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Modification of Gas Inlet Design in Pyrolysis Reactors by using Computational Fluid Dynamics for the Optimization of Bio-Oil Production from Biomass Waste Mixture

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ABSTRACT

The bio-oil production process from biomass waste can be carried out by using a pyrolysis reactor. Pyrolysis is a thermochemical decomposition process of organic materials through a heating process without oxygen, where the raw material will undergo a chemical structure breakdown into a gas phase. The nitrogen gas is needed to suppress or remove the oxygen during the pyrolysis process. Nitrogen flow in a good biomass pyrolysis reactor needs to pay attention to the speed of nitrogen without ignoring the volume of gas storage. For this reason, one thing that can be studied further is the geometry of the inlet of the biomass pyrolysis device. Inlet geometry can be varied based on several parameters, including variations in inlet shape that can affect flow pressure. Therefore, in this research, calculations will be carried out using computational fluid dynamics to obtain optimal outlet velocity and pressure drop results. The simulation will be carried out using inlet discharge data, namely 1 L/min, 2 L/min and 3 L/min which is converted into inlet velocity data. The results show that the modified inlet gas produces a flow rate with a lower pressure and also spreads the nitrogen gas more evenly inside the reactor compared to the unmodified inlet gas.

Keywords:
Bio oil; inlet gas modification: nitrogen; pyrolysis

1. Introduction

Currently, the world is experiencing an energy crisis. The availability of energy sources to meet various needs, both small and large scale, is very limited. This is because it still relies on fossil energy sources, namely petroleum. The non-renewable nature of petroleum makes the situation even more difficult [1]. Oil supplies in the world are increasingly decreasing and prices are increasing. Based on government regulation no. 79/2014 concerning National Energy Policy states that in 2025 the target role of new and renewable energy is at least 23% in 2025 and 31% in 2050, balanced with a reduction in the role of petroleum of less than 25% in 2025 and less than 20% in 2050. For this reason, innovation is needed to create alternative energy that is renewable, environmentally friendly and has abundant availability.

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Over the last 2 decades, special attention has been paid to the conversion of biomass residues and renewable materials into bio-oil. Bio-oil is a liquid product resulting from gas condensation from biomass decomposition at high temperatures without the presence of oxygen [2]. The pyrolysis technique is a thermochemical method where biomass waste is converted into solid fuel (char), gas producer (syngas) and liquid (bio-oil) without the presence of oxygen in a reactor [3]. Pyrolysis is a thermochemical decomposition process of organic material, which takes place without air or oxygen [3]. Heating in fast pyrolysis uses a pyrolysis temperature between 450-700°C. Research on the conversion of bagasse and rice husks into bio-oil through pyrolysis has been widely carried out [4]. In the pyrolysis process in a pyrolysis device or pyrolysis reactor, a flow of nitrogen gas is required during the process, where the nitrogen gas functions to press oxygen gas out so that the combustion process is complete. The use of nitrogen in the pyrolysis process is very important to eliminate the presence of oxygen in the pyrolysis reactor. However, studies regarding the influence of nitrogen gas inlet on the pyrolysis process are still very limited. In previous studies, experiments have been carried out regarding the pyrolysis process which requires nitrogen gas to ensure that the operating conditions of the pyrolysis reactor do not involve oxygen [4-8].

The nitrogen flow rate used in the pyrolysis process varies greatly, Mohamed *et al.,* [9] investigated the effect of Nitrogen flow rate on pyrolysis by varying flow rates of 150, 200, 300, 400 and 500 cm^3/minute. A nitrogen flow rate of 200 cm^3/minute produces the highest bio-oil, namely 46.02%. In this process, it is also known that the biochar and gas produced are 26.69% and 27.9%. Zhou *et al.,* [10] studied the characteristics of the dehydration process in pyrolysis of rice husk biomass waste. In this experiment, the nitrogen flow rate used was 50 mL/minute. Aysu [11] carried out a conventional slow pyrolysis process using raw materials in the form of lilies, the flow rate used in this research was 10 mL/minute. In this research, it was also found that the calorific value of the bio-oil produced was much higher when compared to the calorific value of the raw materials used. Ma *et al.,* [12] in experiments compared the pyrolysis of oil sands using various methods including the nitrogen sweeping method. In this method, gas is used with a flow rate of 0.04 m3/hour. The results of this research show that under vacuum conditions, the yield of pyrolysis products is not influenced by the heating rate of the pyrolysis process. Mishra *et al.,* [13] carried out catalytic thermal pyrolysis on Ginje flower seeds using a batch reactor. In this process, the operating conditions are a pyrolysis temperature of 525 °C, a heating rate of 75 °C/minute and a nitrogen flow rate of 75 mL/minute. The bio-oil yield produced in this research was 45.26 wt%. Das *et al.,* [14] in their latest publication regarding the decomposition of rice husks through the slow pyrolysis process, varied the nitrogen flow rate from 0.87 – 1.5 L/minute. A flow rate of 0.8 L/minute provides the highest bio-oil yield and the highest biomass conversion.

Several researchers have also simulated the pyrolysis process using various software, including Poddar *et al.,* [15] created a model and optimization of a pyrolysis plant that uses pig and goat manure as raw materials. The simulation was carried out using Aspen Plus software. In this optimization process, it was found that the maximum bio-oil was obtained when the pig manure feed was 0.679232 tons/day and goat manure was 0.790000 tons/day. Simulations carried out by Wijayanti *et al.,* [16], show that the pyrolysis process can be simulated using Comsol multiphysics to determine the profile of temperature changes in the reactor. Pyrolysis temperature plays an important role in the distribution of mass and heat during the pyrolysis process. Dadi *et al.,* [17] have studied the importance of pyrolysis simulation using Computational Fluid Dynamics (CFD). CFD can be used to predict the complexity of the pyrolysis process both on a large scale and in quite many phases. Choi *et al.,* [18] simulated the pyrolysis of coffee shell waste using polystyrene corks. In this research, a simulation was carried out using STAR-CCM v9.6 software. This process also requires reactor operating conditions that do not contain oxygen, so nitrogen is needed to expel the presence of oxygen in the reactor. Studies regarding the flow rate and geometry of the nitrogen inlet in the pyrolysis reactor have never been carried out. In this study, the modifications to the nitrogen gas inlet and variations in the nitrogen flow rate on the quality of the bio-oil produced will be carried out and investigated.

2. Methodology

The design of the biomass pyrolysis tool was designed and then used to carry out the simulations. Figure 1 shows the design of a biomass pyrolysis reactor.

(a) (b)

Fig. 1. The design of (a) closure (b) main body in pyrolysis reactor

In this study, the biomass pyrolysis reactor was made from stainless steel which will be supplied with nitrogen. Meshing was used to divide the fluid domain that had been created from the previous geometric model into smaller volumes for computational processing. Before meshing, it was necessary to extract volume from the geometry so that the geometry of the volume to be simulated was obtained. To carry out meshing, Ansys Mechanical software was used which was built into Ansys 16. After that, the quality of the resulting mesh was checked by considering the skewness value. Figure 2 shows the meshing results of the biomass pyrolysis reactor.

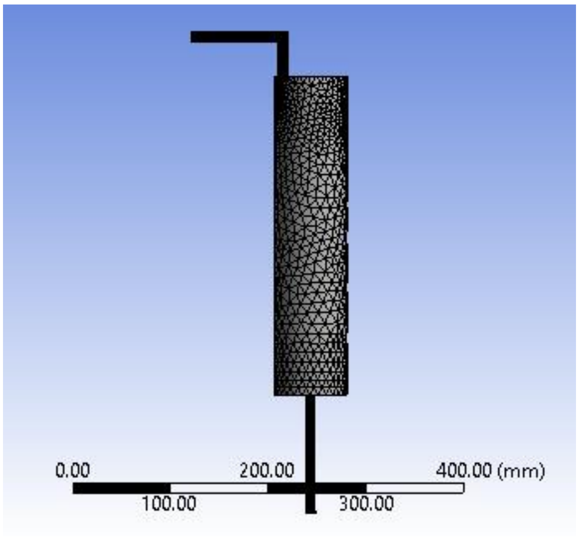
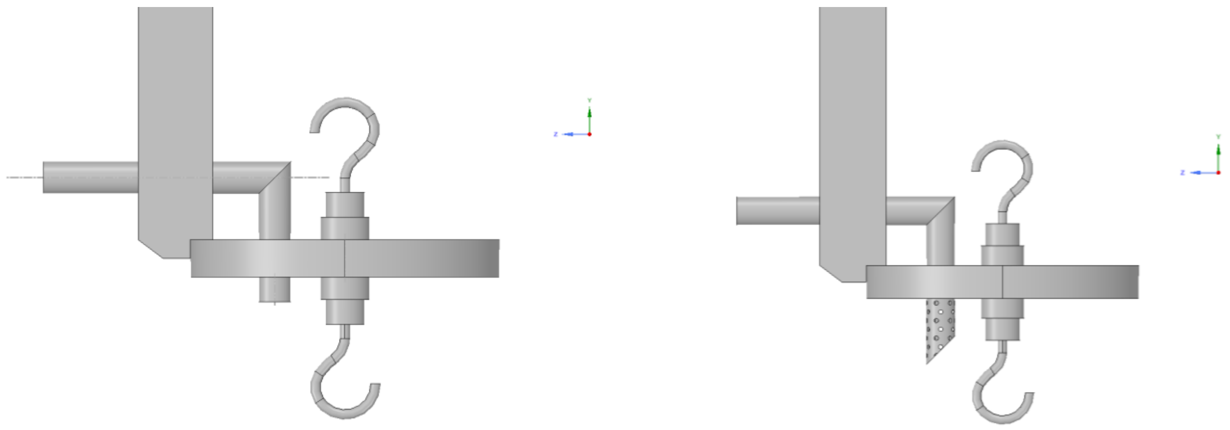


Fig. 2. Mesh result of pyrolysis reactor

In this study, the nitrogen gas inlet in the pyrolysis reactor was modified into 2 different variations. Variation 1 was the unmodified inlet gas while variation 2 was the perforated inlet gas. The detail of the gas inlet as shown in Figure 3.



(a) (b)

Fig. 3. Design of (a) Variation 1 (b) Variation 2

In this study, the simulation was pressure-based simulation with steady time constant. The details of simulation setup are shown in Table 1.

Table 1
Simulation setup

Setup	Description
Solver type	Pressure Based
Velocity Formulation	Absolute
Time	Steady
Gravitational acceleration	-9.81
Multiphase	Off
Energy	Off
Viscous model	k-epsilon

The research data obtained was then analysed to determine the performance of the simulation model on the performance of the biomass pyrolysis reactor with predetermined inlet velocity settings. Then an analysis of these variations was carried out to find out the most optimal geometry based on the velocity, pressure drop and flow rate.

3. Results

3.1 Effect of Inlet Geometry on the Outlet Velocity Profile

Figure 4 shows that variations 1 and 2 produce the same outlet velocity in each inlet variation with no significant differences. At the outlet velocity, each variation experienced an increase, namely at the inlet of 1 l/min the increase was 0.44 m/s, at the inlet of 2 l/min the speed increase was 0.86 m/s and for the inlet of 3 l/min, it was 1.2 m/s.

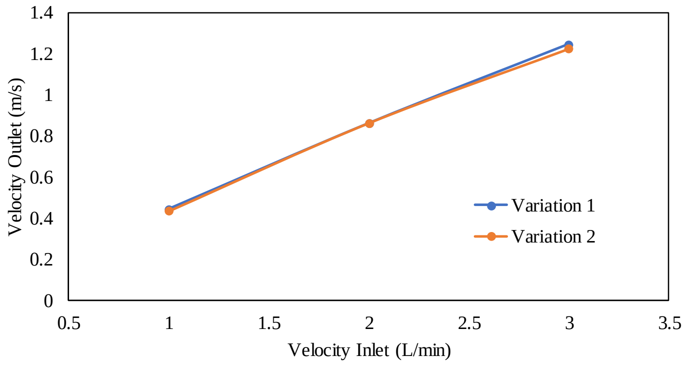


Fig. 4. Effect of Velocity inlet to the velocity outlet

Contours of nitrogen gas velocity in the pyrolysis reactor with different inlet gas geometry are presented in Figure 5 and Figure 6. The nitrogen velocity contour shown in Figure 5 explains how the speed difference moves from the inlet to the outlet. The maximum speed is found at the outlet section where the pressure is at its minimum value. This is under the principle of continuity, namely that the cross-sectional area of the inflow is inversely proportional to the speed [19], which can be seen in the picture of the inlet and outlet having a small cross-sectional area so that the speed is getting larger. At the inlet velocity of 2 and 3 l/min in variations 1 and 2 from the inlet to the outlet, both experience the same increase in speed and there is no significant difference. From the two images, the unmodified inlet geometry collects more velocity contours at the inlet. The maximum speed also can be found at the outlet section.

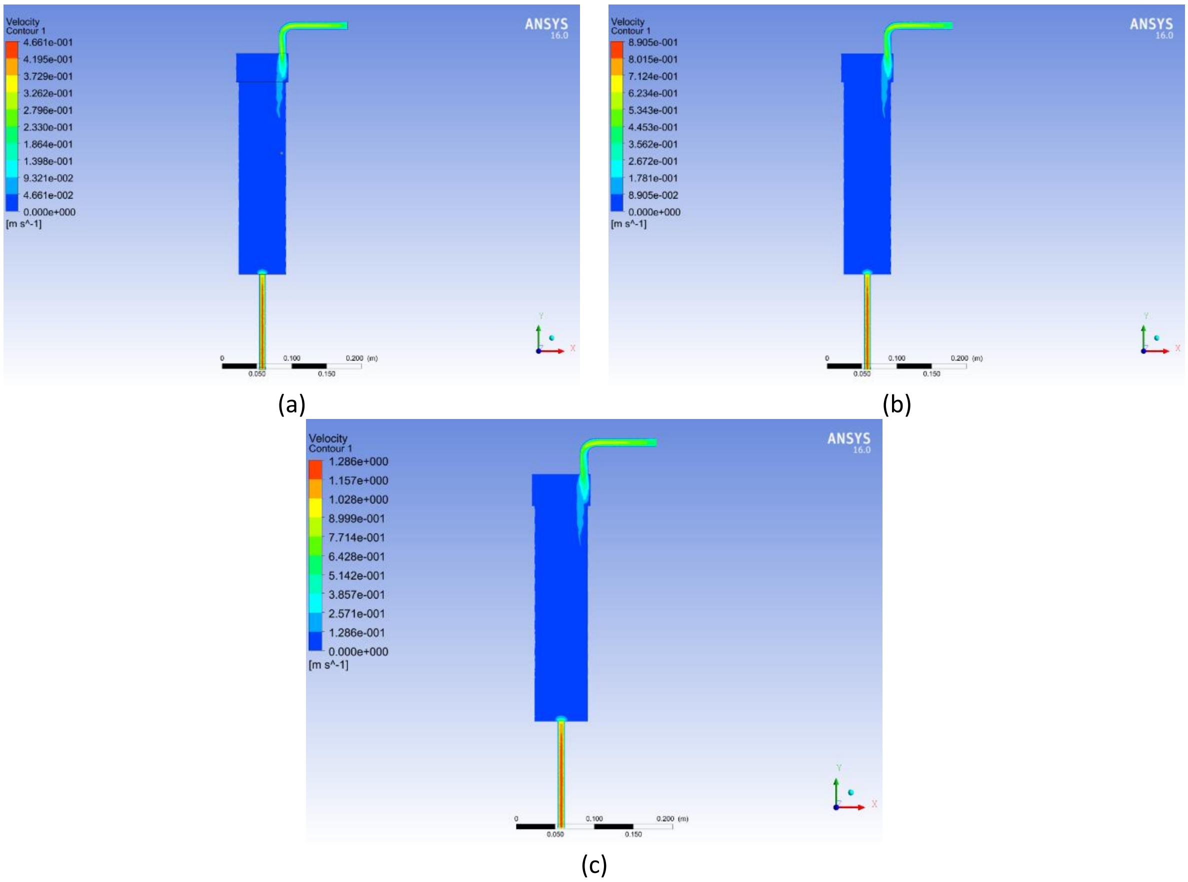
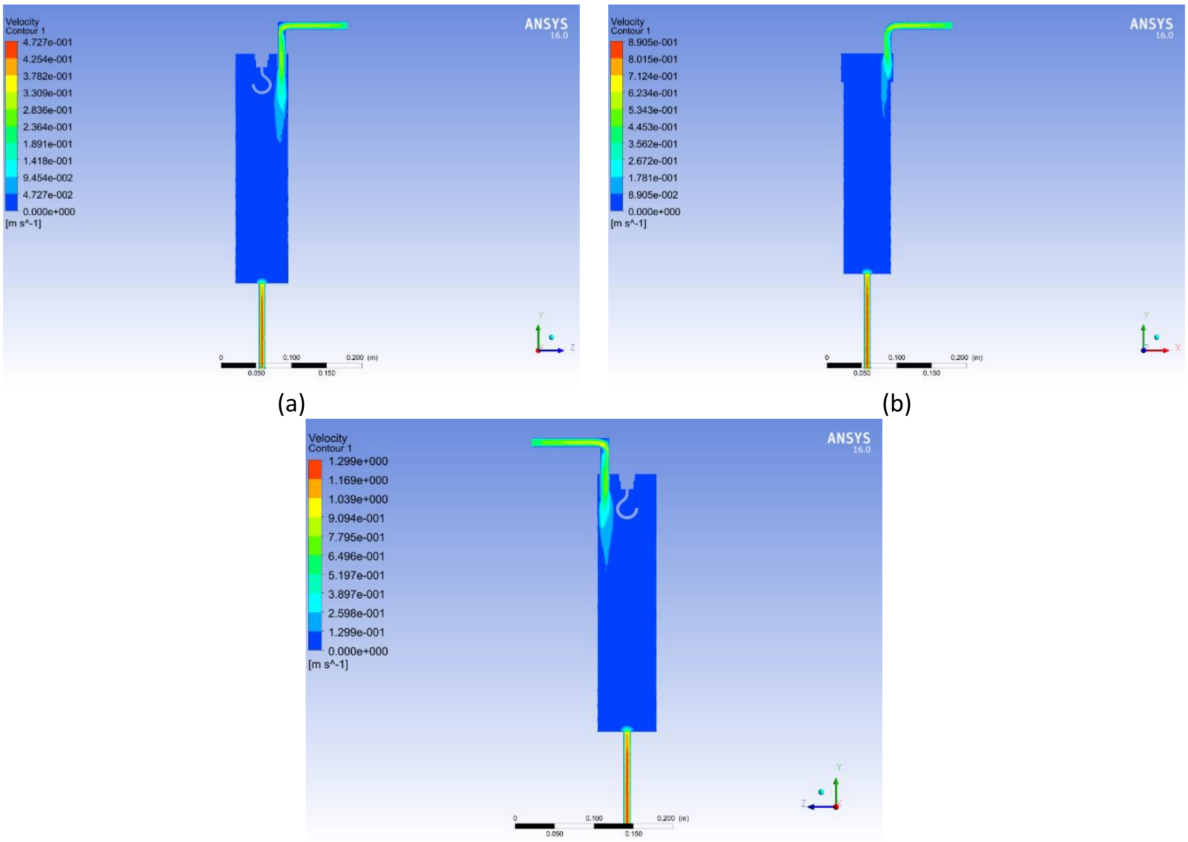


Fig. 5. Velocity contour of nitrogen in the pyrolysis reactor with variation 1 at the inlet velocity of (a) 1 l/min (b) 2 l/min (c) 3 l/min



(a) (b)

(c)

Fig. 6. Velocity contour of nitrogen in the pyrolysis reactor with variation 2 at the inlet velocity of (a) 1 l/min (b) 2 l/min (c) 3 l/min

3.2 Effect of Nitrogen Inlet Velocity on the Pressure Outlet Profile

Figure 7 shows the effect of the velocity inlet on the pyrolysis reactor pressure outlet. It can be seen in the graph of the relationship between inlet velocity and pressure drop. Simulation at the velocity of 1 l/min has the smallest pressure drop and a velocity of 3 l/min means the pressure drop will be at the highest point, with 2.1795 Pa.

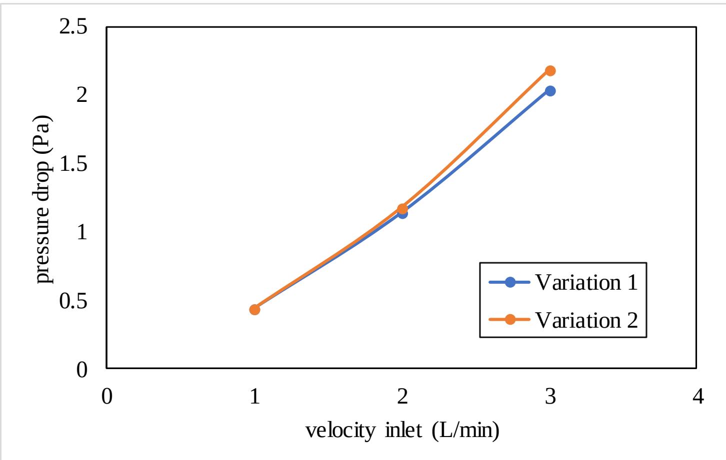
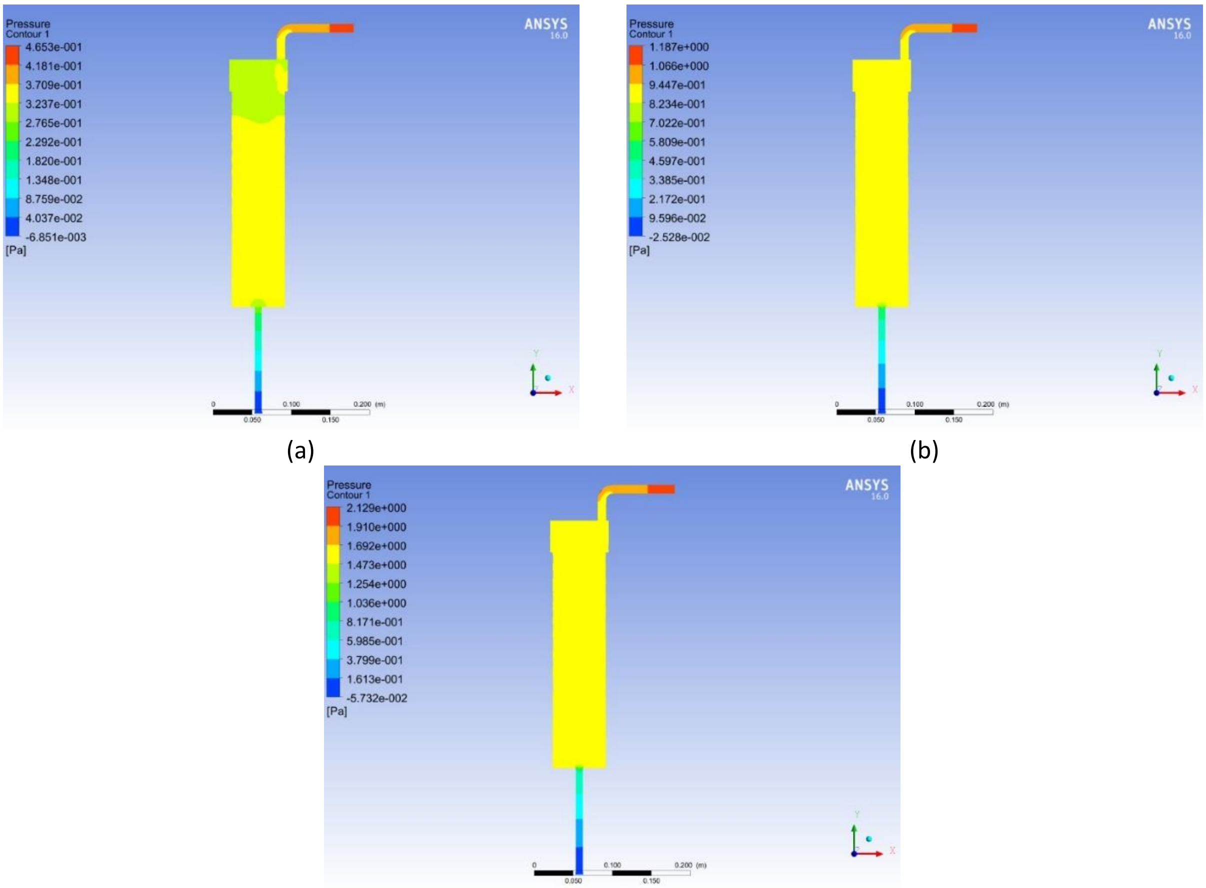


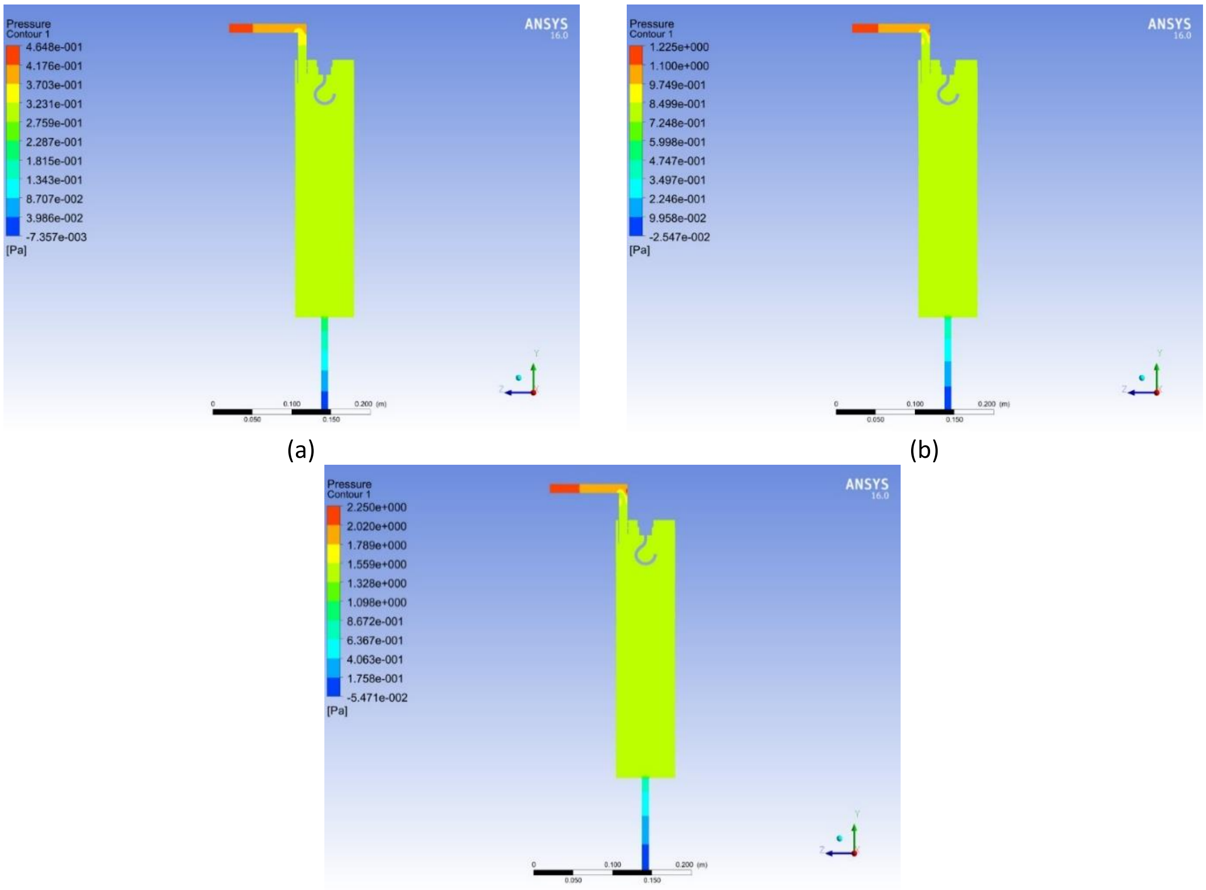
Fig. 7. Effect of Velocity inlet to the pressure outlet

Figure 8 and Figure 9 shows the pressure contour of the pyrolysis reactor with variations 1 and 2 at different inlet velocities. Based on the simulation results, at the inlet velocity of 1 l/min the pressure outlet in variations 1 and 2 is the same, there is no significant difference. While at the inlet velocity of 2 l/min the pressure drops in variation 2 is greater than variation 1 and it goes the same with the inlet velocity of 3 l/min. It indicates that the inlet velocity affects the pressure outlet. For discharge 1 to 3 l/min, the largest pressure outlet occurs at discharge 3 l/min, it shows that the outlet pressure is directly proportional to the inlet flow rate [20].



(a) (b) (c)

Fig. 8. Pressure contour of the pyrolysis reactor with variation 1 at the inlet velocity of (a) 1 l/min (b) 2 l/min (c) 3 l/min



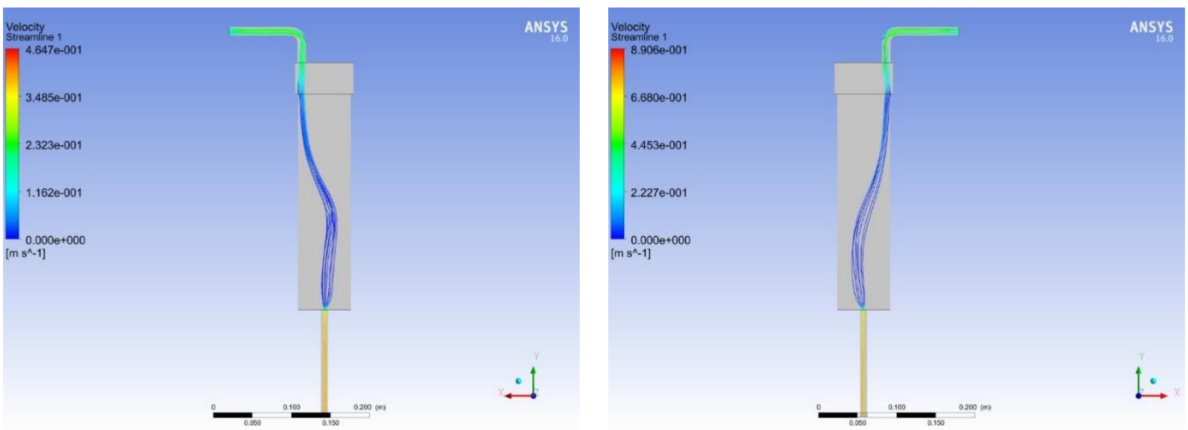
(a) (b)

(c)

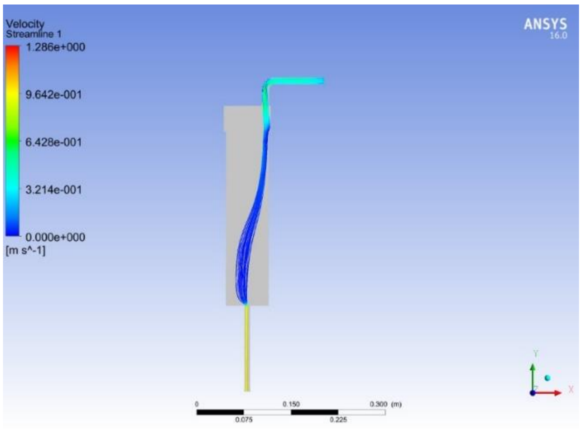
Fig. 9. Pressure contour of the pyrolysis reactor with variation 2 at the inlet velocity of (a) 1 l/min (b) 2 l/min (c) 3 l/min

3.3 Effect of Nitrogen Inlet Geometry at the Velocity Streamline

Figure 10 and Figure 11 shows the nitrogen velocity streamline inside the pyrolysis reactor at different inlet velocities. Based on the Figures, pyrolysis reactor with variation 2 distributes the nitrogen in the pyrolysis device more evenly compared to variation 1. It shows that the perforated design can remove the oxygen inside the reactor better than the unmodified inlet gas design.

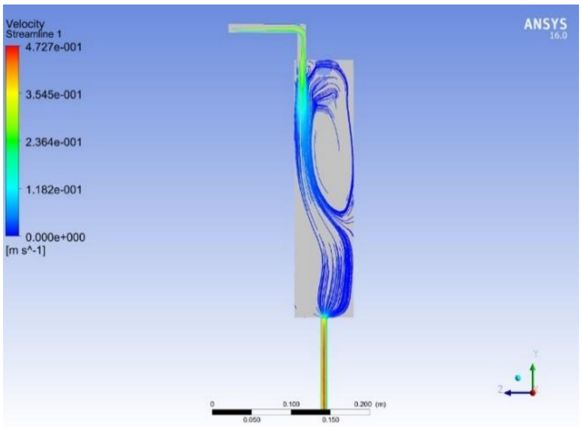


(a) (b)

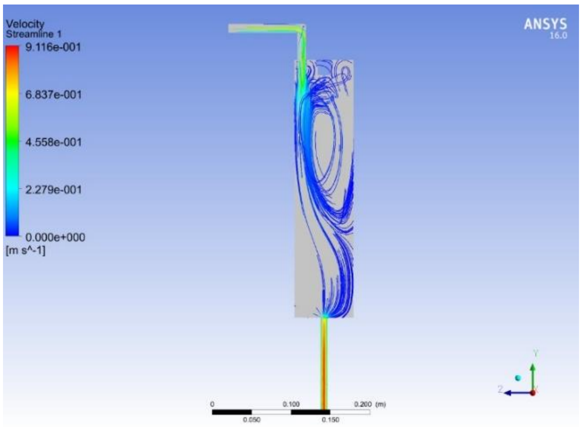


(c)

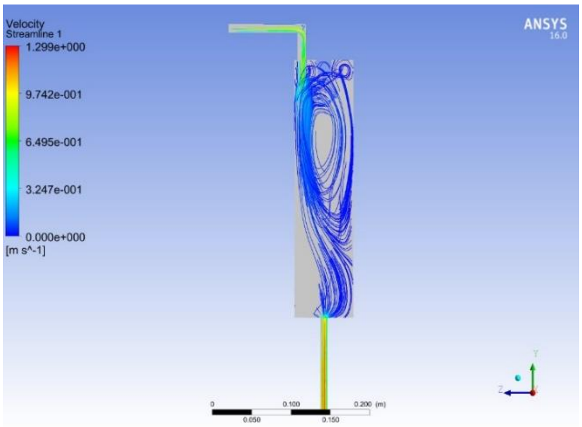
Fig. 10. Streamline velocity inside the pyrolysis reactor with variation 1 at the inlet velocity of (a) 1 l/min (b) 2 l/min (c) 3 l/min



(a)



(b)



(c)

Fig. 11. Streamline velocity inside the pyrolysis reactor with variation 2 at the inlet velocity of (a) 1 l/min (b) 2 l/min (c) 3 l/min

4. Conclusions

The simulation that has been carried out shows that the variations in inlet geometry that have been simulated both produce almost the same outlet velocity. The outlet pressure results in variation 1 are greater than variation 2. The CFD simulation results of outlet velocity was obtained in the best variation, namely variation 2 according to the discharge sequence, namely 0.4349 m/s, 0.8644 m/s and 1.2269 m/s. The pressure drops results in variation 2 are 0.4347 Pa, 1.1737 Pa and 2.1795 Pa. According to the simulation results, variation 2 with a perforated entrance is the optimum option for distributing nitrogen throughout the pyrolysis reactor more uniformly and more widely distributed throughout the tube than variation 1's, according to the velocity streamline.

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