COMPUTER SIMULATION OF A POROUS MEDIA COMBUSTOR FOR SOLID FUEL UTILIZATION

BUNCHA PUTTAKOON

A DISSERTATION SUBMITTED IN PARTIAL FULLFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF ENGINEERING PROGRAM IN ENERGY AND MATERIALS ENGINEERING (INTERNATIONAL PROGRAM)

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Name-Surname	Mr.Buncha Puttakoon
Program	Energy and Materials Engineering
Dissertation Advisor	Assistant Professor Boonrit Prasartkaew, D.Eng.
Academic Year	2020

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ABSTRACT

The fossil fuel combustion scheme causes not only energy resources depletion, but also results in global warming and climate change issues. This study investigated a performance combustion system by applying the concept of porous media technology using waste stainless steel nuts and by using wood charcoal as solid fuel.

The experimental setup was done for two main cases: with porous media (case II) and without (case I) the porous media. The setup with the porous media was further configured according to sizes: 8 mm (case II-A), 10 mm (case II-B), and 12 mm (case II-C). The collected data were used to determine the setup with the highest heat transfer efficiency to the water tubes during combustion thereby giving a higher calorific value to the system and then comparing it to a nonporous kiln. Based on the results, porous media encourages higher heat transfer efficiency as observed from the rise in the temperature of water at the heat exchange chamber during the experiment. Porous media induces both the occurrence of conduction and convection heat transfer to water tubes resulting to higher heating temperatures as compared to the one without porous media.

The simulation solid fuel porous media combustor (SFPMC) system was applied by the computer with ANSYS software. The experimental study was conducted in two important cases: without porous media and with porous media using three sizes of stainless steel nuts (8, 10, and 12 mm). It was found that the results obtained by computer simulations in all cases were consistent with the heat radiation combustion theory of porous media. And it was consistent with the study results from the experiment. From a comparative study of solid fuel combustion combustor with and without porous media installed, it was found that the combustors with installed porous media demonstrated higher heat transfer efficiency than combustors without installed porous media. Furthermore, the effect of using varying sizes of porous media was explored by using 8, 10, and 12 mm. stainless steel nuts in the study. With the porous media technique, the 10 mm size stainless steel nuts with a porosity of 0.53 greatly improved the performance of the proposed solid fuel porous media combustor (SFPMC) system. At steady state combustion conditions, a maximum average combustion temperature reached 1,002℃ and an average thermal efficiency of 67 %, was obtained.

Keywords: computer simulation, porous media, solid fuel, combustion

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Buncha Puttakoon

Table of Contents

Page

Table of Contents (Continued)

Page

List of Tables

Page

List of Figures

List of Figures (Continued)

Page

List of Figures (Continued)

Page

List of Abbreviation

NOMENCLATURE

LHV fuel	=	Lower heating value of fuel
PM	=	porous media
SFPMC	=	Solid fuel porous media combustor
$T_{w,o}$	=	Outlet water temperature
$T_{w,i}$	=	Inlet water temperature
$T_{gas,in}$	=	Inlet gas temperature
$T_{gas,out}$	=	Outlet gas temperature
Without*PM	=	Without porous media
w/o	=	Without porous media
W_{in}	=	Water in
W_{out}	=	Water out
$\dot{m}_{fuel}$	=	Fuel consumption rate
$\Delta H_{im, water}$	=	Heat transfer improvement of water
$\Delta H_{im,gas}$	=	Heat transfer improvement of gas
$\dot{Q}_{g,PM}$	=	The rate of heat transferred to hot gas with porous media
$\dot{Q}_{g,w/o}$	=	The rate of heat transferred to hot gas without porous media
V_t	=	Total amount of water in the container
V_s	=	Total amount of water combined with porous media
C_P	=	Specific heat
$\dot{Q}_u$	=	The rate of heat transferred to hot water
$\dot{m}_w$	=	Water flow rate
$\dot{Q}_{water,PM}$	=	The rate of heat transferred to hot water with porous media
$\dot{Q}_{water,w/o}$	=	The rate of heat transferred to hot water without porous media

GREEK SYMBOLS

η_{SFPMC}	=	The efficiency of hot water production kiln using solid fuel for unidirectional gas flow
η_{im}	=	The improvement in terms of efficiency
ε	=	Porosity of porous media

CHAPTER 1
INTRODUCTION

1.1 World Energy Outlook

Energy seems to be the most important factor for human survival; for all human activities depend on energy. Most of the energy resources consumed by countries around the globe are fossil-based wherein its combustion is the primary energy consumption of about 90% in all countries [1]-[2]. Its excessive use caused a growing concern of its supplies depleting soon and of polluting the environment. With fossil fuels as the primary energy resource, it is a compelling issue to know the most effective way of utilizing it. This is due to the increasingly significant demand for an eco-friendly energy management and for various efficient schemes to be implemented in industrial and commercial purposes [3]. Porous media has been used in various combustion applications and it has gained more attention from researchers in the applications such as biomass combustion, incineration of solid waste, catalytic combustion, coal gasification, in situ combustion for the recovery of oil, diesel engine and pollution control, hydrogen production, grounds polluted by toxic organic shedding recuperation, destruction of volatile organic compounds (VOC) in air [4]. Over the past few decades, the porous media combustion (PMC) has been one of the most well-known technologies to increase the system efficiency and reduce emitted pollutants, and one of the best techniques widely used for an energy efficient combustor. Regarding this technique, Yumlu [3] has presented the experimental study on the performance of a porous flat flame burner. Past studies focused on heat extraction, hydrogen–oxygen and hydrogen-air flames. Various types of researches attempted to improve the performance of PMC over the years, which can be categorized into the phase of fuels used: gaseous, liquid and solid fuels. Most studies focused on gaseous fuel, liquid fuel, and porous combustor as presented in [5]-[12]. Kaplan and Hall studied the characteristics of liquid fuel combustion by spraying n-Heptane into Porous media in the up-flow direction to fuel the experiment. Another one was done by Takami et al. proposing a new fuel combustion technique. It was done by dripping kerosene onto the porous layer instead of spraying the objective. From the result of the said research, it has been successful in applying liquid fuel drops on porous media to burn liquid fuels instead of spraying [14].

The PMC technique has been studied and applied to steady combustion with great success for the past decades of research. This technique was used for both gaseous liquid fuels and solid fuels (coal) and the effect of the combustion feature of such technology is its distinctive performance. Earlier studies of many researchers, focused on both experimentally and theoretical developments of reactors for gas and liquid. [16]-[27] But in order to address the environmental problems of fossil fuel utilization, renewable-energy based systems should be encouraged as well as the development of new combustion techniques. Therefore, new renewable energy or biomass energy sources must be explored to remedy this crisis and environmental problems for the near future [12]. Industries produce a lot of waste materials that can be a potential source of renewable energy. One common source is in the form of firewood that is usually used in rural households. However, when burnt it produces smoke and has low heating value. By converting the firewood into charcoal, its disadvantages are resolved. The charcoal obtained will approximately contain 50% of the wood burnt which still varies depending on the process. Nowadays, due to the progress in using wood as energy, it can now be used to directly produce gas that can run engines successfully [28]. Studies also showed several advantages of renewable energy systems such as its safer operation, worldwide availability, contribution to a clean environment, and production of non-polluting energy [16]-[17]. However, there are still a lack in studies about the application of porous media in solid combustor.

The research is a comparative study of hot water production with combustor solid fuel combustor (wood charcoal) with and without the porous media and compare the results of the experiment with the computer simulation, to reveal the effect of porous media and to compare the heat transfer to the water pipe between the presence and absence of medium. The porous fill in the tube of the chamber. The expected result in the porous media is a kind of material with connected voids, where hot gas can easily penetrate through the medium. Porous media will cause the circulation of hot gas to the porous media by conduction and effective heat radiation. Solid fuel Combustor have been developed using a computer simulation. And to guide the development Combustor Solid fuel in the future.

1.2 Statement of the Problem

To mitigate the aforesaid serious problems, is not only to focus on energy preservation and energy efficiency measures but renewable energy utilization should also be encouraged. This work introduces a novel method to improve the performance of solid fuel/feedstock combustor using the porous media technology. The objective of this research is to examine the performance of the solid fuel porous media combustor (SFPMC) from the reasons and background above. Here are some research questions that will be addressed by this study:

1.2.1 Can the computer simulation in this study predict the proposed system performance?

1.2.2 Can the SFPMC system perform effectively for the solid fuel/feedstock utilization?

1.2.3 Can the reliability of the SFPMC system be improved to obtain higher efficiency?

1.3 Objectives of the Study

This research aims at proposing a new concept of a SFPMC system and presenting the investigation on the performance and feasibility of this high efficiency reactor. The specific objectives of this study are as follows:

1.3.1 To study experimentally on the performance of the SFPMC system.

1.3.2 To simulate SFPMC system by computer.

1.3.3 To study the efficiency of the SFPMC system by a comparative study with a computer simulation.

1.4 Scope and Limitation of Study

The research includes theoretical experimental studies and computer simulation. The scope and limitations of the study are as follows:

Objective 1: To simulation SFPMC system by computer. ANSYS Software. Finally, the results from this simulation was validated by the available experimental data.

Objective 2: For simulation, the input data of solid feedstock was obtained from the literatures.

Objective 3: The experimental study will be conducted in two important cases:

1) Without porous media,

2) With porous media using 3 sizes of nuts: 8 mm., 10 mm., 12 mm.

1.5 Expected Resulted

1.5.1 The proposed SFPMC have been developed using a computer simulation.

1.5.2 To guide the development solid fuel combustor in the future.

CHAPTER 2
THORETICAL AND LITERATURE REVIEW

Porous media have received a lot of attention from researchers, due to the heat transfer technology using porous media. There are advantages that can be applied to the system that has good heat transfer. Past studies have found that using porous media made from a variety of materials. Most of the fuel used is fossil fuel, which is gas fuel and liquid fuel. The design of the experiment equipment is also different to suit the type of fuel. This research is the application of porous material technology for use with combustor of solid fuels (wood charcoal) to study heat transfer and heat radiation with porous media, compared to the with-out porous media and the actual experimental results with those obtained from the computer simulation in order to improve the combustor performance.

2.1 Combustion theory

Combustion is a chemical reaction. Where the combustible material reacts and oxygen with release heat at the same time, it will turn into oxide compounds or burned products with complete fuel burn including carbon dioxide and water. Incomplete combustion leads to wastage. These fuel wastes cause air pollution. Therefore, knowing the principles of the combustion process and the method of complete combustion control is required. It is of great importance to energy conservation and environmental protection. The different forms of heating systems and devices along with guidelines for prevention will help make improvements to the overall system of thermal energy efficiency. Heat is one of the most important energy, used in various industrial production processes. Typically, heat energy is obtained by combustion of fuel in the presence of sufficient oxygen and temperature. Heat conduction in various industries for maximum efficiency depends on two important components: combustion and heat conduction. Combustion is an element that has a great effect on heat conduction, because if the combustion is incomplete, it means that some of the fuel is left without combustion. Complete combustion is exhausting the used fuel. Thermal conductivity in industrial applications can use the heat generated by the direct combustion of fuel for heaters. Direct or indirect, there is a medium to induce heat to the machine such as steam, hot water, hot oil and hot air, etc. Therefore, the goal of the highest efficiency in terms of thermal conductivity is the ability to conduct heat arising from combustion used to maximize benefit.

Fuel refers to a substance that can be easily burned when reacting with air or oxygen. And heat arising from combustion, can be used economically, so what is used as fuel. It needs to be able to produce a lot. They can be easily supplied, stored, transported and used. In addition, the substances produced by combustion (as exhaust, ash, etc.) must not cause environmental pollution such as air, water, etc. Fuels can be categorized according to physical conditions; as gas fuel, liquid fuel and solid fuel.

2.1.1 Gas fuel

Gaseous fuels are fuels that are in a gaseous state under normal temperature and pressure. Divided into natural gas which are naturally occurring and gases produced by separating solid or other liquid fuels.

Gas fuel properties

Advantages

1. Compared to solid fuels and liquid fuels Although the amount of excess air is still small, it can be completely burned more easily. Burns is stable. Have high combustion efficiency.

2. In addition to preheating the combustion air, it can also warm up the fuel. Own as well, so even if the fuel has a relatively low heat value, it can burn at high temperatures.

3. The combustion level can be conveniently adjusted with an adjusting valve, so it can be easily ignited and extinguished. And can adjust the ratio between fuel and air as desired as well as being able to use the system automatic control temperature control system provides local heat or evenly distributed heat. Or adjust the atmosphere inside the kiln easily as well.

4. There is no ashes in the fuel.

5. It contains very little sulfur. Therefore, does not cause air pollution as sulfur dioxide

Disadvantage

1.Compared with the same heat, it requires more volume than any other fuel. Therefore, inconvenient to transport

2. Gas storage requires a gas cylinder. Therefore, having high construction costs.

3. The cost is more expensive than liquid fuel.

4. Safety controls must be strictly controlled because there is a danger of leakage and explosion.

Gas fuel type

1. Natural gas

It is a naturally occurring gas fuel. It is primarily hydrocarbon compounds. Have both gas from oil wells, which are gases that are formed with oil and gas obtained from gas wells which do not have oil. It can be divided into dry gas and moist gas. For dry gas, it contains methane (CH_4) as an element of not less than 95%. Moist gas, in addition to methane, ethane (C_2H_6), also contains hydrocarbons with carbon atoms ranging from propane to (C_3H_8) and above are elements natural gas has a high calorific value (36-48 MJ /$m^3{}_N$) and easily burns. And the exhaust from combustion will produce the least air pollution compared to all fuels. Land transport transports gas along gas pipelines in gas conditions, water transport is transported in liquid condition by inserting tanker vessel, cold storage then transfer it into a gas cylinder above the ground or underground in a typical liquid state. Natural gas that has cooled down to -162 ° C until it becomes liquid is called liquefied natural gas.

2. Gas LPG

Gas LPG refers to gases with a major component of petroleum hydrocarbons which is in the state of gas at normal temperature and pressure but when increasing the pressure or lowering the temperature, it becomes a liquid easily. Generally, mixed gas between propane and butane has a common name called liquefied petroleum gas and are both spontaneous nature in oil wells and as a by-product of crude oil refining gas properties, it has a high heat value and is a clean gas. Convenient in transportation, adjusts the burn level and it burns easily, so it is widely used both in industry and household.

3. Town gas

Liquefied gas is a gas that is transmitted by gas pipelines supplied to factories, buildings and households. Mainly coal but nowadays, the use of natural gas is increasing. Liquefied gas is a clean gas. Has high combustion efficiency and can conveniently adjust the combustion level with volume. Reserve that can be used for a long time. Therefore it qualifies as an ideal fuel. However, there are many types of LPG depending on the raw materials and equipment used. Therefore, it is necessary to use a suitable combustion device for the type of gas.

4. Gas obtained from oil decomposition

Gas obtained from oil decomposition refers to fuel gas obtained from hydrocarbon decomposition. With heat and partial combustion with steam conditioning or by reacting with hydrogen to make it have a smaller molecular size The most commonly used raw materials are: Off-oil from gas refinery gas LPG naphtha Kerosene, heavy oil, etc.

5. Other fuel gases

Coal gas (Gas from coke stove) it is a by-product of coal to be distilled dry (Dry distillation) to produce coke and contains hydrocarbons, hydrogen, carbon monoxide, etc. Hot no more than 22 MJ / Nm^3. It is used as the fuel of the boiler and as a raw material for making cooking gas (Town gas) etc. Gas from blast furnace is the gas that is obtained from the top of the stove in the process of producing steel, it is called gas blast furnace or B gas (Blast furnace gas). It is a gas that is the main component of carbon monoxide, flammable and has a calorific value not more than 3.8 MJ/ Nm^3. It is a waste gas from oil refineries (off gas), a gas released from various oil refining processes in a refinery. The composition will depend on the type of machine, characteristics of crude oil operating conditions, etc. will have hydrocarbons such as C_3, C_4, etc. are abundant.

Figure 2.1 Gas rigs in the US Gulf of Mexico.[63]

2.1.2 Liquid fuel

Liquid fuel refers to fuel that is in a liquid state under normal temperature and pressure. Almost all liquids in use today are petroleum fuels. Liquid fuel production will bring mined crude oil. Obtained from oil wells to separate and decompose (Catalyst decomposition, decomposition by reaction with hydrogen, etc.) to transform it into a petroleum product suitable for each purpose of use category.

Table 2.1 General characteristics of petroleum products.

Fuel	Main component	Boiling point range	High heat value	Objective Main use
Gasoline	C, H	30-210	46.1	Gasoline engine
Kerosene	C, H	160-300	46.0	Small engines for agriculture
Light oil	C, H	160-360	41.9	Small diesel engine
Heavy oil	C, H (O, S)	250-360	42.8-46.5	Boiler, industrial furnace Large diesel engine

Liquid fuel properties

Advantages

1. A high calorific value
2. Cheap price per unit of heat cost
3. Convenient storage and transportation Rarely deteriorates during storage

4. High combustion efficiency

5. Less ash

6. Easy to burn, easy to use automatic control system.

Disadvantage

1. High combustion temperature It produces heat at some point that can be easily too high.

2. Heavy oils contain a lot of sulfur can be the cause of air pollution easy.

3. Fuel burner Some make noise easily.

Types and characteristics of liquid fuels

1. Crude oil

Refers to crude oil extracted from a naturally occurring underground oil well. Crude oil has physical properties. Physics and chemistry differ depending on the source and depth of crude oil. The main components are substances of hydrocarbons, however, common crude oil contains large amounts of paraffin and naphtha hydrocarbons. Sometimes there are large amounts of aromatic hydrocarbons. But crude oil has almost no olefins. Hydrocarbons are included.

2.Gasoline

It is a petroleum product that has the same boiling range as naphtha (30-210 °C) but the ingredients are optimized. In use as a fuel of internal combustion engines therefore separated into a separate type from naphtha. Gasoline is divided into three main categories: automobile gasoline. Gasoline for the essential characteristics of gasoline for a car include knock engine protection. Vaporization easy aircraft and industrial gasoline the essential characteristics of gasoline for a car include knock engine protection. The safety and cleanliness of the knockout engine protection uses the octane value as a measure octane values are divided into ways Research method versus motor method.

3. Kerosene

It is an oil with a burning range of 160-300 °C. In distillation, the fraction sequence is obtained between naphtha and light oil. The density of 0.78-0.80 g/cm^3 has a high calorific value of 46 MJ / kg. It is used as a fuel for heating and cooking such as oil heaters used in small diesel engines, household and used to clean various machinery. Kerosene used in various small engines for agriculture is tea-colored kerosene. Tea-colored kerosene. is a must. It has a certain level of anti-knocking properties, but the smoking point has no problems. Containing high-octane aromatic hydrocarbons.

4. Diesel fuel

It has a burning range of 160-360 °C and is the fuel that is produced between kerosene and heavy oil in the distillation section order. It is mostly used as a fast-speed diesel engine fuel for cars, railway construction machinery or boats and also for hot-bulb engines in fishing boats and small engines for agriculture. High speed diesel engine fuel must have good flammability, not too low ignition point, suitable viscosity, low pour point and low sulfur. Cetane is used for flammability.

5. Fuel oil

Generally, fuel oil is a high molecular weight fuel. Obtained by taking the remaining oil from the refining crude oil residual oil from the breakdown and the rest of the oil from the light oil to mix together originally will be divided into but in the JIS standard, the kinetic viscosity is used primarily to divide the heavy oil. It is divided into 3 types: type 1 (fuel oil A), type 2 (fuel B) and type 3 (fuel C). In addition, type 1 fuel oils are classified according to the sulfur content, number 1 and number 2, and type 3 are also subdivided according to the viscosity is No. 1, No. 2 and No. 3. When the nitrogen in the fuel oil burns, Part will become a compound nitrous oxide released out into the atmosphere. Generally, in fuel oil a there is 0.01-0.03% nitrogen [kJ/kg], fuel oil B and C have 0.1- 0.4% [kJ/kg], which is a smaller proportion than sulfur. There are few heavy metal compounds in the fuel oil. These compounds after burning to ashes, the metals available are: iron, silicon, aluminum, calcium, magnesium, sodium, nickel, vanadium, etc. which when burning, will accumulate on the heat transfer surface of the boiler and block the transfer of heat. Vanadium metal burns will react with sodium or others to form compounds with a low melting point, which will corrode heating pipes or other parts of the boiler. Fuel oil is different from coal in that, if the fuel oil has the same density then the heat value is almost equal, however, if it has a high sulfur content, the heat value can be reduced somewhat. Commercially available fuel oil has valuable high heat between 42.8-46.5 MJ/kg.

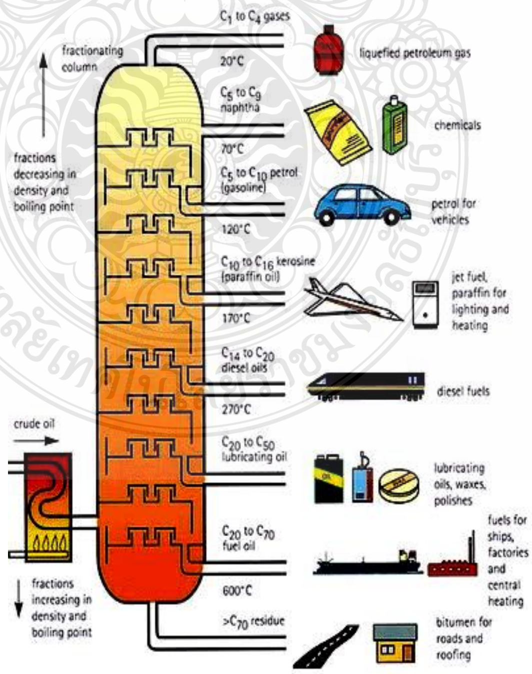


Figure 2.2 Oil refining process [63].

2.1.3 Solid fuel

Solid fuel refers to fuels that operate in a solid state. The main solid fuels are fuels natural such as coal, lignite, peat, wood, etc., and fuels that are obtained from the burning of natural fuels (Carbonization) such as coke, semi-coke, lignite coke, charcoal, etc.

1. Coal

Coal was formed by a primeval plant, slowly turning into coal with heat and pressure below the earth's surface, so the properties of coal therefore depend on the origin of the plant type of origin, the coal rank deposition conditions and the soil condition.

2. Lignite

Lignite is a type of brown coal. Brown coal is black in appearance. If it is brown, it is called lignite. Lignite has more moisture than coal (approximately 30-50% [kJ/kg]). Easily influenced by climate cracks and breaks easily with the heat value of 12.5-16.7 MJ/kg and low combustion temperature. But when drying it will have a low ignition temperature and it burns well apart from being used in factories and houses in the vicinity of the lignite mine.

3. Coke

It is obtained by using caking coal as the main component for Carbonization at high temperatures approximately 1000 °C. It is mainly used for steel smelting and foundry applications. The main components of coke are carbon, good coke, moisture, volatile matter ash, sulfur and phosphorus etc. is Generally, coke is not widely used, but it is used for heating and cooking. and to dry agricultural crops with hot air. Coke has the advantage of being heated higher than coal and has less smoke and black dust (Soot)

2.2 Biomass energy

2.2.1 Introduction to biomass energy

The biomass energy is a source to collect energy from nature and can be used to produce energy. such as waste from agricultural material or waste from the agricultural industrial production process, such as rice husk obtained by milling rice bagasse bark. It is obtained from the production of granulated sugar, mainly from the processing of rubber or eucalyptus wood and some from the forest palm residue is obtained from the extraction of crude palm oil from fresh palm fruit. Cassava residue is obtained from cassava flour production. Corn cobs are obtained by milling corn. By removing the seeds from the clams and coconut shells, it is obtained from the peeling of the coconut to remove the coconut meat to produce coconut milk and coconut oil. Yeast obtained from the production of alcohol, etc. Biomass can be transformed as energy because at this stage of growth, plants use carbon dioxide and water. Already change energy from sunlight through the process of photosynthesis, starch and sugar are produced and kept in the various parts of the plant. Therefore, when using plants as fuel so we get energy. Biomass energy can be used in the form of heat, steam or electric current production. It will use any type of biomass fuel mentioned above for combination. Therefore, biomass is a cheap fuel source. If it is used in areas not far from the source, there will be too much fuel hence reduce the cost of transportation. There is biomass everywhere in Thailand, and more should be used thus reducing the foreign currency loss in importing fuel and generating income for local people. In addition, the production of energy from biomass fuel with the right technology will not cause pollution and does not create a greenhouse effect. Due to the replacement of plants, this makes the carbon dioxide gas generated and circulating and no additional discharge. We also hope that the development of biomass projects can strengthen and Community participation as well.

2.2.2 Biomass benefits

1. The community economy will thrive because biomass is used as fuel, which can reduce trees. Production capital will help to develop local community industries and will create jobs in that area and generates income for the community through the local tax.

2. Farmers will have additional income increasing because they can sell both agricultural products and agricultural waste that had been scrapped will return to a resale price.

3. As a new alternative fuel that are used to replace fossil fuels in the production of environmentally friendly energy.

4. The stability of the country's energy production will increase due to waste material. There is enough energy from farmers in the country to be used as a substitute for fossil fuels in present.

2.2.3 Biomass composition or general matter is divided into four main components [as shown in Figure 2.3]

1. Moisture refers to the amount of water available. Most biomass has relatively high humidity because it is an agricultural product. If wanting to use biomass as energy by combustion the humidity should not exceed 50 percent.

2. Fixed carbon is a stable part of the molecular structure of biomass. It consists mostly of carbon. Biomass with a low or low constant carbon percentage does not combust well. It has low ignition temperature, slow ignition speed due to high humidity.

3. Volatile Matter is the part where molecules are easily burned, so biomass anything with a high Volatile Matter means that it is easily flammable.

4. Ahs are components. of existing original inorganic materials in the biomass that has been oxidized. The majority of biomass contains 1-3% of ash, except rice husk and straw. There will be about 10-20 percent proportional to the ash garden, which will have burning problems.

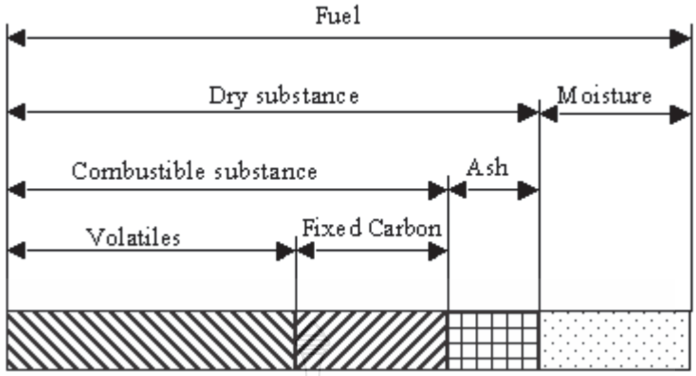


Figure 2.3 Composition of biomass or general matter [72].

2.2.4 Composition of biomass that affects the production of biomass, each has specific properties.

Some features are considered a disadvantage in bringing biomass used to generate electricity, machinery must be designed to be suitable for that biomass. For the best overall performance, however one of the same properties of biomass is that it is lightweight when compared to other fuels. The production of energy with biomass should be close to Biomass production sources to reduce transportation costs. The best for the specific properties of Biomass that must be considered Including:

1. Distribution of biomass sources
2. Size
3. Humidity
4. Adulteration
5. The amount of ashes

2.2.5 Source of materials that can be used as fuel in Thailand, can be classified into 3 types as follows.

Plant residues or residues after harvesting (crop residue), there are many Left in the farms, forests, factories such as sawdust from rice husk sawmills from rice straw mills, etc.

Weed is a plant that grows naturally through various sources that do not want to give up in the area of cultivation. There are plants that grow in the upland area or in the river, such as water hyacinth, water lettuce, papyrus, etc.

Industrial wastes such as rotten flour from flour factories. Fermented yeast from the liquor factory, etc.

Thailand has agricultural waste such as rice husk, sawdust, rice straw. Various peas, corn cob, weeds. These are organic material that is difficult to decompose but has a heat value high enough to be used for energy benefits. The production is divided into solid fuel rods and bars green fuel, to be used as a substitute fuel, firewood or charcoal, fuel properties of waste materials.

2.3 Charcoal

2.3.1 Introduction to charcoal important energy sources in the earth.

The best is solar energy. Plants capture solar energy by photosynthesis and store it in different ways such as in the form of wood, which is a form of agricultural produce. In one year, land plants can generate energy in the form of dry mass between 100 - 125 billion tons and water plants generate dry mass. Approximately 44 - 55 billion tons of this amount of biomass is greater than the use of human energy in 200 times the current. Humans know how to use energy from wood by combustion for warmth and cooking. By chance, since prehistoric period humans know how to transform wood into charcoal. For more than 2,000 years, humans have known how to turn charcoal into gas, running engines for more than 70 years, and humans have known how to transform wood into liquefied fuel. More than 35 years, biomass is an energy source that can be created, but the use of biomass is an inconvenient energy. Like any other energy, however, today there is a fuel crisis. As a result, the price of crude oil in the world market continues to rise. Making humans aware of the importance of urgent study and research on the conversion of biomass into various forms of energy.

Classification of energy consumption in Thailand. Can be divided into 5 parts which are mainly.

1. Energy for transport	27	percent
2. Energy for industrial	23	percent
3. Energy for cooking and service	22	percent
4. Energy for agriculture	7	percent
5. Energy for other businesses	21	percent

Most of the transportation and agricultural energy comes from fuels. The energy for cooking and serving is 48% charcoal, 16% firewood, 22% oil and 14% electricity respectively. The wood source used to produce energy is not cheap and wasted. The energy of this fuel wood should be within a radius of 100 km. Usually, the wood that will be used for fuel should be left over from two sources:

1. Residues obtained from horticulture and forestry such as branches, stumps, roots, leaves and bark, etc.

2. Residues from the wood industry. Such as sawmills, plywood factories and paper factories, etc.

In identifying wood from forest plants, it is sufficient to distinguish different parts. 60-65% of the trunk, 5% of the top trunk, 10-15% of the branches, 5-10% of the trunk and 10-20% of the roots should be part of the branches, stumps and small roots. For other parts of wood, it should be used in the wood industry. Any other fuel that is appropriate first and is considered as the final fuel. About stable carbon is an element with high quantity volatile low ash content and has a high heat value. Fuels with high humidity will cause low heat values. And the calorific value of the fuel is classified as an indicator of one of the fuel properties, the high calorific value fuel is considered to be of good quality fuel, but for the use of charcoal for household cooking, the best quality charcoal is not necessarily a valuable charcoal. Maximum heat, but must have good properties of the charcoal. Other aspects include:

1. An eruption while on fire. The good charcoal will not explode when ignited, or it may and there will be a slight eruption.

2. Weight of charcoal the heavy coals will be burning hot and long.

3. No smoke or strong smell while burning.

4.Have the strength of charcoal. This makes it convenient for use, transportation and storage.

2.3.2 Evolution of charcoal burning method.

This happens according to the different eras of the prosperity that arose if talking about ancient civilizations that existed in the past. From the legacy of this civilization it can be divided into three parts: The middle east, China and the incase. Presently, there is just the middle east and China left, and after that, the era of the middle east and China will reach the civilization of europe. Therefore, the evolution of world charcoal-burning can be divided into.

1. Middle East: Iran, Afghanistan, Pakistan.
2. The era of China, including Korea, Japan.
3. Era of Europe: Europe and the colonies.

2.3.3 Wood Pyrolysis and Charcoal Qualities

Wood contains a large number of different cell groups. The cell wall is made from cellulose. (50%) hemicellulose (20-30%) and lignin (20-30%). All structures are similar in shape to many pipe groups Diameter it is about 4 to 60 microns and has many tiny holes. The pipe walls functions in holding adjacent cells together. The network of structures is complex, both landscape and horizontally. When charcoal is transformed, the cell walls are carbonized and the structure shrinks to approximately one third of their original size. But retains the original shape. Cellulose is the main ingredient in glucose hemicellulose. It contains ingredients from glycoside and lignin, which is a component of aromatic compounds. Therefore, the pyrolysis process is divided into two parts: the first being cellulose and saccharide. The other part is of lignin and hemicellulose which begin pyrolysis at a temperature of about 180 °C and is completed before the temperature reaches 260 °C. Cellulose will pyrolysis very quickly at a temperature of about 275 °C and lignin will begin to pyrolysis when the temperature is about 310 °C and is almost complete at approximately 400 °C and terminated at approximately 500 °C.

2.3.4 Quality of charcoal

The quality of the charcoal depends on two factors. The type of wood used and the carbonization process. In general, hard wood turns into hardwood charcoal and softwood become softwood charcoal. For the duration of the carbonization process, if the carbonization occurs very quickly, the amount of gas from the wood is produced and the charcoal is tough. Less on the other hand, if the carbonization is slow, there will be less gas from wood. Charcoal is stronger, so generally after that, a small air hole is made to control the carbonization. At the same time, the use of new wood this will help the carbonization process progress. And to slowly control the temperature of the carbonization process. This will affect the quality of the charcoal obtained. From carbonization at a temperature of about 400° C, the toughness level is about 5-6, but while using the same wood if the carbonization temperature rises to 700° C, the hardness level of charcoal is about 9 -10.

2.4 Types of Combustor

There have been various designs for gasifier for more than a century may it be small or large scale. The type of gasifier can be classified based on the gasifying agent to be used or according to the source of heat during the process which can be direct or indirect. Generally, it is classified based on the design of the fuel bed and reactor; namely, fixed bed and fluidized bed. Fluidized bed is suitable for large scale coal gasification. Small particles are suspended in an upward flow stream of gas fluid at a velocity enough to enable the particles move like fluid but not too much such that it is carried out of the vessel. The rapid and excellent mixing of particles creates uniformly distributed temperature for gas fluid as it collide with the suspended small particles. Hence, the heat transfer rate is higher as compared to a fixed bed thereby,

providing very high efficiency. For a fixed bed gasifier, there are actually 3 types of design based on the gas flow in the reactor: updraft, downdraft, and horizontal. This is much simpler in design and operation, and causes minimum destruction to the reactor body [Sadaka, 2009].

2.4.1 Updraft Combustor

In an updraft gasifier (Figure 4a), the flow of fuel and gases is countercurrent. The direction of flow of the gasifying agent starts at the bottom of the grate reacting with char from biomass to produce hot gases that will create internal heat exchange as it moves upward. Heat generated pyrolyzes the incoming biomass which is fed on top and then the gas also cools down in the process. The use of combustion heat is effectively used yielding high efficiency. Gases, tar and other volatile compounds ascends at the top of the reactor while ash is removed at the bottom. The disadvantage is the high amount of tar and pyrolysis products because of the chars entrained by the upward flow of the gas. When producer gas is used for heating, the amount of tar does not pose a problem but when used as engine fuel intensive gas cleaning system is required. Slagging is also a huge problem when fluffy, low-density fuels are used.

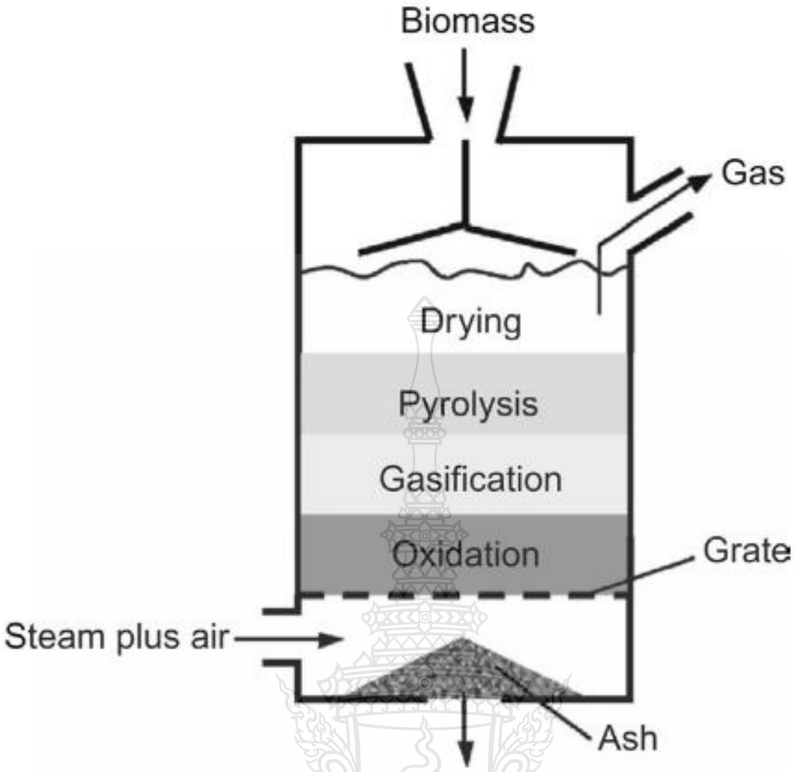


Figure 2.4 Schematic of an updraft gasifier with steam and air as a gasification agent [74].

2.4.2 Downdraft Combustor

It is very similar to an updraft gasifier but the location of the zones are reversed (see Figure 4b) as the biomass and gasifying agent moves co-currently. Feedstock is fed at the top of whereas the gasifying agent is fed on the sides. Generated energy at the lower zones heats the topmost zone where drying occurs. Thermal degradation of the dried fuel takes place as it descends on the lower zones because of the heat generated from the pyrolysis gas produced due to the devolatilization. As it moves further down, gas produced at the upper zone passes through the high temperature oxidation zone wherein it undergoes further decomposition and wherein tar cracking is favorable. Product gas moves downward leaving at the bottom of the reactor. The main advantage is that it can produce lower amounts of tar. Drawbacks are producer gas leaving at very high temperatures leading to lower gas efficiency and because of the downward movement of gas the quality is reduced as it contains high dust particle and ash. This type of gasifier is used in power productions ranging from 80 – 500 kW [Knoef, 2005].

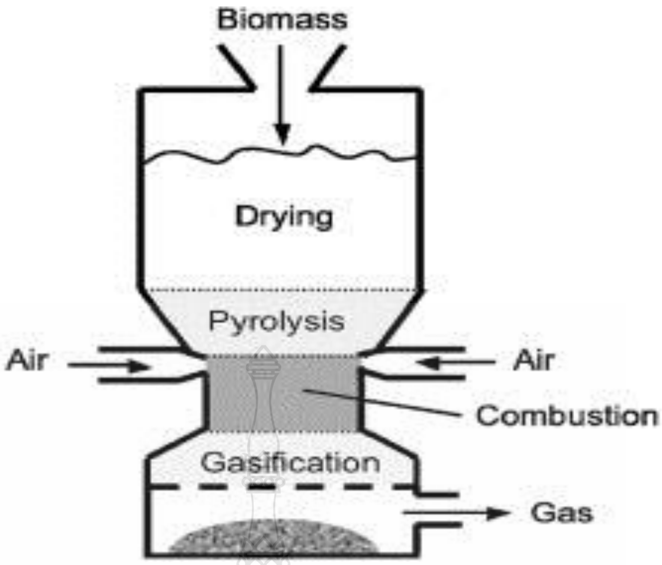


Figure 2.5 Schematic of a throated-type downdraft gasifier [74].

2.4.3 Cross draft Combustor

This type of gasifier has similar operating characteristics with the downdraft gasifier. The main difference is that the gasifying agent enters at high velocity concentrating from one side near the bottom of the gasifier which then creates very high temperature. The product gas is drawn off on the opposite side producing gas with very low tar content. However, this is only applicable for very small scale application, ≤10 kW. and requires very high quality coal having very low ash content.

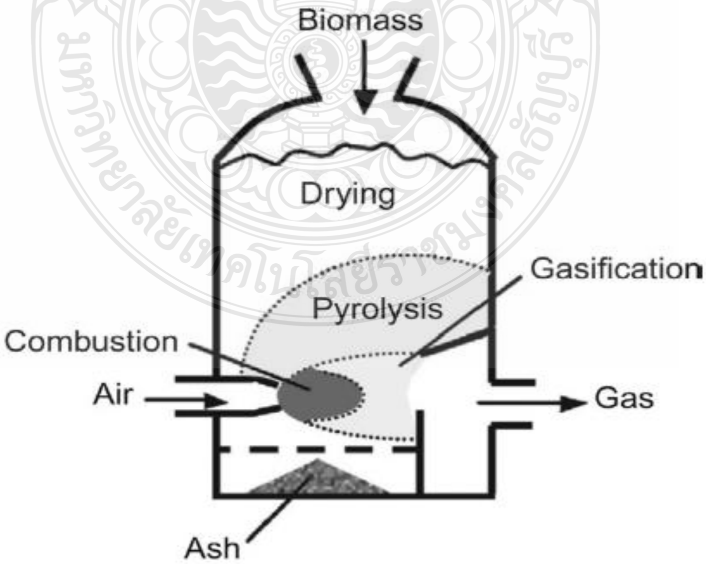


Figure 2.6 Schematic of a cross-draft gasifier [74].

2.5 Heating Value

Heating value defines the amount of energy available in a fuel. The gasifying agent combined with the composition of biomass typically determines the heating value of producer gas. Compared to other fuels, the heating value of biomass is low on a volume basis, because of its low mass density. Heating value is an important property for use in calculations of thermal systems and performance modelling.

Higher heating value (HHV) is defined as the amount of heat released per unit volume or mass. HHV is measured by putting fuel in an environment at an initial temperature of 25˚C, then raising the environmental temperature to the point of complete oxidation, and finally cooling the feedstock back to the starting temperature. HHV is equal to the total amount of heat released during this process. HHV is also referred to as gross calorific value because it includes the latent heat of vaporization of water.

The lower heating value (LHV) is the amount of heat released by totally oxidizing a fuel without the latent heat of vaporization of water, assuming that latent heat is not recovered. LHV is also referred to as the net calorific value.

The relationship between HHV and LHV is defined by:

$$\mathrm{LHV} = \mathrm{HHV} - h_g\left(\frac{9H}{100} + \frac{M}{100}\right) \tag{2.1}$$

where H is the hydrogen percentage, M is the moisture percentage, and h_g is the enthalpy difference between gaseous and liquid water at 25˚C. HHV and LHV may be expressed on "ar", db moisture-free basis, or daf moisture ash-free basis. (Basu, 2018a)

While experimental methods are the best method for determining the heating values of biomass, empirical correlations exist to estimate heating values when experimental methods are not available. Channiwala et. al developed a formula to determining HHV for materials including biomass, coal, liquid, and gas. [Channiwala & Parikh, 2002]

$$HHV = 349.1C + 1178.3H + 100.5s - 103.4O - 15.1N - 21.2 \tag{2.2}$$

where C, H, S, O, N, and ASH are the fractions of carbon, hydrogen, sulfur, oxygen, nitrogen and ash on a dry bulb basis.

2.6 Modeling Techniques

The efficiency of the combustor depends on the nature of the raw materials, gas heating parameters and the combustor design. Mathematical modeling is a valuable tool used to optimize experimental designs to minimize combustor production costs and build-up time. Modeling is also very useful for sizing combustor, from laboratory models to demonstration or commercial scale models. Past studies, many researchers have performed on the analysis of the effects of heat transmission parameters. Such as moisture content, material composition, air flow The temperature of the gas r and the energy content of the producer gas. The mathematical modeling is based on the law of conservation of energy mass and momentum, while more complex models may consider fluid dynamics and chemical reactions. Mathematical modeling in the combustor is limited to three approaches: Thermodynamic Equilibrium, Kinetic and Neural Networks (ANN) or Computational Fluid Dynamics (CFD) Pathways [Baruah & Baruah, 2014].

2.6.1 Thermodynamic Equilibrium Modeling

In equilibrium modeling for gasification, the composition of product gas is predicted through the assumption that reactants completely mix with each other and react at a steady-state condition. Equilibrium models calculate mass, heat, and energy balances throughout the entire gasifier or in certain sections of the gasifier to determine an approximation of gas output composition. These models can be categorized into stoichiometric and non-stoichiometric methods.

In the stoichiometric method, equilibrium constants are used to define a set of chemical reactions occurring in the reactor. The most important reactions are considered while other reactions are ignored which can result in small errors. In the non-stoichiometric method, reaction mechanisms are not required to solve the problem through the use of the minimization of Gibbs free energy. This method is a bit more complex but advantageous because intricate knowledge of the chemical reactions is not required. It is very suitable for biomass gasification, because the elemental composition of the feedstock is all that is needed to obtain the chemical formula through ultimate analysis. [Ferreira, Monteiro, Brito, & Vilarinho, 2019]

Equilibrium models may be simple, but they can describe different gasification parameters and the composition of producer gas quite accurately. This is particularly true for downdraft gasifiers since they typically operate close to equilibrium conditions. [Baruah & Baruah, 2014] However, the equilibrium approach does have limitations. Since thermodynamic equilibrium is not present during low operation temperatures, the equilibrium approach is not an accurate prediction method for gasifiers in this condition. Nevertheless, the equilibrium approach has been successfully used in modeling the gasification process in downdraft gasifiers in many studies.

2.6.2 Gibbs Free Energy

Gibbs free energy is a non-stoichiometric model often used to determine the composition of gas in a gasifier. It is quite advantageous to use in biomass gasification because the chemical composition need not be known, unlike stoichiometric models, and only the elemental composition of the feedstock is used as an input to determine product gases. At the equilibrium state, the minimization of the total Gibbs free energy of the reactor is achieved. The principles of Gibbs free energy and how to apply them to a gasifier were reviewed from Jarungthammachote.

$$G^t = \sum_{i=1}^{N} n_i \, \mu_i \tag{2.3}$$

G^t represents the total Gibbs free energy, n_i is the number of moles of *i,* and μ_i is the chemical potential of species *i.* The chemical potential is represented by:

$$K_i = \overline{G^{\circ}1} + \text{RT In}\left(\frac{fi}{f_i^{\circ}}\right) \tag{2.4}$$

f_i represents the fugacity of species *i.* The superscript o represents a standard thermodynamic quantity, representing the standard Gibbs free energy and standard fugacity of species *i* in the above equation.

If the assumption is made that all gases in the gasifier are ideal gases, equation (20) can be reduced to:

$$K_i = \Delta\overline{G_{f,i}^{\circ}} + \text{RT In}\,(y_i) \tag{2.5}$$

where y_i is the mole fraction of species *i* and $\Delta\overline{G^{\circ}}_{f,i}$ is the standard Gibbs free energy of formation of species *i* which is set to 0 for all elements. Substituting equation (21) into equation (19), a full definition for the minimization of Gibbs free energy of a gasifier can be found:

$$G^t = \sum_{i=1}^{N} n_i \, \Delta\overline{G_{f,i}^{\circ}} + \sum_{i=1}^{N} n_i \, RT \, In\left(\frac{n_i}{n_{tot}}\right) \tag{2.6}$$

The values of n_i which minimize G^t must then be found. The standard method to do this is performed with the Lagrange multipliers method. The elemental balance is defined by eq. (23).

$$\sum\nolimits_{i=1}^{N} a_{ij} n_i = A_j, j = 1,2,3, \ldots, k \tag{2.7}$$

Then, Lagrange multipliers must be chosen to for the Lagrangian function (L).

$$L = G^t - \sum\nolimits_{j=1}^{k} \lambda_j \left(\sum_{i=1}^{N} a_{ij} \, n_i - Aj\right) \tag{2.8}$$

The standard Gibbs free energy of each chemical species can be calculated with the standard enthalpy and entropy of formation in the following equation.

$$\Delta\overline{G_{f,i}^{\circ}} = \Delta\overline{H_{f,i}^{\circ}} - \Delta\overline{S_{f,i}^{\circ}} \tag{2.9}$$

2.6.3 Kinetic Modeling

A kinetic model has the ability to predict temperature and gas composition profiles inside a gasifier. It can also predict overall gasifier performance when certain operating conditions of the gasifier are given as inputs. The kinetic model considers both the hydrodynamics and kinetic reactions inside the reactor which are important if the required residence time for complete conversion is long. Therefore, low operation temperatures tend to be more suitable for relatively low operation temperatures when compared with the equilibrium model. Kinetic models tend to be computationally intensive, and their complexity only increases as more outputs of the model are calculated or desired.

When reaction kinetics are considered inside the gasifier, bed hydrodynamics, mass, and energy balances are used to determine yields of tar, char, and gas at the operating conditions used as inputs. The kinetic model is sensitive to gas-solid mixing in the gasifier, therefore kinetic models can be divided into fixed bed, fluidized bed, and entrained flow categories. On the other hand, hydrodynamics considers parameters from the reactor mixing process. The following models can be developed from reactor hydrodynamics: zero dimensional, one dimensional, two dimensional, and three dimensional.

2.6.4 CFD and ANN Models

Computational Fluid Dynamics (CFD) is a branch of fluid dynamics which analyses fluid flow through the use of numerical analysis and data structures. This type of modelling falls under the finite computation analysis category. Numerical computation is performed through the use of computers which allows CFD to solve some of the world’s most incredibly complex problems. These problems include aerodynamics, combustion analysis, industrial system design, weather analysis, and engine analysis. CFD analysis begins by defining the physical geometry of a structure using computer aided design (CAD). The volume of the fluid to be analysed is then divided into discrete cells comprised of elements and nodes, also called meshing. Meshing must be fine enough to capture the areas of fluid flow of interest in sufficient detail required for the experiment. Then, the physical modelling is defined by the experimental parameters being measured: equations of fluid motion, radiation, enthalpy, conservation, etc. Those equations will be calculated at the nodes defined in the meshing process. Then, boundary conditions are defined at the surfaces of the fluid domain. Finally, the simulation begins and equations are solved iteratively as steady-state or transient flow, which is defined by the user. The results of the calculations are post-processed after the calculation with post-processing software.

Computational Fluid Dynamics CFD models solve equations for conservation of mass, energy, momentum, and species simultaneously inside specific regions of the gasifier or throughout the gasifier. They incorporate both kinetic and equilibrium modeling to yield the advantages of both models. For gasifiers, CFD models predict temperature and gas yield very accurately when gasification hydrodynamics is known and used as an input. It combines specific chemistry, chemical reactions, and particulate flow within the gasifier. This is challenging and computation heavy in CFD because of the complexities involved. CFD models have been used with increasing frequency to study the performance of different gasifiers with varying parameters, feedstock, and design specifications. [Baruah & Baruah, 2014]

Meshing is a process used in CFD models to split a structure into smaller components in order to calculate parameters of a structure with greater accuracy. In meshing, you create a finite number of grid points within a structure called nodes. At these nodes, governing equations are solved numerically for the parameters desired. The governing equations solved at the nodes in the models used in this paper are described in detail in section 1.2 of Methods of Experimentation. The Finite Volume Method is used to solve these equations. The greater the density of the meshing, the greater the accuracy in solving the problems. However, greater accuracy comes at the cost of greater difficulty in solving the equations. Therefore, meshes must be created in a balance with enough density to capture the most important details, but with a low enough density where the software is able to solve the equations in a timely manner.

CFD is a useful tool in optimizing material usage, design parameters, experimental procedures, and time usage for various applications. In recent years, CFD modeling has been used extensively for many applications. For example, Kongkapisuth et. al performed CFD analysis of a wind turbine using the k-ε turbulence model which was useful in determining the effect of the velocity and direction of wind flow on the free spinning speed of several wind turbines. [Kongkapisuth, Roynarin, & Intholo, 2017] Khan et. al explored the thermal and fluid dynamic characteristics of six pin fin heat exchangers through the CFD analysis of their pressure, temperature, and velocity profiles and determined that elliptical pin fins have the best overall performance. [Khan, Baruah, Dewan, & Mahanta, 2009] Kumar et. al developed a CFD model of biomass gasification in which he used a volatile break-up approach for the combustion portion of the gasification model which was useful in studying the effect of the equivalence ratio on gasifier temperature and output as well as the syngas production of varying biomass feedstock. [Kumar & Paul, 2019] In all of these, modeling was determined helpful in gasifier design due to the effectiveness of modeling in saving time, reducing costs, and optimizing design.

Artificial Neural Networks (ANN) are a neural network which uses experimental data mimicking the workings of the human brain to solve models in a human-like manner and to self-learn. This method gives a numerical result without an exact analytical solution. However, if input data differs greatly from the original data it was modeled with then it may return inaccurate results. Therefore, ANN cannot be used without sufficient data and diligence is required to calibrate and evaluate constants within the model. ANN has been used with limited but progressing success to predict gas composition and yield within gasifiers. CFD is sometimes categorized as a ANN. [Baruah & Baruah, 2014].

2.6.5 The Finite Volume Method

The Finite Volume Method (FVM) uses the integration of transport equations governing heat transfer and fluid flow to describe the transport process of pure diffusion in steady state flow. The first step of this process is to discretize the geometric domain into finite volumes. Then each discrete element has partial differential equations integrated over them into algebraic equations. These equations are solved systemically to compute values for the variables desired.

The FVM turns terms in the conservation equation into face fluxes and evaluates them and the faces of the finite volumes. The net flux is equal to zero since flux entering a given volume is equal to that leaving the succeeding volume. In the FVM, implementation of boundary conditions is easy since unknown variables are evaluated at the center of individual volumes and not at their boundary faces. This makes the FVM strictly conservative which makes it an optimal method for CFD. [Moukalled, 2016]

Applications involving fluid flow, heat transfer, and mass transfer are very suitable for use with the FVM and therefore the FVM has developed congruently and closely with CFD technology. Complex applications can now be solved with the help of CFD and the FVM.

2.7 Combustion of solid fuels

Solid fuels are burned in a variety of systems, some of which are similar to those fired by liquid fuels. In large industrial combustor, particularly boilers for electric power generation, coal is pulverized to a fine powder [7] (typically, 50 μm mass mean diameter and 95%smaller by mass than about 200 μm) which is sprayed into the combustion chamber and burned in suspension as illustrated in Figure.2.1 the combustion in the pulverized coal system has many similarities to the combustion of heavy fuel oils. Smaller systems generally utilize fixed- or fluidized-bed combustors that bum larger particles. The latter technologies are also applied to the combustion of wood, refuse, and other solid fuels. Air is fed into a fluidized bed at a sufficiently high velocity to levitate the particles, producing a dense suspension that appears f1uidlike. Heat transfer in the bed must be high enough and heat release rates low enough to keep the bed relatively cool and prevent the ash particles from fusing together to form large ash agglomerates known as clinkers. Noncombustible solids are often used to dilute the fuel and keep the temperature low; most commonly, limestone is used in order to retain the sulfur in the bed at the same time. In contrast to the rapid mixing in a fluidized bed, only a fraction of the air comes in contact with the fuel in a fixed bed, or stoker, combustion system, with the remainder being introduced above the bed of burning fuel. Large amounts of excess air are required to achieve reasonable combustion efficiency, and even with the large airflows, hydrocarbon and carbon monoxide emissions can be quite high, due to poor mixing above the bed. The increased air requirements lower the thermal efficiency of stoker units, so pulverized coal or fluidized-bed combustion is favored for large systems. Most large systems currently in use bum pulverized coal. We shall, for this reason, focus on these systems.

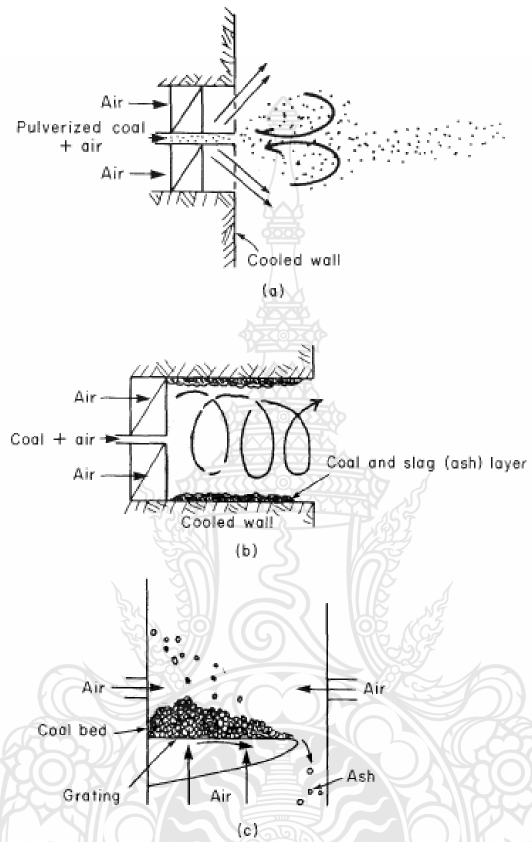


Figure 2.7 Coal combustion systems: (a) pulverized coal burner; (b) cyclone burner;(c) spreader stoker; (d) fluidized-bed combustor [7].

2.8 Porous Medium Combustion

New developments in gas and oil burners in recent years were dominated by the aim of reducing pollutant emissions, reducing burner size and increasing the power modulation range. As far as the pollutant emissions are concerned, many improvements have been achieved. NOx emissions of gas burners have already reached levels in the range of 20 mg/kWh, but there is still a need for further improvements in the power modulation range, keeping the emissions low at the same time. There is also a strong necessity for further burner size reduction for all types of burners, without compromising the characteristics of the pollutant emission behavior.

The processes of gas combustion in an inert porous medium are interesting in many respects. It is widely used in practice and is promising in solving a number of problems in power engineering, chemical technology, ecology and fire and explosion prevention. Porous medium combustion offers exceptional advantages compared with free flame burner techniques in order to achieve these goals. Unlike conventional premixed combustion processes, combustion in a porous medium does not operate with free flames. Rather, flameless combustion takes place in the three-dimensionally arranged cavities of a porous medium.

A novel combustion technique based on combustion in a porous medium has been developed in recent years [7]-[13] The major novelty of this work is the combustion stabilization principle, which allows extremely stable operation of the premixed combustion process in a porous matrix. The flame stabilization layer is placed inside the porous matrix and is well defined by the matrix design.

2.9 Basic Principles of Porous Medium Combustor

In the presented approach, the porous medium combustion process stabilizes itself at the transition zone between two regions with different pore sizes. The most important criterion which determines whether or not a combustion process takes place inside a porous structure is its critical pore size. If the size of the pores is smaller than this critical dimension, flame propagation is prohibited; the flame is always quenched. On the other hand, if the pore size exceeds the critical dimension, flame propagation inside the porous structure is possible. The critical pore size may be determined by a modified Péclet number. The experiments of Backing et al [14] resulted in the following limiting modified Péclet number Pe for flame propagation in a porous medium:

$$Pe \geq 65 \tag{2.10}$$

Where

$$Pe = \frac{S_L d_m c_p \rho}{\lambda} \tag{2.11}$$

Figure 2.8 shows the schematic setup of a porous burner with the preheating region A and the actual combustion region C Depending on the actual application, an additional region may be included in the porous burner where the heat of combustion is transferred to the particular, selective diffusion and heat exchange between gas and porous medium.

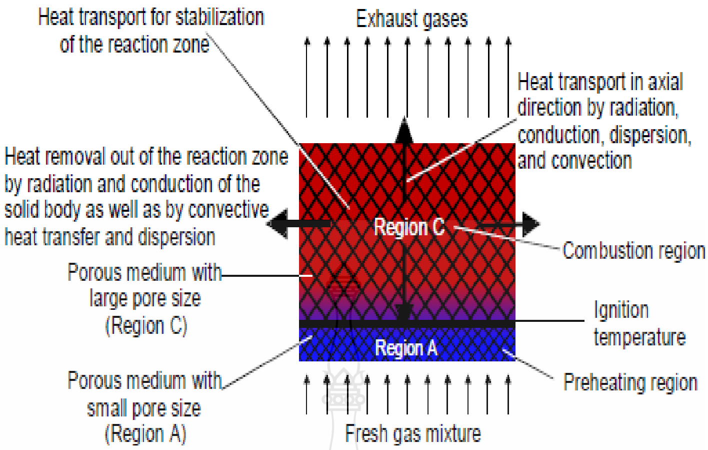


Figure 2.8 Schematic setup of a porous-medium [14].

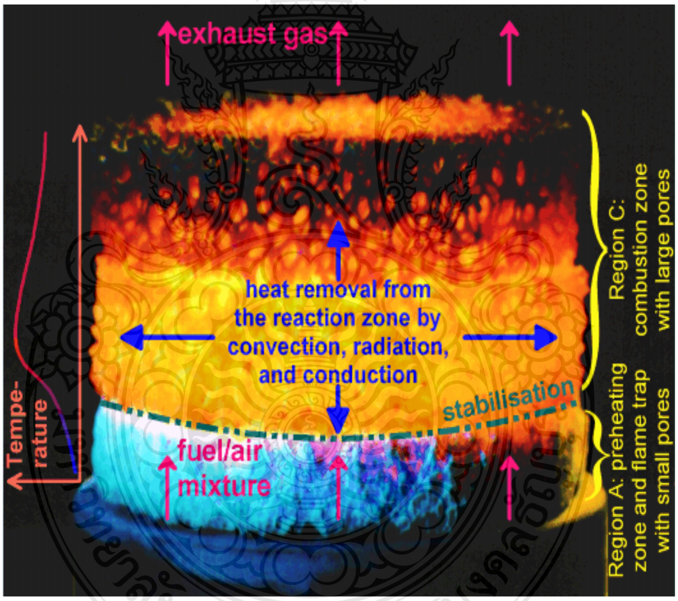


Figure 2.9 Porous-medium stabilization principle [14].

In Figure 2.8, a photograph of a stabilized combustion process in a porous medium is shown and the temperature distribution is indicated. The good heat transfer properties keep the maximum temperature low, which also keeps NO_x emissions low. A very homogeneous temperature field is also achieved, keeping the carbon monoxide concentration in the waste gas low also. A considerable part of the heat from the combustion region is also transported upstream, causing about 10 times higher flame speeds compared with laminar free flames. This translates into a greater power density and better space utilization. Due to these outstanding properties, porous burner technology is attractive for different fields of application.

2.10 Porous Medium Combustor

It is general practice to build gas combustors in such a way that they contain free-burning flames in an enclosure acting as a combustion chamber. The heat gases from the combustion chamber are subsequently fed through a heat exchanger to heat up water or produce steam. Combustors of this kind are characterized by high NO_x formation in the hot combustion region of the flame and by high temperatures of the hot emission gases leaving the heat exchangers or steam generators. Over the past few years, a great deal of investigation on combustion in porous media has been performed, starting with basic experiments mostly by Russian scientists, who found the combustion regimes and the flame propagation criteria for porous medium combustion as reported in Section 2.1. These basic thoughts were taken up and continued of [14] leading to the layout of a porous burner as shown in Figure 2.8

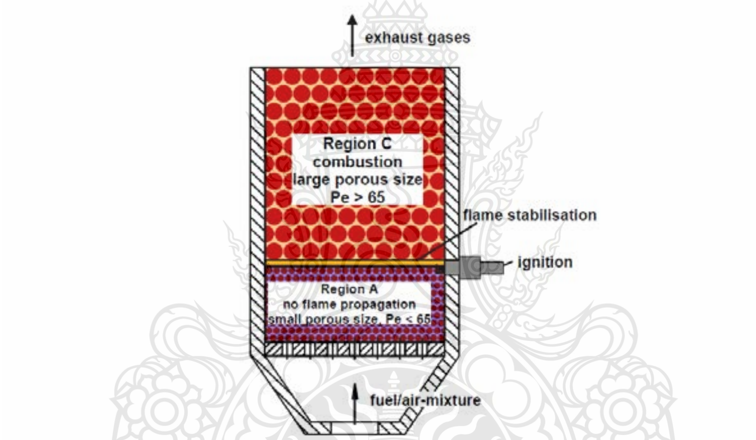


Figure 2.10 Schematic diagram of the combustor with two porous regions [14].

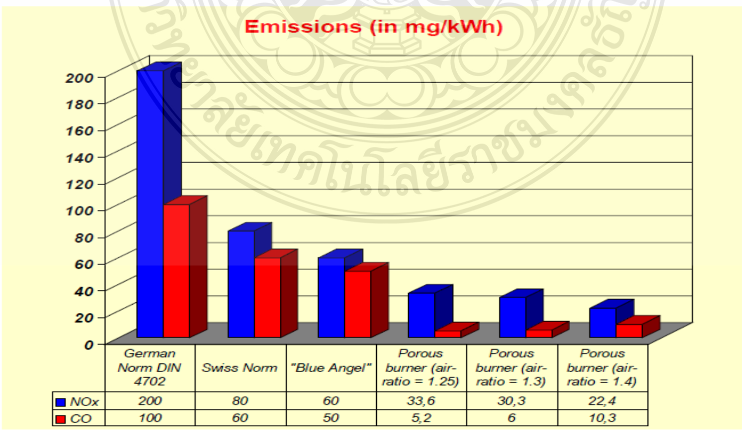


Figure 2.11 Typical emission values of a porous-medium burner compared with international norms [14].

In the case of application of the PMB in a household heating system, where the cooling of exhaust gases takes place, typical measured NO_x emissions for different ceramic materials are shown in Figure 2.11

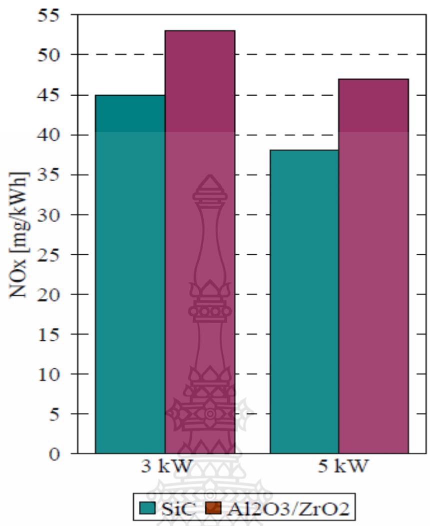


Figure 2.12 Measured NO_x concentrations in flue gases for low-power-operation for different ceramic Materials [14].

Different types of PM combustors with various materials of combustion zone have been developed in recent years (Figure 2.12)

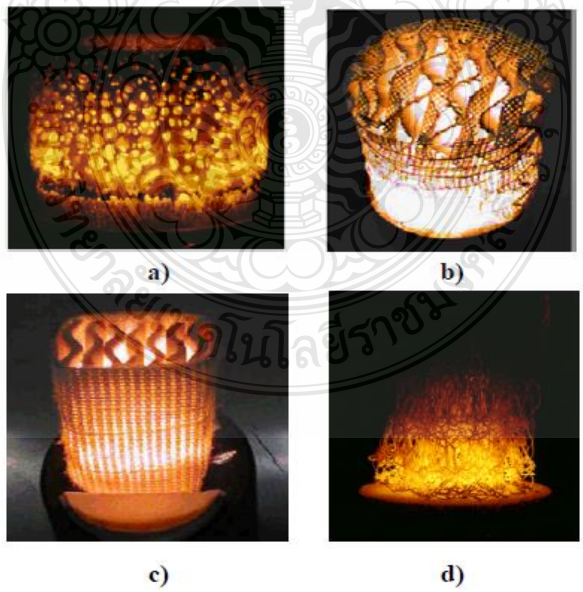


Figure 2.13 Different ceramic porous burners made of (a) C/SiC structure; (b) Al2O3 fibre structure; (c) zirconium foam static mixer; (d) Fe-Cr-Al alloy wire mesh [14].

In Figure 2.13 a, combustion in a ceramic foam as a porous body is shown. The total thermal load is 20 kW with an air ratio number of 1.3. In Figure 2.6b an example of a ceramic fiber structure is presented. The thermal power is 15 kW with combustion at an air ratio number of 1.3. Figure 2.7c shows a static mixer as a suitable structure for porous medium combustion. Static mixers may be characterized by low conduction heat transport, a short start-up phase, excellent radiant heat transport, excellent dispersion properties and a very low pressure drop. The next example of a structure that may be used for porous medium combustion is the metal wire packing or so-called wire meshes. In the small wire packing shown in Figure 2.7d a thermal power of 10 kW is produced with an air ratio number of 1.3. Wire meshes show poor conduction heat transport and dispersion properties, owing to their high porosity. On the other hand, they have a short start-up phase, excellent radiation heat transport properties, very low pressure drop and the high resistance to thermal stresses occurring in its microstructure. More details of materials used in porous medium combustion technology are given in Section 2.2.3.

2.11 Ceramic Materials Employed in the Porous Medium Technique

The intensive heat transfers between the gas phase and the porous medium that this entails gives rise to a unique combination of advantages for combustion technology: the burners are compact, have low pollutant emissions and can be adjusted continuously over a wide range of powers. A special emphasis of optimization work in PMB technology has therefore been the development of high temperature-resistant ceramic and metal components. Important criteria for the selection of ceramics include its temperature resistance, its mechanical stability and its ageing behavior. Also of major importance for the use in PMBs are the pressure drop and the heat capacity of the ceramic materials. The pressure drop influences the necessary power of the blower and therefore also the amount of electrical energy necessary in a crucial way. Larger and stronger blowers demand much higher investment and running costs. Furthermore, noise emission might also be promoted. The heat capacity of the ceramic materials also determines the thermal inertia of the burner. With high thermal inertia, the burner is insensitive to fluctuations of the gas mixture properties. On the other hand, with a high heat capacity the start-up of the burner requires a rather long time until it reaches steady-state operation, leading to significantly increased start-up emissions. The temperature resistance is determined mostly by the melting point, but also by the thermal expansion rate of the material. Moderate thermal expansion rates avoid thermal stresses, which can promote breaking of the porous matrix, as ceramic materials tend to show a poor modulus of elasticity, which even decreases with higher temperatures. These criteria also affect the temperature switch resistance. High heat conductivity of the ceramic materials is also considered to be of major importance as hot spots are avoided, leading to an even temperature distribution with only minor thermal stresses

inside the material. The main materials used today are ceramic foams or structures that resemble the static mixers or regular packing often used in process engineering [16].
The advantages of these structures are as follows:

• The open-pore structures with good flow-through properties keep pressure losses low and, therefore, low-cost burner blowers with a low-energy consumption can be used.

• Heat transfer is excellent. The gas is often forced to flow inwards and outwards, to split and reunite. With the convective heat transfer that this causes, a balanced temperature field is generated at a low level. This is accompanied by low pollutant emissions.

• The structures are characterized by a very low weight. This means that the thermal inertia is low, which has the effect that the burner heats up quickly on starting and adapts to power changes quickly. Metallic materials are less suitable as porous media because of their inadequate thermal stability. Temperature-resistant metal alloys might be used for temperatures below 1250°C. Their thermal properties are a high heat conductivity ranging from 10 W/mK at 20°C to about 28 W/mK at 1000°C, extreme thermal expansion and an extremely good resistance to thermal shock. The emissivity of metals varies strongly with the surface finish processing and the surface itself. It stretches at 300 K from 0.045 for polished nickel to about 0.5 for used stainless steel. For nickel-base and FeCrAl alloys the upper temperature limit is approximately 1400°C. For PMBs, typical maximum temperatures could be between 1400 and 1600°C, and in extreme cases even 1700°C. Therefore, materials based on aluminium oxide, silicium carbide and zirconium oxide are mainly used (Figure 2.14).

Figure 2.14 Commonly used porous ceramic materials [16].

Aluminium oxide ($Al2O_3$) can be used up to approximately 1900°C under air. High SiO_2 contents between 20 and 40% reduce the application limit to approximately 1650°C. Because of its high thermal expansion coefficient and an average thermal conductivity, the resistance to temperature change of $Al2O_3$ ceramics is relatively low.

Silicium carbide (SiC) can also be used at very high temperatures, usually up to 1600°C. The resistance to temperature change of SiC ceramics is very good, which is due to the low expansion coefficients and the high thermal conductivity.

Zirconium oxide (ZrO_2) can be used up to 2300°C but a change associated with a volume increase during cooling can destroy the structure. The high-temperature modification is stabilized by incorporating various additives. In this way, fully and partially stabilized ZrO_2 can be used up to approximately 1800°C. The high thermal expansion and the low thermal conductivity have a negative effect on the resistance to temperature change.

A comparison of the data for materials relevant for use in PMBs is shown in Table 2.2

Table 2.2 Most important material data for $Al2O_3$, SiC and ZrO_2

Parameter	**Dimensions**	**Al_2O_3**	**SiC**	**ZrO_2**
Maximum allowable temperature in air	°C	1900	1600	1800
Thermal expansion coefficient α (20-1000°C)	10^{-6} 1/K	8	4-5	10-13
Thermal conductivity λ at 20°C	W/mK	20-30	80-150	2-5
Thermal conductivity λ at 1000°C	W/mK	5-6	20-50	2-4
Specific thermal capacity	J/gK	0.9-1	0.7-0.8	0.5-0.6
Thermal stress resistance parameter, hard Shock, *R* (σ/*E*α)	K	100	230	230
Thermal stress resistance parameter, mild thermal Shock, *R* (*R*° λ)	10^{-3} W/m	3	23	1
Total emissivity at 2000 K	-	0.28	0.9	0.31

The porosity and structure of porous media also have a strong influence on these property values. The resistance to temperature change is usually greatly improved by porosity. On the other hand, the enlargement of the inner surface due to an increase in the open porosity is a disadvantage if surface chemical reactions occur with the combustion gases. Along with the combination of different materials, it is important to note that a melting point reduction at the contact points can be caused by the formation of a eutectic. For example, the combinations SiC/$Al2O_3$ and SiC/ZrO_2 are critical.

The requirements on the porous medium are very different for the numerous applications for which porous medium burner technology can be used. Depending on the type of fuel, air and fuel flow and burner geometry, the temperatures to which the porous medium are subjected are very different. Moreover, individual criteria such as costs, lifetime, pollutant emission, mechanical stability (very important in the automotive industry), pressure loss and thermal inertia will be weighted differently depending on the application. For that reason, a number of manufacturers have developed different porous media which meet the stringent requirements of PMB technology.

2.12 Energy and Energy Resorts

2.12.1 Biomass Energy

Biomass is the term used to describe all the organic matter, produced by photosynthesis that exists on the earth's surface [17]. The source of all energy in biomass is the sun, the biomass acting as a kind of energy store. To make use of biomass for our own energy needs we can simply burn it in an open fire to provide heat for cooking, warming water or warming the air in our home. More sophisticated technologies have been developed for extracting this energy and converting it into useful power and heat in more efficient and convenient ways. Until relatively recently it was the only form of energy which was used by humans and is still the main source of energy for more than half the world's population for their domestic energy needs. The extraction of energy from biomass is split into 3 distinct categories:

Solid biomass - the use of trees, crop residues, animal and human waste (although not strictly a solid biomass source, it is often included in this category), household or industrial residues for direct combustion to provide heat. Often the solid biomass will undergo physical processing such as cutting, chipping, briquetting, etc. but retains its solid form.

2.12.2 Biogas

Biogas is obtained by anaerobically (in an air free environment) digesting organic material to produce a combustible gas known as methane. Animal waste and municipal waste are two common feedstocks for anaerobic digestion. See the Biogas Technical Brief for more details.

Liquid Biofuels – these are obtained by subjecting organic materials to one of various chemical or physical processes to produce a usable, combustible, liquid fuel. Biofuels such as vegetable oils or ethanol are often processed from industrial or commercial residues such as bagasse (sugarcane residue remaining after the sugar is extracted) or from energy crops grown specifically for this purpose. Biofuels are often used in place of petroleum derived liquid fuels. See the Liquid Biofuels and Sustainable Development Technical Brief.

Solid biomass is widely used in developing countries, mainly for cooking, heating water and domestic space heating. Biomass is available in varying quantities throughout the developing world - from densely forested areas in the temperate and tropical regions of the world, to sparsely vegetated arid regions where collecting wood fuel for household needs is a time consuming and arduous task.

In past decades the threat of global deforestation, provided a focus for the efficient use of biomass (as well as introducing alternative fuels) in areas where wood fuel was in particular shortage. Although domestic fuelwood users can suffer greatly from the effects of deforestation, it often arises because of land clearing for agricultural use or for commercial timber.

There have been many programmers aimed at developing and disseminating improved stove technologies to reduce the burden, primarily borne by women, of fuelwood collection as well as reducing health risks associated with smoke from burning fuelwood. Technologies have also been introduced to help with the processing of biomass to improve efficiency, allow for easy transportation or to make it more useable.

Crop and industrial biomass residues are now widely used in many countries to provide centralized, medium and large-scale production of process heat for electricity production or other commercial end uses. There are several examples in Indonesia of timber processing plants using wood waste-fired boilers to provide heat and electricity for their own needs, and occasionally for sale to other consumers. There are also small scale options to utilizing crop residues.

2.12.3 Biomass as a Renewable Source of Energy

The IEA defines biomass as “any plant matter used directly as fuel or converted into fuels (e.g. charcoal) or electricity and/or heat. Included here are wood, vegetal waste (including wood waste and crops used for energy production), ethanol, animal materials/wastes and sulphitelyes”. Biomass is a carbon neutral fuel. This means that the carbon released during consumption is balanced by the carbon consumed by photosynthesis during plant growth. Thus, the net contribution to atmospheric CO_2 is zero.

2.13 Mathematical of Combustion

2.13.1 Modeling Combustion in a Grate Furnace

Biomass combustion in fixed-bed combustor is complex and difficult to measure. The environment is hostile and difficult to observe, and the overall combustion process is highly complex, being influenced by a wide variety of parameters. As a result, conceptual modelling by means of computational fluid dynamics (CFD) has become a useful tool. Simulations based on validated models can give further insight into the combustion process and aid the optimization of furnace design and operation. In particular, CFD is useful for investigating the influence of individual parameters, since these are easily altered to analyses their effect.

As illustrated in Figure 2.14 grate combustor can effectively be divided into two regions: the fuel bed, comprised of both gaseous and particulate phases; and the freeboard, comprised of gas only. Depending on the objective, CFD can be used to predict combustion in the freeboard, in the fuel bed, or in both together.

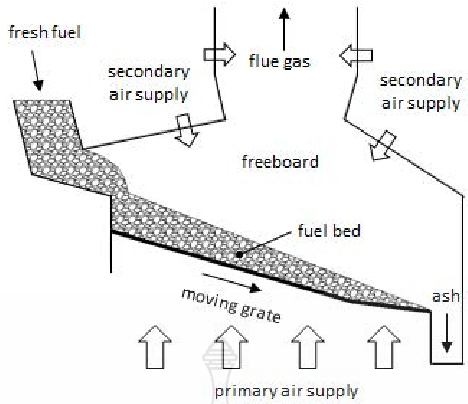


Figure 2.15 Schematic of a fixed-bed furnace with a moving grate [34].

2.13.2 Freeboard modelling

Submodules to simulate gas flow and gas phase combustion are a standard feature of commercial CFD packages. Modelling the gas-only freeboard is, therefore, relatively straightforward for tasks such as optimizing the secondary air supply to increase mixing, improve burnout, and reduce emissions [18]. More specialized simulations, such as predicting the deposition of particulate matter on furnace surfaces or the formation of certain pollutants does, however, require the development and implementation of additional sub models by the user. A common challenge with freeboard-only models is assigning appropriate inlet conditions, *i.e.* composition, temperature, and flow characteristics of the gases leaving the fuel bed and entering the freeboard. These must be determined either by means of measurements or of a fuel bed model.

2.13.3 Fuel bed modeling

Owing to the complex conversion processes of the solid fuel particles, and the intense interactions between the particulate and gaseous phases, modelling the fuel bed in a grate furnace is inherently much more complicated and thus more computationally demanding than modelling the freeboard. The sub models describing these conversion processes are not available as built-in features of current CFD packages; they must be developed and implemented by the user in order to investigate issues specific to the fuel bed.

2.13.4 Heterogeneous reaction models

Char is a porous, carbon-rich solid which is formed during pyrolysis. In addition to carbon, which typically constitutes over 90% of the char [20], small amounts of hydrogen, oxygen, nitrogen, Sulphur, and inorganic matter or ash, are also present. Oxidation of the char occurs through heterogeneous reactions between the solid char and gaseous reactants; the main reactants are oxygen, carbon dioxide, and water vapor. The reaction with oxygen is simply termed char combustion, while char gasification refers to the reaction between char and any gaseous reactant other than oxygen. If the char is assumed to be pure carbon, the reactions can be described as follows:

$$\Omega_c C + O_2 \rightarrow 2(\Omega_c - 1)CO + (2 - \Omega_c)CO_2 \tag{2.12}$$

$$C + \frac{1}{2}O_2 \rightarrow CO \tag{2.13}$$

$$C + O_2 \rightarrow CO_2 \tag{2.14}$$

$$C + CO_2 \rightarrow 2CO \tag{2.15}$$

$$C + H_2O \rightarrow CO + H_2 \tag{2.16}$$

Heterogeneous reaction rates are influenced by many factors, including: the total active surface area, the local gas reactant concentration, local temperature, pressure, char structure, and char composition. The overall reaction scheme can be described by three basic processes [20]:

1. Diffusion of mass and heat through the boundary layer surrounding the solid fuel.
2. Diffusion of mass and heat within the porous structure of the fuel.
3. Reaction of gases with solid surfaces.

Slower of the two 22-26 As a result, three distinct combustion regimes Can be identified, as illustrated in Figure 2.15 with reference to a spherical particle:

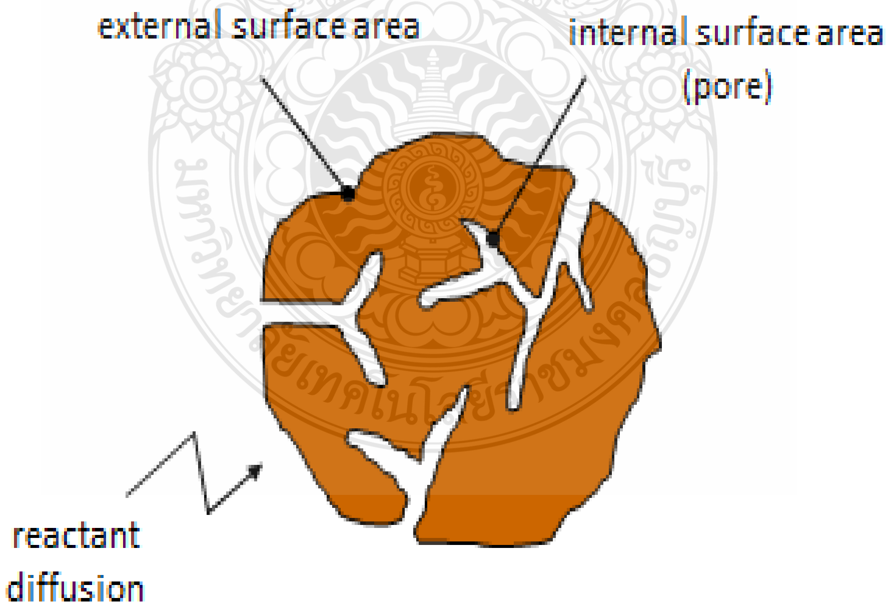


Figure 2.16 Schematic diagram of a porous material. Adapted from [20].

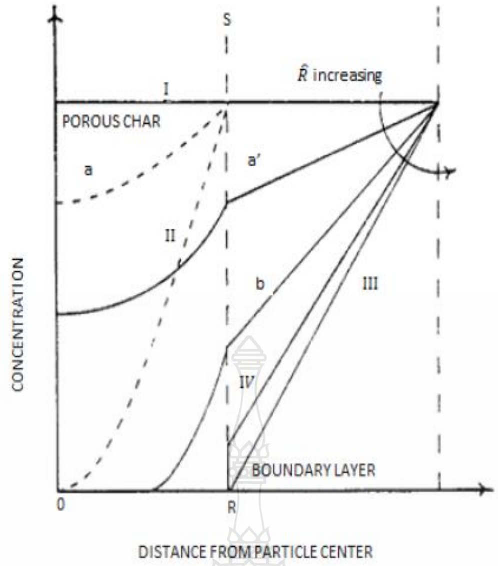


Figure 2.17 Schematic of different reaction zones (for a spherical particle). Zone I – reaction limited, Zone II – reaction and diffusion limited, Zone III (IV) – diffusion limited. Adapted from [20].

Zone I: The chemical reaction is slow with respect to the diffusion of the reactant, effectively limiting the overall reaction rate. Therefore, reactants have time to penetrate the porous structure and the concentration is uniform throughout. The reaction order in this regime is said to be the true, rather than the apparent, reaction order.

Zone II: The chemical reaction and the diffusion of the reactant occur on a similar timescale. The chemical reaction is fast enough that the reactant cannot diffuse through the porous structure fast enough to maintain a uniform concentration throughout the fuel.

Zone III: The chemical reaction rate is so fast that the concentration of the reactant approaches zero. The overall reaction rate is limited by the diffusion rate of the reactants.

Models describing these heterogeneous reactions can be classified as *global models*, which determine the overall rate per unit mass of the fuel using an "apparent" chemical reaction order, or as more fundamental *intrinsic models*, which determine the overall rate per unit internal surface area of the particle using the "true" chemical reaction order.

2.13.5 Heterogeneous reaction models

a) Char structure

The size, density, and internal structure of a particle may change as the particle burns. Since heterogeneous reactions depend on the available surface area, sub models are required to account for these changes. Owing to its simplicity, the most commonly published submodel is the unreacted core model [26, 20], where the internal pore structure is assumed to remain constant during conversion. The size and density of the particle are then inversely related, with changes described as a function of mass loss [27]. A common assumption is that the density also remains constant during char oxidation, with particle shrinkage directly proportional to mass loss.

b) Char composition

To simplify the reactions, the char is commonly assumed to be pure carbon, resulting in Eqs. (2.10) – (2.13). However, in reality the char will contain 5-10%wt db of other elements, mainly hydrogen and oxygen [28, 29]. This can be taken into account by modifying the heterogeneous reactions, as done in [29], as well as the calorific value of the char, which can be estimated from [30].

c) Heat of reaction

Char primarily reacts with oxygen, carbon dioxide, and water vapour. There is some scatter in the literature regarding exact heats of reaction; however, the char combustion (Eq.(2.10)a/b/c) and char gasification reactions (Eqs. (2.10) and (2.13)) are accepted as exothermic and endothermic respectively, with gasification values available in [29, 31]. The heat released during char combustion is a function of the calorific value of the fuel and the of combustion product(s). This necessitates assumptions about the char composition, and the combustion reaction, *i.e.* whether combustion is represented by Eq. (2.10)a, (2.10)b, or (2.10)c, as described in section.

2.13.6 Thermo chemical conversion models

Owing to their simplicity, the constant temperature model and the kinetic model are the most commonly utilized drying models in the literature. In the absence of suitable data for the kinetic model, the constant temperature model should be used, since it gives a reasonable approximation without any experimentally derived inputs. The transport model is more representative of the actual drying process; however, it is worth noting that this model requires extensive input/assumptions from the user which may diminish the potential benefits. Investigations into the pyrolysis of biomass fuels indicated that a single step pyrolysis model cannot closely represent the decomposition process and should only be used as an approximation [32]. If an approximation is sufficient, then the single step model is ideal since it is the simplest to implement, the least computationally expensive, and there is a dearth of kinetic data available. However, given the relevant kinetic data, a more sophisticated model such as a parallel step model, DAEM, or network model should be used. One of the main benefits is that these models account for the dependency of the char yield on the heating rate of the fuel. Of these, the parallel step model offers a significant improvement on the single step model for only a moderate increase in effort and computational expense. It is worth noting, however, that the distributed activation energy model (DAEM) and the network models require a substantial increase in effort to implement and significantly more information from the user. The heterogeneous char reactions can be divided into two categories: the combustion reaction with oxygen, and the slower gasification reactions. At the temperatures typically present in a furnace, the char combustion rate is generally limited by the diffusion of oxygen to the particles, with the chemical reaction rate primarily acting to control the ignition temperature of the fuel. Since the reaction is, there more, primarily limited to the outer surface of the particle (zone III/IV combustion, Figure 2.8), the difference between the simple global model and the more complicated intrinsic model is negligible [33]. The global model is therefore sufficient provided appropriate kinetic data is available. For the slower gasification models, however, the overall reaction rate is likely to be limited both by the chemical reaction rate *and* by the diffusion rate of the reactant to the particle. As a result, the reactions may occur on both the internal and external surfaces of the char particle (zone I/II combustion, Figure 2.8) and are better described by means of an intrinsic model. It is worth noting that the main drawback of the intrinsic model is that it necessitates assumptions regarding the initial internal structure of the char and how this structure changes during burnout. These assumptions vary widely across the literature, for biomass in particular, which may occlude the benefits associated with this model.

2.13.7 Review of Fixed-Bed Modeling

In fixed-bed or grate combustor, aerodynamic forces are insufficient to lift the majority of the particles. As a result, particles lie in contact, with voids between them, forming a well-defined fuel bed, as shown in Figure 2.18 In case, the objective is to simulate a section of a packed or fixed fuel bed in a biomass furnace. Consider the “as modelled”two-dimensional section highlighted in Figure 2.18 There are four approaches for achieving this [34]:

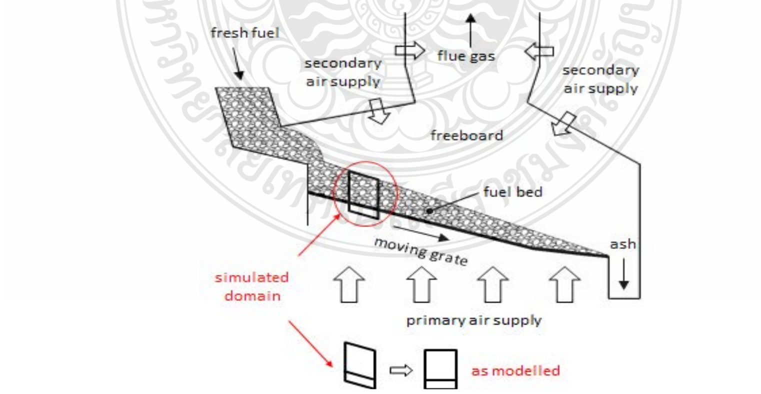


Figure 2.18 Schematic of fixed-bed furnace [34].

(1) An Eulerian-Eulerian approach [24, 33,35,36,37-41]: The solid phase is represented as a continuum, and individual particles are not tracked (Figure 2.16). This

can be subcategorized depending on how the solid phase is represented; whether as a porous medium, or using the theory of granular flow.

(2) An Eulerian-Lagrangian/Discrete Particle Model (DPM) approach [42-44]: Each particle, and its properties, is tracked throughout the computational domain (Figure 2.17).

(3) A neighboring layer approach [45-47]: The bed is split into four layers representing fresh fuel, dry fuel, char, and ash (Figure. 2.18).

(4) A well-stirred reactor model (WSR) [48]: the bed is represented by a cascade of well-stirred, also termed perfectly stirred reactors; in a WSR, transport rates are assumed to be much higher than chemical rates (Figure. 2.19). The properties with the reactor are therefore uniform throughout, and
only the chemical rates need be determined.

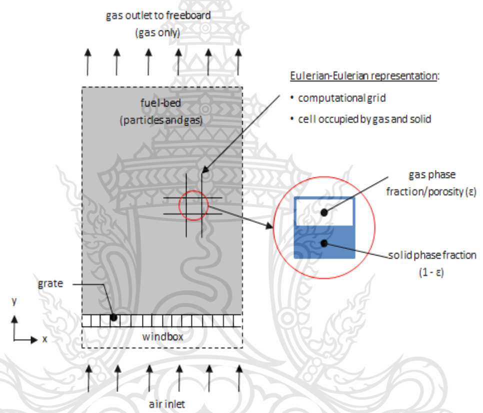


Figure 2.19 Eulerian – Eulerian approach [34].

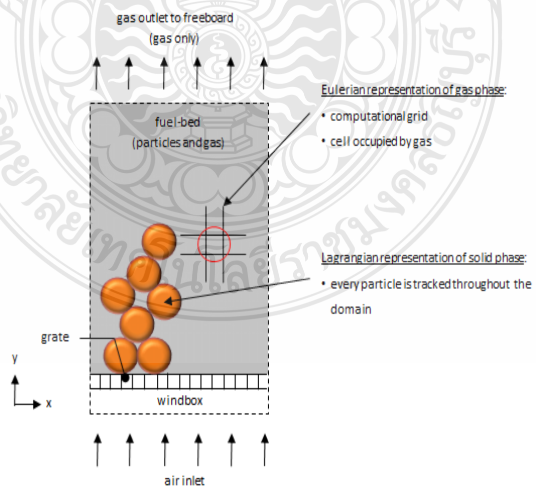


Figure 2.20 Eulerian-Lagrangian approach [34].

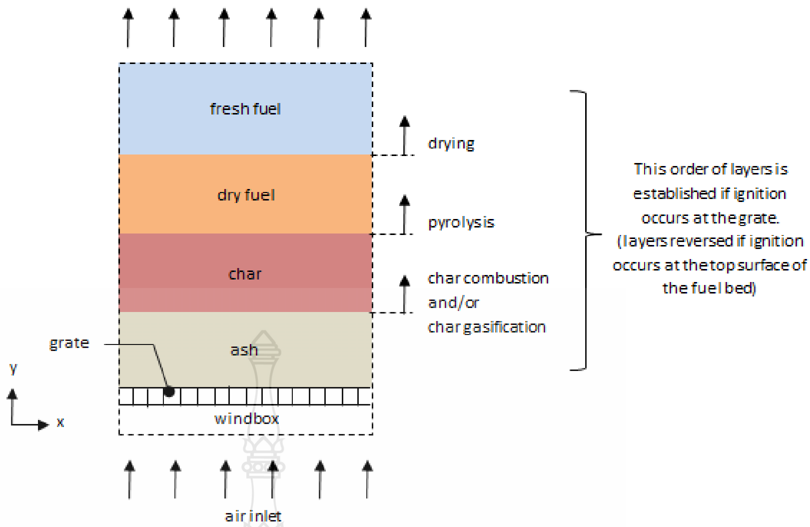


Figure 2.21 Neighboring layer approach [34].

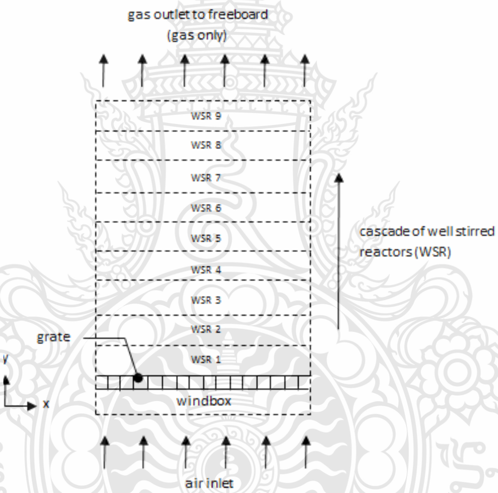


Figure 2.22 Cascading reactor model [34].

In order to obtain a close match between measured and predicted ignition rates, a significant amount of model calibration was necessary. The first step involved identifying a number of parameters that influenced the ignition rate, including the solid phase thermal conductivity, the pyrolysis model and the corresponding reaction constants, the blowing factor, the particle-particle radiation model, and the model for the effective thermal diffusivity of the solid phase. Various relevant models/values for each of the parameters listed above were taken from the literature and varied, in turn, to ascertain their effect on the predicted ignition rate. Owing to the complexity of the overall model, the exact effect of different combinations of these parameters proved difficult to infer in advance. As a result, different arrangements were compared on a trial and error basis until the combination which provided the best match between measurements and predictions was determined. The culmination of the model calibration process is presented in section 2.4.7

Predicted ignition rates closely match the data in the sub-stoichiometric zone. For low air flow rates predictions slightly exceed measurements; nonetheless, the peak ignition rate is closely captured, as is the subsequent fall off in the ignition rate due to convective cooling. In line with the observations of Porteiro *et al*. [49, 50], the model also predicts a decreasing reaction zone thickness as the air flow rate increases. Deviations between measurements and predictions occur at higher fluxes where the model prematurely predicts extinction. In practice, any combustible gases leaving the bed will be completely burned in the freeboard. Some of the heat produced will be radiated back to the bed helping to sustain combustion, but will only penetrate a finite depth below the surface [51]. This is expected to have an increased effect at higher air flow rates due to the narrowing reaction zone, which brings the ignition front closer to the surface of the bed. Since the freeboard region and the associated radiation effects are excluded in the present simulations, this is the most likely cause of the differences in predicted and measured ignition rates at the higher fluxes. Collazo *et al.* [52] also validated their model using the same data. Both models achieve similar agreement between predictions and measurements in the sub-stoichiometric region. Their model, which included the freeboard, performed better in the fuel lean regime; however, it also prematurely predicted extinction. Recalling that the goal of the present study is to investigate channeling in modern industrial grate combustor, where combustion in the fuel bed typically takes place under sub-stoichiometric conditions, and ignition occurs from just above the grate, the model performance is acceptable.

2.13.8 Final results

Predicted ignition rates closely match the data in the sub-stoichiometric zone. For low air flow rates predictions slightly exceed measurements; nonetheless, the peak ignition rate is closely captured, as is the subsequent fall off in the ignition rate due to convective cooling. In line with the observations of Porteiro *et al*. [53, 54] the model also predicts a decreasing reaction zone thickness as the air flow rate increases. Deviations between measurements and predictions occur at higher fluxes where the model prematurely predicts extinction. In practice, any combustible gases leaving the bed will be completely burned in the freeboard. Some of the heat produced will be radiated back to the bed helping to sustain combustion, but will only penetrate a finite depth below the surface [51]. This is expected to have an increased effect at higher air flow rates due to the narrowing reaction zone, which brings the ignition front closer to the surface of the bed. Since the freeboard region and the associated radiation effects are excluded in the present simulations, this is the most likely cause of the differences in predicted and measured ignition rates at the higher fluxes. Collazo *et al.* [52] also validated their model using the same data. Both models achieve similar agreement between predictions and measurements in the sub-stoichiometric region. Their model, which included the freeboard, performed better in the fuel lean regime; however, it also prematurely predicted extinction. Recalling that the goal of the present study is to investigate channeling in modern industrial grate combustor, where combustion in the fuel bed typically takes place under sub-stoichiometric conditions, and ignition occurs from just above the grate, the model performance is acceptable.

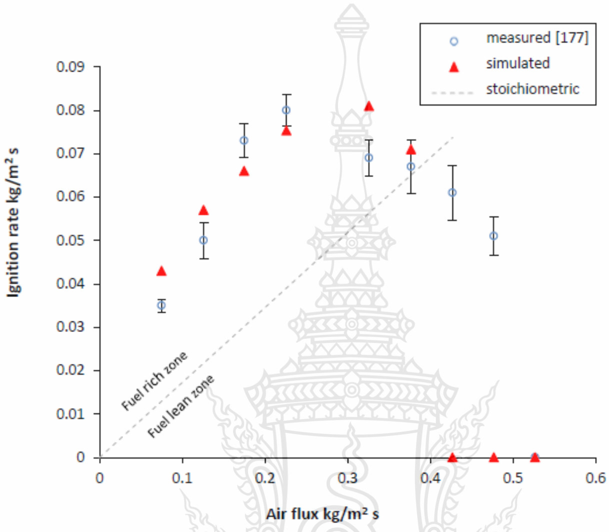


Figure 2.23 Steady-state ignition rate for different air flow rates after 900 s [52].

2.13.9 Development of mathematical model

The aim of modeling work is to describe the behavior of a system by easily varying every parameter, unlike experimental work, where the parameters cannot easily be changed. In this study, the model will be used to design and figure out the dimension of components and operating and efficiency parameters of purpose system.

2.14 Mathematical formulation

Before going to the model formulation, the general approach to modeling this system has been elucidated first. The physical configuration of the model is illustrated in Figure 3.1. It shows a typical fibrous cylindrical DPF. When a slice (red part) is cut parallel to the axial direction of the DPF and is viewed from its top, it seems like a flat porous medium covered with solid fuels. So, an infinitely long flat porous medium is considered as a sample over which solid fuels of diameter of the scale of nanometer to micrometer are attached. The sample is taken long enough for the combustion wave to be completely contained within it and can capture a steady-state solution. Oxidizer is flowing from left to right through the porous medium and adjacent to the surface of fuel. The rate of oxygen diffusion to the surface of fuel is high so that the difference between the concentration of the oxygen at the gas/solid interface and the gas within the porous medium is small. The reaction front propagates from the right to left in the direction of fresh fuel and opposite to the direction of gas flow velocity which is referred to as opposed flow combustion. Since the gas flow velocity is sufficiently larger than the variations of the transport properties, all variations perpendicular to the gas flow velocity become negligible.

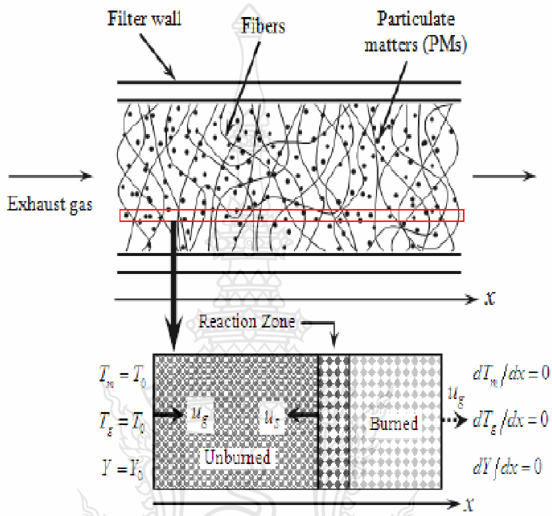


Figure 2.24 Physical configuration of the model [52].

Moreover, the deposited fuel layer is assumed to be thin enough so that the temperature gradient across the fuel can be neglected. Then the resulting phenomena might be treated essentially a one-dimensional and the axial distance is measured by *x* in the direction of gas flow velocity. The temperatures of the porous medium and fuel are presumed to be equal along the *x* direction. The difference of pressure along the porous medium is almost constant. The system has been considered as adiabatic so that the heat loss from the system to the external atmosphere arising only in near proximity to cold sides is taken to be negligible. A two-temperature model is employed where thermal no equilibrium between the porous medium and gas is allowed to occur within the reaction front. For simplicity reasons, a single-step exothermic heterogeneous reaction is considered by which solid fuel is converted (oxidized) directly to the gaseous product following: [solid fuel] (s) + *n* [O2] (g) _ (1+ *n*) [gaseous product] (g) where *n* is the mass of oxygen per mass of fuel ratio (stoichiometric). The present phenomena have been formulated by introducing a new constant parameter, f, termed as deposition of fuel. It is defined by f = *Vf/VV* in which *VV* (= *Vf* + *Vg*), *Vf* and *Vg* are respectively the volume of voids, volume of fuel and volume of gas. This is although taken to be constant but informative. As a result, the species equation of fuel is circumvented from the model and yields a simplified model.

2.15 Literature Review

Yumlu [3] study of had carried out experiments with a porous flat flame burner, with heat extraction, on hydrogen–oxygen and hydrogen–air flames. The temperatures of these flames were determined experimentally and compared with those calculated from the thermodynamic data and the measured heat loss to the burner. The hydrogen concentration profile through the flames was lso determined with a quartz microprobe and a mass spectrometer. Combustion techniques based on PMC have been developed by Trimis (1995), Trimis and Durst (1996), Durst and Trimis (1997), and Durst et al. (1997). The main feature of their work was the combustion stabilization principle, which allowed an extremely stable operation of the premixed combustion process in the porous matrix. The combustion process was said to be stabilized with a sudden change of the pore size, corresponding to a change of the Peclet number inside the porous structure. The first measurements of temperature and species distributions within the submerged reaction zone stabilized inside radiant burners made of reticulated ceramic matrices were reported by Mital et al. (1997). The radiant burners and the flames stabilized within them were characterized in terms of stability limits, radiation efficiencies, and global pollutant emission indices. The burner tendency to flashback with increasing firing rates was observed in their experiments.

Linsheng Wei et al. [5] study of Numerical of Waste Heat Recovery from Tunnel Kiln Utilized to Produce Rare Earth Phosphor. An indirect heat recovery method is adopted to recover waste heat from tunnel kiln supplied by electricity utilized to produce rare earth phosphor. To ensure the quality of products and the life of tunnel kiln, a water tank is installed surrounding the cooling region of tunnel kiln as a heat exchanger. Meanwhile, a computational fluid dynamics model is developed to estimate and optimize the performance of this waste heat recovery. The predicted temperatures are in good agreement with measured results, and the error is within a reasonable range. In addition, a relationship between the inlet mass flow rate and the inlet water temperature is obtained in terms of desired outlet water temperature. Using water tank as a heat exchanger is an effective and reasonable method to recover waste heat of tunnel kiln utilized to further process of rare earth phosphor. The 4443 kg standard coal would be saved a year when inlet water temperature is 285 K. The numerical simulation results are in good agreement with the experimental data. The maximum average relative error between the simulation and experiment is 8.82 % , which is within a reasonable range. The numerical simulation method is very simple and suitable for this heat recovery application. (Figure 2.20).

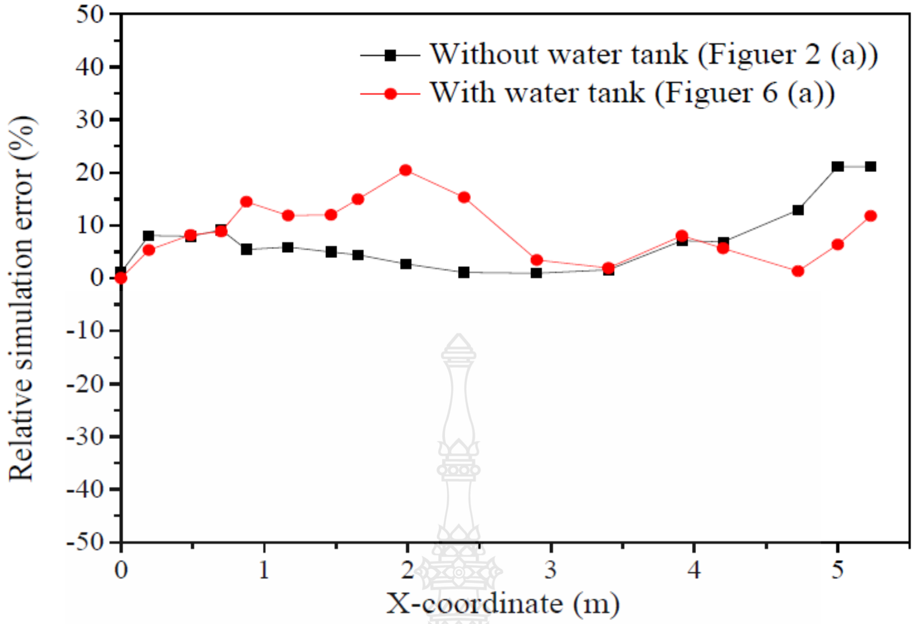


Figure 2.25 Distribution of the error between simulation and measurement results [5].

Hongmin, W., et al. [6] study of Experimental on temperature variation in a porous inert media burner for premixed methane air combustion. The detailed axial temperature variations of the porous media burner during startup and switch-off processes were experimentally measured and analyzed for the premixed methane air combustion. A tubular burner filled by alumina pellets with diameters of 10 mm and 4.3 mm, respectively, was used as the porous media burner to study the effect of the burner inlet gas flow rate, equivalence ratio, and diameter of alumina pellets on the combustion temperature distribution along the burner axis and the combustion wave velocity. The results showed that the super adiabatic combustion could be achieved for the combustion wave velocity greater than zero, and the critical equivalence ratio corresponding to the super adiabatic combustion was bigger for the smaller pellet diameter or higher inlet air flow rate. This study can provide the useful information for the design and operation of the porous media burner, and is significant to understand the combustion phenomena in the porous media burner (Figure 2.26).

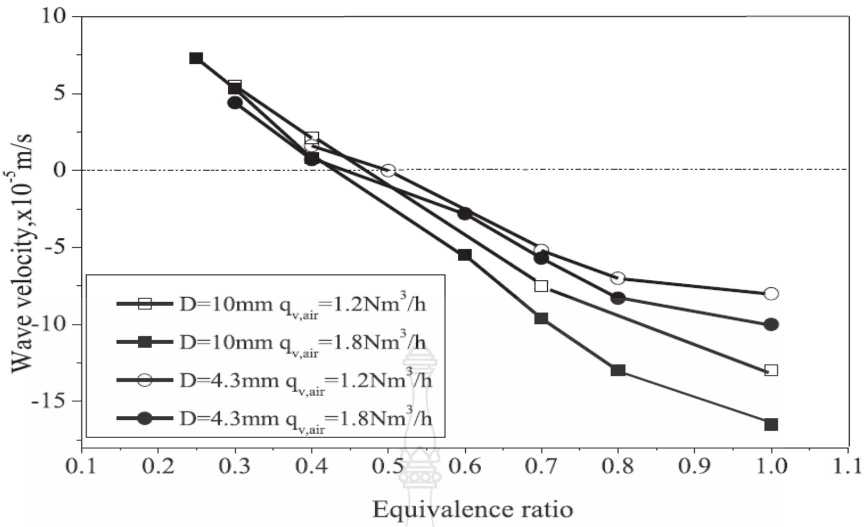


Figure 2.26 Effect of the equivalence ratio on the combustion wave velocity for different air flow rates and pellet diameters [6].

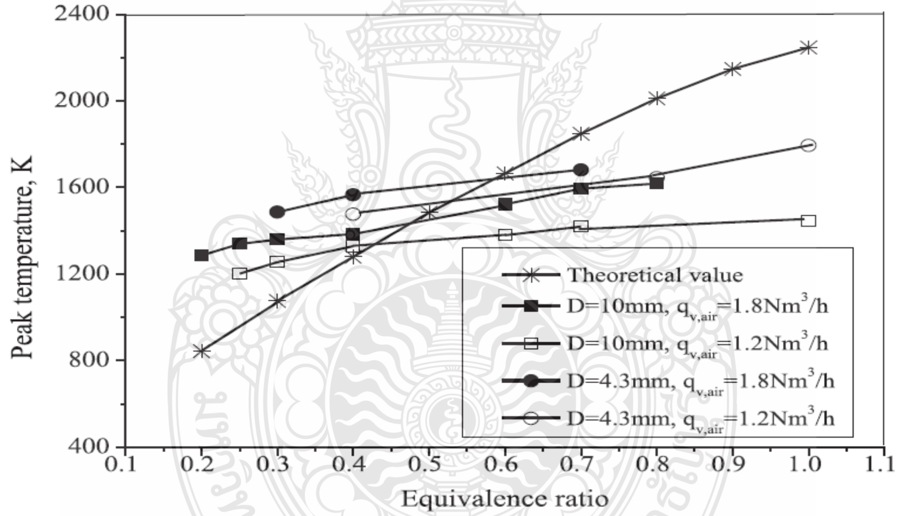


Figure 2.27 Compilation of the adiabatic temperature and the peak temperature in the burner [6].

CHAPTER 3
MATERIALS AND METHODOLOGY

This chapter discusses the components of the laboratory equipment, the preparation of the equipment before the experiment. The principle of operation of the experimental equipment, the planning of operations in accordance with the objectives that have been initially set. Steps to try including measuring instruments used to collect data and save the analysis results. The experimental study will be conducted in three important cases: without porous media, with porous media and hot gas one-way flow. And a process using computers to help make predictions combustor efficiency. The predictions in three important cases: without porous media, with porous media and hot gas one-way flow. The study is divided into the following:

3.1 Experimental

3.2 Simulation

3.1 Experimental and Methods

3.1.1 Experimental setup

Figure 3.1 shows the proposed Solid Fuel Porous Media Combustor (SFPMC) setup with a water heating system. The experimental system consists of a proposed reactor (as shown in Figure 3.1) that was equipped with an air blower, a hot water pump, valves, fittings, and a hot water storage tank. The water was stored in an insulated storage tank and can be supplied as heating load. The flow rate of air and water were manually controlled by its respective flow control valves. During the test, hot water was drawn from the bottom of the storage tank. The pump then circulated the hot water through the water tubes inside the heat exchanger chamber. Air was also supplied into the reactor over the air supply chamber (driven by air blower).

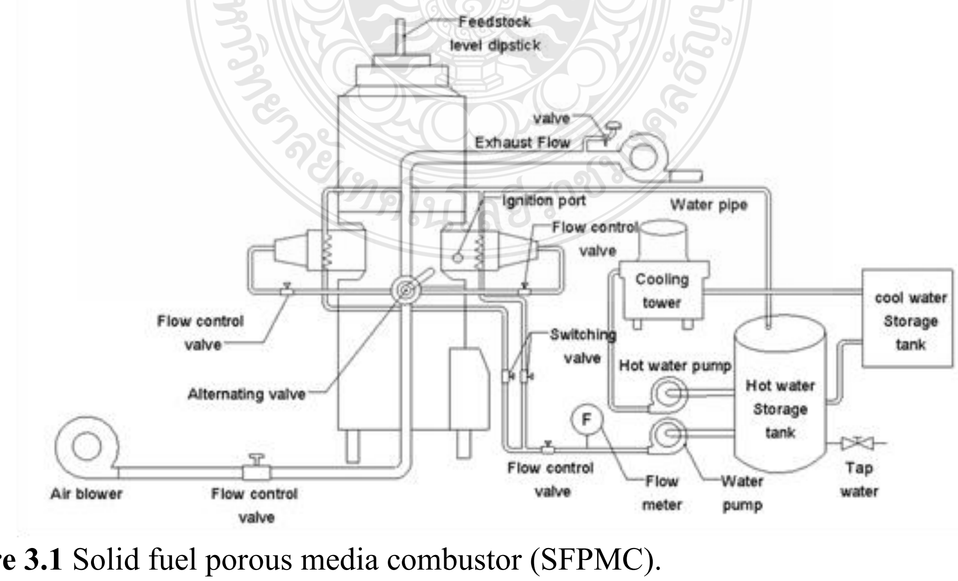


Figure 3.1 Solid fuel porous media combustor (SFPMC).

3.1.2 Experimental equipment components

Experimental equipment for this research a solid fuel combustor with one-way gas flow. To make it easier to study the researcher had ordered 5 section components: 1) Combustor body 2) Porous media storage chamber 3) Combustion chamber 4) Vortex pump system for hot water production 5) Air blowing system into the combustion. Each of which has different functions and priorities. As the following details.

The combustor body has a cylindrical reactor as shown in Figure 3.1, has a size of 1985 mm. [H] height, 600 mm. [OD] outer, 500 mm. [ID] inner size, divided into 3 parts.

The first part the upper part is the contain solid fuel chamber. There is a cover to prevent gas leaks and install a dipstick to measure the fuel consumption during the experiment.

The second part the consists of a combustion chamber and a porous media chamber, installed on the right. Inside the porous media chamber, a group of pipes is installed for hot water utilization. The porous media chamber can be easily disassembled and assembled. In experiments with each size of porous media.

The third is the bottom to collect the combustion ash and the hot gas flows from the combustion chamber into the right porous media chamber through the right hole. (as shown in Figure 3.2).

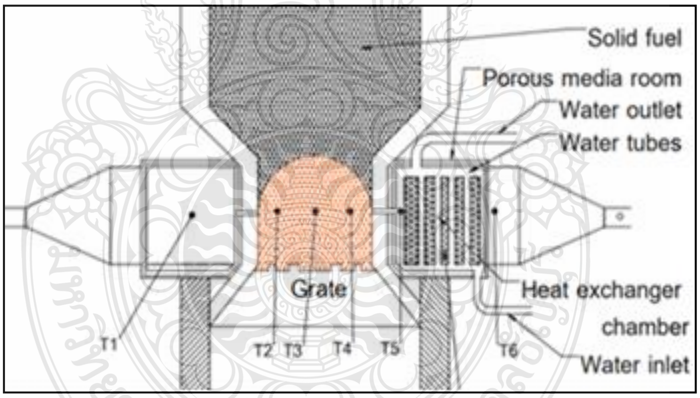


Figure 3.2 Temperature measurement points.

Porous media chamber it has a rectangular shape as shown in figure 3.3. Its dimensions are width 190 mm [W], length 210 mm [L], height 420 mm [H]. Inside, there are 21 water pipes installed, which are made from stainless steel pipes with an outer size of 22 mm [OD.] It grows in 16 mm [ID]. Front and back are separated by a 5 mm. perforated steel grating to prevent the porous media from slipping into the gas flow.

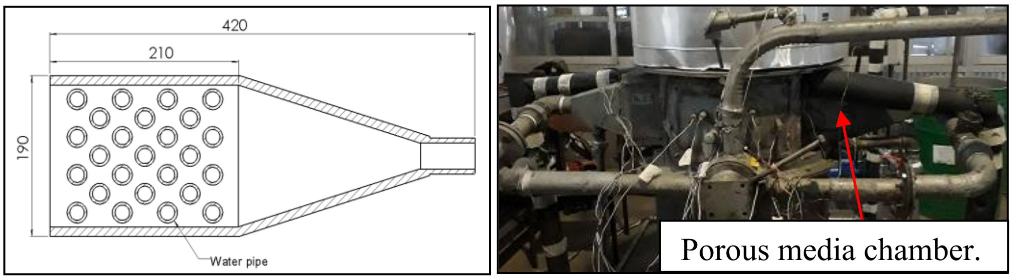


Figure 3.3 Porous media chamber.

The combustion chamber, an experimental device in the study, is designed so that hot gas one-way flows. It flows from the combustion chamber to the right porous media chamber. (as shown in Figure 3.4) through three drilled holes with a size of 12 mm.

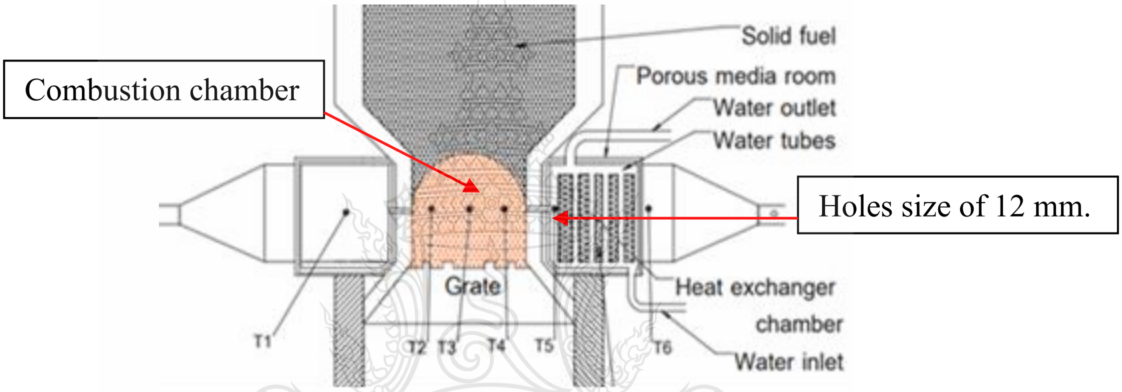


Figure 3.4 Combustion chamber and through three drilled holes with a size of 12 mm.

The water circulation pump system to produce hot water as figure 3.5 consists of a 200-liter hot water tank, cooling water pump sent to the air cooling tower. The flow rate is 5 - 40 liters per minute. The water pump is sent to the hot water system. The flow rate was 5 - 40 liters per minute. The Flow Meter 0.18 - 0.96 cubic meter per hour and the thermostat 10 - 110 °C. This experiment is set at 60 °C.

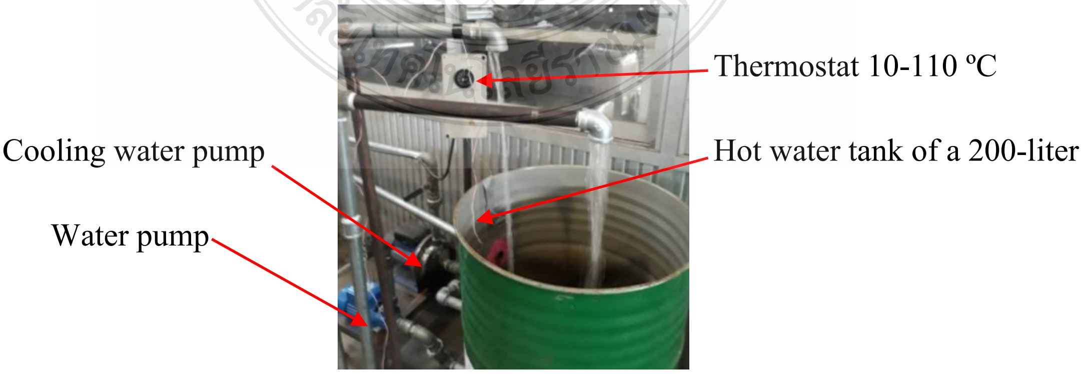


Figure 3.5 The water circulation pump system.

The system for blowing air into the combustor as shown in Figure 3.6 consists of an air blow model NVT-220 2.2 kw. Air volume 318 m^3/hr, pressure gauge and the air storage tank has a capacity of 0.235 m^3.

Figure 3.6 Air blowing system**.**

3.1.3 Data acquisition system

Figure 3.7 Multi-channel logger.

The water temperatures, at the inlet and outlet of heat exchangers were recorded using a data logger (Data Logger model GL820midi Logger) equipped with Type-K thermocouples. On the other hand, the internal temperature of the combustor was recorded at 6 points (T1 to T6) as shown in figure 3.6. Point T1 measured the air supply temperature. Points T2-T4 measured the combustion temperature inside combustor along the air flow from left to right. While points T5 and T6 measured the temperature at the hot gas before and after water tubes, respectively. All temperature data were recorded in 30- second intervals. The water flow rate and fuel consumption rate were manually measured and recorded every half an hour.

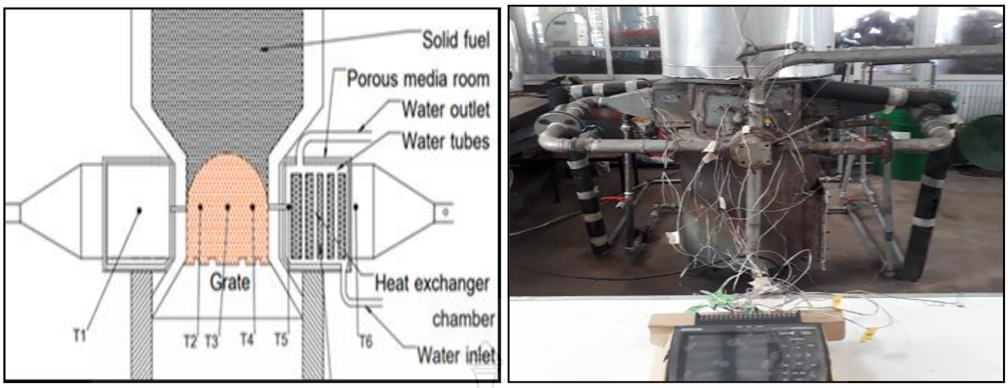


Figure 3.8 Temperature measurement points.

3.1.4 Fuel

Fuel preparation in this experiment will use solid fuel, wood charcoal the solid fuel is that each oxygen molecule comes into contact with the surface of the fuel, resulting in a combustion reaction. Carbon monoxide, a combustible gas along with getting some of the heat out oxygen is then mixed with carbon monoxide, resulting in a complete combustion reaction, eventually producing carbon dioxide. Which is a non-flammable gas along with getting the heat out as well therefore increasing the surface area of the fuel It is one of the parameters for enhancing the efficiency of the furnace for better. In which the researcher uses wood charcoal as a fuel they were ground to a width of 2 cm, a height of 2 cm and approximately 3 cm in length and then dried in the sun to remove moisture for about 8 hours. Only do it once for the whole experiment to obtain fuel of the same size and moisture value in each trial. The charcoal used in this study is from wood and is usually used for cooking (as shown in Figure 3.9). This served as the fuel for the combustor lower heating value of 28.18 kJ/kg. Primarily, the quantity of feedstock used were weighed and recorded before loading into the reactor and beginning the test. The instantaneous feedstock consumption rate was approximately measured using the level dipstick, installed at the top of the reactor.

Figure 3.9 Wood charcoal used in the study.

3.1.5 Porous Media

The porous media is a highly efficient heat exchanger. But compact It can withstand high temperature conditions. With the working principle When hot gas flows through porous media will act as part of the heat absorber. And converts this absorbed part of the energy into heat radiation, which is called an emitter. Radiation to the other side of the material, which acts as a radiation absorber. The choice of material to use as a porous media is of the utmost importance. Due to the direct impact on combustion mechanism, maintenance and efficiency of the furnace, in this experiment, female stainless steel nuts were used. Because they are the same size and shape and are easy to find in the market.

This research used waste stainless steel nuts as the porous media which were categorized into three sizes: 8, 10 and 12 mm. These were used because it does not change its shape when exposed to heat, can easily bend, and can easily be found and bought from the market. The porous media chamber was square in shape as shown in figure 4. The width, length, and height are measured as follows: 190 mm. 210 mm. and 420 mm. It has 21 water pipes inside that is made from stainless steel. The pipe has an outside diameter of 22 mm. The side and backside of the porous media chamber has a 5 mm. steel grating to prevent the porous media from falling out as the gas flows. The porosity of 8 mm nuts is 0.42, 10 mm. 0.53 and 12 mm. equal to 0.62 calculated as equation. (7)

Figure 3.10 Porous media used in this study.

3.1.6 Experimental Procedure

The experiment evaluates the SFPMC with and without the porous media (stainless steel nuts) by determining the improvement in the heat transfer from product gas to the water tubes. The effect of porous media used was further investigated by varying its sizes: 8, 10, and 12 mm. The combustor was initially loaded with 40 kg. of solid fuel. Airflow and water flow rates were equally set. The airflow control valve was adjusted to flow only from one direction. The air flows along the airway duct from left to right then through the combustion chamber. As the solid fuel burns and the temperature rises, the heat from the combustion chamber is brought to the right, at the heat exchange chamber containing the water pipelines. For the first setup, the heat exchange chamber was not filled with porous media. The other setups were then filled with porous media in which each setup was packed with the mentioned variation in sizes. The water pipeline then receives the heat energy from the combustion chamber. At the same time, water flowing through the pipe is also receiving the heat from the combustion causing the product gas temperature to decrease as it exits the heat exchange chamber. The heat absorbed by the water is then pumped back to the water tank, and then the water in the tank with lower temperature is circulated in the heat exchange chamber in a cycle. The results were collected and the data acquired delivering the highest calorific value was determined.

Table3.1 The cases observed during the experiment for the proposed SFPMC with water heating system.

Case No.	Case	Air flow rate (m^3/h)	Water flow rate (kg/s)	$\dot{m}_{fuel}$ (kg/s)	Temperature Water inlet and Water outlet (ΔT)
I	Without *PM	318	0.833	0.00206	5.3
II-A	8 mm PM	318	0.833	0.00206	9.8
II-B	10 mm PM	318	0.833	0.00206	11.2
II-C	12 mm PM	318	0.833	0.00206	7.8

3.1.7 Working principle of porous media

Figure 3.11 shows the case without porous media wherein hot gas transfers heat to the water tube surface by heat convection and heat radiation. In this case, it does not contain porous media for heat storage so, heat is conducted and radiated to the water tube. There is only hot gas and air inside, resulting in low heat transfer capability. As a result, the thermal efficiency is lower than that of with porous media.

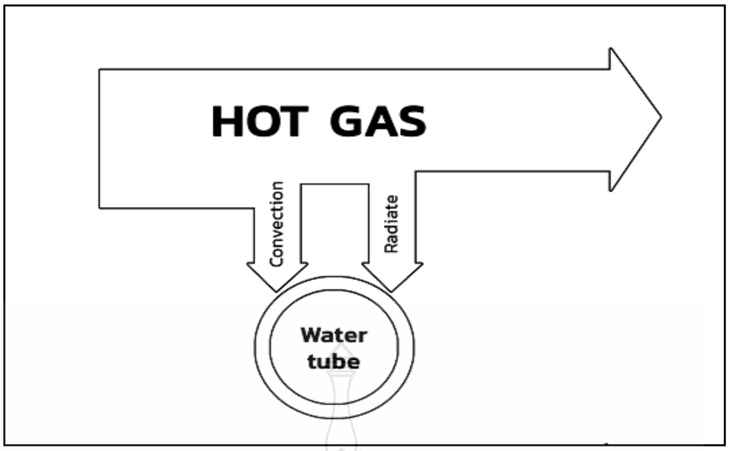


Figure 3.11 Heat exchange of without porous media.

The case with porous media is shown in Figure 3.12, where the hot gas is transferred to the water tube by convection. Porous media as a material helps collect heat from the hot gas, thereby exchanging the heat from the porous media to the water tube. As a result, it conducts and radiates heat, causing increased heat to the water tube hence, promoting efficient heat transfer. The thermal efficiency is higher than in the case where the porous media is absent. The main characteristic of stainless steel nuts used as porous media is its high surface area to volume ratio giving good heat transfer capacity as well as its solid appearance. Hence, it has high absorption and radiation coefficient enabling it to transform energy well. It can be said therefore, that the porous media using stainless steel nuts is a high efficiency but compact heat exchanger.

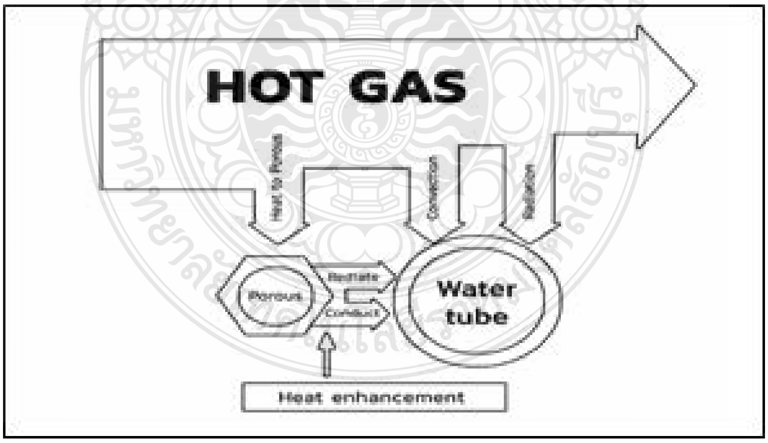


Figure 3.12 Heat exchange of with porous media.

3.1.8 Performance Evaluation

Efficiency of hot water production kiln using solid fuel without porous media and with porous media unidirectional gas flow (SFPMC) proposed in this research calculated as:

$$\eta_{SFPMC} = \dot{Q}_u / [\dot{m}_{fuel} \times LHV_{fuel}] \quad (3.1)$$

Where is the rate of heat transferred to hot water, which is a useful energy This heat transfer occurs under the heat transfer mechanism, both conduction and convection heat radiation of porous media calculated as:

$$\dot{Q}_u = \dot{m}_w C_p (T_{w,o} - T_{w,i}) \quad (3.2)$$

Fuel consumption rate ($\dot{m}_{fuel}$) can be calculated from the amount of fuel used divided by the time being considered or estimated from the total amount of fuel divided by the total time spent in the experiment from the start of the experiment until the fuel runs out. The fuel used in this study is wood charcoal (or cooking charcoal) with the calorific value of 28.18 kJ/kg. Therefore, the fuel consumption rate is calculated as:

$$\dot{m}_{fuel} = \frac{\text{Total amount of fuel used per batch [kg]}}{\text{Total operating per batch [S]}} \quad (3.3)$$

Heat transfer improvement on the basis of hot product gas can be evaluated as follows:

Water side

$$\Delta H_{im,\ water} = \dot{Q}_{water,\ PM} - \dot{Q}_{water,\ w/o} \quad (3.4)$$

Gas side

$$\Delta H_{im,\ gas} = \dot{Q}_{g,\ PM} - \dot{Q}_{g,\ w/o} \quad (3.5)$$

And the improvement in terms of efficiency is,

$$\eta_{im} = \frac{\dot{Q}_{water,PM} - \dot{Q}_{water,w/o}}{\dot{Q}_{water,w/o}} \quad (3.6)$$

Where ΔH_{im} is the heat transfer improvement and η_{im} is the heat transfer improvement efficiency.

$$\varepsilon = (Vt / Vs) \times 100 \quad (3.7)$$

The porosity (ε) of porous media by water substitution method.

3.2. Simulation Geometry and Design as Experimental

There are two types of simulations: with porous media modeling and with-out porous media modeling. The hot gas flows from the combustion chamber into the porous media chamber through a 12 mm hole. This porous media chamber is modeled on a rectangular design as shown in Figure 3.13, width 190. Mm. [W] Length 210 mm. [L] Height 420 mm. [H]. Inside there are 21 water pipes made of stainless steel pipes, external size 22 mm. [OD.], Expandable 16. [ID] front and back are separated by 5mm perforated steel grating to prevent porous media from entering the hot gas flow.

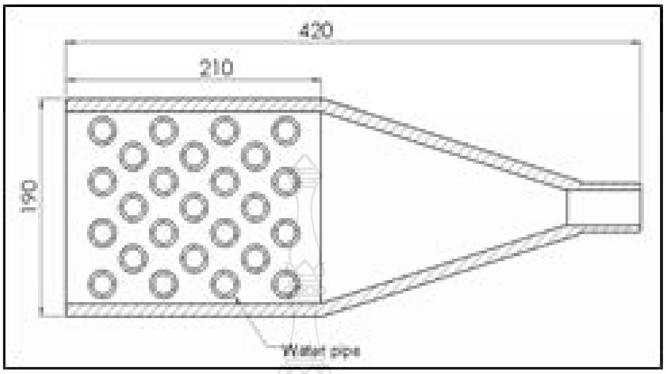


Figure 3.13 Model of the porous media chamber used in the simulation.

3.3 Governing Equations

The equation of instantaneous mass, momentum, and energy conservation is the core that governs the equation in the solution of this model. These equations fluctuate, so they must be averaged over time to model the flow within the porous media chamber. Turbulent flow is assumed to be present in the porous media chamber. Therefore, the results of these mean equations are used as inputs to the turbulent equation.

The continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \boldsymbol{U}) = 0 \tag{3.8}$$

The momentum equations:

$$\frac{\partial(\rho \boldsymbol{U})}{\partial t} + \nabla \cdot (\rho \boldsymbol{U} \otimes \boldsymbol{U}) = -\nabla p + \nabla \cdot \tau + \boldsymbol{S}_M \tag{3.9}$$

where the stress tensor, τ, is related to the strain rate by:

$$\tau = \mu\left(\nabla \boldsymbol{U} + (\nabla \boldsymbol{U})^T - \frac{2}{3}\delta \nabla \cdot \boldsymbol{U}\right) \tag{3.10}$$

The total energy equation:

$$\frac{\partial(\rho h_{tot})}{\partial t} - \frac{\partial p}{\partial t} + \nabla \cdot (\rho \boldsymbol{U} h_{tot}) = \nabla \cdot (\lambda \nabla T) + \nabla \cdot (\boldsymbol{U} \cdot \tau) + \boldsymbol{U} \cdot \boldsymbol{S}_M + \boldsymbol{S}_E \tag{3.11}$$

where $\nabla \cdot (\boldsymbol{U} \cdot \tau)$ is the work due to viscous stresses and $\boldsymbol{U} \cdot \boldsymbol{S}_M$ is the work due to external momentum sources.

Equations of states for both enthalpy and density are necessary to model transport equations as a closed system, therefore they are used in the porous media chamber model. Air is assumed to be an ideal gas during turbulent flow in the porous media chamber. Therefore, ideal gas equations of state are used in this simulation.

$$\rho = \frac{w p_{abs}}{R_o T} \tag{3.12}$$

$$dh = c_p dT \tag{3.13}$$

$$c_p = c_p(T) \tag{3.14}$$

where R_o= 8.314 J/(mol·K), w is the molecular weight, and pabs is the absolute pressure.

Transport equations for turbulence models were solved with the Reynolds Averaged Navier-Stokes (RANS) equations through the introduction of averaged fluctuating components which were derived from equations (3.8)-(3.11). The turbulence kinetic energy, k, and the turbulence eddy dissipation, ε, are introduced through the k-epsilon (k-ε) model to the RANS equations to calculate the Reynolds stresses.

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_m}(\rho U_m k) = \frac{\partial}{\partial x_m}\left[\left(\mu + \frac{\mu_t}{\sigma_m}\right)\frac{\partial k}{\partial x_m}\right] + P_k - \rho\varepsilon + P_{kb} \tag{3.15}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial}{\partial x_m}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_m}\right] + \frac{\varepsilon}{k}(C_{\varepsilon 1}P_k - C_{\varepsilon 2}\rho\varepsilon + C_{\varepsilon 1}P_{\varepsilon b}) \tag{3.16}$$

where $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, σ_k, and σ_ε are all constants. [ANSYS, 2017]

3.4 Meshing

Meshing is a process used to split a structure into smaller components in order to calculate parameters of a structure with greater accuracy. In meshing, you create a finite number of grid points within a structure called nodes. At these nodes, governing equations are solved numerically for the parameters desired. The greater the density of the meshing, the greater the accuracy in solving the problems. However, greater accuracy comes at the cost of greater difficulty in solving the equations. Therefore, meshes must be created in a balance with enough density to capture the most important details, but with a low enough density where the software is able to solve the equations in a timely manner.

The porous media chamber was meshed with 1,902,778 nodes and 8,758,918 elements. The total volume of the mesh was 10,561,267.125,252 mm^2.

A face sizing metric was given to the wall of the chamber containing the nuts, excluding the throat of the chamber and above. This face sizing was necessary to prevent the space between the nuts and the chamber from inflating too quickly and missing features, but being large enough to cause inefficient meshing.

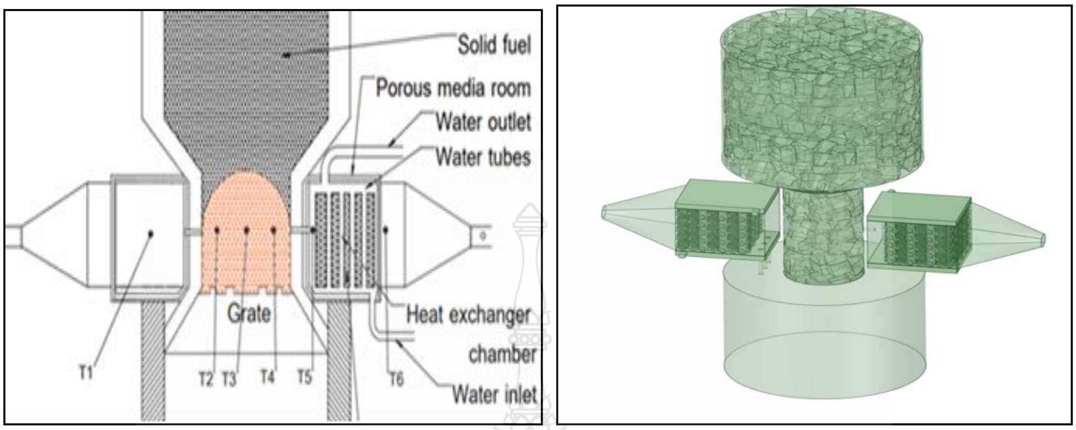


Figure 3.14 Write the image in the program according to the actual combustor.

This picture shows the drawing from the real image for use in simulations in the program.

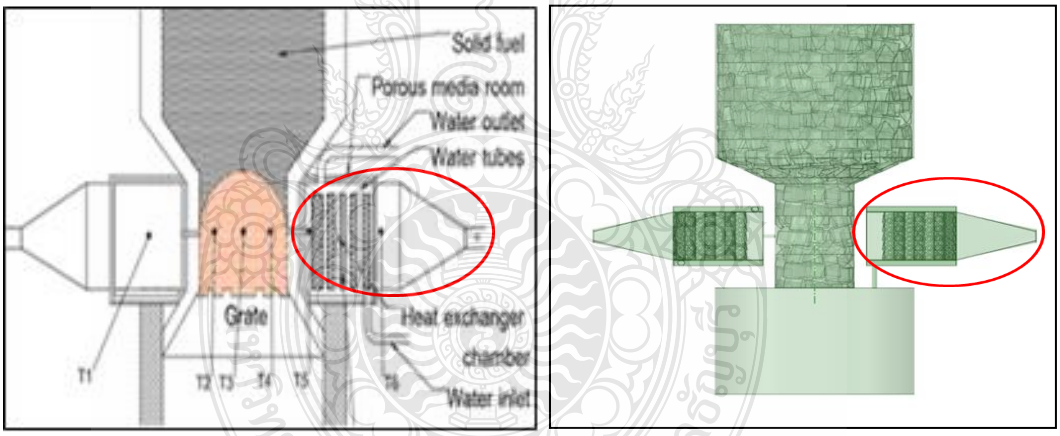


Figure 3.15 Comparison of experiments and Mathematical Model.

To make good models, we will not model the entire system. Because it takes a long time and has a high error value. Therefore, we simulate only the parts that are a priority to this study. In this experiment, we were interested in just one right-side porous media combustor.

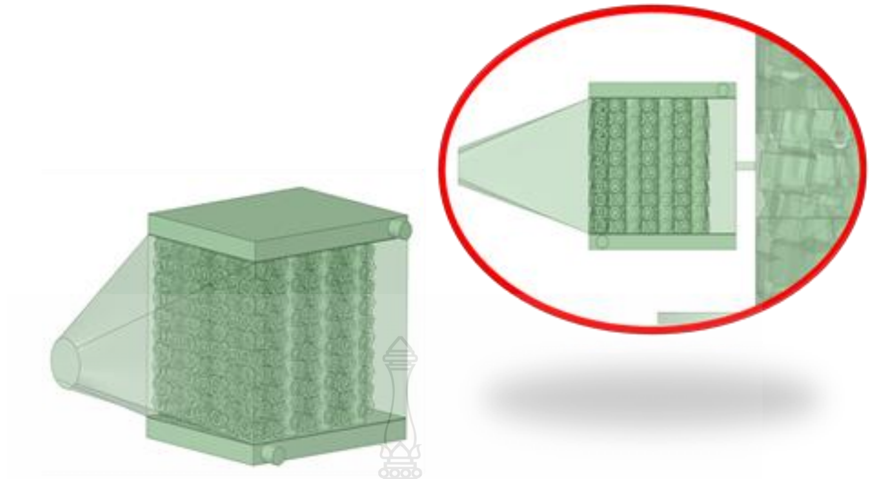


Figure 3.16 Components to be analyzed.

All components that we will analysis by ANSYS program.

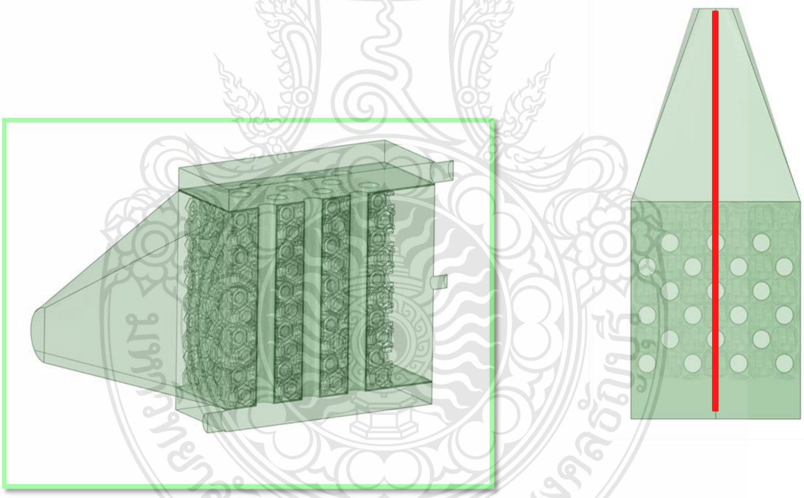


Figure 3.17 The work model is divided into 2 parts.

When starting to use the program to calculate all the components, it was found that the computer worked very hard and took a long time. Therefore, the work model is divided into 2 parts and then using symmetric calculation commands to help calculate the virtual model to the fullest.

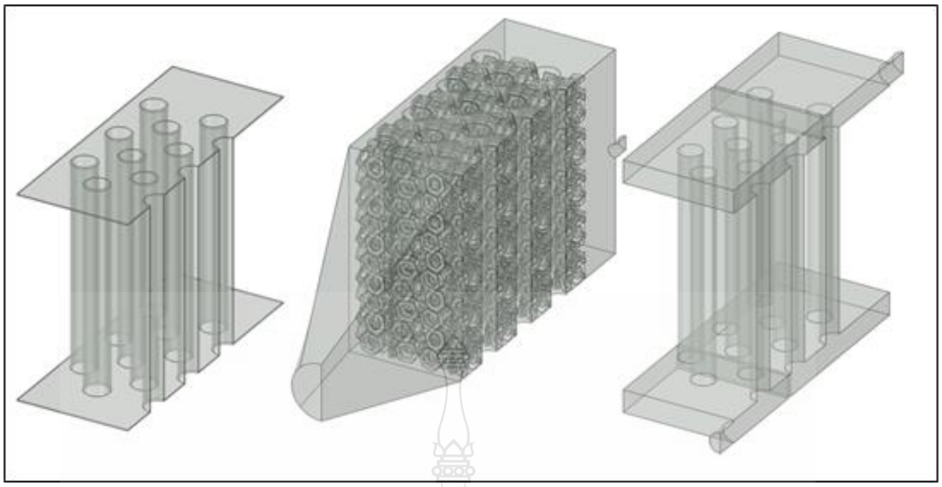


Figure 3.18 Domain of water, air and water pipes.

Pictures show all three domains: water, air, water pipe with air and nut.

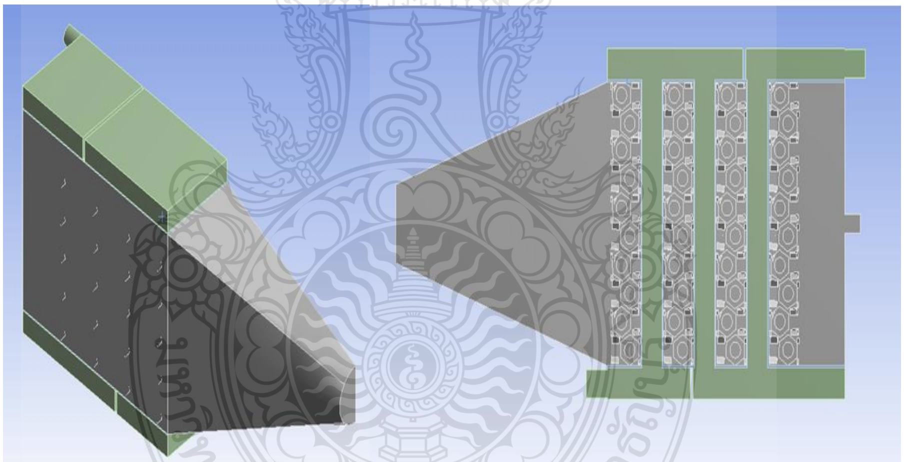


Figure 3.19 Image for all three domains.

3.5 Simulation setup

The porous media chamber details are described in this section. This profile was calculated to compare three size nuts and four case studies, containing 1 size per time, in order size 8 mm, 10 mm, 12 mm porous media chamber, and with-out porous media to compare the efficiency of the combustor.

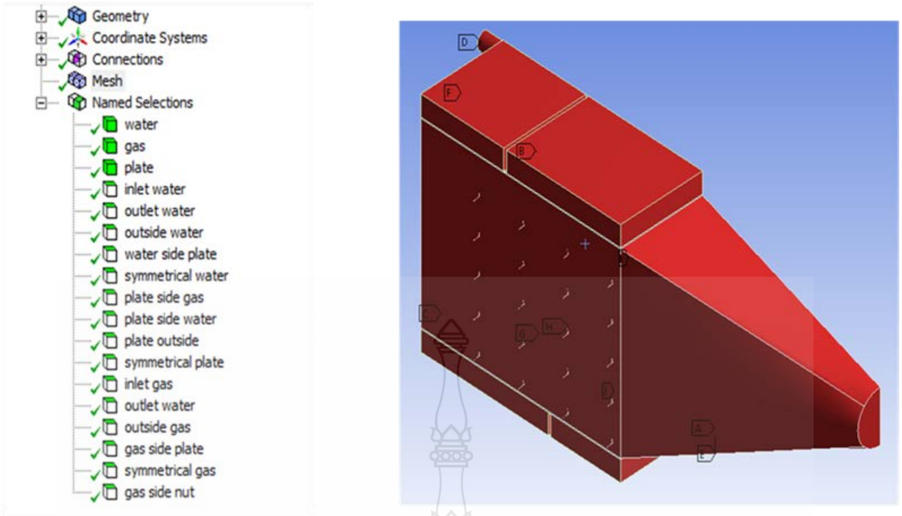


Figure 3.20 The names of All surfaces in order.

Names of all surfaces in order to easily establish boundary by calculating using heat transfer and model.

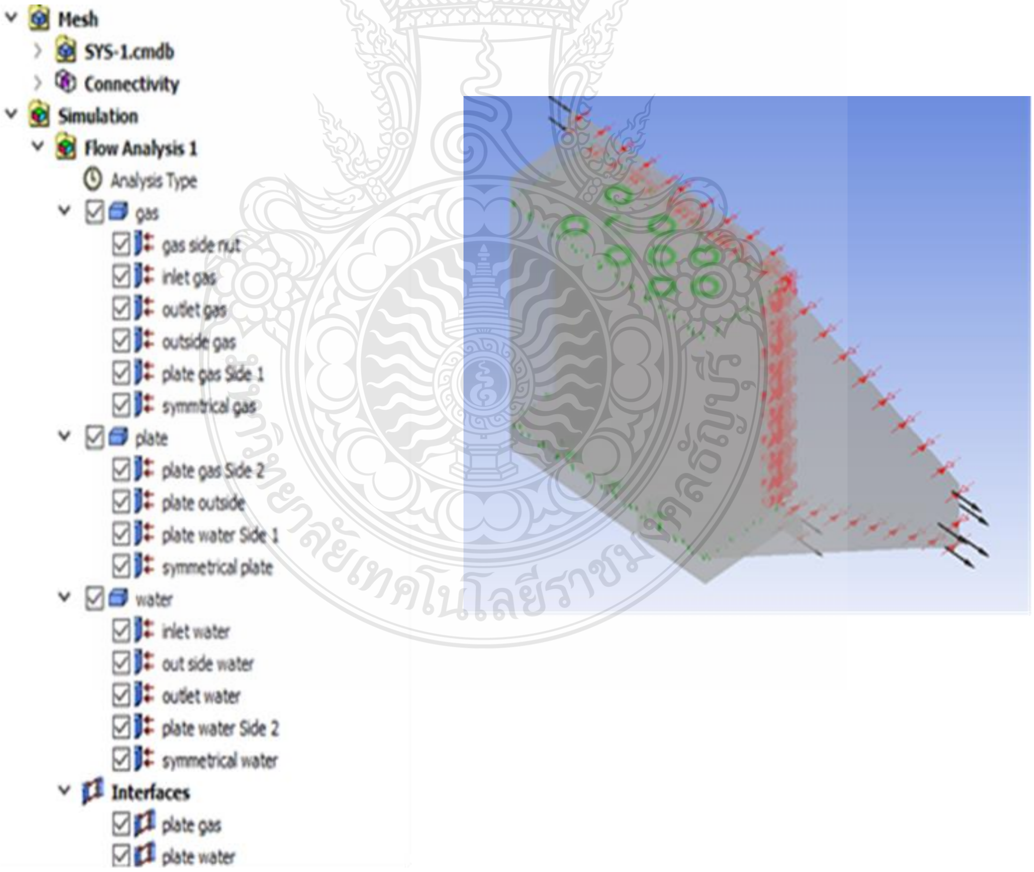


Figure 3.21 The setup boundary.

Set up the boundary by setting the domain name and other values, with the perimeter.

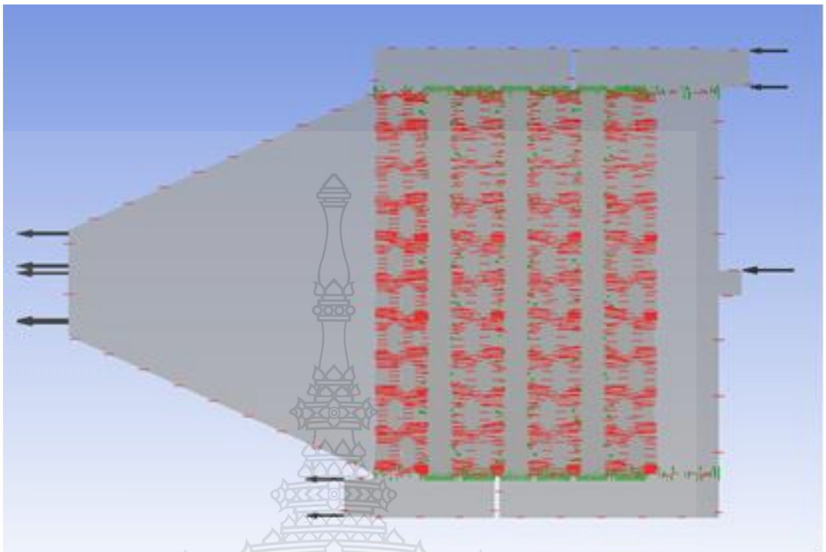


Figure 3.22 Set the gas inlet and outlet as well as water inlet and outlet.

Set the gas inlet temperature and temperature of the air inlet than set the water and air surface into the gas and water outlet.

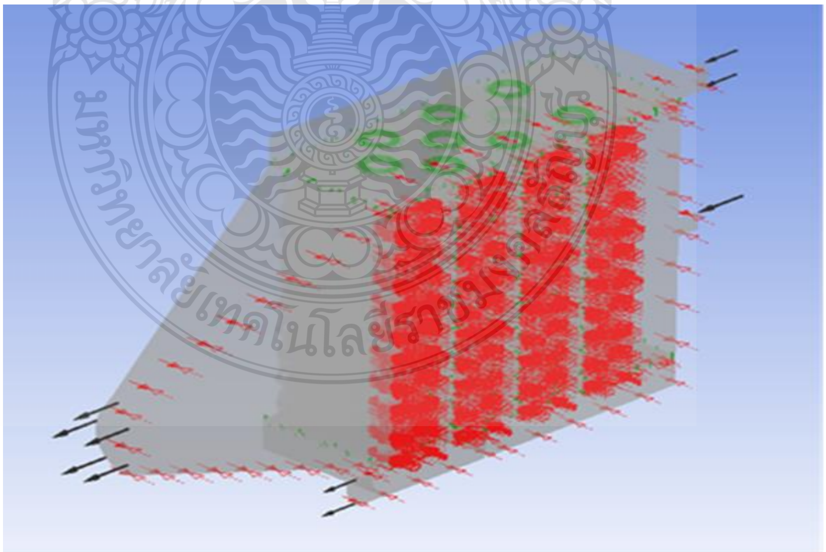


Figure 3.23 The surface that is calculated in symmetry.

All domain is assembled as shown in this figure before mate.

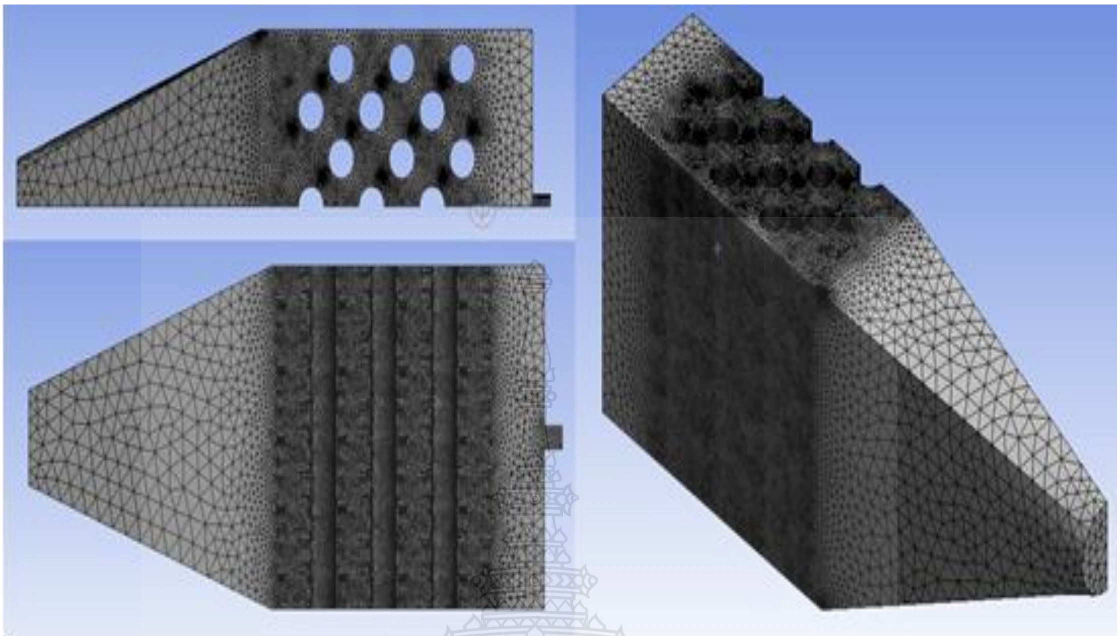


Figure 3.24 View of the mesh from the outside of the gas.

Image of domain gas after the mesh is finished

Figure3.25 View of the mesh from the outside of the plate.

Picture of domain plate after the mesh is finished.

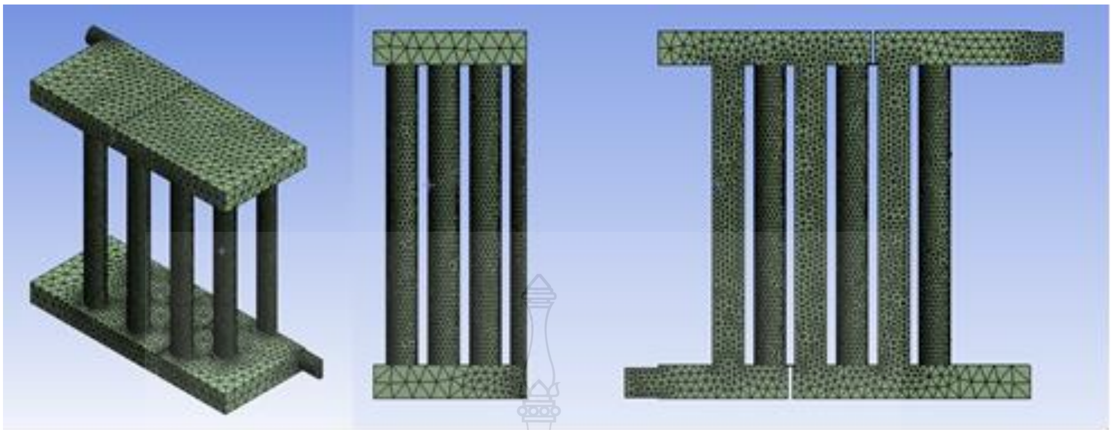


Figure 3.26 View of the mesh from the outside of the water.

Picture of domain water after the mesh is finished.

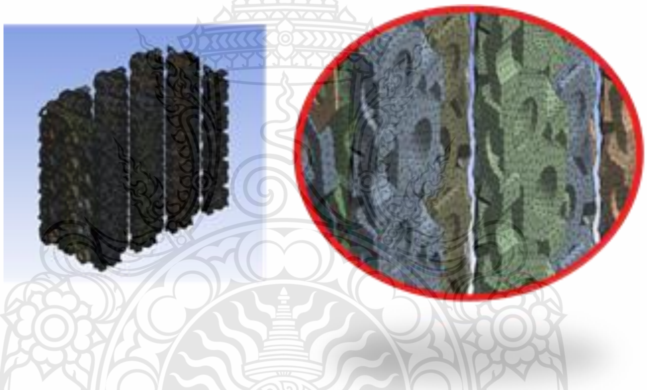


Figure 3.27 View of the mesh from nut.

Picture of domain nut after the mesh is finished.

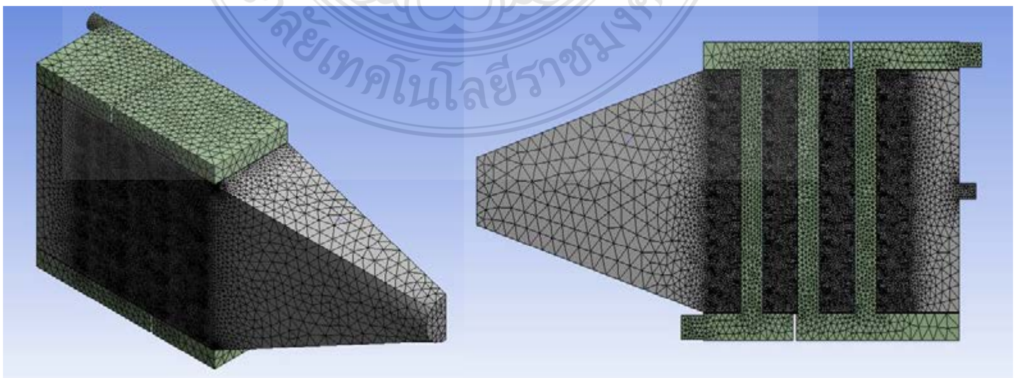


Figure 3.28 View of the mesh from the outside of the porous media chamber.

CHAPTER 4
RESULTS AND DISCUSSION

This research is a comparative study of the efficiency of charcoal fuels using porous media to enhance the efficiency of the furnaces, compared with charcoal fuels that do not have porous media to promote efficiency. The study results are divided into the following:

In the operation of the solid fuel furnace there is still a heat value that is not as good as it should be. That is, the energy received and the energy input is still very different. Some of the energy is lost in the exhaust gas. In which this lost energy will cause pollution If this lost energy is well managed, it well reduces the condition. Reducing energy loss in this area from the study found that putting porous media in the heat exchanging area helps to promote heat, increase the efficiency of the stove to prove that the basic assumptions are true or not Therefore conducting comparison experiments The experiment is divided into 2 parts. which are to find the maximum efficiency of the kiln without porous media in order to find the variable that results in the highest thermal value. And increasing the efficiency of porous kilns by using the parameters obtained from non-porous kilns to compare the thermal efficiency.

Study for the efficiency of the proposed kiln important variables is Thermal Efficiency. Therefore, it is important to know the important variable values which are mass flow rate of hot water, fuel consumption rate and water temperature inlet and outlet furnaces to calculate the rate of heat entering the furnace and the heat that is used In addition, the temperature inside the furnace is maintained (T1 to T7) to analyze the operating conditions of the furnace. In which all the temperature is recorded every 30 seconds by measuring the temperature with thermocouples (thermocouple K-type) and connect the data logger (midi logger) model GL 820. The water flow rate and fuel consumption are record by taking notes every 30 minutes.

In this study, charcoal is used as fuel and since the kiln used in the experiment is designed to be refilled once a batch type, the first step of the experiment is to weigh the charcoal in order to find out the total mass of fuel first then packed in the kiln The fuel consumption rate can be obtained from the amount of fuel used in comparison to the time used, which can be read from the fuel level dipstick installed on the top of the furnace.

The perforated materials used in this experiment are female bolts because they are easily found in the market and are of the same size using 3 sizes of bolts 8, 10 and 12 mm. After installing the perforated material and refueling, the readiness of experimental equipment must be tested such as the water circulation system, data logging systems of data recorders and blower fans. Ignite the burner using an exhaust fan installed at the exhaust outlet and then draws air through the combustion chamber, then use the torch to light the stove by spitting the fire into the hole that has been drilled at the entrance to the combustion chamber. Wait for the fuel to ignite. After the burner is lit for 5 minutes, the experiment begins and the results are recorded.

Typically, porous media acts as a heat emitter and a heat absorber. Therefore, it was proposed as a water heating system. The heat extraction between the porous media was taken into account and noted as an important parameter. Hence, the experimental procedure was divided into four cases, which is shown in table 1, for both with and without porous media configurations.

4.1 Experimental

The temperature profile of the product gas at the outlet was compared with and without the porous media as seen in Figure 4.1 The temperature was plotted from 0 – 190 minutes duration of the experiment. The red line graph shows the outlet gas temperature without the porous media whereas the blue line shows the outlet gas temperature with the porous media. As seen from the Figure 4.1, the profile of the outlet gas without the porous media reached a maximum temperature of 178ºC but the temperature profile of the one with the porous media only peaked at 106ºC. Hence, outlet gas temperature is higher without the porous media compared to the one with it. The reason is attributed to the ability of the porous media to absorb some of the heat energy released from the product gas as it flows out of the temperature exchange chamber.

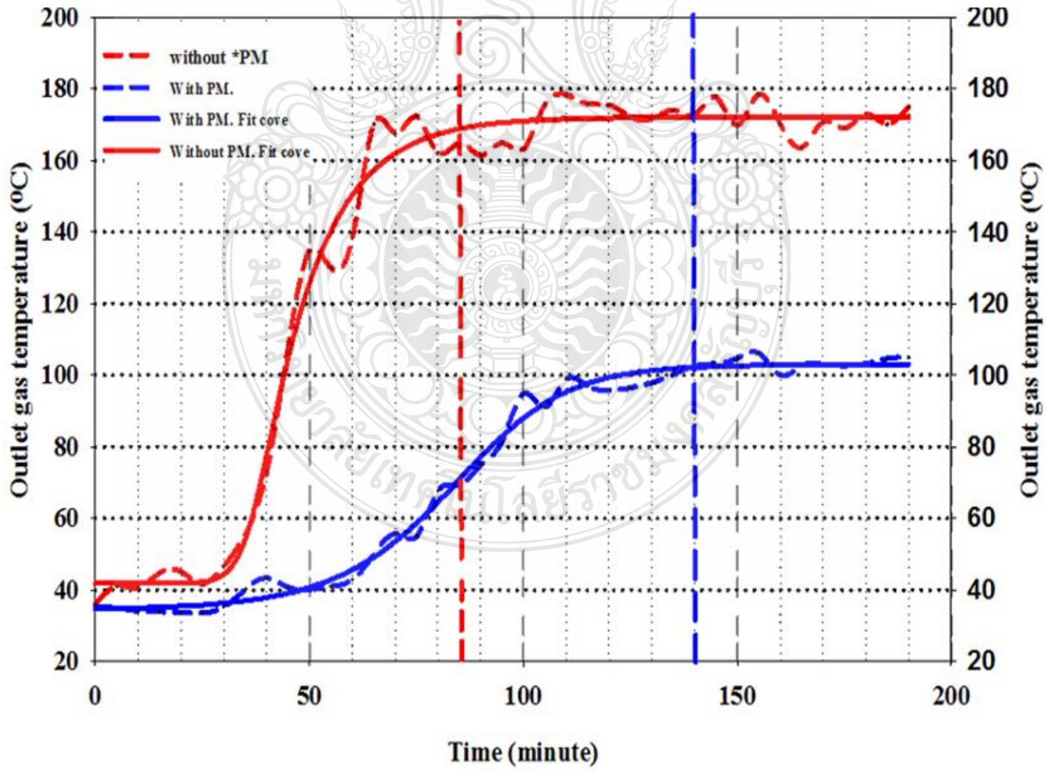


Figure 4.1 Temperature profile of product gas at the outlet point with and without the porous media.

Figure 4.2 shows the gas temperature at various points for the four different cases stated in table 1. The heat exchange chamber was installed on the right hand sides of the combustor chamber, and having water pipelines that can be filled with porous media (shown in Figure 3.2). The water flow rate is 318 m^3/h all throughout the duration of the experiment and the gas flow direction is unidirectional. The results from the experiment found that the average temperature in the middle of the combustion area is approximately 1,002 ºC.

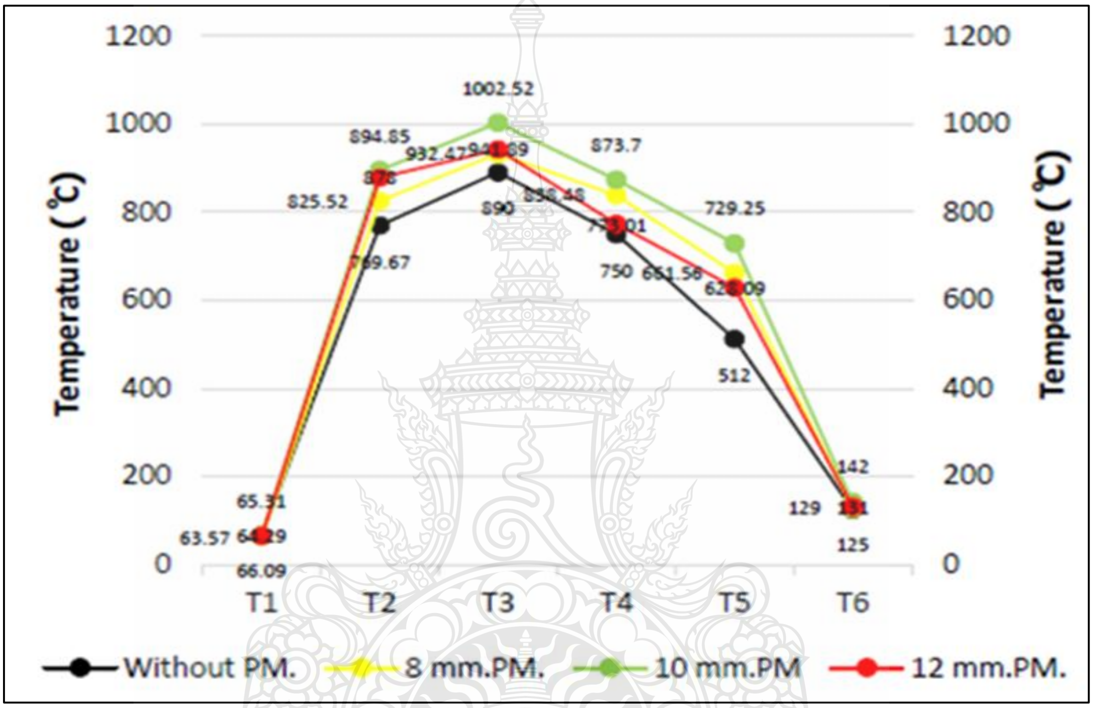


Figure 4.2 The gas temperature at different points for the four experimental cases.

The average inlet (Tgas,in) and outlet (Tgas,out) gas temperature shown in Figure 4.3 was taken within the 85 to 190 minutes duration of the experiment. Between this timeline, the steady state condition was observed. The average inlet gas temperature was observed to be 512ºC, 661ºC, 729ºC, and 628ºC for cases I, II-A, II-B, and II-C, respectively. Whereas the average outlet gas temperature observed for cases I, II-A, II-B, and II-C were 159ºC, 106ºC, 96ºC, and 80ºC, respectively. The graph shows that without the porous media (case I), the Tgas, in = 512 ºC, and Tgas,out= 125 ºC. Whereas for the other 3 cases with the porous media the average inlet gas temperature (Tgas,in) were recorded as 661ºC, 729ºC, and 628ºC for cases II-A, II-B, and II-C, respectively. On the other hand, the outlet gas temperature (Tgas,out) observed were 129ºC, 142ºC, and 131ºC for cases II-A, II-B, and II-C, respectively.

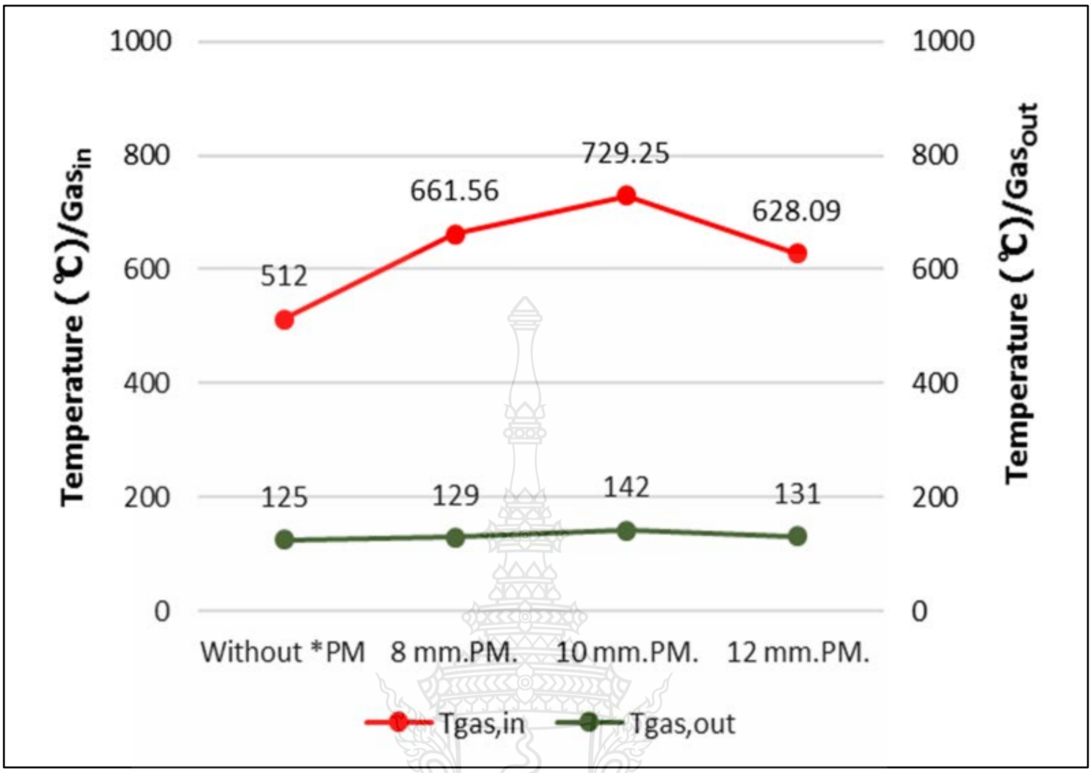


Figure 4.3 The average gas temperature taken at the inlet and outlet points of the four cases at steady state condition.

Figure 4.4 shows the average temperature of inlet gas and outlet gas), and the inlet water temperature (W_{in}) and outlet water temperature (W_{out}) in all four cases; namely, the case without the porous media and with porous media of 8 ,10, and 12 mm. sizes. The difference (ΔT) of the average inlet and outlet gas temperature for each case was calculated. The 10mm size porous media (case II-B) showed the highest with ΔT = 587ºC, followed by the 8 mm. size porous media (case II-A) with ΔT = 532ºC, the 12 mm. size porous media (case II-C) ΔT = 497ºC. and without*PM (case I) the lowest with ΔT = 387ºC. For the recorded data without the porous media (case I), the inlet and outlet water temperature were 49.5ºC, and 54.8ºC, respectively. The other cases II-A, II-B, and II-C (8mm, 10mm, and 12mm sizes) with porous media, reported 48.7ºC, 49.6ºC, and 48.6ºC, respectively at the inlet water temperature (W_{in}). As for the outlet water temperature (W_{out}), cases II-A, II-B, and II-C recorded 58.5ºC, 60.8ºC, and 56.5ºC, respectively. Based on the recorded data, the case with the highest average temperature difference (ΔT) of the inlet and outlet gas temperature was found in 10 mm size (case II-B) porous media at about 587ºC. Moreover, the highest average temperature difference of the inlet and outlet water temperature was also seen on case II-B (10 mm size) having ΔW = 11 ºC. followed by the 8 mm. size porous media (case II-A) with ΔW = 9 ºC, the

12 mm. size porous media (case II-C) ΔW = 7 ºC. and without*PM (case I) the lowest with ΔW = 5 ºC.

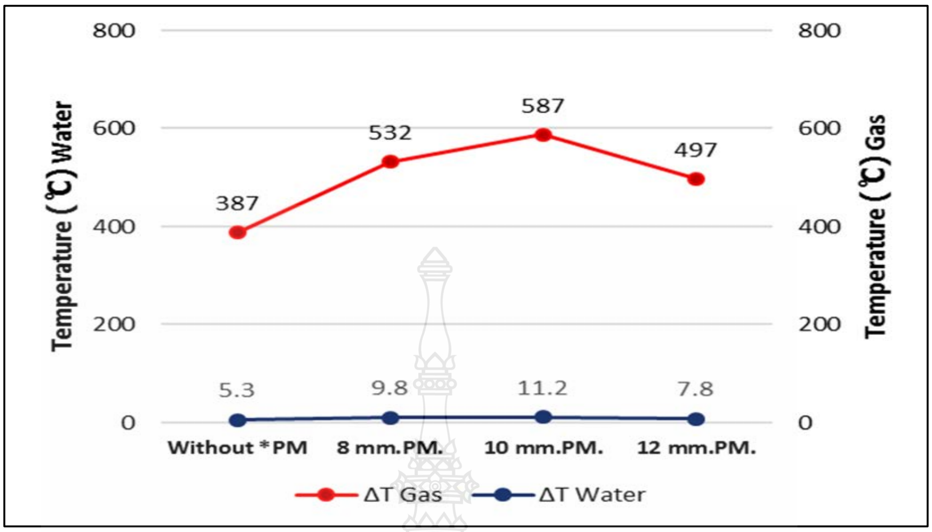


Figure 4.4 The difference of the average inlet and outlet temperatures of the gas and water for the four cases.

The water temperature profile at the inlet and outlet points of the heated water (within the porous media pack) is presented in figure 10 through the calculated absorbed heat rate using equation 2 for each of the four cases. Since the storage tank was controlled to a relatively constant temperature of 60ºC, there were no observed fluctuations concerning the water temperature. Hence, the absorbed heat rate was plotted instead. The maximum absorbed useful heat rate during the quasi-steady state occurred when the 10 mm. (case II-B) steel nuts were used as porous media with a highest value of 39.09 kW.

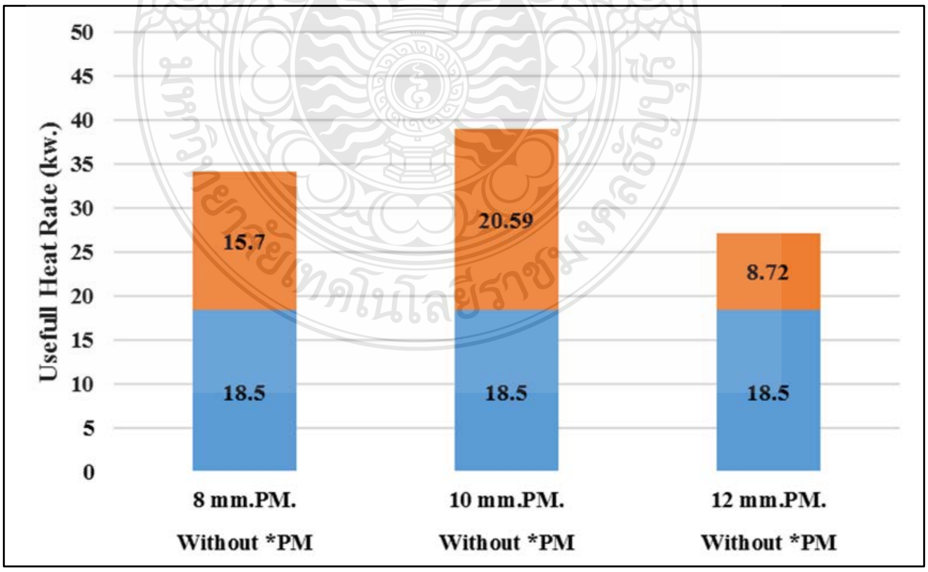


Figure 4.5 The absorbed useful heat rate of the four cases (Without*PM, 8mm PM, 10mm PM, and 12mm PM.

The thermal efficiency of the proposed SFPMC for the four cases: without porous media, 8mm porous media, 10mm porous media, 12mm. porous media, and compared with the research of Arwut and Jarruwat references number 15 are shown in figure 4.6. Results showed that the maximum and the highest average value of thermal efficiency calculated was obtained from using steel nuts porous media that is 10mm in size. It solved achieved the highest value of 39.09 kW. of absorbed useful heat rate, and thermal efficiency of 67.32% thermal efficiency compared to the one without the porous media (shown in Figures 4.5,4.6). With regards to the combustion stability of the system, the use of solid fuel resulted to a high fluctuation rate, which might be due to the high flowrate and combustion rate of the solid feedstock.

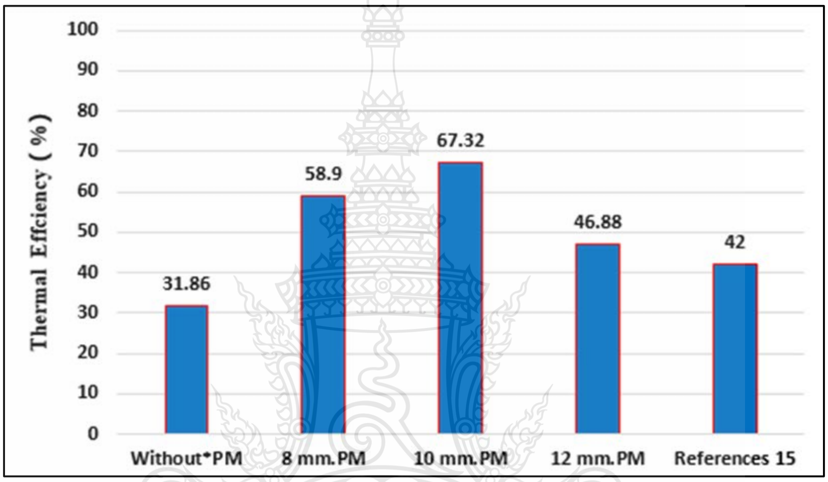


Figure 4.6 The thermal efficiency of the SFPMC system.

The balance the heat of the combustor as the law of energy conservation means the energy entered is equal to the heat energy absorbed. The heat balance between water and gas expendable error less than 10 % (Shows in Figure 4.7).

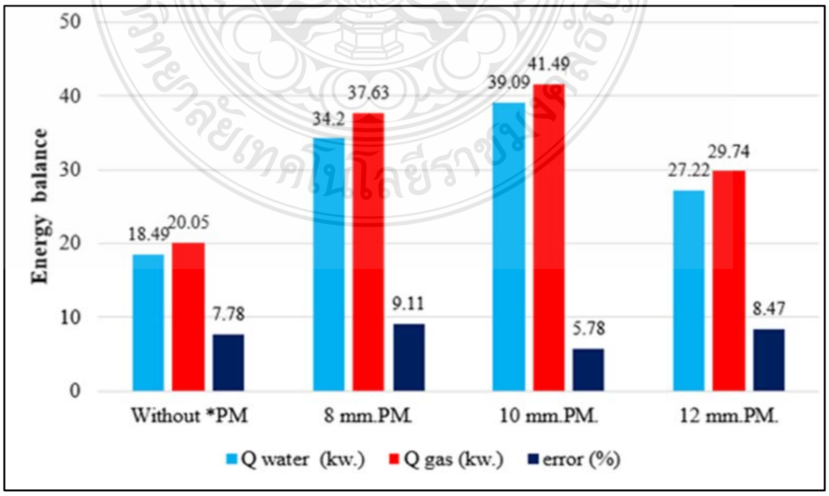


Figure 4.7 Energy balance of heat.

4.2 Simulation

The results of this simulation are presented the results, the data collected, and the implications and importance of that data. It evaluates how this type of simulation provides valuable feedback and insight into optimal porous media design.

4.1.1 CFD Simulation of mesh in porous media chamber

The red area represents the symmetrical calculating surface, while the green area is a splicing surface with heat transfer.

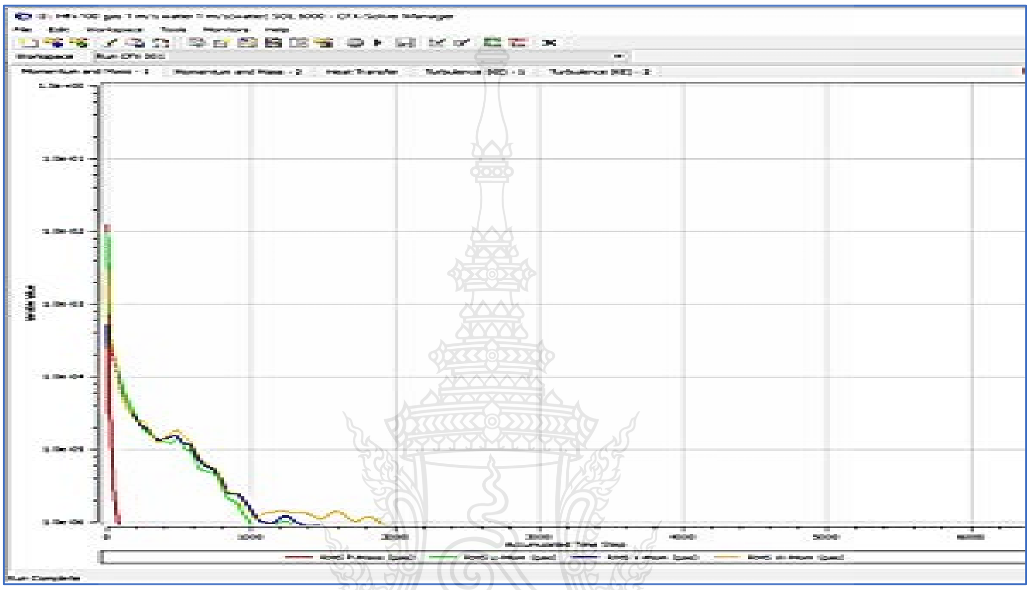


Figure 4.8 Convergence result of gas momentum.

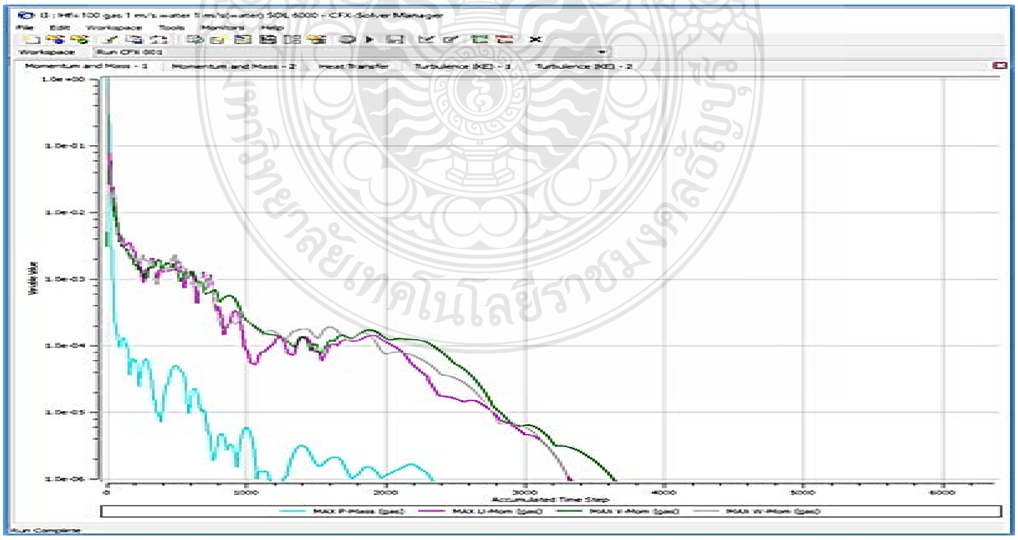


Figure 4.9 Convergence result of gas momentum.

4.1.2 CFD Simulation of hot gas temperature profiles in porous media chambers.

Figure 4.10 shows the velocity profile of the hot gas measured at the center plane of the porous media chamber. Velocities in this figure ranged from 0 to 1.945 m/s. This computer simulation demonstrates the importance of the hole size through which the hot gas passes, and how the simulation can optimize porous media chamber design for shape, size and hot gas particle distribution.

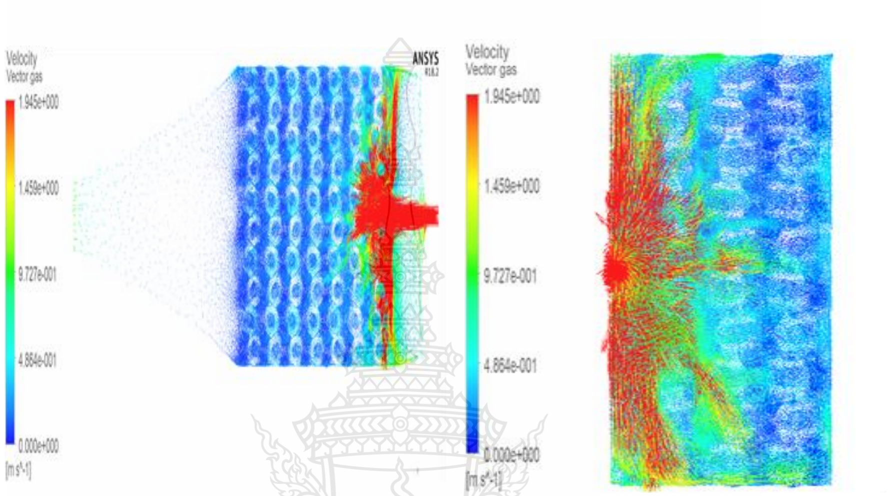


Figure 4.10 Velocity vector of hot gas.

In this section, the results of temperature modeling developed using the heat source and hot gas flow method in porous media chamber Shows that there is a one-way flow of hot gas from the combustor chamber to the porous media chamber filled with porous media.

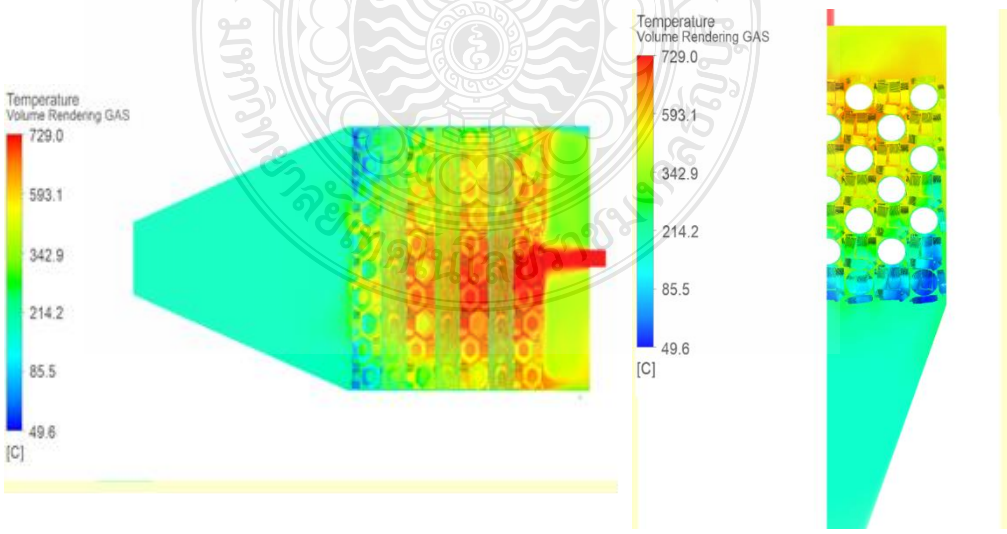


Figure 4.11 Temperature of volume rendering gas

Figure 4.12 shows the velocity profile of water in this figure ranged from 0 to 8.364 m/s. This study focuses on the influence of porous media chamber on the resulting hot water, which affects the efficiency of solid fuel combustor. Stainless steel nut is placed inside the right porous media chamber, which contains hot water pipes. The system has two system configurations: porous media chamber without porosity compared to porous media chamber with porosity.

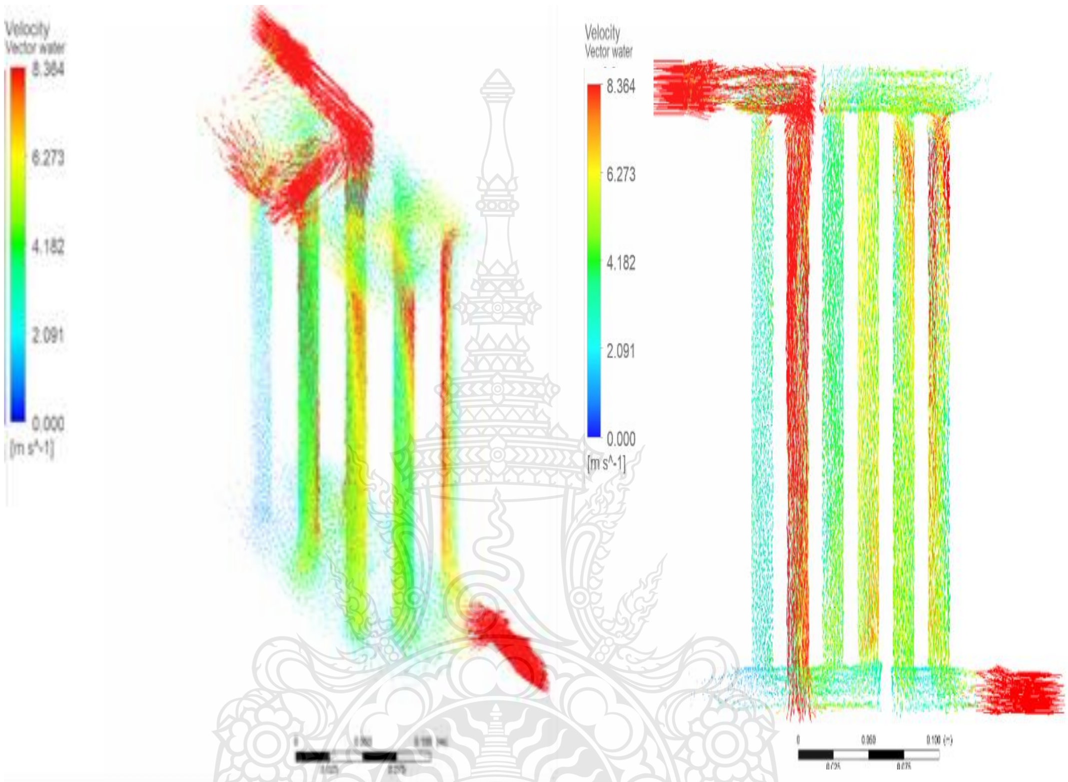


Figure 4.12 The velocity vector of water.

Figure 4.13 shows the chamber temperature profile of a porous media with 21 water pipes temperature of water ranging from 49.6 to 621.6 ºC. The water temperature profile at the inlet and outlet points of the heated water (within the porous media pack) is presented in Figure 4.5 through the calculated absorbed heat rate using equation 2 for each of the four cases. Since the storage tank was controlled to a relatively constant temperature of 60ºC, there were no observed fluctuations concerning the water temperature. Hence, the absorbed heat rate was plotted instead. The maximum absorbed useful heat rate during the quasi-steady state occurred within the 10 mm.

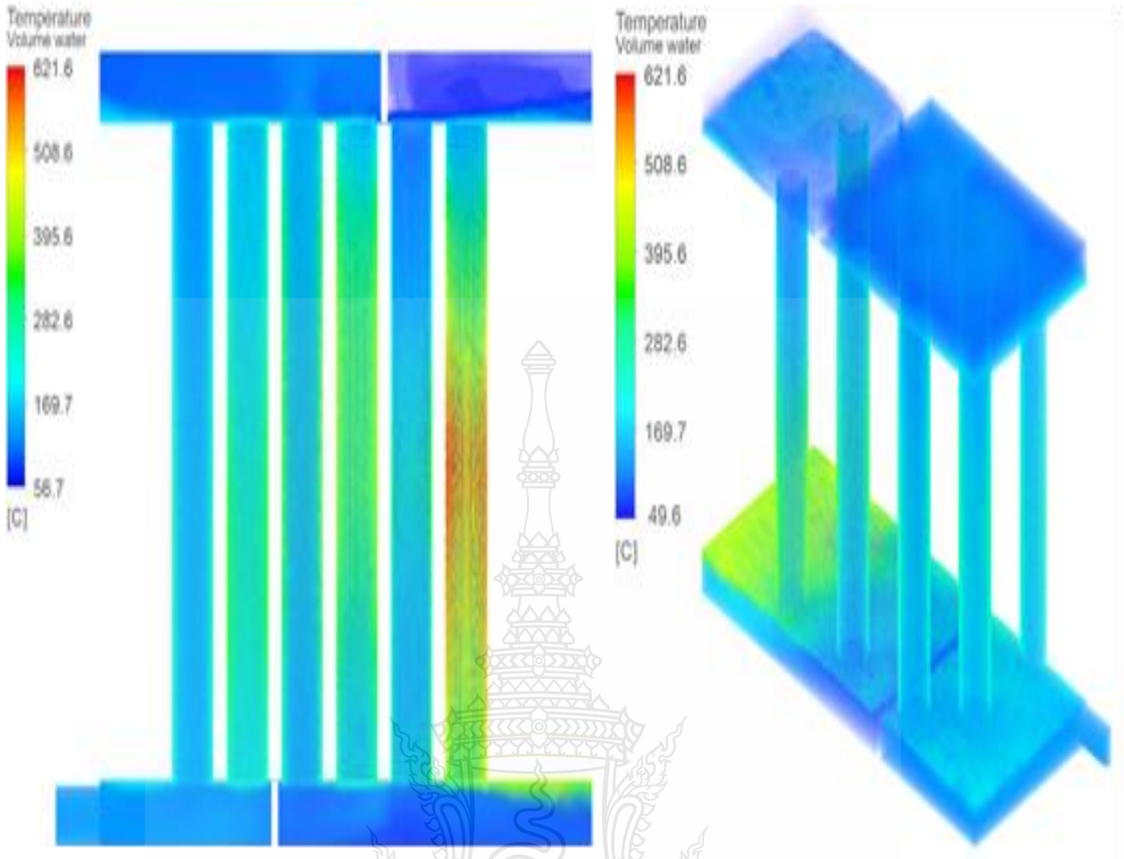


Figure 4.13 Temperature volume water.

The overview of the water and hot gas temperature was good when compared to the experimental results and the computer simulation results.

As shown in Figure 4.14, where the temperature results were compared with the size of the nuts loaded in the porous media chamber by 1 size per time. That is, nut size 8 mm. the first time, nut size 10 mm. the second time and nut size 12 mm. the third time, the water inlet temperature is about 48 ˚C - 49 ˚C. The water output temperature between the experiment results and the computer simulations is about 56 ˚C - 63 ˚C, the computer simulation is a useful tool for predicting water temperature.

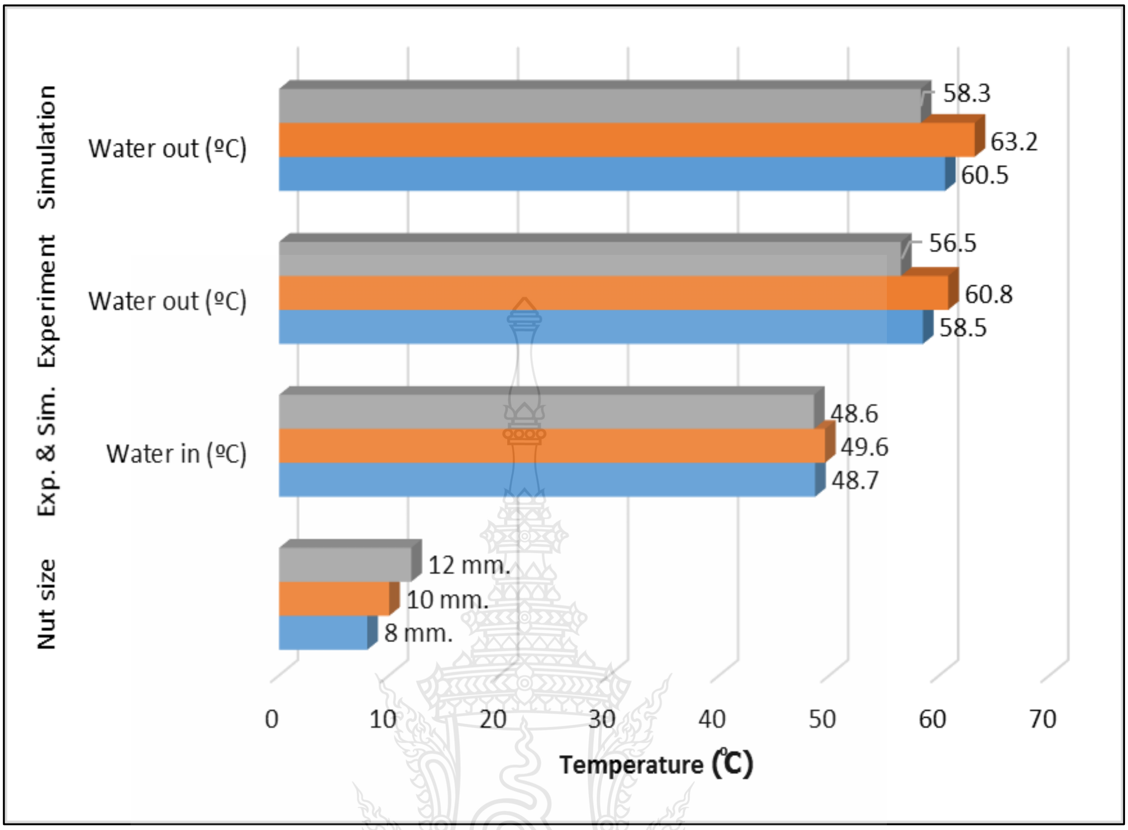


Figure 4.14 Comparison of experiment temperature water to the computer simulation.

As shown in Figure 4.15, where the temperature results were compared with the size of the nuts loaded in the porous media chamber by 1 size per time, time 1 nut size 8 mm, time 2 nut size 10 mm. and time 3, the 12 mm nut, 8 mm nuts size, hot gas inlet experimental results 661 (ºC), hot gas inlet simulation results, 661 (ºC), hot gas out experimental results 129 (ºC), hot gas out simulation results 99.5 (ºC), 10 mm nuts size, hot gas inlet experimental results 729 (ºC), hot gas inlet simulation results, 729 (ºC), hot gas out experimental results 142 (ºC), hot gas out simulation results 89.6 (ºC), 12 mm nuts size, hot gas inlet experimental results 628 (ºC), hot gas inlet simulation results, 628 (ºC), hot gas out experimental results 132 (ºC), hot gas out simulation results 110.3 (ºC),

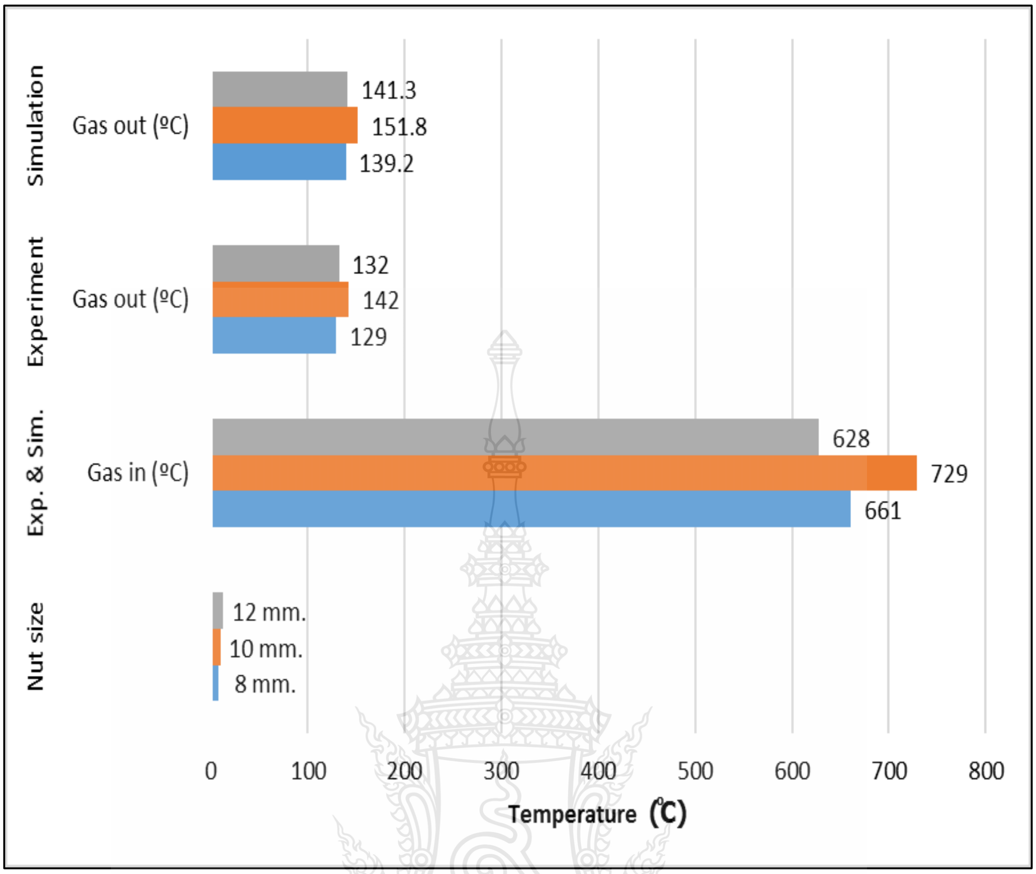


Figure 4.15 Comparison of experiment temperature hot gas to the computer simulation.

4.3 Results Simulation Validation

Table 4.1 shows the comparison of the experimental results with the simulation results. The table consists of 8,10 and 12 mm nuts. For 8 mm nuts, water inlet experimental results 48.7 (ºC), water inlet simulation results 48.7 (ºC), water out experimental results 58.5 (ºC) and the water out simulation result is 60.5 (ºC) and error 2 (ºC). Hot gas inlet experimental results 661 (ºC), hot gas inlet simulation results, 661 (ºC), hot gas out experimental results 129 (ºC) and hot gas out simulation result is 139.2 (ºC) and error 10.2 (ºC). For 10 mm nuts the water inlet experimental results 49.6 (ºC), water inlet simulation result is 49.6 (ºC), the water out experimental result is 60.8 (ºC)and water out simulation result is, 63.2 (ºC) and error 2.4 (ºC). Hot gas inlet experimental result is 729 (ºC), hot gas inlet simulation result is 729 (ºC), hot gas out experimental result is 142 (ºC), hot gas out simulation result is 151.8 (ºC) and error 9.8 (ºC). For 12 mm nuts, the water inlet experimental result is 48.6 (ºC), water inlet simulation result is 48.6 (ºC), the water out experimental result is 56.5 (ºC), the water out simulation result is, 58.3 (ºC), and error 1.8 (ºC). Hot gas inlet experimental result is 628 (ºC), hot gas inlet simulation result is, 628 (ºC), hot gas out experimental result is 132 (ºC), hot gas out simulation result is 141.3 (ºC) and error 9.3 (ºC).

Table 4.1 Comparison of experiment results to simulation results.

Nut size	Water in (ºC)		Water out (ºC)				Gas in (ºC)		Gas out (ºC)			
(mm)	Exp.	Sim.	Exp.	Sim.	error	% error	Exp.	Sim.	Exp.	Sim.	error	% error
8	48.7	48.7	58.5	60.5	2	1.21	661	661	129	139.2	10.2	14.19
10	49.6	49.6	60.8	63.2	2.4	1.51	729	729	142	151.8	9.8	14.87
12	48.6	48.6	56.5	58.3	1.8	1.04	628	628	132	141.3	9.3	13.14

4.4 CFD Simulation of hot gas temperature profiles in porous media chambers. (After fixing the gas heat transfer channel from 1 hole as 5 holes)

Figure 4.16 shows the profile when drilling additional 5 holes. The simulation shows that it can improve the efficiency of hot gas transfer to the porous media chamber when compared with only one hole of heat transfer (Figure 4.11 Temperature Volume Rendering Gas). This computer simulation demonstrates the importance of the number of holes through which the hot gas passes, and how the simulation can optimize porous media chamber design for shape, number and hot gas particle distribution.

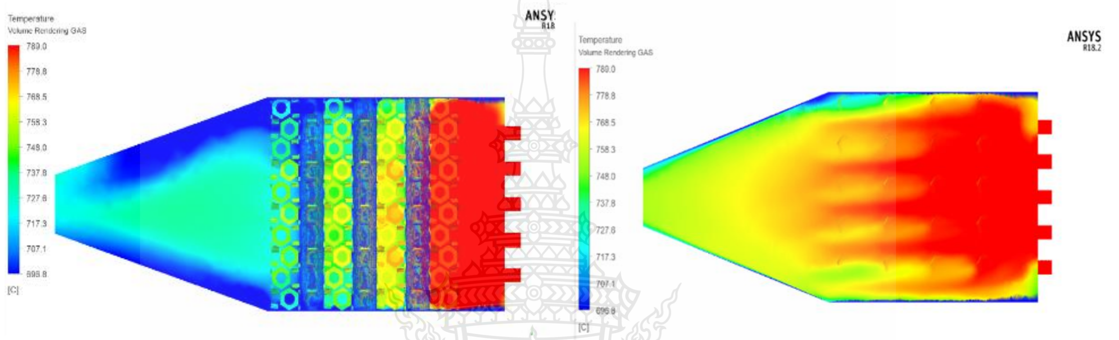


Figure 4.16 Temperature volume rendering gas.

Figure 4.17 shows the water temperature profile of 21 pipes. The water temperature profiles at the inlet and outlet points of warm water ranges from 56.76ºC to 802.4ºC. (Inside the chamber, the perforated media is increased to 5 holes). When the additional holes are drilled, the hot gas is transferred to the bile duct, resulting in higher temperatures compared to the transmission of heat with a single hole temperatures from 49.6ºC to 621.6ºC, (Figure 4.13 Temperature volume water).

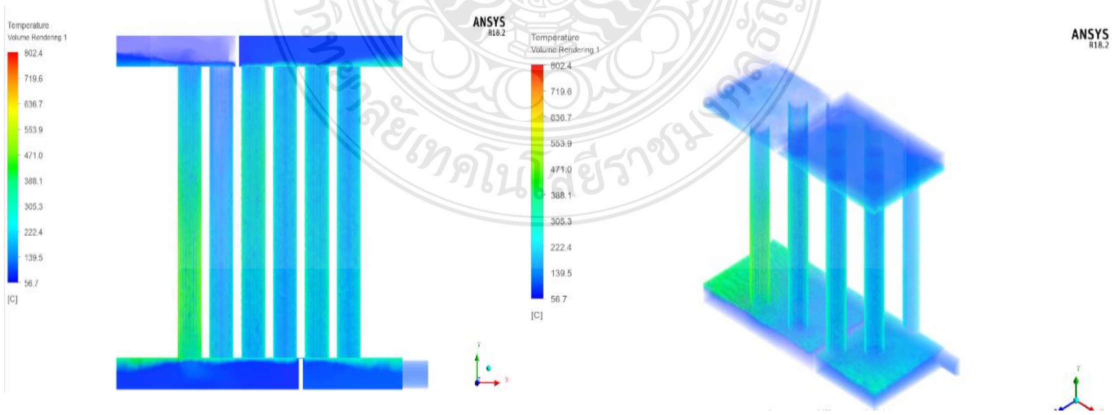
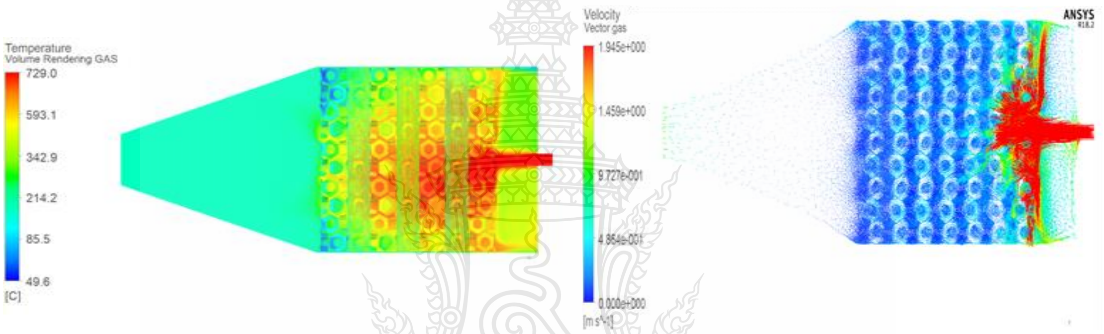
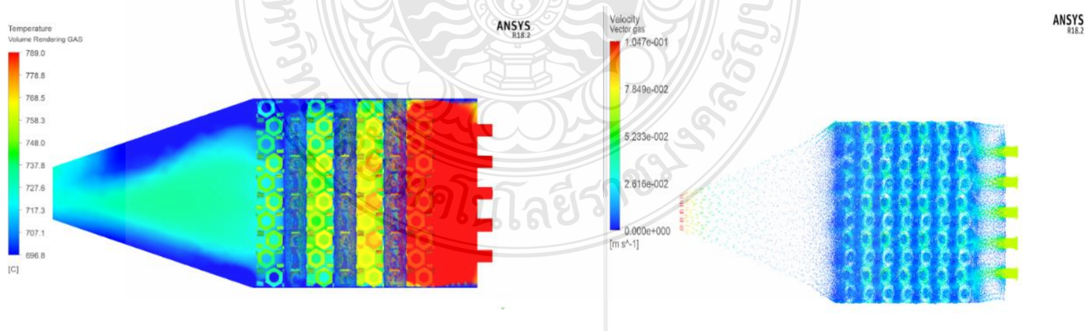


Figure 4.17 Temperature volume water.

Hot gas particle distribution from computer simulations on dispersion of hot gas particles in 1 hole shows that, the hot gas particles are not distributed well as they should. But, from computer simulations of drilling additional 5 holes shows that the particles of hot gas are distributed much better. Looking at Figure 4.18, the simulation results compared between 1 hole gas particle distribution and 5 holes gas particle distribution, the thermal efficiency increased in all cases. The porous media was previously 31.86%, increased to 49.89%. Signed porous material size 8 mm. from 58.90 %, an increase of 76.95 %, porous media size 10 mm. from 67.32 %, an increase of 85.35 %, porous media size 12 mm. from 46.88 %, an increase of 64.91 % (Figure 4.19)



Hot gas particle distribution 1 hole.



Hot gas particle distribution 5 hole**.**

Figure 4.18 Comparison of heat transfer channel from 1 hole as 5 holes.

Thermal Efficiency of SFPMC in this case, compares the heat transfer of only one hole to drilling additional 5 holes. The results showed that the maximum thermal efficiency was calculated using a 10 mm. porous media. Previously, the maximum value was 39.09 kW. After drilling additional 5 holes, the maximum value was 49.56 kW, and the original thermal efficiency was 67.32%. The heat more evenly compared to the heat transfer of a single hole.

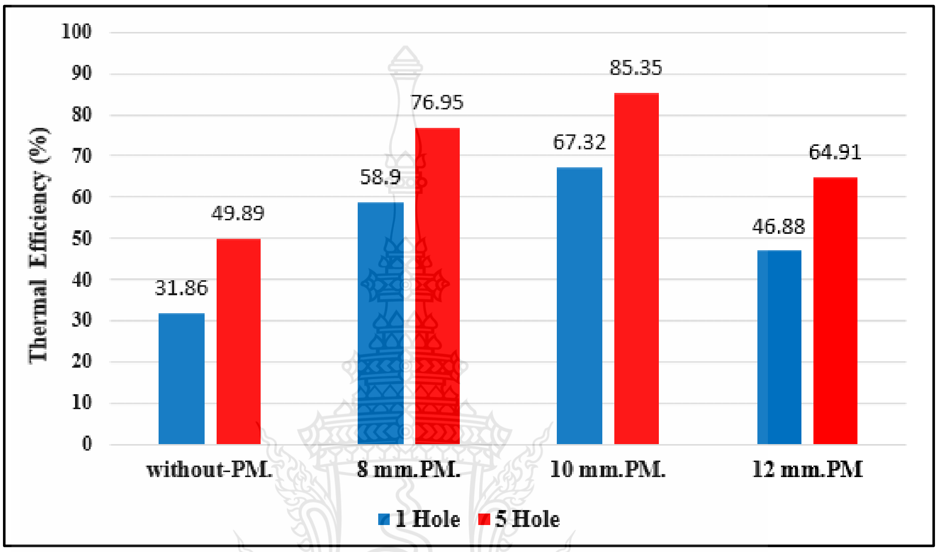


Figure 4.19 The thermal efficiency of the SFPMC system.(After fixing the gas heat transfer channel from 1 hole as 5 holes)

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

In the past decade, porous media combustor (PMC) technology had drawn a great attention of researchers in many applications, regarding heat transfer enhancement processes. The most attractive feature of such technology is its distinctive performance. However, according to porous medium a stationary solid matrix, the fuel can only be fluid. In earlier studies, many researchers focused on both experimentally and mathematical modelling developments of PMC reactors for gas and liquid fossil fuel. This study proposed the new concept of porous media application for solid fuel combustor. The experimental and theoretical (computer simulation) studies were conducted for this study. The experimental study was conducted in two important cases: with- and without-porous media. Three sizes of stainless steel hoax-nuts used in this study are: 8, 10 and 12 mm. The simulation of solid fuel porous media combustor (SFPMC) system was done using the ANSYS computer software. The results from this simulation was validated by using the same input data as using in the experimental study and solid feedstock was obtained from the literatures.

5.1 Conclusion

The experimental system of the proposed SFPMC was setup and investigated on its performance. The waste stainless steel nuts were used as porous media and wood charcoal was used as solid. Regarding this biomass charcoal as the renewable energy, it can be said that the proposed system can be possibly applied for all fuel, both fossil and renewable energy. The experimental setup was done for two main cases: without- and with-porous media, case I and case II, respectively. For case II, the porous media was further configured according to sizes: 8mm (case II-A), 10mm (case II-B), and 12mm (case II-C). The collected data were used to determine the setup with the highest heat transfer efficiency to the water tubes during combustion thereby giving a higher heating value to the system and then comparing it to a reactor (case I). Based on the results, porous media encourages higher heat transfer efficiency as observed from the rise in the temperature of water at the heat exchange chamber during the experiment. This was also seen after comparing the water temperature at the inlet and outlet points of the two main setup. Porous media induces both the occurrence of conduction and convection heat transfer to water tubes result in higher heating temperatures as compared to the non-porous one. Moreover, it was also noted that the size of the porous media affects the efficiency of the heat transfer occurrence to the water tubes. Based on the experiment, the size of the 10 mm size steel nut porous media was found to have the greatest thermal heat transfer rate among the other tested sizes.

The simulation study of the proposed SFPMC system was done by using the ANSYS computer software for two important cases as same as the experiment: without- and with-porous media. It was found that the results obtained by computer simulations in all cases were consistent with the heat radiation combustion theory of porous media. And it is consistent with the study results from the experiment. From a comparison comparative study of solid fuel combustion combustor with and without porous media installed, it was found that the kilns with porous had higher heat transfer efficiency than combustor without porous media installed. Furthermore, the effect of using various sizes of porous media was explored by using 8, 10, and 12 mm stainless steel nuts in the study. With the porous media technique, the 10 mm stainless steel nuts with the porosity of 0.53 greatly improved the performance of the proposed SFPMC system. At steady state combustion condition, the maximum average combustion temperature reached 1,002 °C and the thermal efficiency of about 67 %, was obtained.

5.2 RECOMMENDATIONS

Continuous combustion causes a constant temperature of heat and causes the increase of temperature of the outlet water. Therefore, the size of charcoal fuel affects the burning and efficiency of the furnace. The next experiment should grind the charcoal to about the same size. The size of the air inlet and air outlet hole affects the heat transfer. Because this experiment uses wood charcoal as fuel, it causes some soot to fill the holes causing the holes to become smaller, the hot air that is transferred to the porous material is less. In the next experiment, the inlet and outlet should be enlarged.

The shape of the air inlet and air outlet hole affects the heat transfer. Due to this experiment, the shape of the air inlet and the air hole into a round shape of 12 mm, causing the hot air sent to the porous material not distributed as it should be. The design of the air inlet and outlet should be in a cone shape. To help distribute heat to better porous materials and the next experiment should experiment with cyclic reversal gas flow.

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[74] Charissa Ruthenget Thesis "CFD Simulation of Downdraft Gasification" Master of Engineering (Mechanical and Energy Engineering) Graduate School, Kasetsart University Academic Year 2019.

APPENDICES
(List of Publications)

List of Publications

International Energy Journal

1. **Buncha Puttakoon, Boonrit Prasartkaew and Kitipong Jaojaruek** "Improvement of Heat Transfer on Solid Fuel Combustor System Using Waste Steel Nuts as Porous Media" International Energy Journal September 18, 2020 www.rericjournal.ait.ac.th

International Conferences

1. **Buncha Puttakoon, Boonrit Prasartkaew, "**Experimental study of Porous Medium Combustor Operating on Solid Fuel" Proceedings, The Pure and Applied Chemistry International Conference 2019 (PACCON 2019) TOGETHER FOR THE BENEFIT OF MANKIND, International Trade & Exhibition Centre (BITEC) Bangkok Thailand, February 7- 8, 2019, pp. RE153 - RE158.

2. **B. Puttakoon and B. Prasartkaew** " Development of Porous Medium Combustor Operating on Solid Fuel " The 14th Eco-Energy and Materials Science and Engineering Symposium (EMSES2018) Kyoto, Japan April 3rd – 6th, 2018. Old Paper ID ET1015-07-1-1 New Paper ID (Oral) ET13

National Conferences

1. **Buncha Puttakoon and Boonrit Prasartkaew,** "Solid Fuel Porous Medium Combustor" Proceeding, The 8th Thailand Renewable Energy for Conference (TREC-8), Faculty of Engineering Rajamangala University of Technology Thanyaburi Thailand, 4 - 6 November 2015 pp. 342-346.

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