IMPROVING COOKING STOVE'S EFFICIENCY FOR HIGHLAND SCHOOL

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A SPECIAL RESEARCH PROJECT SUBMITTED IN PARTIAL FULFILLMENT
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Abstract

The aim of this project is to improve the efficiency of the existing cooking stove located at Sahamit School, Chiang Mai, by using Computational Fluid Dynamic technique (CFD). The models are divided into 2 parts of solid fuel behavior which are volatile combustion and char combustion. Both of them are simulated in pseudo steady state. The boundary conditions of both models are collected from the experiment. On the other hand, the initial conditions are predicted by using the correlation. After the models are built, the experiment is set up to validate the model. For volatile combustion, the reaction rate of volatile combustion in gas phase is expressed by using eddy – dissipation model. By comparing the results from the simulation with the experiment, the temperature at the center of cooking stoves, left and right sides of exhaust area have 14.75 % , 24.01 % and 21.83 % deviation from the experiment respectively. For char combustion, the reaction of solid char combustion is modeled by using wall surface function. The results shows that the fuel loss rate and the temperature of center of cooking stove and the temperature of left and right of exhaust area differ from the experiment 4.65 %, 5.09 %, 14.08 % and 14.44 %, respectively. Then, the 17 simulations of the variation of the existing cooking stove configuration are performed to study the effect of cooking stove's geometry on its efficiency. A reduction of cooking stove height, air inlet size, height of air inlet position and exhaust area size make an increase of cooking stove's efficiency. Then, the improved cooking stove is introduced. The way of improving the existing cooking stove is by reducing the stove height from 550 mm to 350 mm. The improved cooking stove's configuration gives the maximum efficiency of 45.44 % in volatile combustion period and 16.53 % in char combustion period respectively. However the existing cooking stove gives the efficiency of 22.20 % of volatile combustion period and 12.30 % of char combustion period, respectively.

Keywords: Cooking Stove/ CFD/ Modeling/ Thermal Efficiency/ Biomass Combustion

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บทคัดย่อ

การศึกษาครั้งนี้จุดมุ่งหมายในการปรับปรุงประสิทธิภาพของเตาหุงต้มปัจจุบันที่ใช้ในการหุงข้าวของโรงเรียนสหมิตร จ.เชียงใหม่ ซึ่งกระบวนการสร้างแบบจำลองทางกลศาสตร์ของของไหลถูกใช้ในการปรับปรุงประสิทธิของเตาหุงต้มดังกล่าวเนื่องจากใช้เวลา และงบประมาณน้อย แบบจำลองดังกล่าวถูกแบ่งโดยพฤติกรรมของเชื้อเพลิงแข็ง โดยแบ่งเป็น 2 กรณี คือ แบบจำลองของไหลของการเผาไหม้ในสถานะแก๊ส และการเผาไหม้ในสถานะของแข็งของเชื้อเพลิง ซึ่งแบบจำลองดังกล่าวทั้ง 2 กรณี ถูกจำลองในสภาวะคงตัวแบบเทียม ซึ่งค่าที่ใช้ในการระบุสภาวะขอบเขตของทั้ง 2 กรณีนำมาจากการทำการทดลอง ในทางกลับกันสภาวะเริ่มต้นของทั้ง 2 กรณีถูกทำนายโดยใช้สมการสหสัมพันธ์ หลังจากแบบจำลองถูกสร้าง มีการทดลองเพื่อพิสูจน์ถึงความถูกต้องของแบบจำลองดังกล่าว สำหรับกรณีการเผาไหม้ของเชื้อเพลงในสถานะแก๊ส แบบจำลองของ Eddy dissipation ถูกเลือกใช้ในการแสดงถึงการเกิดปฏิกิริยาของเชื้อเพลิงในสถานะแก๊ส เมื่อนำผลของแบบจำลองมาเปรียบเทียบกับการทดลอง พบว่า มีความคลาดเคลื่อน 14.75 % , 24.01 % และ 21.83 % ของอุณหภูมิ ณ ตำแหน่งกึ่งกลางของเตาหุงต้ม และทางซ้าย และขวาของช่องระบายอากาศ ตามลำดับ สำหรับกรณีการเผาไหม้ในสถานะของแข็ง การทำนายการเกิดปฏิกิริยาสามารถทำได้โดยการใช้แบบจำลองจลน์ศาสตร์ปฏิกิริยาเคมีแบบ Arrhenius ซึ่งทำให้แบบจำลองดังกล่าวให้ค่าความคลาดเคลื่อน 4.65 %, 5.09 %, 14.08 % และ 14.44 % ของอัตราการเผาไหม้, อุณหภูมิ ณ ตำแหน่ง กึ่งกลางของเตาหุงต้ม

และทางซ้าย และขวาของช่องระบายอากาศ ตามลำดับ หลังจากนั้นแบบจำลองจำนวน 17 แบบจำลองถูกสร้างขึ้นเพื่อศึกษาผลของโครงสร้างของเตาหุงต้มที่มีต่อประสิทธิภาพของเตาหุงต้ม ซึ่งพบว่าการเพิ่มประสิทธิภาพของเตาหุงต้มสามารถทำได้โดยการลดความสูงของเตาหุงต้ม ลดขนาดของช่องอากาศเข้าเตาหุงต้ม ลดระดับความสูงของตำแหน่งที่ติดตั้งช่องอากาศเข้าเตา และลดขนาดของช่องระบายอากาศ หลังจากนั้นวิธีในการปรับปรุงเตาหุงต้มถูกนำเสนอ กล่าวคือ เตาหุงต้มที่ได้รับการปรับปรุงควรปรับลดขนาดความสูงของเตาหุงต้มจาก 550 เป็น 350 มิลลิเมตร ซึ่งส่งผลให้ประสิทธิภาพของเตาหุงต้มเพิ่มขึ้น จาก 16.53 % เป็น 45.44 % ในกรณีของการเผาไหม้เชื้อเพลิงในสถานะแก๊ส และ 16.53 % เป็น 22.20 % ในกรณีของการเผาไหม้เชื้อเพลิงในสถานะของแข็ง

คำสำคัญ: เตาหุงต้ม/ การเผาไหม้ของชีวมวล/ การปรับปรุงประสิทธิภาพ/ การสร้างแบบจำลอง

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CHAPTER 1 INTRODUCTION

1.1 Background

Sahamit School located at Gullayaniwatthana district, Chiang Mai, Thailand has been established for offering educational opportunities for tribesmen. This school is in the rural highland of which people reside in this area have low income. To support two hundred students, the school provides foods for breakfast and lunch in order to reduce their expenditure.

However, Sahamit School uses biomass cooking stove for cooking 40 kilograms of rice per day but 20 kilograms of dry wood are consumed per one time of cooking because the cooking stove is inefficient. So wood's consumption is wasteful.

Due to Sahamit School is located in the precinct under the patronage of the Royal project. The Royal Project has the responsibility to take care people and organization around the Royal Project center. Therefore, the improving cooking stove project is established for increasing the efficiency of the existing cooking stove and reducing wood consumption.

There are many improved cooking stove project methods available in literature. Most of them are based on trial-and-error method and empirical information which consume much time and require high investment cost for constructing the real cooking stove.

Due to the high performance of computer is available; Computational Fluid Dynamic (CFD) technique can be used as a tool for studying the behavior of cooking stove because it provides accurate result and requires low cost investment.

1.2 Objective

1. To model the behavior of cooking stove by using CFD technique.
2. To improve the cooking stove by using CFD model.

1.3 Scopes of work

1. The new design of improved cooking stove will be developed from the existing cooking stove.
2. The modeling of cooking stove will be performed by using CFD technique.

1.4 Research procedure

1. Study and identify factors affecting thermal efficiency of cooking stove.
2. Review literature and related article for modeling behavior occurred inside cooking stove.
3. Collect the data and list assumption required for modeling cooking stove.

4. Construct the model.
5. Solve the governing equations.
6. Study parameters related to thermal efficiency of cooking stove.
7. Analyze the result and purpose the new design of improved cooking stove.
8. Prepare the report.

1.5 Expected results

This research will model the behavior occurring inside the cooking stove and study the factors affecting the thermal efficiency of cooking stove. If this study is worked, the expected advantages are.

1. The model can be used for introducing the improved cooking stove which has higher thermal efficiency.
2. The model can be adapted for improving traditional cooking stove by changing geometry of cooking stove and physical property of cooking stove.
3. The study of parameter affected cooking stove efficiency can be used as a guideline to improve another cooking stove.

CHAPTER 2 THEORIES AND LITERATURE REVIEWS

2.1 Biomass conversion techniques

There are 3 ways of common biomass conversion which are discussed below [1].

2.1.1 Direct combustion

The direct combustion is a simple way to utilize biomass for producing heat. However, this way of combustion requires such as moisture reduction, impurity elimination in order to increase heating values of fuels. As a result, direct combustion of unconverted biomass affects inefficiency heat utilization because heat is lost in the volatilization of moisture.

2.1.2 Pyrolysis

Pyrolysis is irreversible reaction that wood is heated with restricted air flow resulting in the production of charcoal, wood gas, pyroligneous acid and tar of wood oil excluding the moisture content.

2.1.3 Gasification

The process of gasification produces combustibles gases from coal and biomass fuels for heating and power generation. Combustible solid fuels are converted to combustible gaseous product by using gas producer.

2.2 Cooking stove design criteria

Cooking stove is a gasifier that converts solid fuels into combustible gases. Before cooking stove will be designed, the site survey must be done for collecting data of user's needs. Adapting a stove may involve some of the following [1].

- Altering stove dimension to fit the used pot's size.
- Modifying pot supports to accommodate local pot.
- Altering door dimensions to accommodate larger fuels
- Increasing stove stability for safety or local cooking practices.
- Adjusting the material to meet local available.
- Minor design changes to easily build

Moreover there are more design criteria purposed by Dr. Larry Winiarski, which are shown below [2].

- Insulate around the fire using lightweight, heat-resistant materials.
- Place an insulated short chimney right above the fire to burn up the smoke and speed up the draft.

- Heat and burn the tips of the sticks as they enter the fire to make flame, not smoke.
- High and low heats are created by how many sticks are pushed into the fire.
- Maintain a good fast draft from under the fire, up through the coals. Avoid allowing too much extra air in above the fire to cool it.
- Too little draft being pulled into the fire will result in smoke and excess charcoal.
- Keep unrestricted airflow by maintaining constant cross-sectional area through the stove. The opening into the fire, the size of the spaces within the stove through which hot air flows, and the chimney should all be about the same size.
- Use a grate under the fire.
- Insulate the heat flow path, from the fire, to and around the pot(s) or griddle.
- Maximize heat transfer to the pot with properly sized gaps.

Some of design features purposed to help make a stove more fuel efficient or reduce health problems associated with traditional cooking fires [3]:

- Chimney or vent - to remove smoke to outdoors, and improve airflow through the fire.
- Controllable air inflow - requires the fire to be in an enclosure with an adjustable inlet - allows reduction of burning rate to match needs.
- Use of a material with good insulating properties, for the inside walls of the stove - usually ceramic.
- Afterburning - mixing the flue (exhaust gas) with a small amount of new air, to allow the last remaining hydrocarbons and carbon monoxide to burn without a flame.
- Jacketing the cooking vessel, i.e. making the hot flue travel through a narrow passage between the cooker and the pot. This implies that the pot size and cooker size must be matched.
- Use of the flue gas heat for space heating (in cold climates) and/or water heating. To avoid leakage of flue gas into the room, a heat exchanger is needed. In an expensive product this may be a complex stainless steel device, or in a developing nation a simple metal flue pipe.
- Many societies cook only a few types of food and you should design the stove to meet their specific needs
- If they stir a thick material, you will need a well-supported base in order to keep the cooker stable
- There is an optimal separation between the pot and the cooker to allow for the airflow to escape. Design the stove to match the pots and maintain this separation
- If too much material is placed in the burner, not all of the hydrocarbons will be consumed, so consider limiting the amount of space for the flammable material. Also consider what type of material is burned locally when designing this burning area.
- In densely populated areas such as refugee camps, multiple households will want to share the stoves, so consider including insulated handles.

- As always with appropriate technology, the stoves should be locally constructed with local materials, using local techniques. This way, you can seed entrepreneurs to produce, sell and repair the stoves after you leave.

2.3 Mechanisms occurring in cooking stove

2.3.1 Combustion theories

In cooking stove, the combustion generates heat for cooking. Combustion is the chemical reactions between a fuel and oxygen. This reaction releases heat and conversion of chemical component. The heat production can be in the form of either glowing or frame. Fuels that often uses in the combustion are organic compound which in gas, liquid or solid phase [4].

Since, mostly fuels consist of hydrocarbon component or pure carbon and some impurity compound such sulfur. The example of chemical reaction when the combustion of fuels occur, are shown as follows.

$$C + O_2 \rightarrow CO_2 + 24806\ J/g \tag{1}$$

$$2C + O_2 \rightarrow 2CO + 6594\ J/g \tag{2}$$

$$2H_2 + O_2 \rightarrow 2H_2O + 106760\ J/g \tag{3}$$

$$S + O_2 \rightarrow SO_2 + 3479.12\ J/g \tag{4}$$

The factors which can affect the performance of combustion, are shown below [2].

2.3.1.1 Air to fuel ratio

The Air fuel ratio is the ratio between the mass of air and the mass of fuel used in combustion. For optimum combustion the supply of air to fire is important. The effects of air to the performance of combustion are discussed below.

- In sufficient oxygen, if air is undersupplied or poor air distribution, can affect some combustible gases leaving the combustion chamber without burning. Moreover, a fire which generates a lot of smokes shows a problem of this sort.
- Up to certain point, increased air flow can increase both the rate and efficiency of combustion
- Greatly exceeded air flow that is required for combustion may carry off enough heat to lower the temperature of the fuel below its ignition temperatures.
- Excess air may also lower the concentration of flammable gases, inadequate to maintain the high temperatures which necessary to keep combustion continuously.
- The theoretical air to fuel ratio can be calculated from the stoichiometry of the chemical reaction. However, the theoretical is not enough for fully combustion so the oversupply air is required.

2.3.1.2 Size, shape and arrangement of fuel pieces

- The size of fuels pieces can affect to performance of combustion. The smaller piece of wood has a lower volume in proportion to its surface area than does a larger piece. So the high combustion rate will occurs, if the smaller pieces of wood are used. This is because the smaller pieces has a greatly exposure to air.
- The large amount of combustible gases from small wood pieces will not burn due to the supply of air is limited.
- Large pieces of wood may not burn at all, however, if there is no external source of heat. Since, the heat is not enough to transfer to the interior of wood.
- Straight pieces of wood arranged in a parallel style lie tightly together and impede air flow. As a result, gases will move away from areas of sufficiently high temperature before mixing enough air to burn.

2.3.1.3 Moisture in the wood

Wet wood releases less heat because the generation of heat uses into evaporating water. The evaporation of water from wood makes the dilution of flammable gases, which causes the lower efficiency and performance of combustion.

2.3.2 Heat transfer mechanisms

2.3.2.1 Natural convection

For natural convection, the fluid motion can be occurred by without the external forces. When a fluid is heated or cooled, the fluid densities are changed which create buoyant effect. This effect causes natural circulation in which the affected fluid moves by its own accord past the solid surface, the fluid that replaces it is similarly affected by the energy transfer. After that this process is repeated [5].

From the analysis of natural convection of fluid between two parallel infinite plates at different temperatures, aligned with the gravitation direction, shows the velocity of the buoyant fluid to vary directly with the Grashof number. However, the natural convection between 2 infinites plates is quite different from the process occurring in the stove. Nevertheless, it exemplifies the aforementioned fact that natural convection is a function of Grashof number [6].

2.3.2.2 Heat conduction

Heat conduction is one of heat transfer phenomena which heat transfers via the non-motion medium. If there is the temperature gradient between regions of matter, thermal energy or heat spontaneous flows from higher temperature region to lower temperature regions by transferring though matter. This is called heat conduction [5].

The heat conduction can be described by using Fourier's laws which is [7].

$$q = \frac{k}{L}\Delta T \tag{5}$$

Which q = heat flux (W/m^2)

k = thermal conductivity (W/m.K)

ΔT = temperature difference (K)

2.3.2.3 Heat radiation

Radiation is one of thermal energy's transfer mechanisms. It allows energy to be transported with the speed of light through areas of space that are without of matter. According to Stefan-Boltzmann law, the rate of energy transports between two "black bodies" in a vacuum is proportional to the difference of the fourth powers of theirs absolute temperatures. The equation of heat flux emitted by black body is [7].

$$q = \sigma T^4 \tag{6}$$

Which q = heat flux (W/m^2)

σ = Stefan – Boltzmann constant

T = absolute temperature

On the other hand, the emitted energy rate for a non-black surface or real surface is

$$q = \varepsilon\sigma T^4 \tag{7}$$

Which q = heat flux (W/m^2)

ε = total emissivity

σ = Stefan – Boltzmann constant

T = absolute temperature

If the heat radiation from surface 1 to surface 2 is considered, the radiation heat flux depends on the temperature difference and geometry with the geometry or it can be expressed by

$$q_{12} = \sigma A_1 F_{12}(\epsilon_1 T_1^4 - \epsilon_2 T_2^4) \tag{8}$$

Which q = heat flux (W/m^2)

A_1 = surface area of surface 1

F_{12} = view factor between surface 1 and surface 2

ε = total emissivity of each surfaces

σ = Stefan – Boltzmann constant

T = absolute temperature of each surfaces

2.4 Techniques of drawing heat balances

The comprehensive list of items that account for the total amount of fuel used in a stove for a cooking scheme are showed below [8].

- The pan:
  - Heating up the water and food;
  - Heat for chemical reactions during cooking;
  - Production of steam during the simmering period;
  - Heat stored in the pan;
  - Heat lost due to convection and radiation from the pan walls.
- The stove accounting for:
  - Thermal Radiation
  - Convective heat losses of the exposed parts to the environment;
  - The accumulated heat in the stove body.
- Stack losses consisting of:
  - The latter two are a result of incomplete combustion and are called the latent beat.
  - Soot and tar deposits, partly stuck to the pan walls and the inside of the stove body and partly carried away by the flue gases.
  - Un-burnt charcoal in the ash at the end of an experiment.
  - Loss of energy due to the presence of moisture in wood.

2.5 Improving cooking stove guidelines

There are many sources that suggest the criteria of improved cooking stove. Mostly, the main objectives are to minimize heat loss from cooking stove, and to increase the combustion efficiency [9].

The criteria to minimize heat loss from cooking stove are discussed below [2].

- Using a pot skirt to keep the hot air escape the stove in a narrow channel. So hot gas can transfer more heat to the bottom and sides of the pot
- Increasing the speed of hot flue gases that scrape against the pot. The fast gases punch through a boundary layer of still air that keeps slower moving gases from scraping against the surface of the pot because air is a poor heat transfer medium. It takes a lot of hot air to bring heat to the pot

- Using metal pot is better than clay pot, since metal can conduct more heat when compare to clay at the same time.
- The size of the fire determines the size of the channel gap in the pot skirt and the maximum efficiency of heat transfer. Smaller fires that can still please cooks but are not too big will be considerably more fuel efficiency.
- Using wide pots with large diameters which a wide pot creates more surface area to increase the transfer of heat. Make sure that the top of the stove slopes up toward the outer perimeter of the pot

To increase the efficient of fuel combustion, it is possible to facilitate efficient combustion in a stove by ensuring that [9].

- Enough air reaches both the combustion of fuel and volatiles
- The system retains sufficient heat for facilitating complete oxidization of charcoal and the combustion of the volatiles

To achieve above conditions, the cooking stove must be designed by considering suggestion below.

- A small, conical, insulated firebox
- Suitable ventilation comprising a grate and where possible ventilation control

2.6 Testing cooking stove efficiency

The on-field procedure of testing cooking stove efficiency is water boiling point test because it is simple and reliable. This method was initially developed by VITA and then was improved for standardization by University of California-Berkeley. This procedure consists of 3 phases which were developed for simulating a real cooking situation [2].

1. High power, cold start: The pot and water are heated from room temperature until the water reach boiling point temperature.
2. High power, hot start: This phase starts immediately after the first phase finishes while the stove is still hot. The pot refilled with water at room temperature. After that, the operation begins until the water reach boiling point temperature
3. Low power: The stove is operated to simmer water by using the lowest amount of woods or biomass as possible.

According to the second laws of thermodynamics, the definition of the efficiency is the ratio between heat output and heat input. So from the water boiling point test, the thermal efficiency of cooking stove can be calculated in each phase by using this equation [6].

$$n = \left[\frac{m_i c_p (T_b - T_i) + m_{evap} H_i}{m_f H_v}\right] x\ 100 \quad (9)$$

Which

n	=	percentage of cooking stove's thermal efficiency
m_i	=	initial mass of water which is in the pot at the beginning of the test.
c_p	=	specific heat capacity of water (kJ/kg)
T_b	=	temperature of boiling water (ºC)
T_i	=	initial temperature of water in the pot (ºC)
m_{evap}	=	mass of evaporated water (ºC)
H_i	=	heat of vaporization of water (kJ/kg)
m_f	=	mass of fuel burned (kJ)
H_v	=	heating value of fuel (kJ/kg)

2.7 Factor affecting cooking stove efficiency

The problems that cause low-efficiency cooking stove are discussed below [10].

2.7.1 Convective heat loss

The temperature difference between atmosphere and inside of cooking stove can make natural convection occurring. In stoves, the hot gas moves up to the exhaust gap and leaves the cooking stove with high temperature. It carries thermal energy which is convective heat loss

This problem can be solved by reducing the size of exhaust area which can reduce the convective heat loss. Moreover, the reducing of exhaust area can utilize more heat because heat of hot gas can transfer more to the bottom of the pot.

2.7.2 Conductive heat loss

If the wall of the stove is not insulated, the conductive heat loss can occur. The stove has to be insulated for reducing this loss. However, thick of insulation can also reduce stove performance during one or two hours of cooking, since wall absorb more heat than bare walls lose to the outside.

2.7.3 Radiation heat loss

Most of heat generating in cooking stove transfers to the bottom of pot by radiation. Any loss of radiation can reduce the stove efficiency. Radiative heat loss can occur at the exhaust gap. So the way to prevent radiative heat loss is to reduce the exhaust gap.

2.7.4 Size of fuel

One of the problems that occur when stove is tested efficiency even controlling the test condition and standardization is size of the fuels used. The difference of the fuels sizes can affect the cooking stove efficiency varying. The cooking stove efficiency decreases when the size of fuels used increases.

2.7.5 Type of biomass

There are many types of biomass used as the fuels for testing the efficiency of cooking stoves such charcoal, woods and rise husk etc. the difference kind of biomass affect to the stove efficiency when uses the water boiling test method.

2.7.6 Air supply

Since the energy uses in the cooking stove, obtains from the combustion of biomass. The degree of combustion strongly limits stove performance. When the high heating value of wood is used for testing cooking stove efficiency but air is undersupplied, this problem affects heat poorly rendering. On the other hand, if air is oversupplied, a certain amount of heat will be used in increasing the temperature of excess air. This air can leave the stove together with exhaust gas so the efficiency of cooking stove will decrease.

2.7.7 Internal variables

The efficiency of cooking stove depends on the internal variables such grate hole area, exhaust area, air inlet area and stove weight, etc.

2.7.8 Stove material

Due to the cooking stove can be made from either clay, cement or metal, its efficiency varies. For example, clay stove can be saved 40 percent of charcoal comparing to the metal stove.

2.8 Computational fluid dynamic

2.8.1 CFD definition

Computational Fluid Dynamics (CFD) is a computer-based tool for simulating the behavior of systems involving fluid flow, heat transfer, and other related physical processes. CFD works by solving the equations of fluid flow (in a special form) over a section of interest, with specified conditions on the boundary of that section [11, 12].

2.8.2 CFD methodology

There are 3 steps of using CFD which are pre-processing, solving and post-processer

This interactive process is the first pre-processing stage. The objective is to discretize physical structure into a small cells or mesh. Before a mesh can be produced, a closed geometric solid is required. The geometry and mesh can be created in the Meshing application such ICEMCFD and Solidwork etc. The basic steps involve:

- Defining the geometry of the region of interest.
- Creating regions of fluid flow, solid regions and surface boundary names.
- Setting properties for the mesh.

This interactive process is the second pre-processing stage and is used to create input required by the Solver. The mesh files are loaded into the physics pre-processor such CFX-Pre. The physical models that are to be included in the simulation are selected. Fluid properties and boundary conditions are specified. For solving CFD problem, it is solved as follows.

- The partial differential equations are integrated over all the control volumes in the region of interest. This is equivalent to applying a basic conservation law (for example, for mass or momentum) to each control volume.
- These integral equations are converted to a system of algebraic equations by generating a set of approximations for the terms in the integral equations.
- The algebraic equations are solved iteratively.

An iterative approach is required because of the non-linear nature of the equations, and as the solution approaches the exact solution, it is said to converge. For each of iteration, an error, or residual, is reported as a measure of the overall conservation of the flow properties. The solver produces a results file that is then passed to the post-processor.

The post-processor is the component used to analyze, visualize and present the results interactively. Post-processing includes anything from obtaining point values to complex animated sequences.

2.9 Literature reviews

For cooking stove design, there are many ways suggested by stove designer, but most of them are based on trial-and-error experiments and empirical information.

For example, Winiarski's method purposes the ten principles to design cooking stove and also the suitable size of channel gaps between cooking stove and pot for each constant cross sectional area of cooking stove. This method suggests to use the same cross sectional area everywhere in the cooking stove for ensuring sufficient draft for good combustion while resulting in channel gaps that increase heat transfer efficiency. On the other hand, for Baldwin's method, it requires a cooking stove designer picking up a maximum power generated by cooking stove. After that, the size of the channel gap can be specified. This method is based on the pot size of 30 cm diameter. The efficiency of cooking stove made by both methods is about 25 – 40 percent which depends on the firepower. Additionally, they suggest to use small channel gaps to increase heat transfer efficiency [2].

Due to high computer performance, CFD is used as design tool for modeling cooking stove. The simulations of flow, heat transfer, pyrolysis and combustion are done for optimization geometry of cooking stove. The results from CFD have accurate result when validated with experiments [13].

Furthermore, for improving fuel efficiency and indoor air pollution, the wood cooking stove is modeled by using CFD. This work shows the model being accurately when compares with the experimental result. The model can identify the trend of fuel burn rate and heat transfer in the experimental data [14].

Moreover, The Nepali Insert Stove design is selected for CFD simulation and analysis. The goal of design is to reduce the amount of smoke back drafted from the stove's front door. An optimum baffle angle of 40° is found to induce the smallest amount of smoke back drafted into the room where the stove would be located [15].

To improve cooking stove projects, there are 50 cooking stoves were tested efficiency and emissions. The results show that [16].

- Rocket-type stoves can reduce fuel use by 33 percent when compared with three-stone fire
- Use a pot skirt can reduce fuel use and emissions by 25 – 30 percent
- Five forced air stoves reduced fuel use by an average 40 percent and emissions by 90 percent over the three stove fire.

In addition, 14 solid-fuel household cook stove and fuel combinations were tested by using water boiling test. Results shows stoves with smaller-mass components exposed to the heat of fuel combustion tended to take lesser time to boil, have better fuel efficiency, and lower pollutant emissions [17].

A study of parameters affecting charcoal stove performance shows that the physical parameters of cooking stove such as the size of the air inlet area, wall thick ness, gas exhausted area, grate to pot distance, grate hole area affect the cooking stove efficiency tested by using water boiling point test method [18].

The model of mechanism in cooking stove is used for study the effect of physical parameters of cooking stove to cooking stove efficiency. The effect of wall thickness, grate-to-pot distance, the gap area and the area of the opening for the inlet air are investigated [10].

2.10 Model construction

According to the improvement of cooking stove efficiency, the simulation of cooking stove behavior must be built for studying the effect of cooking stove geometry to the cooking stove efficiency.

The 2D model of cooking stove was built by using CFD technique. So the domain of cooking stove is discretized into small volume or mesh and then the governing equations will be solved for obtaining the results of simulation [12].

2.10.1 Model assumptions

1. The simulation is developed in two dimensions.
2. The gases behave as incompressible ideal gases.
3. Apart from densities, all fluid properties are independent of temperature.
4. The devolatilation behavior of fuel is assumed to be one step reaction.
5. The species of volatiles product are grouped into one substance which is wood volatile.
6. The overall rate of reaction of gaseous phase is controlled by turbulent mixing.
7. The char component contains only carbon.
8. The char combustion occurs in one - step reaction.
9. There are no soot, tar and ash generated in the period of combustion.
10. The step of drying process is ignored.
11. The volume of solid fuel is constant.
12. The problems are solved in pseudo steady – state mode.
13. The temperature of each boundary is uniform along its surface.

2.10.2 Governing equation

Due to the mechanisms occurring in cooking stove are related with momentum, energy and mass transfer which can be described by Navier - Stokes Equations. The Navier - Stokes Equations or conservation of momentum, energy and mass equations solved by CFD technique as shown below [12]:

For Mass

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\vec{v}) = S_m q = \sigma T^4 \tag{10}$$

For Momentum

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla.(\rho\vec{v}\vec{v}) = -\nabla p + \nabla.(\bar{\bar{\tau}}) + \rho\vec{g} + \vec{F} \tag{11}$$

For Energy

$$\frac{\partial}{\partial t}(\rho E) + \nabla.(\vec{v}(\rho E + p)) = \nabla.\left(k_{eff}\nabla T - \sum_j h_j \vec{J_j} + (\bar{\bar{\tau}}_{eff}\vec{v})\right) + S_h \tag{12}$$

Which

ρ = fluid density (kg/m^3)

t = physical flow time (s)

$\vec{v}$ = velocity of fluid (m/s)

S_m = mass added to the continuous phase from the dispersed second phase

g = gravity acceleration (m/s^2)

p = static pressure (Pa)

$\bar{\bar{\tau}}$ = stress tensor (Pa)

$\vec{F}$ = external force (N)

E = total energy (J)

k_{eff} = effective conductivity (W/m.K)

$\vec{J_j}$ = diffusion flux of species j (kg/m^2.s)

T = temperature (K)

h_j = enthalpy of species j (J/kg)

S_h = heat of chemical reaction, and any other volumetric heat sources

2.10.3 Turbulence

Due to the high temperature different between inside and outside of cooking stove, and non-zero gravity field, turbulence will be occurred[12]. The standard k-ε model is used to account for turbulence kinetic energy and its dissipation because it is appropriate for modeling natural convection[19]. Turbulence kinetic energy and its dissipation are obtained from the following transport equations:

$$\frac{\partial \rho}{\partial t}(\rho k) + \frac{\partial \rho}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - Y_k + S_k \tag{13}$$

And

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + G_\varepsilon - Y_\varepsilon + S_\varepsilon \tag{14}$$

Which

ρ = fluid density (kg/m^3)

t = physical flow time (s)

k = turbulence kinetic energy (J/kg)

u_i = velocity magnitude (m/s)

μ = dynamic viscosity (Pa.s)

μ_t = turbulent viscosity (Pa.s)

σ_k = turbulent Prandtl numbers for turbulence kinetic energy

G_k = the generation of turbulence kinetic energy due to mean velocity gradients

Y_k = the dissipation of turbulence kinetic energy due to turbulence

S_k = user-defined source terms

ε = specific dissipation rate

σ_ε = turbulent Prandtl numbers for specific dissipation rate

G_ε = the generation of specific dissipation rate due to mean velocity gradients

Y_ε = the dissipation of specific dissipation rate due to turbulence

S_ε = user-defined source terms

2.10.4 Radiation

The effect of char surface and gas radiation to heat transfer via radiation mode is model by using P-1 model [12]. This is because for combustion applications where the optical thickness is large, the P-1 model works reasonably well. The equation of P-1 model is shown below:

$$-\nabla . q_r = aG - 4an^2\sigma T^4 \quad (15)$$

Which q_r = radiation flux (W/m^2)

a = absorption coefficient

G = incident radiation (W/m^2)

n = refractive index of the medium

σ = Stefan-Boltzmann constant (W/m^2.K^4)

T = temperature (K)

2.10.5 Volatile combustion model

Since volatile combustion occurs in case of non-premixed flames, turbulence slowly convects and mixes volatile gases and air into the reaction zones while volatile are fast burning, So the combustion is said to be mixing-limited and the overall rate of reaction is controlled by turbulent[12]. So the complex and often unknown, chemical kinetic rates can be safely neglected. In this case, the Eddy-Dissipation is appropriate to use as volatile combustion model[19].The stoichiometry of the volatiles combustion reaction is estimated by using the data of fuel proximate analysis and ultimate analysis and it is shown below.

$$Wood\ Volatiles\ (g) + 1.17O_2(g) \rightarrow 1.0686CO_2(g) + 1.135H_2O(g) \quad (16)$$

2.10.5.1 Eddy-dissipation Equation

The CFD technique provides a turbulence-chemistry interaction model, based on the work of Magnussen and Hjertage called the eddy-dissipation model. The net rate of production of species *i* due to reaction R, is given by the smaller (i.e., limiting value) of the two expressions below:

$$R_{i,r} = v'_{i,r} M_{w,i} A \rho \frac{\varepsilon}{k} \min_R \left(\frac{Y_R}{v'_{R,r} M_{w,R}} \right) \tag{17}$$

$$R_{i,r} - v'_{i,r} M_{w,i} A B \rho \frac{\varepsilon}{k} \frac{\sum_P Y_P}{\sum_j^N v''_{j,r} M_{w,j}} \tag{18}$$

Which

$R_{i,r}$	=	the net rate of production of species *i* due to reaction, *R*
$v'_{i,r}$	=	stoichiometric coefficients for reactants, products dimensionless
A	=	an empirical constant equal to 4.0
B	=	an empirical constant equal to 0.5
ρ	=	density (kg/m^3)
ε	=	specific dissipation rate
k	=	turbulence kinetic energy (J/kg)
Y_R	=	the mass fraction of a particular reactant, *R*
$M_{w,R}$	=	Molecular weight (kg/kmol)
Y_P	=	the mass fraction of any product species, *P*

2.10.5.2 Boundary condition and initial condition of volatile combustion

Before the simulation can be performed, the initial and boundary condition must be defined for each governing equation. The boundary condition and initial condition of volatile combustion are listed below.

2.10.5.3 Fuel Inlet boundary

The feed of volatile component can be added by specifying mass flux which obtains from the experiment. The fuel inlet position is located at the top of solid fuel surface.

2.10.5.4 Air inlet boundary

The composition of air fed into the cooking stove equals to ambient air composition. The temperature of air steam and pressure equals to atmosphere.

2.10.5.5 Exhaust area boundary

The exhaust area boundary requires the temperature of air back fed into the cooking stove which equals to the temperature of ambient. Moreover, it also requires the pressure at the exhaust area which can be calculated by using the equation below.

$$P_2 = P_1 - \rho_a g h \tag{19}$$

Which P_2 = pressure at the exhaust area, (Pa)

P_1 = pressure at the air inlet position, (Pa)

ρ_a = the density of air = 1.1458 kg/m^3

g = gravitation acceleration = 9.81 (m/s^2)

h = height of cooking stove (m)

2.10.5.6 Wall boundary

The temperature of cooking stove's wall and the bottom of the pan are specified by using the data from the experiment. Moreover, both of them are modeled as no-slip walls.

For solving energy transfers from inside of cooking stove to atmosphere via transfer through both of walls, the 1D – heat transfer calculation is performed as follows:

$$q = h_f(T_w - T_f) + q_r \tag{20}$$

Which q = boundary heat flux (W/m^2)

h_f = fluid-side local heat transfer coefficient (W/m^2.K)

T_w = wall surface temperature (K)

T_f = local fluid temperature (K)

q_r = radiative heat flux (W/m^2)

2.10.5.7 Initial Conditions of volatile combustion

Since, the transient simulation of the cooking stove's modeling is quite complex. Therefore, the pseudo steady – state assumption is needed for modeling cooking stove's behavior.

In addition to the pseudo steady – state assumption, the proper initial conditions of gaseous phase are required for achieving the correct results. The required initial conditions consist of pressure, temperature, velocity and composition in gaseous phase. For the velocity and pressure, they can be estimated by using equation 2.21 [20] and equation 2.19, respectively. Likewise, the temperature of gas phase is specified by using the data from the experiment. Moreover, initial gas composition equals to the air composition

$$v_{initial} = 0.0488(\Delta T)^{0.234} \tag{21}$$

Which $v_{initial}$ = initial air velocity (m/s)

ΔT = the temperature difference between ambient and solid fuel (K)

2.10.6 Char combustion

After most of volatile gases are released from biomass, the remaining of solid biomass is char. For char combustion, the rate of char combustion depends on many factors such as rate of oxygen transfer from air into char volume, reaction kinetics and char temperature gradient, etc. There are many kinetics data representing the char combustion rate in various models, e.g., power law (Arrhenius form) and intrinsic rate [21].

Char combustion is modeled by using wall surface reactions function which creates sources and sinks of chemical species in the gas phase, as well as on the reacting surface. The rate of adsorption and desorption is governed by both chemical kinetics and diffusion to and from the surface. It requires the Arrhenius form of kinetic model. So, power law is used to model char combustion rate as shown below [20].

$$C\ (s) + O_2(g) \rightarrow CO_2\ (g) \tag{22}$$

$$Reaction\ rate = k_0\sqrt{T_s}\exp\left(-\frac{E_a}{RT_s}\right){C_{O_2}}^n \tag{23}$$

Which k_0 = pre-exponential factor = 7.84 x 10^{11} ($1/\sqrt{K}.s$)

E_a = activation energy = 44,000 cal/mole

R = gas constant = 1.986 cal/mol.K

T_s = solid fuel temperature (K)

C_{O_2} = concentration of oxygen at fuel surface (mol/m^3)

n = order of reaction = 1

2.10.6.1 Boundary condition of char combustion

The details of boundary conditions used for char combustion are similar to these of the volatile combustion conditions.

2.10.6.2 Initial condition of char combustion

Since the char combustion is the post-mechanism of volatiles combustion, the initial conditions of gases phase are obtained from the results of volatiles combustion.

CHAPTER 3 METHODOLOGY

To study the effect of factors affected to thermal efficiency of cooking stove and specify position of heat loss, the model of cooking stove behavior should be developed. After the effects are fully investigated, the improved cooking stove can be introduced.

3.1 Develop cooking stove model

To model cooking stove, the model will be developed from the existing cooking stove. Therefore, the details of geometry, dimension of existing cooking stove must be collected. After that the physical properties required for simulating must be determined. Moreover, the sub-model used for determining the physical behavior of fluid should be selected and the assumptions of the model should be specified. Then the CFD model can be solved for obtaining heat balance and thermal efficiency. After that, the CFD model will be validated with experiment.

3.2 Study parameters affect to thermal efficiency of cooking stove.

For increasing thermal efficiency of cooking stove, These parameters suggested to be critical dimensions of designing cooking stoves [1] are listed below.

- Combustion chamber height
- Height of air inlet size
- Height of the position of air inlet
- Height of exhaust outlet size

So, this step aims to determine the effect of each parameter to thermal efficiency of cooking stove. Moreover, the position of heat loss should be determined in this step.

3.3 Analyze the results

After that effect of each factors are investigated, the results will be analyzed for using as improving cooking stove guidelines. Furthermore, the solution of reducing heat loss should be purposed.

3.4 Introduce the new design of improved cooking stove.

The new design of improved cooking stove will be purposed at the end of this project.

CHAPTER 4 RESULTS AND DISCUSSIONS

4.1 Simulations of cooking stove

The simulations of cooking stove are performed to model 2 periods of solid fuel behaviors which are volatile combustion and char combustion in pseudo steady – state mode. Most of boundary conditions used in the model are obtained from the experiment. After the models of cooking stove have been conducted, the experiments are performed to collect the models' required data and validate the models.

4.1.1 Cooking stove geometry

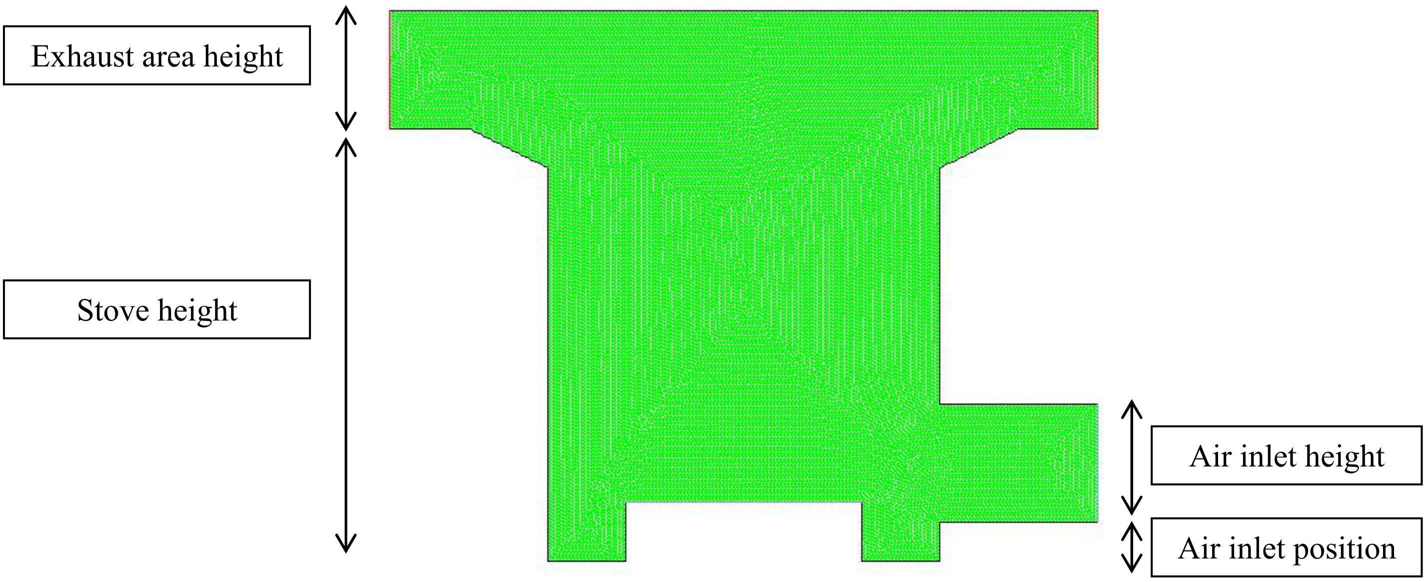

Figure 4.1 The geometry of cooking stove

The description of each location of cooking stove is shown in Figure 4.1. The volume of cooking stove is discretized into around 80,000 meshes which their quality are more than 0.8.

4.1.2 Volatile combustion part

The simulation is developed by using the model described in chapter 2.10. The mass flow of volatile and boundary in each side of cooking stove used in the simulation are collected from the experiment but the initial condition is calculated by the equation (19) described in chapter 2.10.5.7.

4.1.3 Char combustion part

The char combustion is a post mechanism of volatile combustion period. After most of volatile component is decomposed to be gas, the remaining of solid fuel is char. The model of char combustion is developed based on the theories described in chapter 2.10. The boundary condition is collected from the experiment at the time of highest char combustion rate.

4.2 Solid fuels combustion inside cooking stove (Experiment)

The experiment is conducted to collect the models' required data and validate the models' results. Moreover, the behavior of solid fuels is studied from the experiment. The results of solid fuels behavior are shown in the Figure 4.2.

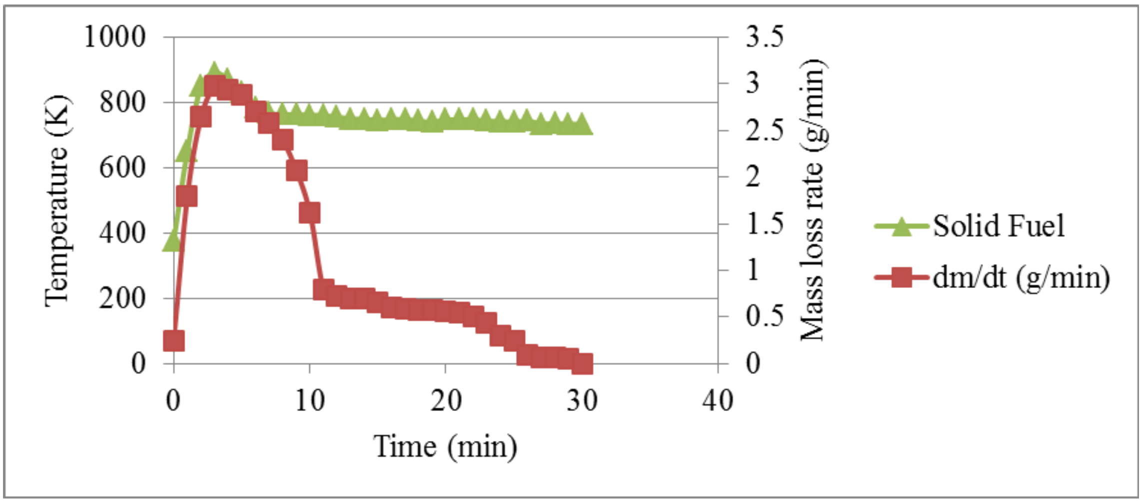

Figure 4.2 The temperature and mass loss rate of solid fuel

The temperature and mass loss rate of solid fuel at each time of experiment are shown in the Figure 4.2. After the fuel is ignited, the solid fuel is decomposed into the volatile component combusting in the gas phase. The heat from volatile combustion transfers to the solid fuel via radiation and convective mode. So this mechanism makes the temperature of solid fuel increase.

Due to the increasing temperature of solid fuel, the rate of solid fuel decomposing to volatile is higher because the energy transferred into solid fuel used to breaking bond between molecules. So the higher temperature increases the mass loss rate of solid fuel. The temperature of solid fuels increases until it reaches the maximum temperature in the experiment of 890 K with the mass loss rate of 2.97 g/min.

After that, the mass loss rate and the temperature drop because most of volatile component releases to the gas phase. The remaining of solid fuel is char. So the char combustion period begins.

In the char combustion period, the temperature drops to 747 K and the highest mass loss rate of char combustion period occurring at the beginning equals to 2.58 g/min. Then char still combusts until the solid fuels turn into ash only.

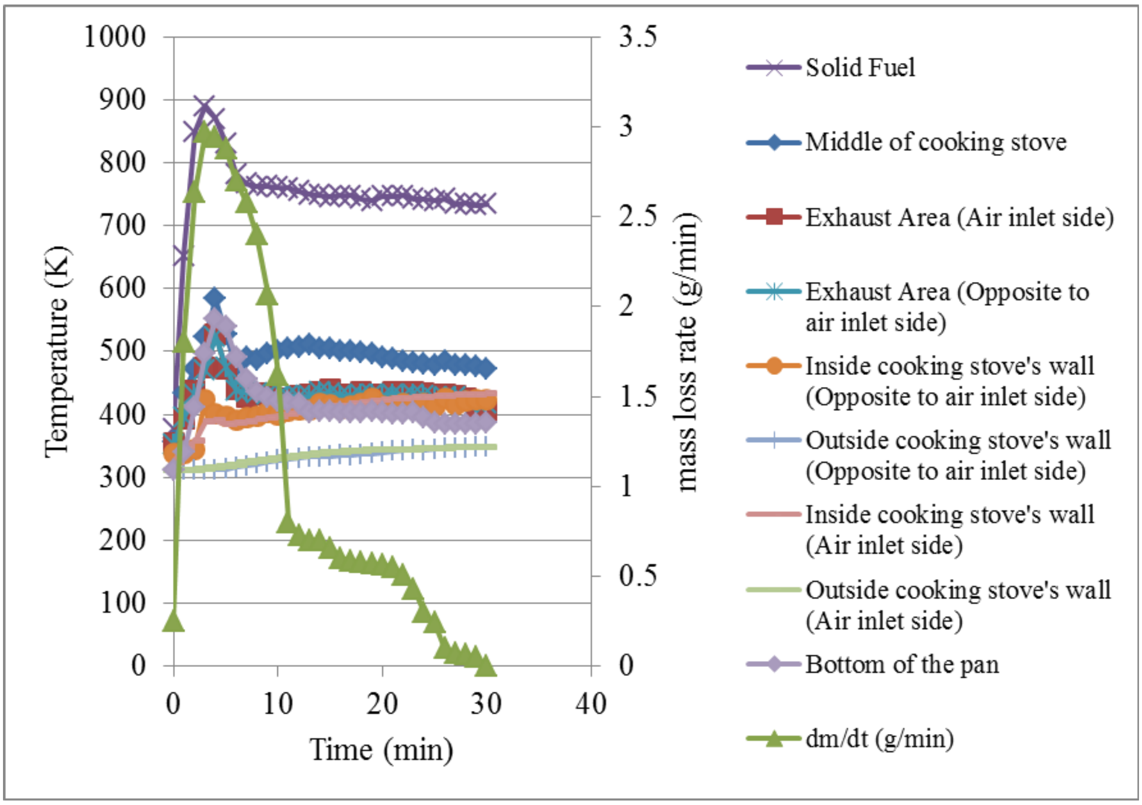

Figure 4.3 Temperature at each location of cooking stove with the temperature and mass loss rate of solid fuel

Figure 4.3 shows the temperature at each location of cooking stove. The temperature at each location is increased by receiving heat from the volatile combustion after fuel is ignited until the time equals to 8 minutes. Then char combustion is the heat source of cooking stove until the end of experiment. The temperature at each location of cooking stove directly changes with the temperature of solid fuel. The maximum temperature of each location of cooking stove is observed at the maximum mass loss rate of solid fuel.

4.3 Simulation results and validating models

4.3.1 Volatile combustion part

The simulation of volatile combustion period is created at the highest reaction rate which is the time of 4 min after the fuel ignited.

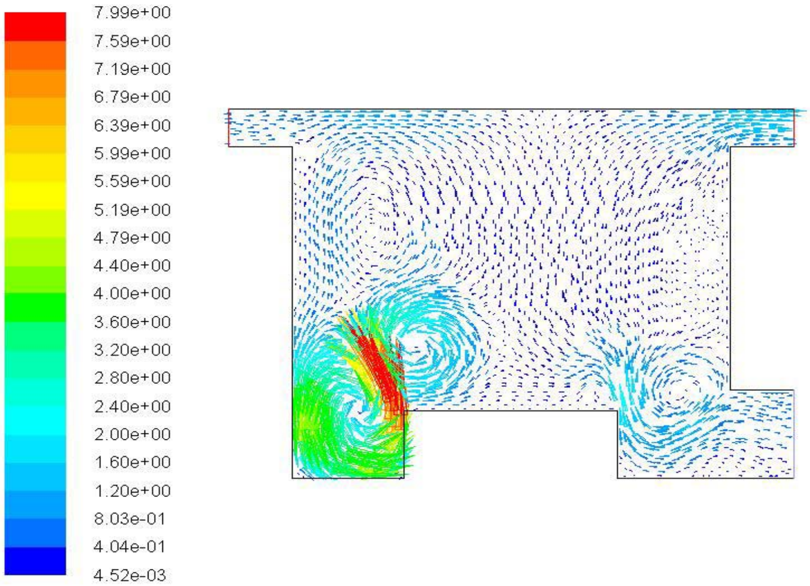

Figure 4.4 Vector of gas velocity inside cooking stove during volatile combustion period (m/s)

After the high temperature difference occurs in cooking stove due to the volatile combustion, the hot gases with high pressure flow out of cooking stove at the top of cooking stove causing the low pressure at the bottom of cooking stove which conform to Figure 4.5. The pressure difference between the bottom of cooking stove and ambient occurs. Therefore, fresh air flows into the cooking stove with the average velocity of 0.42 m/s. For the hot gases flowing out of cooking stove at the left side and right side of cooking stove, the velocity of hot gases equals to 0.52 and 1.22 m/s as referred to Figure 4.4 respectively.

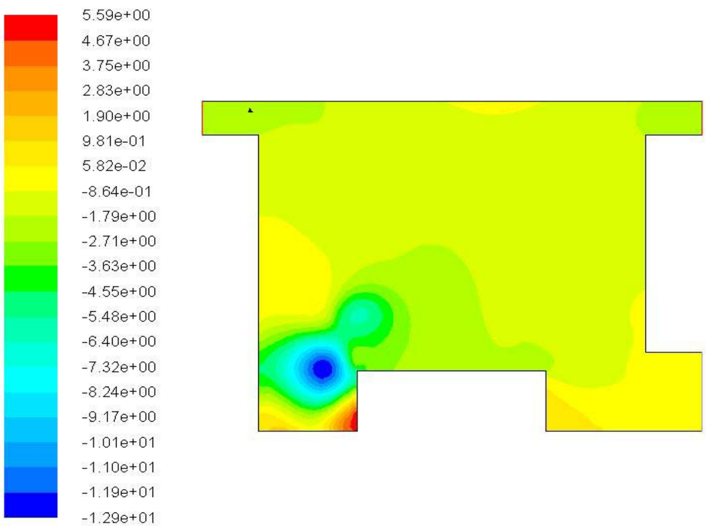

Figure 4.5 Static pressure inside cooking stove during volatile combustion period (gPa)

Since the low temperature of fresh air flow from right side to the left side and the hot gas flows to the top of cooking stove, the fresh air acts as the flow resistance of hot gases resulting in the hot gases cannot flow up to the top of cooking stove. Therefore, the vortex occurs at the left side of solid fuel making the lowest gauge pressure of -0.129 Pa occurring at the center of the vortex. For the gauge pressure at the air inlet and left side and right side of cooking stove equal to -0.09, -2.19 and -2.19 Pa respectively as shown in the Figure 4.5.

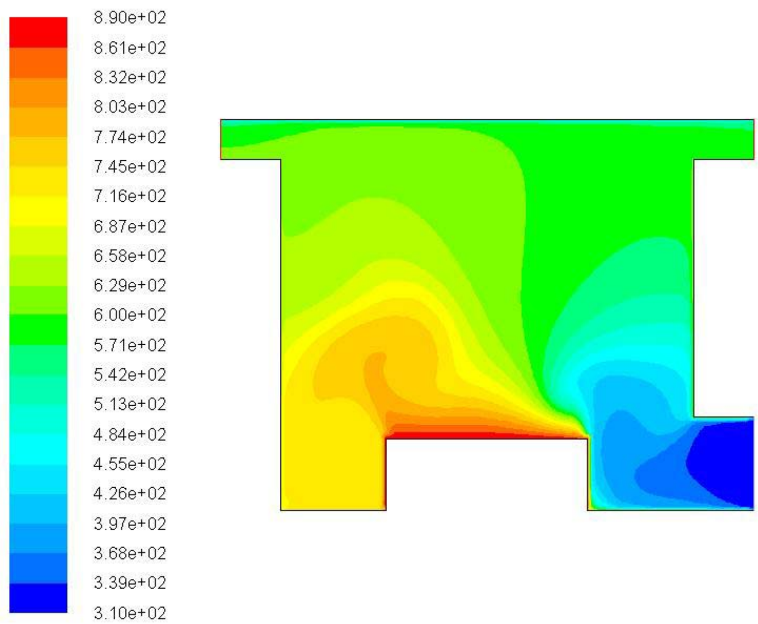

Figure 4.6 Static temperature inside cooking stove during volatile combustion period (K)

The volatile combustion occurs when the solid fuel decomposes into volatile then mixed with oxygen. The volatile combustion is exothermic reaction which the heat of reaction equals to 17,021.68 J/gram of volatile component in this case. The highest temperature occurs at the fuels surface which equals to 890 K. From the Figure 4.6, the temperature of hot gases reduces when flow up to the bottom of cooking stove due to mix with fresh air. So the hot gases temperature at the center of cooking stove is reduced to be 600 K. Moreover, the temperature at the left and right side of exhaust area equal to 588 K and 574 K, respectively.

Table 4.1 Temperature at each location of cooking stove and the percent of error of volatile combustion model

	Temperature (K)		
	Middle of cooking stoves	Left exhaust area	Right exhaust area
Experiment	522.85	474.15	471.15
Model	600	588	574
% Error	14.75	24.01	21.83

From Table 4.1, when the results of simulation are compared with the data from the experiment, the error of temperature at center of cooking stoves, left exhaust area and right exhaust area are 14.75 %, 24.01 % and 21.83 % respectively.

The error of high temperature occurring in the model when compared with experiment is caused by the higher heat loss occurring in the experiment since the assumption of each boundary temperature is required to be uniform along its surface in order to reduce the complexity of the model. However, the actual temperature of each boundary is not constant along its surface, for example, the temperature of cooking stove decreases along the distance away from solid fuel. Therefore, more heat is lost via each boundary in the experiment.

4.3.2 Char combustion part

The simulation of char combustion model is developed at the time of highest char combustion rate which is the beginning of char combustion period.

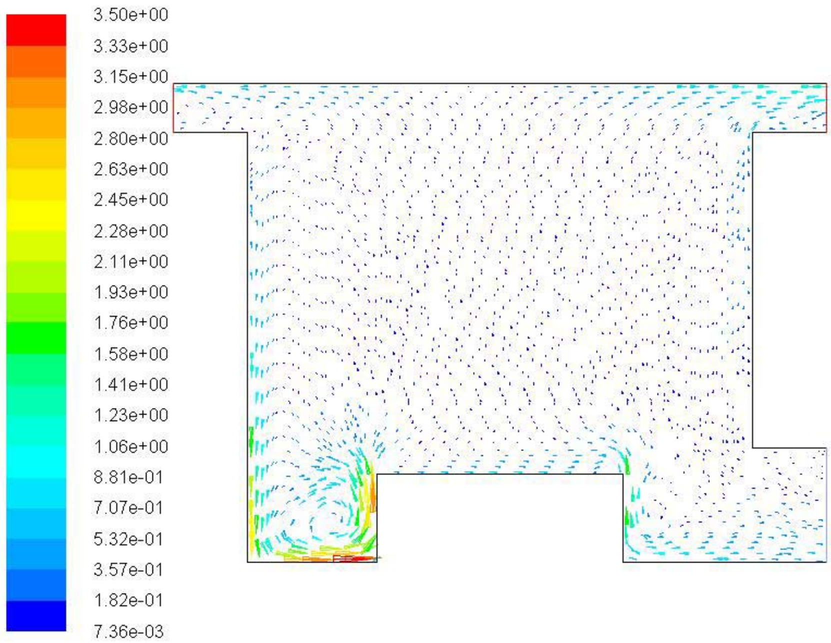

Figure 4.7 Vector of gas velocity inside cooking stove during char combustion period (m/s)

It is the same reason that fresh air can flow inside of cooking stove due to the high temperature difference and pressure difference between inside of cooking stove described previously. The fresh air flows into the cooking stove with the average velocity of 0.24 m/s and hot gases leave the cooking stove at the left and right side of cooking stove at the average of 0.38 m/s and 0.7 m/s respectively.

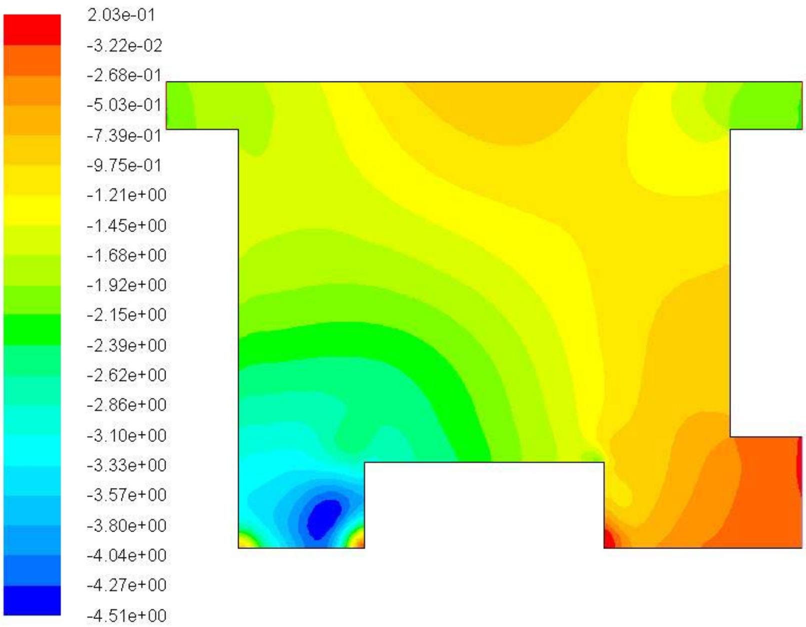

Figure 4.8 Static gauge pressure inside cooking stove during char combustion period (Pa)

The pressure gradient occurring in cooking stove is affected of the hot gas flowing to the bottom of cooking stove. The average gauge pressure at the air inlet, left and right exhaust area equal to -0.05 Pa, -2.17 Pa and -2.16 Pa respectively.

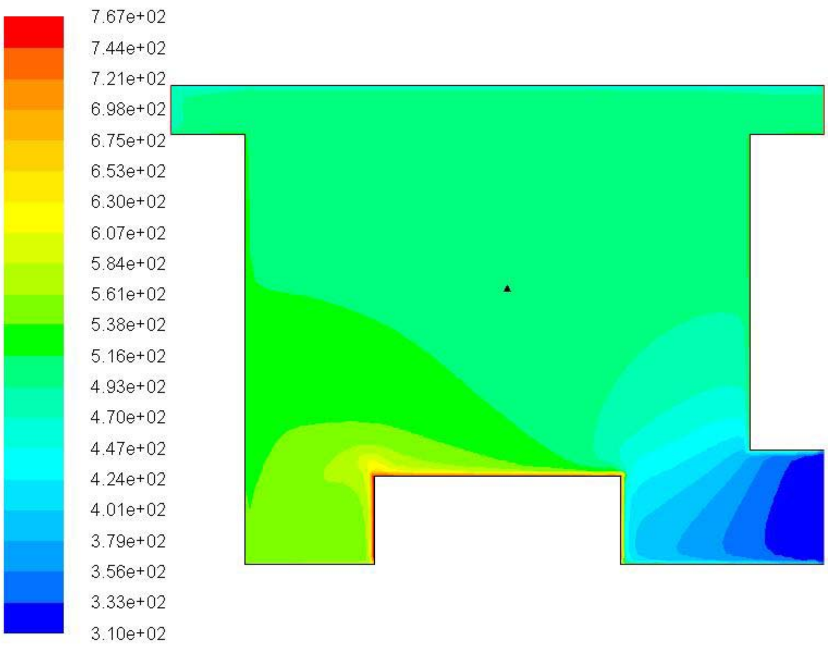

Figure 4.9 Static temperature inside cooking stove during char combustion period (K)

When fresh air flows into the cooking stove, it reacts with char providing heat source of cooking stove with the heat of reaction of -32.8 kJ/gram of carbon. The rate of char combustion from the model equals to 0.041 g/s. The temperature at the center of cooking, left and right of exhaust area equal to 516 K, 489 K and 498 K respectively.

Table 4.2 Reaction rate, temperature at each location of cooking stove and the percent of error of char combustion model

	Temperature (K)			Mass loss rate (g/s)
	Middle of cooking stoves	Left exhaust area	Right exhaust area	
Experiment	490.05	428.65	435.15	0.043
Model	515	489	498	0.041
Error	5.09	14.08	14.44	4.65

By referring to Table 4.2, the results from the simulation are compared with the data collected from the experiment. The percent error of temperature at middle of cooking stoves, left and right of exhaust area, and reaction rate are 5.09, 14.07, 14.44 and 4.65 respectively.

The reason that the temperature of the model is higher than the experiment is the same reason with volatile combustion phase. Due to the assumption of uniform temperature required to reduce the complexity of the model, more heat is lost through each boundary in the experiment.

4.4 Effects of cooking stove's geometry to the efficiency of cooking stove

To study the effect of cooking stove geometry on the efficiency of cooking stove, there are 17 cases of simulation are performed. The details of each configuration are shown in the appendix C. The operating condition obtained from the real operating condition equals to 49.22 kW. The fuel surface equals to 0.1413 m^2.

4.4.1 Combustion chamber height

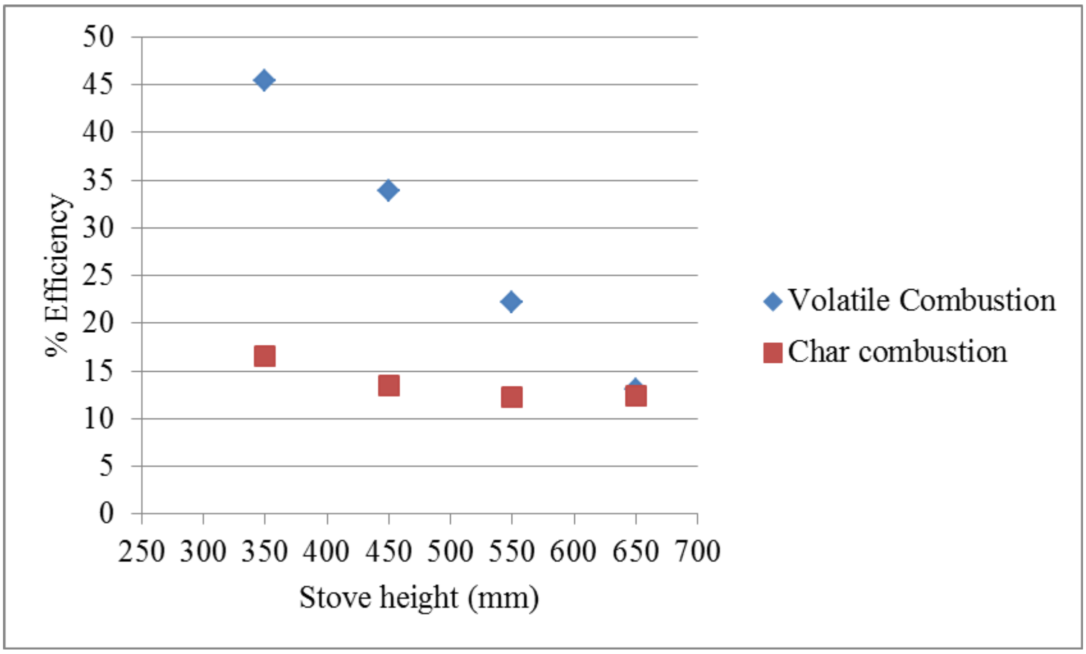

Figure 4.10 The relationship between the cooking stove's efficiency and cooking stove height

The effect of cooking stove's height on the efficiency of cooking stove is shown in Figure 4.10. The stove height of 350 mm gives the maximum efficiency of 45.44 % in volatile combustion period and 16.53 % in char combustion period. The higher cooking stoves of 450 mm, 550 mm and 650 mm attain the efficiency of 33.83 %, 22.19 %, 13.02 % and 12.89 % in the volatile combustion phase and the efficiency of 13.52 %, 12.3 %, 12.34 % and 12.13 % in char oxidation phase respectively.

From Figure 4.10, the efficiency of cooking stove decreases while the height of cooking stove increase. This is because if the wood and the bottom of the pan are closer with each other, fuel radiative heat and convective heat from flue gas can easily reach the bottom of the pan. Hence more heat can be transferred to the bottom of the pan which occurs in both of volatile combustion and char combustion period.

4.4.2 Height of air inlet size

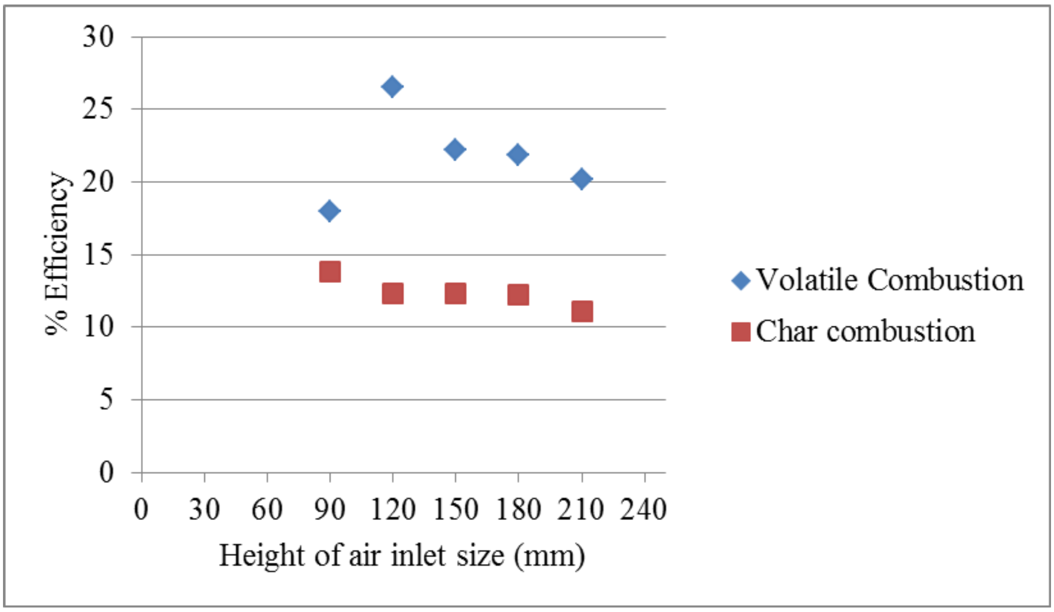

Figure 4.11 The relationship between the cooking stove's efficiency and height of air inlet size

Figure 4.11 shows the effect of air inlet height on the efficiency. For the volatile combustion period, the heights of air inlet of 90 mm, 120 mm, 150 mm, 180 mm and 210 mm provide the cooking stove's efficiency of 17.94 %, 26.54 %, 22.19 %, 21.9 % and 20.2 % respectively.

For the char combustion period, the effect of height of air inlet on the efficiency of cooking stove is same as volatile combustion period. The increasing air inlet height of cooking stove, 90 mm, 120 mm, 150 mm, 180 mm and 210 mm affect to the efficiency decreased to be 13.81 %, 12.3 %, 12.3 %, 12.25 % and 11.06 % respectively.

The cooking stove's efficiency reduces when the larger air inlet size increasing. Since, the efficiency of cooking stove depends on the amount of heat loss from the cooking stove. So the larger air inlet size affects that more heat can transfer out of the cooking stove via radiation and convection. So the efficiency of cooking stove is inversely proportional to the height of air inlet.

Conversely, the 90 mm of air inlet height in volatile combustion period gives the lower efficiency when compare with the 120 mm. This is because the smaller air inlet height makes the lower good draft. The amount of air that can flow to the cooking stove is not enough for combustion so it makes the efficiency decreasing in volatile combustion period.

4.4.3 Height of the position of air inlet

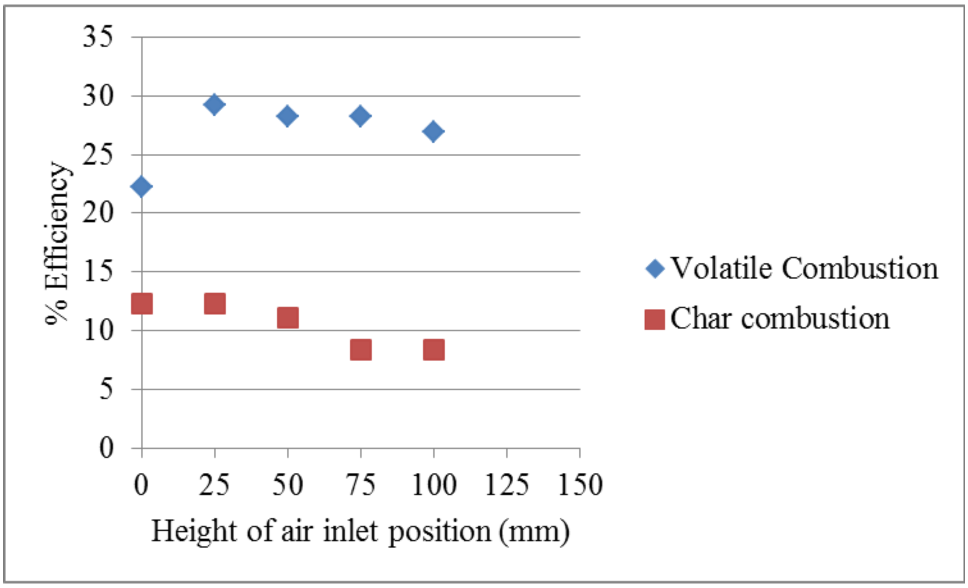

Figure 4.12 The relationship between the cooking stove's efficiency and height of air inlet position

The height of the position of air inlet affects to the efficiency of cooking stove since the higher air inlet position decreases the efficiency of cooking stove in both of volatile combustion and char combustion period. In the Figure 4.12, the heights of air inlet are changed to be 0 mm, 25 mm, 50 mm, 75 mm and 100 mm causing the efficiency of cooking stove to be 22.19 %, 29.2 %, 28.17 %, 28.26 % and 26.93 % in volatile combustion period and 12.3 %, 12.24 %, 11.06 %, 8.379 % and 8.32 % in char combustion period respectively.

Due to the increasing height of air inlet position, the heat loss via radiation through the air inlet position can be reduced so when changing the height of air inlet from 0 mm to be 25 mm the efficiency of cooking stove increasing in volatile combustion phase.

However, the increasing height of air inlet position reduce the ability of fresh air to mixed with fuel in both of volatile and char combustion period. Hence the efficiency drops while increases height of air inlet.

4.4.4 Height of exhaust outlet size

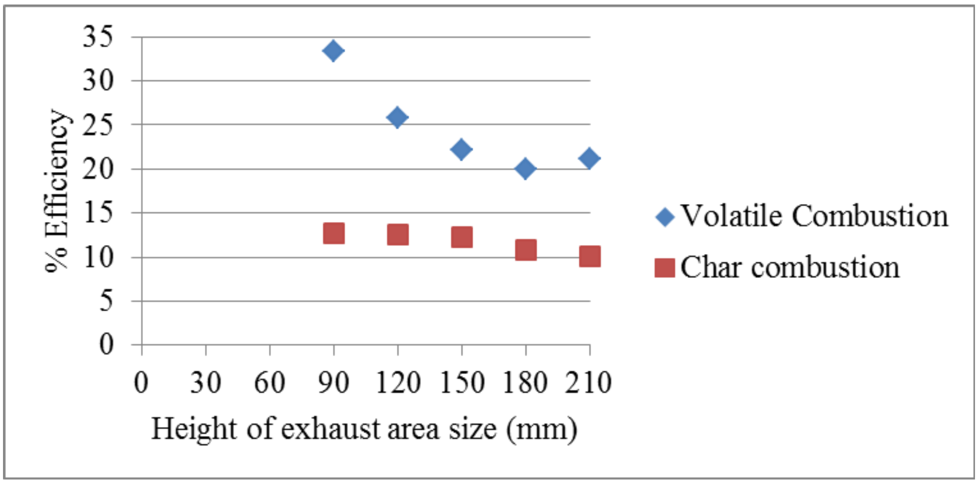

Figure 4.13 The relationship between the cooking stove's efficiency and height of exhaust area size

Figure 4.13 shows the effect of height of exhaust area size on the efficiency of cooking stove. From the result of the simulation, the increased height of exhaust area reduces the cooking stove efficiency in both volatile combustion and char combustion period.

The height of exhaust area of 90 mm, 120 mm, 150 mm, 180 mm and 210 mm gives the efficiency of 33.29 %, 25.81 %, 22.2 %, 19.96 % and 21.2 % in volatile combustion period and 12.7 %, 12.5 %, 12.3 %, 10.87 % and 10.08 % in char combustion period respectively.

Since the reduced height of exhaust area size decreases heat loss via radiation and convective heat loss out of cooking stove. So the efficiency is improved when reduces the height of exhaust area size.

4.5 Comparing cooking stove' s efficiency of each solid fuel behaviors

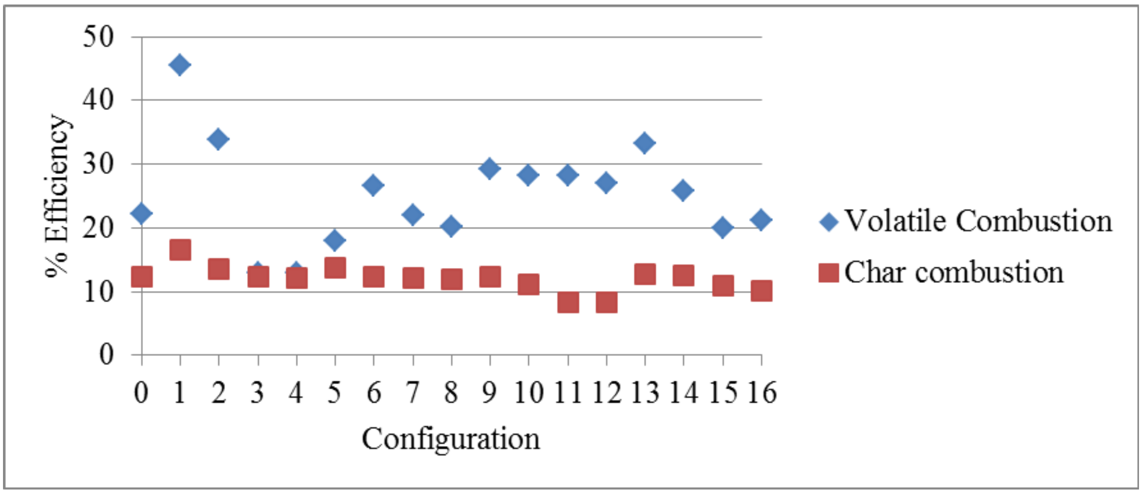

Figure 4.14 The cooking stove's efficiency of each configuration

From the results shown in Figure 4.14, the cooking stove efficiency of each configuration in volatile combustion period is greater than char combustion period owing to the difference of hot gases velocity between the two periods.

Due to the velocity of hot gases in volatile combustion period is greater than that of the char combustion period, resulting in the higher heat transfer coefficient in volatile combustion period. So more of heat stored in hot gases can be transferred to the bottom of the pan that makes the higher cooking stove efficiency of volatile combustion period compared with char combustion period.

4.6 Introducing the improved cooking stove

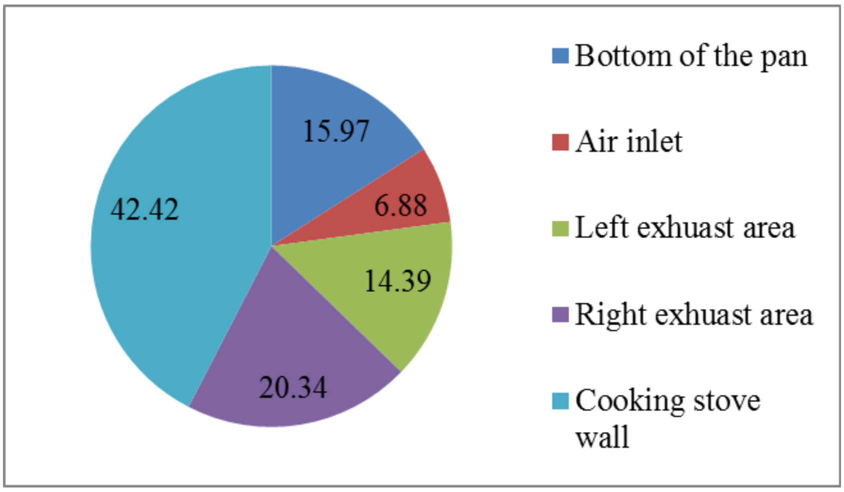

Figure 4.15 The percentage of avarage heat transfer through each position of the existing cooking stove in both of combustion periods.

The percent of heat transfer through each position of the existing cooking stove in both of combustion periods are shown in Figure 4.15. Most of heat (42.42 %) is lost via the cooking stove wall. In order to increase the efficiency of cooking stove the heat loss via the cooking stove wall should be reduced.

The reducing heat loss via cooking stove wall can be done by decreasing the area of cooking stove wall which is either decreasing the cooking stove diameter or cooking stove height. However, since the cooking stove diameter should be kept for supporting the existing cooking pan. So the cooking stove height is chosen in this study to decrease heat loss via the cooking stove wall.

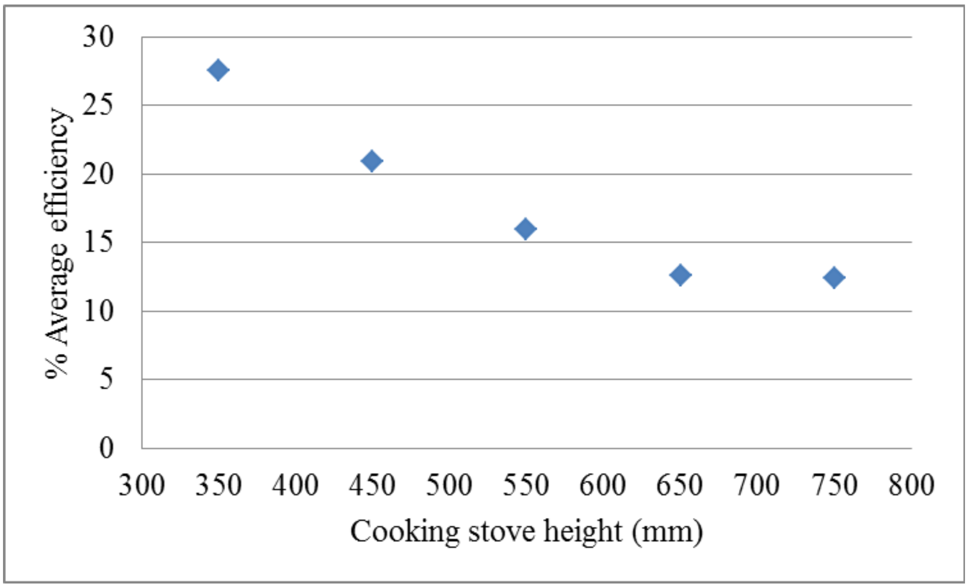

Figure 4.16 The relationship between the average cooking stove's efficiency and cooking stove height

From the previous study, the cooking stove height of 350 mm gives the highest average efficiency of cooking stove. So this configuration is used as the base case in order to reduce heat loss via cooking stove wall.

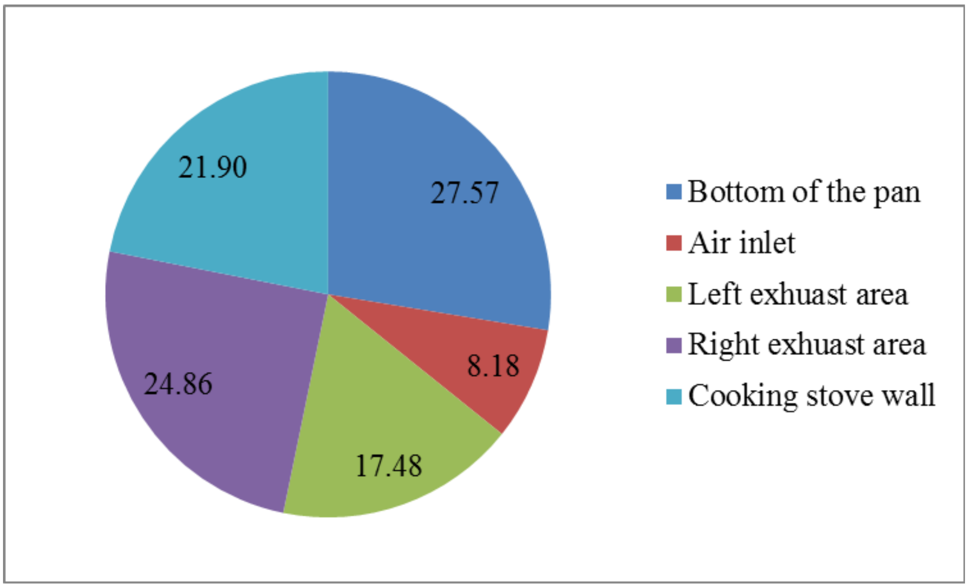

Figure 4.17 The avarage percentage of heat transfer through each position of the 350 mm-height-cooking stove in both of combustion periods.

From Figure 4.17, most of heat is still lost via 3 positions which are cooking stove wall, left and right exhaust area. So the method to reduce more heat loss is either decreasing more height of cooking stove wall or decreasing height of left and right exhaust area sizes.

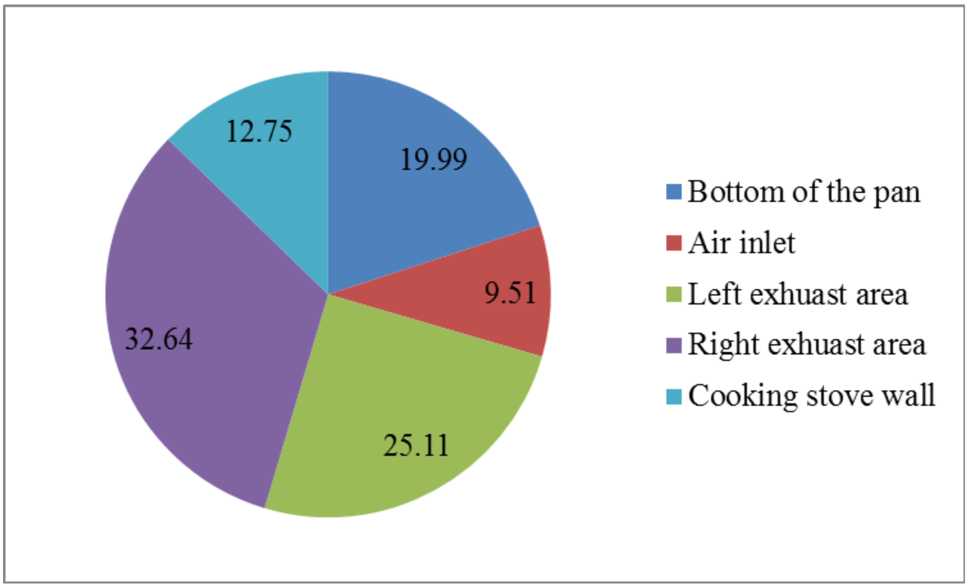

Figure 4.18 The avarage percentage of heat transfer through each position of the 300 mm-height-cooking stove in both of combustion periods.

The height of cooking stove is reduced from 350 mm to 300 mm resulted the decreasing in average efficiency of cooking stove from 27.57 % to 19.99 % as shown in Figure 4.18. This is because the reducing of cooking stove height decreases the draft of fresh air flowing into cooking stove. Moreover, the decreasing of draft decreases the velocity of hot gases. Since the decreasing velocity makes the heat transfer coefficient decrease, the cooking stove's efficiency is dropped.

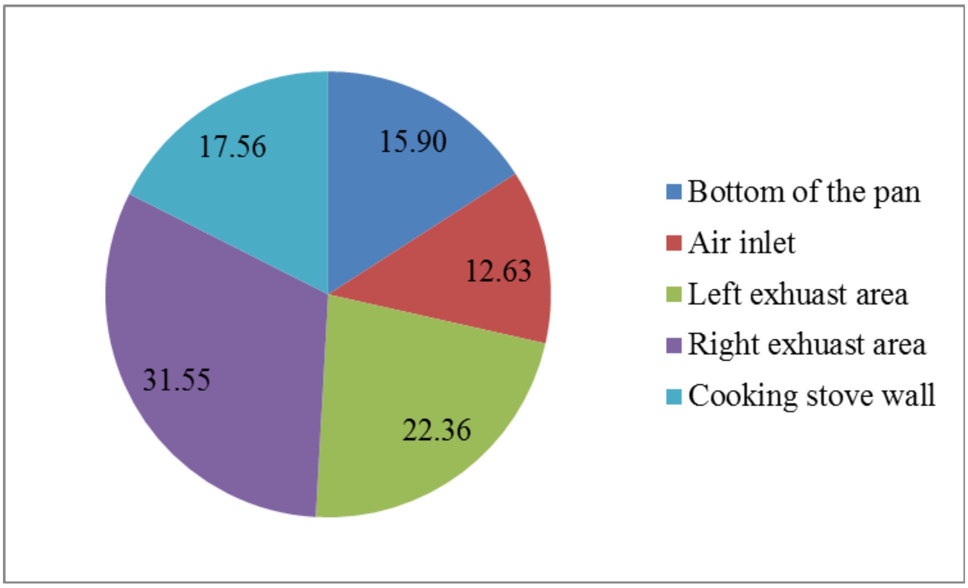

Figure 4.19 The avarage percentage of heat transfer through each position of the 120 mm-height-exhuast area in both of combustion periods.

On the other hand, the height of exhaust area is decreased from 150 mm to 120 mm but the cooking stove height is maintained at 350 mm in order to reduce heat loss in cooking stove. The result shown in Figure 4.19 expresses that the average cooking stove efficiency decreasing from 27.57 % to 15.90 % when reduces the height of exhaust area. This is because the decreasing height of exhaust area results the decreasing draft of cooking stove which affects the reducing in velocity of fresh air flow rate into cooking stove. So the reducing in velocity of fresh air decreases the combustion efficiency resulted in the decrease of cooking stove efficiency.

Therefore, the highest efficiency cooking stove in both volatile combustion and char combustion period is found in the same configuration as the existing cooking stove but changing the stove height from 550 mm to be 350 mm. By comparing the efficiency of the improved cooking stoves with the existing cooking stove, they are 45.44 % and 22.20 % of volatile combustion period and 16.53 % and 12.30 % of char combustion period, respectively.

CHAPTER 5 CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

The aim of this project is to improve the efficiency of the existing cooking stove located at Sahamit School, Chiang Mai, by using Computational Fluid Dynamic technique (CFD). The CFD technique offers low cost and low time consuming operation. The models are divided into 2 parts of solid fuel behavior which are volatile combustion and char combustion. Both of them are simulated in pseudo steady state. For the boundary condition of both models, they were collected from the experiment. On the other hand of initial conditions, they are predicted by using the correlation. After the models are built, the experiment is set up for validating the model.

For volatile combustion, the reaction rate of volatile combustion in gas phase is expressed by using eddy – dissipation model. By comparing the results from the simulation with the experiment, temperature at the center of cooking stoves, left and right sides of exhaust area are 515 K, 489 K and 498 K which have 14.75 %, 24.01 % and 21.83 % deviation from the experiment respectively.

For char combustion, the reaction of solid char combustion is modeled by using wall surface function. The results shows that the fuel loss rate and the temperature of center of cooking stove and the temperature of left and right of exhaust area equal to 0.041 g/s, 515 K, 489 K and 498 K which differ from the experiment 4.65 %, 5.09 %, 14.08 % and 14.44 %, respectively.

Then, 17 simulations of a variation of the existing cooking stove configurations are performed to study the effects of cooking stove's geometry on the cooking stove's efficiency which are the variation of combustion chamber height, height of air inlet size, height of air inlet position and height of exhaust area size. The effects of each parameter are shown below taking into account of volatile combustion and char combustion period.

- The efficiency of cooking stove decreases while the height of cooking stove increase.
- The cooking stove's efficiency reduces when the larger air inlet size is applied.
- The higher air inlet position decreases the efficiency of cooking stove.
- The increased height of exhaust area reduces the cooking stove efficiency.

After that, the improved cooking stove is introduced. The way of improving cooking stove is reducing the stove height of the existing cooking stove from 550 mm to 350 mm. The improved cooking stove's configuration gives the maximum efficiency of 45.44 % in volatile combustion period and 16.53 % in char combustion period respectively. However the existing cooking stove gives the efficiency of 22.20 % of volatile combustion period and 12.30 % of char combustion period, respectively.

5.2 Recommendations

1. The boundary conditions of cooking stove should be collected from real operating condition.
2. The fuel inlet should be varying for cooking the difference type of food.
3. The effect of cooking stove’s grate hole area should be studied.
4. The geometry of cooking stove should be optimized before constructing.
5. The storage of solid fuel should be built for protecting the humidity from ambient.

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APPENDIX A

Geometry of the cooking stove

A.1 Geometry of the cooking stove at Sahamit School

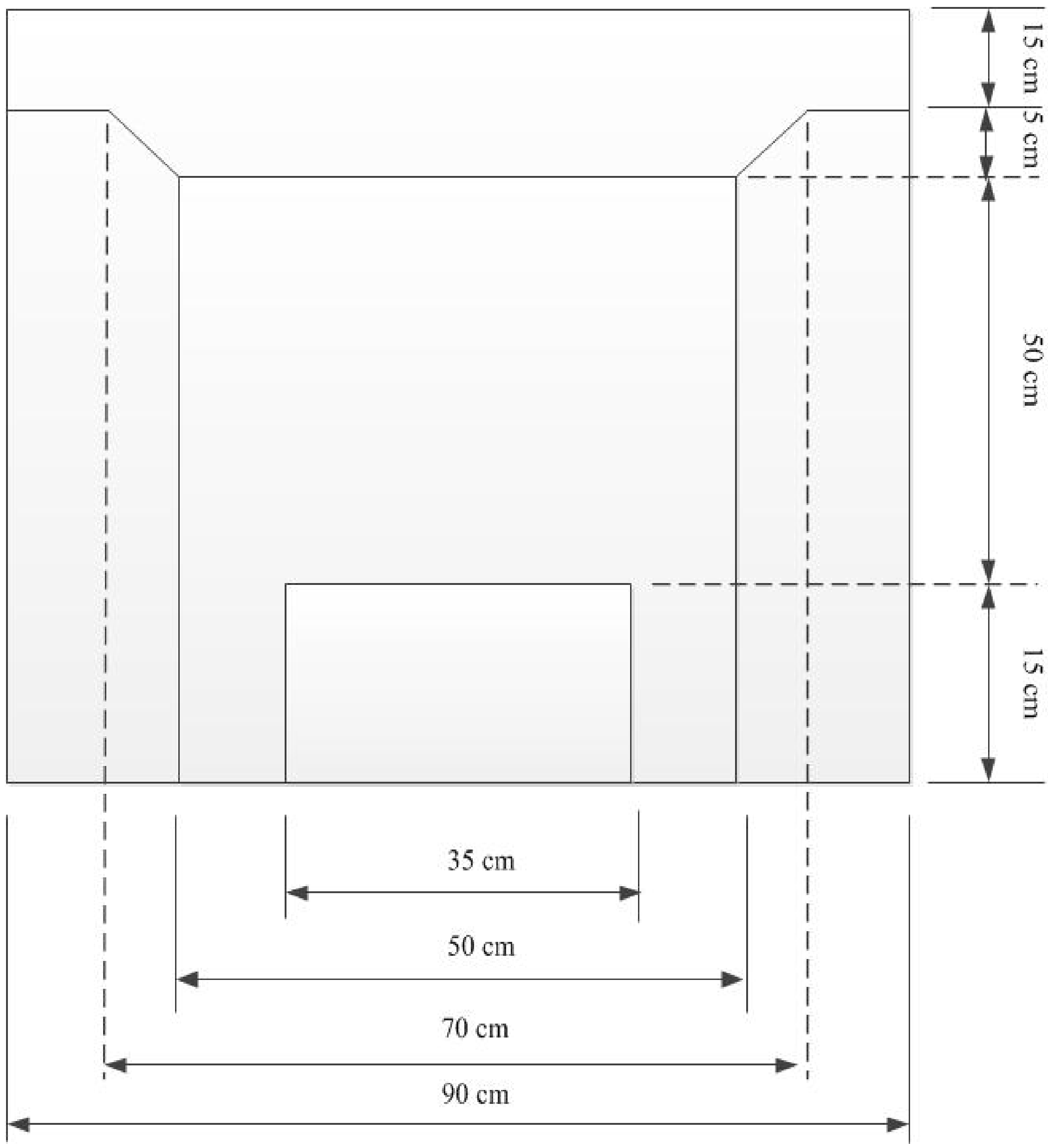

Figure A.1 The configuration of the existing cooking stove at the Sahamit School

A.2 Geometry of the validated cooking stove

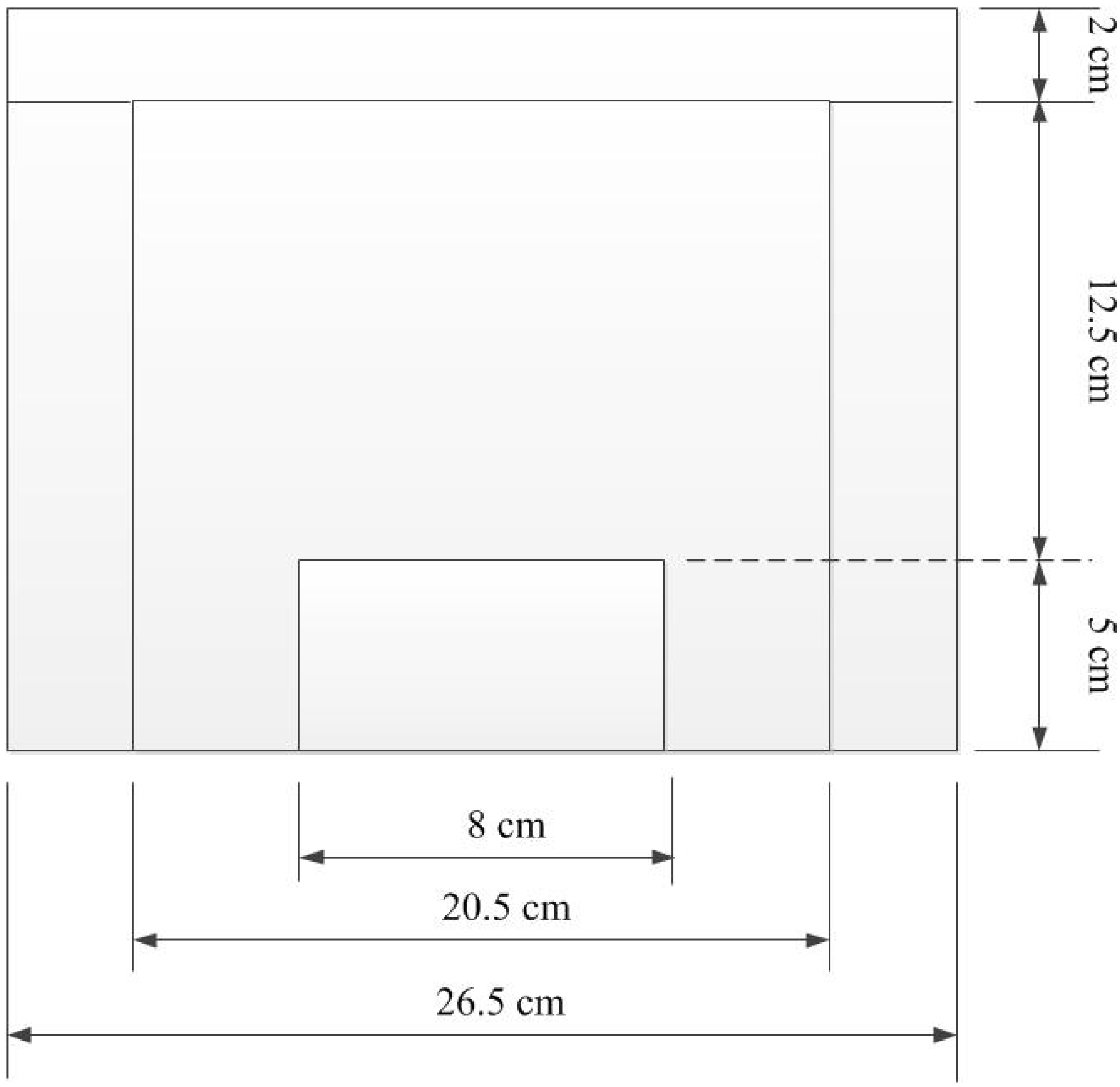

Figure A.2 The configuration of cooking stove used in the experiment

APPENDIX B

Fuel properties

Table B.1 Fuel Ultimate analysis

Component	Percent by weight (Dry basis)
% C	46.06
% H	7.1
% N	0.2
% O	46.64

Table B.2 Fuel proximate analysis

Parameter	Ton Gor
Proximate analysis	
Volatile matter, wt% (dry basis)	87
Fixed carbon, wt% (dry basis)	12.9
Ash, wt% (dry basis)	0.1

APPENDIX C

Experimental results

Table C.1 Temperature at each location of cooking stove and fuel loss rate at each time during experiment

Time (min)	Fuel Weight (g)	dm/dt (g/min)	Temperature (K)								
			Solid Fuel	Middle of cooking stove	Exhaust Area		Inside cooking stove's wall	Outside cooking stove's wall	Inside cooking stove's wall	Outside cooking stove's wall	Bottom of the pan
					Air inlet side	Opposite to air inlet side	Opposite to air inlet side		Air inlet side		
0	81.4	0.252	376.65	356.15	353.65	353.15	337.45	311.35	324.25	311.95	311.15
1	81.148	1.8	651.65	434.45	393.15	394.15	338.55	311.85	347.65	311.25	339.25
2	79.348	2.64	849.65	473.35	437.15	431.15	344.75	311.75	357.75	311.45	411.65
3	76.708	2.97	890.25	522.85	474.15	471.15	424.05	312.05	388.45	313.75	497.35
4	73.738	2.94	869.45	583.85	528.15	524.15	400.75	312.45	390.25	316.35	552.45
5	70.798	2.88	830.85	527.65	472.15	474.65	396.65	313.65	384.35	318.75	538.95
6	67.918	2.7	782.75	476.45	440.65	438.15	391.25	315.85	387.25	320.25	490.65
7	65.218	2.58	766.75	490.05	428.65	435.15	394.55	318.45	388.85	323.15	455.25
8	62.638	2.4	762.25	486.75	433.45	433.25	397.15	321.25	392.45	325.75	436.65
9	60.238	2.07	762.75	497.45	431.15	432.15	403.25	324.15	395.65	328.45	427.85
10	58.168	1.62	760.95	501.55	421.85	428.25	398.45	327.65	397.65	330.95	420.65
11	56.548	0.8	759.65	504.75	425.85	430.25	404.55	328.55	401.25	332.85	418.65
12	55.748	0.726	755.05	506.75	429.45	428.15	407.75	330.15	403.45	333.95	416.65
13	55.022	0.7	749.75	510.45	431.85	429.35	408.15	332.45	407.15	335.75	402.95
14	54.322	0.7	748.65	504.85	436.45	435.25	417.25	332.55	411.25	338.55	405.35

Time (min)	Fuel Weight (g)	dm/dt (g/min)	Temperature (K)								
			Solid Fuel	Middle of cooking stove	Exhaust Area		Inside cooking stove's wall	Outside cooking stove's wall	Inside cooking stove's wall	Outside cooking stove's wall	Bottom of the pan
					Air inlet side	Opposite to air inlet side	Opposite to air inlet side		Air inlet side		
15	53.622	0.66	745.45	505.95	439.95	433.25	415.25	333.55	412.75	339.25	404.75
16	52.962	0.6	747.65	500.15	432.25	430.15	409.95	335.15	413.25	340.45	404.15
17	52.362	0.588	747.95	501.95	428.65	428.25	414.05	334.95	416.95	341.45	403.45
18	51.774	0.576	742.95	499.75	435.15	432.25	417.35	336.65	419.45	342.45	404.25
19	51.198	0.57	739.05	497.85	432.15	431.55	424.65	337.75	421.95	343.65	405.25
20	50.628	0.564	747.05	491.65	429.45	428.35	412.75	339.65	422.65	343.65	404.25
21	50.064	0.552	746.55	488.75	435.35	432.55	413.75	341.45	424.65	345.15	402.15
22	49.512	0.51	747.55	483.75	435.05	427.85	416.65	342.85	425.55	345.15	402.15
23	49.002	0.432	742.65	482.45	435.95	431.25	413.65	343.75	427.55	344.95	402.95
24	48.57	0.3	741.75	481.45	433.45	429.35	418.45	342.95	428.35	345.95	394.75
25	48.27	0.24	739.65	479.15	432.15	425.05	413.45	344.55	428.95	346.25	386.65
26	48.03	0.1	742.65	485.05	431.25	428.55	424.85	345.45	430.25	346.95	385.65
27	47.93	0.072	734.45	478.65	429.15	427.15	416.45	346.95	431.15	347.55	384.65
28	47.858	0.066	735.65	477.95	424.95	422.15	421.35	347.05	431.75	348.25	384.55
29	47.792	0.048	732.65	476.75	412.15	420.15	423.25	347.55	432.35	348.15	385.65
30	47.744	-	734.45	471.55	405.15	417.15	423.35	348.15	433.25	348.95	386.65

APPENDIX D

Cooking stove's configuration of each case

Table D.1 The variation of cooking stove's configuration

Configuration	Stove height (mm)	Height of air inlet size (mm)	Height of air inlet position (mm)	Height of exhaust area size (mm)
0 (Base)	550	150	0	150
1	350	150	0	150
2	450			
3	650			
4	750			
5	550	90	0	150
6		120		
7		180		
8		210		
9	550	150	25	150
10			50	
11			75	
12			100	
13	550	150	0	90
14				120
15				180
16				210

APPENDIX E

The efficiency of each cooking stove's configuration

Table E.1 The efficiency of each cooking stove's efficiency during volatile combustion and char combustion period

Configuration	The percent of cooking stove's efficiency	
	Volatile Combustion	Char combustion
0	22.20	12.30
1	45.44	16.53
2	33.84	13.52
3	13.03	12.35
4	12.90	12.13
5	17.94	13.81
6	26.54	12.30
7	21.90	12.08
8	20.20	11.97
9	29.20	12.25
10	28.17	11.06
11	28.26	8.38
12	26.93	8.32
13	33.29	12.70
14	25.82	12.50
15	19.96	10.88
16	21.20	10.08

APPENDIX F

Fluent codes

F.1 Volatile combustion modeling

Models

Model Settings

Space 2D
Time Steady
Viscous Standard k-epsilon turbulence model
Wall Treatment Standard Wall Functions
Heat Transfer Enabled
Solidification and Melting Disabled
Radiation P1 Model
Species Reacting (5 species)
Coupled Dispersed Phase Disabled
NOx Pollutants Disabled
SOx Pollutants Disabled
Soot Disabled
Mercury Pollutants Disabled

Material Properties

Material: wood-volatiles-air (mixture)

Property Units Method Value(s)

Mixture Species names (wood_vol o2 co2 h2o n2)
Reaction eddy-dissipation ((reaction-1 ((wood_vol 1 1 0) (o2 1.1700691 1 1)) ((co2 1.0685863 0 1) (h2o 1.1346897 0 1)) ((n2 0 1)) (stoichiometry 1wood_vol + 1.1700691o2 --> 1.0685863co2 + 1.1346897h2o) (arrhenius 2.119e+11 2.027e+08 0) (mixing-rate 4 0.5) (use-third-body-efficiencies? . #f)))
Mechanism reaction-mechs ((mechanism-1 (reaction-type . all) (reaction-list reaction-1) (site-info)))
Density kg/m3 incompressible-ideal-gas #f
Cp (Specific Heat) j/kg-k mixing-law #f
Thermal Conductivity w/m-k constant 0.045400001

Viscosity kg/m-s constant 1.72e-05
Mass Diffusivity m2/s kinetic-theory #f
Thermal Diffusion Coefficient kg/m-s kinetic-theory #f
Absorption Coefficient 1/m wsggm-domain-based #f
Scattering Coefficient 1/m constant 0
Scattering Phase Function isotropic #f
Refractive Index constant 1
Speed of Sound m/s none #f

Material: (nitrogen . wood-volatiles-air) (fluid)

Property Units Method Value(s)

Cp (Specific Heat) j/kg-k polynomial (300-1000: 979.04298 0.4179639 -0.0011762792 1.6743943e-06 -7.2562971e-10) (1000-5000: 868.62291 0.44162954 -0.00016872295 2.9967875e-08 -2.0043858e-12)
Molecular Weight kg/kgmol constant 28.0134
Standard State Enthalpy j/kgmol constant 0
Standard State Entropy j/kgmol-k constant 191494.78
Reference Temperature k constant 298.15
L-J Characteristic Length angstrom constant 3.621
L-J Energy Parameter k constant 97.53
Speed of Sound m/s none #f

Material: (water-vapor . wood-volatiles-air) (fluid)

Property Units Method Value(s)

Cp (Specific Heat) j/kg-k polynomial (300-1000: 1563.0767 1.6037546 -0.0029327841 3.2161009e-06 -1.1568268e-09) (1000-5000: 1233.2338 1.4105233 -0.00040291411 5.5427718e-08 -2.949824e-12)
Molecular Weight kg/kgmol constant 18.01534
Standard State Enthalpy j/kgmol constant -2.418379e+08
Standard State Entropy j/kgmol-k constant 188696.44
Reference Temperature k constant 298.15
L-J Characteristic Length angstrom constant 2.605
L-J Energy Parameter k constant 572.4
Speed of Sound m/s none #f

Material: (carbon-dioxide . wood-volatiles-air) (fluid)

Property Units Method Value(s)

Cp (Specific Heat) j/kg-k polynomial (300-1000: 429.92889 1.8744735 -0.001966485 1.2972514e-06 -3.9999562e-10) (1000-5000: 841.37645 0.59323928 -0.00024151675 4.5227279e-08 -3.1531301e-12)

Molecular Weight kg/kgmol constant 44.00995

Standard State Enthalpy j/kgmol constant -3.9353235e+08

Standard State Entropy j/kgmol-k constant 213720.2

Reference Temperature k constant 298.15

L-J Characteristic Length angstrom constant 3.941

L-J Energy Parameter k constant 195.2

Speed of Sound m/s none #f

Material: (oxygen . wood-volatiles-air) (fluid)

Property Units Method Value(s)

Cp (Specific Heat) j/kg-k polynomial (300-1000: 834.82647 0.29295801 -0.00014956371 3.4138849e-07 -2.2783585e-10) (1000-5000: 960.75234 0.15941258 -3.2708852e-05 4.6127648e-09 -2.9528324e-13)

Molecular Weight kg/kgmol constant 31.9988

Standard State Enthalpy j/kgmol constant 0

Standard State Entropy j/kgmol-k constant 205026.86

Reference Temperature k constant 298.15

L-J Characteristic Length angstrom constant 3.458

L-J Energy Parameter k constant 107.4

Speed of Sound m/s none #f

Material: (wood-volatiles . wood-volatiles-air) (fluid)

Property Units Method Value(s)

Cp (Specific Heat) j/kg-k constant 1500

Molecular Weight kg/kgmol constant 30

Standard State Enthalpy j/kgmol constant -6.9443181e+08

Standard State Entropy j/kgmol-k constant 0

Reference Temperature k constant 298.14999

L-J Characteristic Length angstrom constant 4

L-J Energy Parameter k constant 100

Speed of Sound m/s none #f

Material: woodvol (combusting-particle)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1400
Cp (Specific Heat)	j/kg-k	constant	1680
Thermal Conductivity	w/m-k	constant	0.33
Latent Heat	j/kg	constant	0
Vaporization Temperature	k	constant	400
Volatile Component Fraction	%	constant	87
Binary Diffusivity	m2/s	constant	4e-05
Swelling Coefficient		constant	1.4
Burnout Stoichiometric Ratio		constant	2.67
Combustible Fraction	%	constant	12.9
Heat of Reaction for Burnout	j/kg	constant	32789000
React. Heat Fraction Absorbed by Solid	%	constant	30
Devolatilization Model	1/s	constant	50
Combustion Model		diffusion-limited	#f

Material: wood (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	700
Cp (Specific Heat)	j/kg-k	constant	2310
Thermal Conductivity	w/m-k	constant	0.173

Material: brick (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1922
Cp (Specific Heat)	j/kg-k	constant	900
Thermal Conductivity	w/m-k	constant	0.60000002

Material: air (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.225
Cp (Specific Heat)	j/kg-k	constant	1006.43
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.7894e-05
Molecular Weight	kg/kgmol	constant	28.966
Standard State Enthalpy	j/kgmol	constant	0

Standard State Entropy j/kgmol-k constant 194336
Reference Temperature k constant 298.15
L-J Characteristic Length angstrom constant 3.711
L-J Energy Parameter k constant 78.6
Absorption Coefficient 1/m constant 0
Scattering Coefficient 1/m constant 0
Scattering Phase Function isotropic #f
Thermal Expansion Coefficient 1/k constant 0
Refractive Index constant 1
Speed of Sound m/s none #f

Material: aluminum (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2719
Cp (Specific Heat)	j/kg-k	constant	871
Thermal Conductivity	w/m-k	constant	202.4

Cell Zone Conditions

Zones

name	id	type
fluid	2	fluid

Setup Conditions

fluid

Condition Value

Material Name wood-volatiles-air
Specify source terms? no
Source Terms ((mass) (x-momentum) (y-momentum) (k) (epsilon) (species-0) (species-1) (species-2) (species-3) (energy) (p1))
Specify fixed values? no
Fixed Values ((x-velocity (inactive . #f) (constant . 0) (profile)) (y-velocity (inactive . #f) (constant . 0) (profile)) (k (inactive . #f) (constant . 0) (profile)) (epsilon (inactive . #f) (constant . 0) (profile)) (species-0 (inactive . #f) (constant . 0) (profile)) (species-1 (inactive . #f) (constant . 0) (profile)) (species-2 (inactive . #f) (constant . 0) (profile)) (species-3 (inactive . #f) (constant . 0) (profile)) (temperature (inactive . #f) (constant . 0) (profile)))
Frame Motion? no
Relative To Cell Zone -1
Reference Frame Rotation Speed (rad/s) 0
Reference Frame X-Velocity Of Zone (m/s) 0
Reference Frame Y-Velocity Of Zone (m/s) 0
Reference Frame X-Origin of Rotation-Axis (m) 0
Reference Frame Y-Origin of Rotation-Axis (m) 0
Reference Frame User Defined Zone Motion Function none
Mesh Motion? no
Relative To Cell Zone -1
Moving Mesh Rotation Speed (rad/s) 0
Moving Mesh X-Velocity Of Zone (m/s) 0
Moving Mesh Y-Velocity Of Zone (m/s) 0
Moving Mesh X-Origin of Rotation-Axis (m) 0
Moving Mesh Y-Origin of Rotation-Axis (m) 0
Moving Mesh User Defined Zone Motion Function none
Participates in radiation yes
Deactivated Thread no
Laminar zone?no
Set Turbulent Viscosity to zero within laminar zone? yes
Embedded Subgrid-Scale Model 0
Momentum Spatial Discretization 0
Cwale 0.325
Cs 0.1
Porous zone?no
X-Component of Direction-1 Vector 1
Y-Component of Direction-1 Vector 0
Relative Velocity Resistance Formulation?yes
Direction-1 Viscous Resistance (1/m2) 0
Direction-2 Viscous Resistance (1/m2) 0
Choose alternative formulation for inertial resistance? no
Direction-1 Inertial Resistance (1/m) 0
Direction-2 Inertial Resistance (1/m) 0

C0 Coefficient for Power-Law 0
C1 Coefficient for Power-Law 0
Porosity 1
Solid Material Name aluminum
Reaction Mechanism 0
Activate reaction mechanisms? yes
Surface-Volume-Ratio (1/m) 0

Boundary Conditions

Zones

name	id	type
pi	9	pressure-inlet
bs	3	wall
fs_2	4	wall
fs_1	5	wall
po_1	6	pressure-outlet
inlet	7	mass-flow-inlet
po_2	8	pressure-outlet
s_wall	10	wall
bp	11	wall

Setup Conditions

pi

Condition	Value
Reference Frame	0
Gauge Total Pressure (pascal)	0
Supersonic/Initial Gauge Pressure (pascal)	0
Total Temperature (k)	310.15
Direction Specification Method	1
Coordinate System	0
X-Component of Flow Direction	1
Y-Component of Flow Direction	0
X-Component of Flow Direction	1
Y-Component of Flow Direction	0
X-Component of Axis Direction	1
Y-Component of Axis Direction	0

Z-Component of Axis Direction	0
X-Coordinate of Axis Origin (m)	0
Y-Coordinate of Axis Origin (m)	0
Z-Coordinate of Axis Origin (m)	0
Turbulent Specification Method	0
Turbulent Kinetic Energy (m2/s2)	1
Turbulent Dissipation Rate (m2/s3)	1
Turbulent Intensity (%)	10
Turbulent Length Scale (m)	1
Hydraulic Diameter (m)	1
Turbulent Viscosity Ratio	10
Specify Species in Mole Fractions?	yes

(((constant . 0) (profile)) ((constant . 0.21) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))

External Black Body Temperature Method	0
Black Body Temperature (k)	300
Internal Emissivity	0

is zone used in mixing-plane model? no

bs

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	aluminum
Thermal BC Type	1
Temperature (k)	0
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Internal Emissivity	1
External Emissivity	1

External Radiation Temperature (k) 300
Wall Roughness Height (m) 0
Wall Roughness Constant 0.5
(0 0 0 0)
(((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))
Rotation Speed (rad/s) 0
X-Position of Rotation-Axis Origin (m) 0
Y-Position of Rotation-Axis Origin (m) 0
X-component of shear stress (pascal) 0
Y-component of shear stress (pascal) 0
Surface tension gradient (n/m-k) 0
Specularity Coefficient 0

fs_2

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	wood
Thermal BC Type	0
Temperature (k)	890.25
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Internal Emissivity	0.96
External Emissivity	1
External Radiation Temperature (k)	300
Wall Roughness Height (m)	0
Wall Roughness Constant	0.5
	(0 0 0 0)

(((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))
Rotation Speed (rad/s) 0
X-Position of Rotation-Axis Origin (m) 0
Y-Position of Rotation-Axis Origin (m) 0
X-component of shear stress (pascal) 0
Y-component of shear stress (pascal) 0
Surface tension gradient (n/m-k) 0
Specularity Coefficient 0

fs_1

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	wood
Thermal BC Type	0
Temperature (k)	890.25
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Internal Emissivity	0.96
External Emissivity	1
External Radiation Temperature (k)	300
Wall Roughness Height (m)	0
Wall Roughness Constant	0.5
	(0 0 0 0)
	(((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0

X-component of shear stress (pascal) 0
Y-component of shear stress (pascal) 0
Surface tension gradient (n/m-k) 0
Specularity Coefficient 0

po_1

Condition	Value
Gauge Pressure (pascal)	-2.1936456
Backflow Total Temperature (k)	310.15
Backflow Direction Specification Method	1
X-Component of Flow Direction	1
Y-Component of Flow Direction	0
X-Component of Axis Direction	1
Y-Component of Axis Direction	0
Z-Component of Axis Direction	0
X-Coordinate of Axis Origin (m)	0
Y-Coordinate of Axis Origin (m)	0
Z-Coordinate of Axis Origin (m)	0
Turbulent Specification Method	0
Backflow Turbulent Kinetic Energy (m2/s2)	1
Backflow Turbulent Dissipation Rate (m2/s3)	1
Backflow Turbulent Intensity (%)	10
Backflow Turbulent Length Scale (m)	1
Backflow Hydraulic Diameter (m)	1
Backflow Turbulent Viscosity Ratio	10
External Black Body Temperature Method	0
Black Body Temperature (k)	300
Internal Emissivity	0
Specify Species in Mole Fractions?	no
Backflow	(((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))
is zone used in mixing-plane model?	no
Specify Average Pressure Specification	no
Specify targeted mass flow rate	no
Targeted mass flow (kg/s)	1

Upper Limit of Absolute Pressure Value (pascal) 5000000
Lower Limit of Absolute Pressure Value (pascal) 1

inlet

Condition	Value
Reference Frame	0
Mass Flow Specification Method	1
Mass Flow Rate (kg/s)	0.000446835
Mass Flux (kg/m2-s)	0.004468348
Average Mass Flux (kg/m2-s)	1
Upstream Torque Integral (n-m)	1
Upstream Total Enthalpy Integral (w/m2)	1
Total Temperature (k)	890.25
Supersonic/Initial Gauge Pressure (pascal)	0
Direction Specification Method	1
Coordinate System	0
X-Component of Flow Direction	1
Y-Component of Flow Direction	0
X-Component of Flow Direction	1
Y-Component of Flow Direction	0
X-Component of Axis Direction	1
Y-Component of Axis Direction	0
Z-Component of Axis Direction	0
X-Coordinate of Axis Origin (m)	0
Y-Coordinate of Axis Origin (m)	0
Z-Coordinate of Axis Origin (m)	0
Turbulent Specification Method	0
Turbulent Kinetic Energy (m2/s2)	1
Turbulent Dissipation Rate (m2/s3)	1
Turbulent Intensity (%)	10
Turbulent Length Scale (m)	1
Hydraulic Diameter (m)	1
Turbulent Viscosity Ratio	10
Specify Species in Mole Fractions?	yes

(((constant . 1) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))

External Black Body Temperature Method	0
Black Body Temperature (k)	300
Internal Emissivity	0.96

is zone used in mixing-plane model? no

po_2

Condition	Value
Gauge Pressure (pascal)	-2.1936456
Backflow Total Temperature (k)	310.15
Backflow Direction Specification Method	1
X-Component of Flow Direction	1
Y-Component of Flow Direction	0
X-Component of Axis Direction	1
Y-Component of Axis Direction	0
Z-Component of Axis Direction	0
X-Coordinate of Axis Origin (m)	0
Y-Coordinate of Axis Origin (m)	0
Z-Coordinate of Axis Origin (m)	0
Turbulent Specification Method	0
Backflow Turbulent Kinetic Energy (m2/s2)	1
Backflow Turbulent Dissipation Rate (m2/s3)	1
Backflow Turbulent Intensity (%)	10
Backflow Turbulent Length Scale (m)	1
Backflow Hydraulic Diameter (m)	1
Backflow Turbulent Viscosity Ratio	10
External Black Body Temperature Method	0
Black Body Temperature (k)	300
Internal Emissivity	0
Specify Species in Mole Fractions?	no
Backflow	(((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))
is zone used in mixing-plane model?	no
Specify Average Pressure Specification	no
Specify targeted mass flow rate	no
Targeted mass flow (kg/s)	1
Upper Limit of Absolute Pressure Value (pascal)	5000000
Lower Limit of Absolute Pressure Value (pascal)	1

s_wall

Condition	Value
Wall Thickness (m)	0.03
Heat Generation Rate (w/m3)	0
Material Name	brick

Thermal BC Type 0
Temperature (k) 313.75
Heat Flux (w/m2) 0
Convective Heat Transfer Coefficient (w/m2-k) 0
Free Stream Temperature (k) 300
Wall Motion 0
Shear Boundary Condition 0
Define wall motion relative to adjacent cell zone? yes
Apply a rotational velocity to this wall? no
Velocity Magnitude (m/s) 0
X-Component of Wall Translation 1
Y-Component of Wall Translation 0
Define wall velocity components? no
X-Component of Wall Translation (m/s) 0
Y-Component of Wall Translation (m/s) 0
Internal Emissivity 0.93
External Emissivity 1
External Radiation Temperature (k) 300
Wall Roughness Height (m) 0
Wall Roughness Constant 0.5
(0 0 0 0)
(((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))
Rotation Speed (rad/s) 0
X-Position of Rotation-Axis Origin (m) 0
Y-Position of Rotation-Axis Origin (m) 0
X-component of shear stress (pascal) 0
Y-component of shear stress (pascal) 0
Surface tension gradient (n/m-k) 0
Specularity Coefficient 0

bp

Condition Value

Wall Thickness (m) 0.001
Heat Generation Rate (w/m3) 0
Material Name aluminum
Thermal BC Type 0
Temperature (k) 497.35
Heat Flux (w/m2) 0
Convective Heat Transfer Coefficient (w/m2-k) 0
Free Stream Temperature (k) 300

Wall Motion 0
Shear Boundary Condition 0
Define wall motion relative to adjacent cell zone? yes
Apply a rotational velocity to this wall? no
Velocity Magnitude (m/s) 0
X-Component of Wall Translation 1
Y-Component of Wall Translation 0
Define wall velocity components? no
X-Component of Wall Translation (m/s) 0
Y-Component of Wall Translation (m/s) 0
Internal Emissivity 0.6
External Emissivity 1
External Radiation Temperature (k) 300
Wall Roughness Height (m) 0
Wall Roughness Constant 0.5
(0 0 0 0)
(((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))
Rotation Speed (rad/s) 0
X-Position of Rotation-Axis Origin (m) 0
Y-Position of Rotation-Axis Origin (m) 0
X-component of shear stress (pascal) 0
Y-component of shear stress (pascal) 0
Surface tension gradient (n/m-k) 0
Specularity Coefficient 0

Solver Settings

Equations

Equation Solved

Flow yes
Turbulence yes
wood_vol yes
o2 yes
co2 yes
h2o yes
Energy yes
P1 yes

Numerics

Numeric	Enabled
Absolute Velocity Formulation	yes

Relaxation

Variable	Relaxation Factor
Pressure	0.69999999
Density	1
Body Forces	1
Momentum	0.30000001
Turbulent Kinetic Energy	0.8
Turbulent Dissipation Rate	0.8
Turbulent Viscosity	1
wood_vol	0.1
o2	1
co2	1
h2o	1
Energy	1
P1	1

Linear Solver

Variable	Solver Type	Termination Criterion	Residual Reduction Tolerance
Pressure	V-Cycle	0.1	
X-Momentum	Flexible	0.1	0.7
Y-Momentum	Flexible	0.1	0.7
Turbulent Kinetic Energy	Flexible	0.1	0.7
Turbulent Dissipation Rate	Flexible	0.1	0.7
wood_vol	Flexible	0.1	0.7
o2	Flexible	0.1	0.7
co2	Flexible	0.1	0.7
h2o	Flexible	0.1	0.7
Energy	Flexible	0.1	0.7
P1	Flexible	0.1	0.7

Pressure-Velocity Coupling

Parameter   Value

```
    ------------------
    Type       SIMPLE

  Discretization Scheme

    Variable                  Scheme
    -----------------------------------------------
    Pressure                  Standard
    Momentum                  First Order Upwind
    Turbulent Kinetic Energy  First Order Upwind
    Turbulent Dissipation Rate  First Order Upwind
wood_vol                  First Order Upwind
o2                        First Order Upwind
co2                       First Order Upwind
h2o                       First Order Upwind
    Energy                    First Order Upwind

  Solution Limits

    Quantity                  Limit
    ---------------------------------------
    Minimum Absolute Pressure     1
    Maximum Absolute Pressure     5e+10
    Minimum Temperature           1
    Maximum Temperature           5000
Minimum Turb. Kinetic Energy      1e-14
Minimum Turb. Dissipation Rate    1e-20
Maximum Turb. Viscosity Ratio     100000
```

F.2 Char combustion modeling

FLUENT
Version: 2d, dp, pbns, spe, ske (2d, double precision, pressure-based, species, standard k-epsilon)
Release: 13.0.0
Title:

Models

```
   Model                    Settings
   -------------------------------------------------------------
   Space                    2D
   Time                     Steady
   Viscous                  Standard k-epsilon turbulence model
   Wall Treatment           Standard Wall Functions
   Heat Transfer            Enabled
   Solidification and Melting   Disabled
   Radiation                P1 Model
   Species                  Reacting (5 species)
   Coupled Dispersed Phase      Disabled
NOx Pollutants              Disabled
SOx Pollutants              Disabled
   Soot                     Disabled
   Mercury Pollutants           Disabled
```

Material Properties

Material: (carbon . wood-volatiles-air) (fluid)

```
      Property                Units      Method      Value(s)
      ---------------------------------------------------------------------------------------------------
--------------------------------------------------------------------------------------------------------
Cp (Specific Heat)          j/kg-k      polynomial   (300-1000: 1729.566 0.055971235 -0.00018673958 2.1048488e-07 -7.660448e-11) (1000-5000: 1801.2126 -0.12370504 6.2902174e-05 -7.9600504e-09 2.2918272e-13)
      Molecular Weight           kg/kgmol    constant     12.01115
      Standard State Enthalpy    j/kgmol     constant     0
      Standard State Entropy     j/kgmol-k   constant     157994.97
      Reference Temperature      k           constant     298
      L-J Characteristic Length  angstrom    constant     4
      L-J Energy Parameter       k           constant     100
```

Speed of Sound m/s none #f

Material: carbon (fluid)

Property Units Method Value(s)

Density kg/m3 constant 2000
Cp (Specific Heat) j/kg-k polynomial (300-1000: 1729.566 0.055971235 -0.00018673958 2.1048488e-07 -7.660448e-11) (1000-5000: 1801.2127 -0.12370504 6.2902174e-05 -7.9600504e-09 2.2918273e-13)
Thermal Conductivity w/m-k constant 0.33
Viscosity kg/m-s constant 1.72e-05
Molecular Weight kg/kgmol constant 12.01115
Standard State Enthalpy j/kgmol constant 7.1670938e+08
Standard State Entropy j/kgmol-k constant 157994.97
Reference Temperature k constant 298
L-J Characteristic Length angstrom constant 4
L-J Energy Parameter k constant 100
Absorption Coefficient 1/m constant 0
Scattering Coefficient 1/m constant 0
Scattering Phase Function isotropic #f
Thermal Expansion Coefficient 1/k constant 0
Refractive Index constant 1
Speed of Sound m/s none #f

Material: wood-volatiles-air (mixture)

Property Units Method Value(s)

Mixture Species names ((wood_vol o2 co2 h2o n2) (c) ())
Reaction finite-rate/eddy-dissipation ((reaction-1 ((wood_vol 1 1 0) (o2 1.1700691 1 1)) ((co2 1.0685863 0 1) (h2o 1.1346897 0 1)) ((n2 0 1)) (stoichiometry 1wood_vol + 1.1700691o2 --> 1.0685863co2 + 1.1346897h2o) (arrhenius 2.119e+11 2.027e+08 0) (mixing-rate 4 0.5) (use-third-body-efficiencies? . #f)) (reaction-2 ((c 1 0 1) (o2 1 1 1)) ((co2 1 0 1)) ((wood_vol 0 1) (h2o 0 1) (n2 0 1))

(stoichiometry 1c + 1o2 --> 1co2) (arrhenius 7.84e+11 184175.2 0.5) (mixing-rate 4 0.5) (use-third-body-efficiencies? . #f) (surface-reaction? . #t)))

Mechanism reaction-mechs ((mechanism-1 (reaction-type . all) (reaction-list reaction-1 reaction-2) (site-info)))

Density kg/m3 incompressible-ideal-gas #f

Cp (Specific Heat) j/kg-k mixing-law #f

Thermal Conductivity w/m-k constant 0.045400001

Viscosity kg/m-s constant 1.72e-05

Mass Diffusivity m2/s kinetic-theory #f

Thermal Diffusion Coefficient kg/m-s kinetic-theory #f

Absorption Coefficient 1/m wsggm-domain-based #f

Scattering Coefficient 1/m constant 0

Scattering Phase Function isotropic #f

Refractive Index constant 1

Speed of Sound m/s none #f

Material: (nitrogen . wood-volatiles-air) (fluid)

Property Units Method Value(s)

Cp (Specific Heat) j/kg-k polynomial (300-1000: 979.04298 0.4179639 -0.0011762792 1.6743943e-06 -7.2562971e-10) (1000-5000: 868.62291 0.44162954 -0.00016872295 2.9967875e-08 -2.0043858e-12)

Molecular Weight kg/kgmol constant 28.0134

Standard State Enthalpy j/kgmol constant 0

Standard State Entropy j/kgmol-k constant 191494.78

Reference Temperature k constant 298.15

L-J Characteristic Length angstrom constant 3.621

L-J Energy Parameter k constant 97.53

Speed of Sound m/s none #f

Material: (water-vapor . wood-volatiles-air) (fluid)

Property Units Method Value(s)

Cp (Specific Heat) j/kg-k polynomial (300-1000: 1563.0767 1.6037546 -0.0029327841 3.2161009e-06 -1.1568268e-09) (1000-5000: 1233.2338 1.4105233 -0.00040291411 5.5427718e-08 -2.949824e-12)

Molecular Weight kg/kgmol constant 18.01534

Standard State Enthalpy j/kgmol constant -2.418379e+08

Standard State Entropy j/kgmol-k constant 188696.44

Reference Temperature k constant 298.15

L-J Characteristic Length angstrom constant 2.605
L-J Energy Parameter k constant 572.4
Speed of Sound m/s none #f

Material: (carbon-dioxide . wood-volatiles-air) (fluid)

Property Units Method Value(s)

Cp (Specific Heat) j/kg-k polynomial (300-1000: 429.92889 1.8744735 -0.001966485 1.2972514e-06 -3.9999562e-10) (1000-5000: 841.37645 0.59323928 -0.00024151675 4.5227279e-08 -3.1531301e-12)
Molecular Weight kg/kgmol constant 44.00995
Standard State Enthalpy j/kgmol constant -3.9353235e+08
Standard State Entropy j/kgmol-k constant 213720.2
Reference Temperature k constant 298.15
L-J Characteristic Length angstrom constant 3.941
L-J Energy Parameter k constant 195.2
Speed of Sound m/s none #f

Material: (oxygen . wood-volatiles-air) (fluid)

Property Units Method Value(s)

Cp (Specific Heat) j/kg-k polynomial (300-1000: 834.82647 0.29295801 -0.00014956371 3.4138849e-07 -2.2783585e-10) (1000-5000: 960.75234 0.15941258 -3.2708852e-05 4.6127648e-09 -2.9528324e-13)
Molecular Weight kg/kgmol constant 31.9988
Standard State Enthalpy j/kgmol constant 0
Standard State Entropy j/kgmol-k constant 205026.86
Reference Temperature k constant 298.15
L-J Characteristic Length angstrom constant 3.458
L-J Energy Parameter k constant 107.4
Speed of Sound m/s none #f

Material: (wood-volatiles . wood-volatiles-air) (fluid)

Property Units Method Value(s)

Cp (Specific Heat) j/kg-k constant 1500
Molecular Weight kg/kgmol constant 30
Standard State Enthalpy j/kgmol constant -6.9547846e+08

Standard State Entropy	j/kgmol-k	constant	0
Reference Temperature	k	constant	298.14999
L-J Characteristic Length	angstrom	constant	4
L-J Energy Parameter	k	constant	100
Speed of Sound	m/s	none	#f

Material: woodvol (combusting-particle)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1400
Cp (Specific Heat)	j/kg-k	constant	1680
Thermal Conductivity	w/m-k	constant	0.33
Latent Heat	j/kg	constant	0
Vaporization Temperature	k	constant	400
Volatile Component Fraction	%	constant	87
Binary Diffusivity	m2/s	constant	4e-05
Swelling Coefficient		constant	1.4
Burnout Stoichiometric Ratio		constant	2.67
Combustible Fraction	%	constant	12.9
Heat of Reaction for Burnout	j/kg	constant	32789000
React. Heat Fraction Absorbed by Solid	%	constant	30
Devolatilization Model	1/s	constant	50
Combustion Model		diffusion-limited	#f

Material: wood (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	700
Cp (Specific Heat)	j/kg-k	constant	2310
Thermal Conductivity	w/m-k	constant	0.173

Material: brick (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1922
Cp (Specific Heat)	j/kg-k	constant	900
Thermal Conductivity	w/m-k	constant	0.60000002

Material: air (fluid)

Property	Units	Method	Value(s)

Density	kg/m3	constant	1.225
Cp (Specific Heat)	j/kg-k	constant	1006.43
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.7894e-05
Molecular Weight	kg/kgmol	constant	28.966
Standard State Enthalpy	j/kgmol	constant	0
Standard State Entropy	j/kgmol-k	constant	194336
Reference Temperature	k	constant	298.15
L-J Characteristic Length	angstrom	constant	3.711
L-J Energy Parameter	k	constant	78.6
Absorption Coefficient	1/m	constant	0
Scattering Coefficient	1/m	constant	0
Scattering Phase Function		isotropic	#f
Thermal Expansion Coefficient	1/k	constant	0
Refractive Index		constant	1
Speed of Sound	m/s	none	#f

Material: aluminum (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2719
Cp (Specific Heat)	j/kg-k	constant	871
Thermal Conductivity	w/m-k	constant	202.4

Cell Zone Conditions

Zones

name	id	type
fluid	2	fluid

Setup Conditions

fluid

Condition	Value

Material Name wood-volatiles-air
Specify source terms? no
Source Terms ((mass) (x-momentum) (y-momentum) (k) (epsilon) (species-0) (species-1) (species-2) (species-3) (energy) (p1))
Specify fixed values? no
Fixed Values ((x-velocity (inactive . #f) (constant . 0) (profile)) (y-velocity (inactive . #f) (constant . 0) (profile)) (k (inactive . #f) (constant . 0) (profile)) (epsilon (inactive . #f) (constant . 0) (profile)) (species-0 (inactive . #f) (constant . 0) (profile)) (species-1 (inactive . #f) (constant . 0) (profile)) (species-2 (inactive . #f) (constant . 0) (profile)) (species-3 (inactive . #f) (constant . 0) (profile)) (temperature (inactive . #f) (constant . 0) (profile)))
Frame Motion? no
Relative To Cell Zone -1
Reference Frame Rotation Speed (rad/s) 0
Reference Frame X-Velocity Of Zone (m/s) 0
Reference Frame Y-Velocity Of Zone (m/s) 0
Reference Frame X-Origin of Rotation-Axis (m) 0
Reference Frame Y-Origin of Rotation-Axis (m) 0
Reference Frame User Defined Zone Motion Function none
Mesh Motion? no
Relative To Cell Zone -1
Moving Mesh Rotation Speed (rad/s) 0
Moving Mesh X-Velocity Of Zone (m/s) 0
Moving Mesh Y-Velocity Of Zone (m/s) 0
Moving Mesh X-Origin of Rotation-Axis (m) 0
Moving Mesh Y-Origin of Rotation-Axis (m) 0
Moving Mesh User Defined Zone Motion Function none
Participates in radiation yes
Deactivated Thread no
Laminar zone?no
Set Turbulent Viscosity to zero within laminar zone? yes
Embedded Subgrid-Scale Model 0
Momentum Spatial Discretization 0
Cwale 0.325
Cs 0.1
Porous zone?no
X-Component of Direction-1 Vector 1
Y-Component of Direction-1 Vector 0
Relative Velocity Resistance Formulation?yes
Direction-1 Viscous Resistance (1/m2) 0
Direction-2 Viscous Resistance (1/m2) 0
Choose alternative formulation for inertial resistance? no

Direction-1 Inertial Resistance (1/m)	0
Direction-2 Inertial Resistance (1/m)	0
C0 Coefficient for Power-Law	0
C1 Coefficient for Power-Law	0
Porosity	1
Solid Material Name	aluminum
Reaction Mechanism	0
Activate reaction mechanisms?	yes
Surface-Volume-Ratio (1/m)	0

Boundary Conditions

Zones

name	id	type
inlet	7	wall
pi	9	pressure-inlet
bs	3	wall
fs_2	4	wall
fs_1	5	wall
po_1	6	pressure-outlet
po_2	8	pressure-outlet
s_wall	10	wall
bp	11	wall

Setup Conditions

inlet

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	wood
Thermal BC Type	0
Temperature (k)	766.75
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0

Define wall motion relative to adjacent cell zone? yes
Apply a rotational velocity to this wall? no
Velocity Magnitude (m/s) 0
X-Component of Wall Translation 1
Y-Component of Wall Translation 0
Define wall velocity components? no
X-Component of Wall Translation (m/s) 0
Y-Component of Wall Translation (m/s) 0
Internal Emissivity 0.96
External Emissivity 1
External Radiation Temperature (k) 300
Wall Roughness Height (m) 0
Wall Roughness Constant 0.5
Activate Reaction yes
(0 0 0 0)
(((constant . 1) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))
Rotation Speed (rad/s) 0
X-Position of Rotation-Axis Origin (m) 0
Y-Position of Rotation-Axis Origin (m) 0
X-component of shear stress (pascal) 0
Y-component of shear stress (pascal) 0
Surface tension gradient (n/m-k) 0
Reaction Mechanism 0
Surface Area Washcoat Factor 1
Specularity Coefficient 0

pi

Condition Value

Reference Frame 0
Gauge Total Pressure (pascal) 0
Supersonic/Initial Gauge Pressure (pascal) 0
Total Temperature (k) 310.15
Direction Specification Method 1
Coordinate System 0
X-Component of Flow Direction 1
Y-Component of Flow Direction 0
X-Component of Flow Direction 1
Y-Component of Flow Direction 0
X-Component of Axis Direction 1
Y-Component of Axis Direction 0

Z-Component of Axis Direction 0
X-Coordinate of Axis Origin (m) 0
Y-Coordinate of Axis Origin (m) 0
Z-Coordinate of Axis Origin (m) 0
Turbulent Specification Method 0
Turbulent Kinetic Energy (m2/s2) 1
Turbulent Dissipation Rate (m2/s3) 1
Turbulent Intensity (%) 10
Turbulent Length Scale (m) 1
Hydraulic Diameter (m) 1
Turbulent Viscosity Ratio 10
Specify Species in Mole Fractions? yes
(((constant . 0) (profile)) ((constant . 0.21) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))
External Black Body Temperature Method 0
Black Body Temperature (k) 300
Internal Emissivity 0
is zone used in mixing-plane model? no

bs

Condition Value

Wall Thickness (m) 0
Heat Generation Rate (w/m3) 0
Material Name aluminum
Thermal BC Type 1
Temperature (k) 0
Heat Flux (w/m2) 0
Convective Heat Transfer Coefficient (w/m2-k) 0
Free Stream Temperature (k) 300
Wall Motion 0
Shear Boundary Condition 0
Define wall motion relative to adjacent cell zone? yes
Apply a rotational velocity to this wall? no
Velocity Magnitude (m/s) 0
X-Component of Wall Translation 1
Y-Component of Wall Translation 0
Define wall velocity components? no
X-Component of Wall Translation (m/s) 0
Y-Component of Wall Translation (m/s) 0
Internal Emissivity 1
External Emissivity 1

External Radiation Temperature (k) 300
Wall Roughness Height (m) 0
Wall Roughness Constant 0.5
Activate Reaction no
(0 0 0 0)
(((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))
Rotation Speed (rad/s) 0
X-Position of Rotation-Axis Origin (m) 0
Y-Position of Rotation-Axis Origin (m) 0
X-component of shear stress (pascal) 0
Y-component of shear stress (pascal) 0
Surface tension gradient (n/m-k) 0
Reaction Mechanism 0
Surface Area Washcoat Factor 1
Specularity Coefficient 0

fs_2

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	wood
Thermal BC Type	0
Temperature (k)	766.75
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Internal Emissivity	0.96
External Emissivity	1
External Radiation Temperature (k)	300
Wall Roughness Height (m)	0

Wall Roughness Constant 0.5
Activate Reaction yes
(0 0 0 0)
(((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))
Rotation Speed (rad/s) 0
X-Position of Rotation-Axis Origin (m) 0
Y-Position of Rotation-Axis Origin (m) 0
X-component of shear stress (pascal) 0
Y-component of shear stress (pascal) 0
Surface tension gradient (n/m-k) 0
Reaction Mechanism 0
Surface Area Washcoat Factor 1
Specularity Coefficient 0

fs_1

Condition Value

Wall Thickness (m) 0
Heat Generation Rate (w/m3) 0
Material Name wood
Thermal BC Type 0
Temperature (k) 766.75
Heat Flux (w/m2) 0
Convective Heat Transfer Coefficient (w/m2-k) 0
Free Stream Temperature (k) 300
Wall Motion 0
Shear Boundary Condition 0
Define wall motion relative to adjacent cell zone? yes
Apply a rotational velocity to this wall? no
Velocity Magnitude (m/s) 0
X-Component of Wall Translation 1
Y-Component of Wall Translation 0
Define wall velocity components? no
X-Component of Wall Translation (m/s) 0
Y-Component of Wall Translation (m/s) 0
Internal Emissivity 0.96
External Emissivity 1
External Radiation Temperature (k) 300
Wall Roughness Height (m) 0
Wall Roughness Constant 0.5
Activate Reaction yes

(0 0 0 0)
(((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))

Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Reaction Mechanism	0
Surface Area Washcoat Factor	1
Specularity Coefficient	0

po_1

Condition	Value
Gauge Pressure (pascal)	-2.1558
Backflow Total Temperature (k)	310.15
Backflow Direction Specification Method	1
X-Component of Flow Direction	1
Y-Component of Flow Direction	0
X-Component of Axis Direction	1
Y-Component of Axis Direction	0
Z-Component of Axis Direction	0
X-Coordinate of Axis Origin (m)	0
Y-Coordinate of Axis Origin (m)	0
Z-Coordinate of Axis Origin (m)	0
Turbulent Specification Method	0
Backflow Turbulent Kinetic Energy (m2/s2)	1
Backflow Turbulent Dissipation Rate (m2/s3)	1
Backflow Turbulent Intensity (%)	10
Backflow Turbulent Length Scale (m)	1
Backflow Hydraulic Diameter (m)	1
Backflow Turbulent Viscosity Ratio	10
External Black Body Temperature Method	0
Black Body Temperature (k)	300
Internal Emissivity	0
Specify Species in Mole Fractions?	no
Backflow	(((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))
is zone used in mixing-plane model?	no
Specify Average Pressure Specification	no

Specify targeted mass flow rate no
Targeted mass flow (kg/s) 1
Upper Limit of Absolute Pressure Value (pascal) 5000000
Lower Limit of Absolute Pressure Value (pascal) 1

po_2

Condition	Value
Gauge Pressure (pascal)	-2.1558
Backflow Total Temperature (k)	310.15
Backflow Direction Specification Method	1
X-Component of Flow Direction	1
Y-Component of Flow Direction	0
X-Component of Axis Direction	1
Y-Component of Axis Direction	0
Z-Component of Axis Direction	0
X-Coordinate of Axis Origin (m)	0
Y-Coordinate of Axis Origin (m)	0
Z-Coordinate of Axis Origin (m)	0
Turbulent Specification Method	0
Backflow Turbulent Kinetic Energy (m2/s2)	1
Backflow Turbulent Dissipation Rate (m2/s3)	1
Backflow Turbulent Intensity (%)	10
Backflow Turbulent Length Scale (m)	1
Backflow Hydraulic Diameter (m)	1
Backflow Turbulent Viscosity Ratio	10
External Black Body Temperature Method	0
Black Body Temperature (k)	300
Internal Emissivity	0
Specify Species in Mole Fractions?	no
Backflow	(((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))
is zone used in mixing-plane model?	no
Specify Average Pressure Specification	no
Specify targeted mass flow rate	no
Targeted mass flow (kg/s)	1
Upper Limit of Absolute Pressure Value (pascal)	5000000
Lower Limit of Absolute Pressure Value (pascal)	1

s_wall

Condition Value

Wall Thickness (m) 0.03
Heat Generation Rate (w/m3) 0
Material Name brick
Thermal BC Type 0
Temperature (k) 332.85
Heat Flux (w/m2) 0
Convective Heat Transfer Coefficient (w/m2-k) 0
Free Stream Temperature (k) 300
Wall Motion 0
Shear Boundary Condition 0
Define wall motion relative to adjacent cell zone? yes
Apply a rotational velocity to this wall? no
Velocity Magnitude (m/s) 0
X-Component of Wall Translation 1
Y-Component of Wall Translation 0
Define wall velocity components? no
X-Component of Wall Translation (m/s) 0
Y-Component of Wall Translation (m/s) 0
Internal Emissivity 0.93
External Emissivity 1
External Radiation Temperature (k) 300
Wall Roughness Height (m) 0
Wall Roughness Constant 0.5
Activate Reaction no
(0 0 0 0)
(((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))
Rotation Speed (rad/s) 0
X-Position of Rotation-Axis Origin (m) 0
Y-Position of Rotation-Axis Origin (m) 0
X-component of shear stress (pascal) 0
Y-component of shear stress (pascal) 0
Surface tension gradient (n/m-k) 0
Reaction Mechanism 0
Surface Area Washcoat Factor 1
Specularity Coefficient 0

bp

Condition Value

Wall Thickness (m) 0.001
Heat Generation Rate (w/m3) 0
Material Name aluminum
Thermal BC Type 0
Temperature (k) 455.25
Heat Flux (w/m2) 0
Convective Heat Transfer Coefficient (w/m2-k) 0
Free Stream Temperature (k) 300
Wall Motion 0
Shear Boundary Condition 0
Define wall motion relative to adjacent cell zone? yes
Apply a rotational velocity to this wall? no
Velocity Magnitude (m/s) 0
X-Component of Wall Translation 1
Y-Component of Wall Translation 0
Define wall velocity components? no
X-Component of Wall Translation (m/s) 0
Y-Component of Wall Translation (m/s) 0
Internal Emissivity 0.6
External Emissivity 1
External Radiation Temperature (k) 300
Wall Roughness Height (m) 0
Wall Roughness Constant 0.5
Activate Reaction no
(0 0 0 0)
(((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))
Rotation Speed (rad/s) 0
X-Position of Rotation-Axis Origin (m) 0
Y-Position of Rotation-Axis Origin (m) 0
X-component of shear stress (pascal) 0
Y-component of shear stress (pascal) 0
Surface tension gradient (n/m-k) 0
Reaction Mechanism 0
Surface Area Washcoat Factor 1
Specularity Coefficient 0

Solver Settings

Equations

Equation Solved

Flow yes
Turbulence yes
wood_vol yes
o2 yes
co2 yes
h2o yes
Energy yes
P1 yes

Numerics

Numeric	Enabled
Absolute Velocity Formulation	yes

Relaxation

Variable	Relaxation Factor
Pressure	0.69999999
Density	1
Body Forces	1
Momentum	0.30000001
Turbulent Kinetic Energy	0.8
Turbulent Dissipation Rate	0.8
Turbulent Viscosity	1
wood_vol	1
o2	1
co2	1
h2o	1
Energy	1
P1	1

Linear Solver

Variable	Solver Type	Termination Criterion	Residual Reduction Tolerance
Pressure	V-Cycle	0.1	
X-Momentum	Flexible	0.1	0.7
Y-Momentum	Flexible	0.1	0.7
Turbulent Kinetic Energy	Flexible	0.1	0.7
Turbulent Dissipation Rate	Flexible	0.1	0.7
wood_vol	Flexible	0.1	0.7

o2	Flexible	0.1	0.7
co2	Flexible	0.1	0.7
h2o	Flexible	0.1	0.7
Energy	Flexible	0.1	0.7
P1	Flexible	0.1	0.7

Pressure-Velocity Coupling

Parameter	Value
Type	SIMPLE

Discretization Scheme

Variable	Scheme
Pressure	Standard
Momentum	First Order Upwind
Turbulent Kinetic Energy	First Order Upwind
Turbulent Dissipation Rate	First Order Upwind
wood_vol	First Order Upwind
o2	First Order Upwind
co2	First Order Upwind
h2o	First Order Upwind
Energy	First Order Upwind

Solution Limits

Quantity	Limit
Minimum Absolute Pressure	1
Maximum Absolute Pressure	5e+10
Minimum Temperature	1
Maximum Temperature	5000
Minimum Turb. Kinetic Energy	1e-14
Minimum Turb. Dissipation Rate	1e-20
Maximum Turb. Viscosity Ratio	100000

CURRICULUM VITAE

NAME	Mr. Pisit Chaiwiboonpol
DATE OF BIRTH	24 June 1988
EDUCATIONAL RECORD	
HIGH SCHOOL	High School Graduation Trattrakarnkhul School, 2006
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