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Simulation of Placement for Foam Inlet Injector Position on Firefighter Jet Nozzle

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Abstract
Water is a widely used and effective fire-extinguishing medium, but its effectiveness diminishes at high temperatures. By disrupting the oxygen chain in the fire triangle, Foam media can enhance suppression performance. This study simulates the impact of foam injector placement on the effectiveness of jet nozzles in fire extinguishers. Simulations were conducted with foam injectors positioned at the nozzle's inlet, middle, and outlet. Results indicate that placing the foam injector at the outlet provides optimal spray velocity, pressure, and extinguishing performance. These findings highlight the importance of injector placement in improving fire suppression efficiency for liquid-based extinguishing systems.

Introduction

Fires in residential homes are often caused by cooking activities and flammable materials placed near heat sources, which can lead to spreading to nearby structures [1]. Typically, water-based extinguishing agents are used as the initial response to fires [2], [3], [4]. However, water may sometimes be ineffective due to limitations in extinguishing fuel at high temperatures [5]. Meanwhile, in the realm of passive fire prevention, research trends over the past decade have focused on the development of fire-resistant materials [7], [8]. Additionally, the use of environmentally friendly extinguishing media has contributed significantly to technological advancements, particularly in efforts to mitigate fire hazards [9], [10]. Consequently, research on enhancing the effectiveness of fire extinguishers has been relatively rare. In this study, we proposed to enhance the effectiveness of fire extinguishing processes, the addition of foam to water-based agents aims to disrupt the fire chain

Theory and Calculation

Aqueous Film Forming Foam (AFFF) is a commonly used foam agent for extinguishing fires. The fluorocarbon surfactant, a core component of AFFF, has high surface activity, enabling it to spread rapidly and form a watery layer to prevent contact between fuel and oxygen on the fuel surface [5]. Through the combination of foam and water film layers, AFFF can assist in extinguishing fires more effectively than direct water application.

One application of AFFF is in the Compressed Air Foam System (CAFS) used in fire trucks, where the CAFS is considered capable of providing various volumes of consistent foam so that the foam can directly form a film layer on the heat source [11]. Despite of this, CAFS requires an additional pump to provide the necessary pumping power for the foam, which can also increase the nozzle pressure, resulting in a greater spraying distance [12]. In research conducted by Huai-bin Wang on CAFS fire trucks, CAFS was found to help reduce water usage during fire extinguishing processes in high-rise buildings with high pressure to reach fire points at elevated locations [13]. During that time, using foam media other than CAFS requires adding auxiliary equipment, such as foam inductors or foam injectors, to the nozzle.

The shape of the nozzle pipe generally affects the velocity and pressure rates and the spray pattern. The divergence speed of a nozzle is generally lower compared to a convergent nozzle even when both nozzles have identical fluid entry diameters [14], [15], [16]. Firefighter jet nozzles have a convergent shape aimed at releasing high-velocity stream flow to overcome air resistance. Therefore, this model of firefighter jet nozzle requires a significant water supply to fulfill the fire extinguishing process [17], [18]. By adding AFFF to firefighter jet nozzles, the water supply requirement for fire extinguishing can be reduced.

To assess the performance of nozzle designs, simulation and numerical methods such as Ansys Fluent can be utilized to study fluid dynamics [19]. The Large Eddy Simulation (LES) model in Ansys Fluent software can validate and investigate transient flow dynamics, particularly in nozzles, to determine their effectiveness [20], [21].

From the facts above, it is evident that research on firefighter jet nozzles with added foam injectors is an alternative to foam inductors and foam nozzles to mix water and foam media. Therefore, simulation is needed to achieve better results and enhance the effectiveness of fire extinguishing. This study employs simulation methodology using Ansys Fluent software with the LES model to determine the effectiveness of adding foam injector positions on firefighter jet nozzles with specifications like those of fire motorcycle extinguishers.

2.1 Literature Review

There has been considerable research on specialized firefighting nozzles in the past decade. In a study by Harshad Shrigondekar [21] on the performance of mist nozzles in fire extinguishing, the average spray velocity of mist nozzles increases with increasing Reynolds number. However, the spray velocity decreases as the aerodynamic drag force on the spray becomes more dominant than the inertia force of the spray with increasing spray distance from the nozzle for all Reynolds numbers. Additionally, Yue Jiang has researched droplet distribution characteristics of the circular and noncircular nozzles [22]. At low working pressures (100 kPa), the elliptic and rhombic nozzles showed better water distributions than the circular nozzle. There's research about the mechanism of internal flow of a cone-straight nozzle by Tian-Weng Jiang [23]; the study of flow dynamics in a nozzle reveals that maintaining laminar flow near the wall is feasible under low velocities, but transitions to turbulence occur at higher velocities, particularly in the throat section. Laminar flow, turbulent flow, and vortex formation influence skin friction and flow resistance. Optimization of the nozzle design, notably the transition from the converging to the throat section, is essential for improving efficiency and performance in applications like petroleum drilling. Future work should focus on determining the critical velocity for flow transitions and optimizing design parameters to enhance the nozzle's operational effectiveness. Additionally, there is research on the heat transfer rate of swirling jet issuing from the twisted tetra-lobed nozzle by Khwanchit Wonghcaree [24]; the study confirms that twisted tetra-lobed nozzles (T-LT) outperform traditional tetra-lobed (LT) and circular (CT) nozzles in terms of heat transfer efficiency. The swirling motion introduced by the T-LT nozzle enhances the mixing and turbulence of the jet, leading to better heat transfer. Optimal performance is achieved with a small jet-to-plate spacing (L/Dh), a high twist ratio (y/Dh), and a high Reynolds number (Re). These findings suggest that incorporating swirling jet technology can significantly improve heat transfer rates, making T-LT nozzles a superior choice for applications requiring enhanced thermal performance.

There has been considerable research on specialized nozzle foam. A study by Jinping Tu [25] on nozzles using foam media in extinguishing transformer oil pool fires concluded that fire extinguishing using foam media extinguishes more rapidly as the discharge rate of the nozzle increases. Furthermore, research on milk foam steam injection by Carlos Jimenez-Junca [26] demonstrates that increasing steam pressure improves foam production by reducing the injection time and enhancing foamability, stability, and texture. The nozzle type and the mechanism of air entry influence the effect of steam pressure on foam properties. Confined jet nozzles show more pronounced bubble size changes and foam texture than plunging-jet nozzles. Optimal foam characteristics, including low bubble size, high stability, and high stiffness, are achieved at steam pressures between 180 and 280 kPa with a plunging-jet nozzle. Additionally, foam properties such as liquid drainage and compression forces are related to gas volume fraction and bubble size, with higher gas volume fraction and smaller bubbles generally leading to lower drainage rates and compression force. Additionally, there is research on foam nozzles conducted by Qingguo Wang [27], [28], which explains that excessive injection pressure on the foam can cause the foam to bubble or break.

Experimental Method

The research methodology employed involved simulation using Ansys Fluent software. The Firefighter Jet Nozzle under investigation was modeled according to the dimensions of a commonly used 2-inch Firefighter Jet Nozzle, as illustrated in Figure 1.

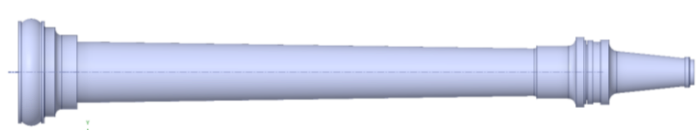


Figure 1. Jet Nozzle Firefighter

Table 1. Variant Jet Nozzle Injector Foam

Variant	Variant sketch	Variant distance (mm)
Variant 1		80
Variant 2		200
Variant 3		350

Foam injectors with an inner diameter of 9 mm and an outer diameter of 15 mm were added to the Firefighter Jet Nozzle model as indicated in Table 1. The injector distance was measured from the nozzle coupling position to the firehose.

To achieve optimal and accurately depict intricate surface with exceptional quality by skillfully adjusting the number and placement of vertices and edge for simulation results, the mesh type utilized in this simulation model is triangular [24], with element quality, orthogonal quality, and aspect ratio values as the mesh quality parameters, as shown in Table 2.

This study focuses on the mixing process of water and foam AF31, as well as the calculation of low-pressure zones resulting from foam injectors penetrating into the middle of the Firefighter Jet Nozzle. To obtain streamlines and fluid mixing contours, the model parameters in this study employ three main models, as depicted in Figure 2, Figure 3, and Figure 4.

Table 2. Quality MESH

Quality MESH	Element Quality	Aspect Ratio	Orthogonal Quality
Variant 1	0.837	1.9005	0.7713
Variant 2	0.83593	1.9008	0.76975
Variant 3	0.837	1.8956	0.7713

[a] Quality MESH uses average values

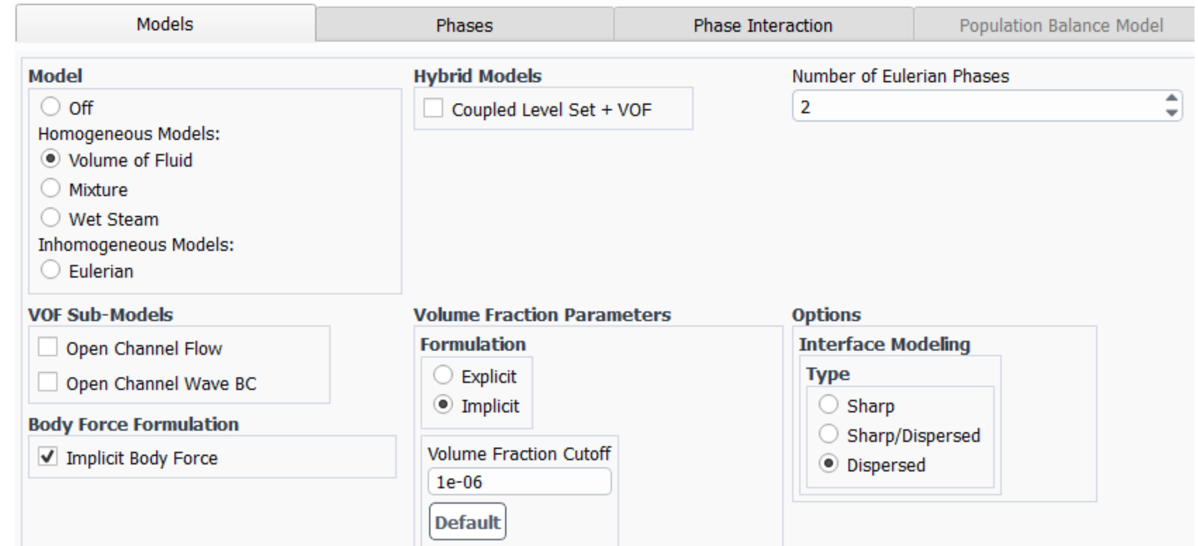


Figure 2. Multiphase Model

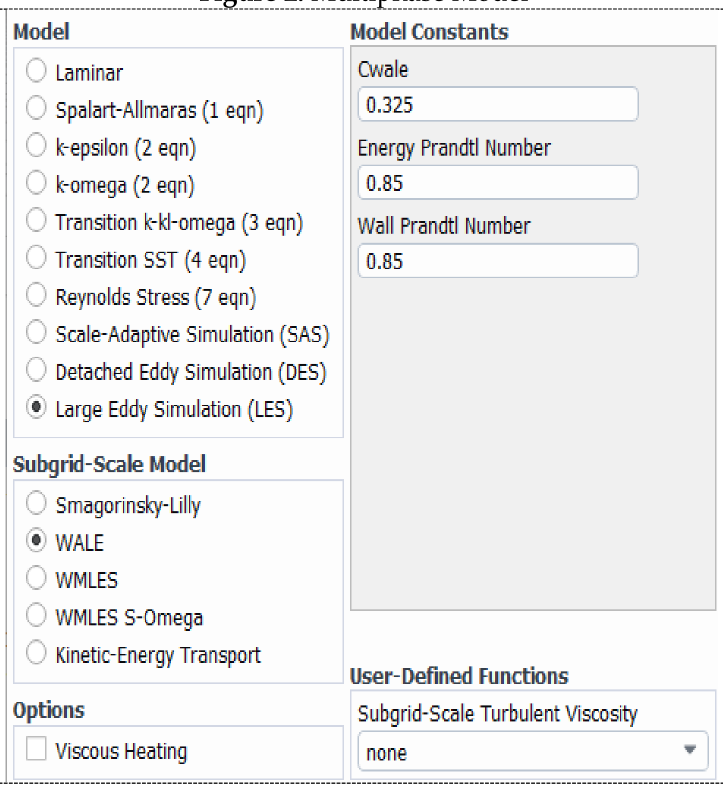


Figure 3. Viscous Model

Table 3. Parameter Materials & Boundary

Properties	Water	AF31
Density (Kg/m^3)	998.2	1015
Cp (Specific Heat) (J/(kg.K)	4182	1006.43
Thermal Conductivity (W/m.k)	0.6	0.0242
Viscosity (kg/m.s)	0.001003	0.015
Molecular Weight (kg/kmol)	18.0152	28.966
Temperature (^{0}C)	25	25
Debit (m^3/s)	0.00451	0.00004556

Figure 2 shows the multiphase model utilizes the Volume of Fluid (VOF) model to define phases and specify the interaction between water and foam. Subsequently, in Figure 3, the phase interaction between water and foam is depicted using a surface tension coefficient of 0.015 N/m as the force acting on the liquid surface. Then, for the figure 4 illustrates the Viscous model using LES simulation to obtain streamlines and contours of water and foam mixing in the model.

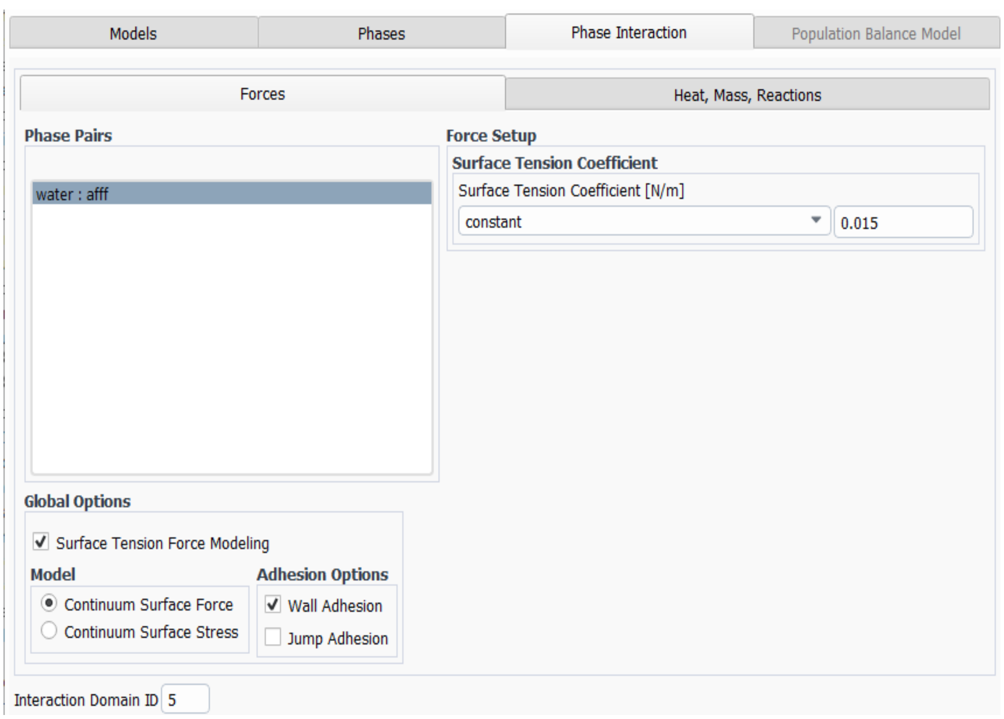


Figure 4. Phase Interaction VOF

Table 3 shows the material specifications for water and foam used in this study. The calculation of the low-pressure zone in the firefighter jet nozzle equipped with foam injectors will utilize basic calculation formulas as follows:

$$Q_1 = Q_2 \tag{1}$$

$$A_1 v_1 = A_2 v_2 \tag{2}$$

$$P_1 + \frac{1}{2}\rho {V_1}^2 + \rho g h = P_2 + \frac{1}{2}\rho {V_2}^2 + \rho g h \tag{3}$$

$$Q = \frac{1}{2}\rho v^2 \tag{4}$$

$$Low\ pressure\ zone = P_2 - Q \tag{5}$$

To ensure that the results from ANSYS Fluent follow the theory of the low-pressure zone, the pressure generated from the parameters in Table 2 is as follows:

$$v_1 = \frac{Q}{A} = \frac{0{,}00451}{3{,}14x0{,}021^2} = 3{,}25 m/s \tag{6}$$

$$3{,}14x0{,}021^2 x3{,}25 = 3{,}14x0{,}020^2 x v_2 \tag{7}$$

$$v_2 = 3{,}58 m/s \tag{8}$$

Q1 represents the water flow rate, and Q2 is the water flow rate that impacts the foam injector of the Firefighter Jet nozzle. For pressure in the Firefighter Jet Nozzle, typically shaped as a converging pipe, the formula used is :

$$P_1 + \frac{1}{2}\rho {V_1}^2 + \rho g h = P_2 + \frac{1}{2}\rho {V_2}^2 + \rho g h \tag{9}$$

$$365275{,}8 + \frac{1}{2}998{,}2x3{,}25^2 = P_2 + \frac{1}{2}998{,}2x3{,}58^2 \tag{10}$$

$$P_2 = 364150{,}87\ Pa \tag{11}$$

However, after adding foam injectors protruding into the shape of the Firefighter Jet Nozzle pipe, a low-pressure zone will be formed in the water flow striking the foam injector. The formula used to calculate the low-pressure zone in variant 1 employs Aerodynamics formulas:

$$Q = \frac{1}{2}\rho v^2 \tag{12}$$

$$Q = \frac{1}{2}998{,}2x3{,}58^2 = 6396{,}66\ Pa \tag{13}$$

After the water passes through the foam injector, the dynamic pressure reduces the initial water pressure.

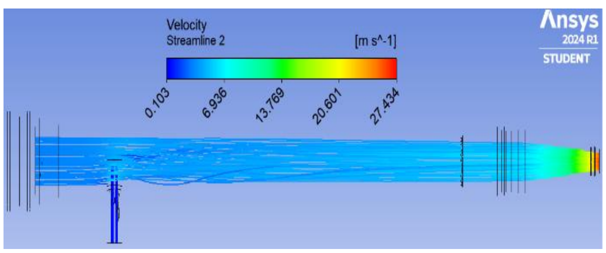
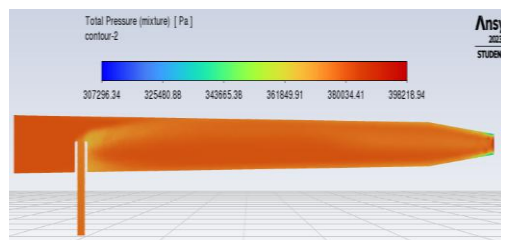
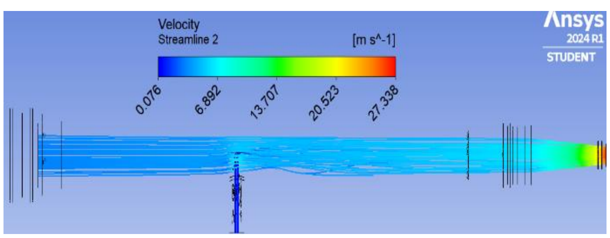
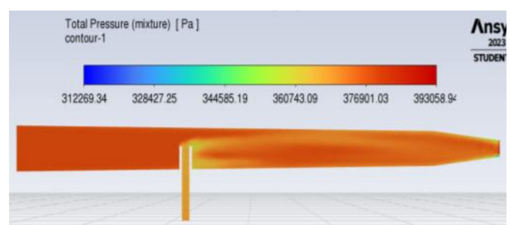
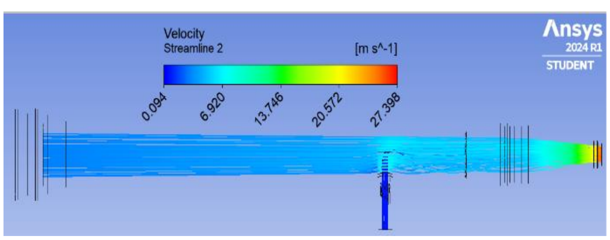
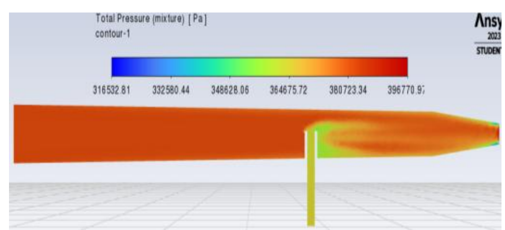
$$Low\ pressure\ zone = P_2 - Q = 364150{,}87 - 6396{,}66 = 357754{,}21\ Pa \tag{14}$$

Results and Discussion

From the simulation results, each variant of the firefighter jet nozzle obtains data as shown in Table 4. The streamlines are depicted as velocity streamlines colored along their trajectories, while the pressure contours are depicted as colored tracks at each part of the firefighter jet nozzle.

Streamlines in Variant 1 show a solid spiral rotation of the flow between water as the base medium and foam as an additional concentration, resulting in turbulent water flow. This turbulence aids in the mixing of foam and water and allows for the addition of air from the mixing process. This is because foam has only a slight pressure difference compared to water. In Variant 2, the water and foam flows form turbulent streams with slightly undulating movements, but there are few streamlines of foam flow experiencing vortex, making it difficult for foam to enter the water flow. In the water flow of Variant 2, at the top part where it impacts the foam injector, there is swirling around part of the nozzle surface, while the water flow impacting the foam injector at the bottom part experiences a vortex, resulting in a decrease in velocity and pressure as seen in pressure contour number 2.

Table 4. Pathlines Firefighter Jet Nozzle

Variant	Flow velocity pathlines	Pressure Contour
1		
2		
3		

Meanwhile, in Variant 3, the movement of foam flow directly descends towards the bottom surface of the nozzle due to lower foam pressure compared to water pressure. The water flow impacting the foam injector rotates around the nozzle surface, while some water flow on the bottom surface of the nozzle experiencing acceleration undergoes a vortex due to sudden impact, leading to a significant decrease in flow velocity and pressure as observed in pressure contour number 3.

The simulation results of the three variants yield varying total pressures, as indicated in Figure 5, Figure 6, and Figure 7

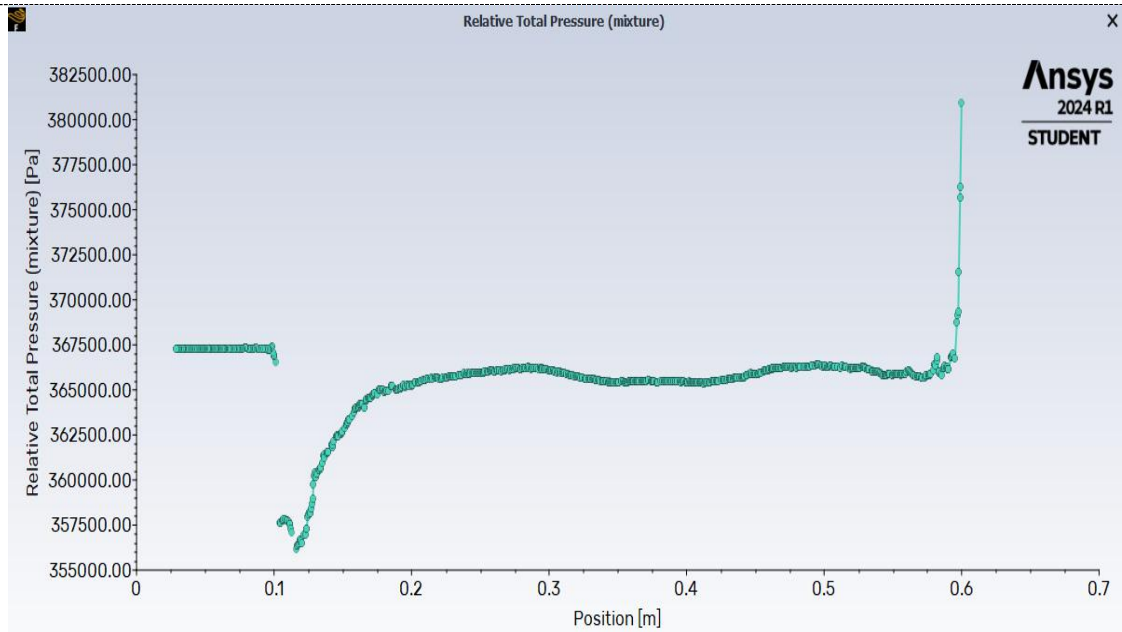


Figure 5. Average total pressure output variant 1

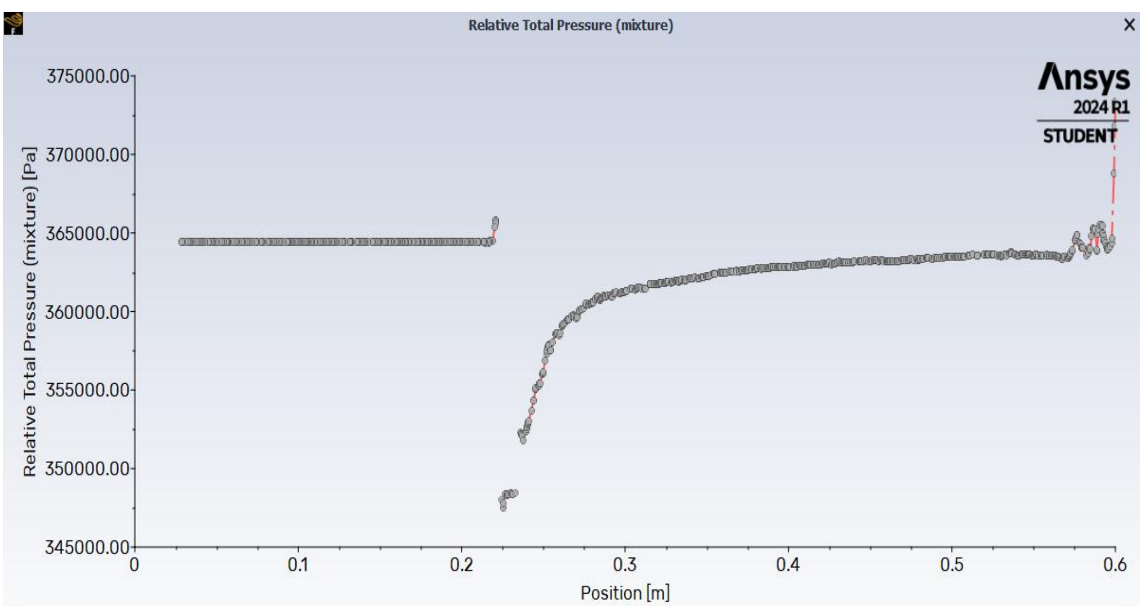


Figure 6. Average total pressure output variant 2

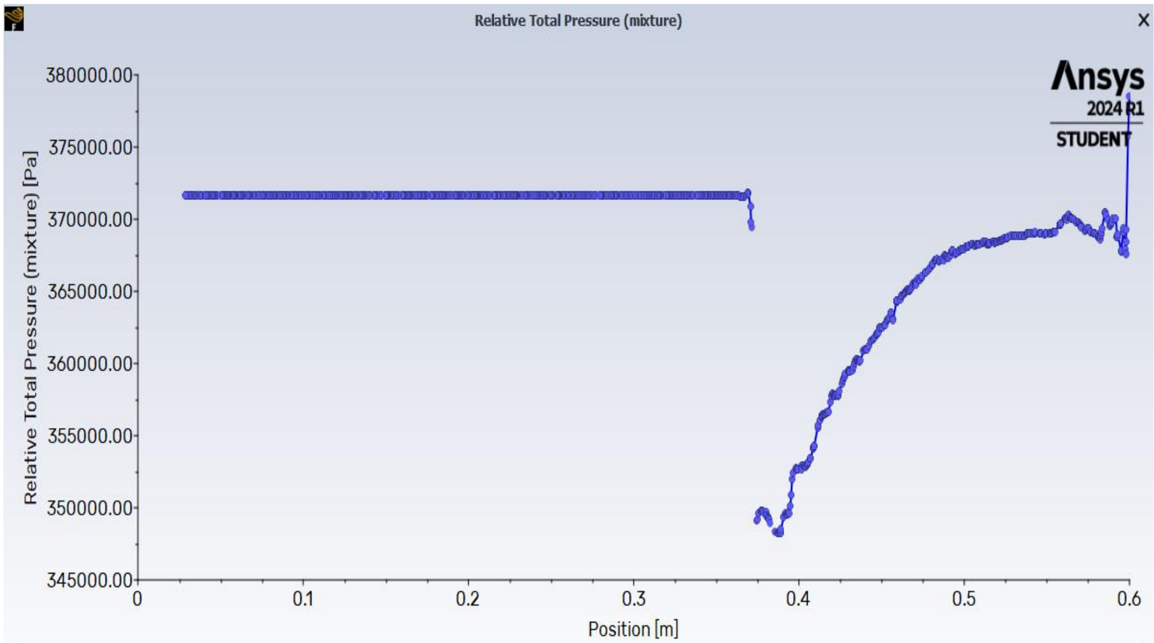


Figure 7. Average total pressure output variant 3

Figure 5 shows that the average exit pressure of Variant 1 is the highest at 371059 Pa, while Variant 2 is only 364305 Pa, and Variant 3 is 369405 Pa. In Figure 6, the water flow impacting the foam injector in Variant 1 experiences a relatively insignificant pressure drop compared to Variant 2 and Variant 3, reaching only 356131 Pa. However, in Figure 7, Variant 2 experiences a significant pressure drop due to the occurrence of vortexes in the unstable water flow, reaching 347397 Pa. Meanwhile, in Figure 8, the water flow in Variant 3, after experiencing significant acceleration upon impacting the foam injector, also experiences a pressure drop, reaching 348559 Pa.

The differences in pressure among the variants occur because the pressure of the water flow upon impacting the foam injector greatly influences the size of the low-pressure zone and the total pressure output.

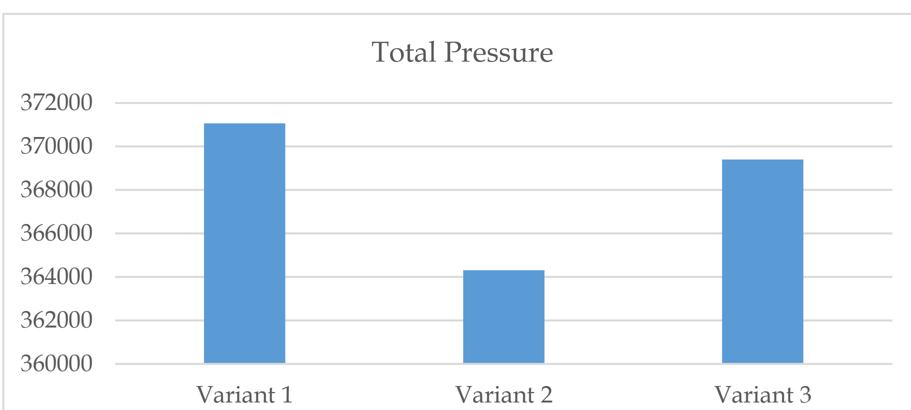


Figure 8. Total Pressure

The results of Figures 5, 6, 7, and 8 show that Variant 1 of the firefighter jet nozzle is the most effective, with a total exit pressure difference of 1.82%. Variant 1 does not undergo a significant pressure drop process like Variant 2 and 3.

Conclusion

To conclude, adding foam injectors to the firefighter jet nozzle can cause the water flow to experience a low-pressure zone. Simulation of jet nozzles with added foam injectors in Variant 1, Variant 2, and Variant 3 shows that Variant 1 yields the most effective results with a total exit pressure difference of 1.82%. This is because Variant 1 exhibits better vorticity, which aids in mixing water and foam compared to Variant 2 and Variant 3.

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