INTERNSHIP REPORT

Charcoal Cooling

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This report is confidential: For internship evaluation only.

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for a sustainable energy economy

UNIVERSITY OF TWENTE.

Preface and Acknowledgement

From the 19th of February 2018 until the 18th of May 2018 I did an internship at the Clean Fuels B.V company at the city of Oldenzaal. The internship is part of two year master program in Mechanical engineering at the university of Twente. The master consists of a year of courses, I am specializing in Thermal and Fluid engineering, followed by a three month internship and 9 months of graduation thesis. With this opportunity I would like to thank the director of Clean Fuels B.V, Dr. Ir. Roland Siemons, for giving me the opportunity to do an internship at Clean Fuels and guide me through my internship with advices, feedback and tips despite his busy schedule. During this process Dr. Ir. Roland Siemons gave me extensive guidance sharing his knowledge and experience as well as made me to understand the working principle of the state of the art charcoal retort plant. The internship at Clean Fuels B.V offered me a professional experience and also helped on my personal development by making me more independent. Furthermore, by learning and understanding a different culture, I now have a broader perspective of the world which is a personal gain of this internship.

But this internship would never be true without the smart initiative of the university of twente which introduces us on the real world during the master program and let us to experience a working environment for three months. Last but not least, I would like to thank my supervisor at the University of Twente, Proff. Dr. Ir. G. Brem, for approving the internship and guiding me.

Summary

To understand the cooling characteristics of charcoal in the true scale set-up, laboratory scale experiments are to be performed. Two different experimental set-ups were built. One is a small scale set-up representing a layer of charcoal inside a true-scale reactor and the other is large scale set-up, representing a column of charcoal inside the true scale reactor set-up. In both cases a vertically oriented gas flow is applied, the gas acts as cooling medium.

For the cooling medium, an oxygen free gas was employed in such a way that it is being recycled, during the course of the experiment. The cooling medium was made from air by reacting the oxygen in the air with a preheated bed of charcoal fines, applying a very slow flow rate. The resulting mixture of nitrogen and carbon-di oxide was stored in the tank of 1 m^3 at ambient pressure. Gravity acting on a mass of water was used to induce an accurate flow of cooling medium through the charcoal sample of which the cooling properties were to be assessed.

In such set-up experiments are carried out, the cooling characteristics of charcoal are analyzed and the useful observations are reported. The results from both these experiment, helps in estimating the actual time for charcoal cooling in realistic conditions of dimensions such as applicable to the Condensing Retort charcoal manufacturing technology of Clean Fuels B.V.

In additional to the lab-scale experiment, an engineering model was developed for selecting a beam with minimum number of support structure using MrReves software developed by Reden. In this assignment, the problem is translated into mathematical model, important knowledge rules are implemented related to the problem, mechanical and heat transfer analysis are performed, user interface is created and based on the results a beam with minimum number of support structure can be chosen. This engineering model assists in designing the commercial condensing retort technology.

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1. Introduction

1.1 Clean fuels B.V

Clean fuels is a technology firm, that mainly supplies carbonization and pyrolysis equipment. The main focus is on the production of sustainable energy carriers made of biomass. Clean fuels also provides a wide range of other services, such as raw material testing, equipment and materials, installation supervision, start-up of the plant, operator training and a use license for the involved Intellectual Property.

The laboratory at Clean fuels is dedicated to research and development in cooperation with others such as University of Twente. The goals of R&D include the following. Firstly, biomass energy conversion technologies, including slow-pyrolysis(carbonization), fast-pyrolysis (liquefaction), combustion of pyrolysis vapors and liquids, as well as gasification of pyrolysis liquids. Secondly, quality improvement and assessment of conversion products, including carbons and pyrolysis liquids.

Clean fuels markets are both in the industrialized world and in developing countries. The firm is being co-financed with an Innovatiekrediet of the Dutch Ministry of Economy.

1.2 Internship objective and project approach

The main scope of the internship is the execution of lab-scale charcoal cooling experiment. This includes ideation and fabrication of the experimental set up, carry out the experiment, analyze and understand the cooling characteristics of charcoal; under the influence of process gas mainly containing nitrogen and carbon di oxide, and reporting the useful observations. This experiment helps in determining the time required for charcoal cooling; therefore estimating the actual time for charcoal production.

In additional to the lab-scale experiment, an engineering model has to be developed for selecting a beam with minimum number of support structure using Mr.Reves software. This engineering model assists in designing the commercial condensing retort technology.

The initial approach is to perform preliminary calculations to determine the amount of charcoal needed for the experiment and other controlling parameters for the experimental set up. Next, two different experiment set up are fabricated. One is a small scale set up representing a layer inside the true-scale reactor and the other is large scale set up, represents a column inside the true scale reactor set up. The scale comparison of the two laboratory experiments with the true scale set up is as shown in figure 1.1. The results from both these experiment, helps in designing an integrated system consisting of condensing retort and charcoal cooling technologies. The advantages of such an integrated system is: the charcoal can be cooled without emitting smoke or harmful process gas.

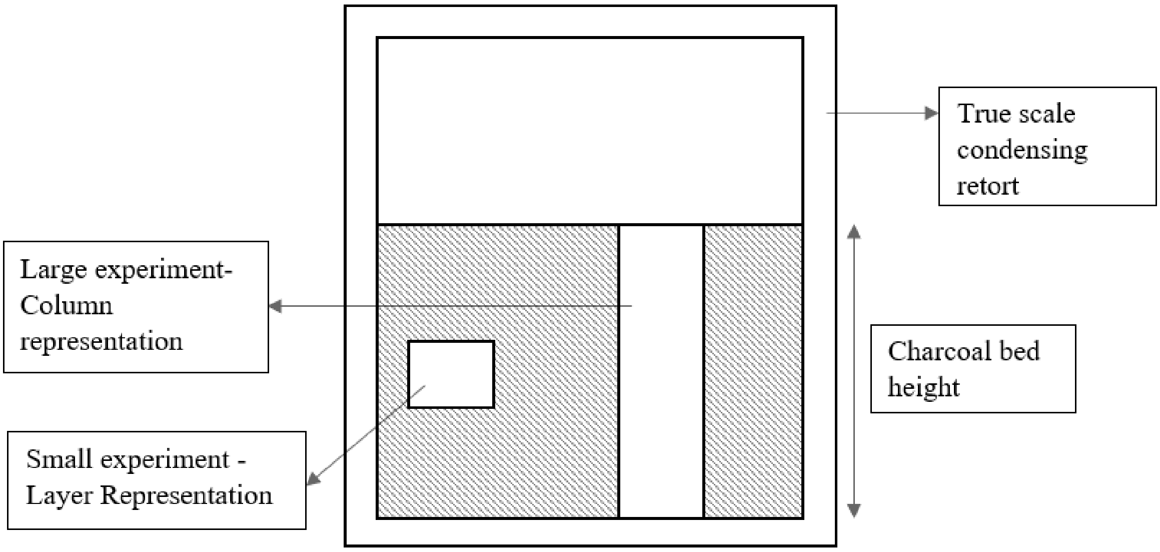

Figure 1.1: Experimental models comparison with the actual true-scale condensing retort.

In the engineering model assignment, the problem is translated into mathematical model, important knowledge rules are applied on the software package, mechanical and heat transfer analysis are performed, user interface is created and based on the results a beam with minimum number of support structure can be chosen.

The report is divided into 6 chapters; chapter 1 is the introduction to the company, internship objective and project approach; chapter 2 deals with charcoal cooling experimental, starting with literature study, defining experiment objective, explaining the components of the experimental set up, working principle of various components, small and large experiment outline and process operation. Chapter 3 discusses the observation and results during the experiment; chapter 4 Implementing engineering model using MrReves; chapter 5 discusses the conclusion and recommendations; and Chapter 6 discusses reflection of the internship. The internship has given hands on work experience in developing the set-up and performing the experiment. The details of all this is continued in the following sections.

2. Charcoal cooling experiment

2.1 Literature review

Charcoal making origins are lost in prehistory and the traditional methods of making it have changed surprisingly little[1]. Charcoal from biomass is the most important alternatives of fossil fuels, this have an important role in the cause of both providing energy requirement of production units and heating for household and healing energy deficit, disperse very less CO_2 than fossil fuels to atmosphere [2]. As a renewable fuel, charcoal has many interesting features like: it contains no sulfur and mercury and is low in nitrogen and ash; it is highly reactive yet easy to store and handle. To predict the kinetics of chemical reactions within and at the surface of charcoal particle, accurate NO_x and SO_2 emissions, fragmentation, attrition, the possibility of ash melting, it becomes necessary to know the charcoal temperature[3]. An important parameter that can be used as a quality criterion for industrial applications is the final pyrolysis temperature of charcoal [4]. Carbonized charcoal has large surface area, this property finds applications as adsorbents, reductant and soil amendment [5]. In the conventional kiln technology, freshly produced charcoal absorbs oxygen, this could lead to an rise in temperature and cause spontaneous ignition. Such technology produces large emission of unburnt methane and volatile organic matters to atmosphere and causes pollution [7].

To use the benefits of charcoal in various application, the hot charcoal produced after carbonization has to be cooled down sufficiently to avoid any spontaneous fire [6]. Therefore, charcoal cooling under controlled environment becomes necessary.

With the modern advancement in technologies the industrial charcoal making has the following advantages [1].

- The yield of charcoal from the wood is higher.
- Carbonization is more rapid.
- Industrial chemical and heat energy can be recovered from the smoke given off during carbonization.
- By recovering by products from the smoke there is less pollution of the environment.

On this common advantages and considering environmental effects, the Clean Fuels have developed Condensing Retort carboniser technology, capable of producing charcoal, pyrolysis oil, pyrolysis vapor and heat; using wide variety of biomass as input. This technology is based on concepts of batch retorts that are operated in counter-phase [7]. The Condensing retort technology proprietary of Clean Fuels can, also be supplemented with an additional cooling system. The cooling system helps in fast cooling of the charcoal from 450 ºC to 70-80 ºC. Below 70-80 ºC charcoal curing can be controlled. This helps in, controlling the yield, reducing the overall charcoal curing time, the production rate of charcoal increases and overcoming any fire hazard. In order to develop such a cooling system, certain parameters are determined from the charcoal cooling experiment.

2.2 Experiment objective

To understand the cooling characteristics of charcoal in the true scale set up, laboratory scale experiments are to be performed. Two laboratory experiments are to be designed, performed, analyzed and reported.

The larger experiment is designed in such a way that the height of the charcoal bed is equivalent to that in the true reactor, therefore the large experiment resembles a column in the condensing retort reactor. Whereas, the small scale set up is designed to represent a layer of charcoal in the true scale reactor.

The previous experiments performed by Clean Fuels was using steam and nitrogen as the cooling mediums. Using steam as cooling mediums, the charcoal cannot be cooled below 100ºC; as it results in condensation of water. The nitrogen used for cooling was not recycled are the drawback of the previous experiment.

In the present experiment, the other objective is to carry out the experiment with oxygen free gas mainly containing CO_2 and N_2 and design the experimental outline in such a way that the cooling medium is recycled. The details of the experimental outline is explained in detail in sections 2.5.1 and 2.5.2. The advantage of this experiment are that; the gas that is used as cooling medium is produced during the course of the experiment; cooling below 100ºC is feasible; faster cooling compared to steam; and the exhaust from the hot charcoal bed is cooled and recycled back into the system.

The experimental results helps in translating the determined cooling parameters to the true scale reactor, hence helps in optimizing the condensing retort technology. The time required for charcoal to be brought back to acceptable temperature, so that there is no chance for further combustion, thereby increasing the yield. Faster cooling implies higher rate of charcoal production are some of the benefits that can be achieved from the experimental results.

2.3 List of components

The following are the list of components required for the experimental set up

Charcoal container -11L : It is a cylindrical vessel made of tin plate with a diameter of 23 cm, height of 28 cm with a capacity of 11litre of charcoal . It weighs 0.70 kg with specific heat of 0.42 kJ/(kg.K). The container has a provision for inserting thermocouple inside the container. It is as shown in the figure 1 in Appendix A. It is placed inside the electric oven during the heating cycle, in order to bring the charcoal to the experiment temperature.

Charcoal container- 47L: It is a steel cylinder of diameter 0.2 m, height 1.5 m and capacity of 47 liters. It is closed at the bottom and top with a lid. The charcoal is filled till 1.25m height and the remaining space is filled with wire mesh so there is no free movement of charcoal. The container is wrapped with rockwool to provide insulation with the atmosphere. This whole set up is placed on top of the hot pebble bed heat exchanger using a short steel flexible hose and this is supported on the cage structure using the cable ropes under tension, as shown in the figure 2 in Appendix A.

Lid structure: The top of the charcoal retort (11L) is covered with a lid structure with the help of a ring clamp. The lid structure is provided with an inlet and outlet pipe for entry and exist of cooling medium, as displayed in figure 3 in Appendix A.

Thermocouple: It is a sensor made up of two different metals forming an electric junctions and thus measuring temperature of the gas and the charcoal lump at the prescribed location. To measure the temperature inside the charcoal lump, a hole is drilled on a selected charcoal and thermocouple is glued to it. Just adjacent and below to the specimen charcoal lump, another thermocouple is used to measure the gas temperature. This configuration of thermocouple is made for both small and large experiment. The some of the thermocouples used are as shown in figure 3 in Appendix A.

Electric Oven: In order for the cooling experiment to begin, the charcoal has to be initially heated to 450^0c, hence an electric oven is used for this purpose. The charcoal is heated by radiation in the small scale set up. Whereas, in the large scale experiment, charcoal is heated indirectly, by passing gas through hot pebble bed then into the charcoal bed.

Pebble bed heat exchanger: It is cylindrical vessel similar to small charcoal container, but filled with pebbles and acts as an heat exchanger; removing the heat from the processing gas and thus will be able to recirculate the gas. It is also used as a heat source for heating the charcoal via process gas in the large experiment set up, thereby acting as both heat exchanger and heat buffer. The pebble bed heat exchanger for small scale experiment is as shown in the figure 4 in Appendix A.

Intermediate bulk container (IBC): Two IBC storage tanks are used in the experiment, each of 1000 liter capacity. Initially one tank is filled with water and other tank with process gas. During the experiment the water is made to flow by gravity from one tank to another, displacing the process gas into the charcoal container. The tank is provided with butterfly valve at the bottom of the tank, this can be used as a regulating valve to control the flow of water and thereby controlling the gas flow in the range of 600-6000 liter/hour. IBC set up used for experiment is as displayed in the figure 5 in Appendix A.

Bidirectional flow control valves: The flow of process gas from one IBC tank into the charcoal container and the gas flow out of the pebble bed into the second IBC tank is controlled through two-way valve, with the arrangement as shown in the figure 6 in Appendix A. The 1 and 2 indicated in the figure 6 represents, the direction of gas flow from the respective storage tank. i.e., if the valves are set to 1, then the gas flows out of the IBC storage tank labelled 1 and vice versa.

Flow control measurement set up: The velocity of the process gas is controlled through the flow meter indicating the flow in liter per hour(L/hr). This set up consist of total two in number, 2-way valves: controlling the water flow through the flow meter between the two IBC tanks. This set up determines the flow rate of water, from this the corresponding flow rate of the process gas can be determined and the set-up is illustrated in figure 7 in Appendix A.

Radiation shields: During the cooling cycle the oven is turned off and the charcoal container is surrounded with radiation shields, so as to minimize external or internal heat transfer between the atmosphere, as shown in figure 8 in Appendix A.

Forklift: For the flow to occur at a pre-determined velocity, the tank filled with water has to be raised above the ground to a predetermined height using forklift. This cause the necessary potential difference for the water to flow to the other tank.

Data acquisition system: Data acquisition system converts analog waveform into digital values for processing, i.e, the temperature data from the thermocouples are stored onto to the computer, using the DAQ system.

Pipe connections: The IBC tanks, flow control valves are connected through pipes and plastic hoses. Hot stream pipe made from metal are used to connect the outlet of charcoal container to the inlet of pebble bed.

Heating or cooling cycle control valve: This valve is used in the large experiment to control the cold inlet gas into the hot pebble bed and then it exits to the bottom of 47 L charcoal container during heating cycle. Whereas in cooling cycle, the flow is directly run to the bottom inlet of the 47 L charcoal container. The valves configuration are shown in figure 9 in Appendix A.

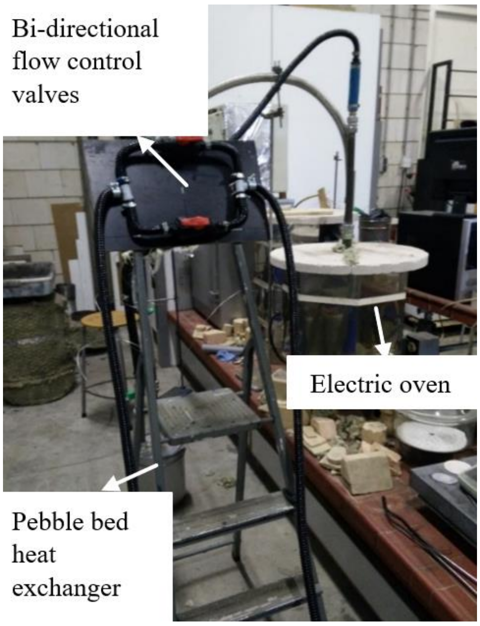

Figure 2.1: Small experiment set up.

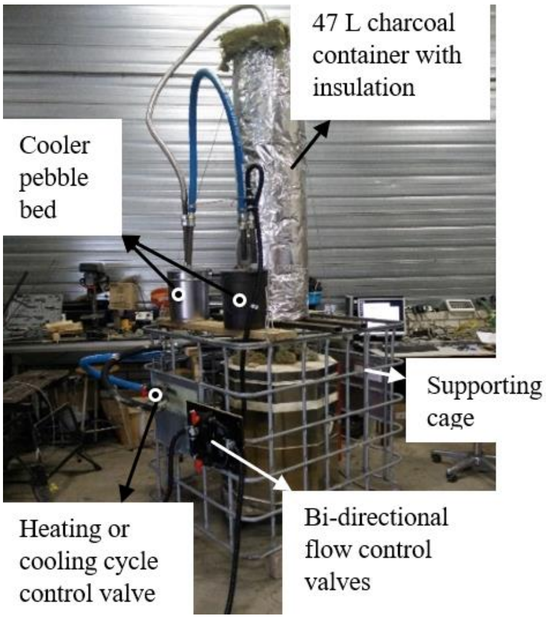

Figure 2.2: Large experiment set up.

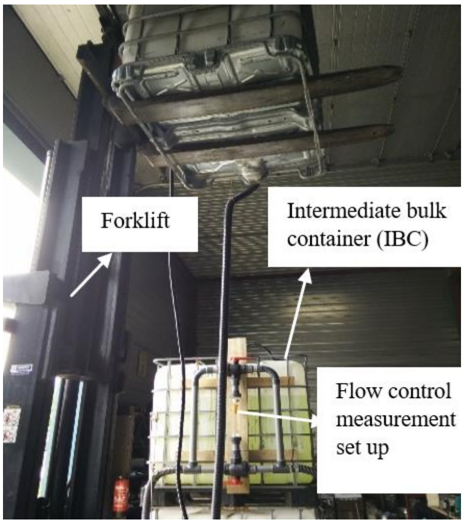

Figure 2.3: IBC storage tank.

The unique part of the experiment set up is that, using the IBC tanks and forklift set up, very accurate gas flow required for the experiment can be achieved. Works on simple principle and yet control the gas flow in the range of 600-6000 l/hr. Need for expensive gas pumping system is avoided, thereby reducing the total cost of the experimental set up. The figure 2.1, 2.2 and 2.3, shows the small experimental set up, large experimental set up and storage tank set up respectively. The detailed set-up explanation is provided in the section 2.5.

2.4 Working principle

Flow principle: The flow of gas, in the system is controlled by opening the butterfly valves and moving IBC tank containing water upwards, using a forklift. This causes the water to flow from the bottom of the tank and enters the second tank (mainly containing the gas), due to potential energy difference. This displaces volume of gas out of second storage tank. This is continued until all the gas flows out of the tank and gets replaced by water. The vice versa is true in the other tank. Then the whole process is repeated by switching the bidirectional flow control valves and IBC storage tank, in such a way as to make the gas flow into the charcoal container.

Process gas: Initially the IBC storage tank contains atmospheric air, and this is passed through the hot bed of charcoal; heated previously with an electric oven. This initiates combustion of charcoal, replacing the oxygen in the air with carbon-di oxide. Every single oxygen molecule gets replaced with carbon atom. The 1000 liter tank, approximately contains 9.4 moles of oxygen and therefore, 9.4 moles of carbon is required to replace the oxygen with carbon di-oxide. The equation 2.1 is the equilibrium equation to replace the oxygen in a 1000 liter IBC storage tank.

$$9.4C + 9.4O_2 + 35.2N_2 \Leftrightarrow 9.4CO_2 + 35.2N_2 \qquad \text{Eq 2.1}$$

As the process continues the oxygen present in the IBC storage tanks gets replaced with carbon di-oxide. In addition, a reaction of oxygen with hydrogen may be expected, thus forming water. However, the quantity of hydrogen present in the charcoal is less than 3%, so that we may disregard this reaction. This process gas collected in the storage tank is used in the next phase as the cooling medium. The temperature difference between the hot charcoal bed and the cooling medium, is the driving force for the cooling experiment, along with IBC storage tank set-up. The process gas which is at ambient temperature can cool down the hot charcoal bed to the required temperature in a given time period.

Energy balance: To get an overview of how much process gas is required, energy balance is made according to the equation 2.2 and the corresponding energy relations are shown in equation 2.3 to 2.5, for both small and large experiment set up. The results are tabulated in table 2.1

$$Energy_{Charcaol} + Energy_{charcoal\ container} = Energy_{Process\ gas} \qquad \text{Eq 2.2}$$

$$Energy_{charcoal} = Mass_{charcoal} * cp_{charcoal} * (T_{begin,C} - T_{end,C}) \qquad \text{Eq 2.3}$$

$$Energy_{charcoal\ container} = Mass_{charcoal\ container} * cp_{charcoal\ container} * (T_{begin,CC} - T_{end,CC}) \qquad \text{Eq 2.4}$$

$$Energy_{Process\ gas} = Mass_{Process\ gas} * cp_{Process\ gas} * (T_{begin,PG} - T_{end,PG}) \qquad \text{Eq 2.5}$$

Where cp is the specific heat of the material in consideration in J/(g.K). $T_{begin,C}$, $T_{begin,CC}$ and $T_{begin,PG}$ is the starting temperature of charcoal, container and process gas respectively. Similarly $T_{end,C}$, $T_{end,CC}$ and $T_{end,PG}$ are the end temperatures. The values of these parameters are tabulated in table 1 in Appendix A.

The process gas is assumed to flow with the same velocity as anticipated for the true scale set-up. From the Clean Fuels data true-scale gas velocity was found to be 0.058 m/s. By assuming the same velocity, the model experiment results can be compared and validated to the true-scale equipment. Using this gas velocity data, the cycle duration can be calculated and hence the flow rate of the process gas, as shown in the table 2.1.

Parameters	**Small set-up**	**Large set-up**	**Units**
Reactor diameter	0.23	0.20	m
Cross sectional area	0.04	0.03	m^2
Charcoal mass	1.61	6.60	kg
Charcoal energy	619.88	2541.12	kJ
Retort mass	0.72	2.83	kg
Retort energy	114.91	537.70	kJ
Insulation		17.50	kg
Insulation energy		5519.50	kJ
Total energy	734.79	8598.32	kJ
Pebble energy	734.79	8598.32	kJ
Pebble mass	2.06	24.09	kg
Gas energy required	734.79	8598.32	kJ
Mass of gas	1.55	18.18	kg
	1.24	14.57	Nm^3
	2.18	25.50	m^3
Velocity	0.06	0.06	m/s
Cycle duration	945.09	13996.73	s
	0.26	3.89	$hours$
Gas flow rate	0.0023	0.0018	m^3/s
Power	0.78	0.61	kW

Table 2.1: Theoretical calculations of the cooling experiments.

The process gas has to be recycled, therefore requires cooling before it is sent back to the tank. Pebble heat exchanger is used for this purpose. The energy balance and the mass of pebbles required is calculated according to the relations in the following equations 2.6 and 2.7.

$$Energy_{Process\ gas} = Energy_{Pebbles} \qquad \text{Eq 2.6}$$

$$Energy_{Pebbles} = Mass_{Pebbles} * cp_{Pebbles} * (T_{inlet} - T_{outlet}) \qquad \text{Eq 2.7}$$

Where $cp_{Pebbles}$ is the specific heat of pebbles in J/(g.K); T_{inlet} and T_{outlet} is the process gas temperature at the inlet and outlet of the pebble bed heat exchanger respectively. The calculated pebble mass is tabulated in table 2.1.

2.5 Experimental Set-up

The following two different experimental activities are carried out.

1) Small lab scale charcoal cooling set up containing; a 11L charcoal retort, 1 external electric oven, 6 thermocouples, 1 pebble bed heat exchanger, 2 flow control valves, flow meter set up, 2 IBC storage tanks, radiation shields and pipe connections.
2) Large scale set up containing; a 47L charcoal retort made from spiral pipe, 1 electric oven, 3-thermocouples drilled to the charcoal lump, 3-thermocouples measuring the process gas temperature, 2- thermocouples measuring center and wall temperatures of pebble bed, 3 pebble bed heat exchanger, 1 heating or cooling cycle control valves, 2 flow control valves, flow meter set up, 2 IBC storage tank, pipe connections, and rockwool insulation.

The process gas would be already present during the actual running of condensing retort, but to demonstrate cooling effect using process gas it has to be produced by burning the charcoal. The reaction takes place in a charcoal container and the process gas is collected in the IBC storage tank. The amount of charcoal needed to replace the oxygen in the 1000 liter storage tank is in accordance with equation 2.1, therefore 9.4 moles of charcoal is equivalent to an amount of 112.8 grams(g) of carbon. A total of 350g of charcoal is taken, accounting for losses such as excessive combustion due to leakage of air into the retort, as indicated in table 2.2.

Theoretical Charcoal to replace oxygen	113	g
Losses:		
charcoal has 90% carbon	12	g
Additional charcoal (excess combustion)	225	g
Total charcoal	350	g

Table 2.2: Charcoal for oxygen replacement.

A preliminary experiment is conducted to remove oxygen. The gas composition is checked after the preliminary oxygen replacement process and it was found to be less than 5% oxygen. As the experiment progress, the oxygen level further decreases in the IBC storage tank.

The other controlling parameters for oxygen removal process are; electric oven heated to 500^0C at a heating rate of 14.2^0C/min and the water flow (i.e. air flow rate) is varied from 600L/hr to 6000 L/hr. After the charcoal has reached 500^0C at all heights of the charcoal bed, then the oven is switched off, the oven lid is removed, insulation is provided with rockwool and allowed to cool naturally.

The temperature data of the experiment is stored in a computer as a text file. This can be used for further analysis. The results of this is further discussed in chapter 3.

2.5.1 Small experimental set up-11L.

In the small experiment set up, the charcoal container has a central inlet pipe, that extend to the bottom of the container. This makes the process gas flow in the upward direction cooling the charcoal from the bottom to the top of the container, i.e., charcoal cooling works on updraft principle. The central piping system is attached to the lid structure as shown in the figure 3 in Appendix A. Therefore, a funnel is used to fill the container with charcoal. The initial weights of the charcoal container, lid structure, ring structure and also after adding charcoal is noted in table 2.3. Also, the final weights are measured after the cooling experiment. The difference between the initial and final weights, determines the quantity of charcoal, that is being cooled during the process.

To understand the temperature profile during the cooling experiment, thermocouples are used at various point. One of the thermocouple is glued to the center of charcoal lump and place at the middle of the container, as shown in the figure 10 in Appendix A . This helps to evaluate intraparticle heat transfer in comparison with gas-particle heat transfer. The other various locations are: at the bottom of the charcoal container; wall of the charcoal container; in the middle, at the exit of the charcoal container and at the outlet of the pebble bed heat exchanger.

Parameters	Measurements	Units
Weight of the Container	858	g
Weight of Lid structure +Thermocouple	3490	g
Container clamp	138	g
Weight of container set up	4486	g
Weight of Charcoal + Total Weight of container set up	5891	g
Weight of charcoal	1405	g

Table 2.3 : various weights of the small experiment set up.

In the schematic figure 2.4, A, A', B and B' represents four different 2 way valves. 1 and 2 represents the position of the valve, indicating the direction of fluid flow in the system. Few of the lines in the diagram is bi-directional, depending on the position of the valves, the gas flows into the respective IBC storage tanks, i.e., if the valves A and A' is set to position 1, then the gas flows into storage tank 1. At the same time, the valves B and B' is set to position 2, directing the gas from the storage tank 2 into the charcoal container. This is only valid, when the water flows from IBC tank 1 to 2. If the valve position are reversed, then the gas flows out of the tank 1 into the charcoal container and gets collected in tank 2.

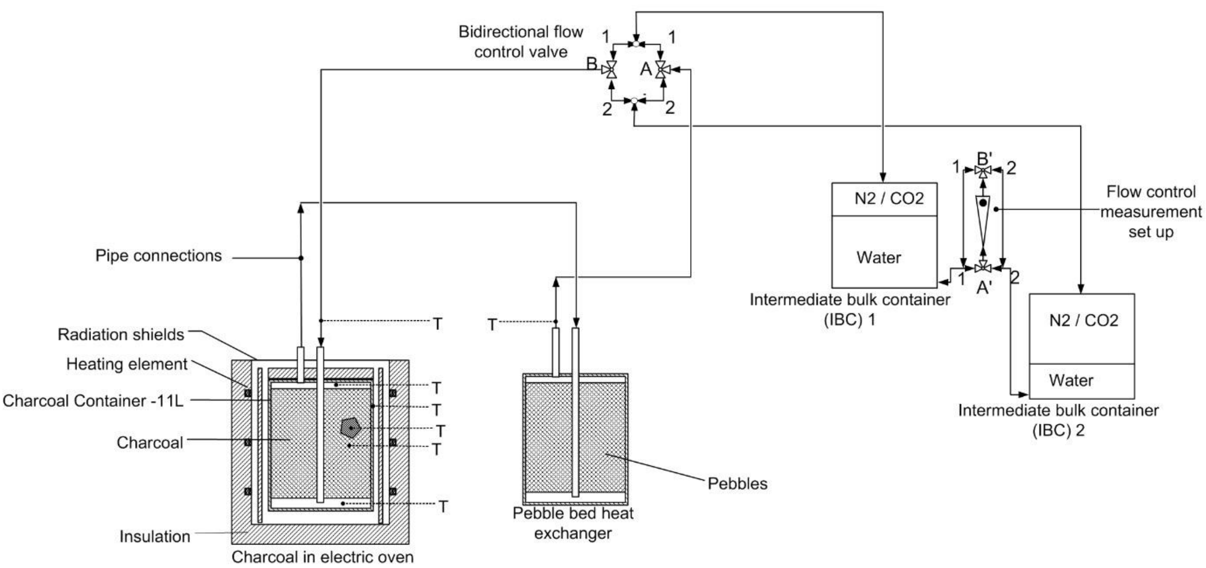

Figure 2.4 : Small scale experiment layout.

The outlet of the charcoal container is connected to the inlet of pebble bed using a steel pipe, with an ability to withstand the experimental temperature of 450^{0}C. The other connections are made using plastic hose pipes, with intermediate connections with rubber pipes to ensure the plastic pipes are not affected by the high operational temperature.

The outlet of the pebble bed heat exchanger is connected to the bidirectional flow control valve A. The hose pipes are connected to valves through hose tails. Depending on the valve position, the process gas is directed to either tank 1 or 2.

Inside the IBC tank, the process gas forces the water, through the butterfly valve located at the bottom of the container, to the next tank. The flow of water is controlled through the flow meter using two separate valves A' and B'   as indicated in the above figure.

Process operation:

Initially, the charcoal is heated in an electric oven with radiative heating elements to a temperature of 450^0C, at a heating rate of 9^0C/min. Although the oven attains the temperature quickly, it takes reasonable amount of time for the entire bed to reach the uniform temperature of 450^0C. Once, the charcoal bed attains uniform experimental temperature, the electric oven is switched off . To avoid external influence during the cooling experiment, the charcoal container is insulated with rockwool and radiation screens.

At the begin of the experiment, IBC1 contains water and IBC 2 contains process gas. To start the cooling experiment, IBC tank containing water is lifted upwards using forklift. The valves A, A' are set to position 1 and valves B, B' to position 2, then the butterfly valve of IBC is opened. This forces the water from tank 1 to 2 through the flow meter. The flow rate of the water is controlled using the butterfly valve and it is set to $6000\ l/hr$, this is equivalent to a gas flow of 6 cm/s inside the reactor , evaluated at an average gas temperature of 250^0C . As the water enters the tank 2, it displaces the process gas into charcoal bed through the valve B of the bidirectional flow control valve.

The process gas starts to cool the charcoal bed from the bottom in an updraft principle. The thermocouples are placed at various locations; the bottom determines the gas inlet temperature; middle two thermocouples are being employed, one thermocouple glued to the charcoal indicates the inner temperature of charcoal and the other indicates the gas temperature at the middle region; and the last thermocouple is placed at the exist of the charcoal bed, indicating the exit process gas temperature. The temperature data from the thermocouples are being continuously stored on to the computer through the data acquisition system.

To recirculate the cooling medium, it is passed through a pebble bed heat exchanger. This helps in cooling the process gas to ambient temperature and hence can be reused and stored again. For safety purpose, a thermocouple is placed at the outlet of the pebble bed, to know the outlet process gas temperature and stop the experiment if it reaches above 70^0C.

The process gas continues to flow until the water in the tank 1 gets empty. At this point the butterfly valve of the tanks are closed, this completes one cycle. Next, the tanks are switched, i.e., tank 1 is lowered and tank 2 is raised. Now, all the A, A' valves are set to position 2 and B, B' valves to 1, this starts the second cycle. It take approximately 11 minutes for one cycle to complete. This process is continued until the charcoal temperature have reached below 70^0C.

This small scale experiment is conducted two times, the results of the experiment are compared with the natural cooling process. At the end of the experiment, the charcoal container is removed from the oven and the total weight is noted. Comparing with the initial weights, the amount of charcoal effectively cooled during the experiment, can be determined. This is followed in the next chapter.

2.5.2 Large experimental set up-47L

In comparison with the previous experiment, large scale experiment set-up has the following distinguishability.

- The height of the charcoal bed represents a column of charcoal in true scale reactor.
- The charcoal bed is heated using the oxygen free gas, which is passed through the pre-heated pebble bed.
- No central pipe needed in the charcoal container, to make the set up work on updraft principle.
- Charcoal container is designed from a spiral steel pipe.
- Extensive cooling of gas is required before recycling into IBC. Therefore more number of pebble heat exchanger is required.
- An extra valve is needed to control the heating or cooling of charcoal.
- This experiment is directly translatable to the true scale charcoal cooling process.

In the large experiment set up, the charcoal container can hold up to 39 liters of charcoal and has a charcoal bed height of 1.25m. The gas is passed through the hot pebble bed and this is used to heat up the charcoal to the experimental temperature.

The bottom lid is provided with coupling, this helps in placing the charcoal container on top of the hot pebble bed heat exchanger, using a short metal pipe connector. The top lid is also provided with the coupling and is connected to cold pebble bed heat exchanger, through hot steel pipe. Both the top and bottom lid is bolted and sealed properly to avoid any gas leaks, as shown in the figure 2 of Appendix A. This also works on the updraft principle.

Parameters	**Measurements**	**Units**
Weight of top lid estimate	0.28	kg
Weight of empty container	4.18	kg
Total weight without insulation	11	kg
Weight of charcoal	6.82	kg
Total weight with insulation	28.5	kg

Table 2.4: : various initial weights of the large experiment set up.

The initial weights of the charcoal container, lid structure, and also after adding charcoal is tabulated as shown above. From this data, and also measuring the weight after the cooling experiment, gives the quantity of charcoal that was cooled.

Thermocouples are located at bottom, middle and top of the container, to measure the temperature. 6 thermocouples are placed in the charcoal container: 3 thermocouples are glued to the charcoal and placed carefully inside the container, during the filling process; 3 other thermocouples located at the same heights, but this are used for gas temperature measurement; 2 thermocouples to measure the hot pebble bed temperatures; and 2 thermocouples for the exit of 2 cooler pebble bed heat exchanger. Therefore a total of 10 thermocouples are used. In this set up, an extra valve (labelled E) is used for controlling the heating or cooling cycle, as shown in the schematic of the experimental layout, figure 2.5.

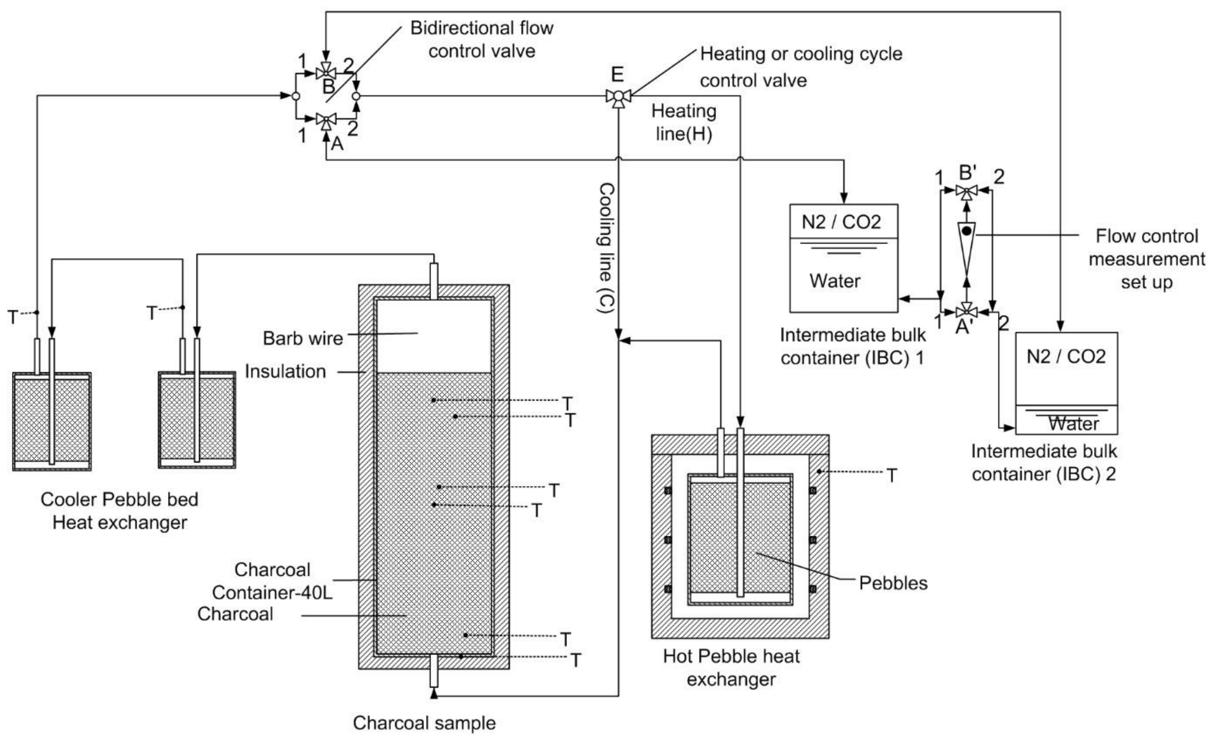

Figure 2.5 : Large scale experiment layout.

The process gas flow set up is similar to the small scale experiment. when IBC tank 1 is lifted, then the following holds good: valves A and A' to is set to position 1; valves B and B' to position 2, this causes the process gas to flow from IBC tank 2, through the charcoal bed and then flows to tank 1. Since the same process gas is used for both heating and cooling the charcoal. An extra heating or cooling cycle control valve E is introduced, the valve can be directed to H for heating or to C for cooling, as shown in the figure 2.5. Depending on the position of valve E, it directs the cold process gas from the storage tank to either hot pebble heat exchanger or directly to cool the already heated charcoal bed.

The charcoal is filled only to a height of 1.25m and the remaining space is filled with wire mesh. The charcoal container is thermally insulated with rockwool, therefore avoiding any undesirable effects on the experiment.

The top of the container is at very high temperature, so a steel pipe is used for connection to the first cold pebble bed. In the first pebble bed, the temperature drops significantly. Therefore rubber and plastic hoses are used for the remaining connections. The second cold heat exchanger is used as a safety precaution to avoid overheating of process gas. A single hot pebble heat exchanger is used for heating the entire charcoal bed. At this high temperature, there are chances for the charcoal to self-ignite and sustain the heating process.

The experiment is conducted in two parts: Initially the charcoal bed is heated and allowed to cool without any external driving force; and in the second time, it is heated once again, but cooled with the help of the gas. The heating and cooling operation cycle is explained in the following section.

Heating process operation:

The pebble bed placed is placed inside an electric oven and heated by radiation. 2 thermocouples are provided, one at the center of the pebble bed and the other at the walls of the pebble bed container. With the help of these thermocouples and data acquisition system, pebble temperature is monitored. Once the pebble bed has attained 450ºC, the heating of the charcoal bed can be started , by positioning the heating or cooling cycle control valve E to the heating line (H). The electric oven is kept on during the entire charcoal heating process.

Next, the IBC 1 containing water is raised to a certain height, using a forklift. All the valves labelled A, A' is positioned to 1 and valves B, B' to position 2. The butterfly valve of the IBC tanks are opened. This creates the potential difference for the water to flow from tank 1 to tank 2, and hence the process gas flows out from tank 2. The process gas cannot enter the charcoal bed directly, because the valve is positioned to heating line. Therefore, the process gas is forced to enter the hot pebble bed. The outlet of pebble bed is directly connected to the bottom of the charcoal container, hence heating the charcoal bed from the bottom to the top. The process gas exiting the top of the charcoal container is reconditioned to ambient temperature in a cold pebble bed heat exchanger.

The flow rate is controlled at $6000\ l/hr$ and it takes approximately 10-11 minutes for the tank 1 to be empty. At this stage , tank 1 is lowered and valves are closed. Then tank 2 is raised, but this time all the valves position are reversed (i.e., A, A' is positioned to 2 and B, B' to position 1). The thermocouple helps to monitor the temperature of charcoal and gas at three different positions. This process is continued until, the charcoal bed attains a uniform temperature, to conduct cooling experiment.

Cooling process operation:

After the charcoal bed has attained a steady temperature of 450^0C, the electric oven, heating the pebble bed is switched off. This avoids any unnecessary heating due to conduction, during the cooling process.

Next, the heating or cooling cycle control valve is positioned to cooling line (C). This divert the process gas to flow into charcoal bed directly, without entering into the hot pebble bed. The process gas flow is started by lifting the tank 1 containing water and positioning all the valves A, A' to 1 and valves B, B' to 2. The process gas entering the charcoal bed is at ambient temperature and starts to cool down the hot charcoal bed from the bottom. The thermocouples are used to monitor the drop in temperatures at bottom, middle and top of the charcoal container.

The exit temperature of the process gas leaving the charcoal bed is high, hence it is cooled down to ambient temperature in the cold pebble bed heat exchanger. When the water in the tank 1 is empty, the tanks and valves are switched accordingly. This process is continued until the charcoal temperature drops below 70^0C. After the charcoal bed is cooled, it is weighed, to determine the amount of charcoal that was being cooled. The temperature data stored in the computer can be used later to plot the cooling curve. This is discussed in the following section.

3. Results and observation

3.1 Oxygen removal

Before the start of the experiment, the oxygen concentration in the storage tank was noted to be approximately 20%. Using the calculated amount of charcoal, it is heated in an electric oven to high temperature in presence of the air, causes the combustion of charcoal. This replaces the oxygen with carbon di-oxide. The final weights after cooling are noted in table 3.1, a total of 121g of charcoal is burnt during the process of replacing oxygen with carbon di-oxide. An additional 7% excess charcoal is being combusted, in comparison to the theoretical calculations in table 2.2.

Parameters	**Measurements**	**Units**
Total weight (charcoal+ container+ pipe structure+ thermocouple)	4592	g
Lid structure +top pipe connection	3372	g
Weight of charcoal+ container	1080	g
Weight of charcoal	229	g

Table 3.1: weights after cooling , oxygen removal

From the plot 3.1, it is clear that the charcoal combustion is observed after 33 minutes, when there is crossing of the lines. This becomes a more significant after 45 minutes, as the charcoal lump temperature exceeds the oven temperature, indicating charcoal combustion. The Charcoal combustion slows down after 125 minutes, this is indicated in the plot by dropping of temperature. The reason for this drop is explained by the decrease in the oxygen concentration in the IBC, after the first cycle of passing the gas.

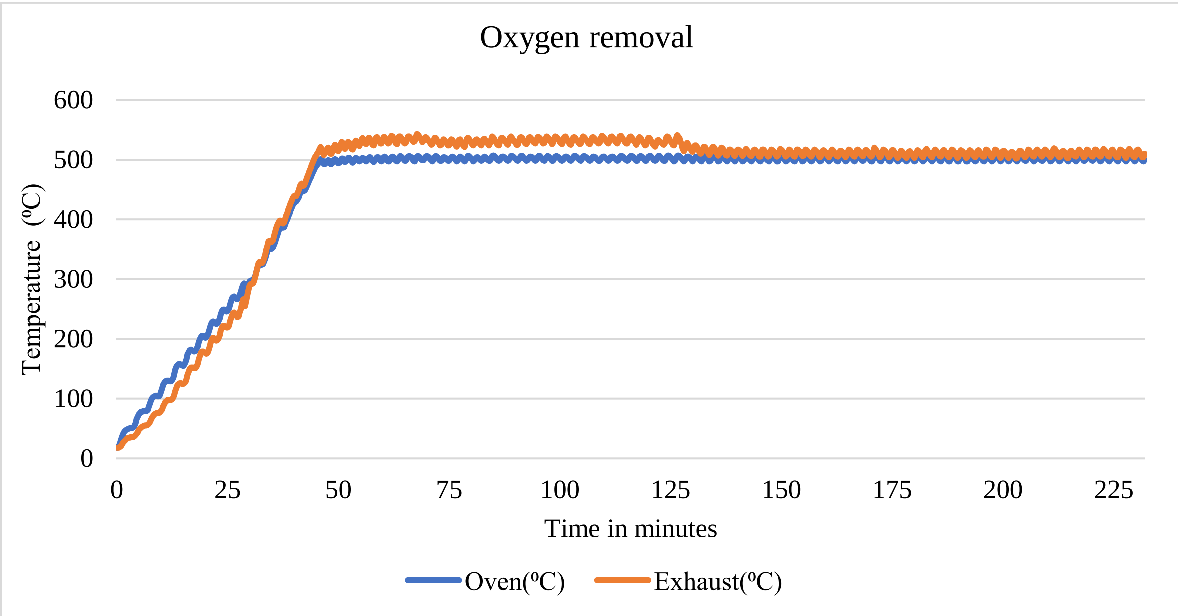

Figure 3.1: oxygen removal.

Therefore, it takes approximately 125 minutes for the 229g of charcoal to attain the peak furnace temperature. The gas concentration is once again tested and the oxygen was found to be less than 6%. This also proves charcoal combustion took place inside the charcoal retort. This concentration further reduces as the experiment progress.

3.2 Small- scale experiment (11L - results and observations)

During the small-scale experiment, light fumes from the charcoal bed exhaust was observed. This could be due to evaporation of moisture from the charcoal. At the beginning of the experiment, the charcoal weighed 1405g. The charcoal is heated, this removes the oxygen present in the process gas due to combustion of charcoal. The heating curve of charcoal for small scale experiment is shown in the figure 3.2. From the plot it is clear that, charcoal takes 65 minutes for it to attain a steady temperature of 450ºC, due to its low thermal conductivity. There is no sign of ignition during this stage.

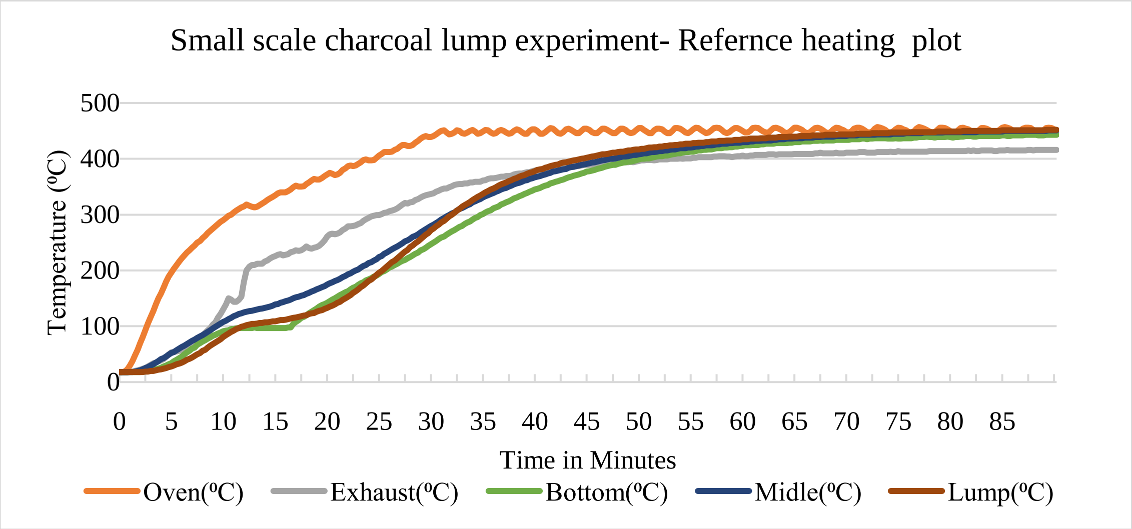

Figure 3.2: Small scale charcoal lump heating curve.

After the charcoal has attained, a steady temperature, oven is switched off and allowed to cool naturally, without any external cooling medium. The reference cooling curve is as shown in figure 3.3. It takes approximately 2.5 hours for 1405g of charcoal to cool down to 50ºC without any external cooling medium. The temperature at the center of charcoal takes longer time than the outer surface of the charcoal, this can be concluded with reference to the lump curve in figure 3.3 takes longer than the other gas measuring points (exhaust, bottom and middle).

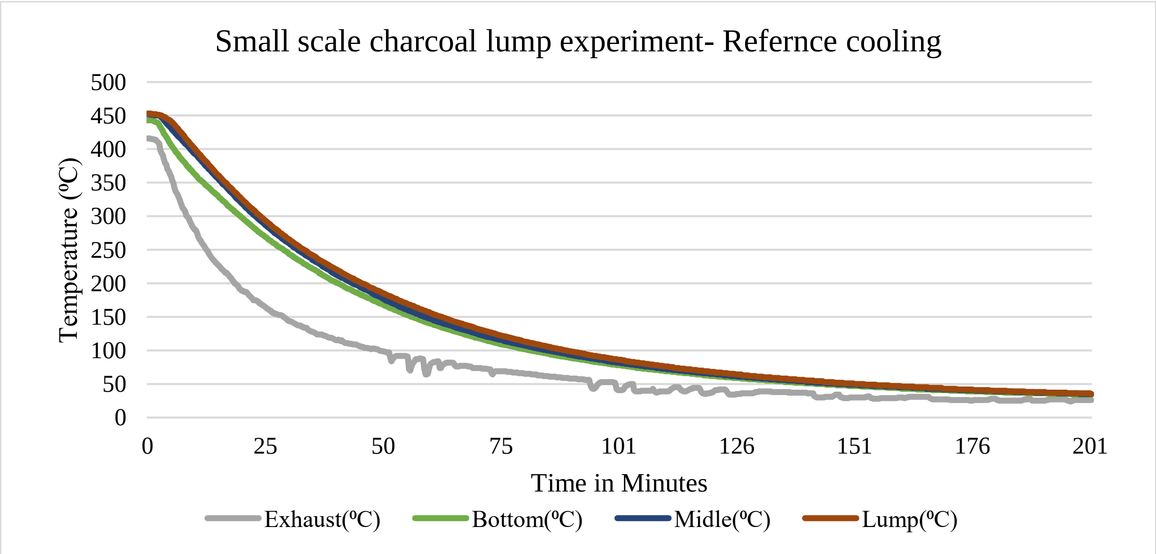

Figure 3.3: Reference charcoal cooling curve- small scale experiment.

Next, two trials of charcoal cooling with process gas was conducted. Therefore, the charcoal is heated once again, but this time there is a temperature rise of charcoal above the oven temperature, indicating ignition of the charcoal, this is shown in the figure 1 of Appendix B. The cooling curve for the trial 1 is as shown in the figure 3.4. The bottom, middle and exhaust curves shows a rise and fall of temperature. These fluctuations of thermocouple signals are due to switching of tanks and the valves during the operation of the experiment. Although the lump curve is not affected by this. There is no significant rise in pebble bed temperature, during the cooling process and it takes approximately 70 minutes for the charcoal lump to reach below 70ºC, as observed in the figure.

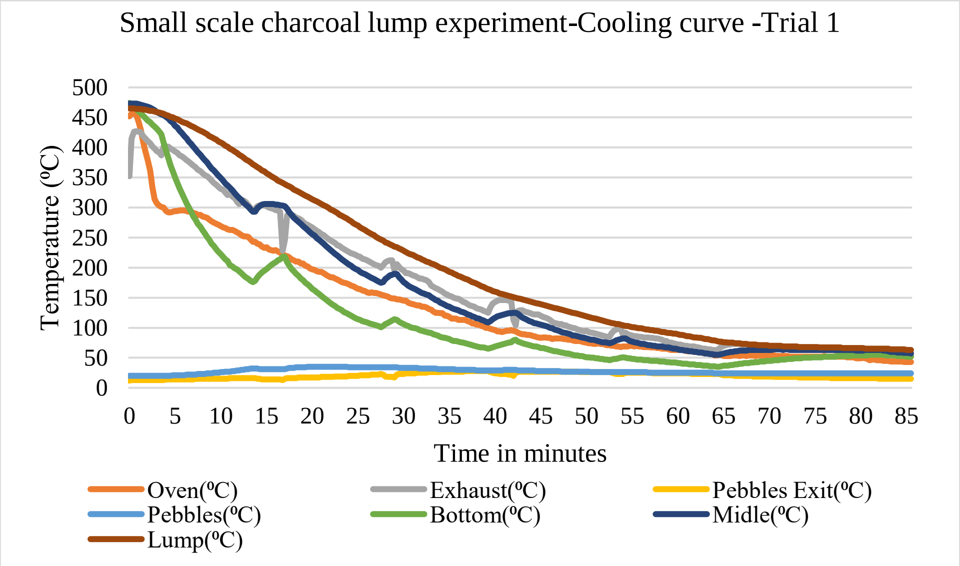

Figure 3.4: Trial 1 charcoal cooling curve.

After the trial 1 experiment, the oxygen concentration in the IBC storage tank was measured and it has decreased from 6% to 3%. This also indicates charcoal combustion inside the container.

Similarly, trial 2 is carried out, the cooling curve is shown in Figure 2 Appendix B. Similar trend lines are observed. In the second trial it took 62 minutes to cool the center of the charcoal to 70ºC. This results are comparable to trial 1 experiment results.

The weights of the charcoal container are measured after each trial and it is tabulated in table 3.2. From the table it is clear that, during trial 1, 231g of charcoal is being combusted during the heating phase. In trial 2, the mass loss is very less, as there is very low percentage of oxygen required for charcoal combustion.

Parameters	**Trial 1**	**Trail 2**	**Units**
Weight of Charcoal + Total weight of container set up	5660	5654	g
Mass loss	231	6	g
Charcoal used for cooling	1174	1168	g

Table 3.2: weights after cooling, small scale experiment.

Charcoal cooling using process gas is more effective than naturally cooling. It takes approximately 1 hour to cool 1168g of charcoal to 70ºC,compared to 2.5hours for natural cooling. From the experimental data, it requires 0.12kW of power to cool the charcoal from 450 to 70ºC as tabulated in table 3.3

Small experiment				
Parameters	**Natural cooling**	**Trial 1**	**Trial 2**	**Units**
Charcoal mass	1.41	1.17	1.168	kg
Charcoal energy	569.42	452.01	449.70	kJ
Retort mass	0.86	0.86	0.86	kg
Retort energy	144.14	136.94	136.94	kJ
Total energy	713.57	588.95	586.64	kJ
Cycle duration	9000	4200	3720	s
Gas energy required		588.95	586.64	kJ
Mass of gas		1.25	1.24	kg
		1.00	0.99	Nm^3
Flow rate		0.2965	0.33	g/s
Power	0.08	0.14	0.16	kW
Cooling rate	2.67	5.42	6.13	$^0C/min$

Table 3.3: Small scale experimental results.

3.3 Large-scale experiment (47L - results and observations)

The large scale experiment results are easily translatable to the true-scale set up at Clean Fuels. The operation of this set up is different from the previous experiment. Here, the process gas is used as a heat carrier to heat the charcoal bed during the heating cycle or cool the bed during the cooling cycle. The charcoal bed can be distinguished into three stage; bottom, middle and top. At each stage, it has 2 thermocouples; one to measure the internal temperature of charcoal lump and other to measure the flow gas temperature. The experiment is carried out in 4 phases; initially charcoal bed is heated; followed by gas free cooling; charcoal is reheated again; and cooling using external gas. The complete temperature profile during the whole experiment is shown in figure 3 of Appendix B.

Before the begin of heating phase, the quantity of charcoal is measured to be 6.82kg. The pebble bed is heated to 470^{o}C. The pebble bed is continuously heated during the process. The gas heats the charcoal bed from the bottom to the top. The reference heating curve is as shown in figure 3.5. From the graph, the charcoal bed gets heated layer wise, starting from bottom moving in the upwards direction. The gas bottom reaches a temperature of 472^{o}C after 96 minutes. Most of the time during the experiment, the gas bottom is above 470^{o}C, indicating ignition of charcoal in the bottom stage. The bottom lump attains 470^{o}C after 106 minutes and remains almost constant at this temperature.

The temperature in the middle and the top is increasing at much slower rate, the reason being layer conduction, low thermal conductivity of charcoal and also the pebble bed center temperature drops continuously during the process. The pebble bed temperature decreases, because it has low specific heat compared to the gas and the heat transfer to the charcoal bed is faster than the heating of the pebble bed.

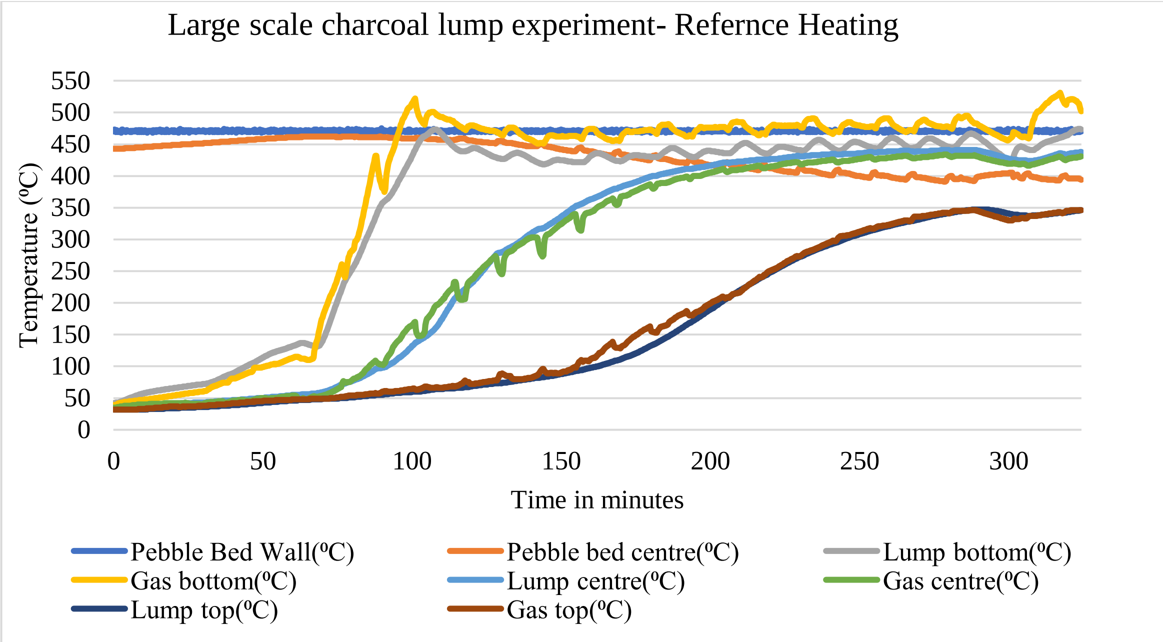

Figure 3.5 : Large scale experiment -reference heating.

After 5.4 hours of heating the middle and the top lump has reached a maximum temperature of 438ºC and 346ºC respectively. At this stage, the heating of charcoal bed is stopped and it is allowed to cool without any external flow. Using the data recorded, a reference cooling graph is plotted as shown in the figure 3.6.

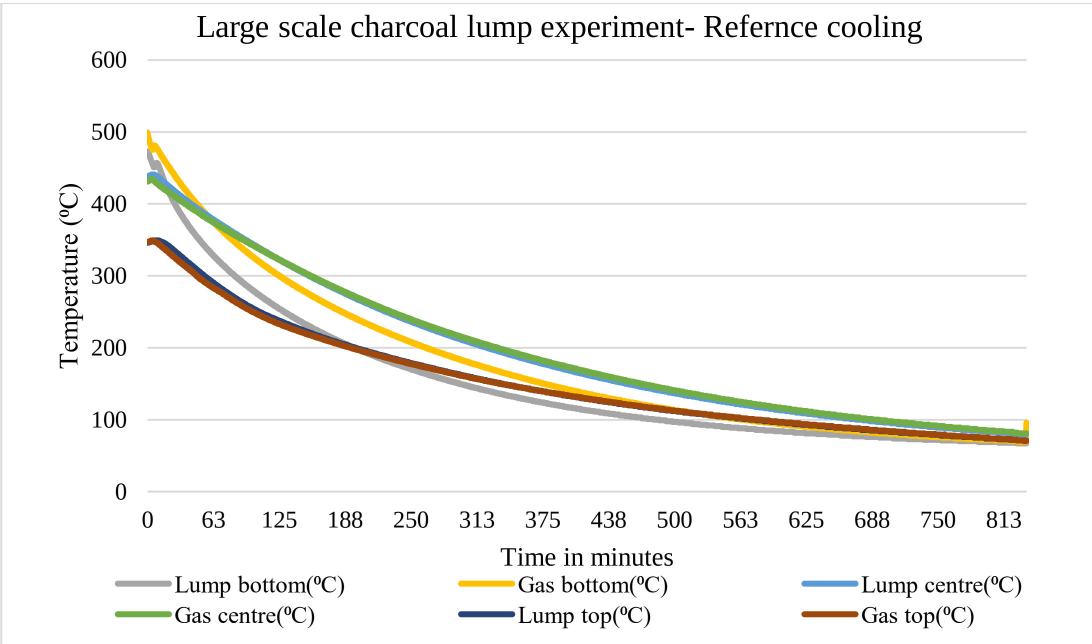

Figure 3.6: Reference cooling curve

It is a slow cooling process, therefore data is collected and stored in the computer over a night. From the plot 3.6, it is clear that the lump bottom and gas bottom cools relatively faster than the at the other stages. This is because, after stopping the supply of heat, the bottom stage acts as a source of heat to the middle and top region. This can be observed by following the green and light blue curve.

The rate of cooling of the green and blue curve is slower compared to bottom and the top, because middle region is close to the bottom, hence heat conducts to the closest adjacent region. i.e., heat flows from bottom region to middle region. The bottom lump cools much faster than the bottom gas, this is because the gas moves inside the bed due to convection. The comparatively colder gas in the top moves down, takes heat from the hottest region, i.e., from the bottom lump. It take approximately 14 hours for 6820 grams of charcoal to cool from 473ºC 438ºC and 346ºC to 67ºC , 80ºC and 70ºC; at bottom, middle and top respectively as shown in table 3.4. From the table it is clear that the maximum temperature initially was at the bottom stage, whereas at the end of the experiment it has moved to the middle region. Gradually, all the stages comes to equilibrium with the atmosphere temperature.

Temperature locations		Temperature at beginning of natural cooling (ºC)	Temperature at the end of natural cooling (ºC)	Temperature at beginning of gas cooling (ºC)	Temperature at the end of gas cooling (ºC)
Bottom	Lump	473	67	456	35
	Gas	502	70	474	34
Middle	Lump	438	80	441	43
	Gas	431	81	437	43
Top	Lump	346	70	363	76
	Gas	347	70	362	73

Table 3.4: Temperature comparison at begin and end of the large cooling experiment.

To understand the cooling characteristics of charcoal under the influence of external gas, the charcoal bed has to be heated once again, following the same procedure. After the charcoal bottom region has attained above 450ºC, the heating is stopped. Then, the cooling is started by positioning the heating or cooling control valve to cooling line. The data obtained from the experiment is plotted in figure 3.7.

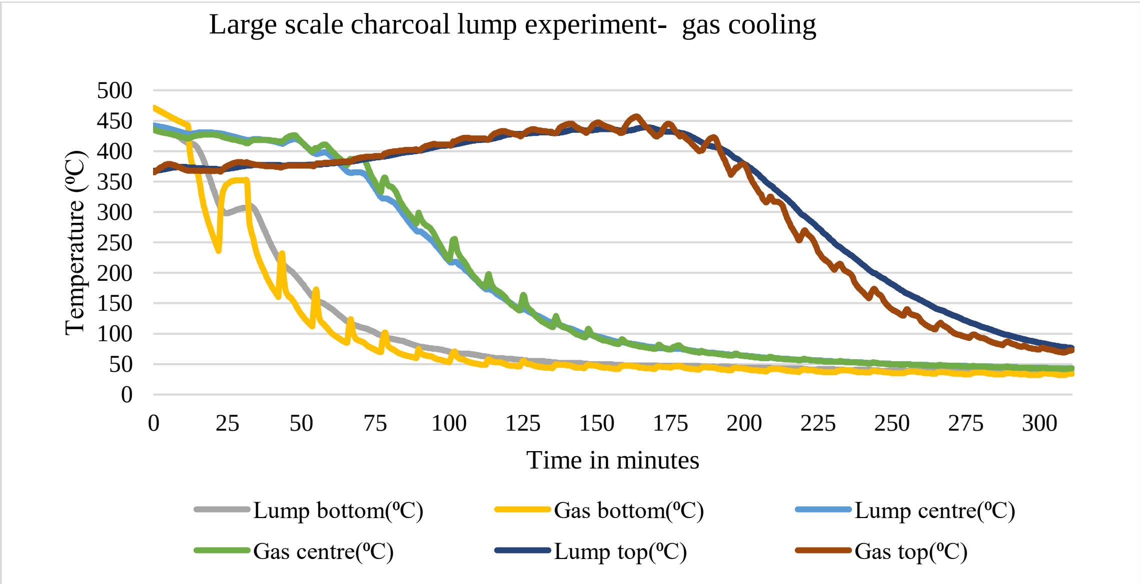

Figure 3.7: Large scale charcoal cooling experiment using gas as a cooling medium.

As expected, the gas and lump bottom, cools the fastest, but the middle and top region has a different trend. In the middle region, for the time interval between 0 and 50 minutes, the temperature drop is slow, because the heat from the bottom layer is being penetrated into the middle region. But after 50 minutes the temperature drop follows an exponential curve as seen in the figure.

In the top region, the temperature continues to increase till 168 minutes and attains a maximum temperature of 439ºC. The reason for this could be that, the energy from the bottom and middle heats the charcoal further or any traces of oxygen in the gas could ignite the charcoal at high temperature and further increase the temperature. The top layer cools back to 70ºC from 439ºC in a time interval of 143 minutes. Therefore, the overall time duration, for the 5920 grams of charcoal to cool back to acceptable temperature was found to be 5.2 hours.

From the figure 3.7, it can be noted that gas cools faster than the charcoal. During the experiment the exhaust gas temperature from cold pebble temperatures are monitored manually and it was within the operating limits of 20ºC -60ºC. The sharp rise and fall of curve at a regular interval, observed in all the graphs is due to the sensitivity of the gas thermocouple to external noise, like; regular switching of tank to keep the continuous gas flow; magnetic and radiation effects.

Large experiment			
Parameters	**Natural cooling**	**Gas Cooling**	**Units**
Charcoal mass	6.82	5.92	kg
Charcoal energy	2395.49	2215.33	kJ
Retort mass	4.18	0.86	kg
Retort energy	702.24	144.14	kJ
Insulation	17.50	17.50	kg
Insulation energy	5359.73	5364.57	kJ
Total energy	8457.45	7724.04	kJ
Cycle duration	50400.00	18660.00	s
	840.00	311.00	min
Gas energy required		7724.04	kJ
Mass of gas		16.33	kg
		13.09	Nm^3
Flow rate		0.8751	g/s
Power	0.17	0.41	kW
Cooling rate	Bottom -0.46	Bottom -1.95	$^0C/min$
	Middle – 0.77	Middle - 3.98	
	Top – 0.30	Top - 3.61	

Table 3.5: Large experiment results

After the completion of the experiment, the oxygen concentration had dropped less than 2% in the storage tanks and the weights of the container is measured and compared with the initial value from table 2.4. 900 grams of charcoal is being combusted, during the entire large scale experiment, but the amount of charcoal lost during cooling phase is negligible. The gas flow rate, power required and the linear approximation of cooling rate at all three regions are determined from the experimental results, as tabulated in table 3.5.

4. Mechanical and thermal Analysis- MrReves

4.1 Objective

To develop an engineering model for beam selection, minimum support structure (ribs), so that condensing retort can be placed on oven wall, without mechanical and thermal failure of the beam.

4.2 Problem and approach

The condensing retort is placed on the oven wall through the support structures and beam, as shown in the outline 4.1. The beam is fixed to the retort, so the retort, beams and support structure moves as a single unit. The entire reactor load will be acting on oven wall through the beam and support structure. The ribs also allows for independent expansion of retort at elevated temperature. A closing plate is provided around the retort, to retain the heat in the system.

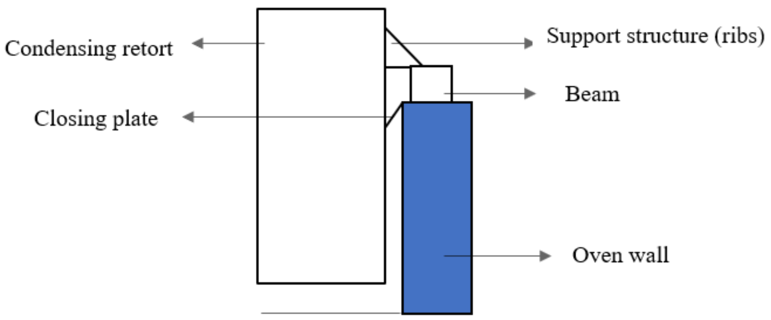

Figure 4.1: Condensing retort with oven wall schematic

Therefore, the beam selection becomes important mechanical design aspect, also the heat losses to the surrounding from the retort walls and support structure should be minimum. Hence, minimum support structure should be selected, so all the heat can be effectively used for carbonizing purpose.

Using MrReves an engineering model has to be created, which helps in verifying the designed beam is able to withstand mechanical and thermal stress, and selecting number of support structure with minimum heat loss to the surrounding.

4.3 Methodology

The MrReves knowledge builder is a software program that was developed by Reden. It is a virtual expert system that rely on the experienced person knowledge of the product. It keeps all the available knowledge related to a particular product, in an easy to access, instantly usable form [9]. The Problem model is converted into mathematical model. Then, a knowledge base is built in the software; every parameter are defined giving a range of value in which the solution should be looked for; a user interface is created. Next based on user defined design parameters inputs, results are obtained. This is explained in the following sections.

4.4 Mechanical stress model

To develop a mathematical model, circular beam ring on which the retort rest is chosen for analysis in such a way that the length of the beam is equal to the distance between the support structure, given by the equation 2 in appendix c. The theoretical model of the beam between the ribs is as shown in figure 4.2. It is a statically indeterminate structure because the number of reaction forces exceeds the equilibrium equations [10].

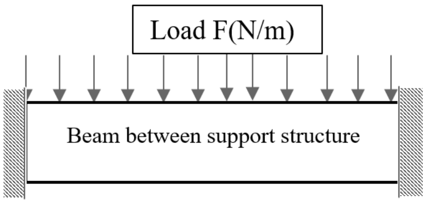

Figure 4.2: Theoretical model of the beam ring between the support structure.

Based on equation 3 - 9 in appendix C, the reaction force; moments at the center and ends; deflection of the beam; stress at the ends; shear stress; shear force; and Von mises stresses for the statically indeterminant beam is calculated. Based on this equations a knowledge database is created in the software. The parameters associated with the knowledge are defined by indicating the lower limit and upper limit, between which the solution to the problem is sought. Also, in the parameters a list of available IPE profile beams, either rectangular or I sections with corresponding moment of inertia can be added; and the beam selection can be made as user input. The knowledge, parameter, input output interface is as shown in the figure 1, 2 and 3 in appendix C.

4.5 Thermal model

The beam rests on a tight gasket of the oven wall. The rubber has operational maximum temperature of 200ºC, therefore the heat transfer from the retort wall to the beam should be less than 200ºC. The heat transfer model for the condensing retort is as shown in the figure 4.3. The heat equilibrium of the beam and support structure with atmosphere is given by the following equations.

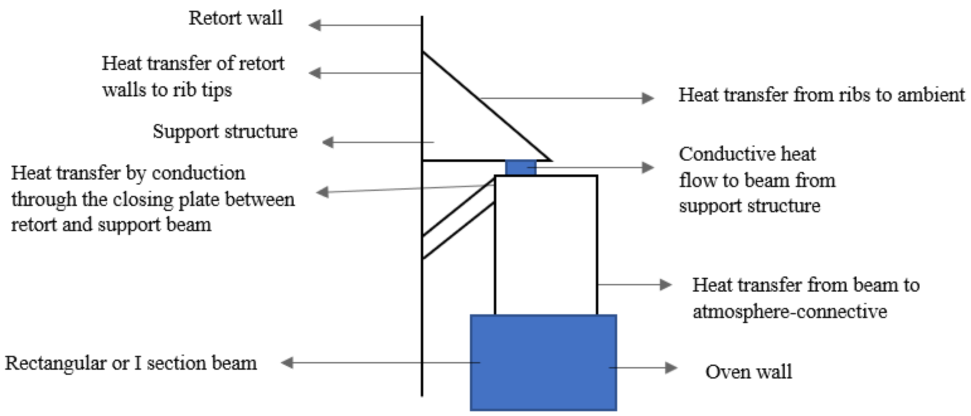

Figure 4.3: Heat transfer model of the beam and support structure

$$Q_{beam\ to\ ambient} = Q_{closing\ plate\ to\ beam} + Q_{ribs\ to\ beams} \quad \text{Eq 4.1}$$

$$Q_{beam\ to\ ambient} = Q_{closing\ plate\ to\ beam} + Q_{ribs\ to\ beams} \quad \text{Eq 4.2}$$

The detailed equations for the model is added in the appendix C. Based on these equations a knowledge base is created with relevant parameters. From these data, MrReves provides a range of possible solutions. The results are visualized in the software.

4.6 Results

The knowledge, parameter, input output interface is as shown in the figure 1,2 and 3 in appendix C. The following parameters are set to be defined by the user: type of beam required to be checked: either rectangular or I section beams; weight acting on the retort; gap between the retort wall and oven wall; the dimension of the beam from a list of IPE beams for which the deflection and stresses needs to be determined; selecting the material for the beam; and the heat transfer coefficient for the thermal model between the outer surface and the atmosphere.

Based on these input, a wide variety of solutions are obtained, this can be plotted with any other parameter used in the knowledge base. A few important results are shown in the figure 4.4. Therefore, it helps to understand the variation of all the parameters and hence validate the selected beam with minimum number of support structure. This model can be implemented while designing the commercial condensing retort technology.

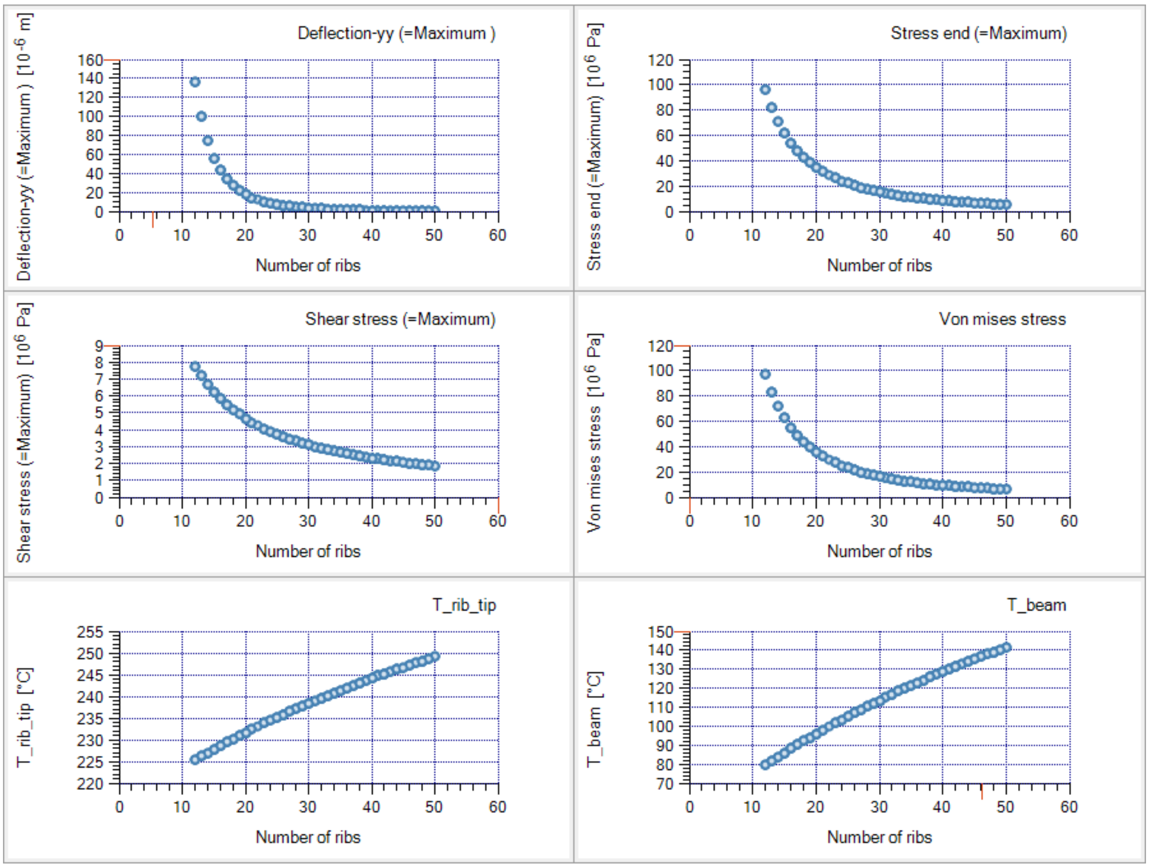

Figure 4.4: variation of different parameter as a function of number of support structure.

5. Conclusions and Recommendations

The experiments conducted at Clean Fuels, using the small scale and large scale experiment set up gave the following results. The oxygen free process gas cooling has a positive measurable effects in both the experiments compared to reference cooling.

The thermocouples drilled and glued to the charcoal lump helps to get better perspective of internal heat transfer due to charcoal particle conduction. From the natural cooling graphs, it is clear there is intraparticle heat transfer and forced cooling plots substantiate gas particle heat transfer.

Using the IBC tanks and forklift set up, accurate flow rates in the range 600-6000 l/hr is achieved and this set up proved to be satisfactory for the whole experiment, with very little water leakages through the hoses connections.

The oxygen concentration measured in the storage tank at the end of the experiments, indicated a less than 2% of oxygen, satisfying one of the objective of the experiment.

In the small scale set up, a linear approximation of the cooling rate resulted in 6.1ºC/min for external gas cooling, in comparison to 2.67ºC/min by natural cooling. However for the large set up a cooling rate of approximately 1.95ºC/min at bottom; 3.98 ºC/min at middle; and 3.6 ºC/min at the top was noted for forced cooling. Natural cooling resulted in a cooling rate of 0.46ºC/min at bottom; 0.77 ºC/min at center; and 0.29ºC/min at the top.

The large experiment, representing a column of charcoal in the true scale reactor, takes approximately 14hours for the 6.82 kg of charcoal to cool from 420ºC to 70ºC, without the influence of external gas. Therefore, this is equivalent to a cooling power of 47 W. However, the forced cooling approximately takes 5.2hours for cooling 5.9 kg of charcoal bed, from a temperature of 420ºC to 50ºC, using oxygen free gas as the cooling medium. This requires a cooling power of 118 W. Although the forced cooling requires 40% more power, concurrently it requires 37% less time than natural cooling.

The 11L charcoal container representing a part of the layer in the retort; used for small experiment. It requires approximately 63 W to cool 1.41 kg of charcoal from 450ºC to 50ºC, naturally. Whereas, forced cooling requires 120 W of power to cool 1.2 kg of charcoal from 450ºC to 70ºC. i.e., forced cooling takes 41% less time, but 52% more power than natural cooling. Also, the quantity of charcoal lost during the cooling cycles is negligible. Therefore, forced cooling of charcoal using process/oxygen-free gas saves enormous amount of time and this could lead to a faster rate of production.

The theoretical calculations predicts the cooling to be faster than the experimental results, this is due to the neglecting the effects of insulations and other losses to the surrounding, hence the theoretical calculations requires refinement. Although the experiment results are satisfactory, there are few drawbacks of the experiment set up, like: during the heating of the charcoal bed, the moisture in the charcoal, starts to condense in the cold pebble heat exchanger. This had to be taken into consideration and regularly directing it to the storage tank; The tanks and the valves had to be switched every 10 minutes for continuous flow of gas, for heating or cooling purpose; thermocouples and data acquisition system have inbuilt inaccuracy.

As the large scale experiment were performed in the last weeks of the internship, due to delay in building up the set-up and the time constraint of the internship. There was not sufficient time to assess the experimental results and translate it to the true scale set up. After internship, it was analyzed. The small set up represents a part of a layer of height 0.28m and 0.225m diameter, Considering a true reactor to have a diameter of 1 m and charcoal bed height of 1.25m. Therefore, 20 such small set up corresponds to the true scale. Each layer takes 1.2hr to cool from 450ºC to 70ºC. Hence a total time of 24hr is estimated for true scale set up. Similarly, the large set up has a diameter of 0.2m and an equivalent charcoal bed height of 1.25m. Hence it requires 5 such layer. Therefore a total duration of 26hr. Further, the time required for cooling the insulation, charcoal container material, effect of cooling from the surrounding environment are to be calculated, as this would not be present in the condensing retort.

The other assignment creating a knowledge base of the mechanical and thermal engineering model of the beams and the support structure for the commercial condensing retort technology was implemented successfully. The model predicts the minimum possible support structure for the selected beam, based on the mechanical and thermal limiting factors such as maximum allowable stress and the maximum operational temperature of the beam. Further, the model can be refined to incorporate more beams and material type selection.

6. Reflection of Internship

There were many tasks assigned during the term of internship, it included; developing an engineering model using Mr.Reves software, that helps in selecting a beam and support structure for commercial condensing retort reactor; build, perform and analyze two experiment set-up. The initial phase was challenging to fill the gap between theoretical knowledge and practical engineering tasks. As the projects came along I acquired more knowledge and became more familiar with the topic.

The design and building of the experimental set-up was interesting and challenging. It involved many labor works like: construction of the charcoal container for carrying out the experiment; fabrication of flow meter set-up; direction valves for flow control; insulation of the equipment from the atmosphere; and designing supporting structures for large experiment set-up. During the last month it was challenging to be working on multiple assignments. The large experiment was conducted in the last week of the internship and the experimental data were analyzed after the internship period.

During the internship I have had a great collaboration with my supervisor. He could steer me in the right direction and narrow down to the goals. Helped me focus on the most important tasks to achieve the right results. As well he was supportive the whole time and even after the internship when finishing my report.

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Appendix A

Figure 1:Charcoal container 11 liter

Figure 2: Charcoal container 40 liter

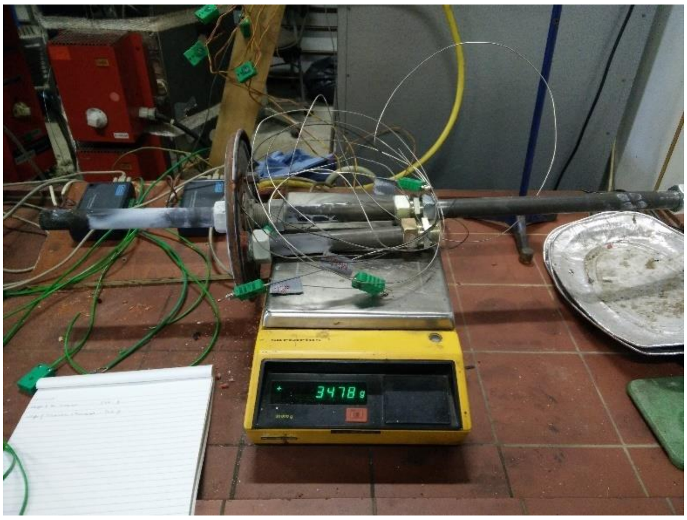

Figure 3 : Lid structure for small charcoal container

Figure 4: Pebble bed heat exchanger.

Figure 5: Two IBC storage container; forklift to lift the tank and cause the potential difference.

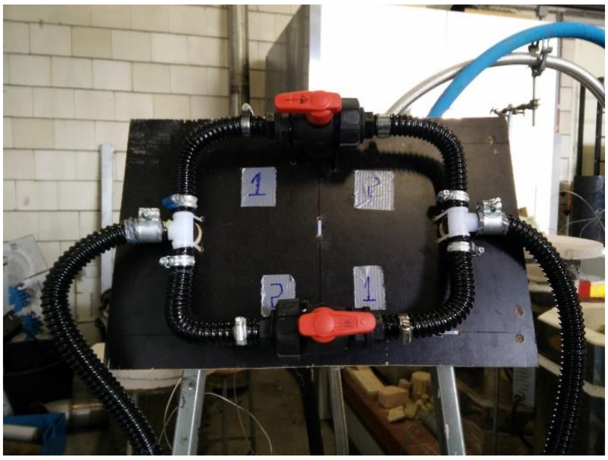

Figure 6: 2 way flow control valve.

Figure 7: Flow control measurement set up.

Figure 8: Radiation shields placed inside the electric oven during the cooling cycle.

Figure 9: Heating or cooling cycle control valve.

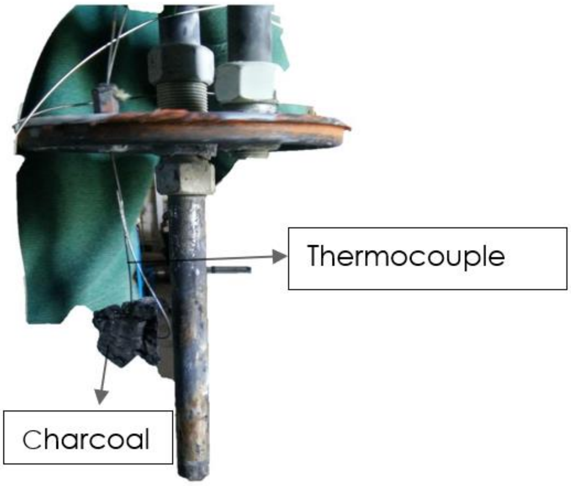

Figure 10: Charcoal drilled and glued to thermocouple.

Parameters		**Value**	**Units**
Cp charcoal		1.01	J/(g.K)
T_begin		450.00	c
Tend		70.00	C
Cp tin		0.42	J/(g.K)
cp steel		0.50	J/(g.K)
Cp thermowool		0.83	J/(g.K)
Cp gas		1.10	J/(g.K)
T_gas_begin		20.00	C
T_gas_out		450.00	C
Gas composition			
co2	44.00	0.20	8.80
n2	28.00	0.79	22.12
			30.92
n	40.34		mol/nm3
cp pebble		0.83	

Table 1: Constants used for calculations

Appendix B

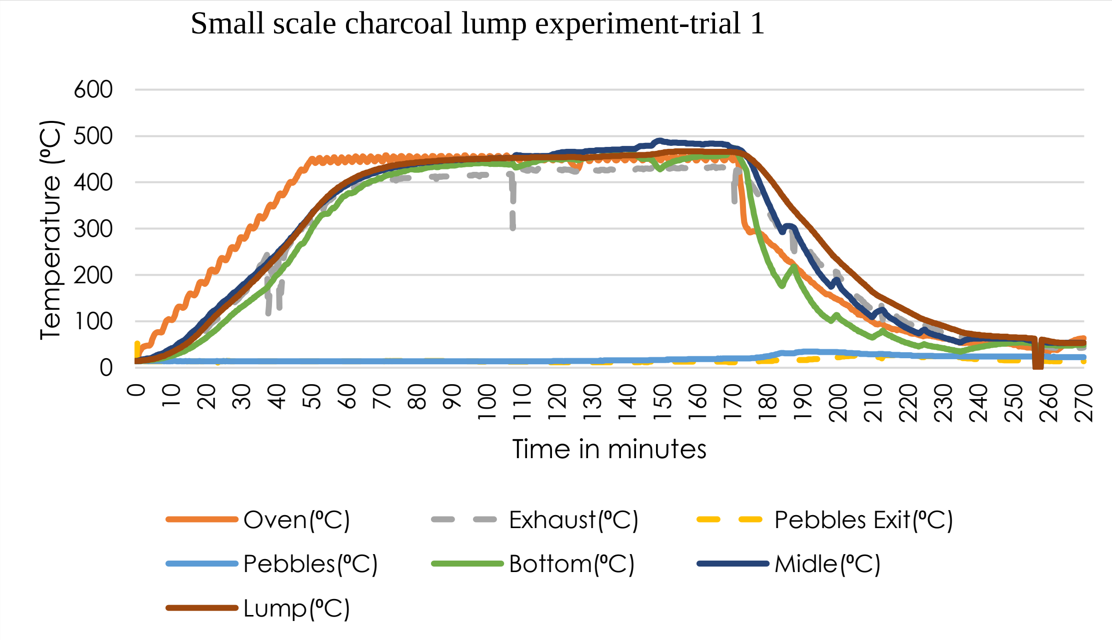

Figure 1: Complete plot of small scale lump experiment, trial 1.

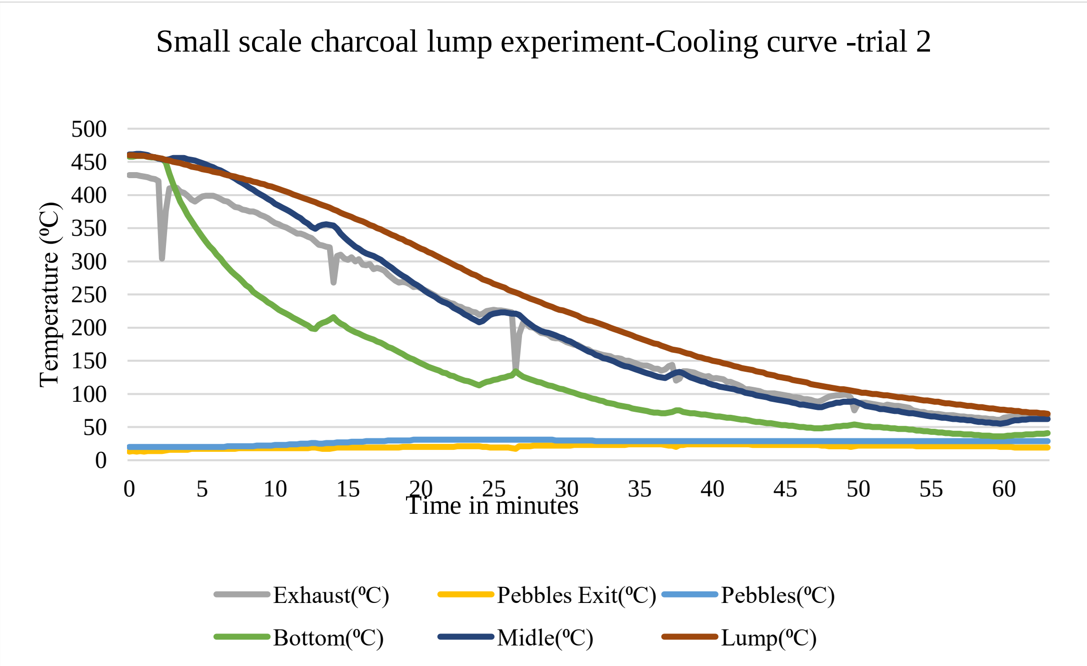

Figure 2: Trial 2 cooling curve of small scale experiment

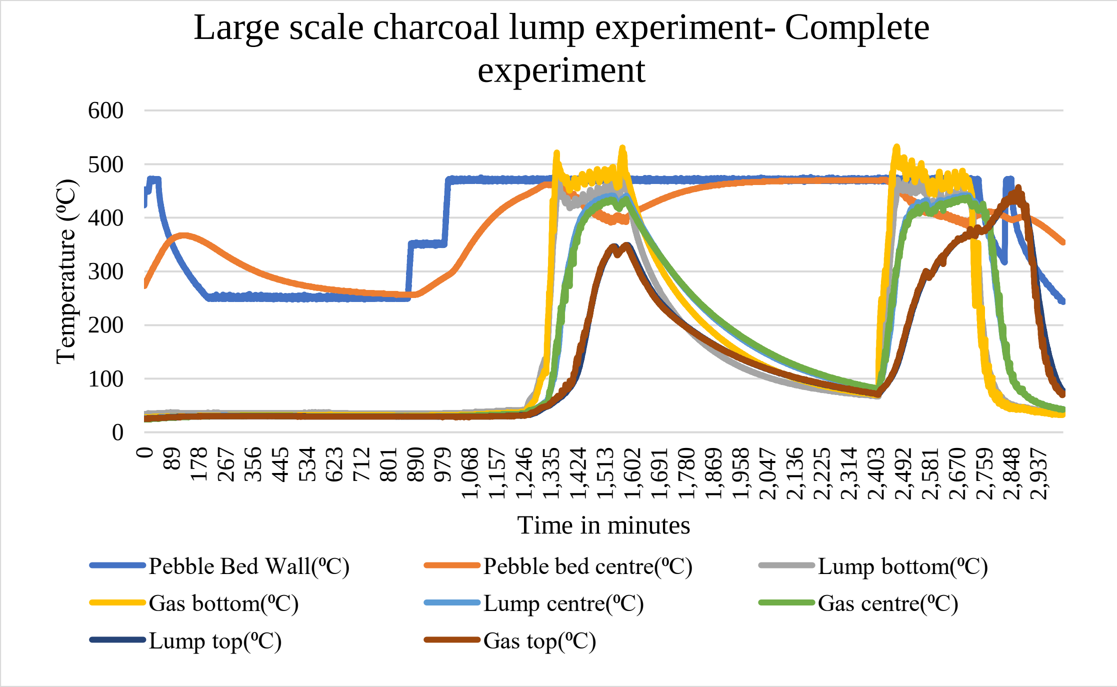

Figure 3: Large scale complete experiment plot.

Appendix C

Mechanical model equations

$$Load\ between\ two\ consecutive\ ribs = \frac{Weight\ of\ retort * acceleration\ due\ to\ gravity}{Circumference\ of\ the\ circular\ beam} \quad \text{Eq 1}$$

$$Length\ of\ the\ beam = \frac{Circumference\ of\ the\ beam\ ring}{Number\ of\ support\ structure} \quad \text{Eq 2}$$

$$Reaction\ force = \frac{Length\ of\ the\ beam *\ Load\ between\ two\ consecutive\ ribs}{2} \quad \text{Eq 3}$$

$$Moments\ at\ the\ beam\ ends = \frac{-\ Load\ between\ two\ consecutive\ ribs * (Length\ of\ the\ beam)^2}{12} \quad \text{Eq 4}$$

$$Moments\ at\ the\ beam\ center = \frac{Load\ between\ two\ consecutive\ ribs * (Length\ of\ the\ beam)^2}{24} \quad \text{Eq 5}$$

$$Deflectionof\ the\ beam = \frac{Load\ between\ two\ consecutive\ ribs * (Length\ of\ the\ beam)^4}{384 * Young's\ modulus * Moment\ of\ inertia\ along\ y\ axis} \quad \text{Eq 6}$$

$$Stress\ at\ the\ beam\ ends = \frac{-\ Moments\ at\ the\ beam\ ends * Height\ of\ the\ beam}{2 * Moment\ of\ inertia\ along\ y\ axis} \quad \text{Eq 7}$$

$$Maximum\ shear\ stress\ = \frac{Static\ moment\ of\ inertia * Shear\ force}{Moment\ of\ inertia\ along\ z\ axis * width\ at\ neutral\ axis} \quad \text{Eq 8}$$

$$Von - mises\ stress = \sqrt{(Stress\ at\ the\ beam\ ends)^2 + 3 * (Maximum\ shear\ stress\ )^2} \quad \text{Eq 9}$$

Thermal model equations

$$Convection\ heat\ transfer\ beam\ to\ ambient = outside\ surface\ area\ of\ the\ beam * Heat\ transfer\ coefficient\ surface\ to\ ambient * (Beam\ temperature - Ambient\ temperature) \quad \text{Eq 10}$$

$$Conduction\ heat\ transfer\ closing\ plate\ to\ beam = Conductivity\ of\ closing\ plate * cross\ section\ of\ closing\ plate * \frac{(Retort\ wall\ temperature - Beam\ temperature)}{Conduction\ distance\ closing\ plate} \quad \text{Eq 11}$$

$$Conduction\ heat\ transfer\ supporting\ structure\ to\ beams = Conductivity\ of\ ribs * cross\ section\ of\ ribs * \frac{(Rib\ tip\ temperature - Beam\ temperature)}{Contact\ height\ between\ the\ rib\ and\ beam} \quad \text{Eq 12}$$

$$\begin{aligned}\textit{Conduction heat transfer retort walls to supporting structure} \\ = \textit{Number of ribs} * \textit{Conductivity of ribs} * \textit{cross section of ribs} \\ * \frac{(\textit{Retort wall temperature} - \textit{Rib tip temperature})}{\textit{Contact height between the rib and beam}}\end{aligned} \qquad \text{Eq 13}$$

$$\begin{aligned}\textit{Convection heat transfer ribs to ambient} \\ = \textit{Number of ribs} * \textit{outside surface area of the rib} \\ * \textit{Heat transfer coefficient surface to ambient} * (\textit{rib tip temperature} \\ - \textit{Ambient temperature})\end{aligned} \qquad \text{Eq 14}$$

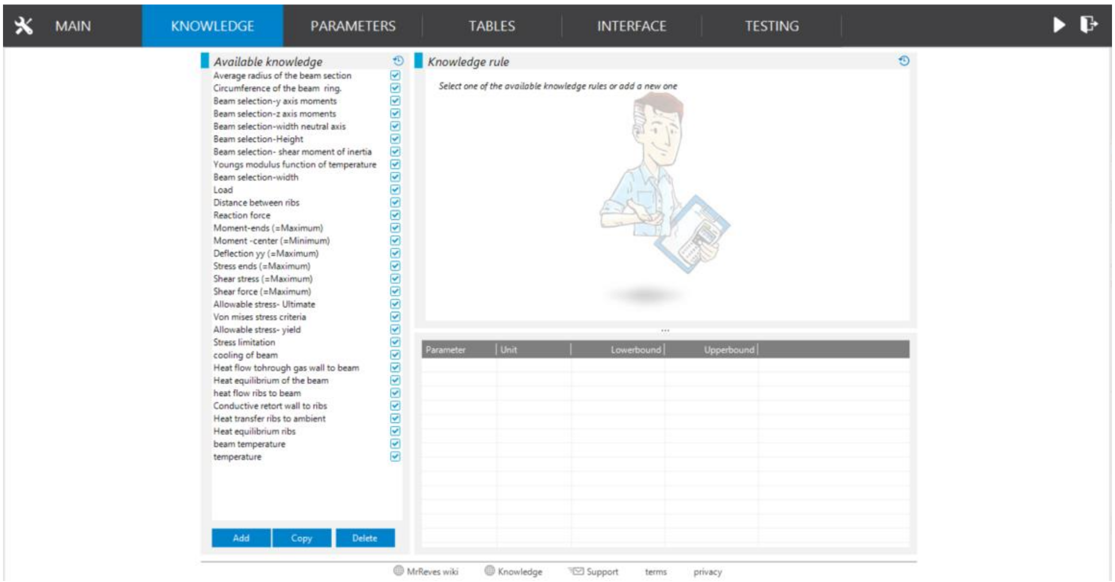

Figure 1: Knowledge data base window used for solving the mechanical and thermal analysis

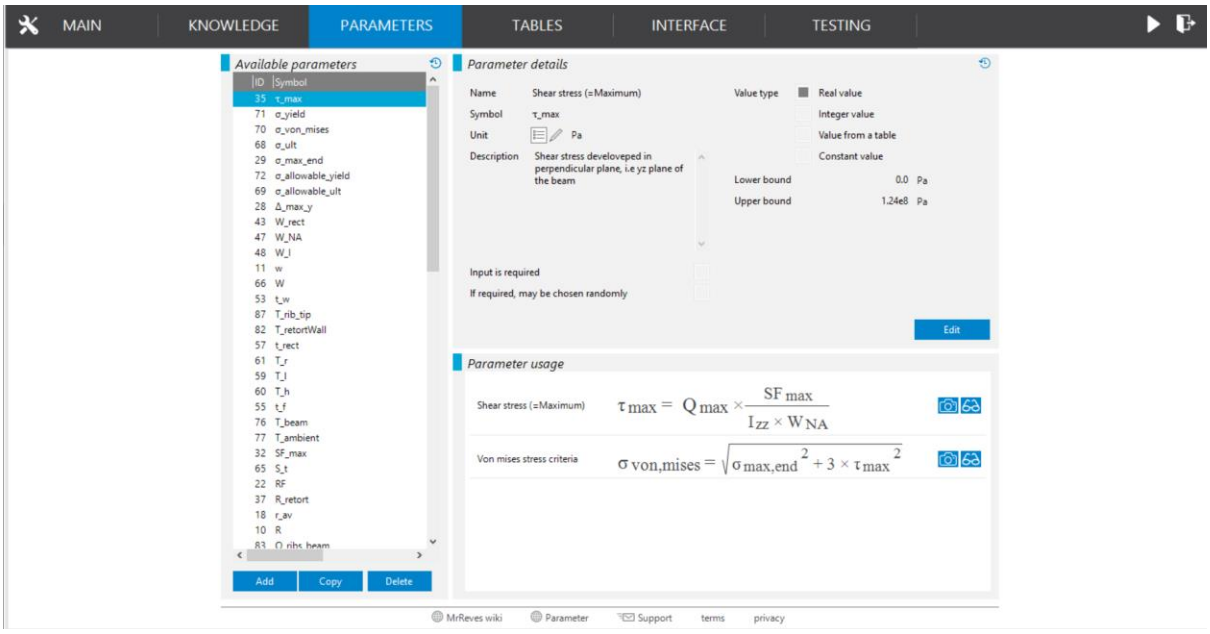

Figure 2: Parameters window

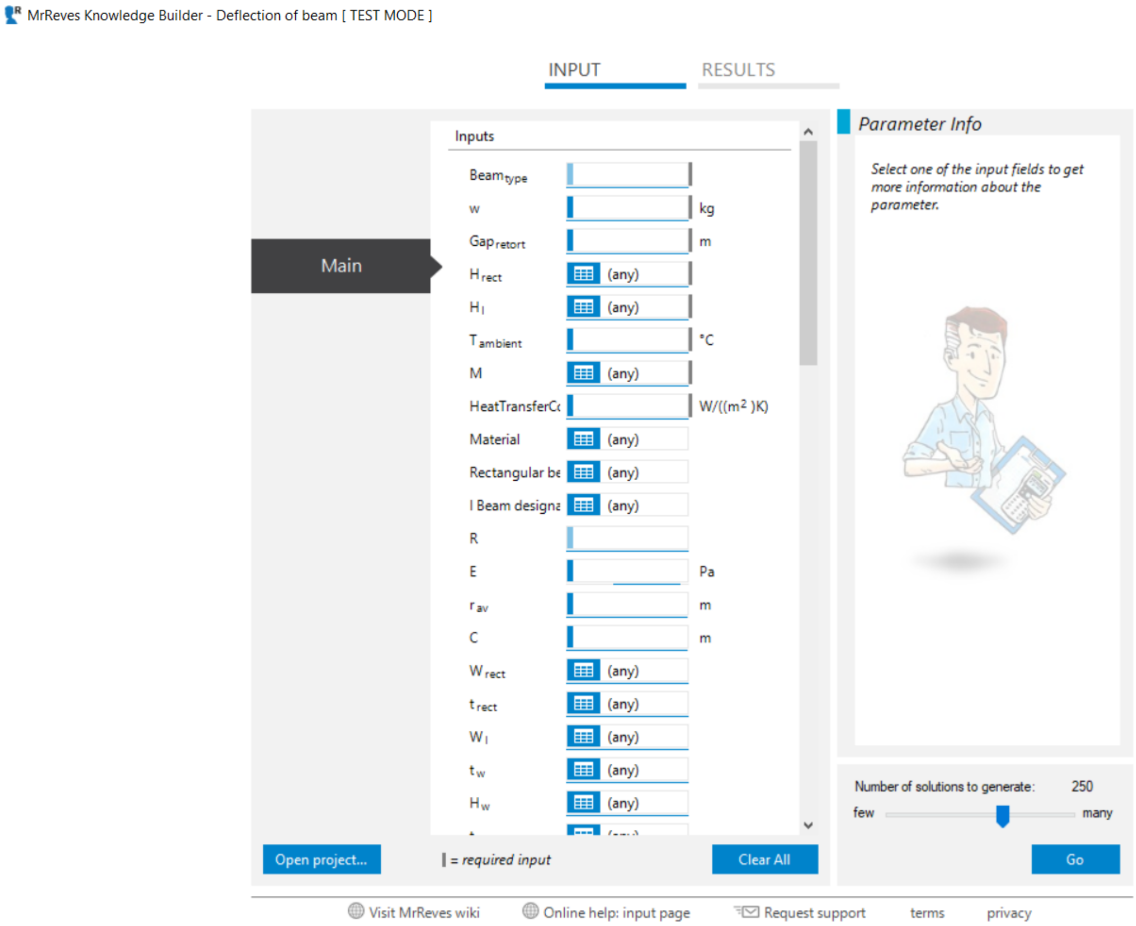

Figure 3: Input window of testing mode