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QUALITY FUNCTION DEPLOYMENT (QFD) AND TRIZ IN BRIQUETTE COOKSTOVE DESIGN AND SIMULATION

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Poor cookstove design can harm the user's health and environment. This research aims to obtain an efficient cookstove design, environmentally friendly and operated easily. The cookstove design process using a combination of QFD and TRIZ. QFD able to capture customer needs through a questionnaire and interview. The data collected then processed to build a House of Quality (HoQ), one of the tools in QFD. QFD results in the design parameter of the briquette cookstove, which is incorporated in the concept design. The TRIZ method is utilized to understand the problem that might occur in the concept design and focus on solving the root causes. The next step is a detailed design where the dimensions, combustion chamber capacity, and supporting features are explained. The combination of QFD and TRIZ result in a briquette cookstove concept design which is easy to clean and operate. The combustion system is Top-lit Up-Draft (TLUD). The burning chamber has two air inlets, namely primary and secondary. The primary air inlet supplies the air from the bottom of the burning chamber, partially burns the briquette, and produces flue gas. The secondary air inlet is in the shape of an oval to supply air in the burning chamber's upper part to burn the flue gas completely. A complete combustion process will increase combustion efficiency and reduce emissions. A computational simulation shows the velocity distribution inside the burning chamber.

Keywords: *Briquette, Cookstove, Energy, QFD, TRIZ..*

1. INTRODUCTION

Liquefied Petroleum Gas (LPG) has become the primary energy source in every household in Indonesia since the government launched a conversion program (kerosene to LPG) in 2009. The government subsidizes the LPG price to make it affordable for middle-low-income households and replace low-cost energy kerosene. The non-subsidy LPG cost is relatively high, and it will disrupt if the subsidy is removed. There is a need for alternative energy that is affordable and sustainable to support the community. Biomass is a renewable energy that is abundant in Indonesia. According to the 2018 Indonesia Energy Outlook report by BPPT [2], biomass is the second-largest energy source, namely 24.82%. In a rural area, people burn raw biomass as an energy source for cooking, causing health problem and the environment. The most common health problem is respiratory tract disorders due to the deposit of particles resulting from burning biomass. Arora and Jains explains [1] the environment's impact occurs because the emissions contain harmful gases and lead to climate change. Appropriate process of biomass will reduce the toxic substances and increase their value. There are several products of biomass, such as briquettes, biogas, and pellets. Briquettes are the most uncomplicated processed biomass, and it is widely used as an energy source for households, SMEs, and power plants.

The briquette cookstove is a furnace designed explicitly for solid fuel such as briquette. According to SNI 7498-2008, "briquette cookstove is a cooking tool made of metal plate and/or ceramic (fireproof) as a heating medium using carbonized briquette and/or non-carbonized briquette". Customers find it difficult to operate and maintain the briquette cookstove because it takes too much time to turn it on and off. Moreover, the briquette cookstove works in a batch. Adding and reducing the briquette is prohibited because it will

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produce higher emission and decrease efficiency. A poor cookstove design causing incomplete combustion process, which results in increased carbon monoxide (CO) and harmful particles causing damage to the respiratory system. Current research of briquette cookstoves [9,14,16] focuses on improving its performance and reducing emissions and particulate matter. Briquette cookstove design could vary in every country because of customer's behavior. According to Obi, *et al.* [11] the briquette cookstove's design success is greatly influenced by the customer's behavior and energy sources' sustainability.

This present study aims to develop a briquette cookstove concept based on a literature review with high efficiency and low emission. Moreover, customer behavior and needs are considered to make it easier for customers to operate and maintain the product. A combination of Quality Function Deployment (QFD) and TRIZ is used to understand the customer need and solve the root cause of the problem. CFD (Computational Fluid Dynamic) will be used to simulate the airflow distribution inside the burning chamber.

1.1 Gasifier Cookstove

Biomass gasification gains considerable interest because it is cleaner and more efficient than biomass combustion. Jetter [13] explains that the gasifier cookstove's efficiency increases by around 35% and the emission is decreasing by 90% compared to a three-stone fire. Gasification takes place when the air is insufficient for complete combustion. The solid fuel or briquette is oxidized partially and convert into the gas phase and solid phase. Molino, et al. [10] shows the gas phase, later called "syngas" has a high heating value, and the solid phase or "char" contains an organic fraction. Top-Lit-Up-Draft (TLUD) gasifier is one of the most popular gasifiers. In the TLUD type design, solid fuel is put into the burning chamber in batches from the top and formed a charcoal bed, then it is burned, and pyrolysis occurs below it. Air enters through the bottom (primary air) [8,9] and partially oxidizes the solid fuel results in syngas and a secondary air from the top to complete syngas' combustion process. Roth [12] explains that the combustible gas produce moves upward because of the pressure difference between the gasification zone and the combustion zone. The hot flame moves downward convert the briquette into char.

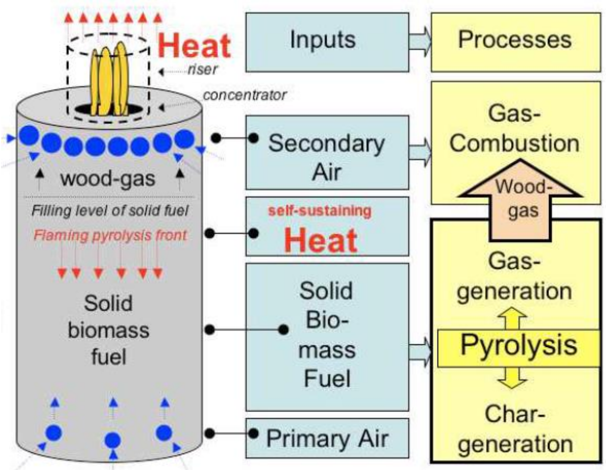


Figure 1 Basic design of TLUD gasifier, Design: Roth [10]

Initially, the briquette stove used the free convection principle to draw air into the burning chamber. This principle widely recognizes because of its simplicity and low-cost development. However, in its development, briquette stoves equipped with fans are more desirable because they can reduce gas emissions and increase heat transfer in cooking equipment. According to Still in Sedighi and Salarian [13], a briquette cookstove equipped with a fan at the very bottom of the briquette cookstove reduces fuel consumption up to 37%, and CO emission drops by 80% compared to natural draft cookstoves. Several studies show that a forced draft TLUD can improve briquette cookstoves' performance, especially in efficiency and emission. However, another energy source is needed to activate the equipment to move the air, mostly using an electrical energy source such as a battery.

Mimi Moto, a briquette cookstove from The Netherlands, is equipped with a 5000 Ah rechargeable battery and solar panel to recharge the battery. In comparison, Philips launches a briquette cookstove with TEG (Thermoelectric Generator) to power up the electric fan and the other type equipped with a solar panel. Unfortunately, the Philips fan stove (Type HD4012) production has been discontinued since 2018. Both products employ high technology, which is also a high price. A single unit is of Mimi Moto up to six times higher than an LPG cookstove.

Figure 2. Commercial gasifier improved cookstove by Philips (left) and Mimimoto (right)

SNI 7498: 2008 is a standard issued by the Indonesian government to protect customers of briquette cookstoves. It explains the design requirement for a briquette cookstove, but not specifically about a clean cookstove. The ISO (International Standardization Organisation) recently released a standard to guide the standard test for emission and performance, safety, and durability. Jetter [5] discloses the overview of ISO 19867-1:2018 in Kathmandu and describes the procedure of emission and efficiency clean cookstove testing. The test procedure should explain the cookstove system, test condition, and cookstove performance at high, medium, and low power. Different cookstove designs such as fuel, cookware, and operating procedures affect cookstoves' performance and should be considered during testing. There are ten-safety test procedures in the standard to protect users, including sharp edges and point, cookstove tipping, containment of fuel, obstructions near a cooking surface, surface temperature, heat transfer to the environment, handle temperature, chimney shielding, flames surrounding the cooking vessel, and flames exiting fuel chamber.

SNI classifies briquette cookstove into two categories based on the chamber capacity. Small cookstove has a maximum capacity of less than 2 kg, and medium size has a capacity range between 2 to 5 kg. The complete requirement of the briquette cookstove shows in Table 2. D is the inner diameter of the cylindrical burning chamber, L is the length of the burning chamber, H is the burning chamber's height, and t is the burning chamber's thickness.

Table 1 Dimension of briquette cookstove (Source: BSN)

No	Description	Capacity < 2 kg	Capacity 2-5 kg
1	Inner burning chamber diameter (mm)	125-150	160-300
2	Burning chamber dimension		
	a. D or L		
	i. Briquette egg type (D or H)	≥ 5 thickness of briquette	
	ii. Briquette honeycomb type (D or H)	≥ 1 cm of diameter of briquette	
	b. H/D or H/L	≥ 1.5	≥ 1.0

1.2 Quality Function Deployment (QFD) and TRIZ

According to Akao, Quality Function Deployment (QFD) is a method to transform a demand from a customer into a design quality. QFD works on every phase of product development. There are four phases of QFD: product planning led by the marketing department, product design to innovate by the engineering department, process planning by the manufacturing department, and process control by the maintenance and quality assurance department. One of the most widely used stages in QFD is HoQ (House of Quality). HoQ is a conceptual map that provides the means for planning and communicating, and to discuss design priorities. The first phase of QFD is the most popular application of QFD, which transforms the customer requirement into engineering characteristics. The marketing department leads the market analysis and surveys to capture the spoken and unspoken customer requirements, and then design engineers formulate it into engineering characteristics. The next step is determining the degree of importance (Importance Rating) to understand which customer needs are essential than others. Consumer needs and technical characteristics are analyzed to determine the relationship between them. There are three types of relationships: strong relationship (9 points), moderate relationship (3 points), and weak relationship (1 point). In order to complete the HoQ, each engineering characteristics is compared to each other, double plus (++) means there is a strong positive correlation, plus (+) means positive correlation, minus (-) means negative correlation, and upside-down triangle (▼) means strong negative correlation. The complete process of HoQ is shown in Figure 3.

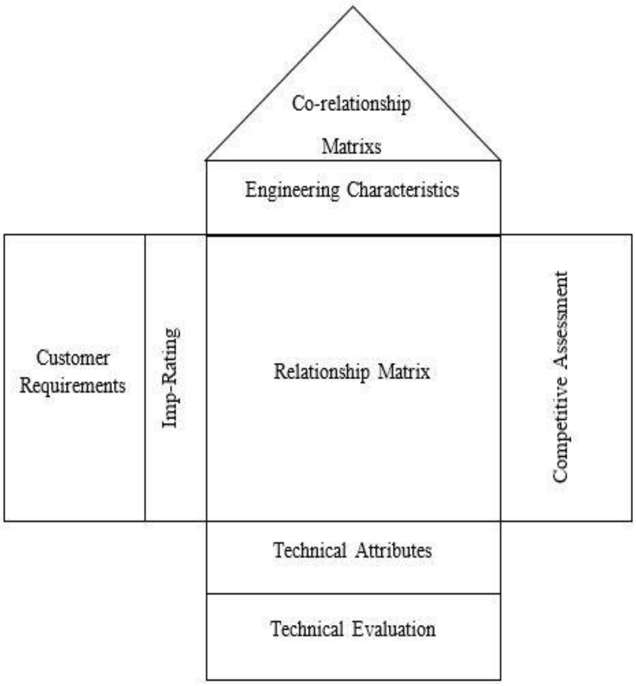


Figure 3. Design of House of Quality

TRIZ is short for "Teoria Reshenia Izobretatelskih Zadatch," which in English means "Theory of Solving Inventive Problems." Genrich Altshuller (1926-1998) discovers this method while works at the Russian Navy's patent office. There are two million patents that have been selected and researched to formulate the 40 principles of the invention. One of the most popular and oldest TRIZ methods is a contradiction. The contradiction occurs when the positive and the negative effect of a system happen at the same time. Since there is no compromise in TRIZ, the negative effect should be deleted; then the positive effect remains intact. TRIZ avoids trial and error to solve the problem. There are four problem-solving steps: problem analysis, problem abstraction, solution abstraction, and real/practical solutions.

Combination of QFD and TRIZ gain interest for the past decade. Both of those methods have shown as a powerful tool in product and process development. QFD and TRIZ have their unique role in each phase. QFD focuses on improving the quality of product subjectively, while TRIZ improves the quality of product objectively. Frizziero, et al. [4] shows the combination of QFD and TRIZ able to optimize the design solution through four steps: (1) QFD analysis based on six-question analysis, evaluation matrix and morphological analysis; (2) QFD result in design requirement and product architecture; (3) TRIZ analysis to optimize the design using the QFD result, and finally (4) the best solution based on QFD and TRIZ achieved. In their research, they choose one of the modern TRIZ tools, Trimming. The function analysis carried out using TechOptimizer® software. Li, et al. [6] shows a different approach in combining QFD and TRIZ. Eliminating the contradiction of the design requirement from QFD analysis is the primary purpose of applying TRIZ. The software quality characteristic generates solution by applying TRIZ principle.

1.3 Computational Fluid Dynamic (CFD)

A Computational Fluid Dynamic (CFD) is a numerical method to analyze the fluid flow, mass and heat transfer, and other simulations based on mathematical modeling. CFD is a part of Finite Element Analysis (FEA). In the FEA, the object is divided into elements and solved by applying weighted methods. According to Madenci and Guven [7], there are several steps in the FEA process: dividing the objects into elements, selection of interpolation functions, element matrix development, assembly of element matrix, applying boundary condition, solution generation, and additional computation if needed. ANSYS® has been widely used as a computational program to simulate engineering problems. There are three main processes in simulation: preprocessor, solver, and postprocessor. In the preprocessor, there are three steps: modeling the product, meshing, and setting the boundary condition. The solver process generates a solution based on the preprocessor parameters. Postprocessor results in visualization of the element behavior under boundary conditions.

2. METHODOLOGY

The design of the briquette cookstove generates with QFD and TRIZ combination. The first step in creating an HoQ is understanding customer needs and their perception of the current briquette cookstove design. Market analysis is one of the ways to find out customer needs. Voice of Customers (VOC) is acquired through an online survey. The target respondent is a briquette cookstove user because they have understood the principle and how to operate and maintain it. Then, the VOC is arranged into customer needs, then translated into engineering characteristics or technical specifications. To understand the product better, another analysis will be conducted using TRIZ. TRIZ is a powerful problem-solving method based on technology development mapping and history. The RCA + (Root Conflict Analysis) is one of the most popular tools in TRIZ to find the real problem and contradiction in a product. The contradiction is a condition that a product or process produces a positive effect and a negative effect simultaneously. The contradiction should be resolved fully and prevent the negative effect of recurring. The output of the TRIZ Analysis is an abstract solution regarding the problem analyzed. There is 40 abstract solution which is called the 40 inventive principles. The real solution for the problem is generated from the 40 inventive principles and depends on the designer or engineer's knowledge and experience. QFD and TRIZ analysis results in a detailed product design concept. It is needed to explain each product component in a detailed design using CAD drawings.

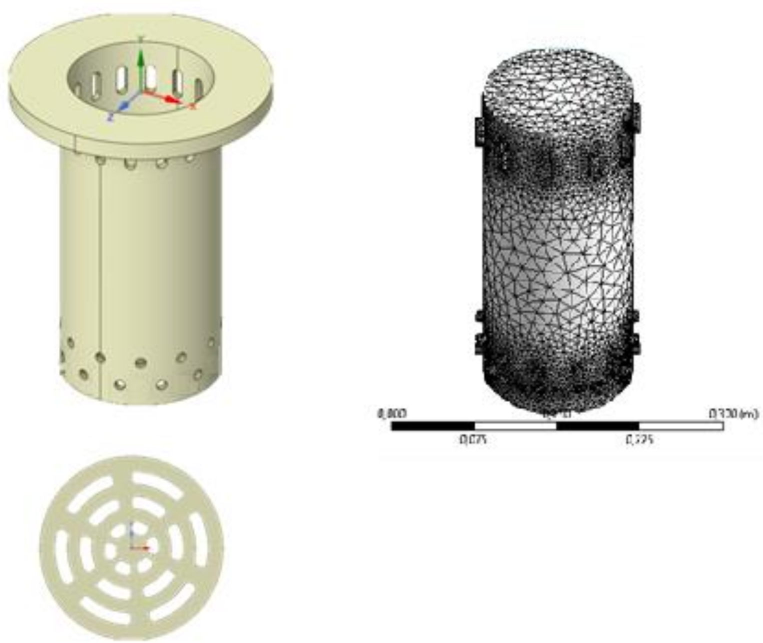


Figure 4. Geometry and the meshing of the burning chamber

Table 2. Boundary condition

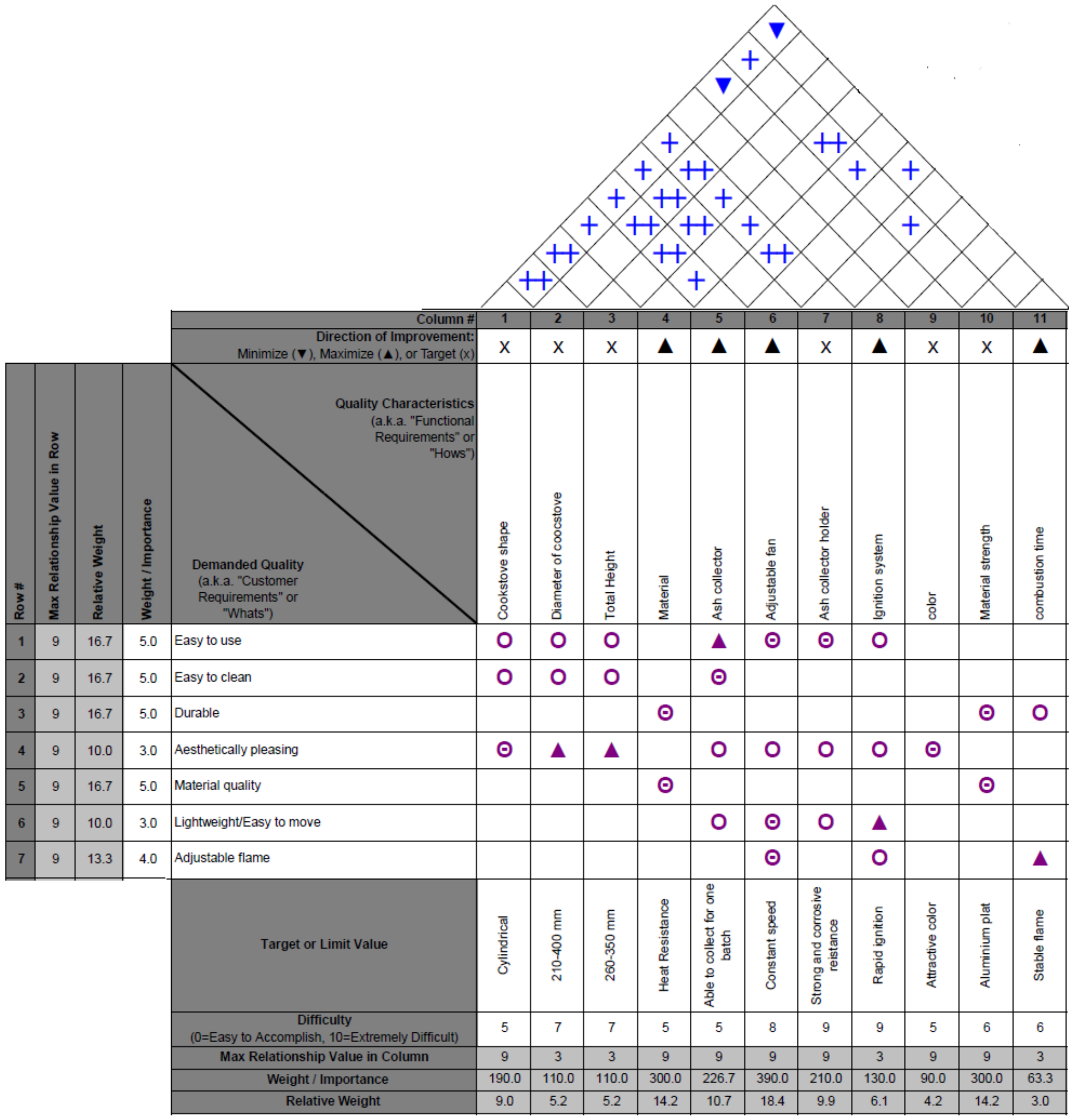
Parameter	Operational Condition
General Condition	• Solver type
Viscous Model	Standart k-ε, Standart wall fn
Spesies Model	Spesies transport, Reaction
Discrete Phase	On
Boundary Condition	Inlet • Velocity 1 m/s • Pressure 1 atm Outlet • Pressure 1 atm Wall • Stationary • No slip wall
Initialization	• Turb. Kinetic Energy 0.001 m^2/m^2 • Turb. Dissipation Rate 0.0001 m^2/m^3

The next step is a simulation of the burning chamber design using CFD (Computational Fluid Dynamics). The simulation aims to understand the air velocity and behavior inside the chamber, especially in the primary air and secondary air hole. The simulation will show how good the primary air and secondary air hole geometry in guiding the airflow. The geometry and meshing of the burning chamber are generated from the ANSYS®. It is necessary to simulate the volume of the burning chamber geometry to understand the fluid movement. Therefore, the meshing is generated on the burning chamber's volume portion, as shown in Figure 4. The meshing in this study shows 34220 nodes, 170467 elements, and 0.24 skewness. The skewness represents the quality of meshing. If the skewness value is less than 0.25, then the quality of the meshing is excellent. The number of nodes and elements shows the simulation accuracy. The higher the number of elements or nodes, the higher the simulation accuracy level. The CFD simulation process is carried out to determine the briquette pile's optimal airflow conditions in free convection conditions. The optimal air supply is required for the gasification and combustion in the burning chamber to produce optimum energy. Table 3 shows the boundary condition for the airflow simulation.

3. FINDING AND DISCUSSION

Customer needs identification was conducted by distributing an online questionnaire. Customers are asked to determine which factors are more important to them and should concern briquette cookstove manufacturers. The data acquired then grouped into several customer needs and sort it based on the importance for them. Customer needs are translated into technical requirements to determine product specifications and design. There are specific targets that will be set based on the analysis of the distributed questionnaire.

HoQ analysis shows the adjustable fan and the type of material have a strong appeal to consumers. Briquette cookstoves with airflow regulation are of interest to customers because each cooking process requires a different heat. Food processing such as boiling, frying, stir-frying, steaming, and simmering needs a specific temperature in the process. Some foods are not suitable for cooking at very high temperatures, as they will ruin the quality and taste, and vice versa. Adding a fan in the briquette cookstove will force the air into the chamber and decreases fuel consumption and PM emission compared to the three-stone fire. A fan's existence increases cookstoves' performance if it keeps in constant speed but regulating the airflow and speed results in incomplete combustion and increases emissions. The materials pose an important factor for customers when they decide to purchase a briquette cookstove. Mostly, the respondent has been using LPG as their energy source for household needs. A modern look of briquette cookstove made of metal is an alternative to replace the gas cookstove. The third highest functional requirement from the table is an ash collector. The ash collector should be removable and easy to clean. The complete design requirement is shown in Figure 5.



Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality
1	9	16.7	5.0	Easy to use
2	9	16.7	5.0	Easy to clean
3	9	16.7	5.0	Durable
4	9	10.0	3.0	Aesthetically pleasing
5	9	16.7	5.0	Material quality
6	9	10.0	3.0	Lightweight/Easy to move
7	9	13.3	4.0	Adjustable flame

Column #	1	2	3	4	5	6	7	8	9	10	11
Difficulty	5	7	7	5	5	8	9	9	5	6	6
Max Relationship Value in Column	9	3	3	9	9	9	9	3	9	9	3
Weight / Importance	190.0	110.0	110.0	300.0	226.7	390.0	210.0	130.0	90.0	300.0	63.3
Relative Weight	9.0	5.2	5.2	14.2	10.7	18.4	9.9	6.1	4.2	14.2	3.0

Figure 5. House of Quality of briquette cookstove

TRIZ is applied to determine the specific problems by finding out the contradiction in the concept design generates from HoQ. We would easily find a contradiction in the design with RCA+. Currently, the gasification process is working in batch by fueling the combustion chamber with full briquettes. The temperature resulting from the burning of the full briquette will be very high. It is undesirable for some cooking activities, while customers want an adjustable product from low to high temperature. Moreover, this type of design only suitable for a long duration of cooking. When users want to cook for a short period, many unburned briquettes are left in the chamber. It will be more convenient if the user can estimate the number of briquettes needed under the estimated cooking time. The briquette cookstove has a specific capacity, and users must follow the operational standard by filling the chamber fully to keep the performance high. Users cannot load the burning chamber partially and add a briquette later. Refueling the burning chamber is prohibited because it will increase the CO gas emission. Figure 6 shows the contradiction in the burning chamber design. “Refueling is prohibited” is the negative effect, and it is translated into the amount of substance. “Keeping the CO emission low” is the positive effect, and it is regarded as the harmful side effect from the 39 Parameters. The Altshuller matrix suggests the solution for this contradiction are local quality, intermediary, inert environment, and segmentation. Faria [3] explains Local quality as improving the quality

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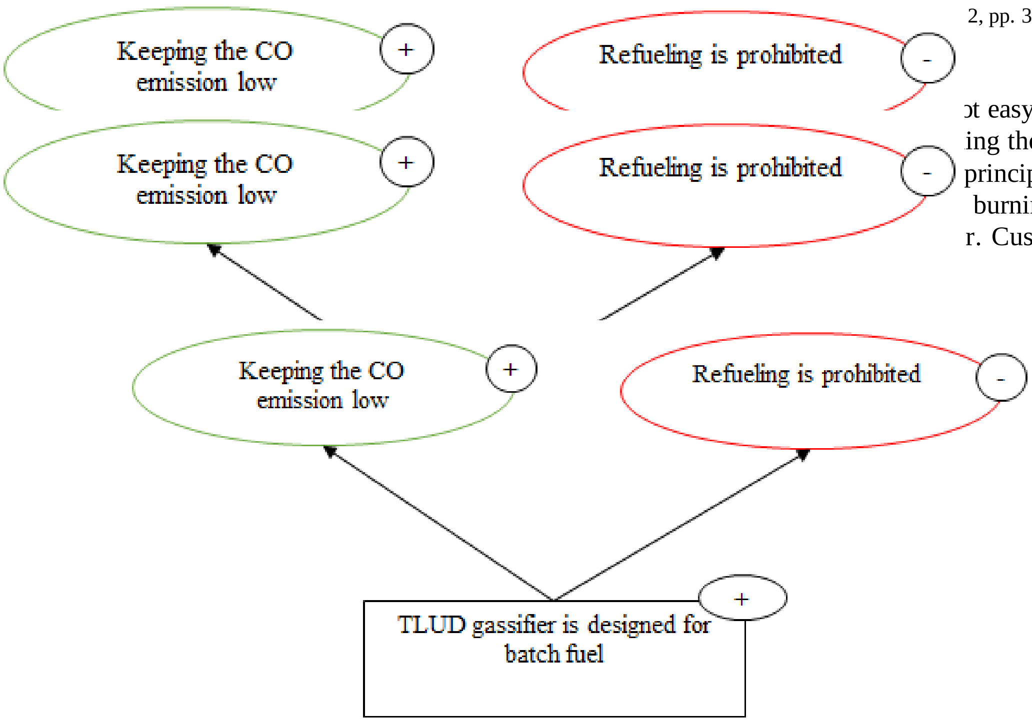
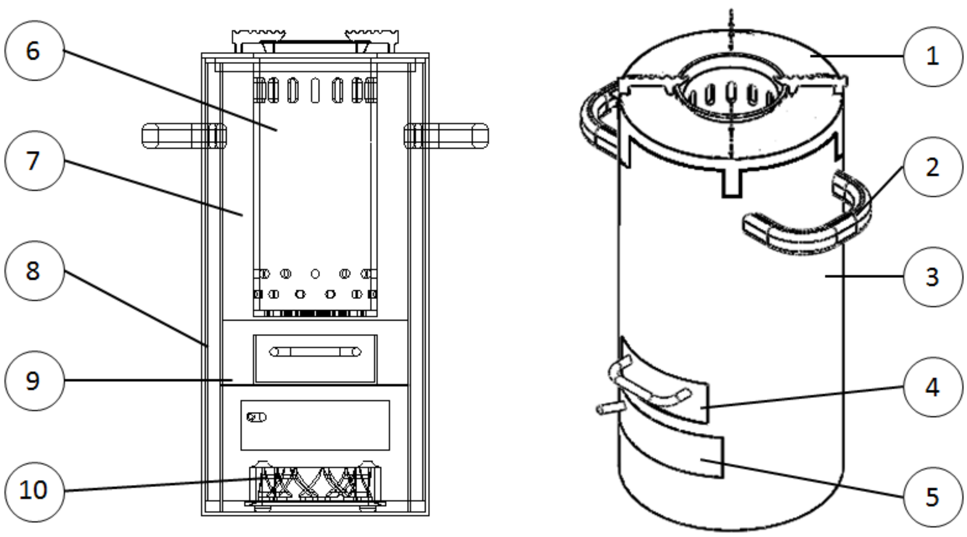


Figure 6. Root Cause Analysis (RCA+) of refueling the burning chamber

The result from HoQ and TRIZ analysis made into the detailed design of the briquette cookstove. The briquette cookstove consists of eleven components/systems, as shown in Figure 7. Pot support (1) is made of steel and has four legs to support the cookware and four latches to lock in the outer wall. Moreover, this part has a function as a top cover of the briquette cookstove. Opening this part gives access inside the briquette cookstove. The handle (2) function is to move the product easily and quickly. It is made of heat-resistant material to prevent heat transfer from the combustion chamber into the cookstove's outer part. The outer wall (3)



keeps all the components intact and gives an attractive appearance to attract customers.

Figure 7. Assembly of briquette cookstove

The ashes produce during the process is collected in the ashtray (4). The ashtray has the capacity of full briquette gasification. It is easy to clean by pulling out the handle, and the pile of ashes can be removed from it. A sliding door (5) is attached to regulate the airflow. Opening the sliding door will let the air flowing, then the gasification process takes place. Closing the sliding door prevents air from flowing into the burning chamber and stopping the gasification and combustion. This process leads to the cookstove to turn off. The burning chamber (6) is made of steel and has two air inlets. The primary air inlet at the bottom part of the burning chamber burns the briquette partially. It produces flue gas and a secondary air inlet at the upper part of the burning chamber to complete flue gas combustion. The heat from the burning chamber is transferred to the inner wall (7) by conduction. These two hot walls, heating the air flowing between them to the secondary air. An insulator (8) of a refractory material separates the inner wall and outer wall to prevent heat losses by conduction. A bracket (9) should be strong enough to support the ashtray in a full load. The fan system (10) consists of a fan, battery, and power button. The airflow is forced into the burning chamber through the primary air inlet and directs the air into the secondary air inlet.

The dimension of the briquette cookstove generates from the Indonesia National Standard (SNI). It classified a briquette cookstove design into two classes: small (< 2 kg) and medium (2 kg -5 kg). The small briquette stove is suitable for household customers. The diameter should be between 12.5 cm to 15 cm, assuming the density is 0.7 kg/L. The thickness of the burning chamber is more than 0.6 mm and can withstand high temperatures (500 ^{0}C- 700 ^{0}C). The burning chamber's design has a diameter of 150 mm, and the height is 207 mm. The secondary air inlet is in the shape of an oval (width of 10 mm) to supply air in the upper part of the burning chamber so that the gas is burned completely. A turbulent flow from the secondary air inlet is preferred to mix the flue gas and air. The primary air inlet is scattered around the burning chamber and the bottom part/base, and the diameter is 10 mm. The total number of primary and secondary air inlets are 12 and 10, respectively. The base not only acts as the primary air inlet but also as the ash's outlet. The burning chamber is equipped with an adjustable base plate that is removable (Figure 8). The adjustable base plate facilitates the customer to set their cookstove burning time.

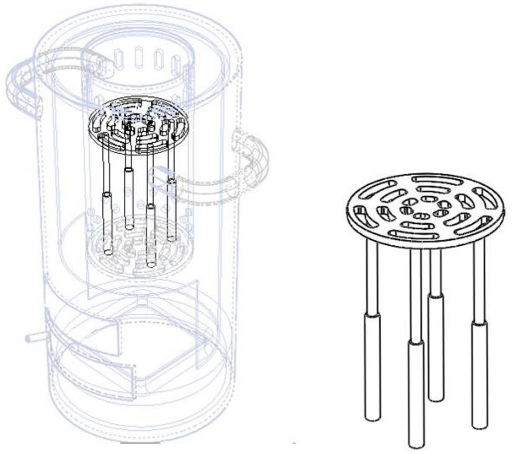


Figure 8. Burning chamber and adjustable base

Figure 9 shows the rate of incoming air with free convection is at optimal conditions. The air velocity is distributed uniformly on each side of the burning chamber, which indicates that the air distribution for the gasification process is running very optimally. The air velocity around the combustion zone is higher than the other area. It gives an advantage for the combustion process because the mixing process between air and flue gas would be faster, and both fluids will be mixed well.

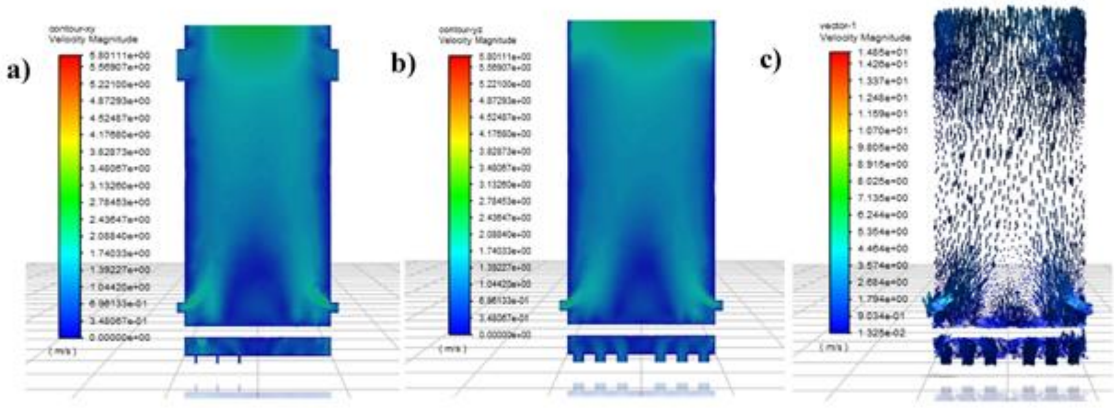


Figure 9. Airflow distrbution (a) XY-axis (b) YZ-axis (c) Vector analysis

4. CONCLUSION

The process design of briquette cookstoves using QFD and TRIZ result in a design, as shown in Figure 7 and Figure 8. The briquette cookstove is designed based on customers' needs. The customers want a product that is easy to use and has an aesthetic appearance. The briquette cookstove is equipped with a removable and adjustable base plate. It gives the customer an advantage because they can adjust their fuel need as the cooking time is needed. QFD and TRIZ complete each other, while QFD focusing on incorporating customer needs into product design, TRIZ focusing on polishing the design by removing unwanted or negative effects. The simulation shows that the inlet design (secondary air) has a higher air velocity to support air and flue gas mixing faster. Further analysis is needed to test their strength and the additional plate's effect on the burning process and performance (efficiency and emission).

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