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MSc Dissertation:
Design of a cooker working with short rotation coppice willow based on the rocket stove principle

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Project for Lammas Low Impact Initiatives Limited
Directed by Paul Wimbush
From an agreement with the Science Shops Wales Network

Dedication

I would like to thank my supervisor Dr. Roy Garwood for all his support and knowledge during this dissertation. He has always been helpful to listen to my suggestions and questions, offering his advice when necessary and taking the time to discuss my ideas. Without your help this dissertation would not be what it is.

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I would like to express my greatest gratitude to my parents Alain and Marion for encouraging and believing in me, to successfully finish my master degree in mechanical engineering. Without your dedication and encouragement I would have never made it through this stage of my life.

Thank you.

Declaration

I hereby declare that this dissertation is result of my independent investigation, except where I have indicated in indebtedness to other sources

Signed…………………………

Abstract

Lammas Low Impact Initiatives Limited is a community composed of nine families who desire to live in a sustainable energy environment, without using electricity or gas. Thus, they need to find a solution for their cooking facility and that is what this dissertation is dedicated to.

The aim is to develop a domestic-scale cooker which is run from short rotation coppice willow, designed on rocket stove principles.

The rocket stoves are some traditional improved wood burning stove. I t works based on some principles such as a uniform cross section all along a well-insulated combustion chamber.

The short rotation coppice willow is an energy bio-fuel which is plant in the Lammas village. The study of its combustion has lead to the determination of the amount of fuel required in order to have the desired cooking temperature.

The combination of the rocket stove principle, the domestic cooker technology and the use of bio-fuel has led to the development to a device that the community can use as an oven or as a hot plate.

By using the Computational Fluid Dynamics technology, the heat flow in the cooker has been analyzed and has provided an oven with a uniform temperature distribution as it is required for a good cooking.

The study of the materials has allowed to provide a good insulation by using ceramics clay on the outside, and a good cooking feature by using steel in order to conduct the heat to the oven and the hotplate.

With a good insulation and the use of a chimney, a flue pipe outlet that will carry away all smoke, a clean indoor environment has been maintained.

Thus, by combining safety and efficiency, the cooker proposed must lead to help the people of the community to build a cost-effective device which will help them in their everyday life.

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Introduction/Project description

The aim of this dissertation is to run a project from a group called Lammas Low Impact initiatives Limited which has been promoted by the Science Shop Wales Network. The topic of this paper is:
To develop a domestic-scale cooker which is run from short rotation coppice willow, designed on rocket stove principles.

This cooker will provide a range of domestic cooking options such as an oven and four cooker rings. It has to provide a flue pipe outlet that will carry away all smoke and provide a clean indoor environment for cooking. In fact, this project must produce a design similar to a standard domestic cooker as it has to be suitable for the use of a family in the kitchen. It has to be well insulated and safe to use. Thus, it has to enable a similar food cooking quality and quantity as a cooker available in the market.
Then, the cooker will run from short rotation coppice willow presented in the form of dry seasoned willow rods ranging from 5mm to 50mm in diameter that can be cut for any recommended length. These rods will be available next to the cooker, available for feeding into the cooker as appropriate. Lammas will be able to provide this fuel in 2012, the process of planting the willow has just been started. They have a need to develop technologies independent from fossil fuels.
The design will be based on the rocket stove principles, based on a super-insulated and low thermal mass cooker in order to reduce the need of biomass fuel.
Finally, the proposed design must be simple, replicable, functional and affordable.
In order to accomplish this project the following tasks will be carried out:

- An understanding of the background theories behind this project.

  Knowledge about the combustion, the using fuel, the rocket stove principles, and the cooker technology.

- A design of the cooker

  Use the theories to design a cooker that satisfy the requirements by choosing the appropriate materials, configurations and design strategy.

- An analysis of the proposed design

  Run analysis with Computational Fluid Dynamics tools and run experiments and testing to check the suitability of the design.

- A critical view on the design and results

  A discussion on the suitability of the project in terms of cost and efficiency.

- Production of the recommendation to build the cooker

  The dimensions and the materials for each part of the cooker.

Background study

Cooking technology

Rocket Stove

In Africa and other poor developing areas, about two billion people are cooking their food over open fires inside their homes. This practice can be dangerous because of gas emission and may not be as efficient as it could be. Thus, rocket stoves are more and more use in these countries. It works based on several principles studied in this chapter which provide a good efficiency while caring of the health and safety.
As a consequence, the improvement of stove, the rocket stove and the key to their success are studied.

Improvement of stove efficiency

The standard wood burning stove can be improved to be more efficient. In order to improve it, the heat transfer, the fuel and the combustion process have to be improved. The aim is to reduce the amount of fuel needed to cook, improving the heat transfer efficiency of energy from the fire to the cooking materials, reduces the amount of energy wasted and thus reducing the amount of wood required. Improving the efficiency of a stove thus requires attention to a number of different factors:

- Combustion efficiency: so that as much of the energy stored in the combustible as possible is released as heat.

- Heat transfer efficiency: so that as much of the heat generated as possible is actually transferred to the content of the pot. This includes conductive, convective, and radiation heat transfer processes.

- Control efficiency: so that only as much heat as is needed to cook the food is generated.

- Cooking process efficiency: so that as little energy as possible is used cause the physic-chemical changes occurring in cooking food.

In order to improve the cooking efficiency, the heat transfer has to be focused on. In fact, according to *Design principles for wood burning cook stoves:* “an open fire is often 90% efficient at the work of turning wood into energy. But only a small proportion, from 10 to 40%, of the released energy makes it to the pot.” In addition, according to *Biomass Stoves*

Engineering Design, Development, and Dissemination: “generally the largest loss, 14-42% of the input energy, is by heat conduction into and through the walls. In massive stoves most of this energy is stored in the wall.”. Thus, it can be seen that improving the combustion is important but even more important is to improve the heat transfer to the pot which leads in a large difference in cooking efficiency. In addition, improving heat transfer efficiency can significantly reduce fuel use.

Heat transfer and stove efficiency

The heat transfer efficiency are discussed first in terms of conductive, convective, and radiation processes going on in and around the stove. These processes are explained based on information from *Biomass Stoves Engineering Design, Development, and Dissemination*:

First the conduction is based on the principle that the faster they are moving the hotter the substance is. In gases, conductive heat transfer occurs when high velocity molecules randomly are in collision with slower particles, giving up some of their energy. This way, heat is gradually transferred from region of higher temperature to those at lower temperatures. An important factor in conductive heat transfer calculations is the ability of a material to store thermal energy, measured as its specific heat. The specific heat of a material is the amount of energy required to raise the temperature of 1kg of its mass by 1°C.

$dE = M.Cp.(dT)$

M is the object mass

Cp is its specific heat

dT is its change in temperature.

Thus, the thermal conductivity carries thermal energy through a material, the specific heat and mass of an object store this heat energy. The larger the mass and specific heat of an object the more energy it can store for a given change in temperature. Consequently, a thermally massive object (large MCp) warms up slowly and a thermally lightweight (small MCp) object will warm rapidly. This is called the thermal inertia of an object and this is an important parameter in the stoves. Reducing the heat loss into and through the stove walls to the outside requires a detailed analysis of the conduction process.

As it is not interesting in term of efficiency to lose energy, the heat recuperation is looking for. Retained energy is mostly lost, so retained energy in a stove doesn’t helps it to cook the food. The heat lost through the stove wall could be used to cook. This will be accomplish by choosing the appropriate material.

It is by convective heat transfer that the hot gas leaving the fire heats the pot. Convective heat transfer occurs when a gas is forced or flows naturally into a region at a different temperature and then exchanges heat energy by conduction, by the interaction of individual particles. Increasing convective heat transfer to the pot is the best way to increase the thermal efficiency of a wood burning stove. Convective heat transfer follows the equation:

$Q= hA(T_1-T_2)$

Q is the heat transfer from the gas to the pot

H convective heat transfer coefficient

A area where is the heat exchange

T_1-T_2 temperature difference between the hot gas and the pot.

To increase the heat transfer Q to the pot there are then, three things one can do. First, the temperature T_1 of the hot gas can be increased. This can be done only by closing the stove and controlling the amount of outside air that enters. Second, as much as the area A of the pot should be exposed to the hot gas as possible. The pot support should be kept small in area so as not to screen the hot gas from the pot. The gas should be allowed to rise up around the pot and contact its entire surface. Third, the convective heat transfer coefficient should be increased by increasing the velocity of the hot gas as it blows past the pot. The flow velocity of a hot gas over the pot is increased by narrowing the channel gap through which the gas must flow past the pot. In fact, the volume of hot gas flowing past any point is constant, its flow velocity through a narrow gap must be faster than through a wider one.

Then, the last heat transfer processes is the radiation. All objects materials continuously emit electromagnetic radiation. The higher the object's temperature, the greater the amount of energy so radiated. Similarly all objects absorb radiation. The ability of a specific material to absorb radiation is equal to its ability to emit it. By closing the firebox and controlling the air supply the average firebed temperature is increased.

As a consequence, the keys to improve the efficiency, based on *Design principles for wood burning cook stoves*:

- To increase the temperature of the gas contacting the pot, having the hot air scrape against both the bottom and sides of the pot in narrow channel, using a pot skirt.

- To increase the speed of the hot flue gases the scrape against the pot.

- To use metal rather than clay pots because metal conducts heat better than clay

- That the size of the fire determines the size of the channel gap in the pot skirt and the maximum efficiency of heat transfer.

- To use wide pots with large diameters. Using a wide pot creates more surface area to increase the transfer of heat.

- To make the fire bed, combustion chamber, closed

The Rocket Stove design principles

Thanks to the knowledge in heat transfer and the way to improve the efficiency of the stove, design principles have been found. In fact, the rocket stove is based on a set of principles that can be applied to any number of different materials and configurations for cook stoves. These principles can be summarized with the Ten Design Principles from Dr. Larry Winiarki based on *Design principles for wood burning cook stoves*:

1 Whenever possible, insulate around the fire using lightweight, heat resistant materials. Insulation should be light and full of small pockets of air. Lightweight refractory brick, loose insulation can surround this type of construction.

2 Place an insulated short chimney right above the fire. The combustion chamber chimney should be about three times taller than its diameter. The very tall combustion chamber chimney can develop too much draft bringing in too cold air that will decrease heat transfer.
3 Heat and burn the tips of the sticks as they enter in the fire. If only wood that is burning is hot there will be much less smoke. Try to keep the rest of the stick cold enough that it does not smolder and make smoke. The goal is to make the proper amount of gas that it can be cleanly burned without making smoke. Smoke is un-burnt gas.
4 High and low heat are created by how many sticks are pushed into the fire. Adjust the amount of gas made and fire created to suit the cooking task.
5 Maintain a good fast draft through the burning fuel. Having the proper amount of draft will help to keep high temperatures in your stove. A hot fire is a clean fire.
6 Too little draft being pulled into the fire will result in smoke and excess charcoal. But too much air just cools the fire and is not helpful. Smaller openings into the fire help to reduce excess air.
7 The opening into the fire, the size of the spaces within the stove through which hot air flows, and the chimney should all be about the same size. This called maintaining constant cross section area. Good draft not only keeps the fire hot, it is also essential so that the hot air created by the fire can effectively transfer its heat into the pot. As a general rule, a door into the fire with a square opening of twelve centimeters per side and equally sized chimney and tunnels in the stove will result in a fire suited to family cooking.
8 Use a grate under the fire. Do not put the sticks on the floor of the combustion chamber. Air needs to pass under the burning sticks, up through the charcoal and into the fire. A shelf in the stove opening also lifts up sticks so air can pass underneath them. When burning sticks, it is best to have them close together and flat on the shelf, with an air space in between each stick.
Air that passes above the sticks is not as helpful because it is colder and cools the fire. A hot raging fire is clean, but a cold fire can be very dirty.
9 Insulate the heat flow path. Cooks tends to like stoves that boil water quickly. If heat goes into the body of the stove, the pot boils less quickly. Using insulative materials in the stove keeps the flue gases hot so that they can more effectively heat the pan. Insulation is full of air holes and is very light.
10 Maximize heat transfer to the pot with properly sized gaps. Getting heat into pots or griddles is best done with small channels. The hot flue gases from the fire are forced through these narrow channels, or gaps, where it is forced to scrape against the pot. The two most important factors for getting large amounts of heat into a pot or griddle are, keep the flue gases that touch the pot as hot as possible, force the hot gases to scrape against the surface quickly, not slowly. Air does not hold much heat. The size of the channel can be estimated by keeping the cross sectional area constant throughout the stove."

In fact, a well constructed rocket stove will allow for air to circulate. The chimney, the combustion chamber and the skirt gap should all have the same cross-sectional area. An excellent air circulation is a key to the success in the design efficiency. A shelf should provide for the fuel so that the air circulates all around the fuel. The chimney should be short, reaching just above the cook pot which allows for hot gasses to flow more rapidly through the system.

For improved efficiency, insulation will be provide around the chamber to improve the efficiency by using the radiation in the combustion chamber

Materials and stove efficiency

As previously said, insulation is one of the key of the design of an efficient stove. Good insulations slow down the passage of heat. Dense materials absorb energy rather quickly while insulation slows the passage of heat. Good insulation is made up of little pocket of air separated from the other tiny pockets of air by a lightweight relatively non-conductive material. In fact, air is very light and cannot absorb and hold a lot of thermal units of heat. Insulation is light and airy.

Another important factor to select the appropriate material is the thermal mass. Placing materials with high thermal mass near the fire can have a negative effect on the responsiveness, fuel efficiency, and emissions of a cooking stove because they absorb the heat from the fire.

Then the material has to be resistant. In fact, a clean burning stove can produce such high temperatures in the combustion chamber that metal, even stainless steel, can be destroyed. One of the common materials used in stove technology is the ceramic which can withstand very high temperatures such as temperatures that range from 1,000°C to 1,600°C. The drawback of the ceramic is its high thermal mass, in order to face it; the least amount possible without compromising its strength is used by surrounding it with an insulation material. In addition, several treatment can be accomplish to reduce the heat loss due to the emission of radiant energy by chemically or mechanically polishing or coating the exterior surface to leave a bright metallic finish. It can be also noticed that most paints will actually increase the radiant heat loss from a stove and should be avoided, that is why the surface must be metallic. Then, double wall can serve for two functions in reducing the heat loss. First, the dead air space between the two walls is moderately good insulator. It should be noted, however, that increasing the thickness of this dead air space does not improve its insulating value. This is due to the convection currents, which flow more freely the larger the space, carrying heat from one wall to another. Second, the inner wall acts as a radiation shield between the fire and the outer wall. On the other hand, this presents difficulty. In fact, the dead air space is a good insulator on its own but attaching the inner wall to the outer will tend to short circuit its insulating value due to the high thermal conductivity of metal. It is necessary that the two walls together be mechanically rigid, but they should not easily conduct the heat from one to the other.

By studying what have been done in poor countries in design of rocket stoves, it seems like the use of recycled materials is possible and provide efficient systems.

Emissions

Just as the reduction of the fuel consumption, the reduction of negative emissions of the stove is a main task for the designer. According to the World Health Organisation, up to 1.6 million women and children die every year from breathing polluted air in their houses. Pneumonia, lung cancer, bronchitis, asthma and other respiratory diseases in children are caused by breathing smoke. That is why the fire has to be clean up. This function can be accomplished with a well engineered cooking stove design. By improving the combustion efficiency, the smoke and harmful emissions that damage health are reduced. One of the key is to meter the sticks of wood into the combustion chamber to make a hot, fierce, jumpy looking fire. This type of fire makes less dangerous emissions.

As with the combustion of any fuel, there will be emissions to air. The emissions produce by this cooker will be from the combustion of the SRC willow which is the using fuel. According to *Good practice guidelines short rotation coppice for energy production* the principal emissions that could arise from the plant are:

"Particulate: tiny particles in the flue gas, which would be minimized by pollution abatement equipment and good combustion control.

Carbon monoxide: burning fuel in an oxygen rich environment, with good fuel and air distribution keeps carbon monoxide emissions to a minimum.

Carbon dioxide: CO_2 is a greenhouse gas. One of the principal environmental benefits of SRC as a fuel is that it is carbon neutral. Any CO_2 emitted will be compensated by the CO_2 fixed by the growing trees planted for fuel. The fuel cycle is neutral over a cropping period of two to five years.

Sulphur dioxide: The sulphur content of wood is 0.1% by weight, compared with UK coal which typically contains 0.8-1% sulphur.

Organics: SRC is not likely to be a major source of toxic organic substances such as PAHs, dioxins and furans, which are produced a a result of many combustion processes. Controlled burning of SRC and use of appropriate pollution abatement equipment will keep these to a minimum.

Nitrogen oxides: wood has small inherent nitrogen content, typically 0.1% by weight for willow SRC, compared with coal which is typically 1%: so using SRC is likely to result in lower emissions.

Water in the form of vapour will also be emitted. The water vapour will form the visual effect of plume but has minimal pollution implications."

Thus the aim is to produce a smokeless wood fuelled cooker.

Health and safety

Developing a domestic cooking device, some safety parameter of the daily life have to be taken in account. Injuries from fire are a major problem that stoves can remedy. Burns are quite common in homes using fire and can be fatal. Preventing burns is quite possibly one of the most important functions of an improved stove. Stoves pot should be stable. Surround the fire with the stove body so that children cannot burn.

Also, a clean fire is an efficient source of heat, so the ash produce by the combustion of the willow should be removed. Thus, in the cooker design a system to do that must be set.

Chimney

To face these problems of emission in the indoor environment a chimney can be used. In fact, it is always best practice to add a chimney to any wood burning cooking stove. Chimney that can take smoke and other emissions out of the living space protect the family by reducing exposure to pollutants and health risks. In fact, even cleaner burning stoves without a chimney can create unhealthy levels of indoor air pollution. Placing an insulated short chimney above the fire helps to increase draft and gives smoke, air and fires a place to combine, reducing emissions.

Testing

In most of engineering development tests are the best way to evaluate the efficiency of a system or to make sure that what is suppose to be in theory is working as it is expected. So testing is essential to rocket stove projects. In fact, without proper testing, stove program will have an unrealistic expectation of the efficiency. There are two types of testing used for stoves. Finding how long it would take to boil water and how much wood is used. Ashes inspection in order to determine if the wood was fully combusted must occur.
"1-We boiled water from a cold start and from a hot start. Hot start means that we started the test when there was already wood burning. The starting temperature for the water was sixty three degrees. 2- We maintained a boil for 30 minutes. We did not start the clock until all of the wood that initially brought the water to a boil had burned out. This gave us more accurate results."

Temperature Control

A good cooker is able to have different temperatures in order to cook the food as the user desires. In fact, people using the cooker might want just to simmer the food or in the other case to cook it with some more heat power. As advice previously as a key to improve the efficiency of the stove, a channel gap in the pot skirt is used. In fact, stoves have to use gaps that are large enough to support the airflow at high power. On the other hand, much less firepower is required to simmer food. But the efficiency of heat transfer suffers because the channels are larger than needed at this reduced rate of flow. That is why without adjustable gaps, stoves tend to display better heat transfer efficiency at high power. As a consequence, the pot skirt with adjustable gaps solves this problem a temperature of cooking variation.

The project

Most of the information provide previously are for the use of one rocket stove, with only one pot. But this project deals with the design of a complete domestic cooker, with a oven and preferably four cooking rings stove. In order to be successful in this project the rocket stove principle of design and all the parameter that make this technology efficient have to be adapt for a more complete cooker.

What is it available on the market?

In order to have an idea of what have already been accomplished in this type of project, similar cooking stoves available in the market are looking for.
The first and the most classic one is the wood burning stove. Most of these devices found are used as the heater stove for a room or house, but it can be used as a cooking facility by adding a grill on top of the flame in order to cook food. In fact, this technique has been improved to produce something more similar than a real cooker by using the location above the flame where the temperature is maximum; an oven has been set, as can be seen on the following image.

Model FM small woodburning or solid fuel with oven by PRITY fireplaces from www.roof-solutions.co.uk

The energy output is 12kW. The designer had the idea to incorporate a wood store in the device in order to have the fuel accessible. In addition, a drawer underneath the stove is noticed; it must be to remove the ashes produced by the combustion.

As a consequence, for the cooker design in this project it would be interesting to have a fuel store and a device to remove the ashes as well.

Another type of cooker available on the market and that can inspire this project is the AGA cookers. In fact, by using the principle of heat storage and the combination of heat source, two large hotplates and two ovens into one unit, the AGA Cooker has been created. Three main models of AGA are currently in production: two, three and four oven versions, with the four oven version wider than the others. The two oven model has three doors behind which are the burner, roasting oven and simmering oven. All models have two hotplates, one as a boiling plate and the other one used as a simmering plate. This cooker offer different fuel options such as kerosene, diesel, bio-fuel, gas or electricity.

Two ovens, two hotplates AGA cooker, 30-amp AGA from www.aga-web.co.uk

The possibility to use different fuel that offer this AGA Cooker is a very good feature but not really interesting for this project as the client specify that he wants his cooker to work with willow. But its ability to deal with different cooking techniques, roasting, simmering… should be something that the cooker which is developed must be able to do.

Then, it has been found that a few brands (KVS, Wamsler…) produce cooker similar to the one which has to be develop in this project, wood burning cooker similar to standard domestic apparel.
The “KVS 9100 wood cooker stove” available from www.stovesonline.co.uk is presented :

Image of the KVS 9100 wood cooker stove from www.stovesonline.co.uk

As can be seen on the picture, the cooker disposes of an oven a cooking area to heat pots and pans. Thanks to a handy baffle the flue gases can be directed either to heat the large hob, or the oven. But when the flue gases are directed around the oven the section of hob above the firebox will still be hot so it is possible to cook on the top too. The system used to choose which part of the cooker is use is described in the web site : « This baffle system is controlled by a slider on the top and at the back of the wood burning stove: pull the slider forward to favour the hob, back to favour the oven. ». This product is sold at about £1500 and can produce heat between 6 and 10kW.

The overall cooker size is 850mm height, 810mm width and 600mm depth. The oven size is 294mm height, 400mm width and 482mm depth. The average wood consumption is 3.5kg/hour. The stove is mostly made of steel.

Thus, a first idea of what the project should look like has been found.

Some people have used this device and had found some problem. In fact, according to *www.ecodiy.org*: "We have had some problems getting the oven hot enough. We find the top of the oven is easy to get hot and have put a steel shelf half way up the oven to make the top half hotter, good enough for bread etc. To get the whole oven really hot means burning the stove for at least an hour at full heat, the top plate gives out lots of heat if you do that. I am planning to make an insulated lid to keep the top heat in when we are using the oven." Thus, in the design, this point should required attention in order to produce a better product. The insulation of the oven cavity have to be focused on.

Cooker and cooking theory

To produce an efficient cooking device, it is essential to know how standard cooker works. A stove that is capable to deal with every culinary technique easily such as burner, roasting oven, simmering oven and baking oven. In fact, in order to be able to produce a cooker which cooks the food properly it is important to have knowledge in terms of cooking theory. Cooking can be defined as the preparation of food for human consumption. It involves in heating ingredients to change their structure and taste, to make them more digestible sometime.

Thus, the physics involved with heating food is studied. First, the use of cooking rings or hot plate is analyzed followed by the oven.

Hot plate

When food is heated, there is an attempt to bring the food and the source of the heat into a thermal equilibrium. When a pot of water is placed on the stove to heat, heat flow is caused from the burner to the water. Thermal equilibrium is never reached because, while the burner is turned on, energy is continually added to the burner. In addition, the burner is always going to be hotter than the water, which cannot exceed its boiling point.

Again the heat transfer plays an important role in the cooking process. In fact, according to *hertzmann.com*, the burner transfers heat to the pot, which in turn transfers heat to the water. Heat transfer rules the process whereby energy flows from the burner and eventually to the water. If the burner is an electric coil, most of the heat is transferred by means of conduction. The heat is conducted from the burner to the pot at the points where the two are in direct contact. Then, there are some radiation transfers, because the burner is sending energy in all directions, some of the energy directed downward is reflected by the metal surface below the burner, the reflector, up between the spaces of the burner coil to the bottom of the pot. Finally, as the air between the burner and the reflector is hot, there is a small contribution to the heating of our pot by convection.

If the burner is gas, like the one developed in this project with heated air, most of the heat transfer is by means of convection where the burning, high temperature gas flows along the bottom of our pot.

Then, ceramic is a common material in the cooking. If this material is used as a cooking surface, heat transfer is mainly by means of conduction. But because pots tend not to be perfectly flat on the bottom, especially after some use, the pot is only in partial contact with the ceramic surface. In the narrow air spaces between the two where there is no contact, radiation and convection contribute to the heat transfer.

As a common practice, water is used to cook some ingredient. In fact, if water is being cooked, the water at the bottom will be warmer than at the top. Also, the sides of the pot will heat up, but not as hot as its base, because they are not directly affected by the burner and depend upon the energy conducted through the metal for heat.

In almost all cooking, either a liquid or gas is used as a heat transfer agent.

When cooking in a water-based liquid, such as braising, boiling, or poaching, the cooking is done at or below the boiling point. Because the temperature of liquid water cannot exceed 100 °C, no matter how much heat is applied to the outside of the cooking pot, the temperature of the cooking liquid and anything in it will never be hotter.

Then, poaching is usually done with a water-based liquid maintained at a constant temperature below the boiling point.

In the braising of tough meat, the goal is to slowly raise its internal temperature to a point where the connective tissue begins to dissolve. Whether done in the oven or on the stovetop, the meat is at least partially submerged in the water-based braising liquid so it never sees high temperatures.

People in their cooking are also interested in eliminate fats. In fact, most fats begin to smoke at a temperature in excess of 150 °C and have much higher boiling points. This means that the cooker must be able to reach these temperatures.

As stated earlier, the base of the pot will be hotter than the sides because it is in contact with the heat source. Consequently, the shape of the pot can be a factor in how an ingredient cooks.

As can be noticed from the previous discussion, cooking involves often in immersing the food to be cooked in the heat transfer agent, either a gas or a liquid. But it is also interesting to know what happen when food is cooked with only a small amount of a heat transfer agent, a process usually called frying. If food is placed on a frying pan over a burner, with the addition of a little oil or some other fat to the pan, a piece of meat in the frying pan is placed, there are a couple of heat transfer processes taking place. The meat that is in direct contact with the surface of the pan is being heated by means of conduction. The portion of meat that is in contact with the oil is being heated by means of convection.

But if the food to be cooked does not contain fat, such as most vegetables, then it will be difficult to evenly cook the food because the heat transfer will have to be mostly by conduction, where the food is in direct contact with the surface of the pan.

As it has been said, it is important to have some heat transfer agent to transfer energy from the heat source to the food being cooked. In addition, the heat must also travel to the center of the food in order to cook it throughout.

High-heat methods will cook food faster than low-heat methods, but they will also produce a greater difference between the temperature at the surface and the temperature at the center.

Oven

Now, the use of oven has to be studied. Previously, cooking food immersed in a liquid heat transfer agent has been discussed. Oven cooking is very similar, with the ingredients open to the air in the oven. Much of the energy comes from the air flowing around the ingredients. With an oven, instead of being immersed in a hot liquid, the ingredients are immersed in hot gas.

The ingredients generally require some means of support in an oven, such as a baking sheet or roasting pan, the support mechanism is also heated during the cooking process. Over time, the support can heat to near the temperature of the oven. As a consequence, the parts of the food being cooked that are in contact with the support mechanism become more cooked than the parts which are not in contact. In fact, conduction is a more effective way to transfer heat than convection.

- Convection cooking equipment

As it has been said in the previous part, there is a small contribution of heat transferred by convection in the cooking physiques. But by looking for the different type of cooker available, it has been found that there is “convection cooking equipment”.

In fact, according to *progress-energy.com*, the term convection refers to the process in which heat is transferred by the movement of a fluid, typically air or steam in cooker. In conventional cooking equipment, the convective effect is slow and inefficient. Thus, convection oven uses a fan to induce a rapid circulation of the heated air to eliminate the envelope of cold air surrounding the food and to distribute the heat evenly throughout the entire oven cavity. The speed with which food can be cooked by convective heat depends on how rapidly the fluid flows across its surface and the fluid's temperature. In fact, cold or partially frozen food is surrounded by a thin layer of cold, slow-moving air, which in effect insulates the food, slowing the cooking process. Then, by forcing the convection cooking technique this problem is solve by creating a very rapid convective flow that blows away the envelope of cold air surrounding the food. Thus, by eliminating the cold air envelope and enhancing the convective heat transfer, cooking times and energy requirements are reduced. In fact, if the four pies cooked in the standard oven took 60 minutes to cook and 4,000 BTUs of heat per pie, they would take 45 minutes and approximately 1,700 BTUs per pie in a convection oven.

- Heat distribution in an oven

Then, as the developed cooker is a domestic type of cooker, there is an oven, so it is important to know what the usual dimensions are and how the heat is distributed inside this equipment. Usually oven in the commerce employ baking and roasting ovens that have a chamber or oven cavity large enough to receive multiple layers of food product to be cooked at the same time. Typical ovens may have provision for up to 8 cake or food trays each measuring 18 by 26 inches.

Convection ovens are equipped with fans capable of moving heated air throughout the cooking chamber at various velocities. These ovens are designed to provide a rapid distribution of heated air over food products which have been placed on pans stacked one above the other. Thus, in general in oven the distribution of heated air must be uniform.

- Domestic oven

In domestic oven, one of the tasks is to make sure that excessive amount of smoke is created. Then, to utilize sources of heat that are properly distributed throughout the oven and which represent a low energy consumed in order to have a good heat cleaning cycle A smoke eliminator can be provide on the top wall of the oven for acting upon the smoke filled oven air before it is exhausted into the room.

In electric domestic oven, the source of heat is divided into three heating elements, a lower bake unit positioned adjacent a bottom wall of the bottom wall of the oven liner. Then, there is an upper broil unit position adjacent of the top wall, it is provide with a downward pan like reflector which overlies the broil unit and protects the upper wall of the oven liner from excessive heat and direct the most of the heat toward the interior of the oven cavity. The third heating element is a mullion heater that is wrapped around the outer surface of the oven liner adjacent the door opening for compensating heat lost through and around the door so that substantially uniform oven wall temperature can be maintained during the heat cleaning cycle. During the broiling operation only the broil unit is energized and it is operated at rated wattage, 3000Watts for example. In addition, the bake and broil unit wattages are substantially equal and the mullion heater is about one half of it.

From this study, important points which will affect the design have been noticed:

- Uniform heat distribution
- Elimination of smoke
- Fast heat circulation
- Heat source on both sides of the oven
- Heat must be conduct through the shelf supporting the food in the oven

Energy supply

Fuel and heat generation

This part is focus on the fuel used in the developing cooker, the short rotation coppice (SRC) willow. Fuel is defined as "combustible matter used to maintain fire, as coal, wood, oil, or gas, in order to create heat or power" according to *dictionary.com*. This fuel is used as a combustible which is defined as a material able to burn by combustion and create heat.
The fuel characteristics are analyzed in order to be able to optimize its used.

Fossil fuels

Fossil fuels or mineral fuels are fuels formed by natural resources they are aged of more than hundred millions years and they contain a high percentage in carbon and hydrocarbon. They are considerate as non-renewable resources because they take millions of years to form. Their content in carbon is a problem because Carbon dioxide is one of the greenhouse gases that contribute to the global warming, which rises the average temperature of the Earth. As example of fossil fuels, there is coal, petroleum, oil or diesel.
In order to reduce these bad effects of pollution by the fossil fuels, another type of fuel can be used, the biomass.

Biomass

Biomass is the oldest energy sources in the world; it is also the most well-established. Biomass can be defined as the conversion of stored energy in plants into some energy that we can use.
Biomasses are different than fossil fuels. In fact, first they do not have the same properties. According to *Energy from Biomass*: "A major difference is the high content of volatile matter in biomass materials (up to 80 percent), whereas coal has less than 20 percent (anthracite coal sometimes even has a negligible volatile content." Biomass differs to the fossil fuels by the fact that it is a renewable energy source. Renewable energy developments are generally considered to be environmentally beneficial by providing clean energy from resources that are continually replaced.

There are different types of biomass; there is wood such as trees, shrubs, wood residue Sawdust, bark, etc... Then, there are wastes such as paper, food, and tires, livestock waste and process waste. There are also aquatic plants such as algae or water weed which are biomasses as well.

The application of the biomass is to work as a fuel. Some properties are important to work with this fuel. Thermal properties of biomass, is the most important properties relating to thermal conversion of biomass, as from a combustion process. According to *Energy from biomass* the thermal properties are influenced by the:

- Moisiture content
- Ash content
- Volatile matter content
- Elemental composition
- Heating value
- Bulk density

The moisture content of biomass is defined as the quantity of water in the material, expressed as a percentage of material's weight. Then, the volatile matter refers to the part of the biomass that is released when the biomass is heated (up to 400 to 500'C). The elemental composition, the major components are carbon, oxygen, and hydrogen. The heating value of fuel is an indicator of the energy chemically bound in the fuel with reference to a standardized environment. It's given by the heating value of the fuel in energy J per amount of matter kg. Finally, bulk density refers to the weight of materials per unit of volume.

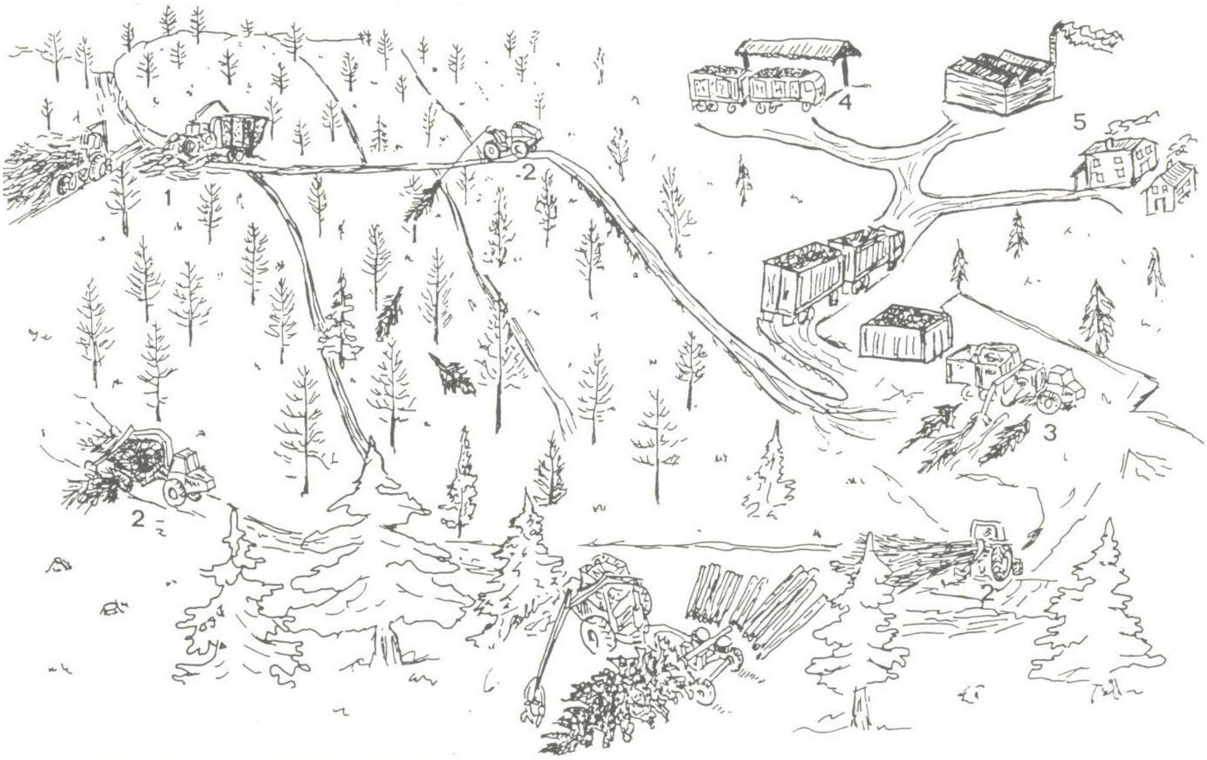
The use of biomass has some advantages.
According to *Energy matters*:

- Biomass are theoretically inexhaustible fuel sources, it is a renewable energy
- When there is a direct combustion of plant mass is not used to generate energy there is minimal environmental impact
- Fuels produced by biomass are efficient, viable, and relatively clean-burning
- They are available sources throughout the world

The most important advantage of the use of biomass is on the environment. In fact, according to *Energy from biomass*: "A benefit of using biomass in place of fossil fuels is that CO emissions are cut as a result. Replacing fossil fuels with sustainable biomass fuel is thus one option that countries may wish to consider in restraining CO_2 emissions." Nowadays biomass, in contrast to fossil fuels, has a unique potential for making a positive environmental impact. In fact, CO_2 is an important greenhouse gas contributing to the global warning. One of the principal sources of man-made carbon emissions is the fossil fuel combustion. As a renewable energy source, biomass may offer significant opportunities to reduce carbon emissions from fossil fuel combustion and as a consequence reduce the risk of future climate change. In addition, biomass can be burned without emitting large amounts of nitrogen oxides NO. Because the sulphur content of biomass is very low, the emissions of sulphur dioxide SO_2 will also be low.
Biomass has also a couple of disadvantages. In fact, it can be an expensive source of energy and used in small scale it can implies a loss of energy, which energy that must be put in to grow the plant mass.

Wood use as a biomass

Wood is one of the main and oldest biomass. Unfortunately wood is often too valuable to be used to burn, woodworking industries are often able to make better use of trees by processing them into construction materials. Otherwise, true residues such as bark, sawdust, and misshapen or odd-sized pieces are frequently more economic to use as fuel.
The main issue with the use of wood in general is the deforestation. Wood is disappearing at alarming rates. On the other hand, wood can be managed as a renewable resource if it is not b cut and burn faster than it can be replant and grow. But in this project, the use of a certain wood as a biomass does not imply some deforestation because this wood will be plant for this purpose.



Method of harvesting forest biomass by S. Baldini from Biomass energy from harvesting to storage

The harvesting process to collect the wood biomass follows the steps illustrated in the previous figure. The first step is the extraction of the whole trees and the chipping in the forest. Then, the skidding operations are carried out using agricultural tractors converted for logging purposes (number 2 on the figure). Chipping operations are then carried out in forests using medium-sized or small choppers operated by agricultural tractors, hoggers with autonomous motors can be used as well (number 3 on the figure). Represented by the number 4 on the figure, the drying of the biomass is important because it is a means of increasing its output in use. The process can be carried out near the forest depending on the type of material looking to be produced. Finally, the biomass is used by the industries and conurbations (step 5).
One of the biomass following this harvesting process is the coppice of willow.

Short rotation coppice willow

This project deals with the use of short rotation coppice willow used as a fuel to run a cooker. Short rotation coppice or SRC are defined as willow or poplar grown as an agricultural crop on a short (2-5years) rotation cutting cycle and at a planning density of 10-20,000 cuttings/ha, according to *Good practice guidelines short rotation coppice for energy production*. It is also described by the *Ecology and management of coppice woodlands* as coppice worked on a rotation less than 10 years to produce stick-size material. It is an energy crop, usually willow or poplar, which is used to produce either heat or electricity or both, known generally as biomass.

Based on information from *Good practice guidelines short rotation coppice for energy production*, the benefits from a well-run SRC energy production industry has an impact on the environment:

- It produces no net increase of the atmospheric carbon
- Reduction of the need of long distance haulage, if fuel is produced next to the place
- It can be an alternative supply of fuel which is renewable faster than a long rotation coppice
- It provides landscape variety. In fact, according to *Short Rotation Coppice (SRC) in the Netherlands* "Willow SRC plantations have a considerable (often surprisingly high) biodiversity, including several rare and threatened red list species". By harvesting after 3 years the landscape shows a diversity of age.
- Reduce the use of chemical, specially compare to longer rotation coppice production

A well-run SRC energy production industry has also an impact on the Economy

- It increases the farm diversification which can be attractive in term of investments
- It can utilize under-used agricultural land
- Provides employment for agricultural workers and unskilled workers

In *Ecology and management of coppice woodlands* the relation between the quality of the coppice and its rotation is shown: "it is possible that a single thinning at a suitable point in the cycle produce could redistribute increment to desirable stems, leading to better quality produce and a shorter rotation length".

Then, using a short rotation coppice influences the composition and the proprieties of this willow. In fact, based on *The handbook of Biomass Combustion & Co-firing*, the selection of the biomass species is one of the most important determining factors for fuel properties but it is influenced by how it grows. For short rotation coppice, the age of the crop influences the content in of N and the ash content due to the varying proportion of wood/bark in the plant and also depending on the amount of small branches. Oppositely, forest residues show, because of their long rotation time, accumulations of environmentally relevant heavy metals such as Cd and Zn, which has a negative impact on the environment. In addition, as the received rainfall increase with the time, the potassium K and the calcium Ca amount

decreases. The K, Cl, S amout must be as low as possible to have a biomass fuel of good quality. In fact, fuels with low ash content are better suited for thermal utilization than fuels with high ash content an Si, Ca, Mg, K, Na and P are the major ash-forming elements occurring in a biomass fuel. The S and Cl , K and Na during the combustion form sulphates and chlorine which show some problem of corrosion. The smaller the amounts of K and Na in the fuel, the better. However wood has a much lower sulphur and nitrogen content than coal which make the use of wood better than the use of coal. Finally, it can be said that after three years the rainfall is enough to provide coppice with a good energetic chemical compositon.
According to *The quests of sustanaible energy, woodfuel meets the challenge*, One of the major factor of efficiency of a biofuel for a combustion is its moisiture content. The moisiture content must be as low as possible. Therefore it is best to reduce moisture content before the wood is burnt so that a greater proportion of the energy from burning the wood goes into useful heat rather than converting moisture in the wood to steam. By drying logs
before chipping, chips with a lower moisture content are obtained. A good way to accelerate drying is to split the logs before stacking. On the other hand, chips produced from freshly felled logs have a higher moisture content.

Using the SRC as a fuel is going to the process of energy production. This process with the use of SRC is still an emerging industry. That is why developing a project in this area required a lot of attention. One of the point which require precaution is the regulations. Planning permission will be required for almost all SRC energy projects. In addition, plants need authorization under Part1 of the Environmental Protection act 1990 from the local authority. Plants may also required Environmental Assessment as well as environmental regulation and monitoring by the local authority. In this study the plants and the supply of SRC is supervised by Lammas.
By using SRC, future energy-cropping activities will involve with the cultivation of fast-growing wood specie such as willow.

The use of biomass in the world

The use of biomass like wood brings a lot of economical benefits in the poorest countries. Some projects using biomass are produced in developing countries in order to face the currency by limited the need of import of fossil fuels. Conversion of crop residues into energy increases the value of agricultural output.
However biomass is a renewable energy resource whose potential has not been fully exploited. Information on modern technologies that convert biomass to useful energy has not been sufficiently widely disseminated. Use of wood and other forms of biomass as fuel for generating heat has become a focus of renewed interest in many parts of the world which really need it because they cannot afford other fuel. But it can be really profitable even for developed country to use these resources, and that is what this project is about. In fact, biomass is an attractive option to reduce the cost and the polluting emissions which is good for everyone. Thus technology using these fuels are developed such as this project using the short rotation coppice willow provide by Lammas.

Lammas and the short rotation coppice willow production

For the use of this cooker Lammas will be able to supply short rotation coppice willow presented in the form of dry seasoned willow rods ranging from 5mm to 50mm in diameter that can be cut for any recommended length. At the moment Lammas workers are planting the coppice, thus the fuel will be available only within three years. At the end, this fuel will be set next to the cooker.

On the Friday 11th September 2009, as can be seen in the *appendix*, a visit has been done on the Lammas community site. There were three sites where the willow has been planted. These three plantations use three different techniques of planting. In fact, Paul Wimbush from Lammas explained that at the first year of growing, the ground floor and the weed have an important impact on the quality of the willow. Thus, in two of these plantations, they use plastic to cover the floor where the willow is growing in order to avoid weed com-petition which has a bad influence on the willow. There is one on plot 6, the small ones, have been mulched with straw and hay. There is one on plot 7, the really big ones, have been planted through sheet plastic, silage plastic technique. The last one is on plot 8, medium size, have been planted through woven plastic mulch, arranged in one meter strips.

Willow plantation in Lammas Eco Village, using the technique where the willow have been mulched with straw and hay

Willow plantation in Lammas Eco Village, using the technique where the willow have been planted through sheet plastic

Willow plantation in Lammas Eco Village, using the technique where the willow have been planted through woven plastic mulch

Fuel in the design, heat production

The amount of fuel required to produce the required temperature in the cooker is looking for. The heat locked up in a fuel is expressed as its calorific value. The calorific value or heating value of a fuel is expressed in kilojoules per kilogram kJ/kg and is a measure of the energy stored in the fuel. The calorific value is only fully realized when one kilogram of the fuel is burned. The ash content of the fuel influences its calorific value and behavior when it is burning. The percentage of moisiture in fuels is also reflected in the calorific value. A high moisiture content will reduce the calorific value of the fuel. According to *engineeringtoolbox.com*, for a dry wood the higher calorific value is 14,400 *kJ/kg* - 17,400 *Btu/lb.* The lower heating value, LHV, of a fuel is defined as the amount of heat released by combusting a specified quantity. The LHV for a willow wood is between 17MJ/kg and 19MJ/kg, based on *www.biofuelsb2b.com*. Thus, the LHV is assumed to be 18MJ/kg, Cv = 18MJ/kg.

Then, another important value for this calculation is the density. The willow density is 420 kg/m^3 according to *www.simetric.co.uk*. Based on *Variation of wood density and fibre length in six willow clones* the "Basic density values between 0.364 kg/dm3 and 0.455 kg/dm3 were found". Thus, the density of the willow is assumed to be $420kg/m^3$.

In order to calculate the amount of fuel required to produced a certain energy, the dimension of this fuel is required. The best way to obtain the size of the fuel is to realize how much fuel it is physically possible to feed into the cooker. In fact, there is no point doing calculation with a huge amount of fuel which is not convenient in the reality. After a discussion with people from Lammas, it has been said that the coppice should be cut with a length l of 60mm, with a diameter between 5mm and 50mm, as previously said. Then, based on the idea of the dimension of the cooker studied in the following chapters, the opening for the fuel must be about 400mm wide. As according to the rocket stove principles the air must flow above and underneath the wood, the calculations are made for one line of 50mm diameter d sticks, so n=8 sticks (400/50=8). The wood sticks are assumed to be perfectly cylindrical. Thus, the volume V of fuel is:

$V = n \,.\, l \,.(\pi \,.\, d^2) / 4$

$V = 8 \times 0.6 \times (\pi \,.\, 0.05^2) / 4$

$V = 0.00943m^3 = 9.43dm^3$

As the density of the willow is assumed to be $420kg/m^3$, The mass m of the amount of fuel is:

m = density x volume

m = 420 x 0.00943

m = 3.96kg

Thanks to the calorific value Cv, from the mass the heat emitted from the fuel combustion is found:

Heat = m . Cv
Heat = 3.96 x 18
Heat = 71.28MJ = 71.28 x 10^6Joules

This heat take a certain time to be produce. Based on the characteristic of the similar cooker available on the market seen in the previous chapter, the KVS 9100, which has a wood consumption of 3.5kg/hour, it is assumed that this amount of heat found is produced in one hour. Then,

Heat = m . Cv
Heat = 3.96 [kg/h] x 18 [MJ/kg]
Heat = 3.96/3600 [kg/s] x 18 [MJ/kg]
Heat = 0.0198MW = 19.8kW

Thus, the heat produced by the amount of fuel suitable in the cooker is 19.8kW.

Combustion

Energy is released during the chemical reaction of the fuel with oxygen, this reaction is called combustion. The most important fuel elements are the carbon and hydrogen, and most fuels consist of these and sometimes a small amount of sulphur. The fuel may contain some oxygen and a small quantity of combustibles (water vapour, nitrogen, or ash..)
The combustion process takes place in a controlled manner in some form of combustion chamber after initiation of combustion by some means, an ignition. This energy is in form of heat, the source of heat is the chemical energy of substances called fuels. The most convenient source of oxygen supply is that of the atmosphere which contains oxygen and nitrogen and traces of other gases. Normally no attempt is made to separate out the oxygen from the atmosphere, and the nitrogen, etc. accompanies the oxygen into the combustion chamber. Nitrogen does not oxidize easily and is inert as far as the combustion process is concerned, but it acts as a moderator in that it absorbs some of the heat of combustion and so limits the maximum temperature reached.

The combustion products are heat energy, carbon dioxide, water vapor, nitrogen, and other gases (excluding oxygen). Stable and efficient combustion conditions require correct mixtures of fuels and oxygen. In theory there is a specific amount of oxygen needed to completely burn a given amount of fuel, this is the stoichiometric condition. In practice, burning conditions are never ideal. To ensure complete combustion it is usual to supply air in excess of the amount required for chemically complete combustion. Therefore, more air than ideal must be supplied to burn all fuel completely. The amount of air more than the theoretical requirement is referred to as excess air, it is more than what is needed to burn the fuel completely. Power plant boilers normally run about 10 to 20 percent excess air, which is a modest amount.

To determine the excess air at which the combustion system will operate we have to start with the stoichiometric air-fuel ratio, known as the perfect or ideal fuel ratio, the stoichiometric combustion. During stoichiometric combustion there is a chemically correct mixing proportion between the air and the fuel. During the stoichiometric combustion process no fuel or air are left over.
On the other hand, if insufficient amount of air is supplied to the burner, unburned fuel, soot, smoke, and carbon monoxide will be exhausted from the combustion chamber. The results is heat transfer surface fouling, pollution, lower combustion efficiency, flame instability. In fact, an uncontrolled and incomplete combustion produce harmful emissions. As a consequence, to avoid inefficient and unsafe conditions, combustion systems normally operate at an excess air level.
Proportionate masses of air and fuel enter the combustion chamber where the chemical reaction takes place, and form which the products of combustion pass to the exhaust. By the conservation of mass flow remains constant, total mass of products equal to the total mass of reactants, but the reactants are chemically different than the products, and the products leaves at a higher temperature
The two sides of the equation must contain the same number of atoms of each elements involved.
It is usual in combustion calculations to take air as 23.3% O_2, 76.7% N_2 by mass, and 21% O_2 and 79% N_2 by volume.

The using fuel is the willow in short rotation coppice. In order to study its combustion process, the chemical composition is looking for.

According to *Research on the chemical composition of bushy willows and their possible application in forestry*, the average between different variety of willow analyzed, the chemical composition of the willow as been find as :

Cellulose	38-43.2%
Lignin	23.1-29.6%
Hemicellulose	23.8-31.6%
Pentosans	21.1-23.4%

Other sources, such as *TSEC-Biosys* the composition stating that the broad chemical characteristics of SRC willow on a percentage basis are: Cellulose 40 %, Hemicellulose 30 % and lignin 30 %.

Then, by looking closer to these elements, the composing atoms are found. Carbon C, hydrogen H and oxygen O are the main components of a biomass fuels. C and H are oxidized during the combustion by exothermic reactions (formation of CO_2 and H_2O). C, H, O concentrations as well as amounts of volatile matter in biomass fuels:
For Woodchips such as willow, According to *An investigation of the thermal and catalytic behaviour of potassium in biomass combustion*:

C 47.1-51.6 % of weight on a dry basis
H 6.1-6.3 % of weight on a dry basis
O 38.0-45.2 % of weight on a dry basis
Volatiles 76.0-86.0 % of weight on a dry basis
Ash about 2-5% of weight on a dry basis

Then, according to *Biomass combustion and co-firing* "this high amount in volatiles, the major part of a biomass fuel is vaporized before homogeneous gas phase combustion reactions take place; the remaining char then undergoes heterogeneous combustion reactions. Therefore the amount of volatile matter strongly influences the thermal decomposition and combustion behavior of a solid fuels".

To be able to run the analysis of the combustion reaction the proportion of each element composing the bio-fuel are required. According to *The Characterisation of the Physical and Chemical Properties of Biomass for Power Generation*, approved by the United Kingdom Accreditation Service and specialist in the preparation and analysis of solid fuel samples, the weight percentage compositions of the coppice of willow are:

Moisture	4,6%
Ash	1,4%
Carbon	47,7%
Hydrogen	5,6%
Sulphur	0,03%
Chlorine	0,03%
Nitrogen	0,5%
Oxygen	40,14%

As previously said, the stoichiometric ratio is the ideal condition, when the combustion is complete. Thus, from the combustion of the chemical element composing the willow, the stoichiometric air/fuel ratio is looking for. Each constituent is taken separately and the amount of oxygen required for complete combustion is found from the relevant chemical equation.

For the carbon C:

$$C + O_2 \Rightarrow CO_2$$
$$12kgC + 32kgO_2 \Rightarrow 44kgCO_2$$

Oxygen required= 0.477 x 32/12 = 1.272 kg/kg fuel
Where the carbon content is 47.7 kg per kg of fuel
Carbon dioxide produced= 0.477 x 44/12 = 1.749 kgCO_2

For the hydrogen H:

$$H_2 + 1/2O_2 \Rightarrow H_2O$$
$$1kgH_2 + 8kgO_2 \Rightarrow 9kgH_2O$$

Oxygen required= 0.056 x 8 = 0.448 kg/kg fuel
Steam produced= 0.056 x 9 = 0.504 kg/kg fuel

For the Sulphur S:

$S + O_2 \Rightarrow SO_2$
$1kgS + 1kgO_2 \Rightarrow 2kgCO_2$

Oxygen required= 0.0003 x 1/1 = 0.0003 kg/kg fuel
Sulphur dioxide produced= 2 x 0.0003 = 0.0006 kg/kg fuel

According to *Boiler operator handbook*: "All fuels contain sulphur which when burned produces compounds which can lead to corrosion. It is possible to remove sulphur from the fuel, but this is a very expensive process." The SO_2 produced in this combustion readily combine with the water from the hydrogen combustion produce acid. To prevent acid corrosion the temperature of the cooker material must be kept high, generally above 200°C there is no acid formation.
Then, the chlorine, the nitrogen, the ash and the moisture are not part of the combustion. High level of chlorine can form corrosive gases such as hydrochloric acid. From the combustion reactions:

Constituent	**Mass fraction**	**Oxygen required kg/kg fuel**	**Product mass kg/kg fuel**
Carbon	47,70%	1,272	1,749 CO_2
Hydrogen	5,60%	0,448	0,509 H_2O
Sulphur	0,03%	0,0003	0,0006 SO_2
Chlorine	0,03%	-	-
Oxygen	40,14%	-0,4014	-
Nitrogen	0,50%	-	0,005 N_2
Ash	1,40%	-	-
Moisture	4,60%	-	-
		1,3189	

Table showing the amount of oxygen required for the combustion

Thus, the oxygen required per kilogram of fuel is 1.3189kg.

As the air is composed of 21% O_2 and 79% N_2 by volume, and the N_2/O_2 mass ratio is equal to 3.29 the nitrogen required per kilogram of fuel is 1.3189 x 3.29 = 4.34kg

The air is assumed to contain 23.3% O_2 by mass, therefore the air required by kilogram of fuel is 1.3189/0.233 = 5.66kg

As a consequence,
Stoichiometric Air/fuel ratio is 5.66

In fact, the total amount of air for 1kg of fuel is equal to 1.3189(0_2) + 4.34(N_2) = 5.66kg
As found in the previous chapter the required mass of fuel is 3.96kg. Thus the amount of air needed is:

5.66 x 3.96 = 22.41kg of air

As the density of the air is 1.2kg/m^3 the combustion chamber must be able to feed a volume of air:

Volume of air in combustion chamber = 22.41 / 1.2 = 18.68m^3

As the amount of fuel is assumed to burn in one hour, this volume is the air which must go through the chamber during this time, 18.68m^3/h.

Now the addition of an excess air can be done. First, for an air supply which is 10% in excess
Actual Air/fuel ratio(10)= 5.66 + (10/100 x 5.66) = 6.226

Then, for 20% of excess air, the air/fuel ratio becomes:
Actual Air/fuel ratio(20)= 5.66 + (20/100 x 5.66) = 6.792

When the stoichiometric conditions are reached, the temperature of the combustion is maximum and the combustion is complete. This temperature is called the maximum adiabatic flame temperature. The constant pressure adiabatic flame temperature is the temperature that results from a complete combustion process that occurs without any heat transfer or changes in kinetic or potential energy. It is the highest possible temperature of combustion obtained. 1977°C is the adiabatic flame temperature of wood according to *Flame temperatures.*
But most of the time an excess air is required to make the combustion faster. It is done be introducing an air flow, some air entrances… With this excess air the adiabatic flame temperature is not reached, that is why the excess air should be chosen carefully. By comparing the temperature with excess air and the adiabatic flame temperature, the efficiency of the combustion is found.
Efficiency = T excess / adiabatic flame temperature
In this combustion process, there is a steady-flow or constant pressure combustion in which the change of the enthalpy ΔH_0 has to be taken in account. In fact,

$$Hp_2 - Hp_1 = (Hp_2 - Hp_0) + \Delta H_0 + (Hr_0 - Hr_1)$$

In which H states for the value of heat, R states for reactant and P for product.
As the main element in terms of heat production and quantity in the fuel is the carbon C, this study is limited on the carbon reaction:

$$C + O_2 \Rightarrow CO_2$$

As in reality, the conditions of the reaction are not stoichiometric and the adiabatic flame temperature (of 1977 C) is not achieved because of the excess air, the heat lost because of the combustion chamber design and because of the dissociation. Thus, the excess air is taken in account and provides the following reaction:

$$C + xO_2 + 3.76xN_2 \Rightarrow CO_2 + yO_2 + 3.76xN_2$$

The equation is balanced in oxygen:

$$2x = 2 + 2y;\ y = (x - 1)$$

The adiabatic flame temperature is not reached, so the final temperature has to be assumed. According to *Research into integrating a wood/charcoal stove into building design*, "the loss of energy into hot flue gases accounts for 22-39 per cent of the total input to wood stove". As a consequence, the efficiency of a wood stove, based on this statement, is 100 – 39 = 61%. Thus, the final temperature is assumed to be 61% of the adiabatic one, 1977 x 61/100 = 1205.97°C

Using the Steady Flow Energy Equation :

$$Q - W = (H_2 - H_1) + (C2_2 - C1_2)/2000 + g(Z_2 - Z_1)/1000$$

But in adiabatic, steady flow, there is no work, no heat lost, no potential and kinetic energy. Thus, the equation becomes:

$$0 = (H_2 - H_1)$$

$$0 = (Hp_2 - Hp_0) + \Delta H_0$$

$$\text{So,}\quad -\Delta H_0 = Hp_2 - Hp_0$$

As, the temperature around the cooker is equal to a usual temperature in a kitchen, it is assumed that the reactants are already at the reference temperature which is 25°C, $(Hr_0 - Hr_1) = 0$. At 25°C, the value of the molar enthalpy for this reaction is

$$\Delta H_0 \text{ @ } 298K = -393\,520 \text{ kJ/kmol}$$

Then, $Hp_2 - Hp_0 = \Sigma_{Products}\, mi\, (Hi_2 - Hi_1)$

By using the specific heat :

$$Hp_2 - Hp_0 = \Sigma_{Products}\, Cpi\, (T_2 - T_1)$$

The mean temperature is: (1205.97 + 25)/2 = 615.485°C = 888.485K

The mean temperature is assumed to be equal to 900K in order to be able to read directly the value of the specific heats from the steam table.

Product	Mass in kg	Cp in kJ/kgK	mi.Cpi
CO_2	44	1.204	52.976
O_2	(x-1).32	1.074	34.368x - 34.368
N_2	3.76x.28	1.146	108.329x

Table showing the calculation of the mass and specific heat for the determination of the excess air

$$(1205.97-25).(52.976+34.368x-34.368+108.329x) = 393520$$

$$1180.97.(18.608+142.697x) = 393520$$

$$21975.490+168520.876x = 393520$$

$$X = (393520 - 21975.490) / 168520.876 = 2.205 \text{ moles}$$

Thus, the reaction becomes:

$$C + 2.205O_2 + 8.291N_2 \Rightarrow CO_2 + 1.205O_2 + 8.291N_2$$

As x is equal to 2.205 moles, to obtain a final temperature of combustion of 1205.97 C, an excess air of 220% must be provided.

In order to check if this calculation is correct, the same procedure is followed but for an efficiency of 100%, so with the adiabatic flame temperature used as the final temperature.

The mean temperature becomes (1977+25)/2 = 1001C 1274K

It is assumed to be equal to 1300K, so:

Product	Mass in kg	Cp in kJ/kgK	mi.Cpi
CO_2	44	1.298	57.112
O_2	(x-1).32	1.125	36x - 36
N_2	3.76x.28	1.219	128.336x

Table showing the calculation of the mass and specific heat for the verification of the excess air

$$(1977-25).(57.112+36x-36+128.336x) = 393520$$

$$1952.(21.112+164.336x) = 393520$$

$$41210.624+320783.872x = 393520$$

$$X = 1.098 \text{ moles}$$

When the adiabatic flame temperature is used as the final temperature, x is almost equal to 1 which shown that the calculations are correct.

Development

Design

Thanks to the previous background study, an idea of the design is made.

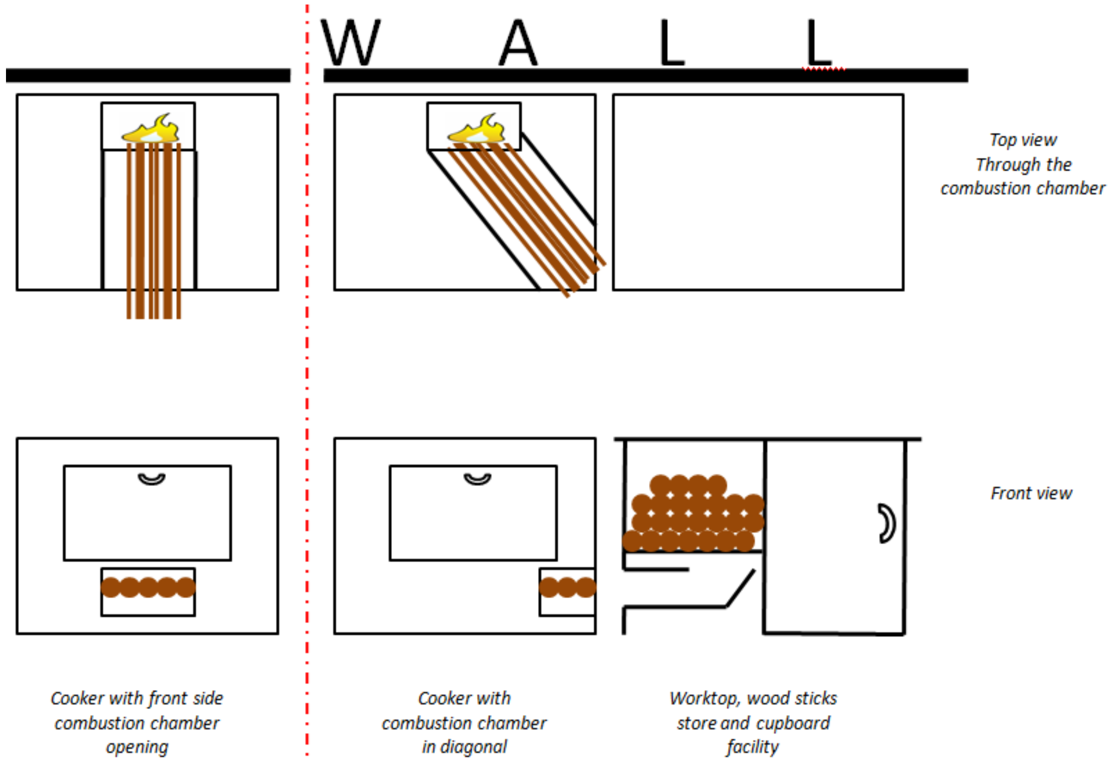
The cooker design is composed of the following parts:

- The combustion chamber
- The oven
- The cooking hot plate
- The door of the oven
- The outside frame
- The chimney
- The device to change the use from oven to cooking plate

The combustion chamber

The combustion chamber follows the rocket stoves principles. Thus, it has the same cross section all along its L shape and the flame is located in the corner of this shape.

After, the visit at Lammas and some discussion with them, it has been said that it will be good to do not have the combustion chamber opening on the front where the fuel is feed. In fact, the opening is on the front the willow stick might sometime be too long and go outside the cooker which can be annoying for the person who is cooking.
Thus, the combustion chamber has been set in diagonal so that it is long enough and the fuel store can be next to it and make the fuel feeding easier. This can be seen in the following sketch:

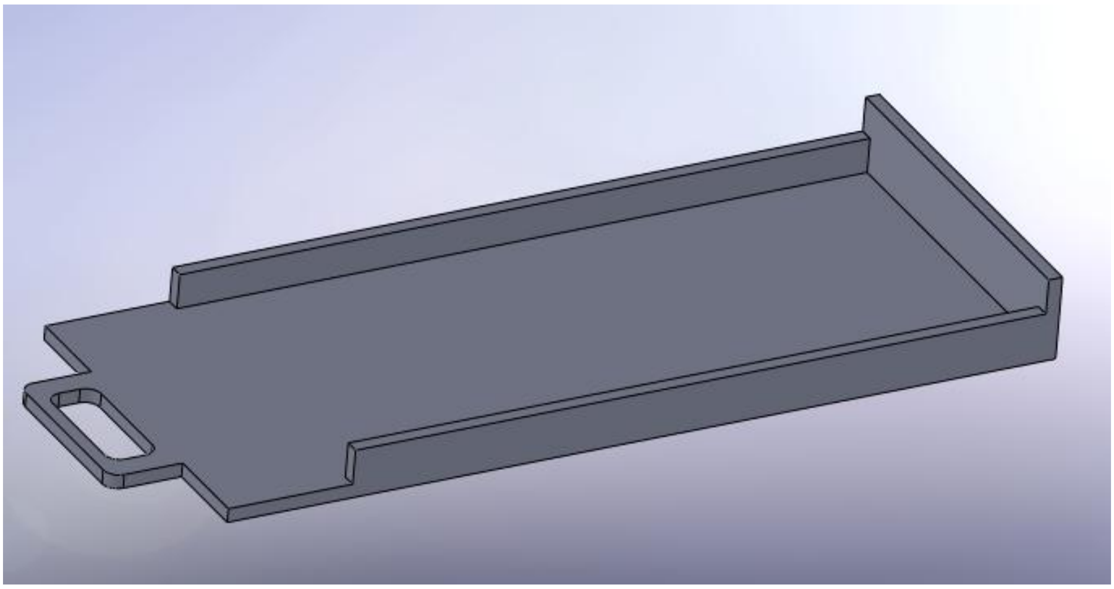


Sketch showing the cooker with the combustion chamber opening on the front with the problem of long stick which is annoying for the person who is cooking, and the diagonal one with the use of a storage facility

Then, the bio-fuel combustion starts with in ignition. Thus, an opening on the side of the combustion chamber will be provided in order to ignite the willow. As a consequence a blowtorch can be used to burn the fuel through the opening on the side of the combustion chamber.

Blowtorch from cook cookware-online.co.uk

An additional device must be set in the combustion chamber in order to remove the ashes produced by the combustion. In order to do that a long shallow plate with a handle is set in the combustion chamber below the fuel shelf and the flame. This device can be seen in the following figure:



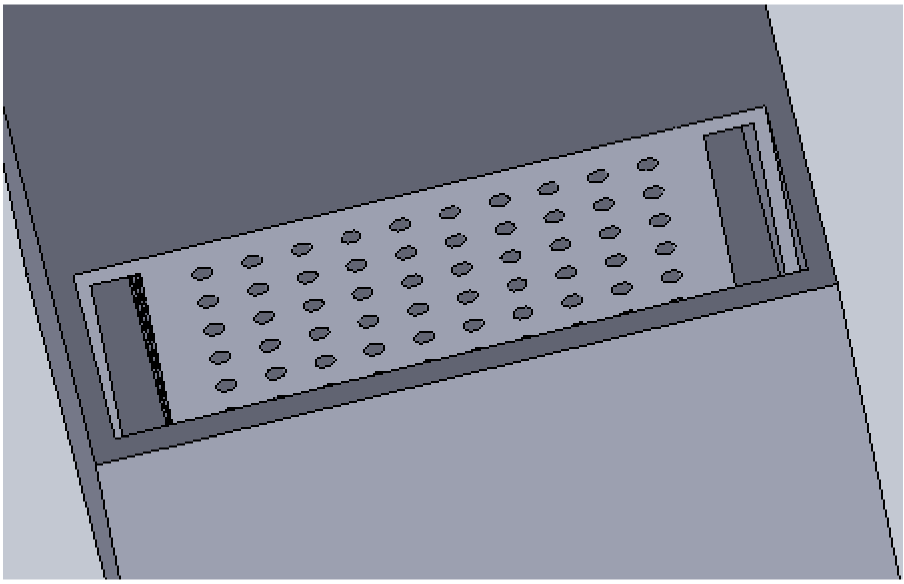
Screenshot from SolidWorks of the design of the plate used to remove the ashes from the combustion

The dimensions of the combustion chamber come from the study of the combustion. As it has been said, the combustion chamber is 400mm wide in order to enable to burn 8 wood sticks of 50mm diameter and 600mm long to produce 19.8kW. It is 200mm high to let the air flow above and underneath the sticks as it is recommended in the rocket stove principles.

The oven

The oven is a space where some food is put in order to be cooked. Thus, the size of the oven depends of the amount of food that is required. For a family, according to what is available in the market in terms of domestic cooker, an oven volume capacity should be at about 50litre which is equal to 50 000cm^3. Thus, the oven for this design has been set as 40cm width, 35cm height and 40cm depth, which gives a volume of 40x35x40=56000cm^3. With these dimension the family must have enough space to cook their meals.
On both side of the oven a small space is set between the oven box and the global structure of the cooker. In fact, this allows the heat from the combustion chamber to flows around the oven in order to have a good heat distribution. This has been inspired by the fact that on electric cooker there are heating units on both side of the oven.

In order to make the heat conduction easier, the oven is composed of plate with holes, so that the heat can flow through the oven.



Screenshot from SolidWorks of the first design of the cooker viewed from the back showing the holes which conduct the heat through the oven and showing the space on both side of the oven in order to let the heat flows around the oven

A shelf must be set in order to put the food in the oven. As said in the cooker chapter "the support mechanism is also heated during the cooking process. Over time, the support can heat to near the temperature of the oven. As a consequence, the parts of the food being cooked that are in contact with the support mechanism become more cooked than the parts which are not in contact". Thus, support must be at the same level than a line of holes in the oven in order to conduct a maximum of heat.

The cooking hot plate

The first requirement for the design of this cooker was to have four cooking ring such as most of the cooker available on the commerce. Having four cooking ring means that these four cooking area must have independent temperature control which is not easy to figure out in a wood burning cooker. Thus, with the agreement of Lammas, it has been decide to employ only one large hot plate with a temperature distribution which allows different temperature area. The dimension of this plate will be ruled by the size of the oven and the outside frame.

The door of the oven

The door of the oven must be large enough to cover correctly the oven inlet. It must enable the user to see through in order to verify if its food is cooked as desired. The door must be linked to the cooker frame thanks to a hinge on the lower side of the door in order to open the door from top to bottom as in usual domestic cooker.

The outside frame

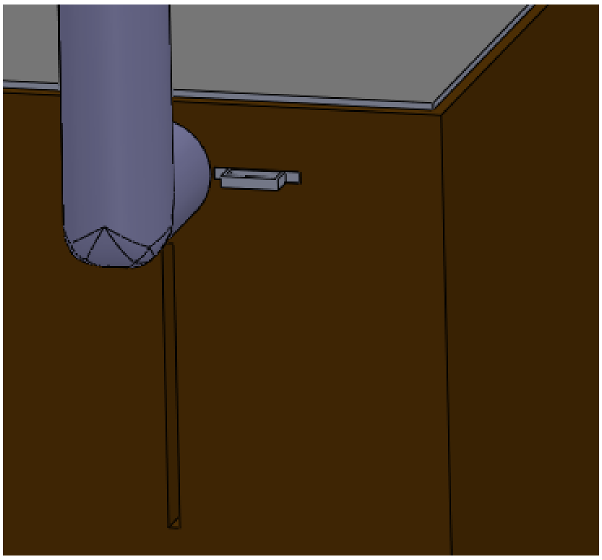
The frame of the cooker is very important as all the elements composing the system are fixed on it. Thus, it has to be able to carry to weight of all the parts and to protect them. Then, it must aesthetic because it is what people see in the kitchen. The global shape is cubic, in order to fit the oven and the cooking plate.

The chimney

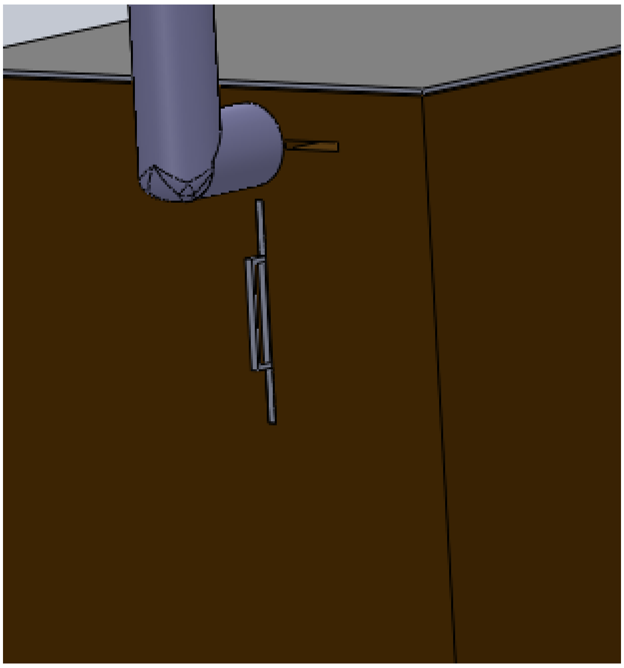
The use of the chimney is essential in order to remove all the smoke from the kitchen to the outside environment. It is the health and safety element of the cooker. The chimney is composed of pipe which geometry depends of the kitchen and the house where the cooker is installed. This device is set at the end of the heat flow in order to avoid a loss of energy.

The device to change the use from oven to cooking plate

As when people used such a cooker, they do not necessary use the oven and the hotplate at the same time, it would be good to have a device which allows the user who only wants to use either the oven or either the hotplate to choose between these facilities. Thus, it has been though to use large insulated plate which can be slide in the chamber in order to block either the heat flows through the oven to use the hotplate or either to block the heat flows to the hotplate to use the oven. This will lead to a higher temperature in the cooking device chosen.



Cooker used as an oven thanks to the device slides in the cooker which deflects the flows to the oven



Cooker used as a hotplate thanks to the device slides in the cooker which deflects the flows to the hotplate

Materials

Materials selection

For the design of the cooker the materials used to produce it have to be chosen. The cooker is divided in different main elements:

- The combustion chamber
- The oven
- The cooking hot plate
- The door of the oven
- The outside frame
- The chimney
- The device to change the use from oven to cooking plate

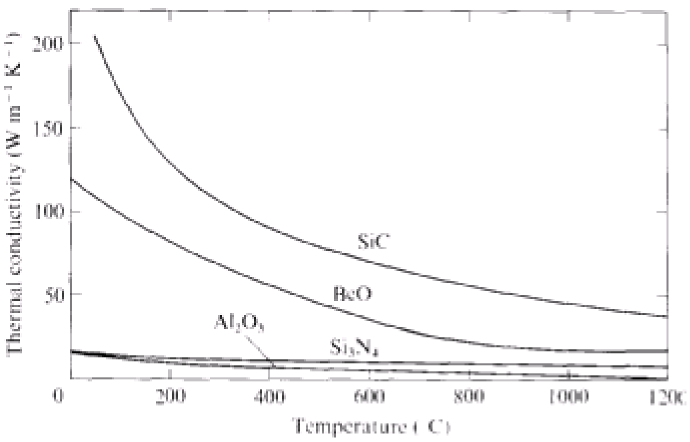
The parameters which are the most influent in the choice of any materials for this project are the efficiency and the cost.

The combustion chamber

The combustion chamber is the main element because that is where the combustion occurs, so where the heat is produced. As said previously in the rocket stove principles section, the key to have an efficient product is to have a good insulation around the fire. Thus, the main propriety of the material used for the combustion chamber is its insulation value, low heat conductivity. The property of materials of letting heat pass from one place to another is called heat transmission that is what is important in the selection of this material. Solid materials have been conveniently grouped into three basic classifications: metals, ceramics, and polymers. In general, the materials which respond to these criteria are the ceramics such as clay or porcelain. According to *Ceramics Physical and Chemical Fundamentals* copper has a thermal conductivity of about 350kcal/m.h°C, aluminum about 175kcal/m.h°C, cast iron about 55kcal/m.h°C and ceramics are usually below 1kcal/m.h C so much more efficient than the other usual materials in term of insulator.

The *Materials science and engineering* book describes ceramics as: "compounds between metallic and nonmetallic elements; they are most frequently oxides, nitrides, and carbides. Ceramics have stiffness and strength comparable to the metallic materials. These materials are typically insulative to the passage of the heat and are more resistant to high temperature than metals." Ceramics density is low, about 5.25g/cm^3 which is good in term of insulation.

Then, based on *Mechanical behavior of ceramics* the thermal conductivity is influence by the temperature, as can be seen on the following figure:



Temperature dependence of the thermal conductivity of some engineering ceramics from Mechanical behavior of ceramics

As can be noticed, the thermal conductivity decrease as the temperature increase which is a good point as the temperature near the flame will be at about 1000°C, and that is where the insulation must be the most efficient.

According to *Mechanical behavior of ceramics*, the properties of ceramics depends highly on their structure. Thus, texture represents a key of the ceramics properties. The fabrication of the materials is influenced by the properties looking for. There are different classes of ceramics such as pottery, heavy clay, abrasives ceramics, refractory, cement… The ones interesting for the combustion chamber are the pottery such as fireclay or porcelain because there are typically used for insulators; otherwise there is the refractory ceramics such as alumina or silica which are mostly used in furnace linings.

Then, the ceramics are often present as bricks which make the assembly of the cooker easier and less expensive as it does not required any manufacturing process such as casting.

In addition, all the literature about rocket stove already studied in the rocket stove principle section recommend the use of insulative ceramics bricks made of clay for the combustion chamber.

As Lammas already has some bricks of clay, as it is ceramics usually used for insulators, it can be used for the combustion chamber design. They also have some sand which can be used to fill the space between the combustion chamber made of brick and the cooker frame. In fact, the sand due to its high thermal mass is a good insulator.

The oven and the cooking hot plate

The oven cavity and the cooking hot plate are elements which transmits the heat from the combustion to the food. As a consequence they must have a high conductivity. In addition, especially for the oven cavity, they are not far from the flame so at high temperature that is why it must be made of some material which is resistant to the corrosion, which leads to a long life expectancy.

The *Materials science and engineer* book defined the metals as good conductor which is what is it looking for. Metals are composed of metallic elements and nonmetallic elements such as carbon or nitrogen in relatively small amounts. Regarding to the mechanical characteristics, these materials are relatively stiff and strong. In addition metals have high density, unlike the insulator materials, about 18g/cm^3 as an average.

In fact, according to *Applications manual*, *Condensing boilers*, one of the most important corrosion factors is the presence of chlorine in the combustion chamber, from the fuel. This book recommends materials for heat exchanger. Two materials are compared, the steel and the aluminum.

Stainless steels in particular AISI 304, 316grades, the 300 series is recommended. They have high resistance to corrosive attack, and may therefore be expected to have a long life expectancy. Also, some specialized stainless steels are available that immune to attack by the more corrosive condensate resulting from burning oil, but this is expensive.

In addition, steel is a common material in domestic appliance.

Certain aluminum alloys show good corrosion resistance. But, under adverse conditions, aluminum can be susceptible to pitting corrosion. Clearly leading this circumstances leading to attack must be prevented. This entails good operation and maintenance. Thus, the use of aluminum seems more expensive than the use of steel.

The other material that can be used is the copper. In fact, as said previously, copper has a high thermal conductivity of about 350kcal/m.h°C.

The steel has been selected as the material used for the oven and the cooking hot plate for its conductivity, efficiency and price. In fact, the copper is a more expensive metal.

An alternative solution to the use of sheet of steel for the oven cavity is to use a former oven cavity from a recover oven so that the size and the cooking facility (grill) are already set.

The door of the oven

The door of the oven must be made in such way that it insulates the heat, smell and emission form the oven to the kitchen environment and which allow the person who is cooking to see the inside of the oven in order to evaluate the cooking of the food. In order to accomplish these functions the iron has been selected. In fact, it is a resistant material which is suitable for a geometry such as a door. Then, it must be able to insulate the inside oven temperature from the outside. Then, as a part of the door a “window” can be set in fibre glass to enable the user to keep an eye on his food.

The outside frame

The outside frame must insulate the heat emitted by the cooker. As the consequence the requirement are almost the same than for the combustion chamber. Thus, ceramics bricks should be used.

The chimney

The material uses for chimney really depend of the house. In fact, the best material to use for this chimney would be the clay brick just as for the combustion chamber and the outside frame for the same reasons, but that imply that the house has the chimney made of brick already set in the wall. Now, as some of the houses of the Lammas community are not built at the moment, it can be done. But for the other house, an alternative solution can be to use metal vents which are pipe within a pipe with air space between the two walls. The inner wall is aluminum to resist corrosion and the outer wall is galvanized steel for strength.

Masonry and Clay Tile Chimney from www.inspect-ny.com

Metal chimney from www.inspect-ny.com

The device to change the use from oven to cooking plate

This additional device to change the use of the cooker, either hotplate or either oven, must be made of cast iron. In fact, as the aim is to insulate the heat flow in order to keep a maximum of energy going to the using cooking facility, the clay would be the best but it is complicated to imagine a device with this geometry made of this material. Thus, cast iron must be implemented as it still provides a good insulation.

Materials calculations

Creep

Materials are often placed in service at elevated temperatures and exposed to static mechanical stresses. Deformation under such circumstances is termed creep. In this cooker, the temperatures are high, so it has to be sure that the selected materials are resistant enough. It is observed for all materials but for metal it becomes important only for temperatures greater than about $0.4.T_{m.}$ T_m is defined as the absolute melting temperature, when the melting point is reached and the viscosity is 10Pa-s.
According the *Engineeringtoolbox* value T_m for the steel is equal to 1510°C. Thus,

$0.4.T_m = 604°C$

Then, the temperature around the oven made of steel must be kept below 604°C. In fact, it is below this value as can be seen in the following chapter dealing with the Computational Fluid Dynamics simulation.
Then, for the iron T_m is equal to 1536°C, so:

$0.4.T_m = 615.14°C$

The temperature next to the door in iron must be below 615°C, in fact the temperature in the oven is about 250°C so it not a problem.

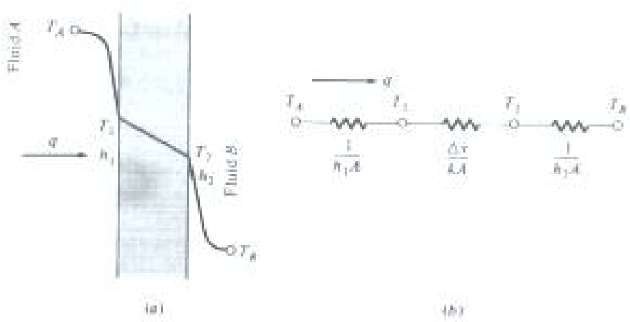
Heat transfer

The heat transfer is an important parameter for this kind of problem. In fact, it is about insulation as noticed in the previous materials selection. The system must have an energy balanced. For this cooker, with Q standing for a value of heat, the energy balance is:

$$Q_{combustion} = Q_{oven} + Q_{hotplate} + Q_{casing} + Q_{flue}$$

$Q_{casing} + Q_{flue}$ represents the heat lost by the system, either from the transfer through the wall or by the flue gas. As the insulation is a key to the success of rocket stove principle and it is one of the most important parameter in the selection of the using material, the heat loss through the wall in clay is looking for.

When the heat flows through the wall from the combustion chamber to the outside, the three heat transfer processes occur successively: convection, conduction and radiation. These processes are represented in the following figure.



Overall heat transfer through a plane wall from Applied Thermodynamics for Engineering Technologists

The convection is evaluated from the equation:

$$Q = k\ A\ dT$$

where

Q = heat transferred per unit time (W)

A = heat transfer area of the surface (m^2)

k = convective heat transfer coefficient of the process (W/m^2K or $W/m^{2o}C$)

dT = temperature difference between the surface and the fluid (K or ^oC)

Then, the conduction is expressed by the following Fourier's equation:

$$Q = k\ A\ dT / s$$

where

Q = heat transferred per unit time (W)

A = heat transfer area (m^2)

k = thermal conductivity of the material (W/m.K or W/m ^oC)

dT = temperature difference across the material (K or ^oC)

s = material thickness (m)

The radiation heat transfer is defined by the following Stefan-Boltzmann equation:

$$Q = \sigma\ T^4\ A$$

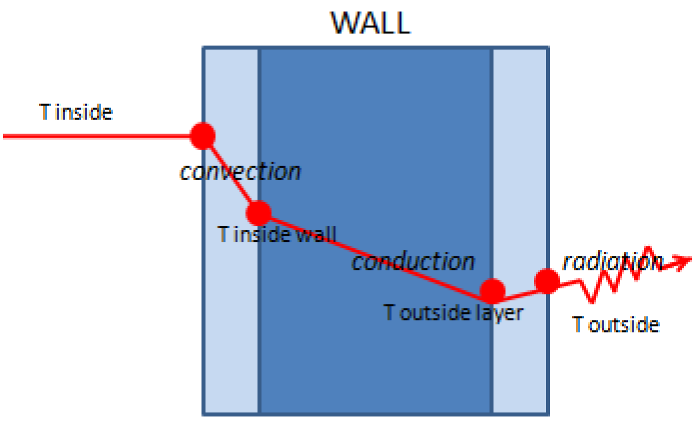
where

Q = heat transfer per unit time (W)

$\sigma = 5.6703\ 10^{-8}$ (W/m^2K^4) The Stefan-Boltzmann Constant

T = absolute temperature Kelvin (K)

A = area of the emitting body (m^2)



Different heat transfer processes through a wall with different temperature

These three reference equations are defined with a temperature. But as can be seen on the previous figure each heat transfer occurs in different layer where the temperature is different. The problem is that to carry out these calculations, these temperatures must be known whereas the only ones known are the temperature inside the chamber and outside. Thus, the overall heat transfer is used.

$$1 / U A = 1 / h_1 A_1 + dx_w / k A + 1 / h_2 A_2$$

where

U = the overall heat transfer coefficient (W/m^2K)

A = the contact area for each fluid side (m^2)

k = the thermal conductivity of the material (W/mK)

h = the individual convection heat transfer coefficient for each fluid (W/m^2K)

dx_w = the wall thickness (m)

The area is always the same and the inside heat coefficient is unknown so the equation becomes:

$$1 / U = dx_w / k + 1 / h_2$$

With dx_w = 100mm as the thickness of the brick in clay of k = 1W/mK and h_2 =17W/m^2K assumed from a similar problem with a furnace in a room from *Applied Thermodynamics for Engineering Technologists*. Thus:

$1 / U = 100 \times 10^{-3} / 1 + 1 / 17 = 0.159\ W/m^2K$

The heat loss Q_{casing} is then found:

$Q_{casing} = U . A . \Delta T$

A is the area where the heat transfer happen, so the back (710mm x 800mm), sides walls (600mm x 800mm) and the bottom (710mm x 600mm), in fact, the top part is the hot plate so heat which goes through it is used for cooking.

The temperature next the wall is assumed to be 450 C according to the results provided by the Computational Fluid Dynamics analysis available in the next chapter.

$Q_{casing} = (1/0.159) \times ((2 \times 0.6 \times 0.8) + (0.71 \times 0.8) + (0.71 \times 0.6)) \times (450 – 25)$

Q_{casing} = 5223W

The heat loss through wall has a value of 5223W.

Another way to calculate it is by using the thermal resistance.

R_b the resistance of the brick:

$R_b = 100 \times 10^{-3} / 1 = 0.1K/W$

R_a the resistance of the outside surface:

$R_a = 1 / 17$ K/W

Using the equation of fluid film $R = 1 / \alpha A$, and the heat transfer coefficient from the outside wall surface to the air in the room is $17 W/m^2K$.

Then, R_t the total resistance of the wall is:

$R_t = R_b + R_a = 0.1 + 1/17 = 0.159$ K/W

As can be noticed the same value than 1 / U is found.

Thus,

$Q = \Delta T / R_t = (450 – 25) / 0.159 = 2673W \quad 2.673kW$

The rate of heat loss per square meter of surface area is 2673W.

In fact, this result can be verified by multiplying with the area:

Q = 2673 x ((2 x 0.6 x 0.8) + (0.71 x 0.8) + (0.71 x 0.6))

$Q_{casing} = 5223W$

The same value is found, the heat loss through wall has a value of 5223W.

The heat produced by the amount of fuel suitable in the cooker is 19.8kW, as it has been found in the fuel background chapter, then it can be said that in this cooker, 5223/19800 = 0.264 so 26.4% of the heat produced is lost by heat transfer through the wall.

Then, the heat going to the hotplate is looking for in order to estimate the temperature of cooking on it.

The overall heat transfer is used to calculate the temperature on the top of the hotplate.

$1 / U A = 1 / h_1 A_1 + dx_w / k A + 1 / h_2 A_2$

First, the heat lost from the inside of the cooker to the atmosphere going through the hotplate is calculated.

The area is always the same and the inside heat coefficient is unknown so the equation becomes:

$1 / U = dx_w / k + 1 / h_2$

With dx_w = 5mm as the thickness of the sheet of steel of k = 17W/mK and h_2 =17W/m^{2}K assumed from a similar problem with a furnace in a room from *Applied Thermodynamics for Engineering Technologists.* Thus:

$1 / U = 5 \times 10^{-3} / 17 + 1 / 17 = 0.059 W/m^2K$

The heat transfer through the hotplate $Q_{hotplate}$ is then found:

$Q_{hotplate} = U . A . \Delta T$

A is the area where the heat transfer happen which is the top of the cooker, the hotplate (710mm x 600mm).

The temperature next the wall is assumed to be 450°C according to the results provided by the CFD analysis available in the next chapter.

$Q_{atm\ hotplate} = (1/0.059) \times (0.71 \times 0.6) \times (450 – 25)$

$Q_{atm\ hotplate} = 3069W$

$Q_{atm\ hotplate}$ represents the heat lost to the atmosphere where the temperature is 25°C, but now what is looking for is the temperature on the hotplate. The same procedure is followed but this time there is no resistance from the film of air outside the hotplate because the temperature of this surface estimated. Thus,

$1 / U = dx_w / k$

$1 / U = 5 \times 10^{-3} / 17$

$1 / U = 2.94 \times 10^{-4} W/m^2K$

Now,

$Q_{atm\ hotplate} = U . A . (450 – T_{hotplate})$

$(450 – T_{hotplate}) = Q_{atm\ hotplate} / (U . A) = (3069 \times 2.94 \times 10^{-4}) / (0.71 \times 0.6) = 2.11°C$

$T_{hotplate} = 447.89°C$

The temperature of the hotplate is 447.89°C.
The heat going through the hotplate can be found,

$Q_{hotplate} = U . A . \Delta T$

$Q_{hotplate} = (1 / 2.94 \times 10^{-4}) \times (0.71 \times 0.6) \times (450 – 447.89)$

$Q_{hotplate}$ = 3057W

The same calculation can be carried out for the oven. The oven is a box composed of five sheets of steel 5mm thick. Three of them are 400x350mm and two are 400x400mm. As for the hotplate,

$1 / U = 5 \times 10^{-3} / 17 + 1 / 17 = 0.059 W/m^2K$

Then, with an inside temperature in the oven of 250°C,

$Q_{oven} = U . A . \Delta T$

$Q_{oven} = (1 / 0.059) \times ((0.4 \times 0.35 \times 3) + (0.4 \times 0.4 \times 2)) \times (450 – 250)$

Q_{oven} = 2509W

This value is assumed for an oven box composed of plane sheet of steel, in fact, the one in the proposal design has holes to improve the heat flows.

Thus, from the energy balance equation:

$$Q_{combustion} = Q_{oven} + Q_{hotplate} + Q_{casing} + Q_{flue}$$

The heat lost by the flue through the chimney can be determinate:

$Q_{flue} = Q_{combustion} – (Q_{oven} + Q_{hotplate} + Q_{casing})$

$Q_{flue} = 19800 – (2509 + 3059 + 5223)$

Q_{flue} = 9009W

With the use of an oven box without holes, 9009W is lost in the flue gas. Then, the global heat lost is found as:

$Q_{flue} + Q_{casing} = 9009 + 5223 = 14232W$

So,

$(Q_{flue} + Q_{casing}) / Q_{combustion} = 14232 / 19800 = 72\%$

Thus, 72% of the heat produce by the combustion is lost by the brick wall or by the flue gas, in a cooker without holes in the oven box. In fact, the holes in the oven allow more heat coming in the oven so less energy lost.

Computational Fluid Dynamics

As the study of the design of a cooker is related to the study of fluid dynamics with the heat distribution inside the device, it is interesting to use the Computer Fluid Dynamics, CFD, in order to confirm or to improve the idea of the cooker design. In fact, from the previous background part about the cooking technology, it has been learn as a main idea that the heat distribution must be homogenous inside the oven and this can be verify by a CFD analysis.

The theory

The need to apply CFD

The need to apply Computational Fluid Dynamics came with the history of the aeronautics, where the major thrust has always been to produce vehicle which fly faster and higher. Such vehicle became real when the computational fluid and dynamics has developed to the point where the complete three-dimensional flowfield over the vehicle can be computed with accuracy. For this study, the fluid is also the air, but the most matter is not the velocity but the temperature of this heated air from the combustion process. As it is difficult to set an experiment for flows inside a cooker which does not exist as yet, The solution of fluid motion equations are found thanks to the used of digital computers and at this time the performance-to-cost ratio of computers had increased at a spectacular rate which provides efficient results.
Then, the CFD appear as a wonderful tool, but it is important to be aware that the CFD is not independent, the theory and the experiment are also important in the analysis of a problem, and the CFD will never replace these approaches. In fact, the theory and then the experiment help to understand and interpret the result. The CFD involve in giving an approximation of the numerical solution, called the discretization method which approximate the differential equations , that describe the conservation of mass, momentum and energy in a flow field, which can then be solve thanks to the CFD software. These are commonly known as the Navier-Stokes equations, even though strictly this only refers to the momentum equations.
Nowadays, It is said that CFD is today an equal partner with pure theory and pure experiment in the analysis and solution of fluid dynamic problems. For the future, the role of the CFD will increase with the technology improvement.

The advantages and disadvantages of using CFD

Using CFD has on one hand a lot advantages but on the other hands it has some disadvantages that it is important to be aware of.
First advantage of the CFD is the possibility to do some analyses that are impossible to do in reality. In fact, as said, it is impossible to experiment a cooker which has not been produced.
Then, the CFD has the advantage to provide fast solutions to some problems. A simple CFD problem can be solve in a few minutes on personal computers. Thus the CFD is good in term

of time consumption. The cooker geometry can be simplified by representing only the area where the fluid flows, in order to make the problem even faster to solve.
Another important advantage of the CFD is its cost. In fact, the CFD can be optimized and produced large saving in equipment and energy costs and in reduction of environmental pollution.
Then, the flexibility and the accuracy of the CFD are also some of its major advantages. For example, Computational fluid dynamic results are directly analogous to wind tunnel results obtained in a laboratory. The CFD software can be used everywhere due to the new technology, it said that the CFD software is a "transportable wind tunnel", thus it is a flexible tool.
In addition, the visualization of the result is very precise, clear and easy to understand.
Finally, it can be said that the CFD technique is fast, precise, and cost-effective and provide good estimations of the real behavior.
Even if the usual wonderful color pictures of the different CFD packages makes good impression, the CFD has some disadvantage. One of these is the fact that an important part of this technique is based on assumptions. In fact, often have to do assumption to simplify the problem such as simplify the geometry when geometry too complicated to modeled on the software. In addition, assumptions and idealization are also done during the discretization process when the differential equations are solved. CFD packages often allow estimating the error risks. But the cooker geometry should not need too much simplification to make the simulation run.
Finally, some of the CFD problem can takes long time to solve because there are codes that may require hundreds of hours and needs largest super-computer. That is due to a complex geometry or boundary conditions, that's why it is important to simplify the problem as much as possible by doing the right assumptions. But once again, it should not occur for this problem.

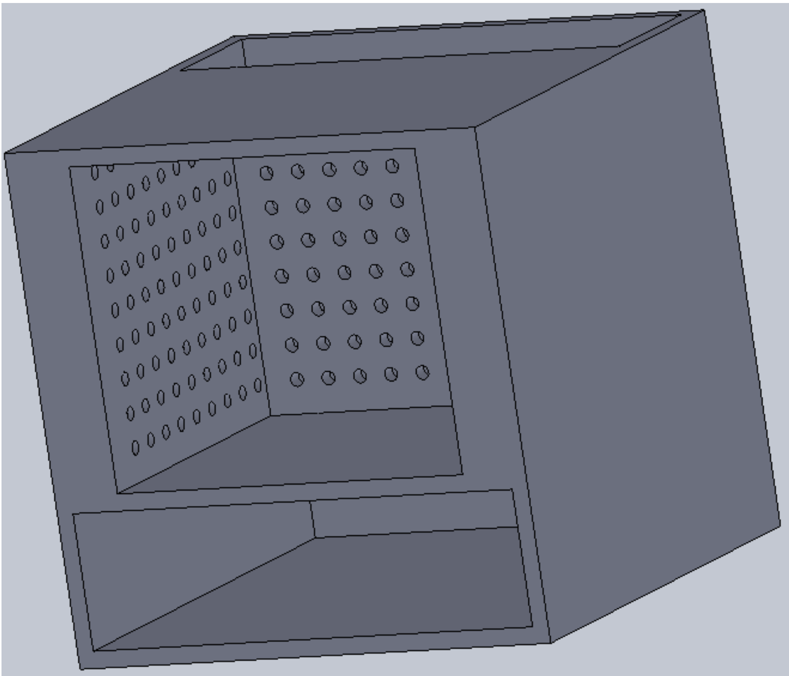
Modelling a physical process

A physical process is the selection of the geometry, grid, the boundary conditions, the initial conditions, and the definition of the fluid. Modelling a physical process means providing a physical representation of the process that occurs in the problem that is modeled. This task is essential because it affects the all analysis and has a major influence on the results.
The most fundamental consideration is how to treat a continuous fluid in a discretized fashion on a computer. One method is to discretize the spatial domain into small cells to form a volume mesh or grid.
There is a standard procedure to model a physical process. First, the geometry, the physical bounds of the problem have to be defined. Then, the fluid and its volume occupied in the domain defined for the problem is divided into discrete cells, this is the meshing. The mesh may be uniform or non uniform. Then, the physical modeling is defined such as the equations of motions or the enthalpy(description of thermodynamic potential of a system, which can be used to calculate the heat transfer). Other very important task as part of the physical process is the definition of the boundary conditions. This involves specifying the fluid behaviour and properties at the boundaries of the problem. When all these parameter are recorded by the

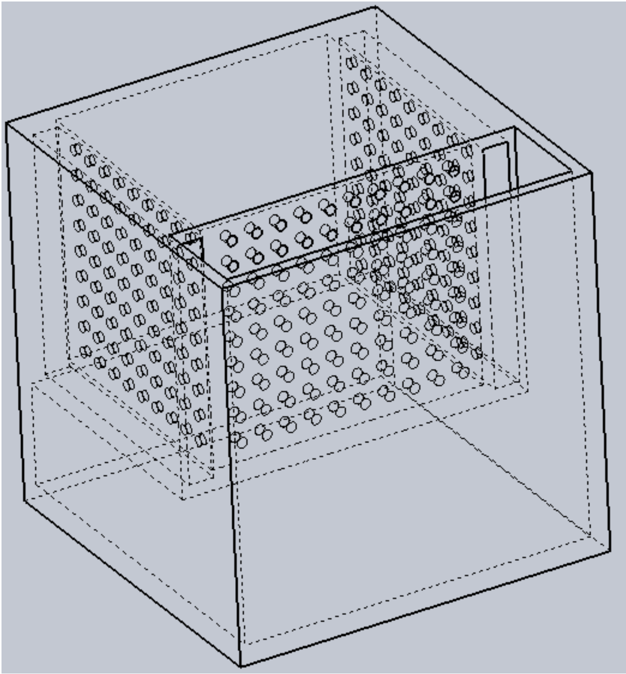
CFD software, the simulation can start and the equations are solved iteratively as a steady-state or transient. At the end of the analysis, a postprocessor is used for to visualize the solution.

The simulations

In the following analysis, the cooker will be modeled on a Computer Aided Design package, SolidWorks and then import on a CFD software, Phoenics, in order to study the heat distributions in the cooker for different for different design. In fact, through the process of the design of the cooker, different geometries have been analyzed.
The first cooker design that has been studied is composed of a combustion chamber with the opening on the front. The design follows the rocket stoves principles such as the same cross section all along the combustion chamber.



Screenshot from SolidWorks showing the first design of the cooker, view from the front



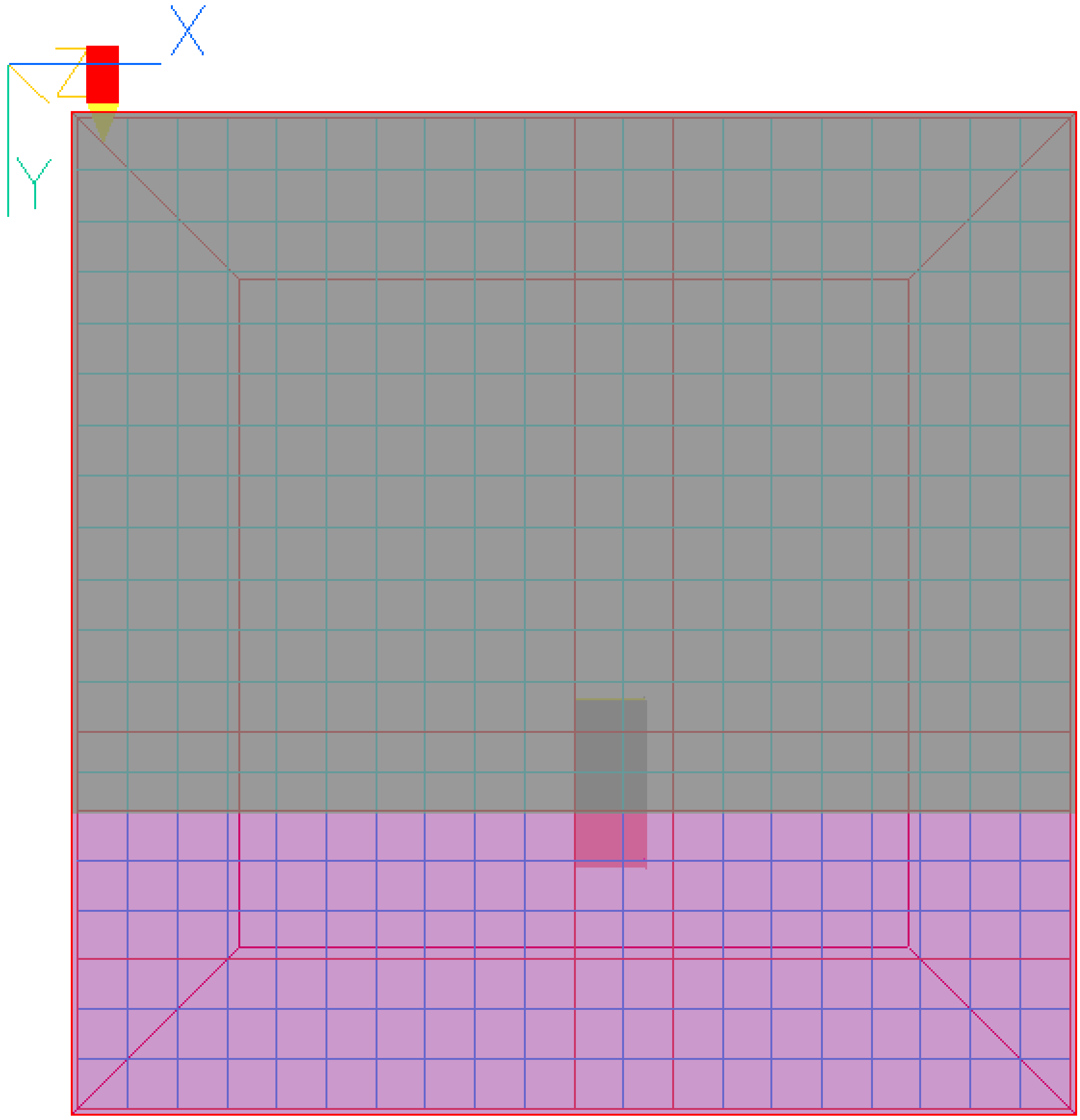
Screenshot from SolidWorks showing the first design of the cooker, view from the back, in hidden lines style

The cooker has been created by using the “extruded based” and “”extruded cut” functions to obtain the global geometry, and then to get the holes in the oven, the matrices have been used.

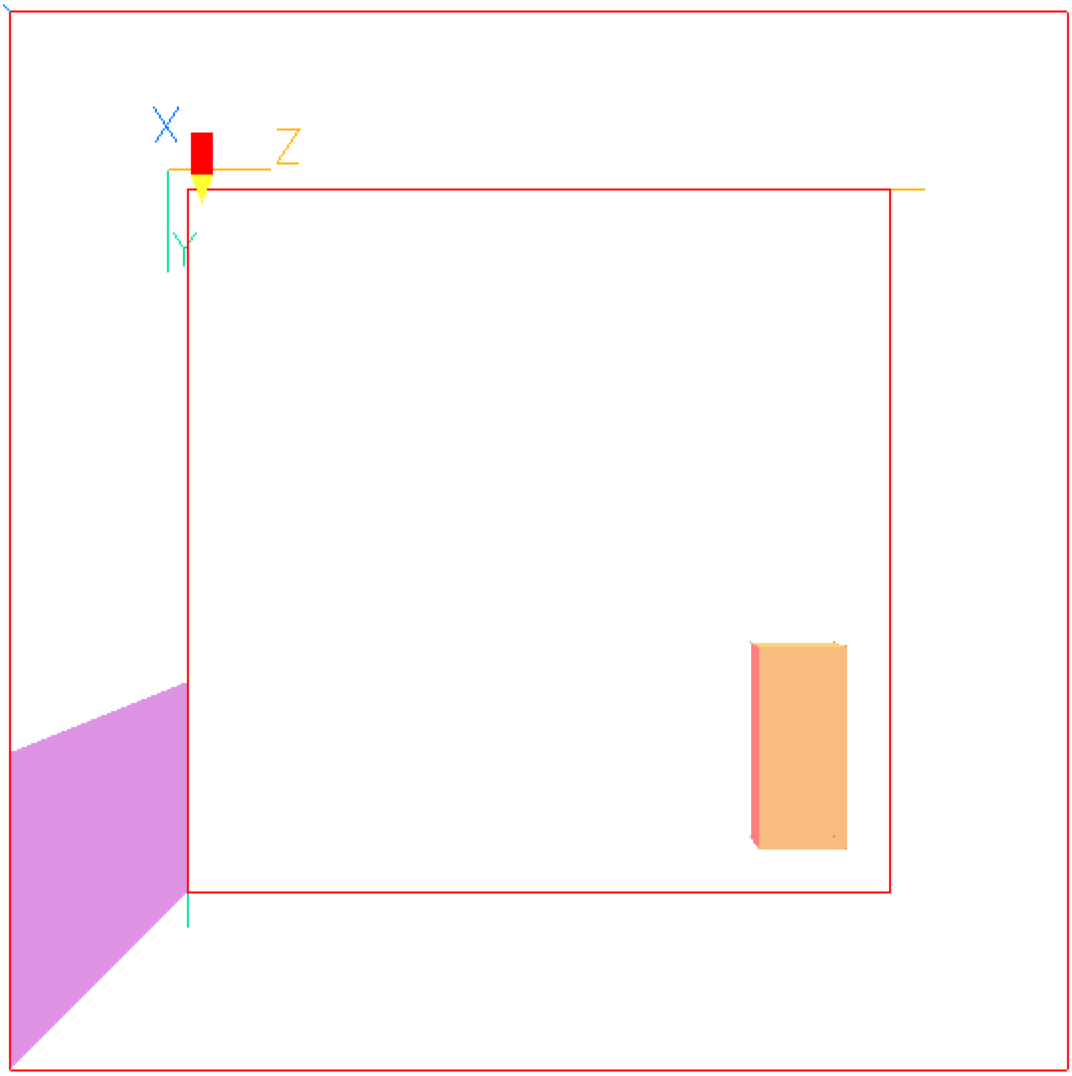
Then, Phoenics, the CFD software is used with the module Flair. In fact, after many attempt to model the combustion with the module Core, the normal one, it has been found out thanks to a series of tutorial that the module Flair allows to model a flame with a default model called Fire.
In the CFD environment, first the domain is empty, so objects have to be added in order to model the cooker. Thus, the cooker geometry is import from SolidWorks to Phoenics thanks to a Stl. File. The cooker is properties are set, the main one is its materials, the steel.
The size of this object and its location are adjusted in the domain. The second object is the flame which is created thanks to the Fire model in Phoenics Flair. This element is set in the combustion chamber, in the corner of the L shape. Fire properties are set in the objects menu, the essential parameter is the temperature of 1205°C, assumed from the adiabatic flame temperature.
As to have combustion, a flame, air is required; the software needs to have defined where the input of air is. Thus, Inlet element is set at the entrance of the combustion chamber. Inlet properties are set in the attributes menu, such as the inflow of 0.2m/s in the Z direction the direction in which the air mainly flows into the combustion chamber. The temperature is defined as the outside temperature of 25°C.

Then, the domain has been defined. The first task was to adjust the domain size; it is a cubic area of 10side. All the objects have to be fit in the domain and nothing should go out of the domain, in order to do that the function “constrain object by domain” has been selected. Then, the domain properties have been define, the chosen turbulence mode “KECHEN”, coordinate

Cartesian and a transient flow .In fact, the problem is not steady as it changes from an initial temperature of 25°C to the flame temperature. The time of the analysis has been defined as 300s divided into 30 steps, in order to have enough time to have significant result and do not make the solver to long. The energy equation has been set as temperature as is the main parameter of this analysis.
Then, the numerical grid has to be set; the space has to be meshed in order to run the analysis. The meshing as been set such as there are 20 elements in each directions. As the domain is cubic, each sides have the same length of 10units, so each length is composed of 20 elements of 10/20=0.5units length. This process is called discritization and it has an important impact on the numerical solution.

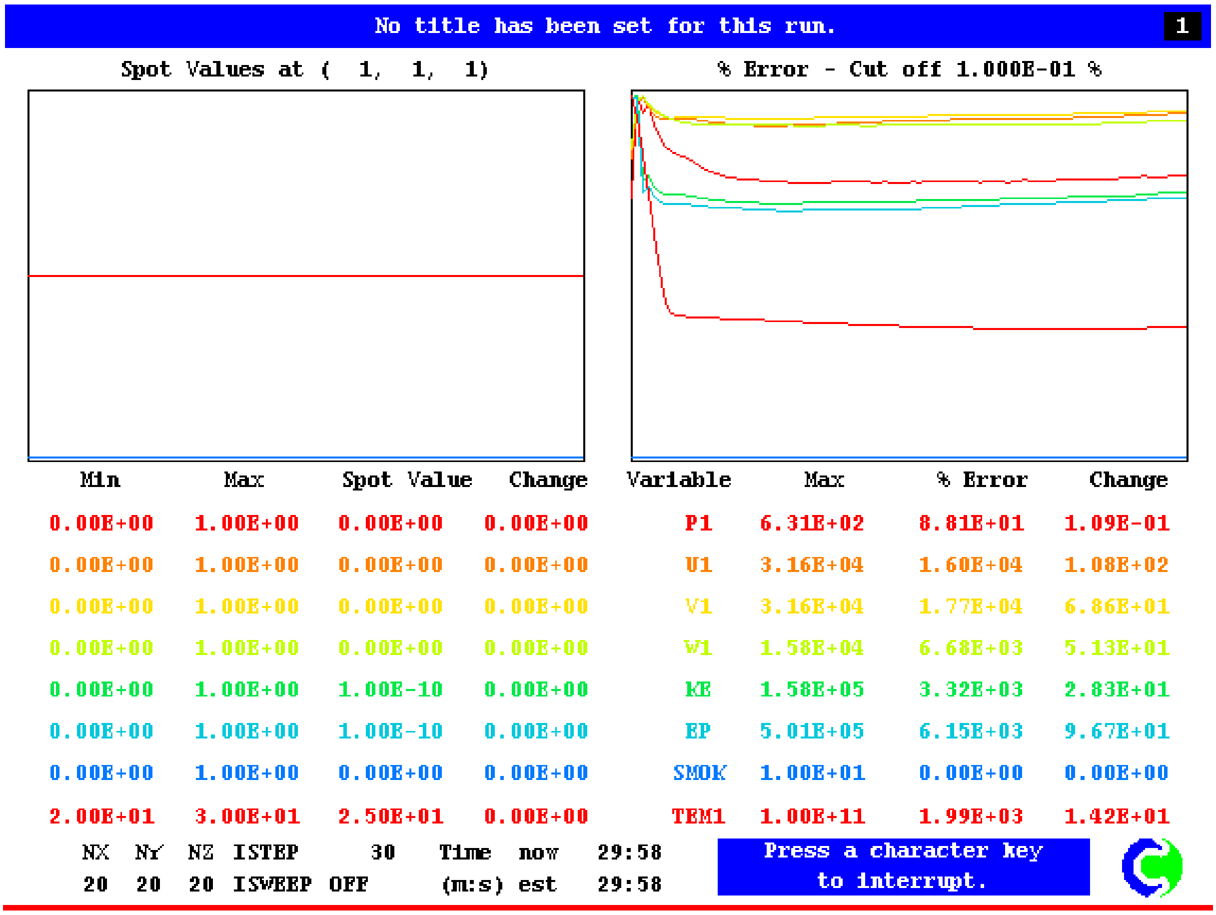


Screenshot form Phoenics of the meshing, the grid, and the inlet in purple



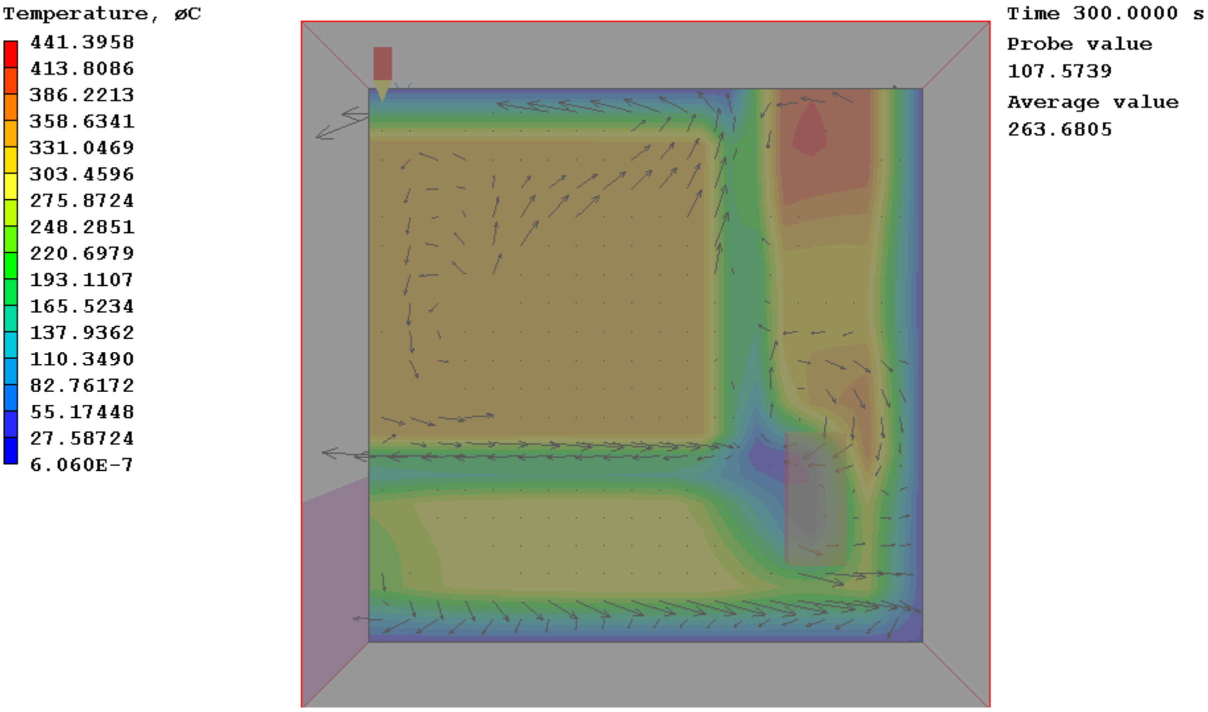
Screenshot form Phoenics of the fire object, orange block on the right side, and the inlet in purple

Then, the solver of the software is run in order to study the fluid dynamics of the problem. The solver is present as the following figure.



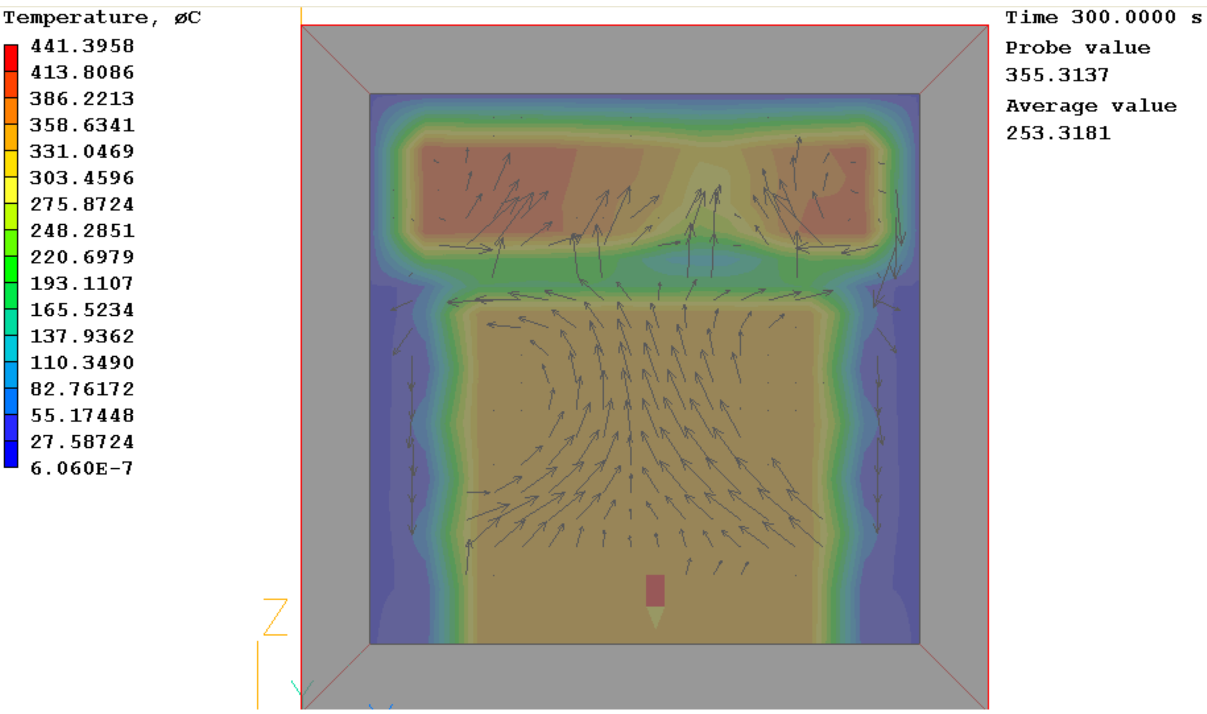
Solver of Phoenics

The following results are presented thanks to screenshots made on Phoenics. The main result is the side views as it shows the distribution of the heat all along the combustion chamber of the cooker. Thus, on the following figure is present the heat distribution, in color and the heat flow, with the arrays.



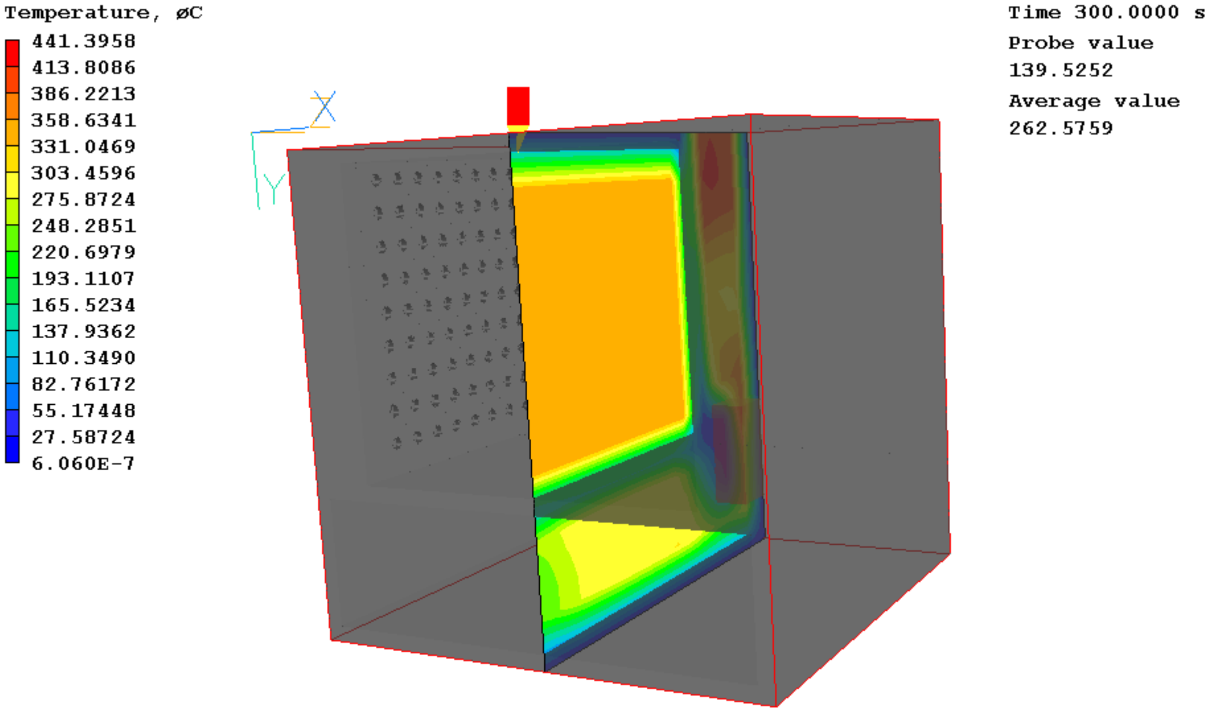
Result of the temperature distribution in the first simulation of the cooker, view from the side

The results confirm the efficiency of the L shape combustion chamber recommended by the rocket stove principles. In fact, above the flame and next to the back of the chamber an increase of temperature occurs. In addition, the heat distribution in the oven is uniform as desired, with a value of 358°C. The top side point of view will confirm the uniform distribution as can be seen on the following figure.

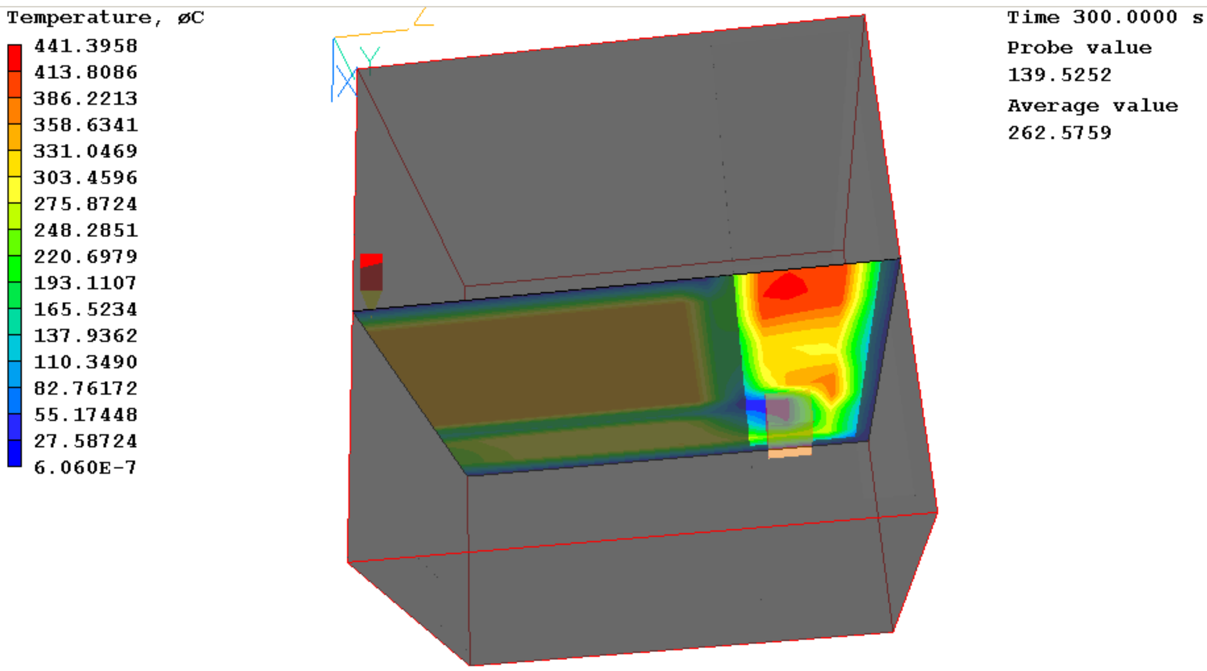


Result of the temperature distribution and the heat flow with the arrays, in the first simulation of the cooker, view from the top

As can be noticed, the passage of the heat on both opposite side of the oven works. In fact, as it is described by the arrays, the heat flows all along this space, goes through the oven and by a backward movement create a uniform heat in the oven.

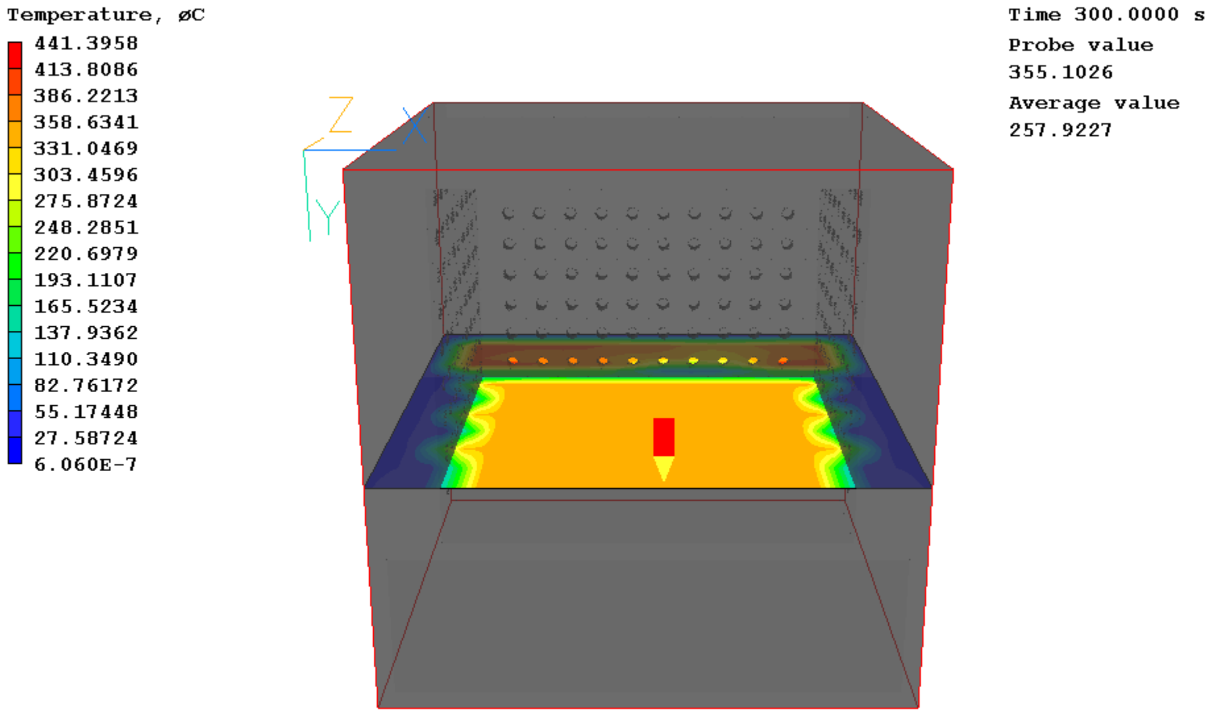


Result of the temperature distribution in the first simulation of the cooker, view from the front



Result of the temperature distribution in the first simulation of the cooker, view in the vertical part of the combustion chamber

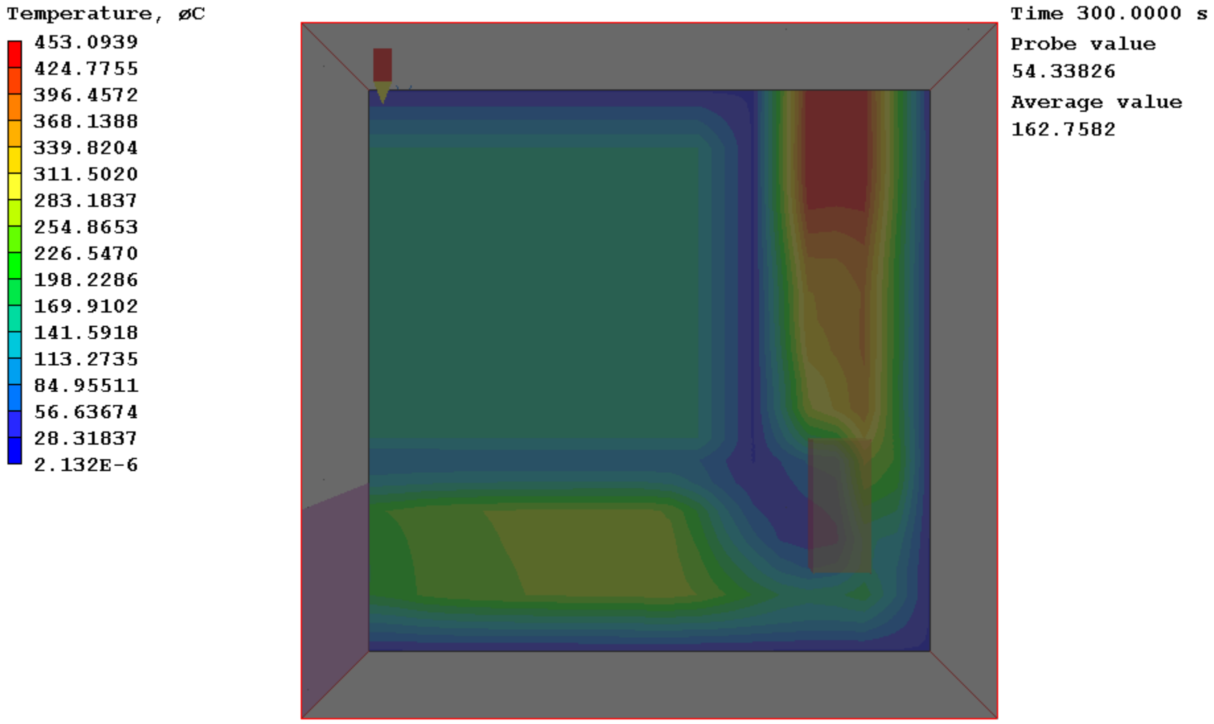
As can be seen on the previous figure, the heat reached its higher value at the top of the combustion chamber. In fact, by hitting the walls the particles get excited and the temperature increased. Thus, the constant cross section recommended by the rocket stove principles works as well. This high temperature at the top side is a very good point as it is the place where the hot plate will be set.



Result of the temperature distribution in the first simulation of the cooker, view of the oven

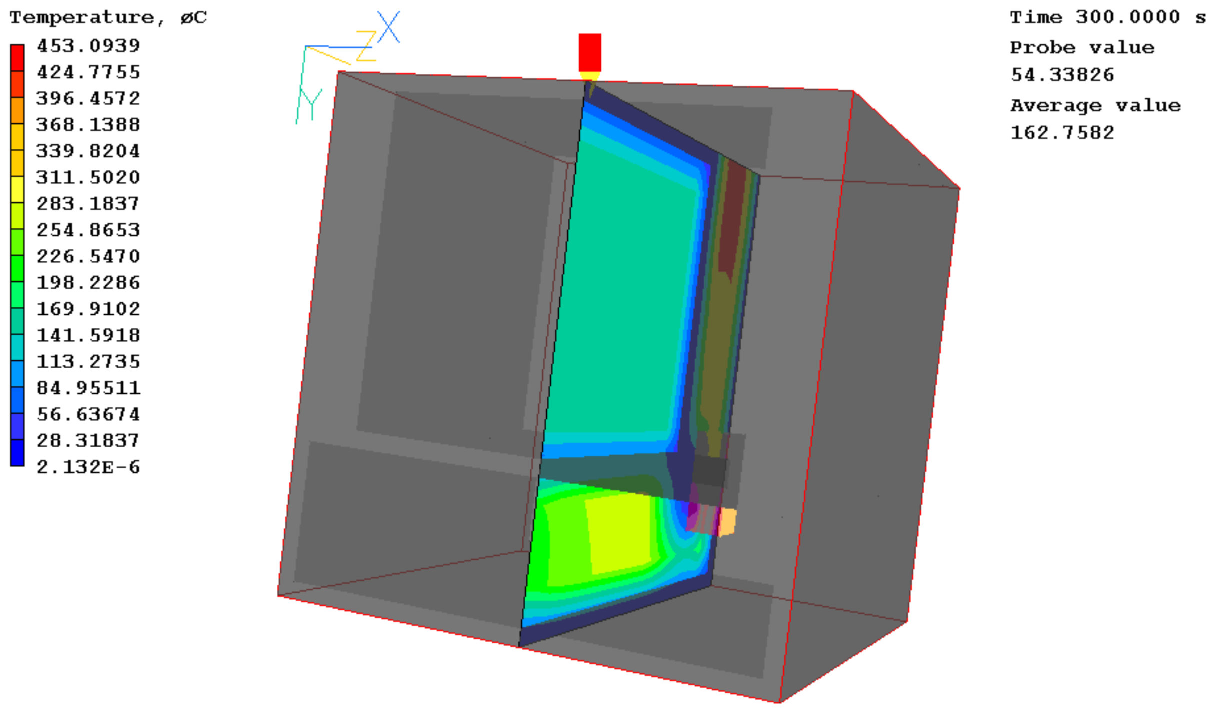
As it has been said previously, flow through narrow section provides an increase of temperature. This theory has been confirmed and it is shown by the previous figure. In fact, on the sides of the oven from the spaces where the heat flows from the flame to the oven, by heat transfer in the steel and by the holes the temperature increased from 165°C (light blue) to 358°C (orange).

Thus, the holes in the oven seem to make the heat flows quiet well. Then, it would be interesting to see how the cooker works without these holes. The following analysis uses the same setting and geometry, the only difference is the absence of the holes on the oven sides.

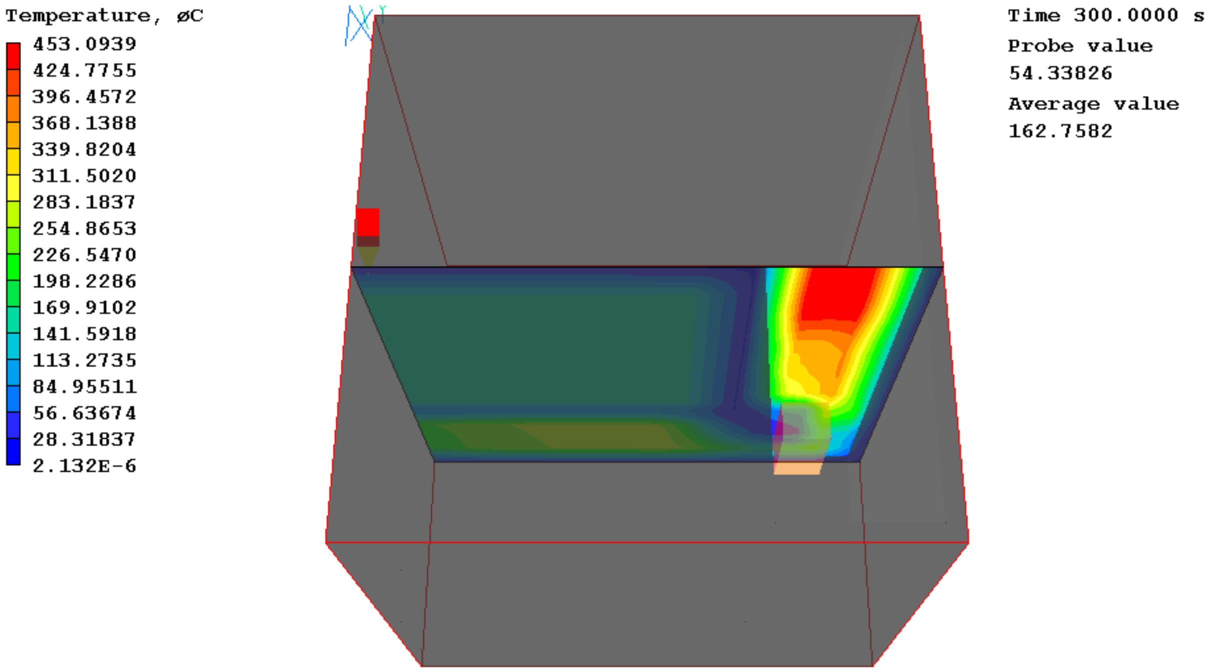


Result of the temperature distribution in the second simulation of the cooker, view from the side

The funding heat distribution follows the same phenomena that in the previous analysis but the absence of holes in the oven leads to smaller temperature of cooking, 169°C instead of 358°C found in the previous case.

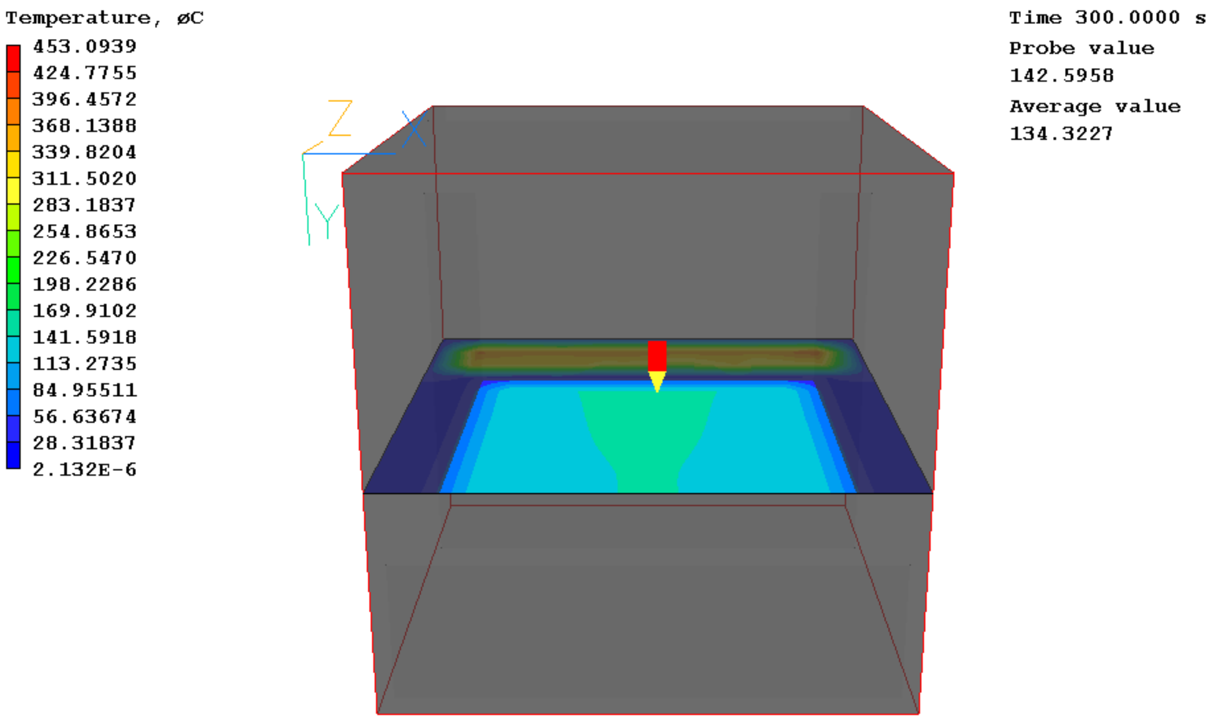


Result of the temperature distribution in the second simulation of the cooker, view from the front



Result of the temperature distribution in the second simulation of the cooker, view in the vertical part of the chamber

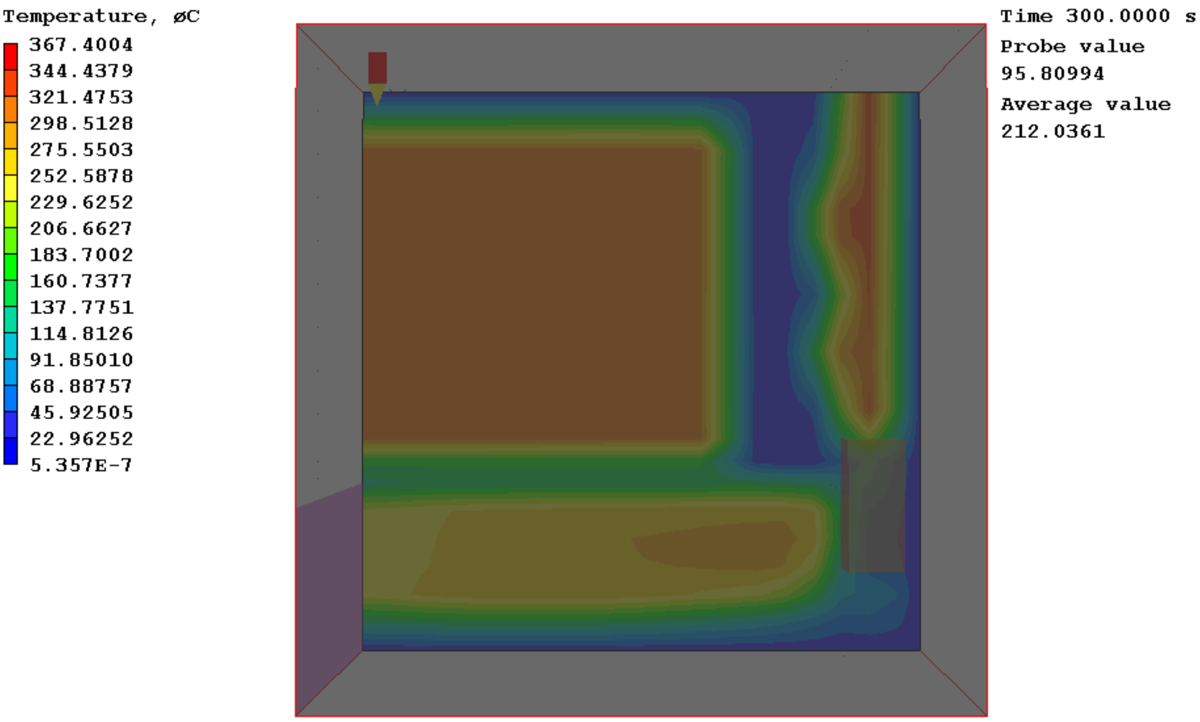
Then, the heat increase generated at the top of the chamber leads to the same temperature than in the previous case, 453°C. Thus, the hot plate in both case will receive the same temperature.



Result of the temperature distribution in the second simulation of the cooker, view in the oven

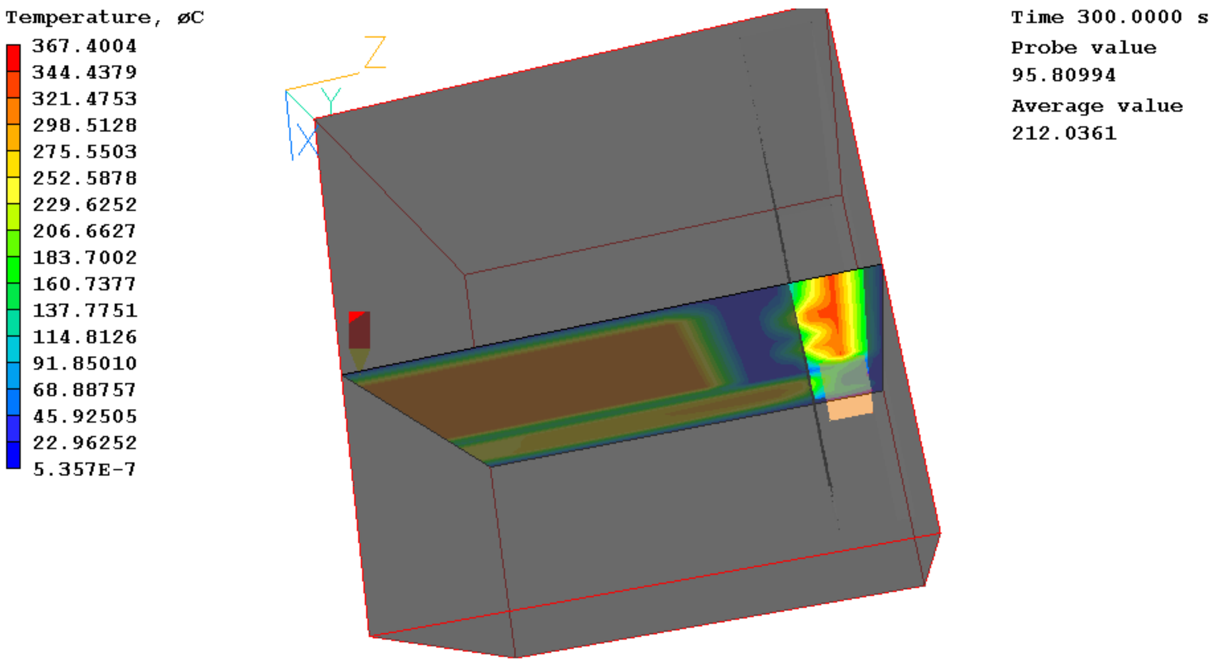
In fact, as can be noticed on the previous figure, as there is no hole in the oven there is no narrow section effect. As a consequence the flow is smoother and only heat transfer through the steel creates high temperature in the oven but this temperature is lower than with the use of holes because there is not the same particles excitation.

As in the real cooker, the combustion chamber opening might not be so large, the following analysis is accomplished using the same configuration but with a cooker composed of a smaller combustion chamber, half of the size of the former combustion chamber cross section. This provides the following results.

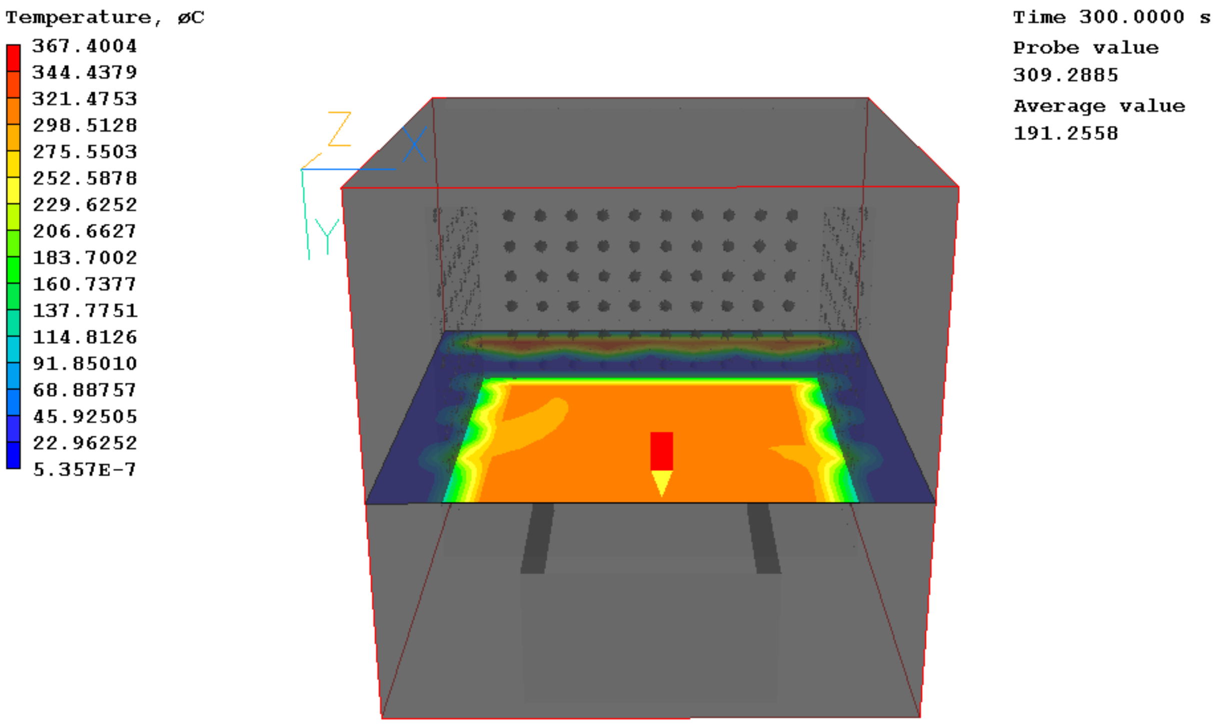


Result of the temperature distribution in the third simulation of the cooker, view from the side

As can be seen on the previous figure, the temperature reach in the oven is a lower than the one found in the first analysis. As the flame is at the same temperature, it must be because there is not a much air flow than in the first study. Then, it seems that the fact of reducing the cross section made the heat flow straighter. In fact, in the vertical part of the chamber the heat distribution is straight, reaching 367°C at the top, which is again lower than in the first simulation.



Result of the temperature distribution in the third simulation of the cooker, view in the vertical part of the combustion chamber



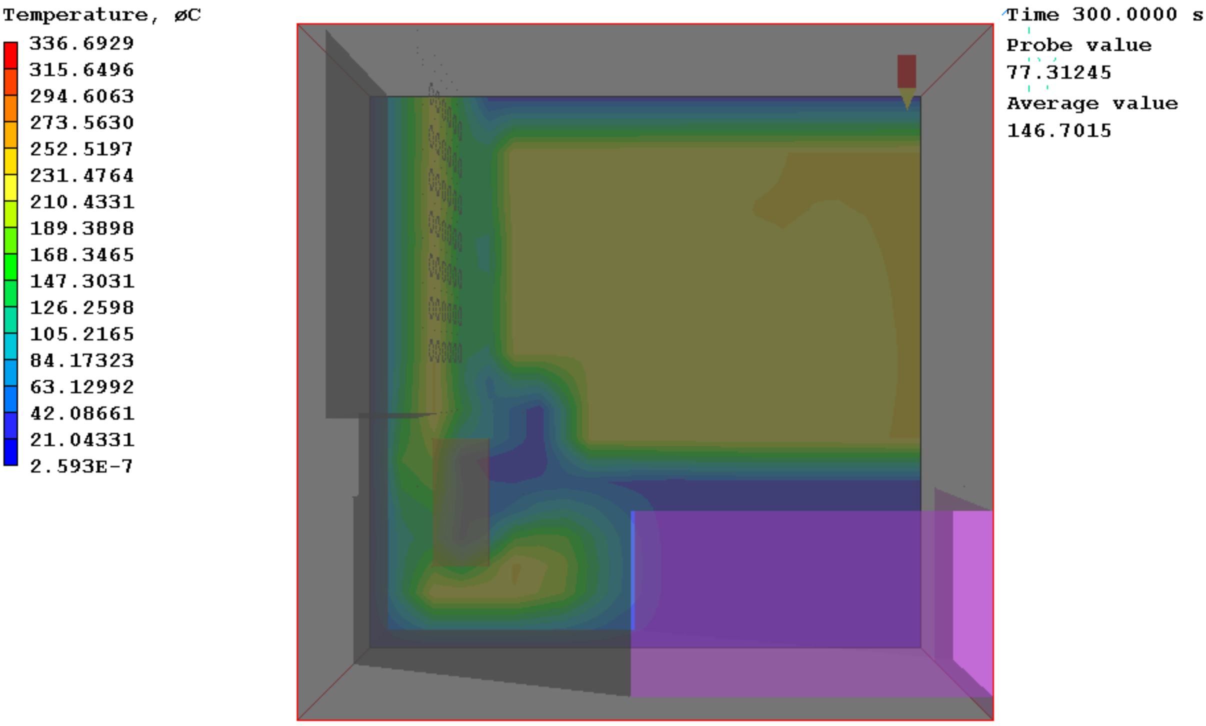
Result of the temperature distribution in the third simulation of the cooker, view in the oven

For this simulation, it has been found that the temperature distribution is still uniform but with a lower value of 298°C.

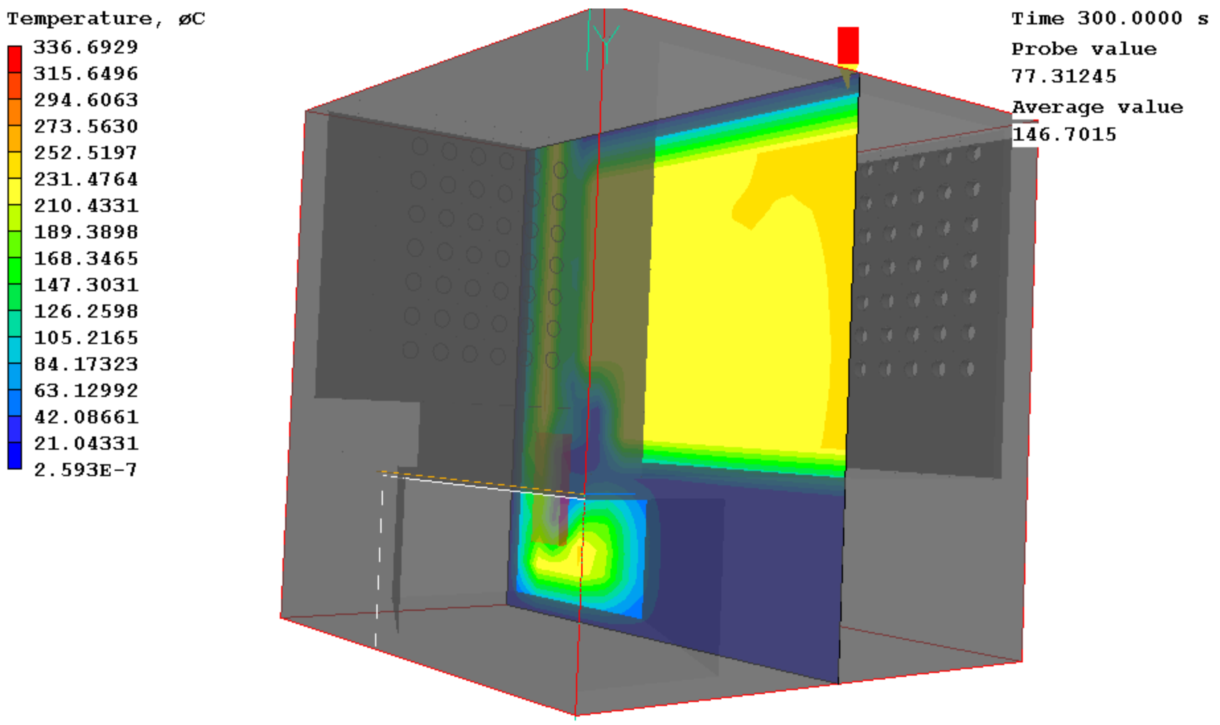
As it has been noticed, a thin chamber in the vertical part of the L shape chamber provides a better heat flow, while still respecting the uniform cross section rule. Then, if this vertical part becomes thinner, the flame will not have enough space, so the cross section around the flame will be the same than in the previous simulation while the vertical part will be thinner, but wider to keep the same cross section.

Then, in order to improve the design and the ergonomic, it has been decide to set the combustion chamber in diagonal in order to avoid the wood sticks feeding the combustion chamber going out of it and disturb the user of the cooker who desire to be in front of his machine.

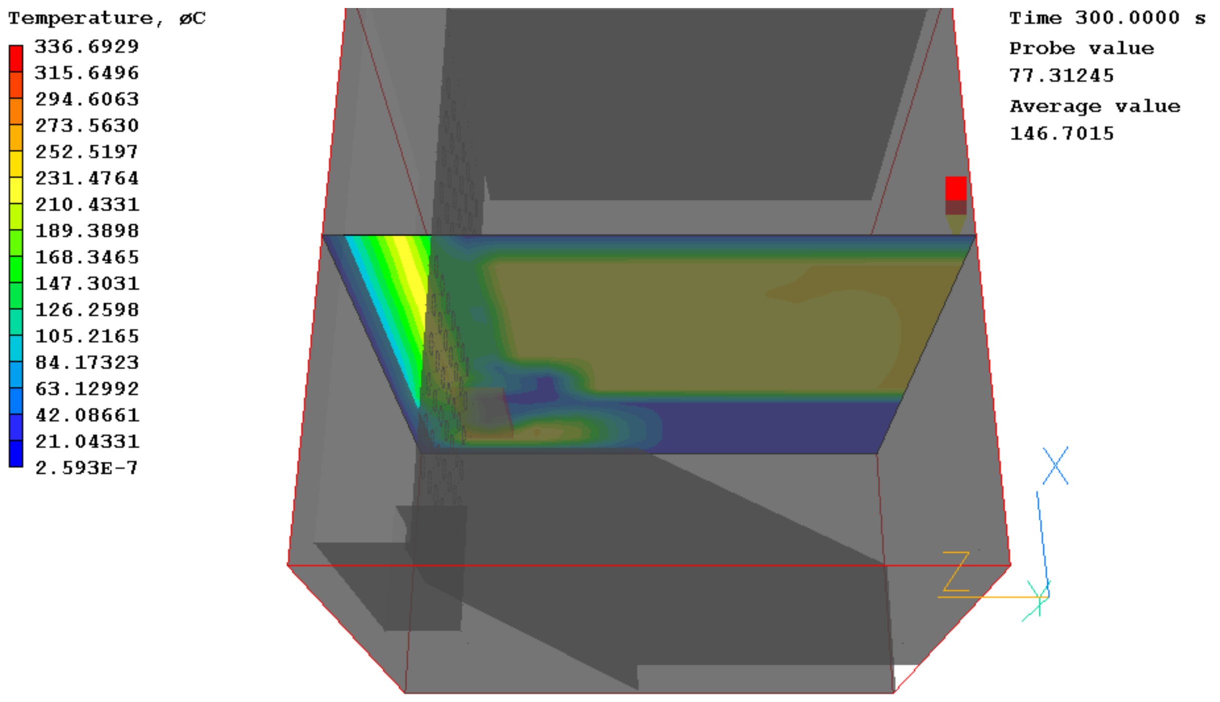
This leads to the following results.



Result of the temperature distribution in the fourth simulation of the cooker, view from the side



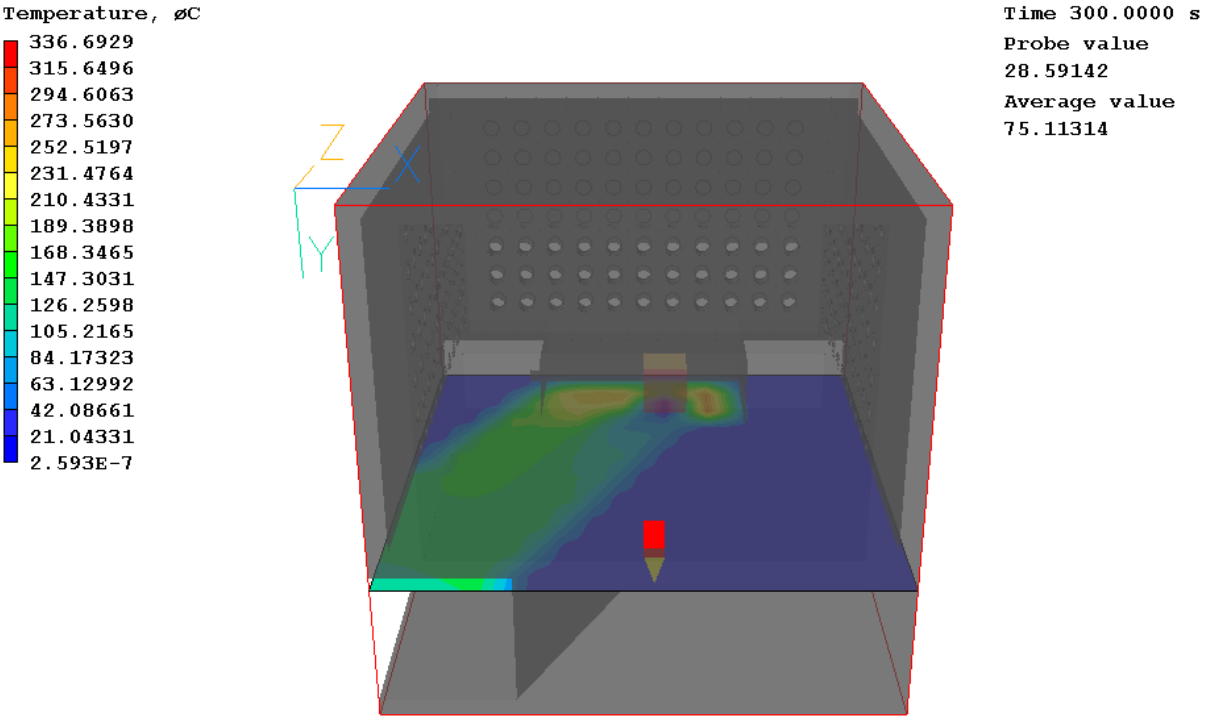
Result of the temperature distribution in the fourth simulation of the cooker, view from the entrance of the combustion chamber



Result of the temperature distribution in the fourth simulation of the cooker, view in the vertical part of the combustion chamber

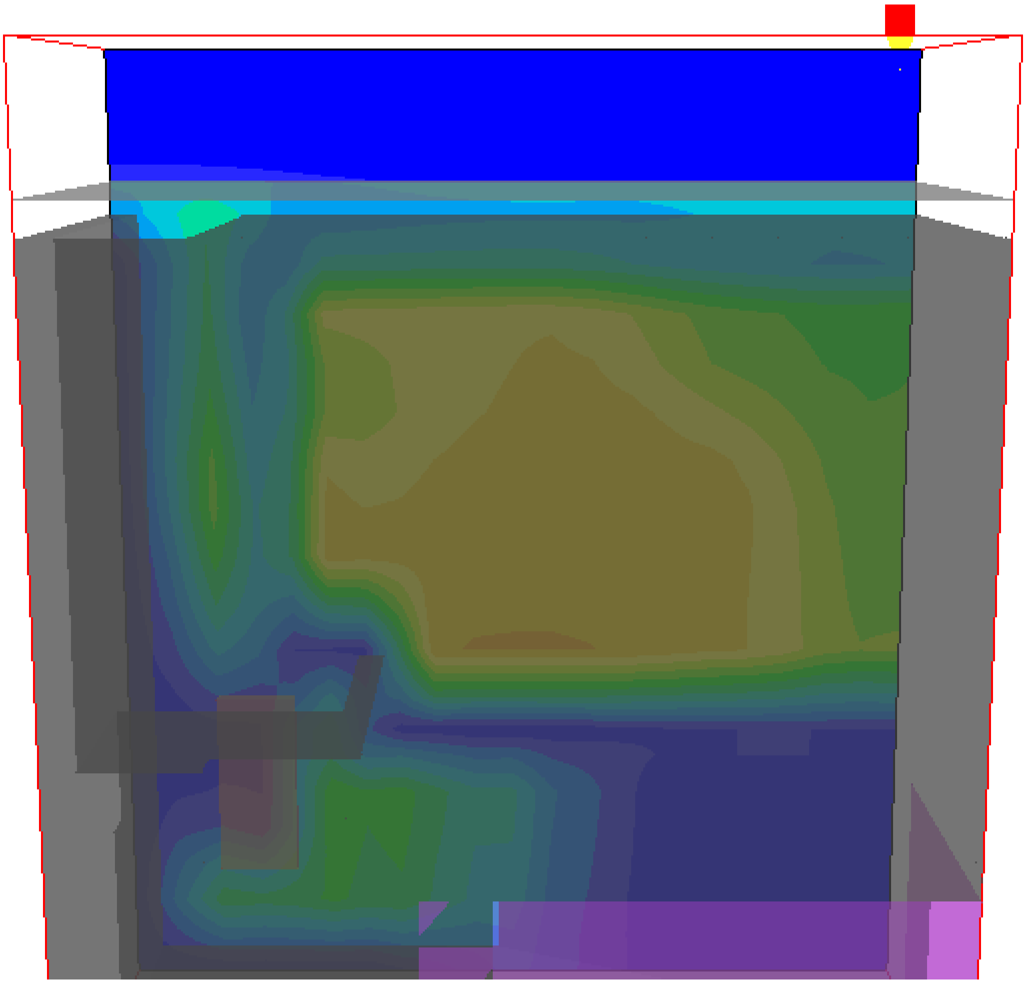
As can be visualized, the heat distribution follows the same displacement than in the previous simulation. The result in term of temperature is lower than in the other analysis, with 252°C in the oven and in direction of the future hot plate, which is more than enough to cook. In fact, in domestic cooker the maximum temperature in oven is usually 220°C. Thus, even though the design seems to be less efficient than the previous ones, it is the one desire by the users of Lammas.

In addition, the use of the diagonal combustion chamber entrance does not seem to imply problems. In fact, the same increase of temperature is observed at the angle of the chamber.

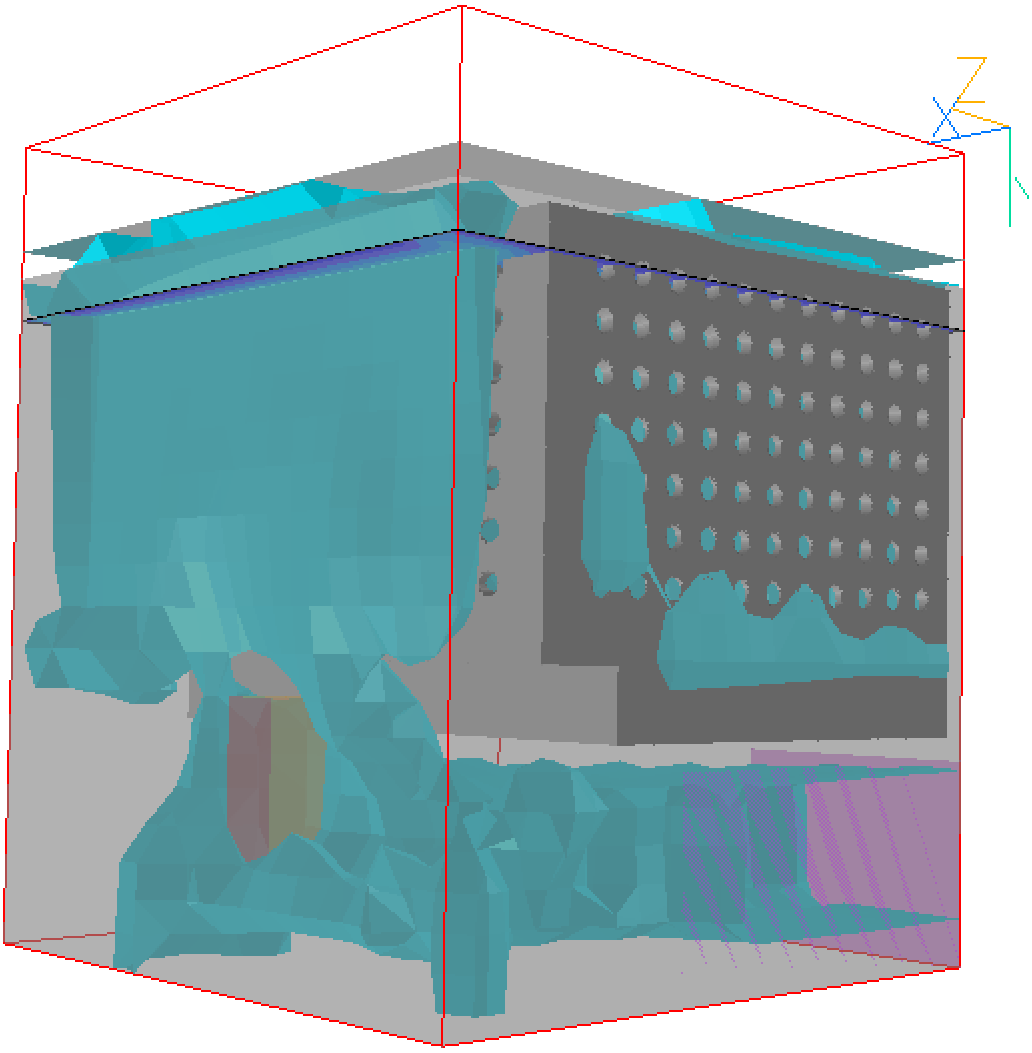


Result of the temperature distribution in the fourth simulation of the cooker, view through the combustion chamber

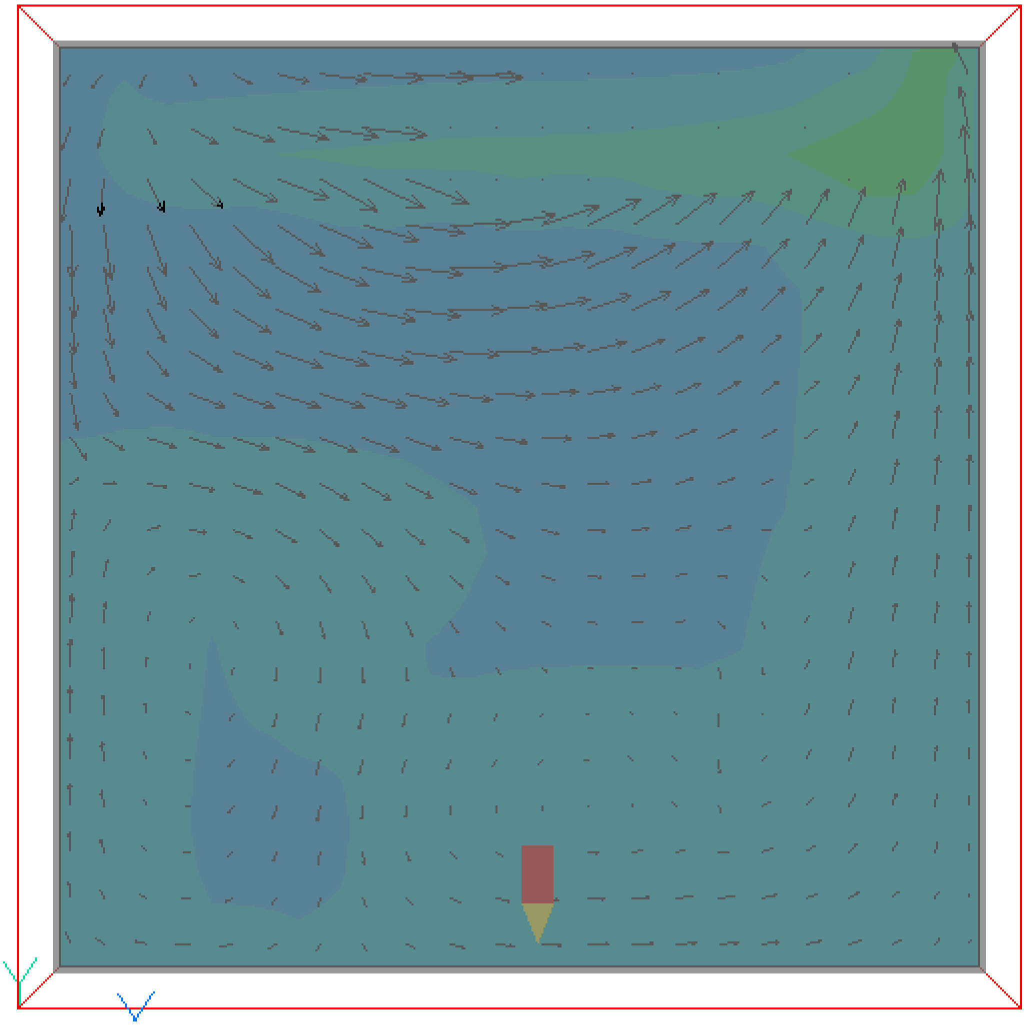
The last step to complete this series of simulation is to set the different materials and the hot plate on the top of the cooker. In fact, in the previous analysis the all cooker was modeled as in steel but in the real cooker, the combustion chamber is insulated using clay bricks, and only the oven box and the hot plate are in steel. That is the only parameter changing from the previous analysis. In order to achieved that the cooker is divided in three elements: combustion chamber, oven and hot plate in order to define the different materials for these parts. This provides the following results.



Result of the temperature distribution in the fifth simulation of the cooker, view from the side



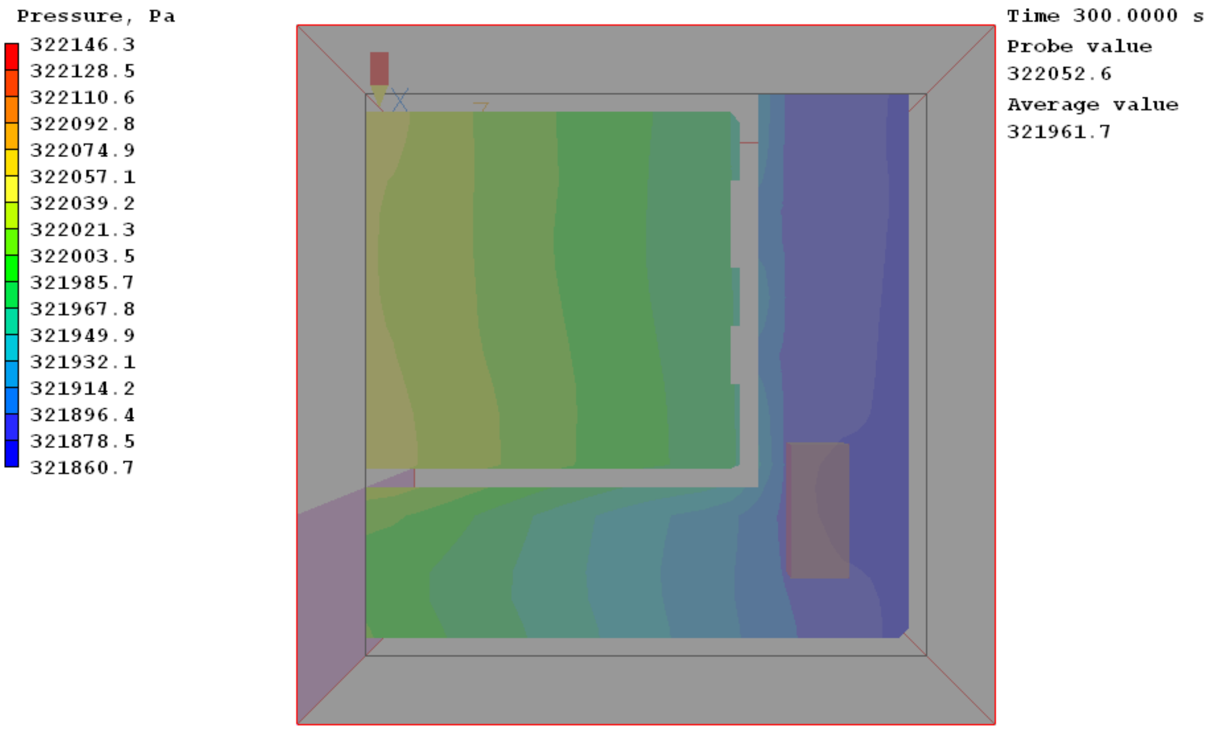
Result of the heat flow in the fifth simulation of the cooker, view from the back



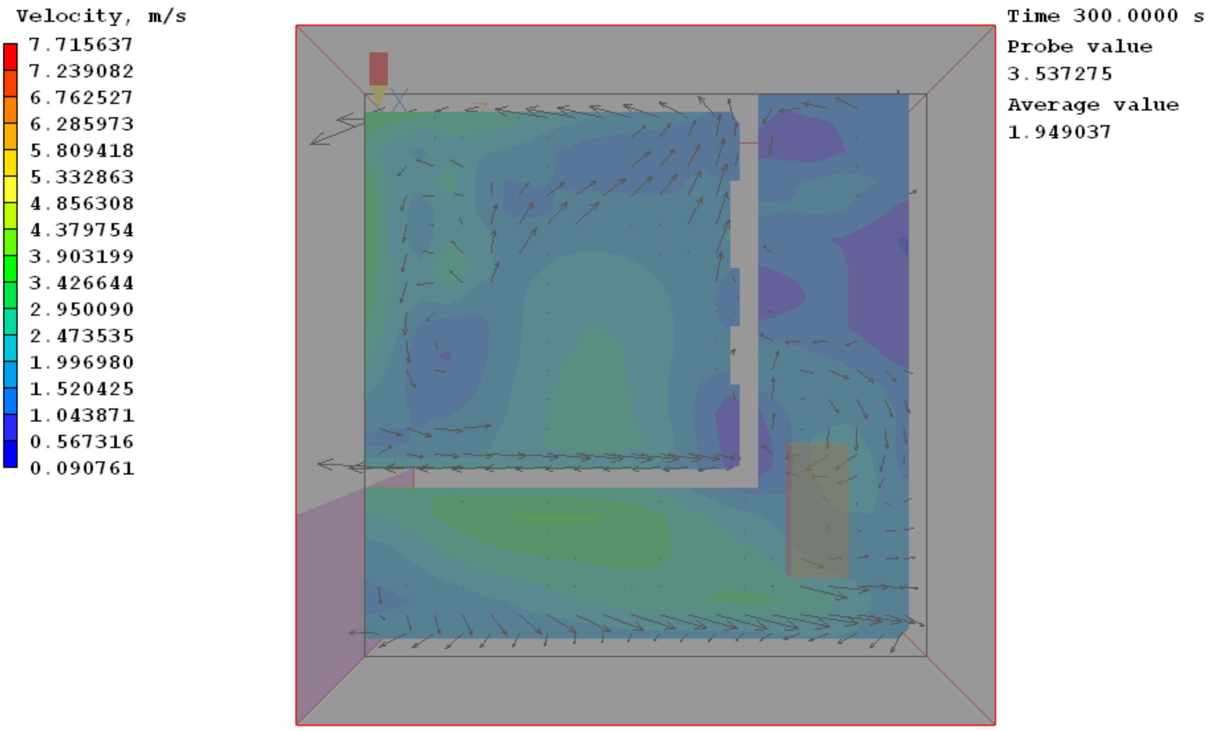
Result of the heat flow in the fifth simulation of the cooker, view from the top

This last screenshot is very interesting as it shows the heat distribution on the hotplate, which is a parameter essential to know in order to enable the user of the cooker to cook as he desires. Then, the figure also shows how the heat flows on this surface. Thus, the end of the flow is noticed to happen in the top right corner of the figure which gives the location of the chimney. As can be noticed, the resulted values of temperature are not presented, as the value found did not seem to be correct for this simulation. In fact, with the addition of the steel hot plate blocks the heat flow which leads to very high temperature. This in the real design can not happen because of the addition of the chimney, which will release some of the flow.

It can be interesting in order to have a better understanding of the fluid dynamics to study other parameter than the temperature. In fact, the velocity of the heated air and the pressure are presented as the result of the first simulation, cooker in steel with wide combustion chamber opening.



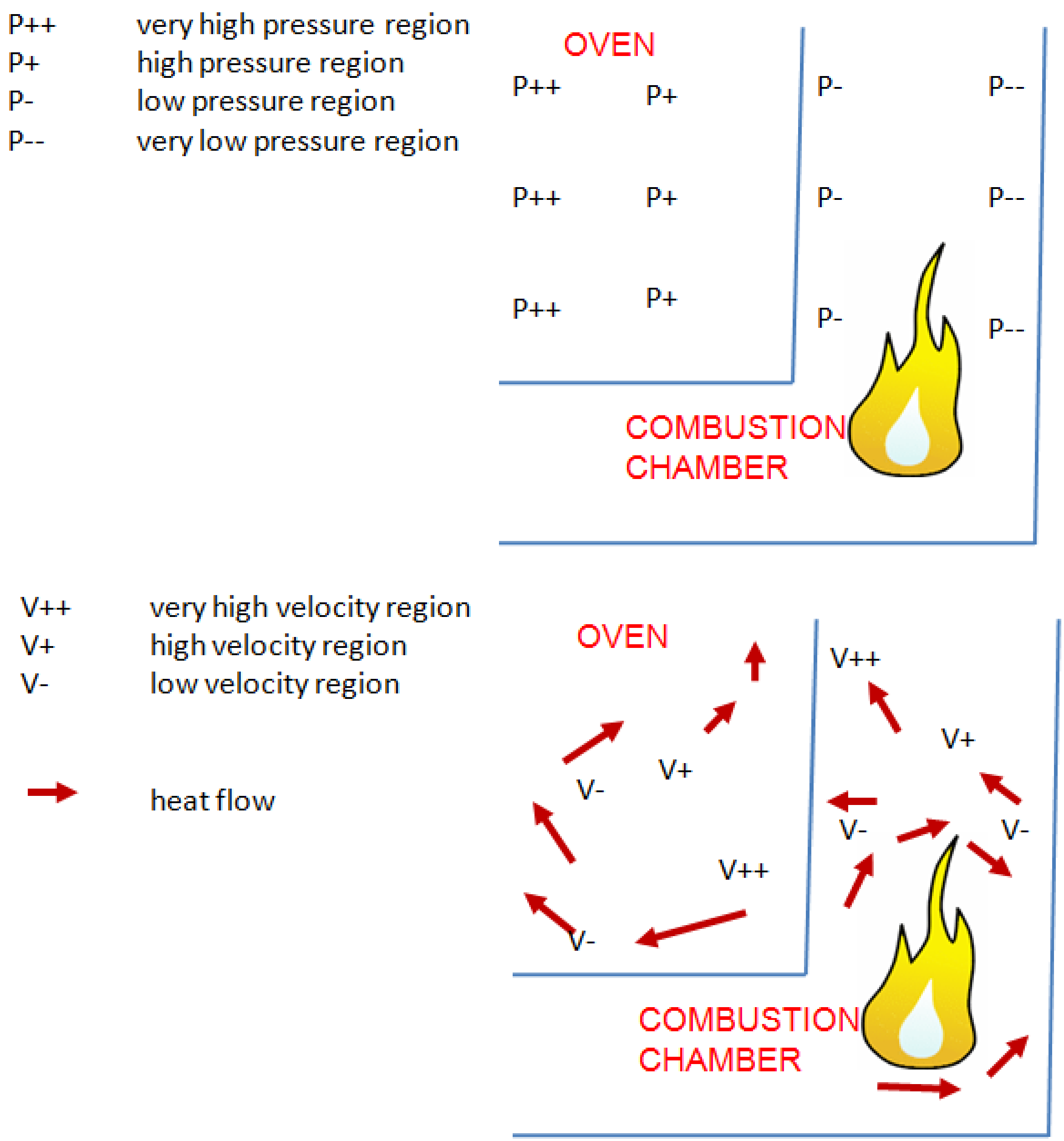
Result of the pressure distribution in the first simulation of the cooker, view from the side



Result of the velocity distribution in the first simulation of the cooker, view from the side

By analyzing these two previous figure is as been noticed that as the air flows through the combustion chamber to the vertical part of the chamber the velocity and the pressure change. As announced in the rocket stove literature the corner of the L shape chamber provide an increase of the velocity which is benefic in term of heat generation and cooking efficiency.

Then, it seems like when the velocity increases, the pressure decreases according to the results presented above, following the next figure:

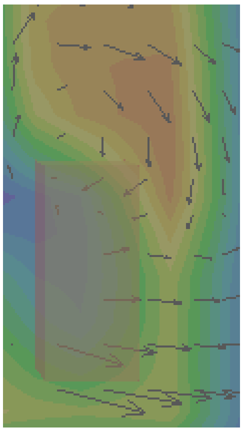


Pressure and velocity distribution in the combustion chamber

As can be seen on the previous draw, the pressure is important inside the oven. It can be noticed that the velocity increased inside the oven as well, when the fluid comes from the narrow sections of the holes in the oven. Thus, the velocity increase as it goes out of the narrow section while the pressure decreases. A fast heat flow is good in term of cooking so it is interesting that this increase not just happen in the back of the flame but also inside the oven.

This can be explaining by the Bernoulli principle and the theory of the incompressible flow. In fact, it said that for an inviscid flow, an increase in the speed of the fluid occurs

simultaneously with a decrease in pressure. Then, it said that by applying the continuity equation, the velocity of the fluid is greater in the narrow section, so the velocity starts to increase as it goes in the oven.
By looking at the streamlines, it can be seen that the fluid mostly moves following the shape of the chamber, from the opening to the top, but some reverse motion is created at some point and leads to another flow in the opposite direction. This can explain the fact that there is a decrease of the velocity as the heat flows to the top, by a creation of an important reverse flow.



Zoom on the velocity streamlines, from Phoenics screen

In fact, by hitting the walls of the combustion chamber the flow becomes unsteady and then does not moves as streamlines anymore producing eddies. It is a vortex effect, as it is illustrate in the following figure.

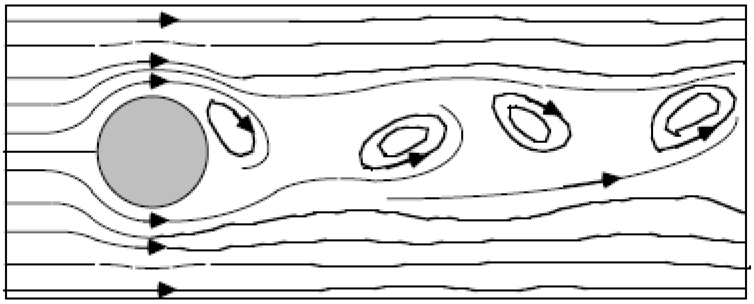
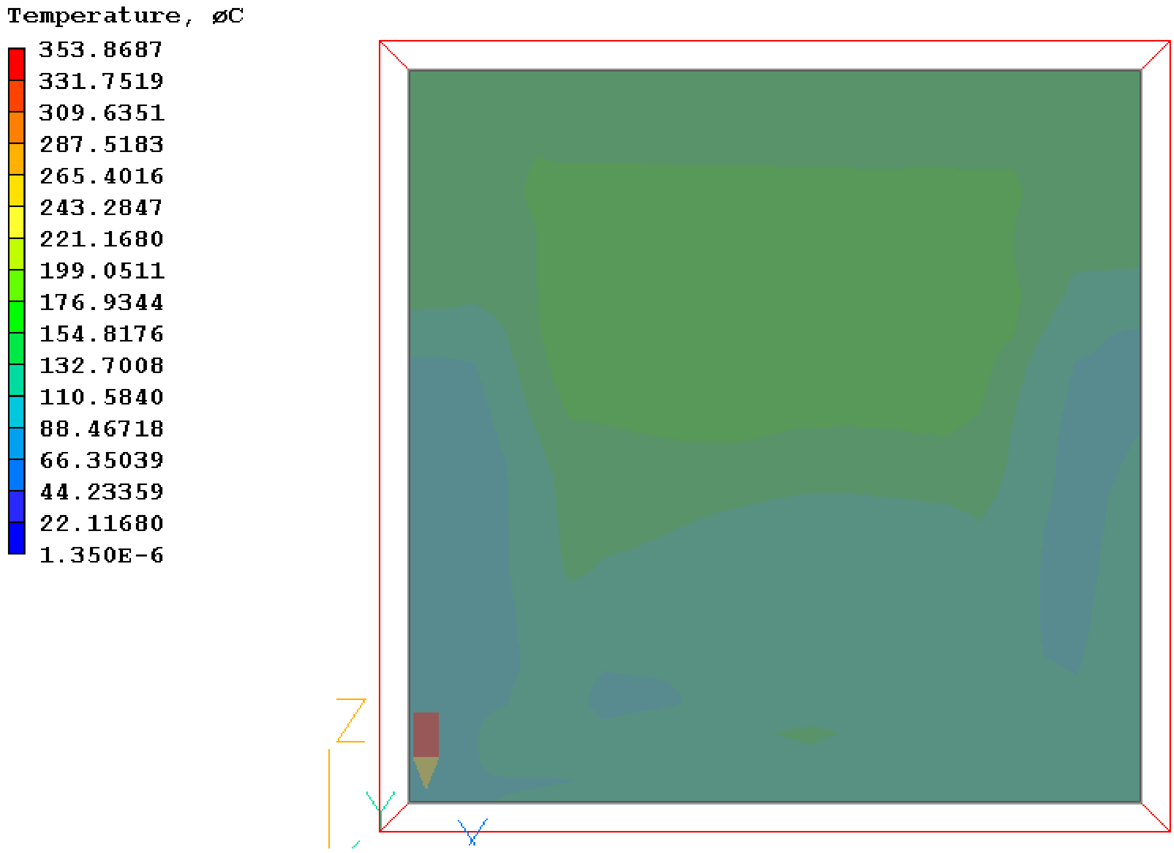


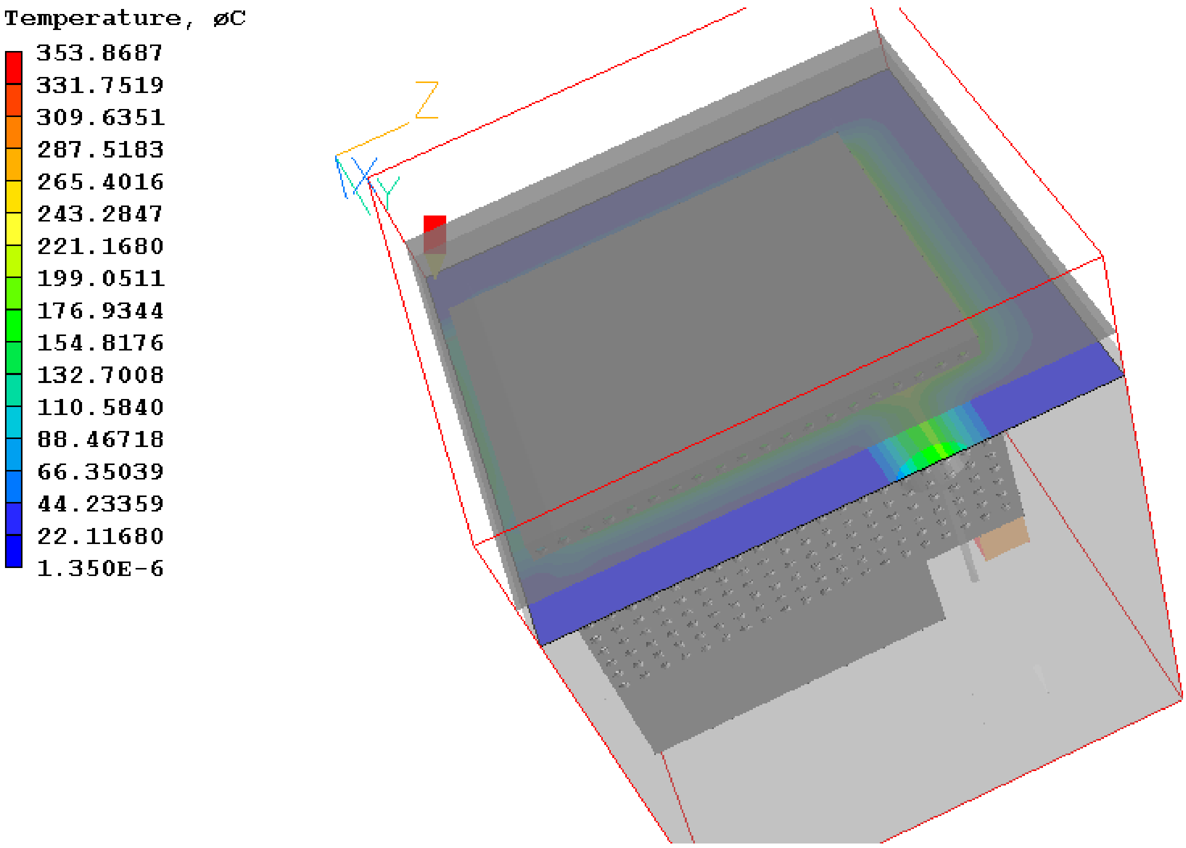
Figure showing turbulent vortex around a cylinder from Rotational Flows: Circulation and Turbulence

So as it can be seen, for fast flows the vorticity can be large a good distance downstream from a surface. In this case, the fluid cannot bend around the cylinder quickly enough
so it is "torn" away from the surface sending the vorticity downstream. When this happens the flow becomes turbulent. The turbulence is often described by the Reynolds number.

Finally, the result for the final cooker design are presented. Thus, the effect of the chimney and the temperature of the hotplate can be visualize.

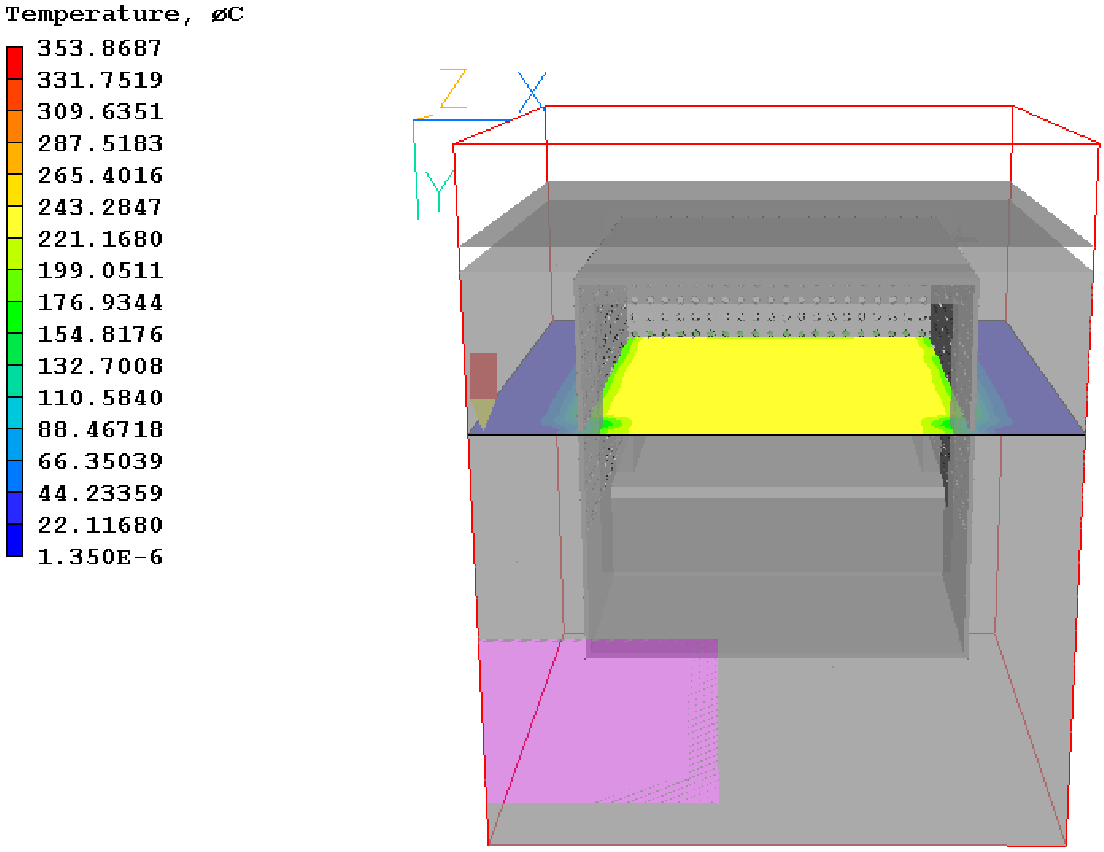


Result of the temperature distribution in the final design simulation of the cooker, view from the hotplate

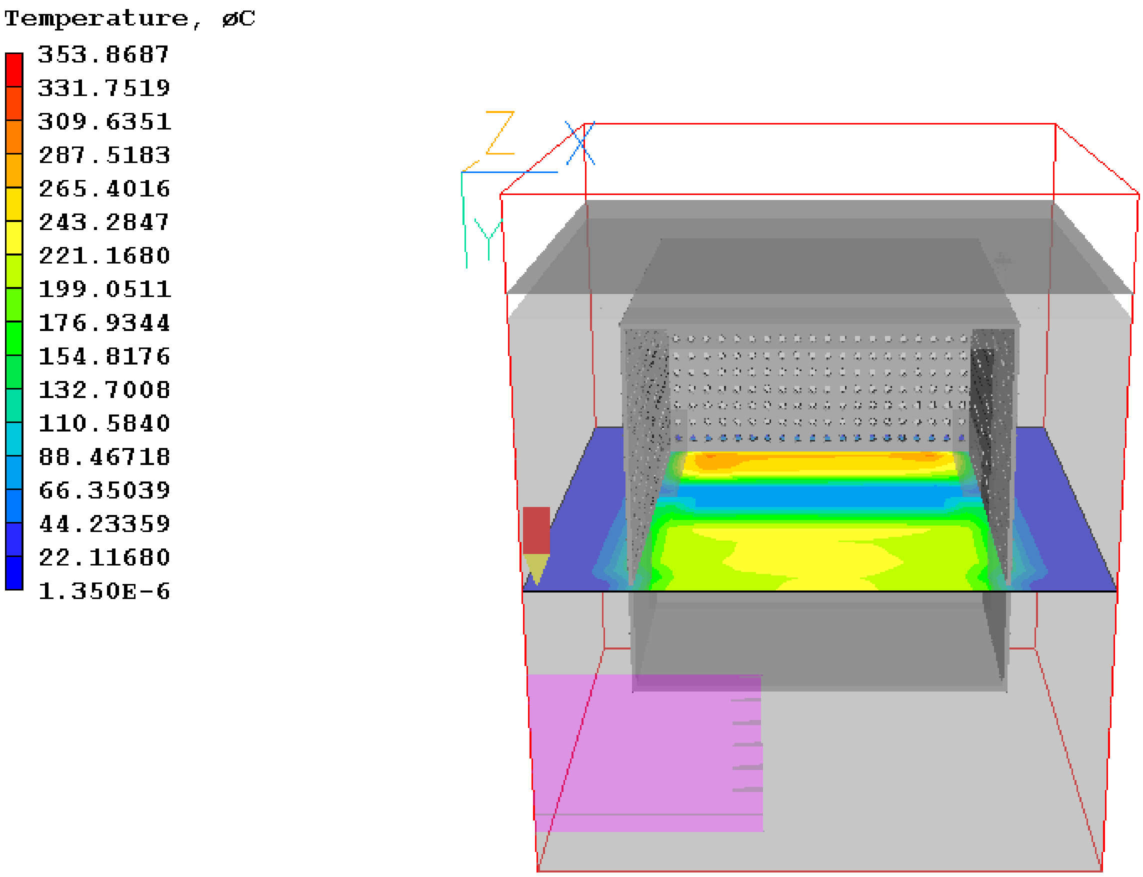


Result of the temperature distribution in the final design simulation of the cooker, view from the chimney hole

Then, it is interesting to know what is the temperature in the oven of the final design. Plus, the oven shape has an angle at the back, which provide an edge just above the flame. Thus, a higher temperature can be expected in this location.



Result of the temperature distribution in the final design simulation of the cooker, view inside the oven

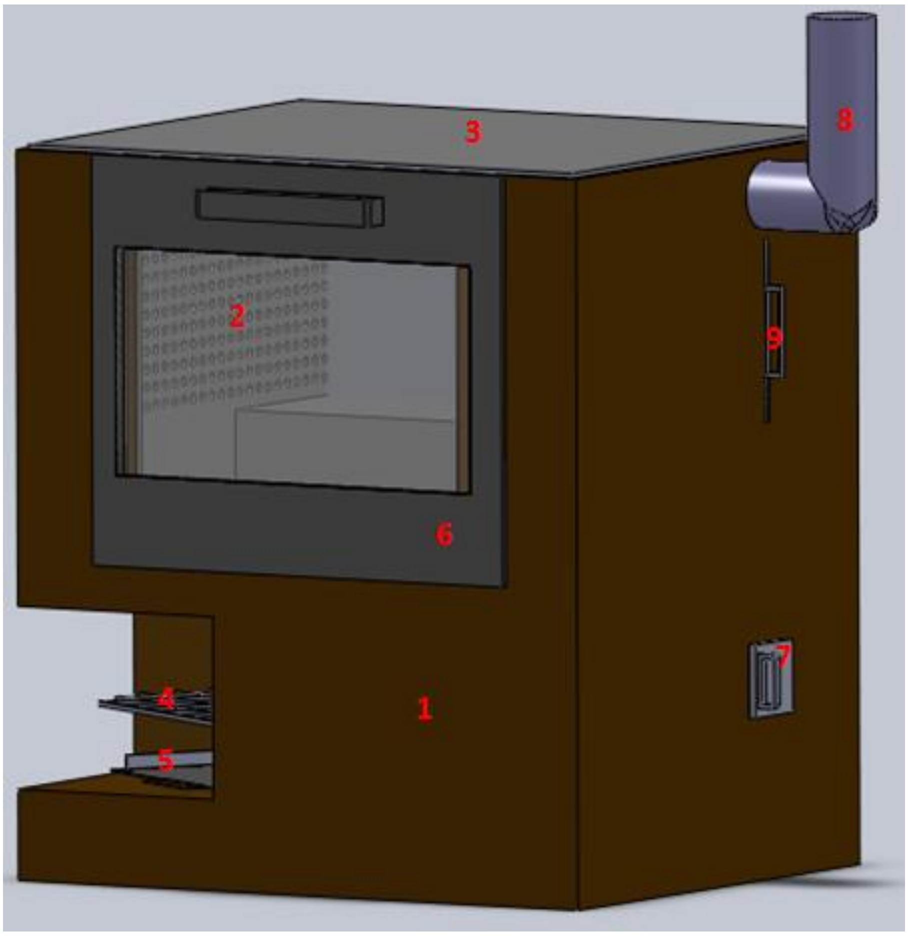


Result of the temperature distribution in the final design simulation of the cooker, view inside the lower part of the oven

Thus, according to the CFD simulation, the produced design is a cooker which provide an oven with a global temperature of 243°C and a maximum temperature of 287°C located in the back on the edge. The cooker provides an hotplate which enable a cooking from 221°C, at the back, to 110°C in the front part of the plate.

<u>Proposal and recommendations</u>

From background study of the cooking technology and of the fuel combustion, to the material, geometry and computational fluid dynamics analysis, the following cooker has been produced.

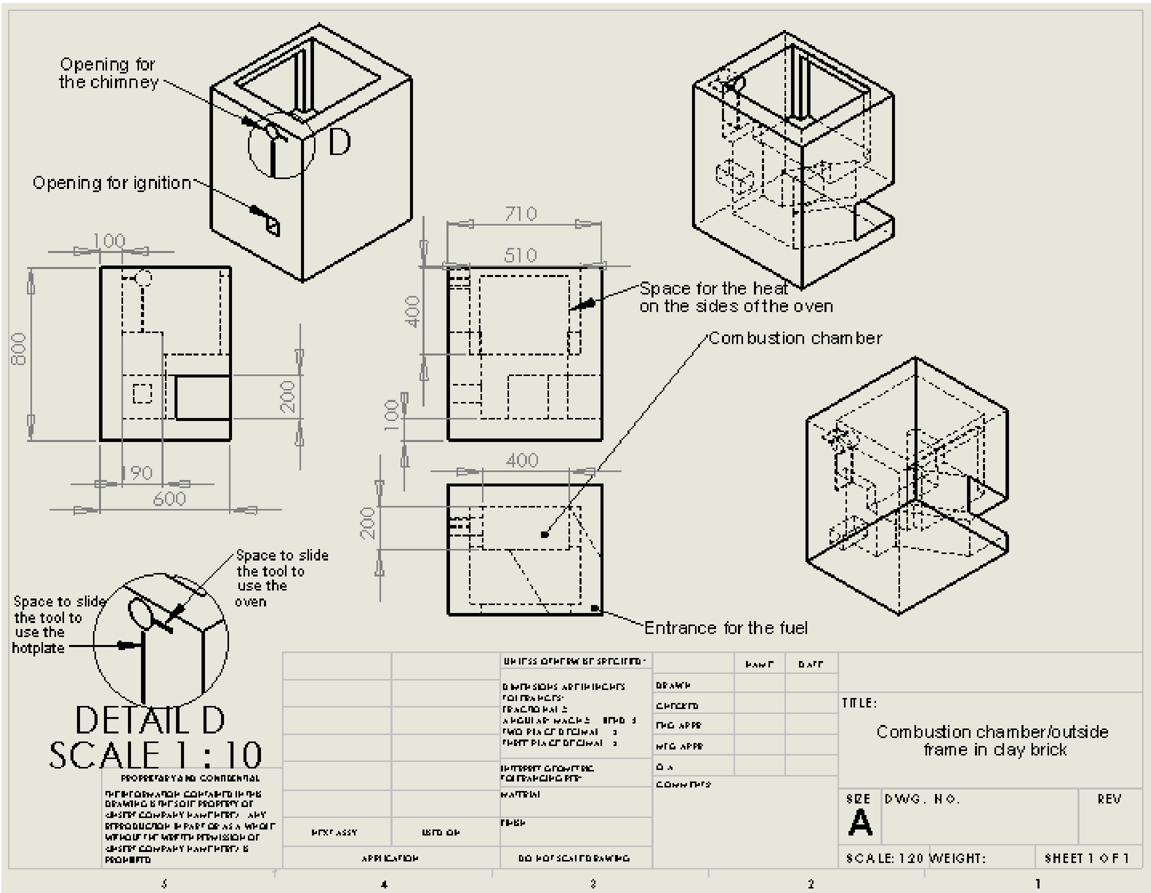


The proposal of the designed cooker, modelled using SolidWorks, with every parts numbered

Ref.	Part	Material	Assembly
1	Combustion chamber/outside frame	Clay, sand	Cement
2	Oven box	Steel 300serie	Screw, cement
3	Hotplate	Steel 300serie	Screw
4	Fuel support	Iron	Fit in
5	Ash plate	Iron	/
6	Oven door	Iron, fibre glass	Screw
7	Ignition opening	Iron	Screw
8	Chimney	Aluminum, steel	Fit in
9	Cooking facility selection tool	Iron	Fit in

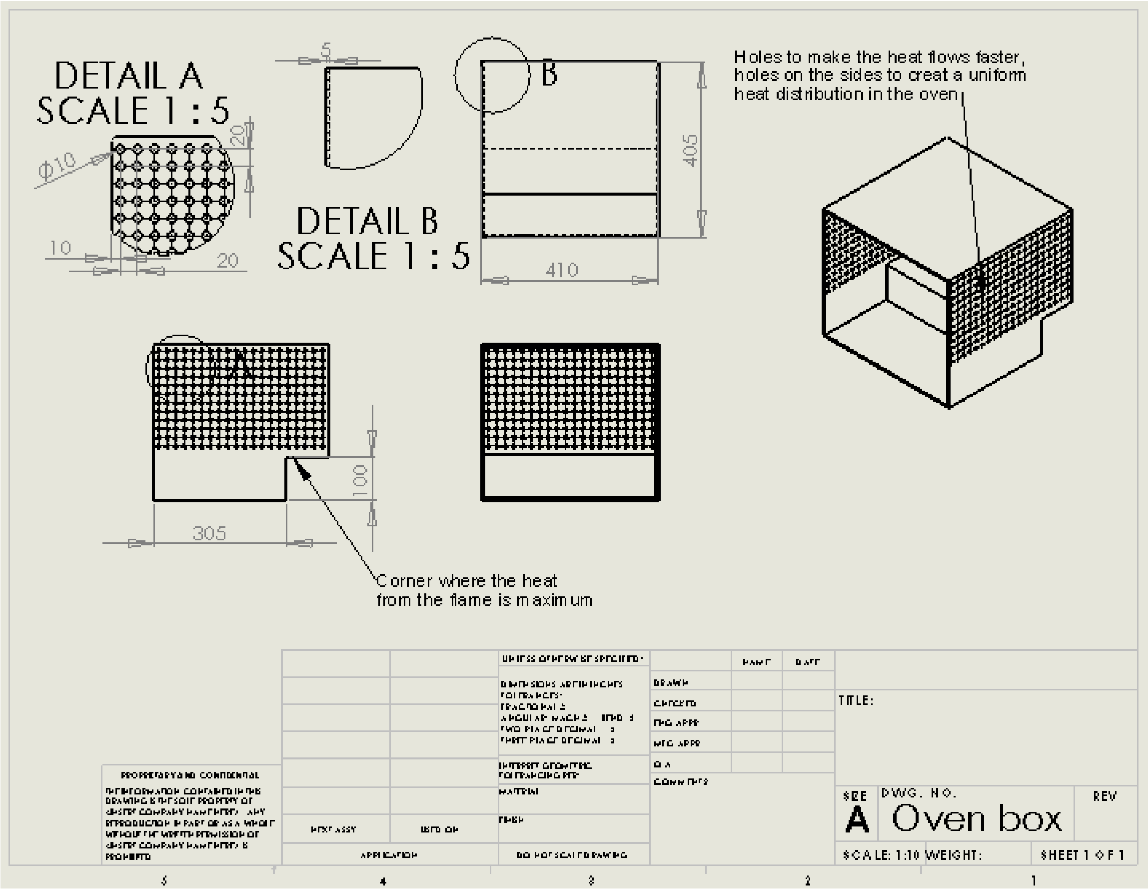
Table of the parts composing the cooker and their materials and how they are assembled to the rest of the device

The combustion chamber and outside frame of the cooker can be build using clay brick (preferably), sand and cement, using the provided geometry and dimensions shown on the following figure:



Draft from SolidWorks of the combustion chamber/outside frame of the cooker

Then, the oven box, by using sheet of steel must have the following geometry to be fit in the cooker:



Draft from SolidWorks of the oven box

Then, recommendations are made in order to have an idea on how to build this machine and how to use it, thanks to the following procedures.

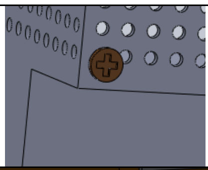
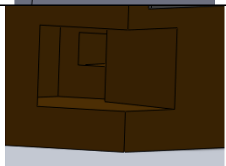
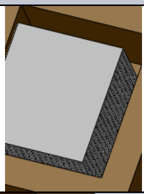
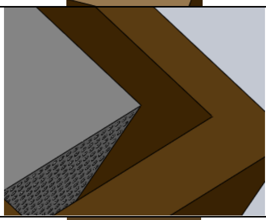
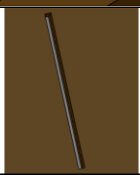
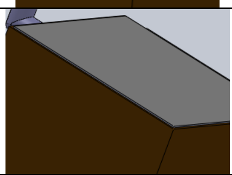
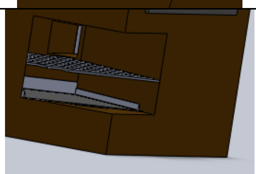
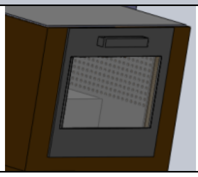
Illustration	Description
	Build the oven box using screws with the given dimensions.
	Build the lower part of the combustion chamber with the brick of clay and the cement, following the provided dimensions. Fill the empty space with sand.
	As the surface where the oven is in contact with the combustion chamber is build, fit the oven on the combustion chamber and use the cement to stick it.
	Carry on the upper part of the brick assembly, making sure that the space between the oven and the back wall provides a constant cross section, similar than the one in the combustion chamber.
	By placing carefully the bricks and the cement create the space for the device to use either the oven or the hotplate.
	The same way, leave a free space in the brick assembly to put the chimney and surround it by cement in order to fix it.
	When the brick assembly is finish the hotplate is set on the top, making sure that there is some space between the oven box and the hotplate.
	Set the ash device and the grill supporting the fuel in the combustion chamber
	Fix the door on the cooker using screws suitable for the brick.

Table giving the procedure to build the cooker

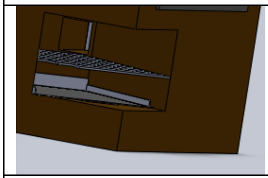
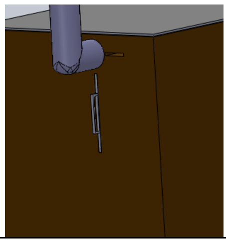
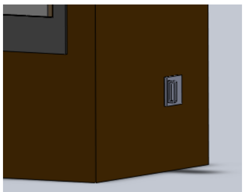
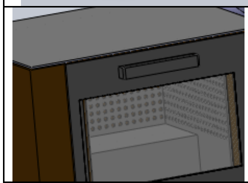
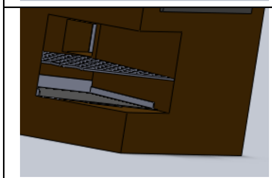
Illustration	Description
	Feed the fuel on the grill support in the combustion chamber, about 8 wood sticks of 50mm diameter, or equivalent.
	Slide the top iron plate if the oven is used or slide the side iron plate if the hotplate is used. If both cooking facilities are used, this step is avoided.
	Open the small door on the side and ignite the wood sticks
	Put the food in the oven or on the hotplate
	Remove the ashes produced by the combustion using the plate below the wood.
	Push the willow in the combustion chamber while the food is cooking

Table giving the procedure to use the cooker

Discussion

The proposal of the cooker and the study of the design have been done. Thus, now it is interesting to have some discussion about this project in order to give some orientation for improvements.

First, the efficiency of the cooker can be discussed. In fact, it has been found in the materials section with the study of heat transfer that 72% of the heat is lost by the casing and the flue, which gives an efficiency of 28%. But this calculation has been done for a oven without holes to facilitate the heat flow. Thus, the real efficiency of the cooker must be higher
Then, another way to estimate the efficiency is to use the computational fluid dynamic simulation which has shown that with a flame temperature of 1200°C, the temperature in the oven is 250°c and 220°C on the hotplate. But, the temperature around the flame is 450°C, so from the combustion chamber to the cooking facility half of the temperature value is transmitted.
Also important, the flame temperature has been set from the assumption that the 60% of the adiabatic flame temperature of 1977°C occurs during the combustion of the willow. This assumption can be pessimistic; maybe in the reality the quality of the fuel can provide a temperature closer to the adiabatic one.

Then, the study of combustion has provided an amount of excess air which is recommend making the combustion efficient. As there is no device to control the air flow in the design, this parameter is hard to control. The physical opening of the combustion chamber will determine this parameter. In the way, it has been found that $18.68m^3/h$ of air should flow through the fuel during the combustion. The wind speed, the atmospheric conditions, the kitchen environment will affect this air flow, but from the cooker design point of view it has been impossible to use this parameters.

From the background research on the fuel it has been found that 19.8kW will be released from the combustion of a certain amount of fuel. Now, this amount of fuel can be bigger, but less air will be able to go through the chamber and it will take more time to combust. In the background theory it has been said that the faster a fuel burn the better it is in terms of efficiency and emissions. It has also been assumed that this amount of fuel will burn in one hour. Thus, the relation between efficiency, time consumption and pollution is a topic that can be improved for more control. Then, there is different diameter of wood stick available. It might be interesting to study the difference between the combustion of a small diameter willow and a large one.

The cooking technology study has shown that a cooker should have the ability to manage different cooking techniques. This task is complicated to manage with such a design where two cooking facility are controlled from one unique flame. On the other hand, the hotplate provides a surface with a range of temperature from 220°C, at the back, to 110°C in the front part of the plate and the oven enable a cooking at 250°C with an area in the back side where the temperature can reach 280°C. In fact, this temperature range must allow the use of different cooking techniques.

Then, the proposal of the cooker design can be discussed as well. First, the ignition door on the side where the user is supposed to ignite the fuel might not be at the easier place to access. Thus, a better user friendly solution for the ignition can be studied. Then, the shape of the combustion chamber and the all cooker frame might be in certain location, like in the diagonal part, hard to build with brick. Thus, the outside shape can be improved while the inside combustion chamber has been design respecting the rocket stove principles cannot change.
The cooker has been improved by employing two boards in iron which can be used to deflect the heat flow in order to use either the oven or either the hotplate. These devices and their heat transfer can be study deeply in order to make them really effective. In fact, the possibility to choose between the two cooking facilities, the oven and the hotplate, is one of the difficult points of this project which can be improved. In addition, maybe something more easy to use than some iron boards can be imagined.
For the chimney, an alternative solution using metal has been employed but it is important to understand that the best solution is to have the chimney in clay brick in the continuity of the combustion chamber providing a better insulation. But as the chimney has to lead the smoke outside of the kitchen, the chimney in brick has to be build with the kitchen wall.

The CFD results can be discussed, as it gives an estimation limited by certain parameters. In the CFD simulation, the flow is limited by the domain. In fact, there is no heat lost outside the domain. Thus, the 26.4% heat produced lost by heat transfer through the wall found in the materials section is not taken in account. As the consequence the results, especially the temperature values, are limited by this theoretical heat loss through the brick walls.
Then, in order to create a heat motion in the simulation an air flow velocity has been assumed. In real condition, in this cooker there is nothing that allows the user to have a control on the velocity of the air flow coming inside the combustion chamber. Thus, the heat might not flow as fast as in the simulations.

Another important task in this type of project is to produce a low cost device. In fact, the way of life of the people from the Lammas community do not provide them a lot of money. Thus, by using cost affordable materials, the cooker must by a low price device compare to the other similar cooker available on the market. In addition, by using a former oven box and oven door, the price of production can be cut. In the same way the materials are resistant and must provide a device which lead to a long life expectancy.

The health and safety is an important issue in the mechanic industry but it is even more important when the machines are in the domestic environment. In fact, the families who will use the cooker have children so it is important to prevent from injury or contamination. By using a chimney which carry the smoke away and a casing in brick which insulate well the heat produce by the flame, the cooker must be a safe device. Also the height of the hotplate should be enough to prevent from the contact of little kids.

Finally, the most important point is the satisfaction of the client, the people from Lammas. By meeting the people from this community and by discussing and exchanging idea about the cooker, the final design is in accordance with what they expected. But the first headline of the topic of this dissertation was to produce a “domestic cooker” which means something similar to what is available in the market. The cooker produced in this project does not have the same facility and than an electric cooker which has four hot rings with independent temperature controls... But on the other hand the device is cheaper, use a bio-fuel available in the community field, and able to cook food for a family.

Conclusion

Thanks to a wide background study of the cooking technology, rocket stoves and standard cookers, and of the energy production, fuel combustion, the design of a family sized cooker working with short rotation coppice willow has been made.

On one hand, this design has shown some efficiency with a good transmission of the heat produced by the combustion to the cooking areas. With a good material selection, the cooker is cost-effective, durable and easy to build with most of the material already available in the Lammas center. Then, by using the short rotation coppice willow as a fuel, the cooker shows some environmentally friendly features. Finally, with a design made for a kitchen and similar to a standard domestic cooker, the designed cooker is quiet a user friendly apparel.

On the other hand, this design can be criticized for its weakness in term of ignition system and temperature control. Thus, this project can be improved in different way. The design can be modified in order to make the ignition easier, the configuration of the combustion chamber might be improved in order to have a better air flow, using narrow sections for example. Then, the ability to enable the user to choose the cooking facility that he wants to use, hotplate or oven, can be improved with a better technical solution and a study of the heat flow with the use of this technology. Finally, the best continuation of this project would be an experimental part. In fact, the computational fluid dynamics simulations and the background study have brought a lot of knowledge, but the experiments can provide some unique information which can confirm, improved and concretize this project. Unfortunately, the lack of time made that this task has not been accomplished.

The study provided in this project report has given recommendations which will help the people of Lammas to produce a cooker which will be used as a cooking facility for their families.

This dissertation has been an interesting opportunity to improve the engineering skills that have been learned during this course. In fact, a new way to use Phoenics, the CFD software, has been employment for this project, in order to study different type of problems than the ones learned at the university. Then, the combustion and heat transfer have been some of the key topic of this dissertation. As a consequence, the knowledge in these areas have been applied to a concrete project which has lead to some learning.
Then, this project has provided a great opportunity to work with people who really need the accomplishment of the designed cooker for their everyday life. It has been a personal choice to work with the Science Shop Wales in order to do some engineering project with a regard to the environmental issue. Thus, the project has been done with the agreement of people from Lammas, a sustainable energy community, who have been really welcoming and who have gave some suggestion and idea on the design of the cooker. As a consequence, personal interest in the relation between engineering design and environment has been confirmed thanks to this study.

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Appendices

Visit of Lammas, The Eco Village

On the Friday 11th of September, I went to Lammas Eco Village in *Pembrokeshire* near Clunderwen in Wales. Thus, I have met the person who gave the cooker project to the Science Shop Wales, Paul Wimbush.
The aim of this visit was to have more information about the project, to show them what I have done so far and to have their opinion and critics. The feedback of this visit is prsented in the following sections.
<u>About Lammas</u>
The community just received the planning permission to build an ecovillage in Wales which combines the traditional smallholding model with the latest innovations in environmental design, green technology and permaculture. The site is about 31 hectares and is divided in 9 eco-smallholdings, 9 families. So the cooker involve in this dissertation will be used by 9 families (9 cookers).
The community is looking forward to build a community centre to make them able to have a place dedicated to their social life as a community.
The main objective for the Lammas resident is to live independently from the use of electricity and gas, and have their own food resources form plantations and farms. Lammas through its eco village will aims to become a demonstration model for low impact living.
<u>About the SRC Willow</u>
There is actually three sites where the willow has been planted. These three plantations use three different techniques of planting. In fact, Paul Wimbush explained that at the first year of growing, the ground floor and the weed have an important impact on the quality of the willow. Thus, in two of these plantation, they use plastic to cover the floor where the willow is growing in order to avoid weed com-petition which has a bad influence on the willow.
While having present them a summary of what I have been studying for this project, I have shown them my study of the combustion process and they notice that for the moisiture content of the willow I used 4.6%. But according to one of the member of the community, the moisiture should be closer than 12%
<u>About the design of the cooker...</u>
As I told them that it will be difficult to have four cooking ring as in the usual domestic cooker in the commerce, and I show them that there some cooker with a unique large hot plate with a gradual temperature distribution, they are agree to employ this system for the cooker.
Then, we talk about the using of a plate underneath the combustion flame in order to remove the ashes produced during the burning of the fuel.
In the design of the cooker that I present them the opening of the combustion chamber where the fuel is feed in on the front. So we have noticed that if the food sticks are too long it will go outside of the cooker and then be annoying for the person who is cooking and would like to stand in front of its cooker. Thus we agree on the idea of using a combustion chamber in diagonal...

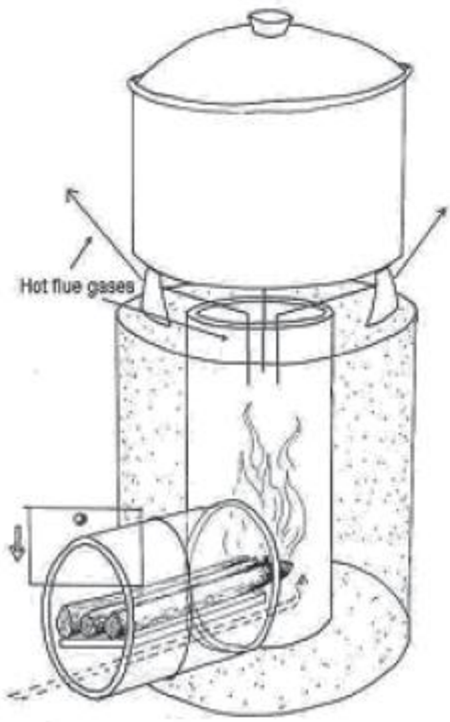
Then, it has been said that for the chimney, the heat flow must be studied in order to locate the end of the flow because the optimum chimney must be there.

About the production of the cooker..

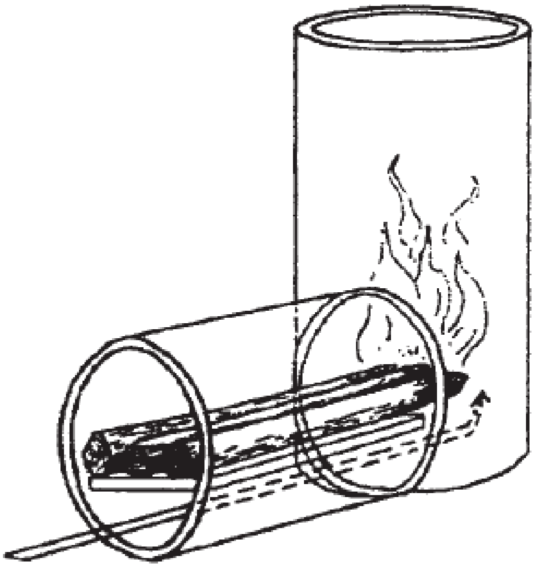
After having explained them the materials that I plan to use, ceramic for insulation and steel for heat conductor, they told me that they already have some clay bricks and sand which can be used as an insulator.

Then, for the use of sheet of the steel for the oven box, one of the member of the community gave the idea of using the oven inside structure of an old cooker in order to obtain something with the appropriate dimensions and properties.

Rocket Stove



Diagrams showing the principles behind the fuel efficiency in rocket stoves, diagram by Peter Scott from Getting Technologies to the market – the case of the Rocket Stove in Malawi



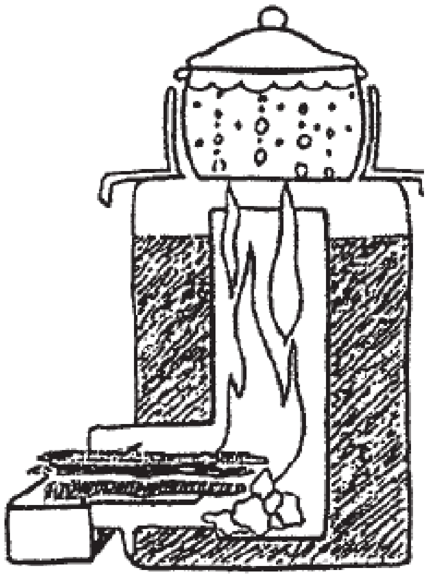
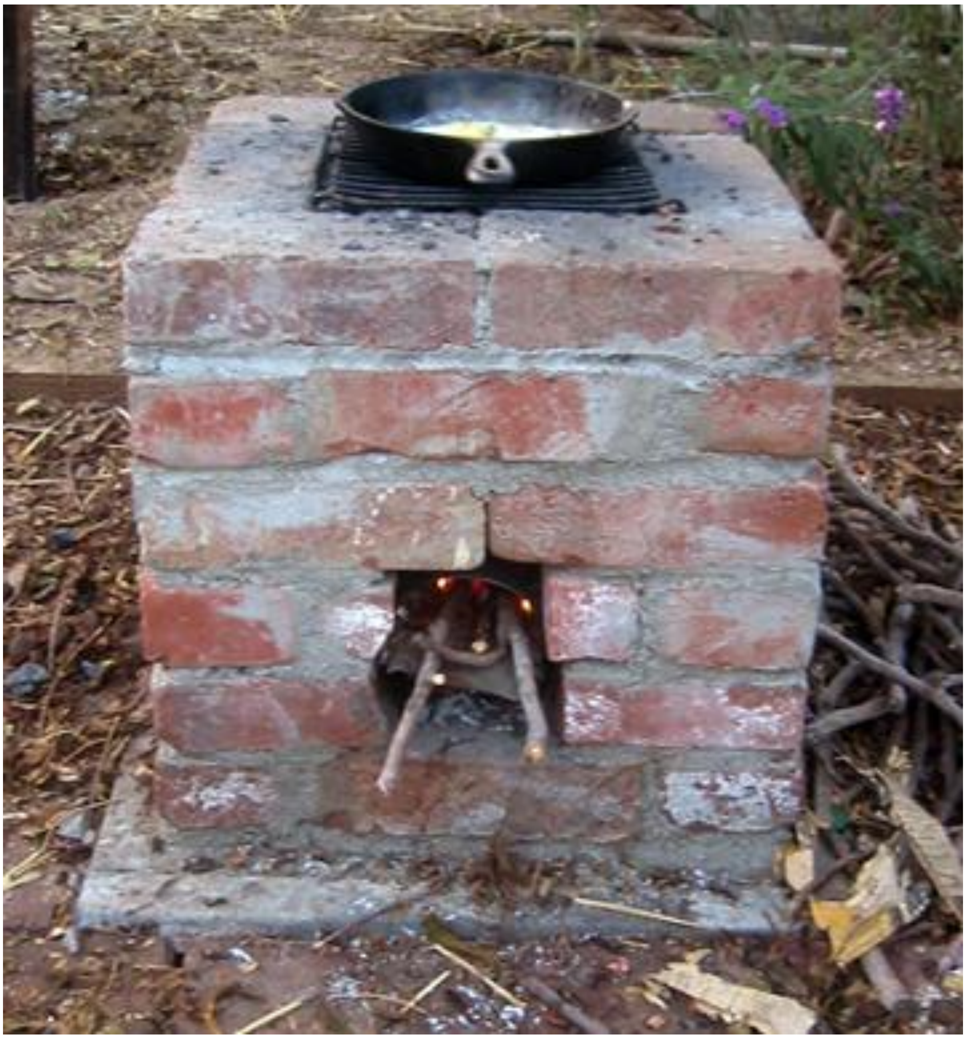


Diagram of Rocket stove, from Increasing fuel efficiency and reducing harmful emissions in traditional cooking stoves



Rocket stove from Emergency Stoves and Fire Starters