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Effective height of chimney for biomass cook stove simulated by computational fluid dynamics

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Abstract. This paper presents the results of numerical modelling of temperature distribution and flow pattern in a biomass cooking stove using CFD simulation. The biomass stove has been designed to suite the household cooking process. The stove consists of two pots. The first is the main pot located on the top of the combustion chamber where the heat from the combustion process is directly received. The second pot absorbs the heat from the exhaust gas. A chimney installed at the end of the stove releases the exhaust gas to the ambient air. During the tests, the height of chimney was varied to find the highest temperatures at both pots. Results showed that the height of the chimney at the highest temperatures of the pots is 1.65 m. This chimney height was validated by developing a model for computational fluid dynamics. Both experimental and simulations results show a good agreement and help in tune-fining the design of biomass cooking stove.

1. Introduction

Energy plays a very important role in people's lives. Almost all sectors of life can not be separated from the needs of energy consumption [1]. One of the major is household energy consumption, which is used for cooking [2]. Energy savings in this sector will have a significant impact on the welfare of society as well as the environment.

Biomass is one of energy source that is still widely used for cooking in households, especially those in rural areas in many countries around the world [3]. Estimated biomass energy use by 2030 is about 2.6 billion people still dependent on this fuel. Almost half of domestic energy use in many countries and 95% in poor countries used biomass fuel. [4]. Although developed countries tend to exchange the biomass uses to cleaner fuel sources, the reality shows that the use of biomass fuels in developing countries is increased [5], [6].

Biomass stove is a tool used to convert the energy contained in the fuel into heat through the combustion process. Fire and heat which is generated from the combustion process of biomass in the stove are used for cooking [7]. Stove is a term that refers to the physical structure that serves to retain and then direct the heat generated from the fuel burning process to the cooking pot as the target [8].

There are many disadvantages of traditional stove designs that are widely used by the community. These weaknesses are a challenge for engineers to design a better biomass stove [9]. There are two main things that are important to consider in the design to get a better biomass stove, i.e. energy saving and indoor air pollution problem [10].

The energy savings in a stove can be measured based on the value of its thermal efficiency. The thermal efficiency is influenced by the fuel combustion process factor and also the heat transfer process resulting from the combustion process of the fuel [11]. The stove with an open combustion process into the environmental air has good combustion process efficiency, but the heat transfer process is less effective. In contrast, the process of heat transfer in biomass stove with wall structures is usually more effective but has a low burning efficiency. The consideration of these two factors becomes an interesting thing in designing a better stove [12].

A good combustion process is when all the carbon elements present in the fuel completely react with the oxygen element [13]. There are many factors that influence a good combustion process. Airflow, turbulence and temperature are some of the factors that greatly affect the combustion process [14]. Control of the amount and rate of air supply to the combustion chamber is one of the things that can be done to create a better combustion process.

Traditional biomass stoves are generally single-pot stoves, which is pot as container is placed on the fire. Heat from the exhaust gas directly discharged into the environmental air. If there are two or more dishes, there will be a parallel cooking process, which is one burning for one cooking process. Biomass stove with multi pottery system is one of the ways advised by experts to improve the efficiency of the biomass stove. The main pot is usually located in a position that can receive direct heat from the combustion process in the combustion chamber. The next pot is positioned after the main pot which can absorb heat potency from the flue gas stream of combustion [15].

Cooking with traditional biomass stoves usually produces an amount of smoke pollutants that fills the kitchen room. Smoke pollutants caused discomfort to the cooker when working and may affect the taste of the food [16]. The most important thing is that the smoke pollution is harmful to human health, even if the smoke was generated from the perfect combustion process [10].

2. Chimney Uses in Biomass Stove

Chimney uses in a biomass stove will generates a continuous flow of draught through a stove that will be able to supply air for combustion needs in the combustion chamber. Sufficient air supply will create a better combustion process. The real combustion requires excess air to obtain sufficient amount of oxygen for better combustion process [13]. However, air contains another element which is inert and absorbs heat such as nitrogen. Too much excess air will produce useless excess heat, which will be absorbed by the inert gases then flow and discharged through the chimney into the environment. The stove with multi pot system also requires a chimney [17]. The natural draught of the chimney serves to draw the flue gas and flow it through each pot. The potential heat contained in the flue gas will be transfered to the pots when it contacted the surface of the pot. The natural draught of the chimney must be adequate to overcome the flow of frictional obstacles as it flows in the stove channel. In addition, the chimney also serves to overcome the smoke pollution in the kitchen room where the stove is operated. The chimney will direct the flue gas out of the kitchen to the environmental air [15].

Winiarski has developed the concept of chimney uses in the early 1980s by creating a stove that create clean combustion and increase heat transfer efficiency. Placing a short chimney on the stove can increase the draught and reduce emissions. This concept has been used in many stove models such as, Stove Z, Vesto Stove, Wood Gas Camp Stove, Rocket stove, Tso-Tso stove, etc [18]. The Eindhoven Group has also used a chimney on a stove that produces a clearer combustion process [9].

Chimney is a channel with a certain height that serves to generate natural air draught. The height of the chimney is the vertical distance measured from the bottom of the combustion chamber to the end of the chimney. The tests conducted by Stone and Shelton had shown the characteristics of the exhaust gas temperature at each chimney height [19]. The results of this study showed a general formula for the relation of temperature profile to chimney height variation.

Height of the chimney ($hchim$) is one of the main geometric parameters of the stove which refers to the vertical distance from the source of hot flue gas to the ambient air.

$$\Delta P_{induced} = g h_{chim}(\rho_{ambient} - \rho_{hot}) = g h_{chim} \rho_{ambient} \left[1 - \left(\frac{T_{ambient}}{T_{hot}}\right)\right] \quad (2.1)$$

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The natural draught value of a chimney is determined by the height of the chimney and the temperature gradient of the flue gas in the chimney and ambient air. The pressure gradient described by equation (2.1) is translated into the mass flow rate ($\dot{m}$) flowing through the stove which depends on the height of the chimney, cross sectional area of the chimney (A), the loss coefficient (LC), the temperature of the combustion gas ($Thot$) and Ambient temperature ($Tambient$). The relationship is described as equation (2.2). The loss coefficient (LC) in this equation represents the losses associated with friction and viscosity of the flue gas due to stove geometry and the heat lost through the chimney wall. The results showed that $LC \approx 0.5$ without pots and $LC \approx 0.35$ with the pots on the stove [20].

$$\dot{m} = LC * A \left(\frac{\Delta P_{induced}}{R_s T_{hot}}\right) \sqrt{2gh_{chim}\left(\frac{T_{hot}-T_{ambient}}{T_{ambient}}\right)} \quad (2.2)$$

The consideration of the chimney uses in a biomass stove is a good thing. Chimney uses in biomass stoves function to create a better combustion and heat transfer process and also to overcome the pollution problems in the kitchen room. Based on these reasons, the determination of chimney height that affects the three aspects is very necessary to be done.

3. Biomass Stove Improvement Researches

Biomass stove improvement research was initially conducted in developing countries around 1970 by researchers incorporated in NGOs. Winarski is the one who had introduced the basic principles of biomass stove improvement [9]. The improvement of the stove at that time was intended for fuel savings due to concerns about deforestation for household energy demand [21], [22]. Biomass stove improvement efforts are then also intended to improve health by reducing the impact of air pollution and the safety of biomass fuel uses that are in line with climate change prevention programs [23], [24].

Early stove research was done experimentally in several stages. The research stage was carried out using several standard methods that have been developed, either for laboratoric test, such as Water Boilling Test (WBT), Combustion and Exhaust gas Test, or field test such as Control Cook Test (CCT), Kitchen Performance Test (KPT) and others [25], [26], [27]. Several field researches have also been conducted to understand how a stove can be received and used continuously over a long period of time [28], [29], [30]. Hundreds of stove implimentation programs had been done in many country of the world and showed different sizes, scope and type of the stoves, as well as its technological design improvement, distribution and financial benefits. So far the research has been aimed at developing a new stove design form with priority to improve the production process, marketing techniques and financial incentives of the stove applied [31].

Biomass stove research then also done in simulation along with the development of computer technology. Computational fluid dynamic (CFD) has been widely used to simulate fluid flow, heat transfer, pyrolisis and chemical reactions to the design process of several biomass stoves. CFDs have provided more information that helps designers to develop their design stoves. There are many academic papers containing general information relating to the simulation of CFDs in cooking stoves. However, only a few clearly explain the reasons for choosing a model specification and display the actual scanned documentation of the use of CFD apps.

There are specific examples of simulations of small-scale biomass burning equipment using CFDs that help to understanding the applied approaches. Menghini et al. [32], [33], describes the use of CFD applications to simulate the equipment used to burn wood. The purpose of the simulation is to optimize the heat transfer process in the heat exchanger in the equipment. No modeled combustion reactions and no discussion of exhaust emissions are produced. The simulation result is a heat of advection without reaction to estimate the heat from the combustion process.

Ravi et al. [34], [35] has developed a simulation method for a sawdust fuel stove. The process of simulating CFDs is done iteratively by assuming that there is a heat flux from the flame returning to the fuel. The fluid flow is modeled on steady state and uses the steady flow formula and assumes that there is no transient flow occurs. The completion of long time scale fuel consumption is preferred to be focused over shorter transient flow timing scales.

Bojko and Branc [36] describe the simulation process of CFDs in wood-fired stoves with detailed geometry models. The mass flow of pyrolysis gas occurring on the fuel surface is regarded as a constant fuel source. The heterogeneous combustion phase is ignored and is considered to be combustion occurring as a homogeneous phase. Burning diffusion flame is modeled by eddy-disipation method. Radiation transfer is modeled through the discrete ordinate method. The air entry boundary conditions are defined as mass flow that explicitly defined based on the naturally induced excess air ratio due to buoyant effects through inlet pressure conditions.

Bryden et al. [37], [38], and Urban et al. [39], have used a graphical evolution algorithm to optimize geometric parameters of heat transfer surfaces in a plancha biomass stove. The geometric boundary is applied to the channel boundary between the gas stream and the inside surface of the plancha stove. Burnham-Slipper [40], [41], has developed a process for using genetic algorithms, which automatically optimize the overall combustion chamber of the biomass stove.

Miller-Lionberg [8] has simulated a wood-fired biomass stove developed. The biomass stove is only a single pot and without a special chimney with a meaningful height. Provide results of flow conditions and temperature distribution. Testing was also conducted experimentally by installing a number of temperature measuring devices in the stove to validate the simulation results.

4. Reseach Method

The research is conducted on biomass stove that has been designed to fit the needs of cooking in the household. This biomass stove is a stove with multi pot system (double pot). The first pot is placed above the combustion chamber. It receives heat directly from the fire generated from the combustion process of the fuel. The second pot is expected to be able to receive heat from the flue gas before it is flowed through the chimney. A variable height chimney is placed at the end of the stove to produce the natural air draught that is required for stove operation. In addition to solve the smoke pollution problem, the function of the chimney primarily intended to improve the combustion process and heat transfer in the stove.

The test consists of two stages, e.i. the stage to determine the effect of chimney height on the biomass stove conducted by CFD simulation and experimental testing with the water boiling test method.

4.1 Simulation Method

The simulation process is initialized by drawing geometry and mesh of the biomass stove by using Gambit software as a preposessor. The geometry of the stove is drawn for a variety of chimney height i.e. 1.1 m, 1.45 m, 1.55 m, 1.65 m and 1.85 m. Furthermore, the meshing process is done using the automated method in Gambit.

The heat flow that occurs in the system is assumed only in the gas domain. Therefore the volume control only covers the gas domain volume whereas the solid area domain volume on the stove is ignored. The volume control domain is divided into a mesh or grid cell, which allows the represention by linear mathematical matrices where the fundamental equations constructed are solved by using boundary volume methods. Several different approaches have been applied to achieve the appropriate mesh. The mesh should be smooth enough to complete a small limit feature, such as biomass fuel mesh and the bottom of the pot mesh. The mesh of fluid domain must fit along a solid boundary to overcome the effects of the thermal boundary layer and momentum. The problem is very complicated actually because the boundary layer can be interconnected with one and another [42].

Mesh geometry significantly influences the simulation of unsteady flow and turbulences. Mesh evolves rapidly from the basic mesh size. The minimum scale of unsteady motion and turbulences completed in the simulation is a function of the local mesh size. The mesh specification should be good enough to complete the flow feature, but the number of cells should be as low as possible to maintain the practical speed of the calculation. Therefore the mesh density becomes increasingly

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reduced to the part that is farther away from the basic mesh zone that requires a good resolution. Effort in meeting the requirements between adequate resolution and minimum number of cells are often a tremendous challenge.

The created mesh needs to be re-examined to ensure that the meshing process is done properly. The border layer feature checking scheme starts with the small elemental thickness continuing to the next larger elements with standard growth rates. Mesh checks are performed to ensure the mesh is well established so that the definition of geometry can be performed.

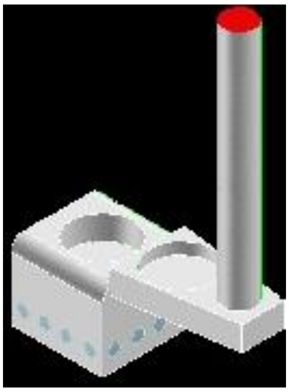


Figure 1. Colour view of boundarry layer on Gambit of the stove

After the process of making geometry and meshing was complete then simulation and analysis with CFD application was proceed. The selected system is 3D. The first step is to import the mesh model from Gambit to the CFD application. All mesh results on specimens that have been built on the Gambit program are imported in this process. Mesh checks need to be done to make sure the mesh and grid are good so that the analysis process can proceed. Furthermore, it is necessary to select the formula solver. The choice of solver formula is applied equally to all specimens and settings in the CFD program. The next step is to determine the basic model and equation so that the test results can convergen.

The determination of the boundary conditions in the stove uses many assumptions that reflect the overall system applied to the simulation. The fuel reaction conditions are assumed to be steady and without feedback to reduce the thermal response time of the whole system being modeled. The phenomenon of steady flow field motion is assumed to occur over a short time scale. The walls of the combustion chamber are assumed to achieve rapid thermal equilibrium with improved flow conditions and new reactions. The simulation does not attempt to explain the heat flow in the stove structure which is assumed to be isolated. The heat leaves the domain across the wall surface along the inside of the combustion chamber without conduction of heat along the domain boundary. The heat conduction along the boundary surface on all solid structure has been ignored except at the bottom of both pots. Operating pressure is set at 1 atm. Characteristics of the materials used are the characteristics of air at a constant state.

After determine the solution control parameters and initialization of the flow field is done. Furthermore iteration is run. When iteration begins then all defined conservation equations are solved simultaneously and parallel. After all processing steps are completed then post-processing steps can be performed to show the simulation results.

4.2 Experimentaly Method

Experimental tests were performed to get the best performance from the stove for each chimney variation. Performance parameters concerned are the water boiling time in pot 1 and thermal efficiency of the stove. Experimental chimney height variations have the same height as simulations.

So the result can be compared with the thermal effect obtained by simulation test. Figure 2 shown the experimental testing process performed on the stove.

Figure 2. Experimental stove testing

Testing is done by using water boiling test method. The test is carried out for stove operating conditions consisting of high power and low power. High power consists of cold start and hot start while low power is called simmer. Cold start is a process of operation that starts with the condition of the stove is still cold. Cold start operating conditions are common when the stove is operated in the morning when the stove has not absorbed the heat from the combustion process yet and the temperature is close to ambient temperature. Hot start is a process operation with the stove already in a hot condition because the stove has absorbed heat from the previous process and its temperature higher than the environmental temperature. While simmer is the process of operating stove with low heat to maintain the water boiling point for a certain time interval. Differences in temperature fluctuations in simmer conditions are not greater than 5 ^{o}C. Simmer operating conditions in the cooking process with the stove is usually done to make meals more cooked but not burned. The test time for high power starts when the fire lit and ends up when the water in the first pot boiled. While the time used for the simmer operation process in this test starts when the water in the first pot boiled and ends up in 45 minutes [25].

The amount of heat absorbed by water for each test operating condition can be calculated as the amount of useful energy. While the amount of energy supplied to the stove system can be calculated based on the amount of burned-out fuel mass multiplied by the calorific value held by the type of fuel used in the test. This calorific value calculation has considered the wood humidity and air humidity factors, charcoal and dust masses generated from the combustion process. A comparison of useful heat to the energy given for each operating condition is the thermal efficiency value of the stove under test.

In this test, three repetitions were performed for each chimney height variation. The data obtained then tabulated and calculated to get the average value. The results are then depicted in graphical form to show the relationship between water boiling time in pot 1 and thermal efficiency of the stove to the height variation of the chimney. So it can be compared with the thermal effect of the simulation result. Figure 3 showed the experimental testing process performed.

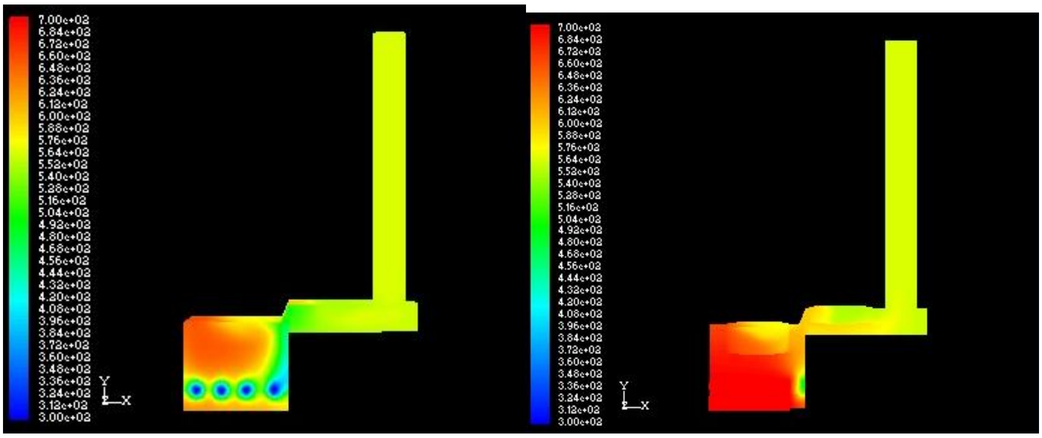
5. Testing Results and Discussion

The following sections report the CFD simulation results and experimental tests conducted to validate the simulation. Run time simulation is only about one third of the duration needed for cooking. While the thermal balance of the stove naturally takes more than an hour. Thermal aspects greatly affect the behavior of the stove so that temperature is one of the important and interesting properties in the simulation to be discussed. Although the parameters considered different from the simulation and experimental results but both of them are the thermal aspects of the stove system that closely relate each other. So the thermal aspects obtained by simulation will be comparable with the experimental results.

5.1 Results of simulation test

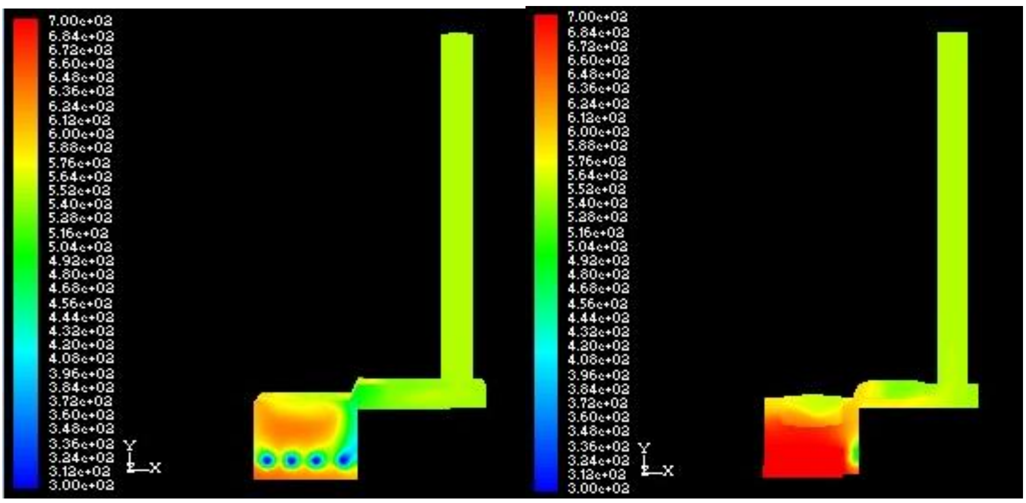
After all processing steps are completed then post processing stage can be done to show the simulation result. Because it has a three-dimensional control volume, the CFD simulation results can be assigned to any location in the stove. The CFD simulation results have a clear visual where the domain retains the shape of the stove. Some actual results are evaluated and displayed in 3D space, including fluid flow pathways and various iso surfaces.

The main simulation results are reported in two dimensional forms. The forms provide a view on longitudinal plane of the stove. The simulation results are also given in cross section view in longitudinal plane image to show the conditions inside the stove. The temperature contours shown are the convergen results of the iterations performed. Each chimney height variation has different temperature contour. The temperature contours for each of the varied flue stove elevations are shown in Figures 3 to 7. Image shows visual orientation of the resulting contour plot graphics.



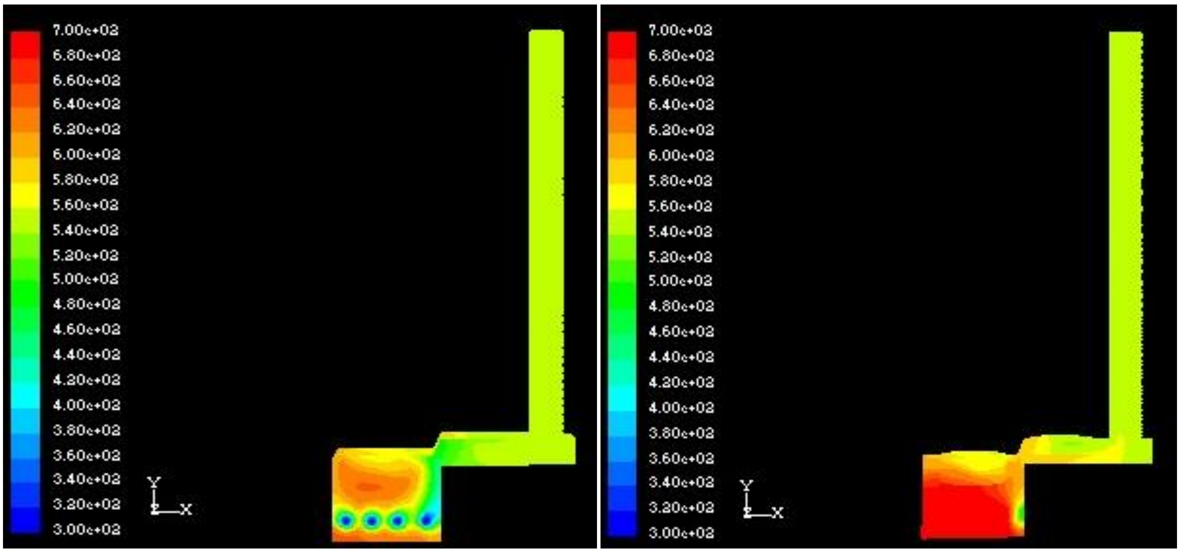
(a) (b)

Figure 3. Temperatures contour of fluid flow in stove with 110 cm height of the chimney (a) View on longitudinal plane, (b) Cross section view in longitudinal plane.



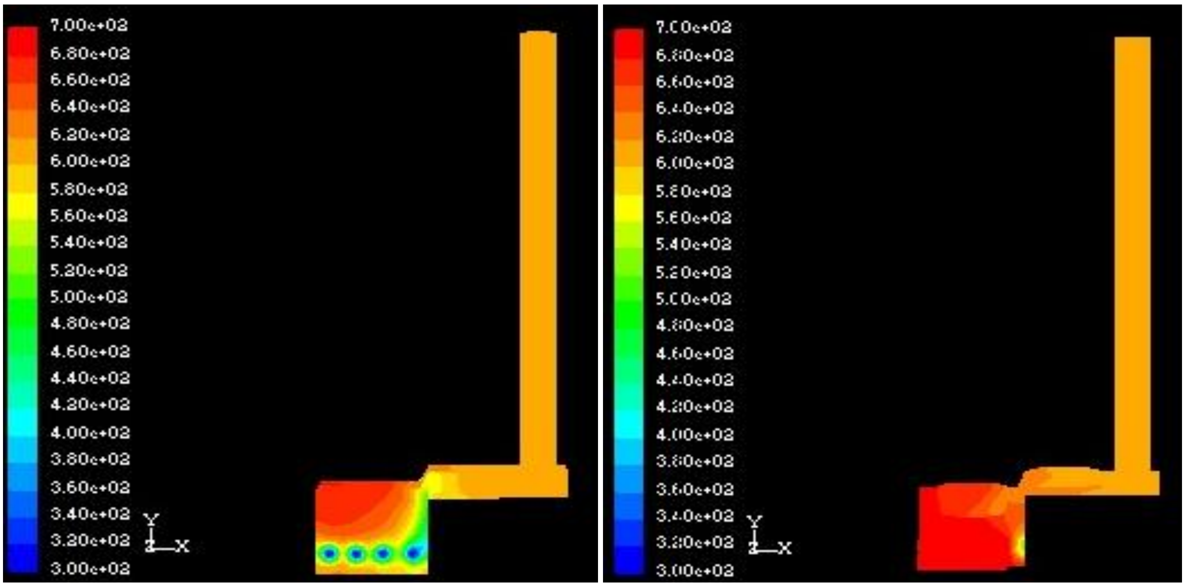
(a) (b)

Figure 4. Temperatures contour of fluid flow in stove with 145 cm height of the chimney (a) View on longitudinal plane, (b) Cross section view in longitudinal plane.



(a) (b)

Figure 5. Temperatures contour of fluid flow in stove with 155 cm height of the chimney (a) View on longitudinal plane, (b) Cross section view in longitudinal plane.



(a) (b)

Figure 6. Temperatures contour of fluid flow in stove with 165 cm height of the chimney (a) View on longitudinal plane, (b) Cross section view in longitudinal plane.

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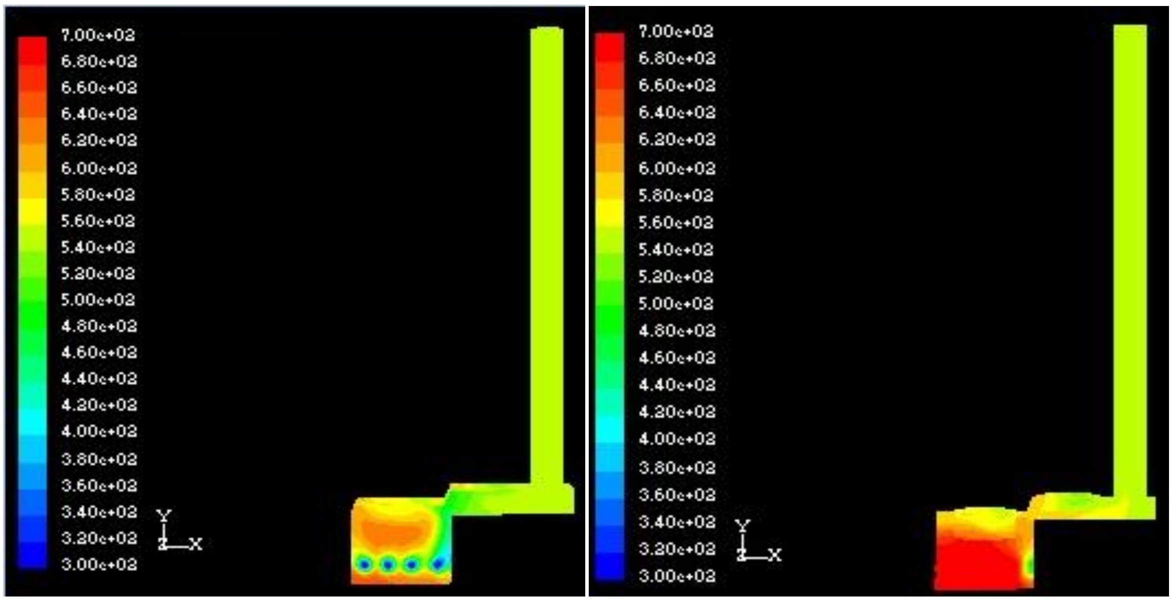

(a) (b)

Figure 7. Temperatures contour of fluid flow in stove with 185 cm height of the chimney (a) View on longitudinal plane, (b) Cross section view in longitudinal plane.

The results of the temperature distribution and flow pattern are useful for understanding the general effect of the chimney to the flame position, flow path and stretching. The temperature distribution combined with the heat flux on the solid surface is useful for optimizing heat transfer in the stove. Useful heat can be maximized by controlling and directing a better gas flow to the pot. More detailed statistical analysis of the temperature distribution values will also provide additional information for combustion scientists and stove designers such as information on fire position stability and possible emissions generation.

There is a lot of data obtained through simulation results that can be discussed. However, only a few data are selected and shown here to help provide information that can be used as a basis for determining the effective chimney height of the designed stove. The temperatures in each pot and on the out-let chimney are the data that is considered important that can show the thermal effect of the stove. Based on these considerations, the simulated results data of those sections are selected to show the effect of the chimney height variation.

Table 1. Simulation result data of temperature at pot 1, pot 2 and outlet to the chimney height variation

Chimney Height (m)	1.1	1.45	1.55	1.65	1.85
Paths	Temperature (K)				
Pot 1	645.26175	625.14104	628.47114	665.67156	623.29761
Pot 2	580.25653	569.51124	570.48503	619.02604	568.96524
Outlet	566.49196	555.13441	555.81833	609.92467	554.58899

The simulation results data of the temperature at pot 1, pot 2 and outlet of the stove to the height variation of the chimney can be seen in Table 1. Based on the temperature data, a comparison graph of temperature change at pot 1, pot 2 and the stove outlet for each chimney height variation is created as shown in Figure 8. Based on the graph, it can be seen that the height variation of the chimney results a difference thermal effect on the stove. Noted that the temperature at pot 1, pot 2 and outlet have different values for each chimney height variation. The stove simulation results with 1.65 m chimney height give the highest thermal effect at pot 1, pot 2 and out-let which is indicated with the highest temperature value at each part compared with the other height.

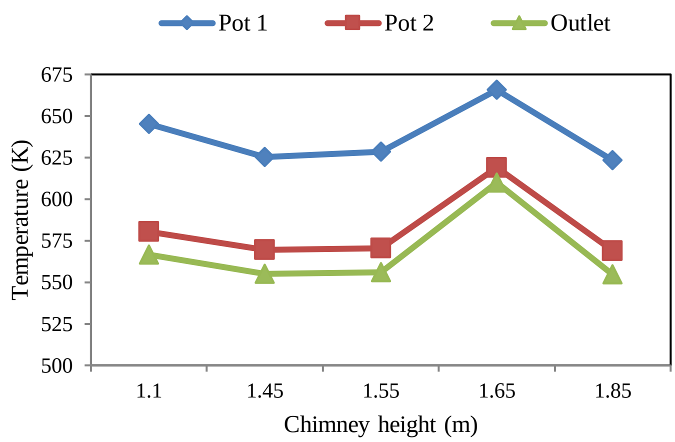

Figure 8. Graph of temperature at pot 1, pot 2 & outlet of the stove to the chimney height variation

5.2 Experimental Test Results

The parameters of experimental test results shown below were only the relation between water boiling time in pot 1 and the thermal efficiency of the stove. The values that described the thermal effect were the average value of the test results. Both values for each variation of the chimney are given in graphical form.

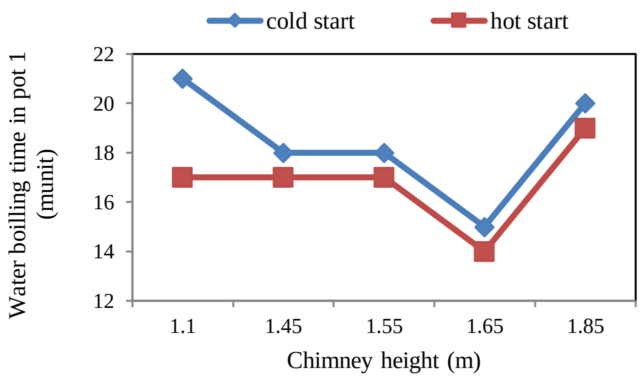

Figure 9. Graph of water boiling time in pot 1 of stove to the chimney height variation.

Figure 9 shows the graph of water boiling time in pot 1 of the stove for hight power operation. It can be seen that water boiling time in pot 1 for hot start is shorther than cold start. It is caused by the heat generated in the combustion chamber on the cold start does not immediately transfer to the water in the pot maximally, due to part of it was absorbed by the stove and other part transfered to the environment as heat losses. The stove will continue to absorb the heat from the combustion to the maximum until the stove reaches its thermal balance when the cold start operation. While the hot start operation is carried out when the stove condition has absorbed heat from the previous operating process and is already in thermal equilibrium and only part of it is transfered to the environment as heat losses. However, both graphs of both operations show similar tendencies. Both graphs showed that the shortest time is obtained at 1.65 m of chimney height.

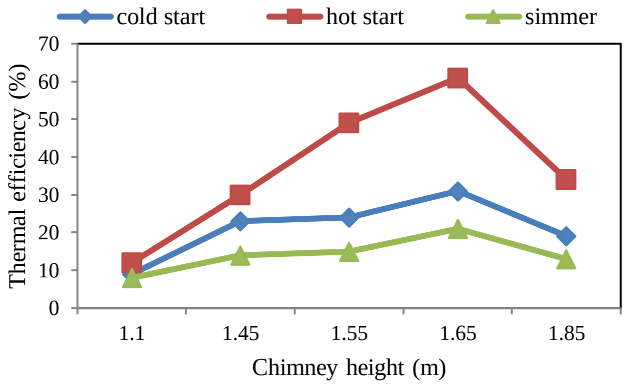

Figure 10. Graph of thermal efficiency of stove to the chimney height variation.

Figure 10 showed the thermal efficiency of the stove at cold start, hot start and simmer for each of the chimney height variations of the stove. The thermal efficiency for the simmer operating conditions is always below the cold start and the hot start. This is because simmer is a low power operating condition. The flame in the combustion chamber of the stove during simmer operation is attempted in small sizes only to retain water in pot 1 being at a constant temperature boiling point. While cold start and hot start is a high-energy stove operation condition. Figure 6 also showed that the thermal efficiency of the stove for hot start was always above the cold start. As explained earlier this is because the stove in hot-start operational condition has reached its thermal equilibrium so that more useful energy transfered to the water in the pot compared to the cold start condition. Overall, each graph shows a similar trend of efficiency value to the chimney height variation. It appears that the highest thermal efficiency of the stove is achieved at 1.65 m chimney height for all operating conditions, either for low power or high power.

6. Conclusions

The CFD simulations developed to evaluate the behavior of double pots biomass stove with the chimney have been achieved a fairly good process. The control volume assumed to be on the gas domain only by ignoring the solid domain of the stove has yielded satisfactory thermal effects. Accurate and well-finished stove simulation results have also been obtained with a relatively shorter time than required for cooking. Boundary layer resolution and accurate thermal effect values obtained through the simulation results are useful for selecting the effective height of the chimney on the stove.

The result of double pot system stove simulation can be correlated with experimental test result. Both test results showed that the best thermal aspect value is obtained for 1.65 m chimney height. This has been proven either through simulation or experimental tests. Based on the results obtained through both tests, it has provided data and information that assists in designing the biomass stoves. The biomass stove had shown a good performance so that it was believed to provide advancements in addressing efficiency and pollution problems compared to traditional biomass stoves generally.

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