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Design Simulation and Development of Prototype Filling Nozzle in Food Industry

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ABSTRACT. This project necessitates the use of simulation to design the filling nozzles for the food industry. Filling nozzles are used for food packaging production and the speed and efficiency are dependent on the filling nozzle design. The current filling nozzle design is only capable of producing a low volume of production due to the design limitation. Therefore, the new design was proposed to solve this problem by improving several components that can be modified based on the density of the food and the volume of the liquid to be filled. Several designs were proposed and simulated using finite element analysis (FEA) to observe the efficiency of the fluid flow behaviour to imitate the filling process. The same properties of coconut milk utilized in the industry were used for the simulation with A DENSITY OF 1014 kg/m^3 and a viscosity of 0.00161Pa.s. All proposed designs were evaluated using the Pugh method and the best design with more outflow channels was proposed which appeared can provide higher flow velocity and a smoother flow at the outlet and eventually lead to higher production.
Keywords: *Design simulation; FEA Analysis; Filling Nozzle; Food Industry*

INTRODUCTION

Filling operations can be found in a wide range of industries related to food and beverages, home products including soaps, cleansers, chemicals, paints, and solvents, medications, and automotive products [1]. Small food processing companies usually develop production levels when a filling machine is considered. A filling machine is required at most when there are higher production volumes, compact containers, or a lack of available labour. Filling machines, also known as fillers, are used in the processing sector to quickly deposit products such as liquid, paste, or small pieces of solid food material into containers at the exact weight or set volume of the packaging containers [2, 3]. The filler used for setting weight and volume is two different equipment which are volumetric fillers and net-weight fillers. This operation is at the end of the food processing which is the packaging process. Food packaging is one of the important operations for several functions such as containment, protection and preservation, convenience, and communications purposes. The packaging can be in the form of boxes, jars, bottles, can, or retort pouch depending on the food material, packaging operation, and filling equipment used [3].

An auger filler is used to dispense powder materials. A liquid filler with a nozzle pumps product into the bag in the case of liquid pouch filling machines. The filling mechanism accurately measures and releases the precise amounts of product to be dropped into each manufactured pouch [4]. Nozzles are another item that is frequently custom-made for a specific project. The size of the nozzles may vary depending on the size of the containers or container opening.

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Depending on the filling principle, nozzle types may vary. The nozzle material, like the tubing, will be chosen to match the product while not causing unnecessary wear and strain [5].

The smoothness of the flow and the precision of the fluid distributed during each operation are both affected by the nozzle design. As the fluid flows through the nozzle, the edge angle and inner and outer diameters of the nozzle might influence bubble formation at the edge of the nozzle output, affecting measurement accuracy and product quality. The outflow diameter determines the size of the bubble that is formed. This is also true for the edge angle; as the angle decreases, the size of the generated bubble shrinks [6]. To lower outlet diameter and enable for high-precision dispensing, the original design used many slanted outlets.

The present study aims to analyse and improve the original nozzle design by considering several criteria such as the density of the food and the volume of the liquid to be filled. The purpose is to increase the production of food packaging by doing improvement nozzle design based on FEA analysis and Pugh method evaluation.

METHODOLOGY

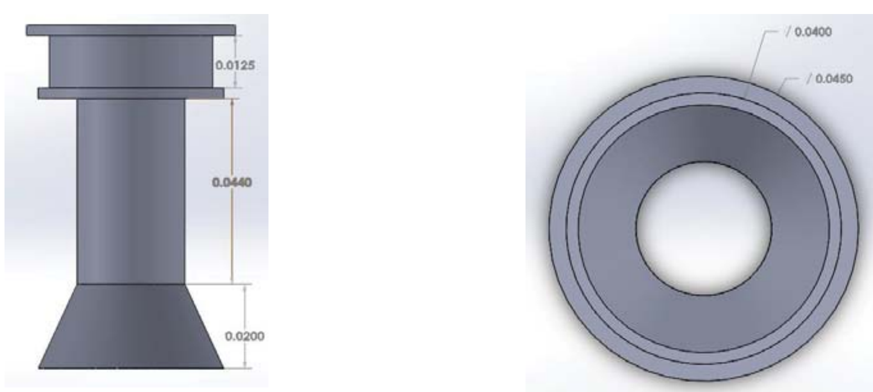
The methodology consisted of several sections which cover the fluid flow analysis, fluid flow calculation, proposed new design, and FEA analysis. Each stage discussed the factors and important elements in designing the filling nozzle in the food industry.

Fluid Flow Analysis of Nozzle Structures

Several nozzle structures were considered and compared to get the best design. Multiple outlet nozzles were used for fluid extrusion in smaller velocities and pressures following smaller fluid outflows. This reduced the formation of bubbles in the flowing fluids and avoids common problems in the packaging process.

In a study made using carbonated beverages that contain a lot of air bubbles, sealants of the packaging can absorb gas molecules in different ratios than under typical atmospheric conditions. Furthermore, certain conditions or processes, such as pasteurization, are expected to increase the moisture level in the headspace of packages. More moisture can be absorbed through the sealant due to temperature changes, and as a result, the seal quality may be damaged [7].

The only disadvantage of the use of multiple outlet nozzles is the slow flow velocity which can restrict the number of products. The urge to redesign the nozzle is to increase the velocity flow at the outlet at the same time reducing the bubble formation. This can boost packaging yields and guarantee more profits to the manufacturing company. The design of the nozzle also may vary to improve the filling process's efficiency and consistency according to the machine type and the product type. As illustrated in **FIGURE 1 (a)** and **FIGURE 1 (b)**, it shows the original design of the nozzle while **FIGURE 2** shows how the nozzle was attached to the filling machine in the production line.



(a) (b)

FIGURE 1. *(a) Nozzle design (front view), (b) Nozzle design (top view) unit in mm*

FIGURE 2. *Nozzle attached to the filling machine*

Fluid Flow Calculation

The flow analysis through the nozzle was mainly focused on the relationship between the velocity flow rate, pressure drop, and geometry. It was essential in this project because the velocity flow at the outlet was influenced by the geometry of the nozzle which also affected bubble formation. The mathematical calculation involves the Bernoulli equation where the velocity of the flow increases as the area of the outlet nozzle decreases at constant pressure. This also causes the bubble formation to decrease. The continuity equation for the fluid material in the nozzle is as follows:

$$\sum(AV)_{inlet} = \sum(AV)_{outlet} \quad (1)$$

- Inlet area: 7.068 x 10^{-3} m^2
- Inlet velocity: 1×10^{-3} m/s
- Outlet area: 2.827 x 10^{-5} m^2

Outlet velocity = $\frac{(AV)_{inlet}}{10A_{outlet}}$ (for 10 outlet nozzle design)

$$\dot{m} = \frac{dm}{dt} \quad (2)$$

- Change in mass: 30 pcs x 1 kg = 30kg
- Change in time: 60 s
- Change in mass: 50 pcs x 1 kg = 30kg
- Change in time: 60 s

Mass flow rate, **(for 30 pieces of production)** = 0.5 kg/s
Mass flow rate, **(for 50 pieces of production)** = 0.833 kg/s

$$\dot{m} = \rho VA \quad (3)$$

- Density of coconut milk = 1010 kg/m^3 **(constant)**

Based on the mass flow rate equation in Equation 3, it is clear that the mass flow rate can be increased by manipulating the velocity or the opening area at the outlet. Somehow, if the area of the outlet increases, the bubble formed throughout the flow also increases [8]. Meanwhile, the velocity at the outlet can be completely controlled through the inlet velocity as stated by the continuity equation above. The other best modification can be made to increase the outlet velocity without modifying the inlet velocity and not increasing the outlet area is to increase the number of outflow channel.

Proposed Improved Design of Filling Nozzle

TABLE 1 shows the existing or datum design as well as several improved conceptual designs of the nozzles. Pugh Chart in **TABLE 2** shows the comparison and evaluation between the designs that have been created from improvising the datum design. Several criteria are considered in the selection process, as well as meeting the demands of the customer. The selection criteria include an increase in outlet velocity, reduce bubble formation, and smoothness of the outflow.

Based on the evaluation made based on the Pugh chart, it is shown that design B is the best compared to other designs based on the selection criteria. There are several slanted outlets on this nozzle, as well as an additional outlet pipe in the centre. This nozzle increases the mass flow rate by allowing more outflow from the filling machine to the packaging pouch. In comparison to the original design, the proposed nozzle has less bubble formation in the outlet flow, which can lead to a better quality of the fluid product dispensed.

TABLE 1. *Proposed nozzle design*

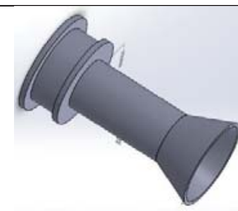
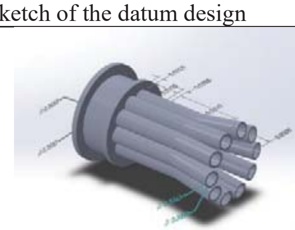
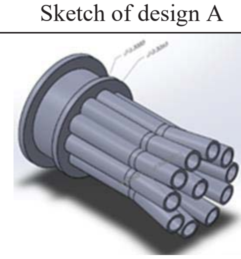
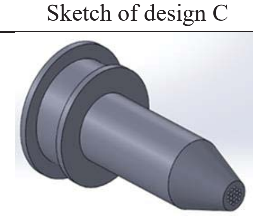
Design	Details Design	CAD Design
Design (datum)	The datum design is the original design as shown in the right column. This nozzle is used to dispense coconut milk to the packaging before it is being sealed. This nozzle allows high-velocity flow but somehow produces several bubbles that affected the packaging seal and further development on the design of a nozzle is needed to reduce the bubble formed in the production.	 Sketch of the datum design
Design A	The figure on the right is the first proposed design for the filling nozzle that has several smaller outlets. These small outlets slow down the food fluid flow but are capable to reduces the bubble formed. The purpose of making the outlet multiple is to maintain the outflow velocity despite having small outflows.	 Sketch of design A
Design B	Design B as shown in the right column is designed with an additional outlet pipe in the middle part of the nozzle. This nozzle allows more outflow from the machine to the packaging pouch, thus also increases the mass flow rate.	 Sketch of design B
Design C	Design C which is shown in the right figure is most likely the same as the datum except that the pipe hole is much smaller, and the wall of the holes is thicker. This design might decrease the outflow velocity because of the increase of wall friction, but this can reduce the bubble formation in the final products.	 Sketch of design C
Design D	The figure in the right column illustrates the nozzle of design D, which differs from the others in that it has one outlet with many small outlet holes rather than multiple outlet pipes. Because of the larger outflow pipe, the fluid flow will be at a high velocity, but it will be regulated by the numerous small holes at the ends, which can also control the bubble formation in the packaging pouch.	 Sketch of design D

TABLE 2. Pugh Chart

Selection Criteria	Concepts				
		A	B	C	D
Increase outlet velocity		S	+	-	S
Reduce bubble formation		+	+	+	+
Smoothness of the outflow		+	+	+	S
Total of +	DATUM	**2**	**3**	**2**	**1**
Total of S		**1**	**0**	**0**	**2**
Total of -		**0**	**0**	**1**	**0**
Overall total		**2**	**3**	**1**	**1**
Rank		**2**	**1**	**3**	**3**
Continue?		**No**	**Yes**	**No**	**No**

Simulation

To justify the improved design of the nozzle, a simulation is made using Ansys 2020 software. Ansys generates and provides CAD/CAM and Multiphysics engineering simulation software for industrial design, testing, and operation. **FIGURE 3** show the meshing resolution of the datum design. Both nozzle designs are simulated in Ansys with the newly defined material properties to match the coconut milk properties with the density of 1014 kg/m^3 and viscosity of 0.00161 Pa.s. The inlet velocity was set up low at 0.75 m/s to ensure the flow simulated in smoother and stable discharge. Finally, the simulation was run with the time step of 0.00125s with the size of time step 1500**.**

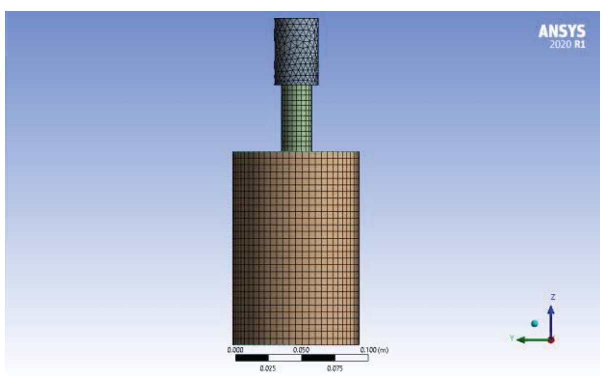
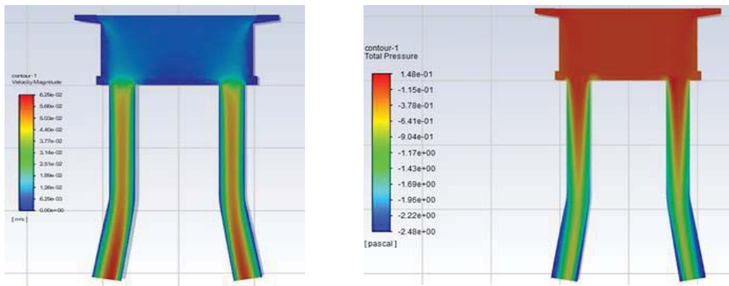


FIGURE 3. *Meshing of the datum design*

The material chosen is water fluid material. However, the densities of the water fluids differ depending on the formulation. As a result, the valuation approach is used, and the density is estimated to be around 998.2 kg/m^3 using the optimization model. The hydrodynamic viscosity of water is about 1.003×10^{-3}kg/m-s at the ambient temperature. The inflow velocity is 1×10^{-3} m/s. The outlet pressure is zero at standard atmospheric pressure, the reference pressure is one standard atmospheric pressure, the wall thermodynamic temperature is 0 K, the wall-free sliding boundary condition is used, and the flow field mode is laminar.

RESULTS AND DISCUSSION

The numerical simulation of the extrusion process is carried out using the finite element simulation ANSYS FLUENT software. **FIGURE 4(a)** shows the velocity analysis in the nozzle. The outlet velocity is faster at the middle part and near the outlet wall. part. The maximum velocity simulated at the outlet is 6.29 $\times 10^{-2}$ m/s. Meanwhile, **FIGURE 4(b)** shows the pressure analysis done on the nozzle design. The lowest pressure at the outlet of the nozzle is -2.48 Pa, which is much lower than the inlet pressure. The pressure reduction in the nozzle affects the material of the nozzle. The pressure has the greatest impact on the flow and viscosity of the food fluid.

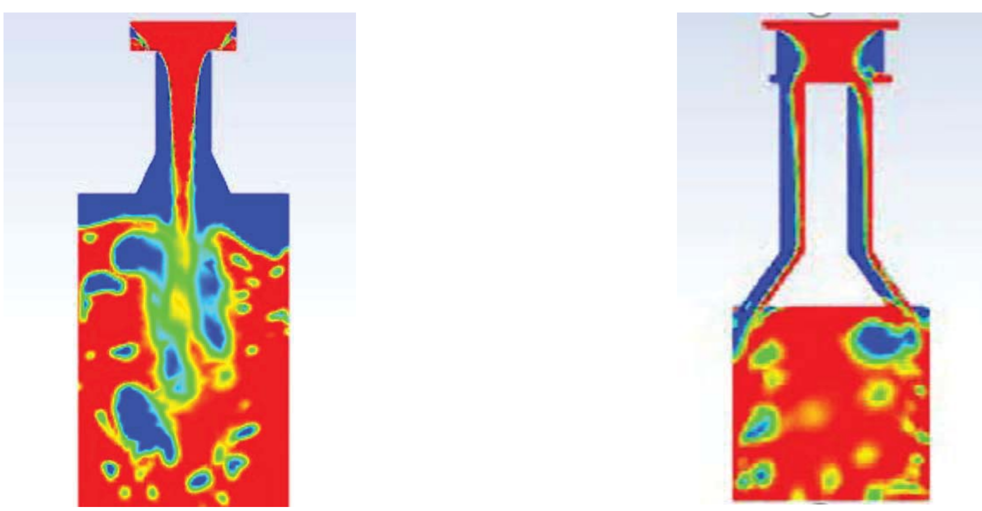


(a) (b)

FIGURE 4. *(a)Velocity analysis on nozzle design (b) Pressure analysis on nozzle design*

The next simulation that was performed was a 2D analysis of the nozzle design. The 2D analysis does not represent the exact geometry for both the nozzle and pouch designs, however, it provides an early indication of which design generates better fluid flow. In this simulation, the density and the viscosity of the fluid are following the right value for food fluid which are 1014 kg/m^3 and 0.00161 kg/m-s respectively

The simulation for the single outlet and multiple outlets shows the flow throughout the nozzle. Based on **FIGURE 5 (a)**, the simulation for the single outlet results in less smooth flow compared to the flow in the multi-outlet nozzle in **FIGURE 5 (b)**. This also resulted in the velocity flow in the single outlet is much higher compared to the multi-outlet nozzle. Besides, this simulation also indicates that the multiple outlet nozzle will produce fewer bubbles in the pouch packaging which is a good sign.



(a) (b)

FIGURE 5. *Fluid flow for (a) 2D single outlet simulation, (b) 2D multiple outlet simulation.*

In addition, a 3D simulation was also performed using a simplified geometry of the nozzle design that would take a shorter time to simulate. **FIGURE 6** shows the currently used single outlet nozzle design that had resulted in high-velocity flow and high torrents that lead to more bubble formation. While in **FIGURE 7**, the multi-outlet came out with a smoother flow which produces smaller and fewer bubbles in the packaging. In short, this simulation proves that the more outlet nozzle, the better the outflow in terms of the flow rate and the bubble formation.

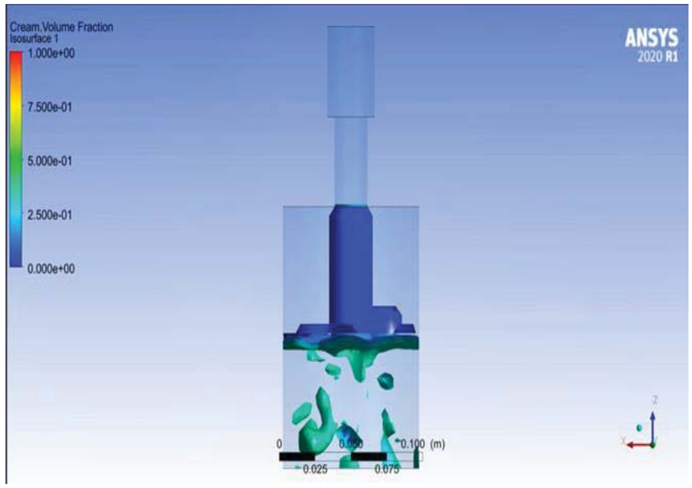


FIGURE 6. 3D single outlet simulation (datum) of original filling nozzle

FIGURE 7. 3D multiple outlet simulation of proposed filling nozzle

CONCLUSIONS

On the whole, this project was conducted to choose the best-improved design for the currently used filling nozzle design through the Pugh evaluation concept and 2D/3D ANSYS simulation. From the results, it is proven that the quality of the product using the nozzle can be enhanced using a multiple and smaller outflow design nozzle. The production rate can also be increased as the number of outflow channels increases the company's productivity. Through the evaluation concept, the design with more outflow channels was chosen as it increases the outflow velocity and also maintains the least bubble formation in the final product.

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