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CFD Analysis of Orifice Placement and Thickness on Pressure Drop in Entrance and Fully-Developed Flow Regions

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ABSTRACT

Having reliable data is important for analyzing the fluid behaviour inside the pipe. Hence, the selection of the fluid flow measurement instrument becomes critical to fulfill its objectives. Among various devices use for fluid flow measurement, orifice plate continues to be widely used despite pressure differrence occurs between its upstream and downstream regions due to its installation in the fluid flow inside the pipe. However, understanding the pressure drop situation of the orifice plate in the entrance region and fully-developed flow region remains a relatively underdeveloped problem to be investigated. A numerical study is conducted on this research to find the influence of the orifice plate's thickness and the location of the installation of the orifice plate on the fluid flow to the pressure difference in the upstream and downstream sides of the orifice plate. The results show that the pressure drop at its highest will happen when a thicker orifice plate is chosen and it is located in the entrance region. This result will hopefully give better insight for orifice plate research in order to reduce pressure drop in fluid flow, which could ultimately increase the efficiency of the process of fluid flow inside the pipe. Future work can be expanded to study the orifice plate's mechanical behaviour due to pressure from fluid flow.

Keywords: orifice plate, fluid flow, CFD, entrance region, pressure drop

ABSTRAK

Penting dalam memiliki data pengukuran yang dapat dihandalkan untuk menganalisis perilaku dari fluida di dalam pipa. Oleh karena itu, pemilihan alat pengukuran aliran fluida menjadi penting untuk memenuhi tujuan yang telah disebutkan. Dari berbagai jenis alat yang digunakan, *orifice* plate terus digunakan secara luas walaupun instalasinya pada aliran fluida di dalam pipa menyebabkan terjadinya penurunan tekanan antara daerah *upstream* dan *downstream*. Namun, memahami situasi penurunan tekanan pada daerah *entrance* dan *fully-developed flow* relatif menjadi masalah yang jarang dikembangkan untuk diselidiki. Studi numerik dilakukan pada penelitian ini untuk mengetahui pengaruh dari ketebalan plat *orifice* dan lokasi dari instalasi plat *orifice* di aliran fluida kepada perbedaan tekanan yang terjadi di sisi *upstream* dan *downstream* dari plat *orifice*. Hasil ini menunjukkan bahwa penuruna tekanan terbesar terjadi ketika plat *orifice* yang tebal dipilih dan plat *orifice* diletakkan pada daerah *entrance*. Harapannya, hasil ini dapat memberikan bayangan yang baik akan penelitian mengenai plat *orifice* untuk mengurangi dampak penurunan tekanan pada aliran fluida, yang pada akhirnya dapat meningkatkan efisiensi pada proses aliran fluida di dalam pipa. Penelitian selanjutnya dapat dikembangkan untuk mempelajari sifat mekanik plat *orifice* akibat dari munculnya tekanan pada aliran fluida.

Keyword: orifice plate, fluid flow, CFD, entrance region, pressure drop

1. Introduction

Flow measurement is fundamental for analyzing fluid behavior. Therefore, having reliable data on flow measurement is important before delving into the analysis, as mentioned earlier [1]. Differential-pressure flowmeters remain the most commonly used device to measure the fluid flow [2]. As the fluid passes through a constriction in the pipe, it undergoes linear acceleration, leading to a change in velocity which eventually produces a pressure difference across the constriction [3].

The orifice is the predominant choice among various flow measurement devices due to its robustness, simplicity in design, reliability, and ease of use and maintenance [4]. An orifice flowmeter consists of a plate with a circular or semicircular hole drilled in it [5]. The installation of the orifice plate inside the fluid-carrying pipe measures the pressure difference between the upstream and downstream sides of the plate, which indirectly provides the flow rate measurement [6]. On the other hand, the orifice plate has its own limitations, such as large sensitivity in inlet city profile [7], inaccuracy of measurement results, and occurrence of irrecoverable pressure drop [8]. The latter disadvantage is commonly discussed as it has a significant impact on the fluid flow.

Both experimental and numerical studies are being carried out to discuss the pressure drop due to the installation of the orifice plate on the fluid flow. Durdevic et. al [2] have done an experimental study to compare the utilization of single and multi-hole orifice plate to gas flow inside the piping installation. The earlier study is being validated by conducting a numerical study through computational fluid dynamics (CFD) simulation, resulting in identical patterns [1]. Hariguru and Srinivasan have performed similar work [9], who conducted an experimental study later validated by CFD simulation to discuss the influence of single and multi-hole orifice plates on differential pressure and permanent loss pressure in water flow. Gulsacan et al. have exploited a particle image velocimetry (PIV) experiment and CFD simulation [10] to investigate the effect of orifice thickness-to-diameter ratio on turbulent orifice flow, which resulted in decreasing turbulent kinetic energy and Reynolds shear stress with increasing thickness-to-diameter ratio, as a result of the pressure drop. Ma et al. conducted an experimental study for both circular and slotted hole types of multi-orifice plates to inspect the pressure drop that occurs in the stratified and intermittent regions of the wet gas flow [11].

Chamfer geometry of perforated plates with thin orifices was considerably used for debris filtering bottom in Brazilian nuclear plants, where the results indicate that in turbulent flow, the small chamfers greatly reduce the pressure drop compared to large ones [12]. Mali et. al have carried out CFD simulations [13] to study how various geometrical parameters of honeycomb types of orifice plates affect the pressure drop and cavitation behavior in multiphase mixture flow. Fluid with extreme conditions (such as high pressure and high temperature) will influence the pressure drop and cavitation on its flow, the modified cavitation model is implemented to evaluate aforementioned circumstances by conducting both experimental and numerical studies [14]. An optimized multi-hole conical-edge orifice plate is presented in order to reduce pressure drop around the plate, this objective is validated by conducting experimental and numerical analysis [15]. Meanwhile, Chinello [16] has proposed a theoretical equation to estimate the Pressure Lost Ratio of refining Urner and Reader-Harris orifice plate model in incompressible flow which resulting about 1% experimental value at a 95% confidence level. The influence of the orifice plate's thickness and Reynolds numbers are investigated to obtain pressure drop data on the plate's area due to fluid flow, the results indicate that the highest pressure drop occurs when the highest thickness and Reynolds number are chosen [17].

Previous research did not mention any analysis of the influence of installation orifice plate for entrance and fully-developed flow regions on fluid flow behaviours. Akhyan and Arviansyah [18] have performed an experimental setup to understand the pressure drop and discharge coefficient occurring due to the variation of the orifice plate's thickness in the entrance and fully-developed flow regions. The results show fluctuation of pressure difference between the upstream and downstream regions for various thicknesses of the orifice plate, with the highest pressure drop occurring when a 2.5 mm-width orifice plate was chosen for the fully-developed flow region. Theoretically, the result is inaccurate since the highest pressure drop is supposed to happen for the chosen thickest orifice plate in the entrance region.

This research aims to conduct numerical analysis to determine the pressure drop that occurs in upstream and downstream sides of the orifice plate due to the choice of various orifice plate thicknesses for fluid flow in the entrance and the fully developed regions.

2. Methods

CFD is a simulation-based approach method to analyze the fluid behaviors, with particular focus on the fluid flow and heat transfer [19]. This method employs the fundamental equation of fluid flow to examine a wide range of complex situations to deliver both qualitative comprehension and quantitative forecasting by applying an approximation of discrete equations at a mesh of grid points, which is derived by using finite difference or finite volume techniques [20].

As mentioned earlier, the installation of orifice plate in the fluid flow inside the pipe will result in difference pressure around orifice plate area which will eventually causes the drop in pressure along the fluid stream. The occurring pressure drop is irrecoverable, thus it is important to choose orifice plate for fluid flow measurement carefully. The illustration of irrecoverable pressure drop is presented on the Figure 1 [21].

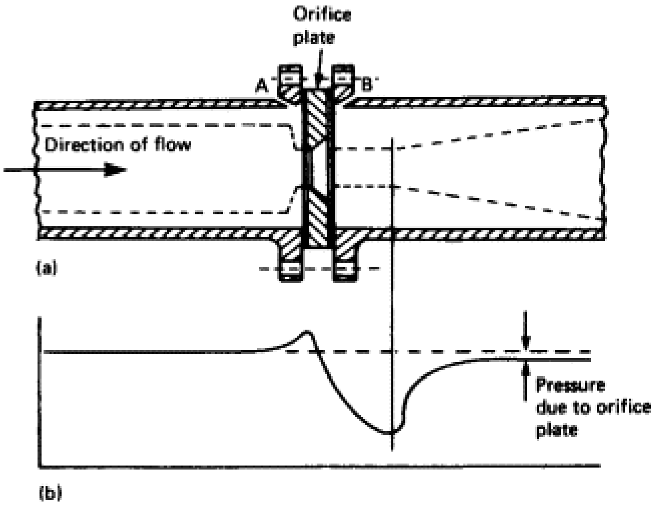


Figure 1. Pressure drop due to installation of orifice plate in fluid flow

Our research goal is to obtain the pressure difference between the upstream and downstream sides of the orifice plate. For the incompressible fluid flow inside the pipe, it is widely known Bernoulli equation applied on its flow by following governing equation [22]:

$$\frac{p}{\rho} + \frac{1}{2}v^2 + gz = c \tag{1}$$

where p is pressure, ρ is density of fluid, v is fluid flow's velocity, g is gravity acceleration --about 9.81 $\frac{m}{s^2}$-- and z is the height of fluid from reference point. Symbol of c indicates that the sum of left-hand side of equation (1) is considerably constant irrespective of point of observance where it is assessed along the pipe. Basically, CFD will be performed to solve equation (1) to determine the pressure, with any other variables contained on the equation are acted as inputs.

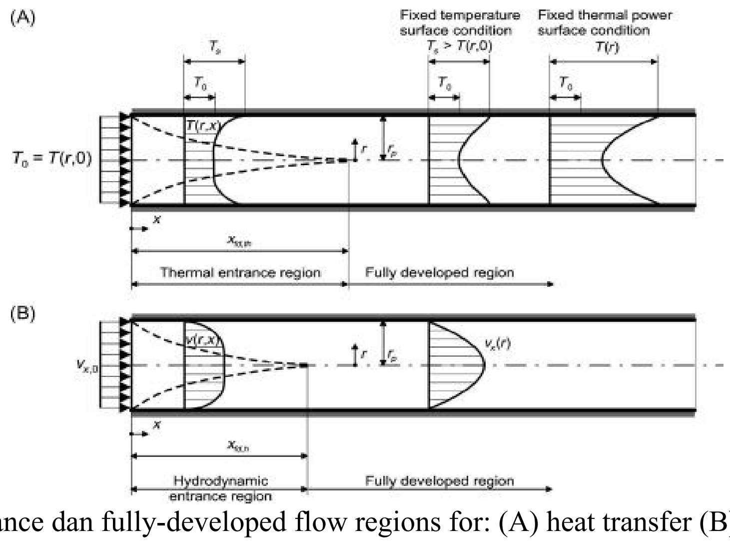


Figure 2 Entrance dan fully-developed flow regions for: (A) heat transfer (B) mass transfer

When the fluid enters the pipe, the fluid velocity profile remains uncertain for sometimes in certain length. This length is known as entrance length region. Larger pressure gradient occurs on this region which will eventually cause higher pressure drop [23]. Once the fluid velocity profile reaches uniform condition, the velocity of fluid flow is relatively constant until fluid reaches exit point [23]. Regions of fluid flow are illustrated in Figure 2 (B) [24]. The entrance length (L_e) of fluid can be determined by [25]:

$$\frac{L_e}{D} = 0.06Re \quad (2)$$

for laminar flow ($Re < 2300$),

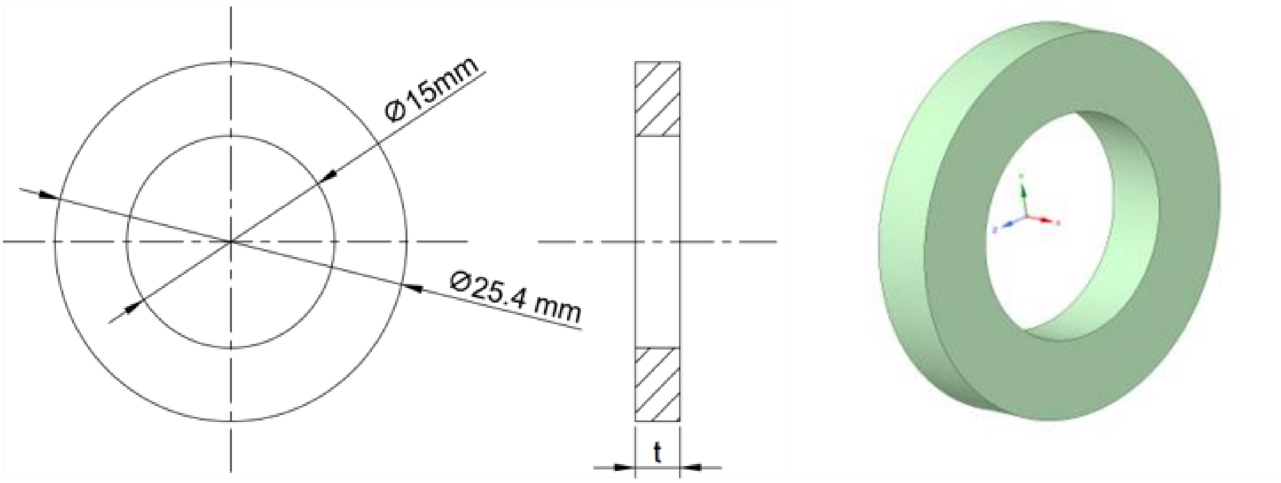
$$\frac{L_e}{D} = 4.4Re^{1/6} \quad (3)$$

for turbulent flow ($Re < 4000$). D and Re stand for internal pipe diameter and Reynolds number respectively.

Numerical simulation is done by capitalizing on some features of ANSYS R2 2024. The orifice plate geometry model is produced on SpaceClaim feature, where the design is presented in Figure 3. Boundaries between the solid and fluid regions are also defined in SpaceClaim to support and simplify the CFD process. CFD simulation is conducted on the Fluent feature. Simulation parameters used during this study can be seen on Table 1.

Table 1. Simulation parameters

Parameters	Value	Unit
Fluid	$Water$	-
Temperature	27	^0C
Flow rate	20	LPM
Kinematic viscosity	8.532×10^{-7}	m^2/s
Internal pipe diameter	25.4	mm



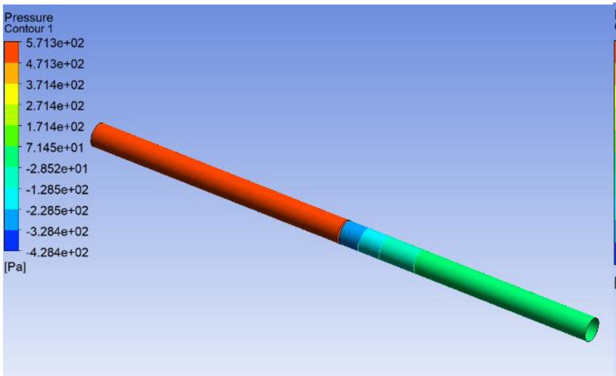
(A) (B)

Figure 3 Orifice plate geometry model: (A) 2-D view with dimensions (B) 3-D view

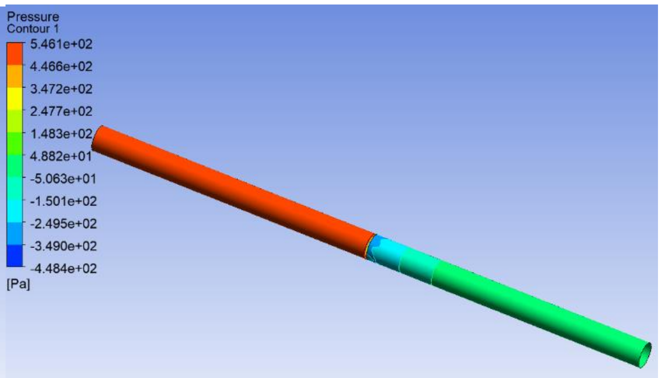
For the entrance region, the source of fluid is assumed to enter the pipe exactly at its entrance point. The orifice plate is located at the centre of the pipe for this condition. While in fully-developed flow, the entrance length region is determined from Equation (1) or Equation (2), depending on the Reynolds number, then the orifice plate is installed exactly at the end of the entrance length region. The variations of the orifice plate for the simulation are 2 mm, 2.5 mm, 3 mm, 3.5 mm, and 4 mm.

3. Results and Discussion

After the CFD analysis is completed, the results are obtained as shown as Figure 4 and Figure 5 for location of the orifice plate in the entrance region and the fully-developed flow region, respectively. The various colours of the results define the magnitude of the static pressure that occurs along the fluid stream inside the pipe.



(A)



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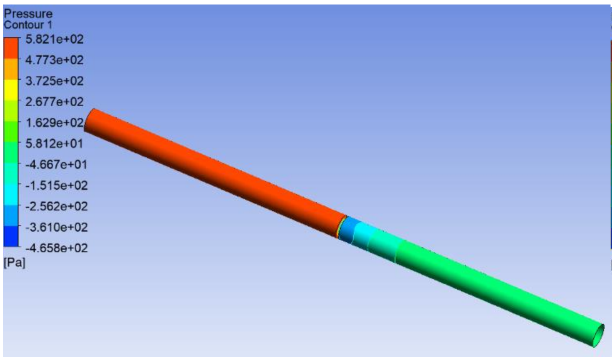

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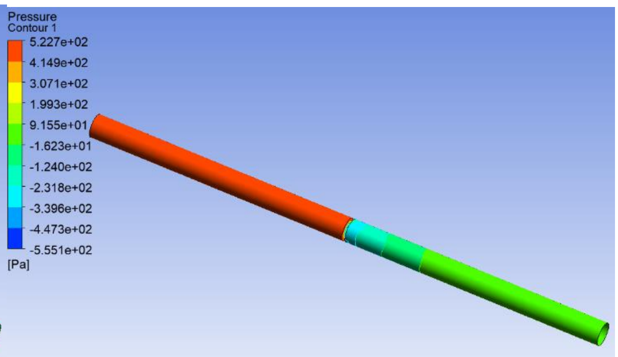

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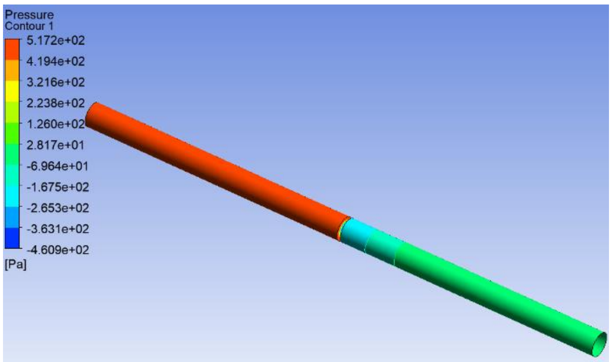
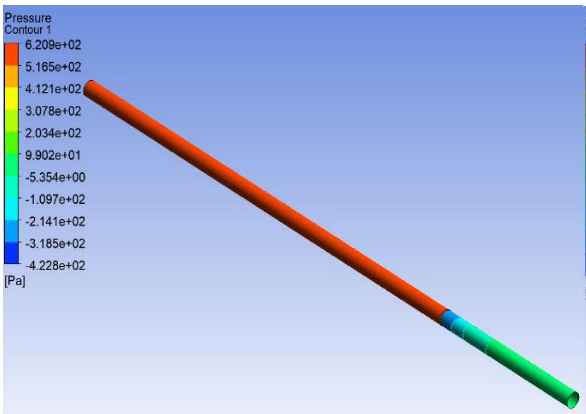
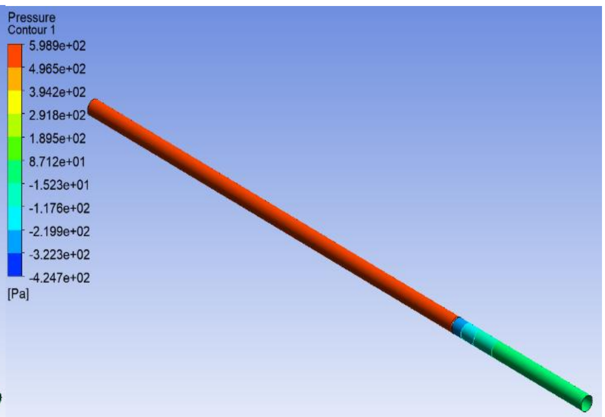


(E)

Figure 4 Simulation results of the entrance region for the following orifice plate's thickness: (A) 2 mm (B) 2.5 mm (C) 3 mm (d) 3.5 mm (E) 4 mm



(A)



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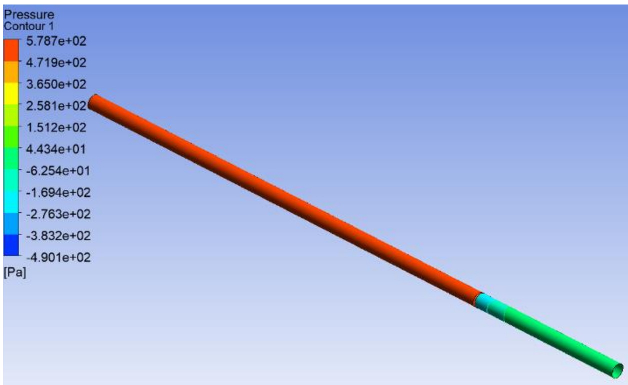

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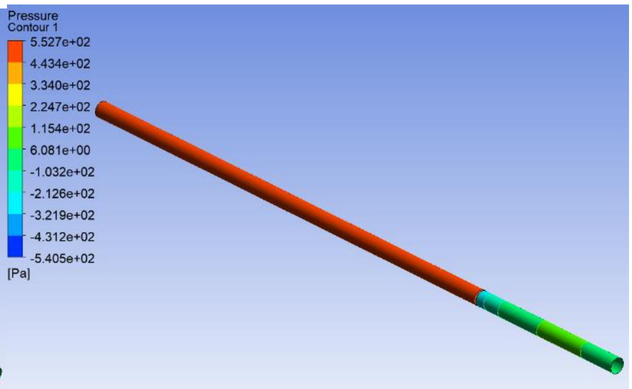
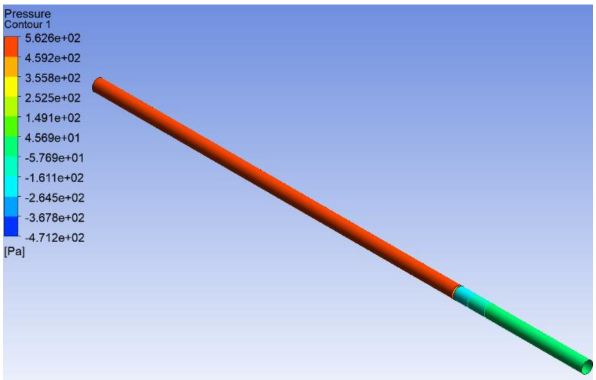


(D)



(E)

Figure 5 Simulation results of the fully-developed region for the following orifice plate's thickness: (A) 2 mm (B) 2.5 mm (C) 3 mm (d) 3.5 mm (E) 4 mm

The magnitude of static pressure on the fluid flow before it hits the orifice plate should be the same since the chosen fluid is identical for all different kinds of simulation setups. Nevertheless, the different results in that area appear for each thickness and fluid flow regime. It might happen due to the random choice of the number of grids during the meshing process for every simulation. Since our goal is to find the pressure difference between the upstream and downstream sides of the orifice plate, the aforementioned results are not really critical to fulfill our research objectives.

The pressure results around the orifice plate are presented in Table 2 For better visualization, the pressure drop results are included in Figure 6.

Table 2 Pressure results around the orifice plate for respective thicknesses and fluid flow regimes

Thickness (mm)	Entrance region			Fully-developed flow region		
	Upstream	Downstream	Pressure drop	Upstream	Downstream	Pressure drop
2 mm	571.3 Pa	74.15 Pa	497.15 Pa	620.9 Pa	203.4 Pa	417.5 Pa
2.5 mm	546.1 Pa	48.82 Pa	497.28 Pa	598.9 Pa	176.7025 Pa	422.2 Pa
3 mm	582.1 Pa	58.12 Pa	523.98 Pa	578.7 Pa	151.2 Pa	427.5 Pa
3.5 mm	522.7 Pa	-16.23 Pa	538.93 Pa	552.7 Pa	115.4 Pa	437.3 Pa
4 mm	517.2 Pa	-69.64 Pa	586.84 Pa	562.6 Pa	45.69 Pa	516.91 Pa

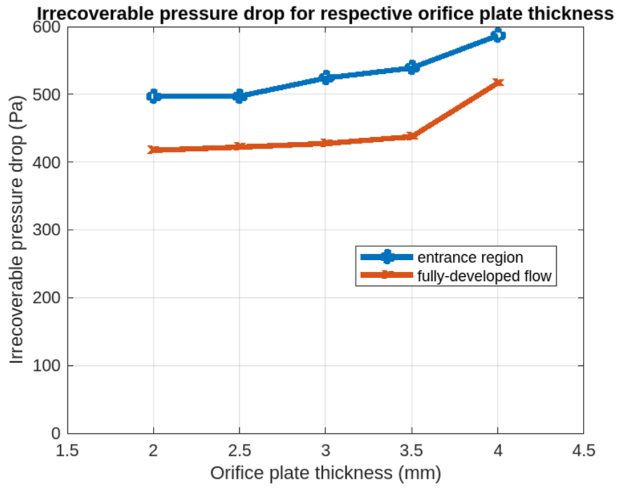


Figure 6 Simulation results for both entrance and fully-developed flow regions for every chosen orifice plate's thickness

The previous research conducted by Akhyan & Arviansyah [18] showed inconsistent results for every orifice plate's thickness and fluid flow's regimes. Since it was experimental study, these deviations might happen in regards to experimental condition. Experimental process was done in an open area, therefore environment parameters (such as temperature, pressure, humidity, etc.) affected the collecting data process. The study must be experimented in the dedicated room to anticipate aforementioned variations. Our research proposed the numerical study to recondition earlier study by Akhyan & Arviansyah [18] and it gives consistent results with underlying theory.

The highest pressure drop, according to the results shown by Table 2 and Figure 5, for both entrance and fully-developed flow regions happened when 4 mm thickness of orifice plate was selected. This phenomenon is appropriate in accordance to our initial hypothesis that the thicker orifice plate, the greater disturbance occur to fluid flow. In entrance region, fluid flow undergoes continuous evolution into fully-developed flow due to its proximity to the source of fluid, which means higher pressure gradient occurs within time before it enters the fully-developed profile. Consequently, irrecoverable pressure drop in entrance region is larger than fully-developed flow region.

4. Conclusion

From the results shown in section 3, t is preferable to select a thinner orifice plate for fluid flow measurement as it reduces the irrecoverable pressure drop that occurs in fluid flow. The location of installation of the orifice plate is important to minimize adverse impacts and optimize its application. Therefore, for both better results and efficiency, fully-developed flow region is favoured as the location of the installation of the orifice plate.

For upcoming works, it is important to understand the orifice plate structure's mechanical behaviours due to pressure in fluid flow. Both numerical and experimental studies can be conducted to investigate structural analysis of this aspect.

5. Acknowledgement

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