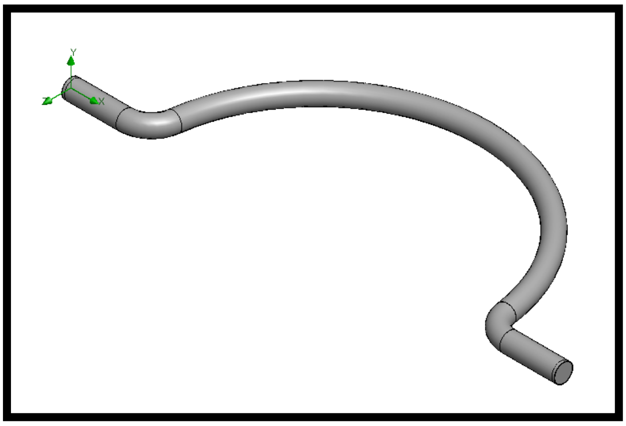


Fig. 10. Type III expansion loops are semicircular shape.

The semicircular expansion loop as shown in **Figure 10.** has a more streamlined shape than the other types. Therefore, this type causes the lowest pressure drop which can be seen in **Figure 3, 4** and **5**.

3.7 Pump Power Due to Pressure Drop

Table 6. The results of power calculations in simulations with variations in flow speed.

Flow speed (m/s)	Pump power			
	Type I (watt)	Type II (watt)	Type III (watt)	Type IV (watt)
1	53.220	41.629	39.318	39.778
1.5	157.958	123.023	112.760	121.496
2	359.276	273.742	255.096	278.416
2.5	669.753	514.168	485.917	520.627
3	1115.554	867.676	819.492	882.923
3.5	1736.189	1334.677	1260.752	1391.375
4	2503.223	1947.593	1866.306	2086.22
4.5	3517.133	2788.296	2596.654	2958.202

Table 7. The results of power calculations in simulations with variations in fluid density.

Density (kg/m^3)	Pump power			
	Type I (watt)	Type II (watt)	Type III (watt)	Type IV (watt)
851.4	874.0505	677.7418	637.7877	689.6507
900	914.6138	716.798	667.6847	724.0491
950	944.2075	739.9358	701.9192	764.6221

1000	1000.08	780.0048	733.7049	792.5278

Table 8. The results of power calculations in simulations with variations in fluid viscosity.

Viscosity (Pas)	Pump power			
	Type I (watt)	Type II (watt)	Type III (watt)	Type IV (watt)
0.00168808	683.5617	534.2085	515.6136	578.451
0.00244981	731.2145	566.0748	547.6121	610.0067
0.00405437	780.5357	605.64	578.0425	651.9962
0.0075977	854.142	658.5524	615.9979	675.5938
0.00910988	882.6544	670.4124	642.8541	686.6416

The pressure drop that occurs in the piping system will cause an increase in pump power. The following are the results of pump power calculations for variations in flow velocity, fluid density and fluid viscosity assuming 100% pump efficiency.

3.8 Additional Costs Per Year Due to Expansion Loop

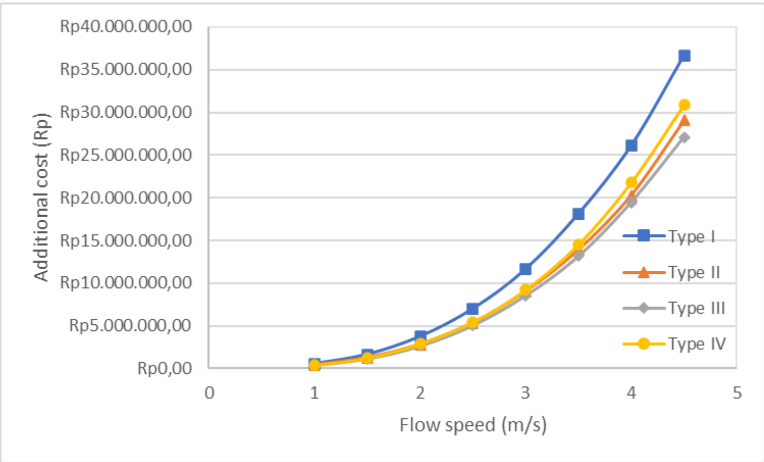


Fig. 11. The addition of electricity costs per year due to the expansion loop in the simulation with variations in flow velocity**.**

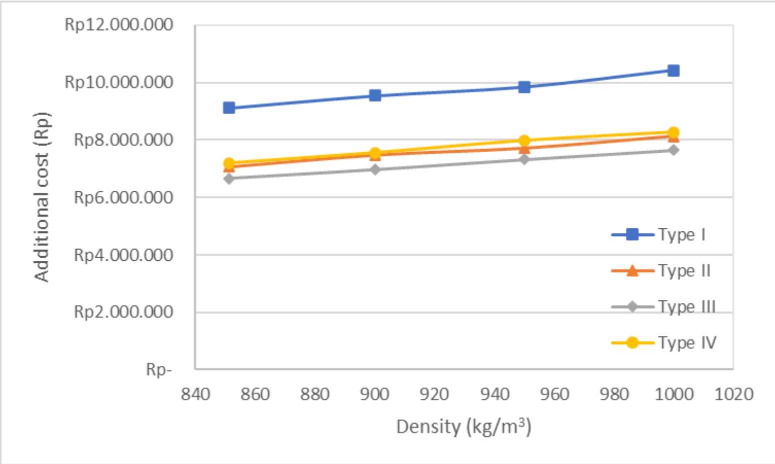


Fig. 12. The addition of electricity costs per year due to the expansion loop in the simulation with variations in fluid density.

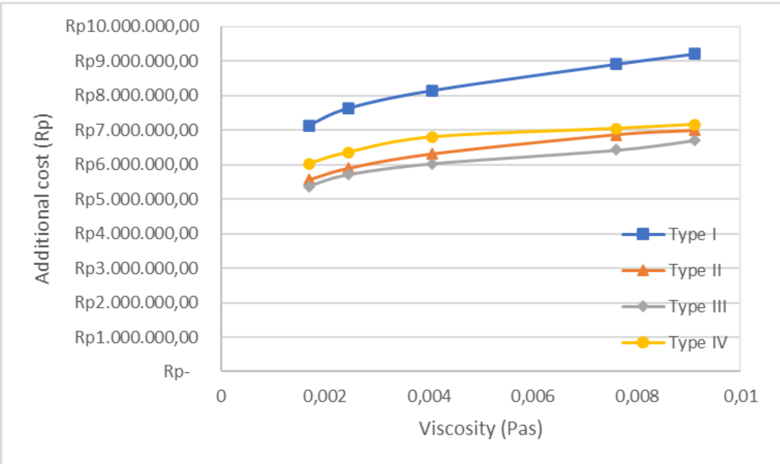


Fig. 13. The addition of electricity costs per year due to the expansion loop in the simulation with variations in fluid viscosity.

Calculate the additional electricity costs per year used due to the expansion loop. The assumption used is that the pump runs for 24 hours a day and the price for electricity is categorized into groups for large industrial purposes at high voltage with a power of 30,000 kVA and above (1-4/TT) [11]. Therefore, the perkWh price is IDR 1,191.00. The formula for calculating the annual cost is as follows.

$$\frac{Electricity\ cost}{Year} = \frac{W}{1000} \times Year(hour) \times \frac{electricity\ cost}{KWh} \tag{1}$$

With the same calculation, the additional electricity costs per day are obtained for the three variations of the simulation as shown in **Figures 11, 12** and **13**.

From **Figure 11, 12,** and **13**, the type III expansion loop (semi-circle type) is the best expansion loop in terms of the additional costs incurred. The additional costs incurred by type III are lower than the additional costs due to other expansion loops. So, based on the resulting pressure drop and the addition of operating costs, the order of selecting the best expansion loops in a row is type III, type II, type IV, and type I. However, based on the calculation of additional operating costs, the difference in additional costs when compared to type III, then type II and IV are not significant because the difference in the average cost is only 5.87% and 9.14%. Meanwhile, when compared with type I, the difference in the average cost is quite significant, namely 36.43%. This happens because the expansion loop type I has 4 elbows of 90º so that the friction that occurs between the fluid flow and the pipe surface is much greater than the expansion loop types II, III and IV.

3.9 Optimum Parameters to Generate Economical Cost

In this study, there are 4 factors that determine the operating costs incurred for the installation of expansion loops. The four factors are fluid flow velocity, fluid density, fluid viscosity and the shape of the expansion loop itself.

Based on the research that has been done, the increase in flow velocity is the variable that has the most effect on pressure drop. **Figure 3** shows that an increase in flow velocity causes a larger pressure drop increase compared to the density and viscosity variables as shown in **Figures 4** and **5**.

To determine the most optimum parameters, the right choice is to choose the parameters that cause the lowest pressure drop. Therefore, the most ideal flow conditions in this study were a flow velocity of 1 m/s, a density of 851.4 kg/m3, and a viscosity of 0.001688 Pas. Then for the most ideal shape is a semicircle or type III.

In addition to determining the optimum parameters to determine the most economical cost, there are other factors that need to be known in the installation of expansion loops, namely the pipe strength factor. In a study conducted by Pujiyanto on several expansion loops, it was found that type III did not meet the requirements because it exceeded the allowable stress of the material [11]. Therefore, before carrying out economic calculations on the installation of expansion loops, a strength analysis must be carried out first.

4 Conclussions

Based on research that has been done on expansion loop types I, II, III and IV. the following conclusions are obtained. The following are the conclusions obtained.

Changes in fluid flow velocity affect the pressure drop. The greater the flow velocity, the greater the pressure drop. In this simulation, there is an increase in the average pressure drop for every 1 m/s increase in flow velocity. Type I experienced an average increase of 2339.33 Pa, type II experienced an average increase of 1856.37 Pa, type III experienced an average increase of 1727.01 Pa and type IV experienced an average increase of 1983.58 Pa.

Changes in density affect the pressure drop. The greater the density of the fluid, the greater the pressure drop. In this simulation, there is an increase in the average pressure drop for every 1 kg/m^3 increase in fluid density. Type I experienced an average increase of 3.466 Pa, type II experienced an average increase of 2.817 Pa, type III experienced an average increase of 2.637 Pa and type IV experienced an average increase of 2.83 Pa.

Changes in fluid viscosity affect the pressure drop. The greater the viscosity of the fluid, the greater the pressure drop. In this simulation, there is an increase in the average pressure drop for each increase in fluid viscosity of 0.001 Pas. Type I experienced an average increase of 135.83 Pa, type II experienced an average increase of 91.22 Pa, type III experienced an average increase of 91.40 Pa and type IV experienced an average increase of 83.3 Pa.

Type III is the type that causes the lowest pressure drop compared to other types. However, based on the calculation of additional operating costs, the difference in additional costs when compared to type III, then type II and IV is not significant because the difference in average costs is only 5.87% and 9.14%. Meanwhile, when compared with type I, the difference in the average cost is quite significant, namely 36.43%.

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