Computer Model of a Domestic Wood Burning Heater

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Abstract

Between April 2003 and April 2004 a project, funded by Technology New Zealand, was undertaken to develop a computer model of a wood burning heater for use at Applied Research Services Ltd. Applied Research Services Ltd is a science and engineering research company that specialises in the testing of wood burning heaters. The computer model will be owned by Applied Research Services Ltd and will be used to improve the design of their customers' heaters so that they may pass the particulate emissions and efficiency standards of AS/NZS 4013:1999.

The computer model used the software program, Engineering Equation Solver as a platform to solve the model equations. EES was particularly easy to use and more emphasis was able to be placed on the actual modelling. The final model included over eight hundred variables and equations. It included radiant, convective and conductive heat flows, over thirty heat balances, Arrhenious based rate expressions and many empirical equations derived from experiments and data acquired at Applied Research Services Ltd.

At the beginning of this project the objective was for the model to match the test results to within 10%. This has been met for the tests on the high airflow setting where the model error is 4% for flue temperature, 8% for heater output and 16% for flue oxygen. Unfortunately on low airflow setting, the model does not reach this target with model errors of 18% for flue temperature, 25% for heat output and 13% for flue temperature. The excellent results for the high flow setting are partially attributed to the use of calibration factors. The calibration factors model the processes in wood combustion that could not be modelled by this project, due to lack of time and resources. Some of these factors are the proportion of air that flows onto the charcoal ember bed or logs, radiation shape factor changes due to firebox geometry, convection heat transfer coefficients changing with turbulence. The calibration of the model only has to be completed once for each heater. The reason why the model does not work as well on low airflow setting is that with less airflow the proportion of air to the charcoal bed opposed to the logs would decrease, therefore decreasing the burn-rate.

This model can be used to determine the changes to a heater's performance from changes to air inlet areas, insulation type and thickness, wetback size, baffle size, primary vs secondary air, air bypass ratio and door size. The model provides all the results that are obtained from an emissions test plus extra information such as the amount of excess air, smoke conversion in each combustion zone, flame temperatures and distribution of heat output. The smoke conversions for each combustion zone are particularly helpful in diagnosing where problems with the combustion occur. The reasons for incomplete combustion, lack of temperature or oxygen, can be found and fixed by increasing either insulation or air areas.

The model can be used by Applied Research Services Ltd to improve heater designs. For the short term this will involve the author working as a part-time consultant. The project could be built on by another student by using CFD modelling for the sections of the wood burning process not modelled by this model and adding a graphical user interface to make the model easier to use.

Table of Contents

Table of Figures

Nomenclature

Variables

A	Surface area	[m^2]
be	Burn energy release rate	[kW]
br	Burn-rate	[kg/s]
D	Diameter	[m]
DP	Pressure drop	[Pa]
DT	Temperature difference	[°C]
e	Reaction extent or emissivity	[kmol],[-]
E	Energy of reaction (Arrhenious term	[kJ]
F	Mass flow-rate	[kg/s]
FV	Volumetric flow-rate	[m^3/s]
h	Heat transfer coefficient	[kW/ m^2 C]
k	Rate constants	Many different units
m	Mass	[kg]
MM	Molar mass	[kg/mol]
Q	Heat content	[kJ]
qr	Heat flow-rate	[kW]
sf	Radiation shape factor	[-]
T	Temperature	[°C]
V	Volume	[m^3]
XA	Cross-sectional area	[m^2]
x	Fractions, concentrations or distance	[-,-,m]
y	Stoichiometric factors	[-]
z	Stoichiometric factors	[-]

Heater Sections

b	Baffle
ba	Baffle air (Firebox air above baffle)
c	Charcoal (Charcoal bed at the base of the firebox, assumed to cover entire floor)
d	Door
f	Flame
fb	Firebrick
fl	Floor
flhs	Floor heat shield
flue1	Lower half of the air inside the flue, below 2m
flue	Upper half of the air inside the flue, below 2m
flue2	From 2m to the top of the flue, 4.7m high
fluew	Wall surrounding flue air
flue1w	Wall surrounding flue1 air
Flue2 wall	Wall surrounding flue2 air
fw	Front wall
hs	Heat shield
hsa	Air between heater walls and heat shield
i	Inside (Closest to the logs)
l	Log
lw	Lower wall (Wall behind firebricks)
o	Outside (Furthest from the logs)
pa	Primary air (Lower half of the firebox air)
r	Calorimeter room air
rw	Calorimeter room walls
sa	Secondary air (Upper half of the firebox air)
sh	Shell of heater
sha	Air between heat shield and heater shell
st	Stand
tw	Top wall
uw	Upper wall (Wall above firebricks)

The variables can then be combined with the heater sections. For example:

The heat flow from the logs to the door is	qrldi
The cross sectional area of the flue is	XAflue

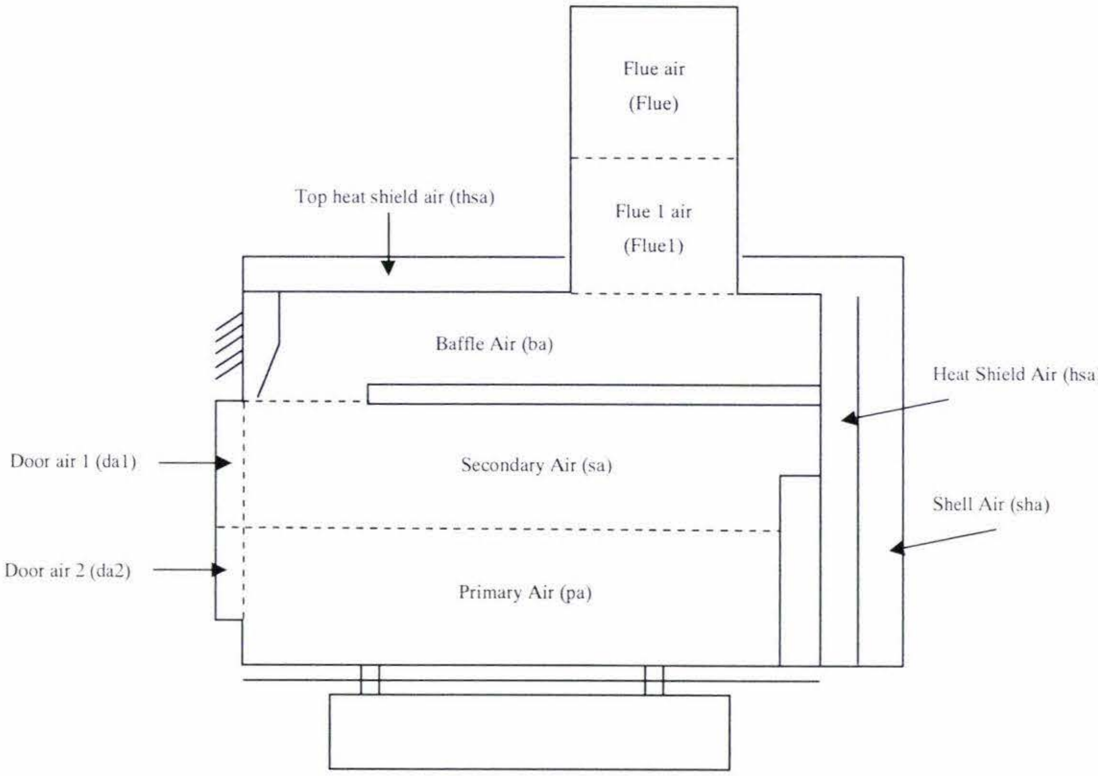


Figure 1: Air section naming convention for the final model

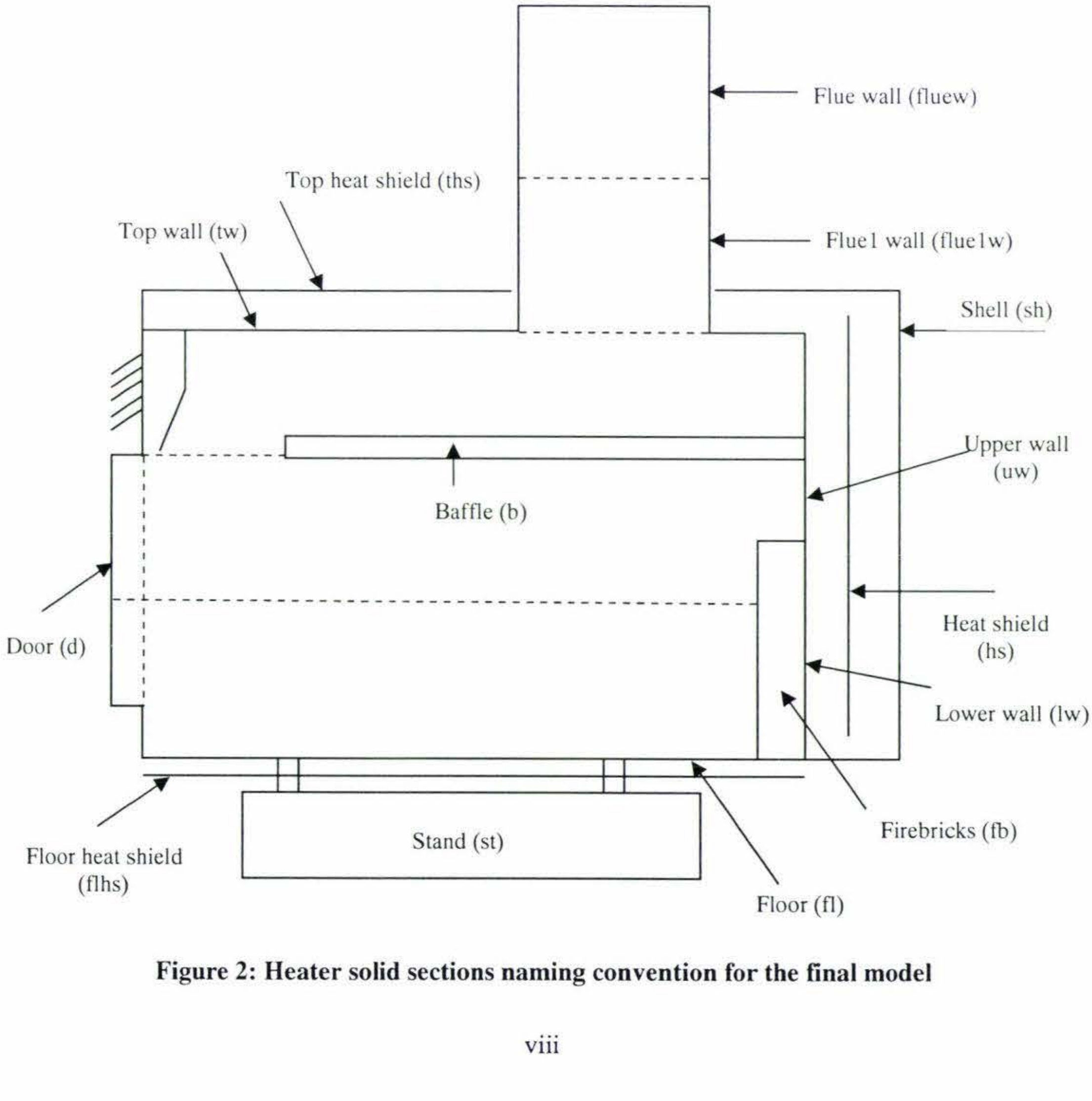


Figure 2: Heater solid sections naming convention for the final model

1 Introduction

The problem was that the wood burning heater testing company, Applied Research Services Ltd, did not have access to a computer model that calculates the emissions, efficiency and heat output of a wood burning heater. This model would enable the company to provide changes in design parameters in order to reduce emissions, and which could be used to predict heater performance based on design refinement for their clients.

1.1 Objectives

1. Review previous wood combustion computer models and other research in this field.
2. Determine the most suitable software package for developing the model.
3. Create a detailed computer model starting with simple concepts and improving them in small steps.
4. Test the model at Applied Research Services Ltd by comparing the model's results with measured heater results data to determine its accuracy.
5. Refine the model to make it a more realistic simulation of the fuel wood combustion process.
6. Produce an instruction manual for use by the staff of Applied Research Services Ltd.

1.2 Project Background

Applied Research Services Ltd contacted Technology NZ, with the proposal for this project in late 2001, with the objective of finding a Technology/Engineering student to undertake the project for one year with Massey University helping to provide technical support and awarding a Masters Degree upon successful completion of the project. However, it wasn't until January 2003 that a suitable student stepped forward to accept the project. The student, author of this thesis, had just completed a BE (Hons) in Chemical and Process Engineering at the University of Canterbury.

1.2.1 Applied Research Services Ltd Background

Applied Research Services Ltd is a small science and engineering research company located in Nelson, New Zealand. Total employees are four, with a combined experience of over 30 years in the science and engineering research industry.

A large portion of their work is the testing of domestic wood burning heaters. Some of the manufacturers that test their heaters with Applied Research Services Ltd are Masport, Pioneer, Yunca, Kent, Hewitson Ltd, Landsdowne Resource and Warmington Industries. Other work includes product testing for consumer organisations and specialist engineering and scientific consultancy services. More information can be found on their website, www.appliedresearch.co.nz.

During the testing process, Applied Research Services Ltd often make recommendations to the manufacturers of the heater in order to tune their heater's performance. To improve this service to their customers it was proposed that a computer model of a heater be developed. This would greatly increase the amount of information available to Applied Research Services Ltd, and as a result it is anticipated that their recommendations to customers would improve.

1.2.2 TIF Funding Scheme

The project took the form of a Technology for Industry Fellowship (TIF), funded by Technology New Zealand, a division of the Foundation for Research, Science and Technology. "The Foundation for Research, Science & Technology invests in research, science and technology on behalf of the New Zealand Government to enhance the wealth and well-being of New Zealanders" (FRST, 2004). The fellowship provides funds to both the university that helps with the project and the fellow who completes the work.

This project was approved for FRST funding because of its benefits to the nation's renewable energy usage and air pollution. More efficient and lower polluting wood burning heaters will make the heaters more popular leading to more use of renewable energy and less reliance upon electricity and fossil fuels for home heating. This is very important, as New Zealand imports a large percentage of its energy in the form of petroleum products. If some of these imports can be replaced by domestic resources New Zealand's balance of payments can be improved and uncertainty of energy supply can be decreased. One way to do this is to change the way in which homes are heated. Over 50% of a household's energy requirement is used for water and space heating. This is often supplied by electricity, 30% of which is generated by the burning of fossil fuels. Although approximately two thirds of New Zealand's electricity is generated from renewable hydro and geothermal electricity, the extra electricity above base-load that is used by homes during winter is supplied by the North Island thermal power stations. Another plus to reducing power usage is that extra hydro power stations, including Meridian Energy's proposed project Aqua, would no longer be needed.

1.2.3 Christchurch Smog problem

Another and more important reason for securing the funding was that the project may help heaters produce less particulate emissions and help alleviate air pollution in many of our cities, particularly Christchurch where the problem can be particularly bad in the middle of winter (Fig.3)

Figure 3: Winter air pollution over the city of Christchurch (Source: Ecan, 2004)

The air pollution problem in Christchurch is caused by both carbon monoxide and PM_{10} pollution. Carbon monoxide (CO) is produced by the incomplete combustion of hydrocarbons. Normally when hydrocarbons are burnt carbon dioxide is produced (CO_2), but without adequate oxygen CO is the result. The main carbon monoxide source in cities is motor vehicles. Carbon monoxide is also produced by wood burning heaters, but this is not significant compared to the amount produced by motor vehicles (Ecan, 2004)

PM_{10} is particulate matter that is less than 10μm. This is smaller than both the thickness of a human hair and the finest beach sand (Fig.4).

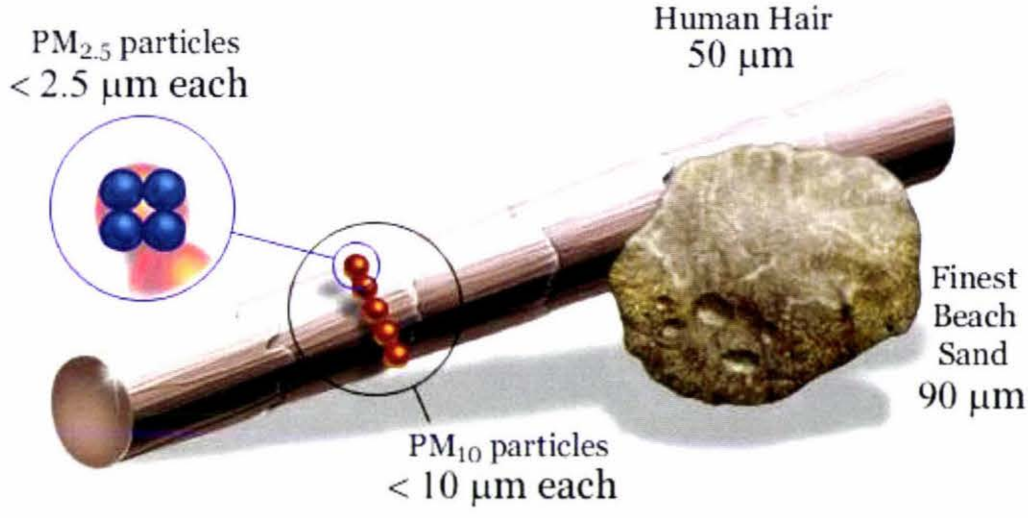


Figure 4: Size of particulate matter emitted by a wood burning heater (Source: Ecan, 2004)

A great deal of work has been completed by Environment Canterbury on the causes of air pollution in Christchurch and the result of this is that PM_{10} is considered the worst pollutant, "Home fires, open fires and burners, create 90% of Christchurch's pollution". Of the remaining 10%, 6 % is created by industry and 4% by motor vehicles (Ecan, 2004).

Fig.5 shows that of the 90% of emissions from home fires, 47% is from 16,000 open fires, 37% is from 34,000 wood burners and 16% is from 2,200 coal burners. This shows that open fires are the worst appliances in terms of their particulate emissions.

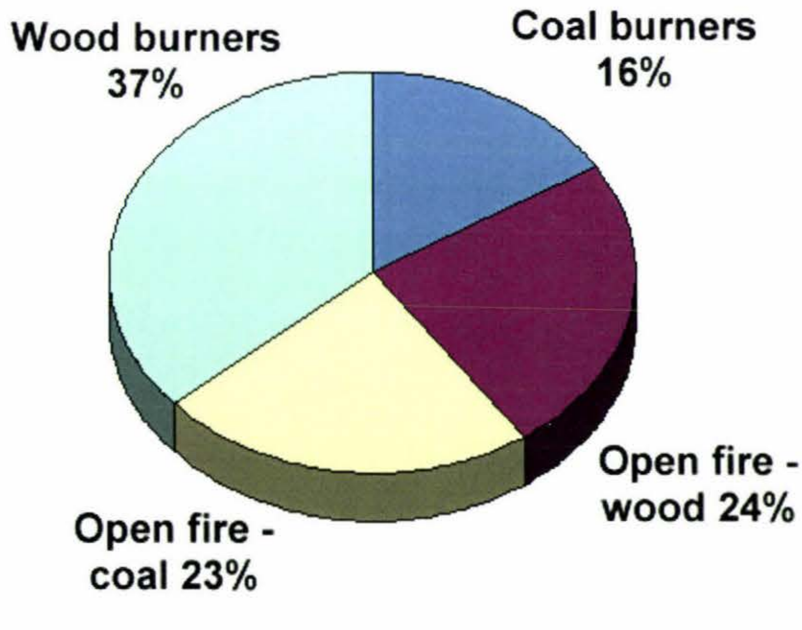


Figure 5: Proportion of emissions in Christchurch (Source: Ecan 2004)

1.2.4 Health Effects of Smog

"Our bodies have ways of protecting us from breathing dust, pollen and germs. Air pollution is an additional stress on the body's defenses. Air pollution hurts the body both by directly inflaming and destroying the lung tissue and by weakening the lung's defenses. A sticky substance called mucus lines our air passages. It traps germs and particles before they can enter the lungs. Then cells with tiny, waving hairs called cilia push the mucus up and out of the body. Air pollution can paralyze or even destroy the cilia. That allows dirt and germs to build up in the mucus, leaving our bodies more vulnerable to disease. Our bodies also try to defend themselves against pollution by trying to breathe less. Air passages tighten temporarily and breathing becomes harder. Smoking also harms the body's defenses, making the body more vulnerable to pollution and disease. It can make the effects of air pollution much worse" (Ecan, 2004).

1.2.5 New Environment Canterbury Regulations

Environment Canterbury is taking steps to decrease Christchurch's smog problem with its proposed air plan. Open fires produce nearly half the emissions and are only one quarter of the installations (Fig.5). Add to this the fact that open fires are so inefficient that it is actually cheaper to use electricity, one can easily see what needs to be done. Environment Canterbury has banned the use of open fires, both wood and coal, for home heating from 2006. Subsidies are being offered for conversions to efficient, low polluting heaters. Also in the air plan is a new restriction on the performance of wood burning heaters. The New Zealand standard is that the heater must have an emissions figure of less than 4 g of particles per 1kg dry wood burnt. The new standard in Christchurch is 1g/kg and the space heating efficiency must also be greater than 65%. Wood burning heaters that do not pass these limits will be phased out, with a time limit of 15 years given for heaters that are currently installed. Subsidies are also being offered for conversions to the low emitting heaters. Currently, most of the heaters that pass this standard are wood pellet burners, but there are approximately five log wood burning heaters that also pass the standard when burning dry wood.

2 Review of the Technology

2.1 Wood Combustion Theory

Combustion is a very complicated process, with fluid mechanics, thermodynamics, mass transfer, heat transfer and complicated chemical reactions all playing important roles. For this reason, many texts have been written on the subject of combustion.

Katzer (1998) provided a good explanation of the complexities of wood burning. "Solid wood does not burn. To get heat out of the wood the fuel must pass through several stages. First, free water is driven off (water not chemically bound with the wood). In the second stage the wood breaks down into volatile gases, liquids and charcoal (pyrolysis reaction). Finally charcoal is also gasified burning with a very short flame close to the surface that appears to glow. In wood burning heaters all stages proceed simultaneously."

2.1.1 Wood Composition

Wood is made up of cellulose, hemi-cellulose and lignin, with small amounts of extractives (resin). Cellulose is a complex polymer, with a repeating unit of anhydroglucose. Hemi-cellulose is also a complex polymer, but the repeating units can be D-Glucose, D-Manose, D, Xylose, D-Galactose, D-Arabinose, D-Rhamnose or D-Glucoronic acid. Lignin, often considered the "glue" holding the wood structure together, is composed mainly of phenylpropane units linked together by various means (Tillman, Rossi and Kitto, 1984). The proportions of these three constituents vary between wood species, but for pine they are 45% cellulose, 29% lignin and 26% hemi-cellulose on a dry weight basis.

As well as the above analysis of wood there are two other widely used compositions, proximate and ultimate. The proximate analysis breaks the wood down into volatile matter, fixed carbon and ash. Volatile matter is the gases that are produced from the pyrolysis reactions. Fixed carbon is the proportion of wood that turns into charcoal and ash is the proportion of wood that is incombustible, mainly metal oxides such as SiO_2, CaO, Al_2O_3. The proximate analysis for wood also varies between wood species and for pine is approximately 80% volatile matter, 19.5% fixed carbon and 0.5% ash. Most of the ash is found in the bark. The proximate analysis is not a perfect method for describing wood, as under different burning conditions more or less charcoal (fixed carbon) is created. At lower temperatures more charcoal is produced while at higher temperatures more volatile matter is produced. This means that the composition of the volatile matter must also change so that the chemical elements can remain balanced.

A better method of representing the composition of wood is the ultimate analysis, which breaks the wood down into its elemental composition. The elements in wood are carbon, hydrogen, oxygen and traces of nitrogen, sulphur and ash. The carbon and hydrogen provide the energy content of the fuel, while the proportion of oxygen, and water content, are the reasons behind wood having a lower energy content per mass than coal and oil. The ultimate analysis of dry pine is 53% carbon, 6% hydrogen and 41% oxygen, giving an empirical formula of $C_{4.4}H_{6.3}O_{2.5}$. The empirical formula for charcoal was found by Applied Research Services Ltd (2003) to be $C_{12}H_2O_{0.5}$, which shows that some of the volatile matter remains with the charcoal.

The composition of wood is extremely variable and different burning conditions change the composition of the pyrolysis products. This is further complicated by the presence of water in the wood. Water is attached to wood in two separate methods, absorbed and adsorbed. The absorbed water (free water) is water in the void spaces of the wood, known as lumens. The adsorbed water (bound water) is water that is chemically bonded to the wood microstructure. The effect that water has on the combustion process is described by Tillman, Rossi and Kitto (1984). The three major effects are:

1. The energy needed to heat the wood to pyrolysis temperature is higher, owing to the energy needed to increase the water to its boiling temperature and to then vaporise the water. Water has a higher specific heat than dry wood (4.2 vs 1.4 kJ/kg °K).
2. The second influence of water is to place a ceiling on the wood temperature because at the vaporisation temperature the wood looses heat from the vaporisation energy so stays just above the vaporisation temperature (100°C).
3. The third influence of water is to increase the thermal conductivity of the wood. Because the absorbed water in the wood can move around, it can transport heat with it.

2.1.2 Wood smoke combustion

The most important phase of wood burning is when the volatile matter from the pyrolysis reactions (smoke) is burnt with air. This provides over two thirds of the burn energy of the wood and if it does not burn well the volatile matter that is not burnt causes nearly all the smoke and emissions from the wood burning heater. Volatile matter is also known as pyrolysis gases or smoke. Both terms are used in this project, depending on where the gases are in the burning process. The volatile matter is a mixture of many different organic compounds e.g. methane, tars, and aromatics.

The most important factor in the volatile combustion is that there is enough oxygen for the combustion. A stoichiometric amount of oxygen can be calculated, which is the amount of oxygen required for the combustion of the volatiles where no oxygen is wasted. Over twice the stoichiometric oxygen is required for complete combustion in a wood burning heater. The extra air, "excess air" reduces efficiency and increases emissions of wood burning heaters because all it does is cool down the heater and remove its heat up the chimney. The extra air is required because some air can bypass the areas where it is needed and more importantly there is only so long for the combustion to take place, so it must be easy for the smoke to mix with the oxygen. With more oxygen present, it will be easier for the volatiles to mix with the oxygen.

The volatiles and oxygen must be brought together so that they can combust. The turbulence of the flames helps this and this turbulence is increased in wood burning heaters by the direction and velocity of the inlet air vents as well as baffles. The last requirement for good volatile combustion is the activation energy required for the combustion. Because the volatiles can be quite large and complex compounds, the activation energy required for the chemical reaction can be large. This means that the temperature of the combustion needs to remain over 600°C, to give good volatile combustion. This can be a problem for wood burning heaters as one is trying to remove useful heat from the heater, while the volatile combustion needs as much heat as possible to stay inside the heater and keep the temperatures high.

2.1.3 Heater air-flow

In order to keep heaters safe for their occupants the smoke and other dangerous hot and toxic gases must be removed from the heater. The flow through a heater is caused by natural draught. Draught is a pressure difference that is caused by the hot gases in the heater and chimney having a lower density than the cooler gases of the surroundings. This produces a force (pressure) on the gases so that they are rise up the chimney. Draught is proportional to the density difference and the height of the chimney.

$$\Delta P_{draught} = \Delta\rho \; g \; \Delta h \qquad \text{(Eq 2.1)}$$

$\Delta\rho$ = Density difference between the flue gases and the outside air (kg/m^3)

g = Acceleration due to gravity ($9.81\ m\ s^{-2}$)

Δh = Height of chimney/flue (m)

For air as the fluid, the equation can be simplified, using the ideal gas law, to give:

$$\text{Draught (Pa)} = 3458\ (1/T_{flue} - 1/T_a)\ \Delta h \qquad \text{(Eq 2.2)}$$

Tflue = Average temperature of the air column inside the flue (°C)

Ta = Ambient temperature of the air outside of the flue (°C)

Δh = The difference in height between the outlet and inlet of the heater (m)

Equations 2.1 and 2.2 were found from ASHRAE (1996).

2.2 History of Wood burning

To obtain an understanding of how modern day heaters operate and why they are designed how they are, the author studied the history of wood burning particularly from Shelton (1983).

In the 19th century wood was the predominant energy source, but declined until the oil shocks of the 1970's. Now with society's increasing awareness of global warming wood use is becoming more important again. This is because it is a renewable resource and nearly carbon neutral. Carbon neutral means that the carbon dioxide that is produced from burning the wood is balanced by the carbon dioxide absorbed by the tree as it grows. Only processing and transportation energy requirements make wood not a completely renewable and carbon neutral fuel.

Wood burning heaters have come a long way. Fire was the first method used to heat a home, with the cavemen simply creating a fire inside the cave. When man started building stone and wooden houses, the method of home heating hadn't improved much (Fig.6). This type of wood use still exits today in some countries, usually for cooking purposes. This can cause the same health effects as mentioned in section 1.4.2, but the problem is intensified because the concentrations of the particulates in the air are many times greater when used inside.

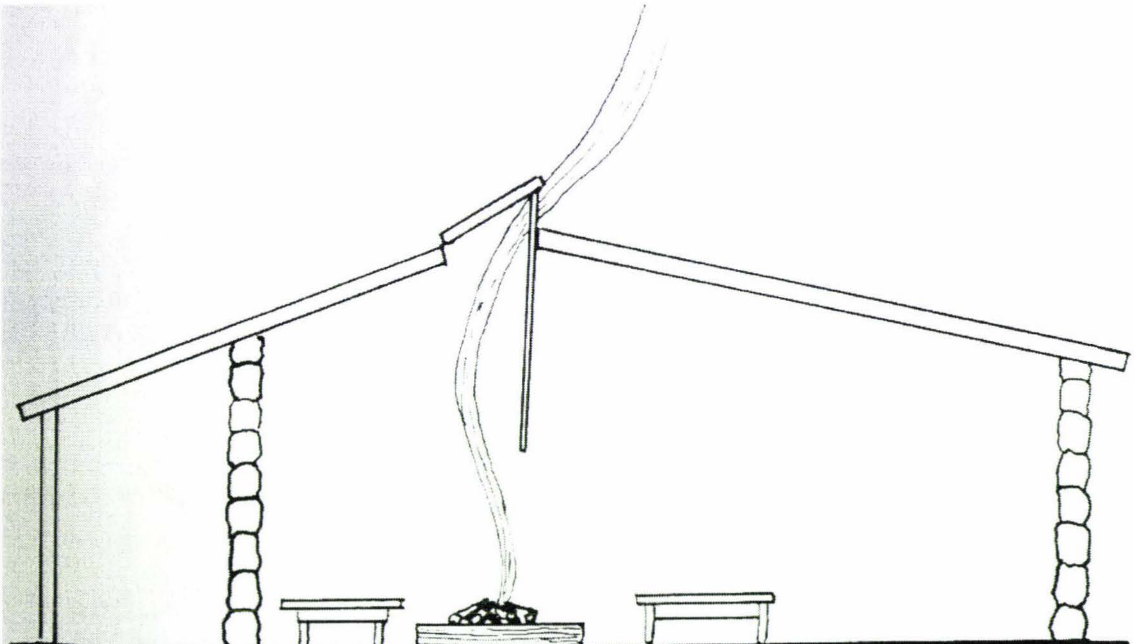


Figure 6: Early use of wood for home heating (Source: Shelton, 1983)

This system is extremely efficient because all the hot gases, that today exit out the flue (or chimney), stay in the room. However there are far more important problems of health and safety for the house occupants. For this reason the first chimneys were developed. These chimneys were very short (Fig.7) so that there was still a large amount of smoke entering the room, due to a lack of draught in the chimney.

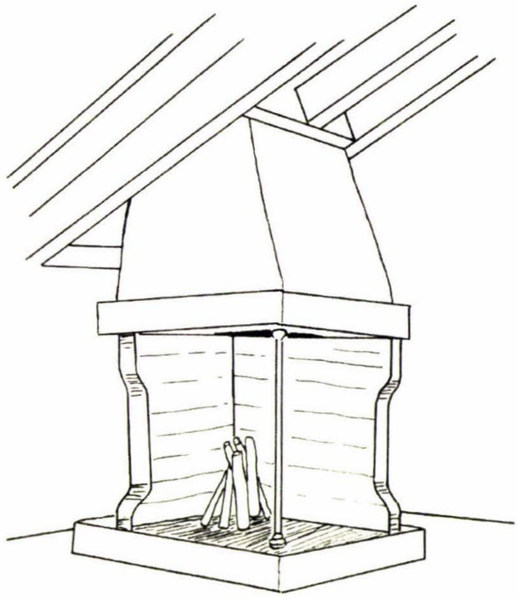


Figure 7: First primitive chimneys (Source: Shelton, 1983)

As understanding of fluid dynamics and the use of masonry to build houses increased fireplace design improved markedly mainly through the use of higher, insulated chimneys that produced a larger draught so that the smoke and other hot gases are removed from the room. This led to the fireplace form that most people in New Zealand will now be able to recognize (Fig.8).

Figure 8: Modern day fireplace

The main problem with fireplaces is that so much air is drawn through the large opening and up the chimney that their efficiency is very low. The combustion temperature is also low so that emissions are high. One answer to this is to restrict the flow up the chimney, but this leads to increased smoke entering the room as the room can become a better chimney than the chimney itself.

The answer to these problems was to enclose the fire and have very small inlet air areas. This is so that only the air that is required for combustion is drawn into the fire, and the draught of the chimney is kept high. This removes the need for large chimneys because there are less gases flowing out of the heater so metal chimneys around 150mm diameter can be used. These metal chimneys are referred to as flues. A major advantage of the small flue is that it can be internal so that the heat from the flue surfaces can also heat the room.

Early versions of this type of heater were standard fireplaces with doors added. Modern wood burning heaters are generally made of steel, but some are cast iron and others are made predominantly from insulating materials e.g. firebrick, ceramics. Many different design layouts were tried early on in the history of this type of heater. Examples of these are:

1. Primary air entering from under the fire. This is still used for coal burners.
2. The opposite, where the flue gases leave from under the fire. Excellent emissions results from this type of heater because the smoke exits from the heater via the hottest part of the heater, which is the charcoal ember bed. Unfortunately, this type of heater is extremely difficult to start the combustion process.
3. S-type where air enters the top of the heater and flows down the door before hitting the charcoal bed and logs (Fig.10 in section 2.4). The air then exits around a baffle and up the flue. This path forms an S, which is how the design gets its name. The S-type's main advantage is that the fresh air sweeping down the door keeps the door clean so that the flames can easily radiate to the room and be seen, which is an important feature for most users. This reason among others has meant that the S-type heater is now the predominant airflow design.

The modern wood burning heater is still a relatively simple device in that most do not require electricity. This is a very important reason for many people to have them in their homes, as in a power failure the heater keeps working and can be a life saver if the power failure occurs in winter. The Masport LE2000 is a typical modern wood burning heater (Fig.9).

Figure 9: Masport LE2000, typical modern wood burning heater

2.3 Austrian Collaboration

Part of this study involved a period of four weeks spent in Austria for collaboration with the Austrian Biomass Centre (ABC) in Wieselburg. ABC is a group of scientists that perform consultancy services with the objective of increasing the use of bio-energy in Austria. One project they were working on was the improvement of a wood pellet boiler, both by conventional means and by CFD modelling (section 2.6.2).

ABC are closely associated with the larger BLT Wieselburg (Budesanstalt fur Landtechnik), which conducts similar work to Applied Research Services Ltd. BLT test and recommend improvements to wood burning heaters. The wood burning heaters tested at BLT are usually boilers, where the heat from the wood combustion is used to heat water, which is then piped into radiators throughout the home to provide the space heating requirement.

The Austrian visit highlighted the differences between the techniques used to heat homes in the two countries. The Austrian's used more advanced methods for burning wood including:

Pellet burners — One of the major problems in designing a low emissions log wood burning heater is that it is a batch process and the rate of combustion is controlled by the air flow. This means that if one wants to slow the burn-rate of the heater, the airflow is decreased, which produces more smoke so that the burn-rate slows. A better way to operate a heater would be to control the rate of the fuel feed. This system is used in pellet burners. Pellets are small pieces of wood that are made predominantly from sawdust. Other advantages of pellet burners are that they utilize blowers (fans) to suck the air through the heater, which means that extremely low flue temperatures can be achieved i.e. less than 100°C. This gives very high efficiencies, due to the flue gases having a lower energy content, which means that less heat is wasted by going up the flue. Pellet burners are very popular at the moment due to their ease of use. Over thirty pellet burner manufacturers exist in Austria as well as several pellet manufacturers.

Boilers — Overcoming the problem of having both combustion and heat transfer in the same location, boilers separate these by using the flue gases of the fire to heat water to approximately 80°C and then using this hot water to heat the home via radiators. This system also has the added benefit of being able to install a hot water accumulator that can store the hot water so that one can heat the home even without the boiler running. Draught problems because of the low flue temperatures are overcome by using a blower to suck the air through the burner. The fuel for these boilers can be a normal wood log method or usually it is wood pellets or wood chips, which have the added benefit (as mentioned above) of controlling burn-rate with the rate of fuel feed.

Tile Stoves — This type of wood burning heater uses large amounts of heat storage (over 1 tonne of masonry) to even out the heat emitted by a fire. In this way one can load the fire full and burn the fuel rapidly for around one hour and the heat from this burn could heat the house for the remainder of the night. This method is very popular in northern Europe where nights are so cold that one wants their heater to keep heating for the entire night. It is also less effort on the part of the operator, only having to load the fire once or twice. In Austria technology exists that controls the rate of air inlet to the fire and can even light the fire for the owner.

Although all these methods are known and used in New Zealand, in Austria the technology is far more predominant, mainly due to the added need of heating systems in the colder Austrian winter climate. Pellet burners are gaining popularity in New Zealand because of their ease of use and excellent performance. They are used as replacements in the conversion from old high emitting wood burners, which is required in the proposed Environment Canterbury air plan.

2.4 Designing wood burning heaters

Section 2.3 showed there are many designs of appliances that can be classified as "wood burning heaters". The type of heater that will be modelled by this project will be the type that is the majority of the New Zealand market and which are most commonly tested by Applied Research Services Ltd. This type is the S-type wood burning heater, with a glass door at the front and single baffle at the top of the firebox (Figs.9&10).

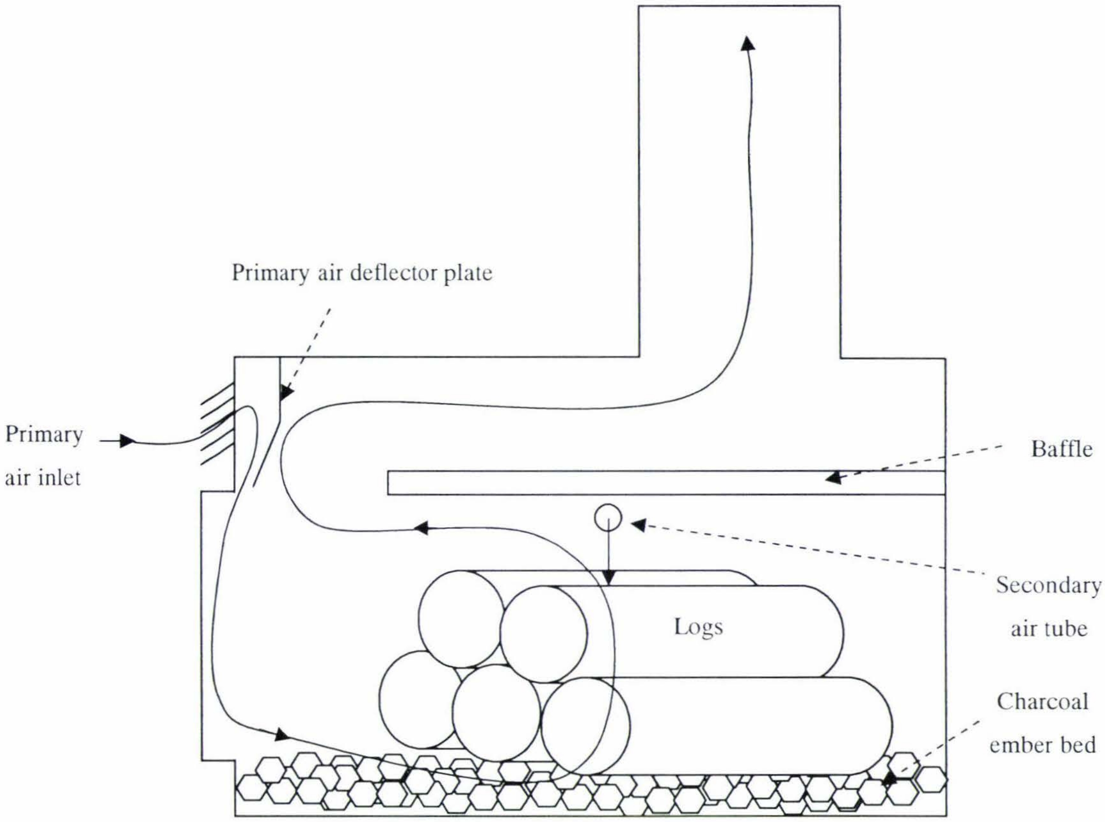


Figure 10: Airflows through an S-type wood burning heater

When designing this type of heater, there are many parameters to decide (Table 1).

Table 1: Selected design parameters for a wood burning heater

Parameter	Effect
Firebox volume	Increases the amount of wood that can fit into heater and therefore increasing burn-rate and/or burn-time.
Primary air area	Increases burn-rate as the charcoal bed burn-rate increases, which provides more heat to the pyrolysis of the logs.
Secondary air area	Because the oxygen in the primary air can be almost completely used up by the charcoal bed combustion the flame can be lacking in oxygen. Secondary air is used to increase the oxygen content in the flame and therefore decreases emissions. It also increases turbulence in the flame, which also helps decrease emissions. If it is not directed where it is needed it only cools the heater and reduces efficiency.
Insulation	Adding insulation stops heat exiting from the heater so usually reduces efficiency. However, the increased firebox temperatures mean that the wood gases burn more easily so there are fewer emissions. Insulation can be increased in many ways: firebricks can be added, walls can be made from an insulating material or heat shields that stop radiation from the heater due to their low emissivities can be added.
Baffling	Adding baffles into the heater helps increase turbulence and smoke residence time. Every modern heater in New Zealand has a baffle at the top of its firebox. It also helps insulate the fire from the cooler top surface of the heater. This means a higher combustion temperature, which leads to fewer emissions.
Primary air deflector	The primary air deflector deflects air from the primary air inlet down the glass door and into the charcoal bed. It is very important that the air is deflected down so that it can be of some use to the fire rather than being lost straight into the flue, above the baffle (as shown by the grey line in Fig.10).

2.5 The Emissions test

The emissions test at Applied Research Services Ltd is performed to the Australian/New Zealand standard 4013: 1999. The test is carried out in conjunction with a measurement of power output and efficiency using the methods set out in the joint Australian/New Zealand standard 4012: 1999.

A calorimeter room constructed by Applied Research Services Ltd lets air in one side, which then exits out a duct on the other side of the room (Fig.11). The room is well insulated and air tight so that all heat from the heater exits out the air duct. The heat output from the heater is determined from the difference in temperature between the calorimeter room outlet and inlet air temperatures and the air flow-rate. The flue gases flow up a flue 4.6m high and into the dilution air stream. Before the dilution tunnel, the flue gases are sampled and analysed for oxygen, carbon dioxide and carbon monoxide.

The flow-rate of the dilution air stream is measured and a sample flow removed, which is also measured so that a dilution factor can be calculated. This sample stream is then filtered through glass fibre filters and the extra weight of the filter, between the finish and start of a test, is the particulate emissions from the heater. Over 90% of the particulate emissions are PM_{10} with the remainder slightly larger than 10 μm.

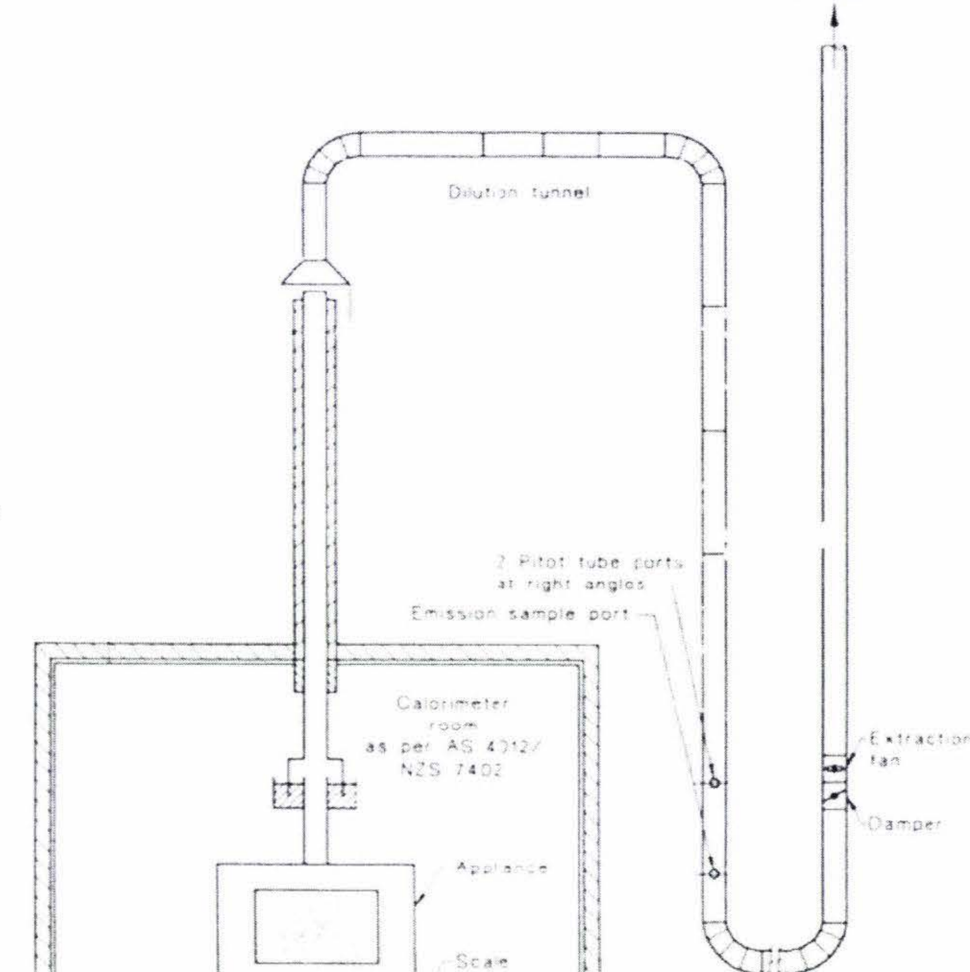


Figure 11: Emissions rig diagram (Source: Applied Research Services Ltd)

2.5.1 Emissions test procedure

At the time of this project the emissions test procedure was:

1. Measure heater dimensions including air inlet areas, firebox dimensions, baffle height and overall dimensions.

2. Calculate log mass and length from the firebox volume and longest firebox length. The volume of the logs is set at 16.5% of the firebox volume, while the length of logs is set at 75% of the longest firebox length.

3. The diameter of the logs is set to be between 75mm and 110mm. This is accomplished by cutting the logs into the right length from 100mm X 100mm timbers. The square cross-section of the timber is then turned into an octagon so that it better represents a normal cylindrical log. Four sets are made for each test, three for the actual test and one for the preliminary test.

4. Start heater using kindling and then larger rectangular wood pieces. This is to get the heater up to its operating temperature so that each test starts at the same point.

5. Wait for a good ember bed to be created, and then add the wood for the preliminary test. This test is to make sure that the heater is up to its operating temperature. If the heater was cooler at the start of a run than the end, energy would have been used to heat the heater's mass. This energy would be removed from the output so that both output and efficiency would be lower than it should be. This can also work the other way. If the start up burn is too fast then the heater can be hotter at the start than the end so that its efficiency will be higher than it should. Tests are only used if the start and end outputs are within 10%.

6. First test is started, the wood is added and recordings of heat output, flue temperature, flue oxygen, flue carbon dioxide, flue carbon monoxide and net mass of heater are recorded both in person and by a computer. Net mass of the heater is a measure of the mass of wood left inside the heater and is used to calculate burn-rate. At the start of the run the heater door is left open for a few seconds so that the combustion of the wood can start. Once flames are established the door is closed and the primary air control set to the required setting.

7. Three tests are required, high, medium and low. This is a measure of the primary air inlet area, which determines the rate of combustion. The high and low areas are provided by the manufacturer with the medium being an average of the two. For the medium and low runs the air control is set on high until 20% of the wood mass has been burnt. This lets the fire become established so that the wood doesn't smoulder and produce extremely high emissions.

8. The test is run until the net mass of the heater returns to the value it was at the start of the run. At this time the emissions filter is removed and placed in a room of standard temperature and humidity and left to dry until its weight remains constant. The next filter is then placed into the sample stream and the next run is started by adding another load of wood onto the charcoal ember bed.

9. Three tests are made for each airflow setting, giving a total of nine tests, which are averaged to give an efficiency in % and an emissions in grams of PM_{10} per kilogram of wood burnt (g/kg). Efficiency

is calculated using the gross calorific value (GCV) based on the dry wood weight. This means that the energy content of the wood (denominator of efficiency calculation) is calculated from the wood GCV (MJ/kg) multiplied by the mass of the dry wood.

2.5.2 Emissions test relevance

There is a trade-off in the emissions test between representing operation of the heater in real life and having a test that gives the same results every time. Under home conditions, the fuel used is irregularly shaped and has a different chemical composition and water content.

The heater can also be used differently than in the test e.g. a heater may be turned down low and some large logs added to the fire, so that the fire will last the entire night. This procedure produces large amounts of smoke as the fire does not get hot enough to burn the large amounts of smoke produced at the start of a burn. There are certain heaters that have been designed to burn overnight. They do this by insulating the firebox walls (especially the floor) extremely well to keep the charcoal hot. In the morning the charcoal ember bed only needs to be turned over and hot charcoals are available to start a new fire.

Because Environment Canterbury are currently introducing their new air plan they are very interested to find out if the emissions test at Applied Research Services Ltd gives the same results as the actual use of wood burning heaters in a home situation. A project has been set up to see if there are any differences between in home use and the Emissions test. This has been split into three sections:

1. Applied Research Services Ltd carry out an emissions test that lasts six hours (refuelling of heater is required) and uses a variety of fuels at the laboratory in Nelson.
2. Carry out the same tests as in step one in volunteer homes throughout Christchurch and Nelson. A mobile emissions sampler was constructed by Applied Research Services Ltd and the efficiency was calculated using the stack loss method, where the output of the heater is calculated from the energy from the wood minus the energy that is carried up the flue with the hot flue gases.
3. The mobile emissions sampler is kept in place while the volunteers use the wood burning heater in the manner in which they would normally use it, not the standard test of six hours as used in steps one and two.

This project is ongoing as at April 2004 so no results are available yet. It should be very interesting to see how close the in-home results are to the test results and to see how important heater operation is to the performance of wood burning heaters.

2.6 Previous wood burning models

Webley (2003) of Applied Research Services Ltd had spent considerable effort on this search already and had found many previous wood burning models, which were of some interest. Many of these concentrated on details of wood burning e.g. pyrolysis rates. Other examples of computer models for wood burning are:

Shopping mall fire	"A CFD model was constructed to find the flame and flow structures of steady-state or transient fires in three-dimensional enclosures. The computations provide the flame location, flow patterns and distributions of velocity, temperature and species concentrations in the enclosure" (Markatos and Pericleans, 1983). This model enabled the user to see how fast a flame would propagate through a shopping mall and how effective preventative measures like fire doors were.
Char bed burning rates	"A numerical simulation model of char bed combustion in a recovery boiler has been developed. The model couples together chemical and physical phenomena in the char bed and the gas field above it", (Pekka, S. et al. 1993). This computer model calculated the charcoal burn-rate, incorporating many different chemical reactions that occur in this complex process.
Kanury Pyrolysis	"Conventional analyses on the problem of combustion of cellulosic solids assume that the energy transfer in the interior of the fuel element is adequately described by an unsteady state conduction equation provided with an Arrhenius type pyrolysis term", (Kanury and Blackshear, 1970). This project attempted to model some of the secondary effects, which in some equations become non-negligible and take a dominating role in control of the net burning rate. The secondary effects modelled included: Heat transfer via convection of pyrolysis gases leaving the wood logs. Secondary reaction of tar cracking to form smaller weight gases as it travels through the charcoal surface of the wood. Diffusion, due to concentration differences, of pyrolysis gases into the centre of the wood.

Only two computer models were found that attempted to model an entire wood burning heater. This may be because domestic heating systems are usually offered by local companies that could not afford computer modelling so far (Musil and Jordan, 2003).

2.6.1 Woodsim

Canada Mortgage and Housing Corporation engaged the Scanada Sheltair consortium to develop a computer model of a wood-burning heater, to predict its effect on house depressurisation and ventilation (Woodsim, 1987). Their main objective was to improve the safety of wood burning heaters. This was done by finding conditions where flue reverse flow occurs and determining surface temperatures of the heaters. Flue reverse flow is particularly dangerous as hot and toxic gases spill into the room. Surface temperatures of the heater are also very important to safety as they can be used to calculate the clearances of the heater from combustible materials.

Woodsim was an outgrowth of Fluesim, which used the same ideas but was used for the simpler, steady state burning of gas and oil fired appliances. This computer model was quite simple in the way it dealt with the actual burning of the wood inside the fireplace, because this was not its main concern. Woodsim had its own graphical user interface where the user could input all the dimensions of a heater and its flue/chimney. The user interface was very easy to use and the author easily ran a number of simulations to find out how much information Woodsim provides. Because Woodsim is designed to find conditions where reverse flow occurs, the bulk of the results of Woodsim were house pressures, which were not applicable to this project. House pressures were calculated to show the depressurisation of a house with a wood burner and the effect that this can have on the burner. The burner draws air out of the house at a high rate and if the house is too tight then not enough air is drawn back into the house and the pressure inside the house falls.

Many ideas used in this project were adapted from Woodsim and it provided a good starting point. Scanada Sheltair consortium could not be located for extra information about their model but the software for both Fluesim and Woodsim was found at Applied Research Services Ltd.

2.6.2 Austrian CFD Model

CFD is short for computational fluid dynamics; see section 2.7.2 for an explanation of CFD. Musil and Jordan (2003) successfully modelled a pellet burning boiler using the CFD package FLUENT. The burn-rate of this type of heater is simpler to model than an S-type log burner because the heater is burning pellets not wood logs. This lead to the assumption that the combustion was homogenous, so that the pyrolysis reactions did not need to be modelled. The common approach for modelling the pyrolysis in this case is that the solid fuel is separated into already volatized gases and char. The objective of the model for Applied Research Services is to model log wood combustion and the assumption of homogenous combustion can not be made. Therefore, this type of model could not be used for the Applied Research Services model.

The modelling was very successful, with the most successful section of the modelling being the airflow pathways that showed if there was any bypass problems in the heater. Some of the combustion gases were not flowing through the entire combustion system but had found a short cut out of the heater. This problem was fixed and it contributed to improving the emissions of the boiler.

2.7 Modelling Theory

This project used a theoretical model where a set of mathematical equations was used to represent the system being modelled. The idea of utilizing a collection of mathematical equations as a "surrogate" for a physical process is at once ingenious as well as expedient (Ogunnaike and Ray, 1994).

2.7.1 Lumped capacity analysis

In order to model a system by a set of mathematical equations certain assumptions must be made. The natural world works as a combination of a vast number of molecules, each acting independently. Unfortunately current computational power and scientific understanding cannot possibly model systems on this atomic scale. A compromise must be used where sections of the system to be modelled are lumped together as one variable, which has the same properties throughout i.e. same temperature, pressure, specific heat. For a heater it may mean that the steel walls are assumed to be one variable and are therefore at a uniform temperature. This leads to modelling errors, but this can be tolerated because the measurement of the system i.e. the emissions test, also includes errors.

2.7.2 Computational fluid dynamics

A very powerful computer modelling tool is computational fluid dynamics (CFD). CFD uses the ideas of lumped capacity analysis but on a much smaller scale. It is used to determine the fluid-flow profile around or through a system. The fluid area of the system is divided into thousands of small sections, usually squares or tetrahedrons. Tetrahedrons have become more popular recently because they are easier to fit into complicated geometries. Navier stokes equations are then used to apply mass, energy and momentum balances on these fluid sections, so that temperature, pressure and velocity profiles can be found.

The advantage of CFD modelling is that it can be more accurate and programs exist, like CFX and Fluent, which take care of all the equations and fluid properties. The user only has to input the geometry of the system into the computer and define the fluid and other boundary conditions. This is also CFD's main disadvantage for this project because for every different heater the model is used for, a highly detailed diagram of the heater must be drawn into the program. This would take a long time and could easily be harder work than the emissions test.

2.7.3 Mass and energy balances

Mass and energy balances are widely used in the field of chemical and process engineering. The basic idea is very simple, in that mass or energy must be conserved in any given system.

$$\text{Accumulation} = \text{Inputs} - \text{Outputs} + \text{Generation} - \text{Consumption} \qquad \text{(Eq 2.3)}$$

Accumulation	mass or energy increase in the system
Inputs	mass or energy entering the system
Outputs	mass or energy leaving the system
Generation	mass or energy created in the system
Consumption	mass or energy consumed in the system

Both generation and consumption are only used when a chemical/nuclear reaction is occurring and one chemical is generated whilst another is consumed. Because the terms other than accumulation are usually calculated as rates, the whole equation needs to be integrated. This gives an equation that can be used in computer modelling.

Accumulated mass/energy = Integral (Inputs – Outputs + Generation – Consumption) (Eq 2.4)

When using this equation for an energy balance the accumulated energy can be used to calculate the temperature of the object using the heat capacity equation:

$$\text{Heat stored in object (kJ)} = m\, Cp\, (T - T_0) \qquad \text{(Eq 2.5)}$$

m = Mass of object (kg)

Cp = Specific heat of material (kJ/kg °K), found in Perry and Green (1998) and Mills (1995)

T = Temperature of object (°C or °K)

T_0 = Ambient temperature (°C or °K)

2.7.4 Bernoulli

Bernoulli's equation is commonly used in the subject of fluid dynamics, which deals with the flow of fluids. The equation includes the four ways in which a body of fluid can change its pressure.

Dynamic — Changes in velocity cause a change in pressure, higher velocity produces lower pressure. This causes the lift for aeroplane wings.

Static — How much other fluid is above causing a force on the fluid. This produces atmospheric pressure i.e. the air above the Earth is pressing down on the air at the Earth's surface.

Friction losses — Energy, and therefore pressure losses due to friction. This is calculated using K factors. The equation used is:

$$\Delta P_{friction} = K\,(\rho/2)\,u^2 \qquad \text{(Eq 2.6)}$$

The idea here is that friction slows the flow of the fluid. If the object exerting the friction completely stops the fluid, K would be 1. K values can be well over one due to fluid circulation.

Pumping — Mechanical energy from a pump increasing the fluid's energy and therefore pressure.

These four factors are balanced so that the pressure at any one point can be found from a previous point. The Bernoulli equation is shown below. A more detailed explanation of it can be found in Holland and Bragg (1995):

$$(P1-P2) + \rho g(h1-h2) + \rho/2(u1-u2)^2 = \Delta P_{friction} - \Delta P_{pumping} \qquad \text{(Eq 2.7)}$$

P = Pressure (Pa)

ρ = Density of fluid (kg/m^3)

g = Acceleration due to gravity (9.81 ms^{-2})

h = Height (m)

u = Velocity of fluid (m/s)

ΔP = Pressure change (Pa)

1 and 2 are the two points that the equation is being used between.

The Bernoulli equation was developed with the assumption of a constant temperature, which leads to constant density. When using this equation to model the flow through a wood burning heater, this assumption is obviously not correct as the temperature of the air passing through the heater changes from 20°C at the inlet to 600°C in the combustion zone and then back to 200°C at the exhaust. Because of this, the equation was used very carefully in this project.

2.7.5 Heat transfer

There are three mechanisms for the transfer of heat.

Radiation

Every object in the universe emits a certain amount of radiation which depends on its temperature. The emmitance of an object is given by:

$$E = \varepsilon A \sigma \Delta T^4 \qquad \text{(Eq 2.8)}$$

E = Radiation energy emitted by an object (kW)

σ = Stephan-Boltzman constant, which is an easily remembered 5.67E-08 kW/m^2 K^4.

A = The surface area of the object (m^2)

ε = The emissivity of the object, which for a non-transparent surface is equal to one minus the fraction of radiation reflected by the object. Emissivities for many materials are listed in heat transfer texts. For this project (Mills, 1995) and (Perry and Green, 1998) were used.

When the heat transfer between two objects is required one simply finds the difference between the two radiations. In more complicated geometries shape factors must be used to represent the fraction of radiation from one surface that reaches the second surface. Many equations exist for the calculation of these shape factors, but since a heater is such a complex shape (flames and logs etc), in this project only estimations of the shape factors were used.

Convection

Convection heat transfer is heat transfer between two different phases i.e. from solid surface to a fluid. The actual processes behind convective heat transfer are very complex so an analytical method for its caiculation does not exist. However, empirical formulas can be used instead.

$$Q = h\,A\,\Delta T \qquad \text{(Eq 2.9)}$$

Q = Heat exchange rate (kW)

A = Area of heat transfer (m^2)

ΔT = The difference in temperature between the solid surface and the fluid (°C or K)

h = heat transfer coefficient (kW/m^2 K), which can then be calculated from various fluid properties e.g. Reynolds numbers, Prandtl numbers.

Conduction

Conduction is heat transfer through one phase.

$$Q = k\ A\ dT/dx \qquad \text{(Eq 2.10)}$$

dT/dx = Temperature gradient

k = Conductivity of the object. Large tables of k values for many different materials exist, some even showing how k changes with temperature.

First order approximations of the temperature gradient can be made so that the equations can be used to find the conduction between just two points. Equation 2.7 is reduced to:

$$Q = k\ A\ \Delta T/x \qquad \text{(Eq 2.11)}$$

x = The distance between the two temperatures one is interested in.

For a more in-depth explanation of heat transfer mechanisms see Mills (95).

2.7.6 Rate expressions

Rate expressions are generally empirical, using a rate constant to relate different variables to the specified variable. There are some specific forms that are constant throughout chemistry. One of these is the effect of temperature on the rate of a chemical reaction. This relationship is often modelled by an Arrhenious equation.

$$\text{Rate constant} = A\ e^{-E/RT} \qquad \text{(Eq 2.12)}$$

T = Reaction temperature (°C)

R = The universal gas constant of 8.314 J/mol K

A and E (J) are the constants used with the Arrhenious equation and can be found in textbooks for many simple chemical reactions. The rate constant is then multiplied by the concentrations of reactants to give the reaction rate.

3 Methodology

3.1 Software selection

Before any modelling could be undertaken, the most suitable software package needed to be identified. The software needed to be user friendly to both the author and the end user. This would include an effective method for defining the model (standard equations or a graphical interface) and an easy method for the end-user to specify the heater parameters (graphical interface). The model would need to be able to solve hundreds of simultaneous equations and ordinary differential equations (ODEs).

Many options were discovered on the Internet and through discussion with modelling experts, (Bakker, 2003) and (Jordan, 2003). The software packages explored were Microsoft Excel, C++, Vensim, EES, Mathcad and Matlab. The different packages each have advantages and disadvantages, which are listed below.

3.1.1 Microsoft Excel (Visual Basic)

Excel is widely used and will therefore be reasonably user friendly for the end user. However, it does not automatically solve ODEs, so a numerical ODE solver, such as "Runge Kutta", which is a technique used to solve derivatives, would have to be programmed as well. This would make the program more difficult to write and also more complicated if someone wanted to modify the program.

3.1.2 C++

"Woodsim" (Section 2.6.1), used C++ for its program. This means that ideas could be taken directly from the Woodsim program, after copyright considerations. However, this software also had the disadvantages of Excel, in that it doesn't automatically solve ODEs. The author was not familiar with the C++ language, and it was thought that anything that this language can do should be capable using Visual Basic and Excel.

3.1.3 Vensim

Vensim is used to solve systems problems, when presented in the form of casual loop diagrams. The author was familiar with the software after using it whilst at the University of Canterbury. Causal loop diagrams (Fig.12) are drawn into the program and relationships added later. This gives a good graphical representation of the system which is useful for developing and explaining the model.

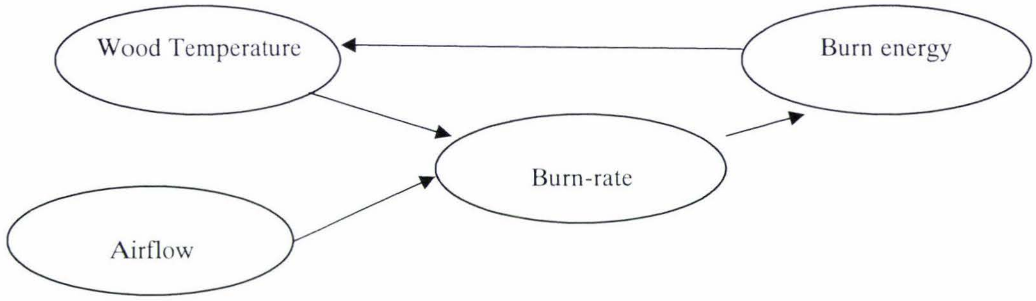


Figure 12: Causal loop diagram as used in Vensim

If an arrow ends at a balloon the equation for that variable can include the variables of the previous balloons e.g. the equation for burn-rate can include airflow and wood temperature while the equation for burn energy can only include burn-rate.

An advantage for this software is that ODEs can easily be solved. Unfortunately it was predicted that when it came time for the end-user to run the program, entering the various parameters would be time consuming and confusing. The diagram above will get extremely complicated once all factors associated with wood combustion are accounted for.

3.1.4 Engineering Equation Solver (EES)

EES is a numerical solving program, which solves up to 6000 simultaneous equations, including ODEs. There is also a "parametric table" where users can easily input the parameters. Another advantage is that more than one process can be modelled at a time, so that comparisons can easily be made. One disadvantage of EES is that it is relatively unknown as modelling software, compared with Mathcad and Matlab. It also lacks an ability to add a graphical user interface to the program in order for the end-user to more easily enter parameters and obtain results.

Equations are entered into an equation window in exactly the same way that you would write them down on a piece of paper. Equations can be added in any order and they don't need to be the right way around. The only requirement is that the degree of freedom of the equation set is correct i.e. that there is the same number of variables as equations. EES was found at www.fchart.com, where a free test version is available. Fortunately for this project, Massey University invested in an academic version.

3.1.5 Mathcad

Mathcad is a well-known mathematical equation solver. It solves equations analytically, so a numerical ODE solver would still need to be added to the program because the model equations will be non linear. Mathcad uses a similar approach to EES when defining the problem. Equations are simply added to an equations window as one would write them down on paper.

3.1.6 Matlab

Matlab is the standard mathematical equation solver and was recommended by both Bakker (2003) and Jordan (2003). Matlab includes a simulation program "Simulink", which is similar to Vensim in that equations are added to the program through diagrams. This aids the understanding of the model, especially during its development. Matlab also includes abilities to interface with Excel, C++, FORTRAN and a graphical user interface can also be added. When using simulink, graphs are very simple; however the data can be transported to the Matlab domain and graphed there. This produces very impressive graphs, which none of the other software packages can match.

3.1.7 Software overview

In the end, EES and Matlab emerged as the two preferred packages. EES is simpler and very easy to program, while Matlab is harder to program but graphical user interfaces can be added to make it easier to interpret the data for the end user. Matlab is also proven, while EES is relatively unknown. Both Matlab 6.5 and EES 6.746 were available at Massey University and copies were made available for this project.

EES was chosen, predominantly because of its ease of use when developing the model and it is also capable of interacting with other programming languages so a graphical interface should be possible.

3.2 Model Development

The initial expectation was to model the different sections of the process separately. The process was split into three sections; wood combustion model, airflow model and heat transfer model. When modelling commenced it was quickly discovered that one section of the process could not be modelled without the others due to complex interactions e.g. burn-rate is affected by heat transfer and airflow, airflow is affected by heat transfer and heat transfer is affected by airflow. Therefore, a new approach was used, where the model would develop slowly from a very simple model to begin with, with many assumptions e.g. constant air-flow, same temperature throughout wood. The model was then complicated by adding extra sections, so as to eventually remove as many of the assumptions as possible.

3.2.1 Model 1

This first model was extremely simple and included only the following relationships and assumptions:

- Burn-rate using the relationship used in Woodsim (br = constant*wood surface area*airflow).
- Convection from logs to air.
- Radiation from logs to walls.
- Convection from air to walls.
- Convection from walls to room.
- Radiation from logs to room.
- Mass and energy balances for logs, air, walls.
- Flue temperature calculated from air temperature minus heat losses from the flue.

Important assumptions for Model 1 are:

- No flame or coals. Energy from wood burning is added to the wood energy balance.
- Same air temperature throughout firebox.
- Same temperature throughout firebox walls.
- Same temperature throughout logs.
- Complete combustion.
- No radiation from walls to room, only convection.

3.2.2 Model 2

The model was made more realistic by adding a flame and charcoal bed, with the flame receiving the log burn energy. Two burn-rates were calculated, one for the logs and one for the charcoal bed. Other additions were:

- A fixed time step was added to provide much needed control of the solving process. Before this EES would pick the time step, which sometimes led to the solving process becoming unstable. The fixed time step was much less than what EES was using so the solving was made more stable

- Area of the charcoal bed was given by the area of the logs, so that when logs burn away charcoal bed area increases
- Radiation from flame to logs, walls and room
- Convection from flame to air
- Conduction from charcoal bed to logs
- Radiation from charcoal bed to walls and room
- Convection from charcoal bed to air

3.2.3 Model 3

Model 3 added a combustion efficiency expression and a radiation term for the heat flow from the heater walls to the room. An overall balance was also added to determine if the model was working correctly. It was found that the overall energy balance was not balancing. This was due to the fact that the heat of the pyrolysis gases was being added to the airflow, but was not removed from the logs. With this problem fixed, another problem found in models 1 and 2 was also remedied. The log temperature would not decrease as fast as expected, when burn-rate decreased. What was happening was that the heat in the logs was decreasing slowly (with the change, it now decreases more quickly) and the mass was also decreasing so, from $Q = m\ Cp\ \Delta T$ (Eq 5), the temperature remained reasonably constant.

The problem of the overall balance not balancing occurred nearly every time changes were made to the model. This occurred if one section of the heater was increased by a heat flow and the corresponding section was not decreased. For example if a new heat flow was calculated for the convection from the logs to the air. Let this heat flow be named qrla (qr=heat flow, l = logs, a = air). The overall balance would not balance if qrla was removed from the log energy balance and not added to the air energy balance. This sounds like it is very simple and should never happen but when there are over one hundred heat flows to add or subtract to over thirty energy balances, it happens quite regularly. Other reasons for the overall balance not balancing are using the wrong specific heat for a temperature calculation (Eq 2.5) or not balancing the airflows through the heater correctly. The overall balance was an excellent check to see if the equations were set out correctly. Other additions were:

- Overall efficiency expression added to account for the accumulation of energy in the entire system. Some heaters have a large heat store so that when they are heating up their efficiencies are shown lower than they should. This equation was developed to remove this problem.
- Radiation from heater walls to room walls. Until now only convection had been the mode of heat transfer to remove heat from the outer walls.
- All other radiation heat flows into the room now use the room walls as the cold temperature, not the room temperature as used previously. Room walls temperature is 25°C, while room air temperature is 20°C.
- Combustion efficiency calculated empirically from secondary airflow and log temperature. Increased secondary air increases combustion efficiency and increased log temperature also increases combustion efficiency. This equation was not intended to be used to calculate emissions but to remove some of the heat from the system, in the form of un-burnt volatiles.

3.2.4 Model 4

Model 4 added a variable air flow, where the flue draught controls the flow through the heater. Previously the air flow through the heater had been set at a constant value. The extra features of Model 4 are:

- Used EES's built in functions to calculate air density and specific heat as they changed with temperature and pressure. Ideal gas is assumed by EES.
- Added a baffle with convective and radiation heat flows to and from it.
- Split air into three sections: primary air directly above logs; secondary air at the top of the firebox; baffle air above the baffle.
- Split flue air into two sections: flue air below the measurement point of 2m, flue2 air above the measurement point. Assumed that only the heat from flue's walls (not flue2's walls) heats up the room.
- Airflow expressions using pressure balances and draught calculation (Eq.2.2).
- Pressure drop calculations using K factors (Eq.2.6).

3.2.5 Model 5

Model 4 still assumed that the logs were at one temperature. In model 5 this was changed, which lead to the ability to calculate drying and pyrolysis rates inside the logs. Also added in Model 5 was:

- Logs divided into six concentric cylinder sections (Fig.13). One section was the surface which was set as 10% of the total mass. The other five were inside this section and were divided to be of equal mass. The sections were defined as concentric cylinders because the conductivity of wood is much greater along the grain than across it. For this reason an assumption was made that the temperature is the same anywhere along the grain of the logs.

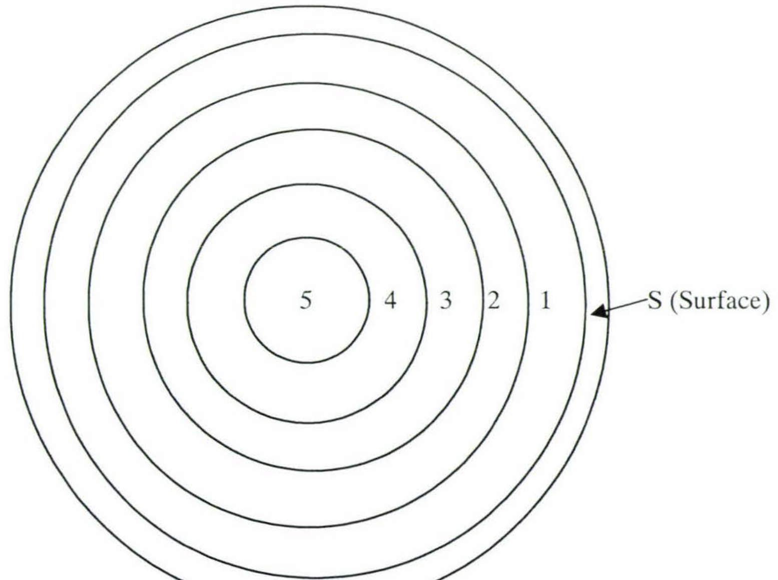


Figure 13: Wood section numbering

- Drying rate equations were added using a constant and a temperature difference. Drying rates were calculated for each log section.

  Drying rate = Constant * (Temperature of Wood – 100) (Eq 3.1)

- Mass of each section calculated from the total mass. This was so that the mass of no one section went to zero, which would lead to dividing by zeros and stopping the solving process.
- Three burn-rates: pyrolysis gases that burn in the flame; charcoal burning at the log surface; charcoal burning in the ember bed. Volatile combustion was still calculated by an empirical combustion efficiency.

  Pyrolysis rate = Constant *Mass of wood * (Temperature of wood – 200) (Eq 3.2)

  Charcoal burn rate = Constant * Area * Mass (Eq 3.3)

3.2.6 Models 6

This model was developed to let each section of the logs act independently. The log sections each had their own mass calculated by mass balance and not from the overall mass as in Model 5. This meant that the mass of the outside sections decreased to zero, which produced problems when calculating $T = Q / m\ Cp + Tr$ (Eq 2.5). This was resolved by using many "If" statements. When the wood section's mass was zero, all parameters calculated from it were changed to appropriate values and the section just inside it was changed to become the surface. This produced large changes in the variables at these changeovers, and the system often became unstable.

3.2.7 Model 7

It was thought that if the number of cylinders was increased, variable changes at the changeovers would decrease and the system would become more stable. Therefore Model 7 was produced with 20 concentric cylinders. This slightly increased stability but the system still went unstable, just less often. Another problem with Model 7 was its solution time, which approached two hours.

Trying to develop models 6 and 7 took approximately one month and it must be considered a failure. However, much knowledge was learnt about how EES operates and the compromise solution, model 8, used many of the equations developed in Models 6 and 7.

3.2.8 Model 8

The compromise made in model 8 was that the mass loss from the charcoal burning at the surface of the logs is spread evenly between the sections. Below is a list of advances over model 5. Most of these were made in models 6 and 7.

- Pyrolysis and drying gases from inner sections cool down the outer sections. It was assumed that the gases flow through the log so slowly that they reach thermal equilibrium with each section above itself.
- Conduction heat transfer coefficient (k) was increased so that the inner sections heated up faster. In reality this is due to convection currents inside the wood (Kanury and Blackshear, 1970), but for this model the two processes were bundled together as one conduction heat transfer.

- Conduction heat transfer parameters, length and area, are calculated from section masses, not just estimated, as in Model 5.
- Coal burning at logs is adjusted empirically to allow for the process where the pyrolysis gases remove all oxygen from the log surface and the coal burn-rate at the surface is lowered.
- Logs split into nine sections (still concentric cylinders). This was thought to be a good compromise between solution speed and accuracy. Also anything over 10 sections would make the naming convention slightly confusing.
- Outside wall temperature calculated from the inside wall temperature – 100°C. This expression was used to model the effect of the firebricks and radiant heat shields around the heater, before this was modelled using heat flows and resistances.

3.2.9 Model 9

It was felt that Model 8 was a good model of the burn-rate of wood. The problem with model 8 was that it was still extremely simple in all other respects; there was only one heater section, which was named walls. Model 9 added many extra heater sections and therefore many extra heat transfer terms. Firebricks, heat shields and multiple walls were added. This added much greater complexity to the model and the author was no longer able to keep track of all the different heat transfer relationships. A system was developed where the variables were ranked by temperature: flames first, followed by char, with the heat shields last. This was developed in Microsoft Excel and was called "Heat Transfer". It can be found in Appendix 2. This system helped keep track of the many variables used in calculating the heat transfer inside the heater.

The results of Model 9 were very similar to Model 8, but without the set 100°C drop from inside wall to outside wall temperature. Also many more temperatures were calculated and more design parameters e.g. firebrick thickness, were used. This allows the model to be much more useful than Model 8. This model also found that the heat shields are a far better insulator than the firebricks.

3.2.10 Model 10

Model 10 was developed to overcome the assumption of uniform air temperature in the firebox. Previous models had used just two temperatures in the firebox; primary and secondary air temperatures, with primary occupying the lower half of the firebox and secondary the upper half. In Model 10 six new air sections were developed (Fig.14). These were four door air sections that occupied a space just behind the door where the primary air travels. It was thought that this section of air would be much cooler than the other sections because of the cooling influence of the cold primary air. The other two new air sections were log air and coal air. These were around the logs and coals respectively.

The door air was divided into four sections because there were four places where the primary air can end up; secondary air, primary air, log air and charcoal air.

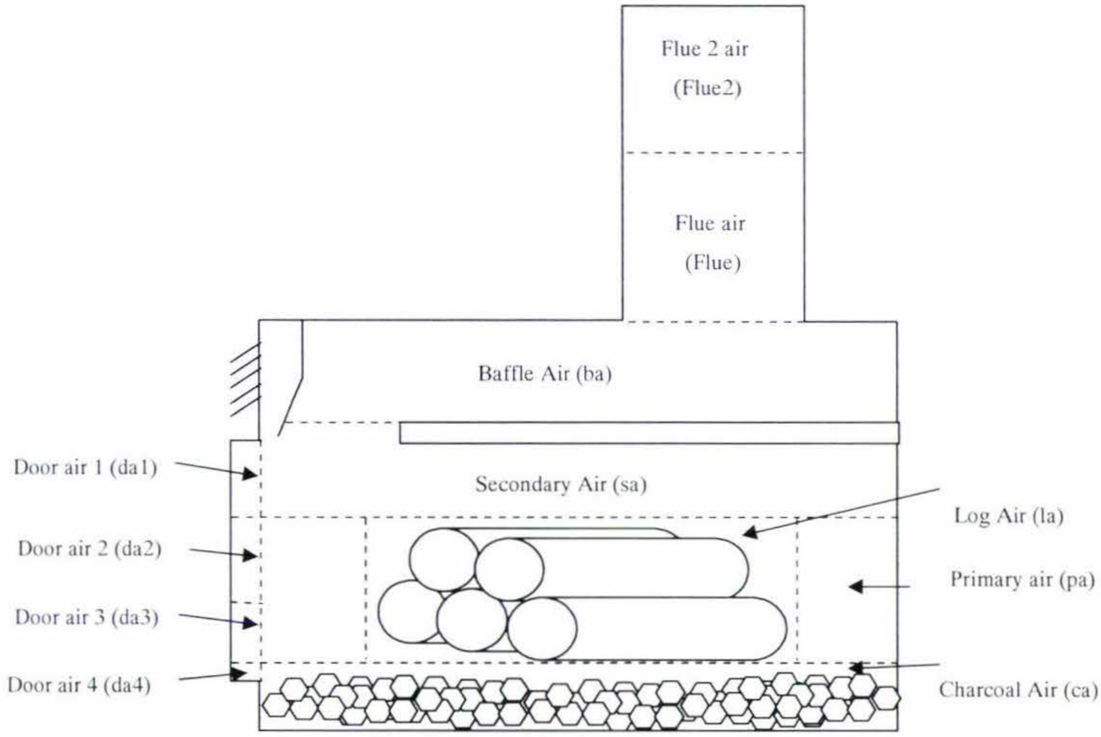
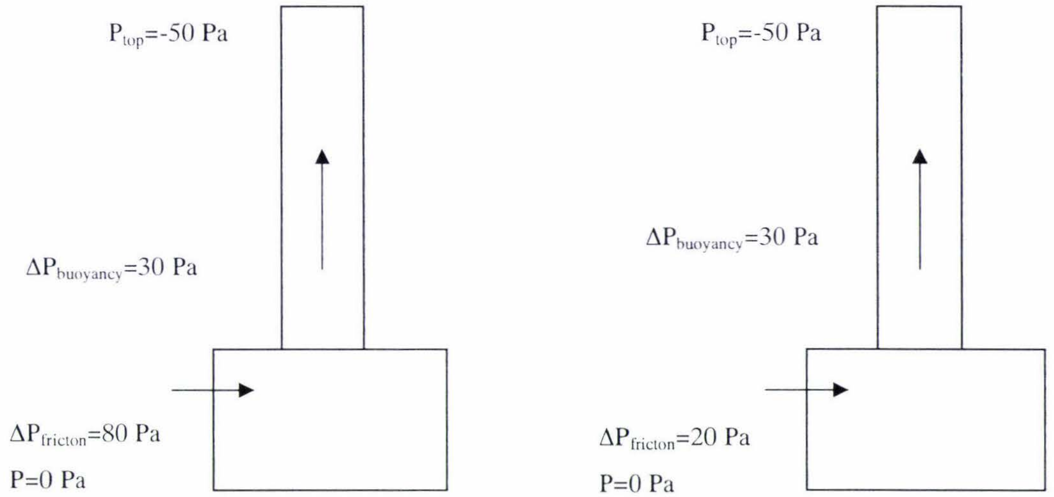


Figure 14: Air sections used in Model 10

The primary air inlet that flowed into the secondary air section came from the first section (da1), the primary air from the second section (da2), the log air from the third section (da3) and the charcoal air from the fourth section (da4). Percentages were used to calculate how much of the primary air would go where, with the intention that these percentages be calculated from other parameters later on e.g. At lower primary air flows, a lesser percentage will make it down to the bottom (charcoal air) because of the lower velocity of the inlet air. The six different air sections meant that the convection heat transfer rates were now more correct because the air temperatures were more realistic.

During development of model 10 many equations were re-written so that their units matched. This led to the draught equation being changed and when it was put back in place, the sign was mistakenly altered. This led to a situation with much more pressure drop than before and therefore less flow. When the pressure drop equations had originally been developed, the K factors used were much larger (3-5) than had been anticipated, so this mistake is actually how draught should be calculated. After the change the K factors were as expected (1-2). Figure 13 explains the calculations made before and after the change.



Before: Pbottom-DPfriction + DPbuoyancy = Ptop

0-80+30 = -50

After: Pbottom-DPfriction - DPbuoyancy = Ptop

0-20-30 = -50

Figure 15: Flue draught modeling – before and after correction

3.2.11 Model 11

Model 11 attempted to change from only one flame temperature to five flame temperatures, one for each air section (charcoal, logs, primary, secondary and baffle). Unfortunately having five different flame temperatures led to a much greater complexity in the model, with the solution taking two hours to complete compared with 5 minutes for model 10.

Model 11 also added an expression for the transmittance of the door glass. Transmittance data of Robax glass for different radiation wavelengths was used along with the program BBRAD, which was developed by Webley (2003). Microsoft Excel was used to find a polynomial regression equation that fitted the data provided by BBRAD. The equation turned out to be a third order polynomial relating the radiation temperature to transmittance of the Robax glass. See the Microsoft Excel spreadsheet "Transmittance", in Appendix 2 for these calculations and curve fit.

3.2.12 Model 12

With more complexity expected from introducing chemistry into the model, the five flame temperatures idea was dropped. Also dropped at this stage were the log air and charcoal air. These were considered extra complexity and their effect could be modelled far more easily by simply changing the convection heat transfer coefficients. Because of the removal of these two air sections, the door air was now only split into two section (Fig.16).

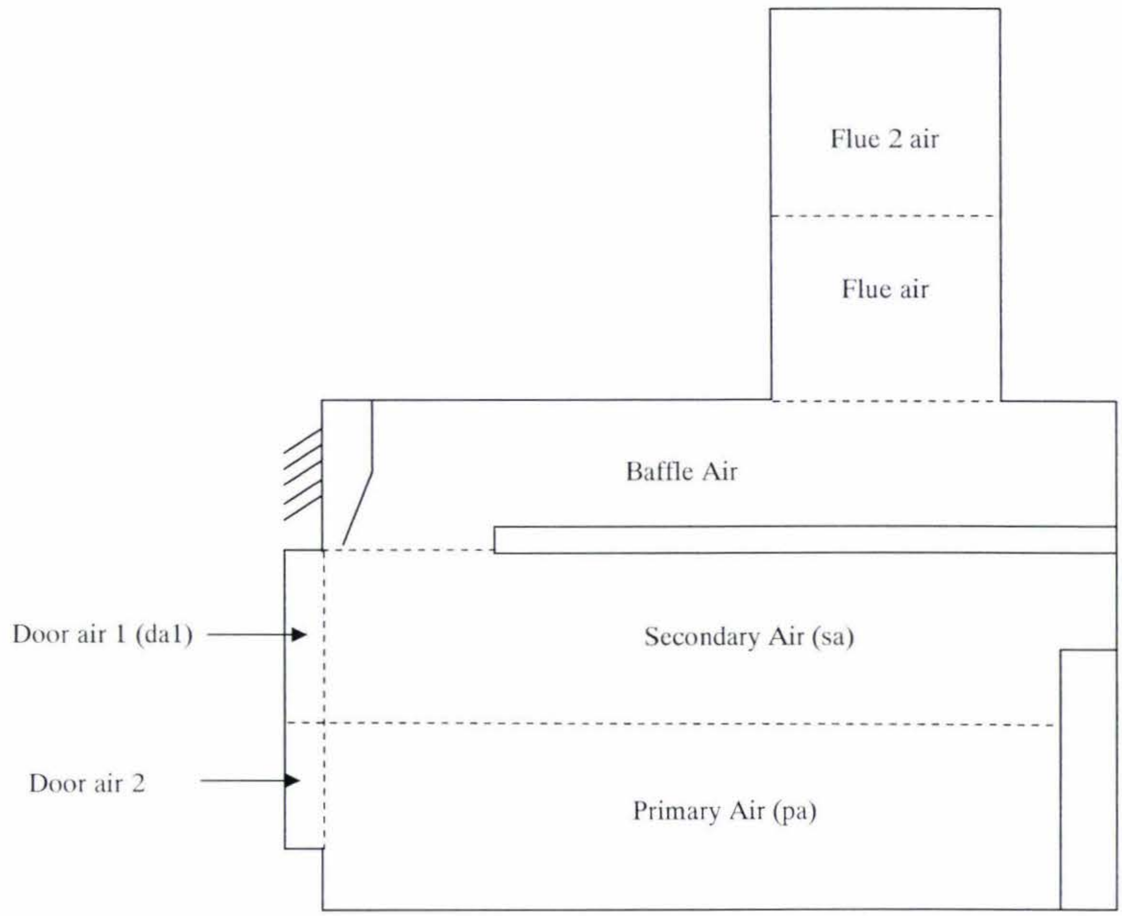


Figure 16: Air sections used in model 12

Model 12 removed the extra flame and air heat balances. The equations for the flame heat balance were also changed to the way that adiabatic flame temperature is calculated. That is the amount of energy into the flame from the combustion equals the amount of energy of gases leaving the flame i.e. no heat capacity in the flame. A simple addition of the radiation losses from the flame to the energy of the gases leaving the flame gives a non-adiabatic flame.

3.2.13 Model 13

Chemistry equations were added during development of model 13. This was done by adding a simple chemistry equation set and calculating a rate for each equation. The chemistry equations were:

$$C_{4.4}H_{6.3}O_{2.5} \rightarrow C_{2.5}H_{6.1}O_{2.4} + 0.16\ C_{12}H_1O_{0.5} \text{ (Pyrolysis)} \qquad \text{(Eq 3.4)}$$

$$C_{12}H_1O_{0.5} + 12\ O_2 \rightarrow 12\ CO_2 + 0.5\ H_2O \text{ (Char burning)} \qquad \text{(Eq 3.5)}$$

$$C_{2.5}H_{6.1}O_{2.4} + 2.8\ O_2 \rightarrow 2.5\ CO_2 + 3.1\ H_2O \text{ (Gaseous burning)} \qquad \text{(Eq 3.6)}$$

$C_{4.4}H_{6.3}O_{2.5}$ = Wood (Applied Research Services, 2003)

$C_{12}H_1O_{0.5}$ = Char (Applied Research Services, 2003)

$C_{2.5}H_{6.1}O_{2.4}$ = Volatiles (Composition so that the pyrolysis equation balances)

The 0.16 in front of the char in the pyrolysis equation (Eq 3.4) was calculated so that 25% of the wood is pyrolised into char with 75% into gases. The char percentage was found from Di Blasi (1993).

Mass balances were created for each chemical species with the above equations representing either the generation or consumption terms. Using chemistry equations allowed the model to calculate the emissions of the heater from the difference in the pyrolysis rate and the rate of volatiles combustion. The model also showed analytically, the process where char burning is slowed at the peak of the fire because of the lack of oxygen at the bottom of the firebox. This meant that the empirical relationship used to calculate the charcoal burn-rate could be replaced with an equation where the burn-rate was linearly dependant upon oxygen concentration.

3.2.14 Model 14

Model 14 attempted to improve model 13 by making the chemistry section more complex. This was modelled by dividing the wood into cellulose and a combination of hemi-cellulose and lignin. The main reason behind this idea was that Jones (1993) reported a kinetic scheme for the burn-rate of wood using this idea. The kinetic scheme worked using Arrhenious laws for the pyrolysis rate of both the cellulose and the hemi-lignin (combined hemi-cellulose and lignin). Unfortunately, this kinetic scheme was quite specialised in terms of temperature range. Since this model requires an expression that works all the way from 20 to 1000°C, this kinetic scheme didn't work correctly. At lower temperatures (~300°C), burn-rate would still be very low, but as soon as the temperature was high enough the burn-rate would take off resulting in higher temperatures and an even faster burn-rate.

3.2.15 Model 15

Model 15 attempted to make the Arrhenious pyrolysis rate equations work correctly. This was done by changing the two Arrhenious constants (A and E). In order to stop the burn-rate taking off at high temperature, the Arrhenious constant E was dropped so that the exponential expression has less effect. There was no scientific explanation to doing this, only to try and get the model to work correctly. The Microsoft Excel spreadsheet "Arrhenious" was used to determine what value E should be set to. "Arrhenious" can be found in Appendix 2.

It was discovered that in order to get the model working correctly the Arrhenious equation ended up very close to a linear relationship because E was lowered so much. The Arrhenious relationship was removed and a linear temperature dependence was returned. In affect the burn-rate expressions for Model 15 were now exactly the same as Model 13.

Model 15 also added an extra flue section. It was thought that having just one flue section below 2m meant that the actual temperature profile was not adequately modelled. With just one flue temperature it must be assumed that the whole flue, below 2m, is one single temperature. This is obviously not correct as the flue gases cool as they flow up the flue. The heat transfer from the flue will be incorrect with just the one temperature as at the bottom of the flue much more radiation and convection occurs than at the average temperature. Although this will still be a problem with two flue sections, it should be smaller. This is the main problems with lumped capacity analysis and cannot be completely removed.

3.2.16 Model 16

In the previous models since the walls of the heater were divided into many sections, most of the temperatures have been equal to other temperatures due to symmetry i.e. back fire brick and side firebrick temperatures were calculated separately, but in the same way, so that they ended up the same temperature. Model 16 combined the items that were the same. This resulted in approximately half the number of variables, which led to a quicker calculation time and therefore more time available for added complexity. It also led to the model being easier to understand and the possibility of listing the start temperatures for each section. Previously these were only estimates but now the final temperatures from the previous run can be inserted into the model as start temperatures, so that differences in heater performance at start-up versus completely warm can be determined. This must still be performed manually but it may be possible for this to be automated using another computer program.

3.2.17 Model 17

In Model 17 equations obtained from Mill (1995) were used to calculate all of the convection heat transfer coefficients. These equations produced some very surprising results, which were remembered during future modelling. An example of this is that the heat transfer coefficients for the inside walls were approximately half of those earlier predicted. This led to lower flue temperatures so that the amount of energy from the flame to the air had to increase to return to the correct flue gas temperatures. Also changed was that the pyrolysis rate was made proportional to the remaining volatiles in the wood section not the entire mass, so as to remove the bumps in burn-rate and the problems associated with the mass of wood falling below zero.

3.2.18 Model 18

The equations for the heat transfer coefficients were removed as they didn't allow enough flexibility in changing the model. This is because the extra data obtained from temperature measurements on the Masport LE2000 were available at this point. These heat transfer coefficients were then altered to give the same results as the testing. See section 3.4.1 for details on this experiment.

An expression for log conductivity calculated from the char content was added. Char is an excellent insulator so a higher char content gave a lower conductivity. This meant that at the start of a run, where the wood has no char, it is more conductive so that it heats up faster. This expression helped bring the burn-rate peak closer to the start of the run, which was what the model testing had shown.

3.2.19 Model 19

For this model, nineteen log sections were used instead of the original nine to remove the remaining bumps in the burn-rate. Also removed were most of the heat transfer coefficients so that there was less parameters to juggle when calibrating the model. Now there was only an outside heat transfer coefficient for the outer surfaces convecting into the room and an inside heat transfer coefficient for the inside surfaces.

The model burn-rate was still not peaking quickly enough. It was thought that this is because the wood sections had too large a mass so that it took too much time to heat them to the temperature where pyrolysis begins. This is a problem in the lumped capacity analysis, where discrete masses must be used to model processes that actually work on atomic scales. To overcome this problem Model 19 introduced a new log section called log section zero. Log section zero behaved in the same way as the other log sections except that its temperature was set to the charcoal ember bed temperature so that it starts pyrolysis as soon as the run starts. The mass of this section was set as only 50g so that it doesn't affect the energy balance too much, obviously the first law of thermodynamics has been broken by this procedure as the energy required to raise the section's mass to that of the charcoal ember bed hasn't come from anywhere.

This change also had a very welcome side effect. Until this change was made the model was very unstable at the start of the run. This was because there was no burn energy so that the flame energy balance had no energy input and the calculation of its temperature was often a problem. The model should have just set the flame area to zero and then the equation would have balanced as zero equals zero, but in some instances this did not happen and flame temperature would either head to negative or positive infinity.

3.2.20 Model 20

Model 20 reverted back to just nine log sections to decrease the solving time required by the computer. The temperature used for calculating the volatiles burn-rate was changed from the firebox air temperatures to the flame temperature. This led to smaller change in emissions between high and low runs, which was seen in the actual data.

The Bernoulli method of calculating the airflow was removed at this point in favour of a more empirical approach. This was because airflow experiments made on the Masport LE2000 showed a linear relationship between draught and flow, where as the Bernoulli equation gives a relationship of flow proportional to the square root of draught. See section 3.4.2 for details on this experiment.

Many housekeeping alterations were made to make the model just right. Included in this was that all units for the various variables were fixed so that each equation had the same units on both sides of the equation. EES is very helpful for doing this as it provides a list of unit errors and a table to insert the correct units for each variable. Other housekeeping was to use the parametric table only for the heater's dimensions and the fuel load used in the test; this is the information that can be changed in order to improve heater performance. The equations window is used for adding other parameters, such as material properties, calorimeter room dimensions and start temperatures.

3.2.21 Model 21

Until Model 20 the only heater modelled had been the Masport LE2000. When the model was used for other heaters the model did not perform as well. This is because of factors that could not be modelled due to a lack of time and resources. An example is the distribution of inlet air between the charcoal ember bed, the logs and air that bypasses the combustion zone. This inlet air distribution could not be modelled using this model and would require CFD. To overcome this problem calibration factors were introduced into Model 21 to model these factors. See section 3.3.3 for a detailed explanation of the calibration of the model.

Model 21 also changed the way in which material properties were specified. Before, the heater sections were assumed to be steel, firebrick or glass. This is not very flexible so in Model 21 the system was changed so that the user could specify that any heater section had any material properties e.g. the walls could be made out of firebrick or even gold if required.

3.3 Final Model

An instruction manual has been produced for use with the model (Appendix 1). The following relationships and assumptions were used in the final model:

3.3.1 *Relationships*

- Radiation heat transfer between solid surfaces calculated from (Eq.2.8).
- Convection heat transfer between solid surfaces and gases calculated from (Eq.2.9).
- Conduction heat transfer inside solid surfaces calculated from (Eq.2.11).
- There are over thirty solid sections in the final model, each having its own energy flows and balance. Below is an example of how the temperature of the inside surface of the baffle was calculated (bi).

  Heat flows in and out of bi

  The spreadsheet "Heat Transfer" in Appendix 2 was used to keep track of all the heat flows in and out of the various heater sections. To find the heat flows into bi, look down the spreadsheet until you reach bi, then head across and every red square indicates radiation heat transfer, blue indicates convection and yellow indicates conduction. Once you reach the black square head down and the coloured squares then indicate heat flows out of the heater section.

  Heat into bi

  $qrfbi=sffbi*o*Aflame*eflame*(Tflame^4-Tbi^4)$ (Eq3.7)

  $qrcibi=sfcibi*o*Aci*ecoal*(Tci^4-Tbi^4)$ (Eq3.8)

  $qrlbi=sflibi*o*Alogs*elogs*(Tl1^4-Tbi^4)$ (Eq3.9)

  $qrfbibi=sffbibi*o*Afbi*efb*(Tfbi^4-Tbi^4)$ (Eq3.10)

  $qrsabi=hin*Abi*(Tsa-Tbi)$ (Eq3.11)

  Heat out of bi

  $qrbibo=kb*(Tbi-Tbo)/xb$ (Eq3.12)

  $qrbiuwi=sfbiuwi*o*Abi*eb*(Tbi^4-Tuwi^4)$ (Eq3.13)

  $qrbidi=sfbidi*o*Abi*eb*(Tbi^4-Tdi^4)$ (Eq3.14)

  $qrbirw=sfbirw*o*Abi*eb*(Tbi^4-Trw^4)$ (Eq3.15)

  Heat balance for bi

  $mbi=Ab*xb/2*Denb$ (Eq3.16)

  $Qbistart=(Tbistart-To)*Cpb*mbi$ (Eq3.17)

  $Qbi=Qbistart+Integral(qrfbi+qrcibi+qrlbi+qrfbibi+qrsabi-$
  $qrbibo-qrbiuwi-qrbidi-qrbirw,t,0,time,ts)$ (Eq3.18)

  $Tbi=Qbi/(mbi*Cpb)+To$ (Eq3.19)

- The model includes seven air sections. The order of the air sections, from inlet to outlet is door air 1, door air 2, primary air, secondary air, baffle air, flue1 air, flue air (Fig.16). Primary, secondary and baffle air are also the zones where combustion takes place. Each of the seven sections has an energy balance exactly like the solid sections.

- Four distinct rate processes; drying, pyrolysis, charcoal burning and gaseous burning.

Drying

There is a drying rate for all nine log sections. The example below is for the 3rd concentric log section from the surface.

```
If (ml3w<1E-10) THEN
fdry3:=0
ELSE                                                        (Eq3.20)
fdry3:=kdry*ml3w*(Tl3-20)
ENDIF
```

Pyrolysis

There is a pyrolysis rate for all nine log sections. The example below is for the 3rd concentric log section from the surface.

```
Tpyro=200
IF (ml3<1E-10) THEN
fpyro3:=0
ELSE
IF (Tl3<=Tpyro) THEN
fpyro3:=0                                                   (Eq3.21)
ELSE
fpyro3:=k1*ml3*(Tl3-Tpyro)
ENDIF
ENDIF
E13=fpyro3/MMG
```

Charcoal burning

The energy from the charcoal burning was added to the heat balance for the inside half or the charcoal ember bed. The rate equation used was:

```
e2=k2*sqrt(xO2pa)*Aci*(mc+mlc)                              (Eq3.22)
bec=e2*MMChar*GCVChar                                       (Eq3.23)
```

Gaseous burning

Gaseous burn rate calculated in each of the three combustion zones; primary air, secondary air and baffle air. It is proportional to the smoke and oxygen concentrations and has an Arrhenious dependence on temperature.

```
e3pa=k3*10^6*xGpa*xO2pa*(1E-06+exp(-EG/(R*(Tpa+273))))      (Eq3.23)
e3sa=k3*10^6*xGsa*xO2sa*(1E-06+exp(-EG/(R*(Tsa+273))))      (Eq3.24)
e3ba=k3*10^6*xGba*xO2ba*(1E-06+exp(-EG/(R*(Tba+273))))      (Eq3.25)
```

e3=e3pa+e3sa+e3ba (Eq3.26)

beG=e3*GCVG*MMG (Eq3.27)

- Logs were divided into nine concentric cylinders, each with its own pyrolysis and drying rate. The example below calculate the various properties of the log sections as they loose mass from the pyrolysis and drying processes.

ml3v=ml1vstart-integral(e13*MMW,t,0,time,ts) (Eq3.28)

ml3w=ml1wstart-integral(Fdry3,t,0,time,ts) (Eq3.29)

ml3c=integral(ze1char*e13*MMChar-ml3c/(mlc+mc)*e2*MMChar,t,0,time,ts) (Eq3.30)

ml3=ml3v+ml3w+ml3c (Eq3.31)

Dlog3=sqrt(4*(ml3+ml4+ml5+ml6+ml7+ml8+ml9)/(Denwood*Nlogs*Llog*Pi)) (Eq3.32)

Alog3=Nlogs*(Llog*Pi*Dlog3) (Eq3.33)

xlog34=0.5*(Dlog3-Dlog4)+0.5*(Dlog4-Dlog5) (Eq3.34)

kl34=kchar+klx*(ml3v+ml4v)/ml1vstart (Eq3.35)

qrl3o=(Fpyro3+Fdry3)*Cp(Air,T=Tl3)*(Tl3-To) (Eq3.36)

qrdry3=Fdry3*hfg (Eq3.37)

qrl34=kl34*Alog4*(Tl3-Tl4)/xlog34 (Eq3.38)

Ql3=integral(qrl23-qrl34-qrl3o-qrdry3,t ,0,time,ts) (Eq3.39)

Tl3=Ql3/(ml3*Cpwood)+To (Eq3.40)

- Three heat transfer coefficients were used representing; inside of the firebox (hin); inside of the upper chamber and flue (hflue) and the outside surfaces of the heater (hout).

- Airflow into heater was proportional to draught. This relationship was found from testing at Applied Research Services Ltd.

Uflue=Fflue/(Density(Air,T=Tflue,P=Pr)*XAflue) (Eq3.41)

DPflue=3*Density(Air,T=Tflue,P=Pr)/2*Uflue^2 (Eq3.42)

Draft=-(Density(Air,T=Tflue,P=Pr)-Density(Air,T=To,P=Pr))*
g*(Lflueheight-Lflue)-DPflue (Eq3.43)

Draftmm=Draft/(Density(Water,T=To,P=Pr)*g)*Convert(m,mm) (Eq3.44)

Fin=Kflow*Draft+0.002 (Eq3.45)

Fpai=XApa/(XApa+XAsa)*Fin (Eq3.46)

Fsai+Fpai=Fin (Eq3.47)

- Elemental balances in the three combustion zones for oxygen (O_2), nitrogen (N_2), water vapour (H_2O), carbon dioxide (CO_2) and pyrolysis gases ($C_{2.5}H_{6.1}O_{2.4}$). The equations below calculate the elemental balance for the secondary air section.

Fsaba=Fpasa+Fsai (Eq3.48)

xCO2pa*Fpasa+ze3CO2*e3sa*MMCO2=xCO2sa*Fsaba (Eq3.49)

xO2i*Fsai+xO2pa*Fpasa=xO2sa*Fsaba+ze3O2*e3sa*MMO2 (Eq3.50)

xH2Oi*Fsai+xH2Opa*Fpasa+ze3H2O*e3sa*MMH2O=xH2Osa*Fsaba (Eq3.51)

xN2i*Fsai+xN2pa*Fpasa=xN2sa*Fsaba (Eq3.52) xGpa*Fpasa=xGsa*Fsaba+e3sa*MMG (Eq3.53)

Checksa=xCO2sa+xO2sa+xH2Osa+xN2sa+xGsa (Eq3.54)

Conversionsa=e3sa*MMG/xGpa*Fpasa (Eq3.55)

- Radiation transmittance of door glass was calculated from the temperature of the radiator. The equation was found by using the program BBRAD developed by Webley (2003). The results of using this program are found in Appendix 2 "Transmittance". The equation used in the final model was:

  fxtrans:=Min(1,Max(0,-1.95E-10*T^3+4.07E-07*T^2+2.14E-04*T-0.0247)) (Eq3.56)

- Flame energy balance equates the energy from the gaseous burning to the energy radiated from the flame and the energy of the gases leaving the flame. The flame balance was:

  Fflame=Kflame*e3*(MMG+ze3O2*MMO2) (Eq3.57)

  qrfsa=Fflame*Cp(Air,T=Tf)*(Tf-Tsa) (Eq3.58)

  beG-qrdryflame=qrfci+qrfl+qrffbi+qrfsa+qrfbi+qrfuwi+qrfdi+qrfrw (Eq3.59)

  Aflame=Kflame2*beG (Eq3.60)

3.3.2 *Assumptions*

- No re-radiation between solid heater sections.
- No radiation from gases.
- First order approximation of Fourier's Law for conduction produces negligible error.
- Lumped capacity analysis produces negligible error.
- The solving process of EES produces negligible error.
- No energy created or consumed by the pyrolysis reactions.
- Log density is constant throughout run.
- Glass doors are made of Robax.
- Pyrolysis gases and water vapour do not cool down wood as they exit the wood logs.
- Flame has a negligible heat capacity.
- Radiation shape factors are constant throughout the run.
- Convection heat transfer coefficients are constant throughout the run.
- Perfect mixing of gases in each air section. This was assumed by using lumped capacity analysis.
- Pyrolysis reactions produce the same products every time.
- Complete combustion of carbon monoxide to carbon dioxide.
- Solid charcoal is burnt, not gasified and then burnt.

3.3.3 Model calibration

Because some of the assumptions of section 4.1.2 are probably incorrect, this can have a large effect on the heaters performance, hence the model did not always reach the required limits of 10% uncertainty. The assumptions that are particularly important are that the radiation shape factors and convection heat transfer coefficients remain constant and that there is perfect mixing in each air section. The calibration factors that were used are:

calRate	Increases the pyrolysis and charcoal burning rates. This means that the overall burn-rate will be higher leading to shorter runs. The reason for this factor is that there is not perfect mixing in the firebox. Different heaters let different proportions of air onto the charcoal bed and logs, which changes the burn-rate. This is very difficult to predict from the dimensions of the heater.
calIncreaseOutput	Increases approximately ten variables that directly affect the heater's heat output e.g. shape factors from flame to room, convection heat transfer coefficients from heater walls to room. The reason for this factor is that different heaters will have different geometries and therefore shape factors and convection heat transfer coefficients.
calVolatiles	Changes the gaseous burn-rate so therefore changes the emissions of the heater. This factor is representing the mixing conditions for the gaseous combustion.
calWetback	Changes the heat transfer coefficient for the wetback. This would change because of the air flow field around the wetback pipe and the amount of smoke deposited on the wetback.
Kflow	This factor is the proportionality constant for the relationship between inlet air flow and draught. Different heaters have different amounts of pressure drop designed into them, which is why this factor would change.

Calibration factor values were found after the results of one high run of the emissions test. The average values of heat output, flue temperature, efficiency, wet-back heat output and emissions are used in the calibration. The five calibration factors were changed until these five average values were similar for the model as for the emissions test. This can be reasonably difficult to do and is the main reason why the author will continue to use the model in the short term under contract to Applied Research Services, even though this study has been completed.

3.4 Model testing

3.4.1 Heat Transfer data

Until Model 16 the model had been produced to meet estimations of parameters, such as firebrick temperature. These estimations were based on the author's experience with the temperatures mentioned in the combustion textbooks (Shelton, 1983) and (Jones, 1993). Flue temperature was the only temperature that had a large amount of data because it is measured in each emissions test at Applied Research Services Ltd. In order to improve the model further, extra temperatures needed to be measured so that the model could be refined to produce the same results. An experiment was developed, where an old heater that was no longer needed at Applied Research Services Ltd was set up with seven thermocouples and three pressure sensors. The seven thermocouples were sheathed in Incotherm alloy so that they could operate at the high combustion temperatures (>800°C).

The pressure sensors were manometers and measured the pressure at the bottom of the firebox, the pressure above the firebox and the pressure just at the exit of the flue. The pressure measurement aimed to find where the pressure drop occurred inside the heater, was it at the inlet air entrance, the exit from the firebox into the baffle chamber or out through the flue spigot?

Holes were drilled into the heater to get the thermocouples inside. Some thermocouples had to be sealed in place with cement or rivets. Unfortunately the only aluminium rivet used melted away so the values for the steel wall surface (5) were treated cautiously. The seven locations for the thermocouples were:

1. Upper surface of the baffle
2. Lower surface of the baffle
3. Inside surface of the side firebrick (closest to flames and logs)
4. Outside surface of the side firebrick
5. Steel wall surface above firebricks
6. Primary air (lower half of firebox)
7. Charcoal ember bed (as close to the top surface of the charcoal ember bed as possible)

The door temperatures could not be measured as the measuring device would be heated faster by the flame radiation, due to it being opaque, while the glass transmits a large amount of the flame radiation. Flue temperature and surface temperatures were also measured. Flue temperature was measured in exactly the same way as in the emissions test.

This experiment was conducted in the safety rig at Applied Research Services Ltd, which is usually used to find the required clearances of the heaters from walls. It is set up to record up to 30 different temperatures so was perfect for this experiment. The surface temperatures measured were:

8. Side heat shield (half way up)
9. Top heat shield

10. Flue wall temperature (at the same height as flue temperature)

11. Stand temperature

The procedure of the emissions test was followed and both high and low airflow tests were performed, with measurements of all the temperatures and pressures recorded by computer. Mass scales are not used in the safety rig so the end time of the run had to be estimated by looking at the size of the charcoal ember bed. This was performed with the helpful assistance of both Chris Mildon and Robert Kay, who have much experience in deciding when a run is finished and what the ember bed looks like at this point. The burn-time was very close to the times measured in the emissions test so it can be concluded that the heater operated in the same way in this experiment as it did in the emissions test and that this test was a good representation of the emissions test.

3.4.2 Airflow test

For the majority of the modelling, Bernoulli's equation was used to calculate the airflow through the heater. Bernoulli's equation assumes constant temperature and density of the fluid, but this is not the case in a wood burning heater. When using the Bernoulli equation it was assumed that the effect of different temperature and density was negligible. This assumption was tested by an experiment using the Masport LE2000 at Applied Research Services Ltd.

A fan was used to provide a draught and the flue airflow was measured using an anemometer. The fan was powered with a Variac, used to change the power into the fan and hence airflow. In this way many different draughts can be created and the flow caused by this was measured. Graphs of draught (Pa) versus flow (g/s) were created and these were checked against the results of the Bernoulli equation.

The results of this test were that the graphs showed a linear relationship between draught and flow up to the limits of the test which were 25Pa of draught, not the squared relationship that exits with the Bernoulli equation. For the models after this test (Models 19, 20, 21) the Bernoulli equation was removed and replaced with a more empirical approach. The airflow was calculated from a constant multiplied by the flue draught. The results and calculations used in this experiment can be found in "Bernoulli", Appendix 2.

4 Results

4.1 Model performance

The model was used on various heater designs including the Masport LE2000, Ethos FS100, Masport Verona, Hewitson Lady Kitchener and Hewitson Contessa Insert. However, only the Masport LE2000 and Hewitson Lady Kitchener have been modelled completely and reports sent to the manufacturers so this is why they have been chosen to represent the model's performance in this study.

The Masport LE2000 is a standard S-type wood burning heater with promat and heat shields used to insulate the heater. Because it was used as the standard, its calibration factors are all 1. The Hewitson Lady Kitchener is a different type of heater, which is the reason why it was chosen as the second heater to test. It has an extremely well insulated firebox (designed for overnight burning) and a largely finned top surface, which is designed to remove as much heat as possible. The Lady Kitchener also has a large wet-back heat exchanger added above the baffle.

4.1.1 Masport LE2000, high airflow setting

The model works well for the Masport LE2000 on the high airflow setting (Fig.17-19). This was not a great surprise because the flue temperature profile was used as one of the many parameters to refine the model so that it matched the LE2000 test results as closly as possible. Both the flue temperature and flue oxygen were very similar to those obtained from the emissions test.

The average deviation between the model and actual emissions tests was calculated for the three graphs by averaging the difference between the two graphs. The average deviation for the flue temperature (Fig.17) was 4%, while the flue oxygen was 16% (Fig.19). This large deviation was mainly due to the start of the run where the model is slower to decrease than the emissions test data resulting in significant differences in the average deviation calculation because the flue oxygen is falling so quickly.

The heat output (Fig.18) was different to the emissions test results as it peaked earlier and higher. The average deviation of the output was 8%, which is within the project's 10% uncertainty objective. This high average deviation could be due to many different factors and is discussed in section 5.1.

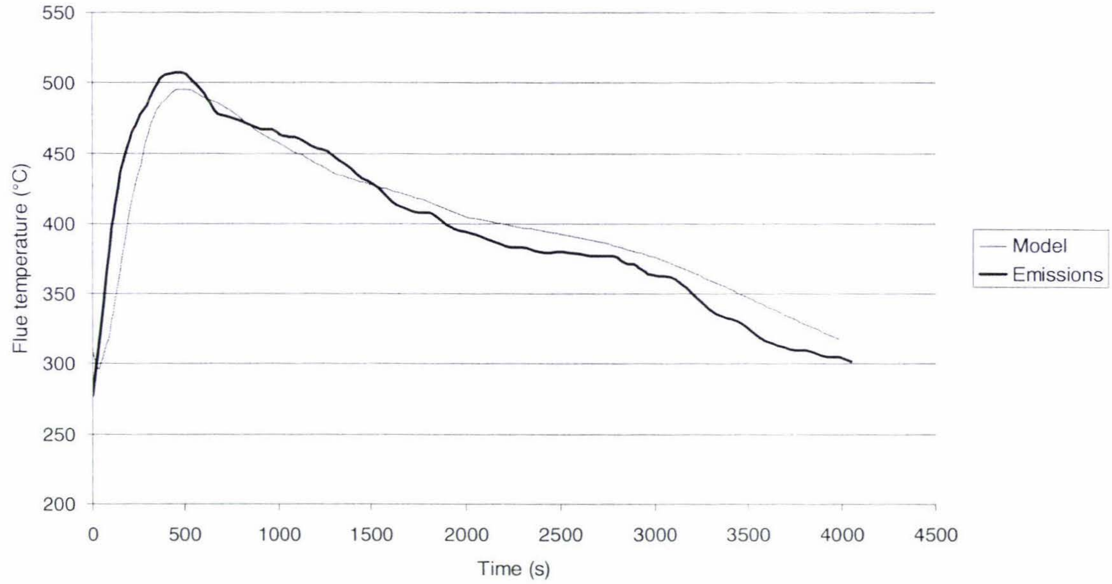


Figure 17: Flue Temperature of Masport LE2000, High airflow setting

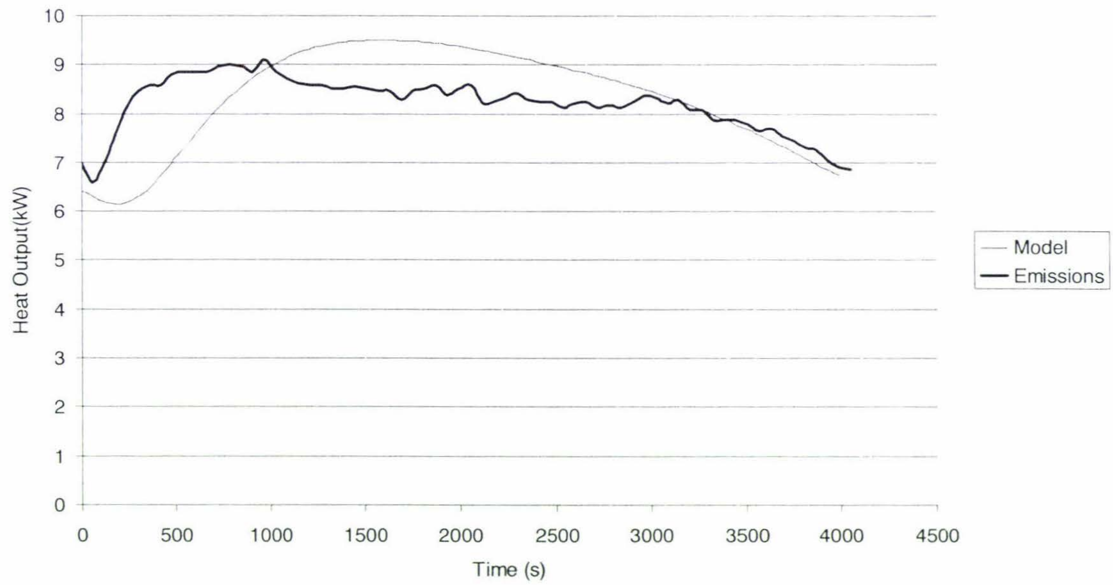


Figure 18: Heat Output of Masport LE2000, High airflow setting

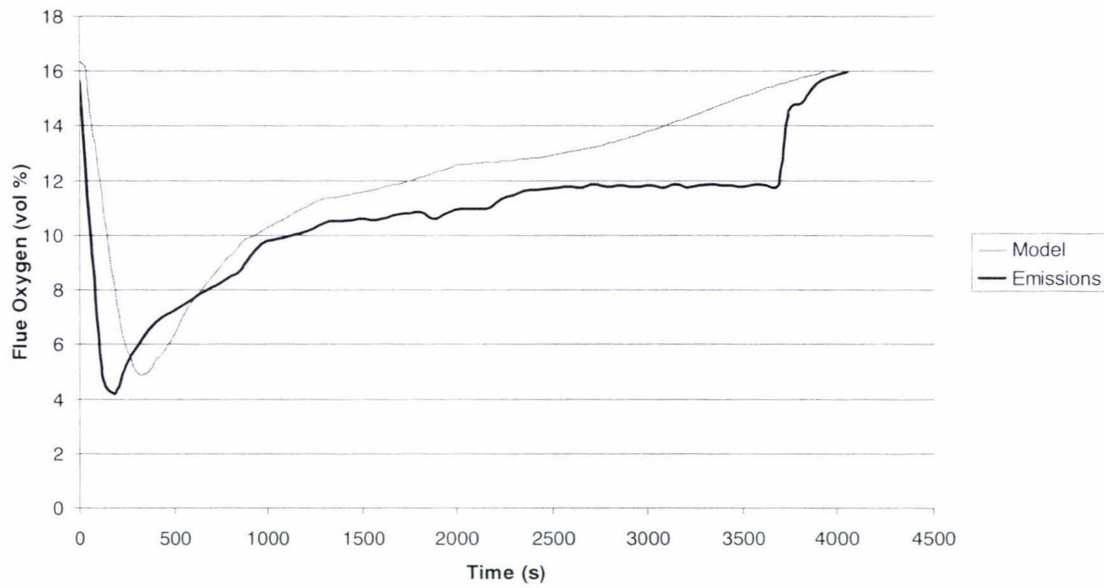


Figure 19: Flue oxygen volume fraction for Masport LE2000, high airflow setting

4.1.2 Masport LE2000, low airflow setting

Compared to the model's excellent performance for the Masport LE2000 on a high airflow setting, a low air setting showed large differences between the model and emissions test (Fig.20-22). The average deviations were 18%, 25% and 13% respectively). The main problems occur at the point where the heater is turned down from high to low airflow setting at 600s (section 5.1).

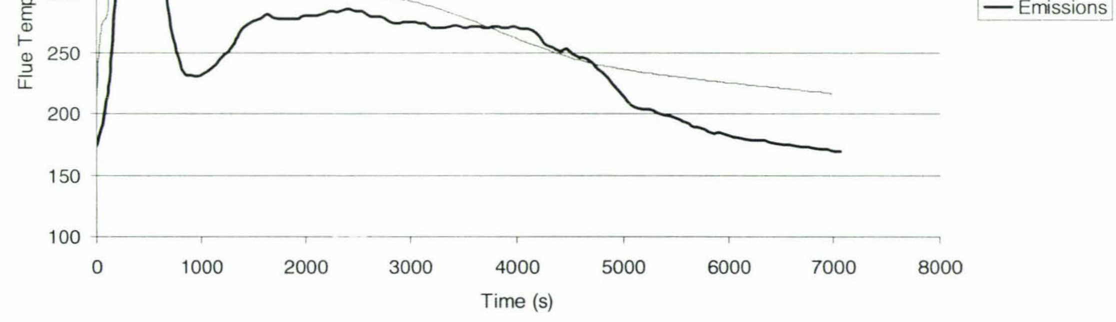


Figure 20: Flue Temperature for Masport LE2000, low airflow setting

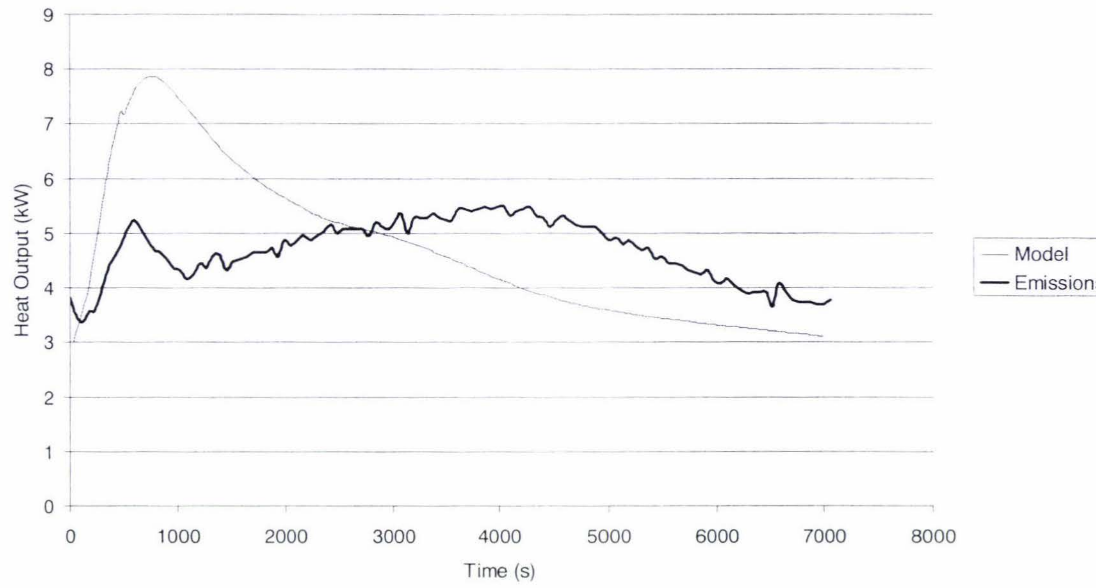


Figure 21: Heat Output of Masport LE2000, low airflow setting

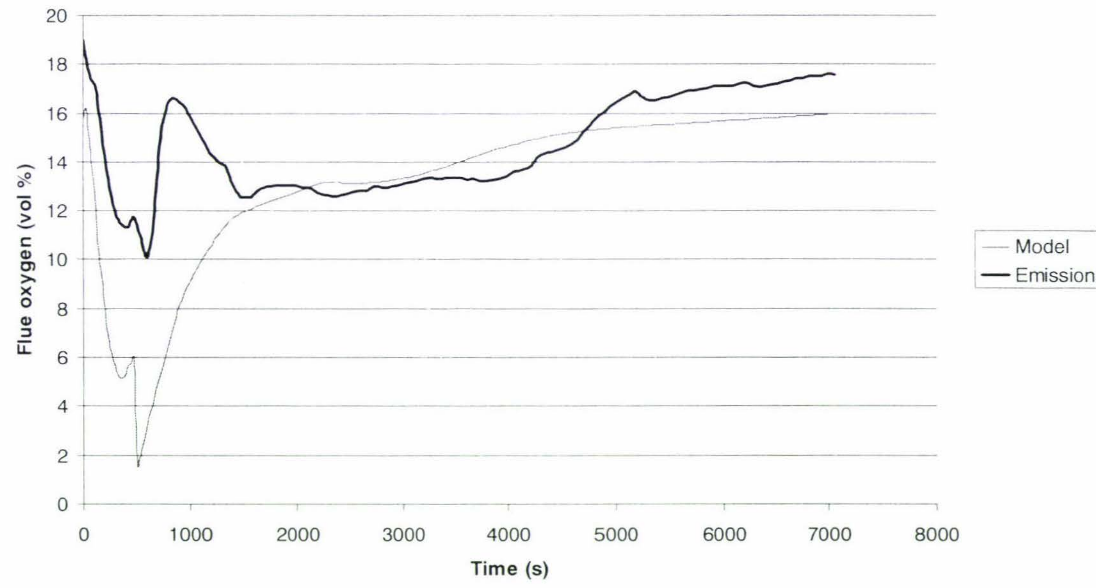


Figure 22: Flue oxygen volume percent of Masport LE2000, low airflow setting

4.1.3 Hewitson Lady Kitchener, high airflow setting

The Model worked extremely well for the Hewitson Lady Kitchener on high airflow setting. This shows that the model can be used for heaters other than the Masport LE2000, which the model was designed for. The model was calibrated for the Lady Kitchener (section 4.2.1) using calibration factors:

calRate	0.75
calIncreaseOutput	1.2
calVolatiles	0.8
calWetback	1.6

These values are not too far from the standard of unity which shows that the relationships and assumptions used by the model were adequate for modeling the Lady Kitchener. The calibration only uses average values to calibrate the model (section 4.1.3), so when these values versus time were very similar to the emissions test (Fig.23-25) the model was obviously working correctly. The average deviances for the Lady Kitchener were 2%, 16% and 11% respectively. This is a very similar result to the Masport LE2000, although the heat output still has the same problem of peaking too early in the run (section 5.1)

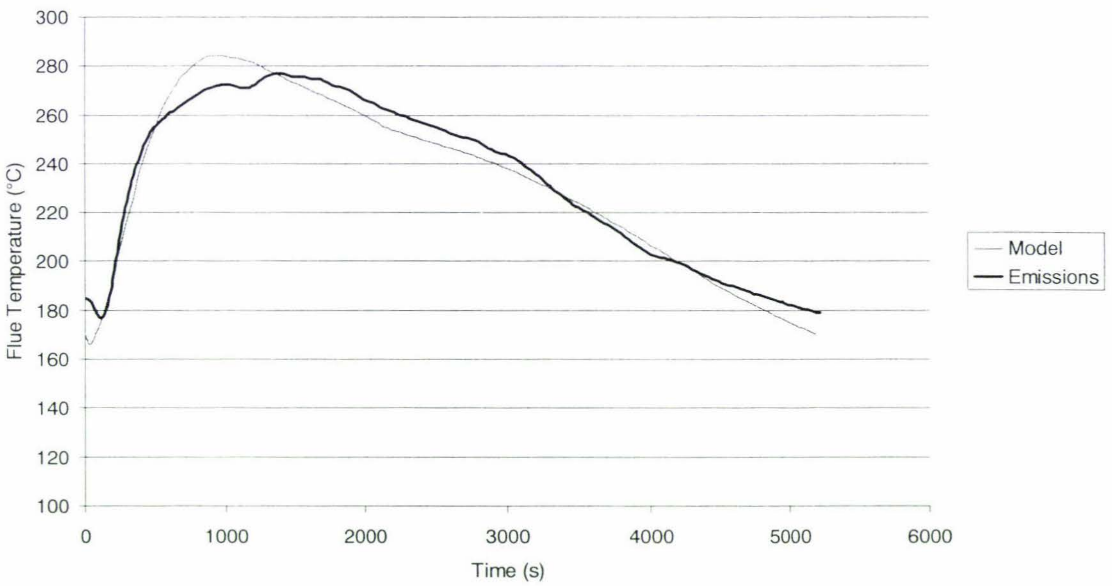


Figure 23: Flue Temperature of Hewitson Lady Kitchener, High airflow setting

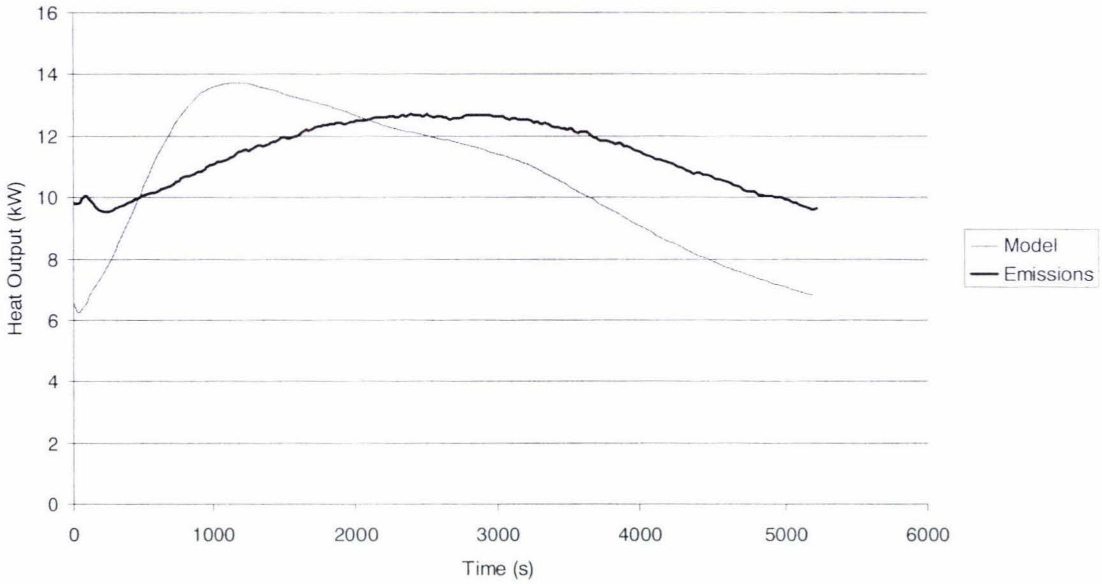


Figure 24: Heat output of Hewitson Lady Kitchener, High airflow setting

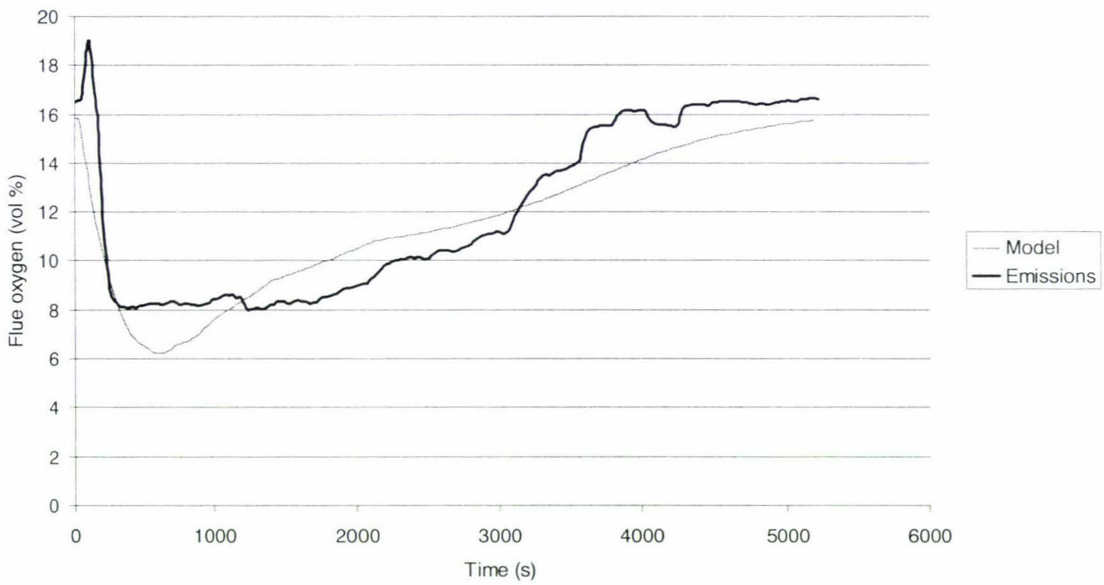


Figure 25: Flue oxygen volume percent of Hewitson Lady Kitchener, High airflow setting

4.1.4 *Hewitson Lady Kitchener, low airflow setting*

Unfortunately the model did not work well for the Lady Kitchener on low airflow setting, due to the same problems as for the Masport LE2000 low airflow setting section. The average deviations for the Lady Kitchener on low airflow setting were 25%, 28% and 25% respectively.

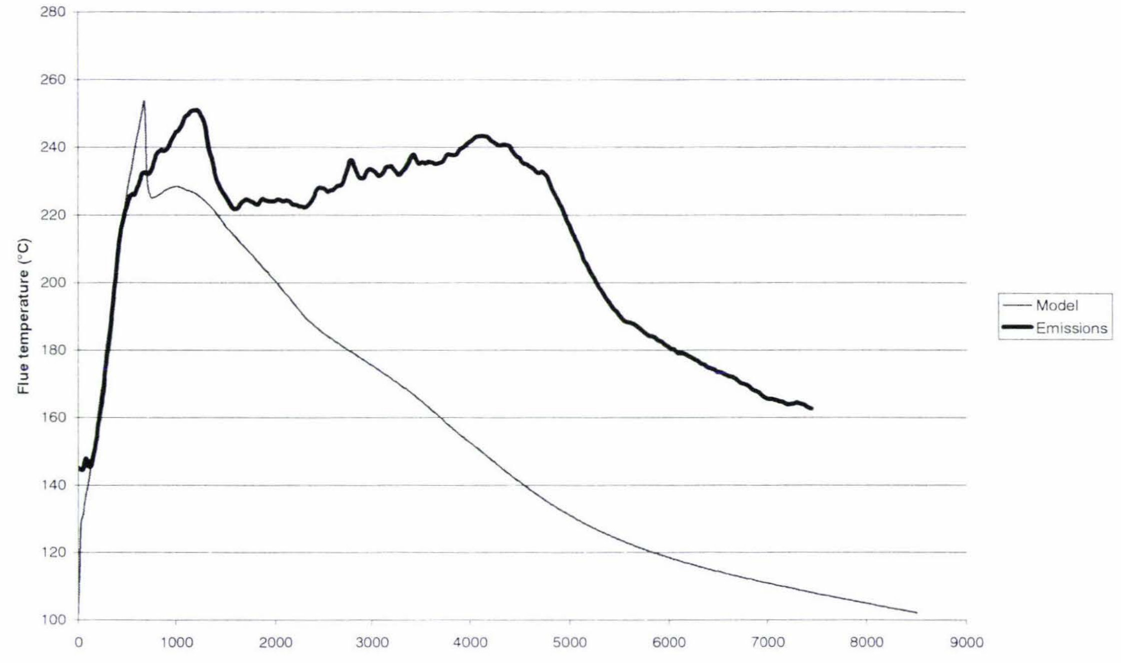


Figure 26: Flue Temperature of Hewitson Lady Kitchener, Low airflow setting

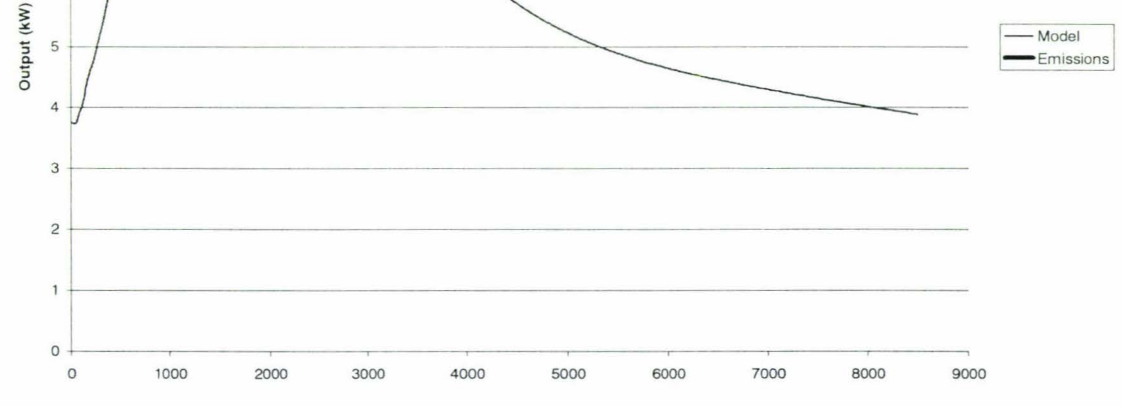


Figure 27: Heat output of Hewitson Lady Kitchener, Low airflow setting

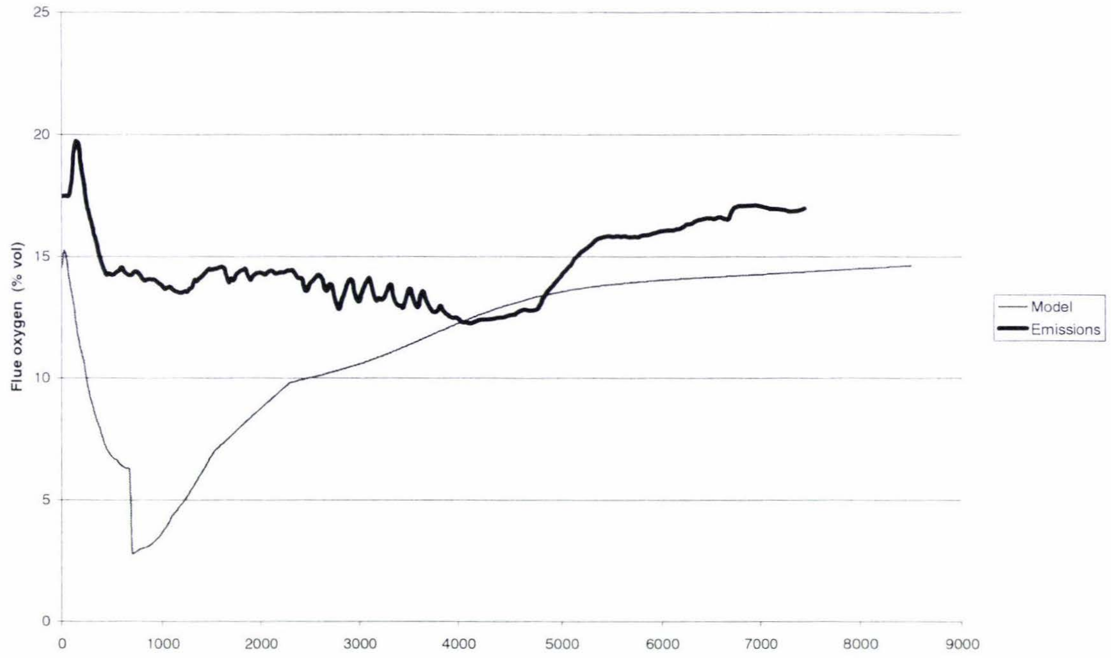


Figure 28: Flue Gas Oxygen of Hewitson Lady Kitchener, High airflow setting

Heat output distribution

The model enables more detailed results to be obtained than was possible from the emissions test. One of these results is that the model provides a break down of the heat output. It gives the radiant heat flow through the glass door, the heat output from the sides, top, front and flue as well as convective vs radiant heat. This is valuable information for heater manufacturers because radiant heat is often felt to be a more comfortable heat and if a house is poorly insulated, convective heat can be wasted as the hot air flows upwards into the ceiling and to the outside. Table 2 shows the heat output distribution of the two heaters, Masport LE2000 and Hewitson Lady Kitchener.

Table 2: Heat output distribution

	Masport LE2000	Hewitson Lady Kitchener
Radiation through door (%)	25	36
Other front (%)	27	26
Side walls (%)	17	13
Top wall (%)	13	11
Flue wall (%)	18	13
Radiation (%)	56	69
Convection (%)	44	31

The Lady Kitchener heater has a large amount of insulation on the sides of the heater. This means that less heat exits out the sides of the heater (13% versus 17% for the LE2000) and the firebox temperatures are higher so that more heat radiates through the door (36% versus 25%). This also leads to the Lady Kitchener producing more radiant heat instead of convective heat (69% vs 56%). Table 2 also shows that for these two heaters over 50% of the heat output is obtained from the front of the heater.

4.2 Combustion conversions

A second result that the model provides which is not known from the emissions test is the combustion conversions in each of the three combustion sections, primary air (lower half of firebox), secondary air (upper half of firebox) and baffle air (above baffle). The combustion conversions are the mass of smoke that is burnt in the zone divided by the mass of smoke that entered the zone. Smoke exits the logs and flows into the primary air section, then into the secondary air section and baffle air section before exiting the heater via the flue pipe (Fig.8). The combustion conversion is controlled by two factors, air temperature and oxygen % in the combustion zone. Increased oxygen aids combustion conversion and higher temperatures also aids combustion conversion via an Arrhenious relationship. Table 3 shows the combustion conversions for the Masport LE2000 and Hewitson Lady Kitchener.

Table 3: Combustion Conversions for different zones in heater

		Masport LE2000	Hewitson Lady Kitchener
Primary air zone	Conversion (%)	90	93
	Oxygen (vol %)	9.1	8.4
	Temperature (°C)	461	500
Secondary air zone	Conversion (%)	91	94
	Oxygen (vol %)	11.4	10.2
	Temperature (°C)	483	561
Baffle air zone	Conversion (%)	81	54
	Oxygen (vol %)	13.1	11.7
	Temperature (°C)	430	322

The conversion in the baffle air zone for the Hewitson Lady Kitchener is very poor, at only 54%. The reason behind this is that the Lady Kitchener has a large wetback and highly finned top wall, which remove large amounts of heat from the baffle air. This drops the temperature of the baffle air dramatically which means that the Lady Kitchener is highly efficient, but it harms the emissions of the heater. There is a trade-off here between efficiency and emissions.

4.3 Internal temperatures for Masport LE2000

The Heat transfer test of the model involved placing seven thermocouples into the Masport LE2000 and seeing their change over a standard emissions test. The flue temperature (Fig.29) shows the profile that would be expected of temperatures inside a heater. The primary air temperature, which represents the air in the lower half of the firebox and surrounding the wood logs behaved much differently (Fig.29). At the very beginning of the run the temperature fell and only after ten minutes did the temperature revert back to the standard curve of the other temperatures. All other temperatures, flue temperature for example, fell at the very beginning of a run but only for approximately one minute. This can be explained by the cooling influence of the cold wood logs being added to the heater as well as the door being opened, which lets much more cold air into the heater. For the primary air though this does not explain the above phenomenon because it lasts for ten minutes, not only one minute. When the model was examined to find a source for this cooling influence, there was only one other process that had a cooling effect on the primary air. This was the cool pyrolysis gases and water vapour exiting the wood. Although these gases can be as hot as 200°C, they are still a cooling influence on the primary air, because the primary air temperature is 400 – 500°C. The model was changed to show this effect by decreasing the heat transfer from the flames and log surfaces to the primary air so that the cool gases have a larger effect.

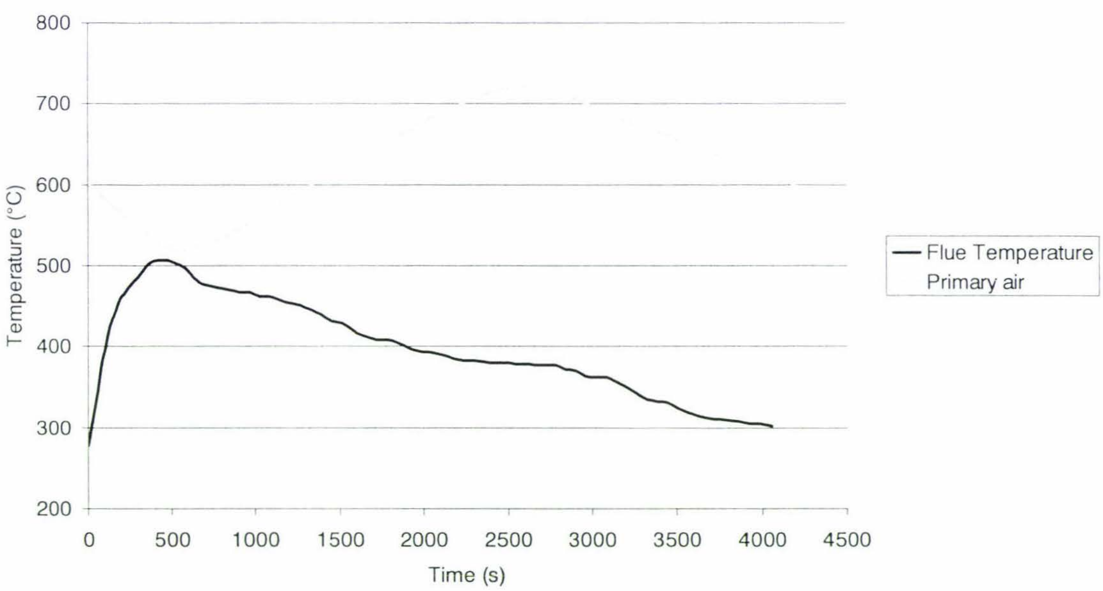


Figure 29: Primary air temperature for Masport LE2000, high airflow setting

The conclusion made was that the cool gases exiting the wood and also the energy required to vaporise the water led to the decrease in primary air temperature for the first ten minutes of a run. This effect is very important as lower air temperatures leads directly to more emissions. With the burn-rate of the fire often peaking around ten minutes this leads to large emissions if this effect is large. If there is more water in the wood then this cooling effect on the primary air temperature would be larger, because of the extra energy required to vaporise the extra water in the wood. This is the main reason why burning wet wood results in higher emissions.

5 Discussion

5.1 Model performance

The results (section 4.2) compared the performance of the model with actual emissions test data. The model performed well for both the Masport LE2000 high airflow run and the Hewitson LE2000 high airflow run but was very poor for the two low airflow runs.

The heat output result gave a high error for high and low airflow setting, which can be attributed to the heat capacity of the calorimeter room. The calorimeter room is designed to have a low heat capacity. It does this by using reflective materials on the side walls so that less radiant energy flows into the walls, where it can be stored. This does not completely solve the problem though and the emissions test standard, which is not very strict on the calorimeter room heat capacity, shows that the calorimeter room does in fact have a significant heat capacity. The large heat capacity is a problem for the model because it means that the emissions test output is flatter than it should be so that the model output does not match the emissions test results. Some steps were taken to try and model the affect of the calorimeter room heat capacity, but this was removed after it was felt that it didn't help and that the old way better represented what was actually happening with the heater.

The major problem for the model is that it is very poor when used on low air-flow setting. The main problem is at the point where the heater is turned down from high to low air setting after 20% of the wood has been burnt. The model continues to create the same amount of smoke (because pyrolysis rate is only affected by temperature not airflow) and therefore the flue oxygen falls quickly because there is less air going into the heater, but the same flow is still used to burn the smoke. The emissions test does show this happening, but it is a very small factor and the log pyrolysis rate quickly slows so that the system returns to an equilibrium. The reason for this problem is that in reality, at lower airflow rates less air reaches the bottom of the heater so that the charcoal burn-rate decreases. A decreased charcoal burn-rate provides less energy to the logs so that the log pyrolysis is slowed. This process is not included in the model because a CFD package would be required to find the proportion of primary inlet air reaching the charcoal ember bed.

5.1.1 Model Calibration

The model requires the use of calibration factors, which represent the processes that cannot be modelled due to either lack of time or lack of understanding of why they happen. Examples of these factors are the airflow around the primary air deflector and baffle which affects the amount of air that bypasses the firebox and enters directly into the baffle chamber. The calibration factor that represents this process is calBypass. Applied Research Services Ltd is working on developing a technique for measuring bypass so if this is successful the results from this test can be added to the model using this calibration factor.

The calibration factors are determined so that the average values of key parameters (Flue temperature, Burn-time, Heat output, Efficiency and Emissions) are the same as the emissions test result. This gives the model a starting point and from there one can find improvements that can be made to the model. Once a heater has been calibrated it never has to be calibrated again.

The other calibration factors are calRate, calVolatiles and callncreaseoutput. calRate increases the rate of pyrolysis and charcoal burn rates and in real life this effect is produced by slightly different heat transfer to and from the logs or different distributions of the primary air as it enters the firebox. A heater will burn faster if more primary air reaches the charcoal bed and therefore increases the charcoal burning rate. It would require CFD modelling to determine what proportion of the primary air reaches the charcoal bed.

calVolatiles increases the gaseous burn-rate and is used to adjust the emissions value of the heater. It has been found that calVolatiles is usually near the standard value of one for all the heaters modelled so far. This means that the equations used for the calculation of the emissions have been reasonably successful. It has also been found that to control emissions the most important factor was to match the pyrolysis rate with enough oxygen for the combustion. When pyrolysis rate was too high and the airflow too low many emissions were created. Having well insulated combustion chambers, for high temperatures and therefore good combustion is of no use if there is not enough oxygen for the combustion. The processes modelled by this calibration factor are the mixing processes, which are important for gaseous combustion and which can only be modelled using a CFD package.

When the model was being developed, more information was known about the test heater (Masport LE2000) than is known when calibrating a new heater. With the LE2000, internal temperatures were known so the distribution of the heat had to produce these temperatures. This led to being able to find out where the heat exits the heater i.e. if everything else is correct the heat output distribution must be correct. This is the same philosophy used in calculating the combustion conversions.

5.2 EES

EES performed exceptionally well throughout this project. The method of adding the equations into the program was very simple and the fluid properties available made that section of the modelling extremely easy. There were some problems however and these are detailed below.

5.2.1 Divide by zero

During models 6 and 7 the logs were divided into nine sections to better model the burn-rate of the wood. This lead to the problem where the mass of the outer sections falls below zero so that their temperatures cannot be calculated by EES because of the mathematical error created by dividing by zero. This problem was eventually overcome by making sure that all masses never fall below zero. The rates of all the processes (drying, pyrolysis and char combustion) were all made proportional to their respective masses so that the mass can never fall below zero. In reality, of course, the mass of the logs and charcoal does reach zero but since the model cannot cope with this then the modelling had to be modified to keep EES working.

5.2.2 Flame equations

Another instance of EES being unable to handle the equations provided to it was when the flame was being modelled.

- Flame temperature was used to calculate the rate of energy provided from the burning of the pyrolysis gases.

- Flame area was calculated from this burn energy
- Flame temperature is affected by the flame area because of its radiant energy losses

This loop can be calculated by EES but if any other variable is calculated from one of the variables in the loop, EES shows an error that the problem is "improperly formatted". This was a major problem because it was hoped that the radiation shape factors from the flame could be calculated from the flame area, so that larger flame areas would radiate more into the top section of the heater than the firebox. The author could not understand the reason for this problem but assumed it had something to do with the degrees of freedom in this particular section of the equation set.

5.2.3 Degrees of freedom

Like any mathematical solver, EES required the correct degrees of freedom for the equation set. This meant that there were as many equations as independent variables. As the model became more complex it soon became extremely difficult to keep track of all the variables so a naming convention and diagram of the heat transfer was used to maintain understanding of the model. The naming convention can be found in Appendix 1. The diagram of heat transfer was created in Microsoft Excel and can be found in Appendix 2, "Heat Transfer".

5.3 Features not modelled

5.3.1 Bernoulli's equation

Bernoulli's equation was used to determine the airflow through the heater from Models 4 through to Model 20. Before Model 4 the airflow was set at 10g/s. After Model 20 the model used an experimentally defined equation where the inlet airflow was found to be proportional to the flue draught. The experiment was conducted at Applied Research Services Ltd (section 3.3.2) and produced surprising results. The experiment could not be repeated due to a lack of time, but the new equation was used as it made the airflow calculation much simpler and easier to follow, which was a great advantage.

One hypothesis of why the Bernoulli equation did not work for a heater is that the viscosity of gases is higher at higher air temperatures and this will lead to higher pressure drops through the heater. Another reason may have been that the heater doors were not completely air-tight so that there was extra air getting into the heater. This flow would even out the differences between the high and low air-flow settings, which is exactly what the experiment showed. Due to this experiment being conducted near the end of the modelling period, the reasons for the results were not able to be tested because of a lack of time. The new equations aided model understanding so remained for the final model. Another plus for the new equations was that it was easier to calibrate the model using the new equations than the Bernoulli equation where the user could change a number of parameters in order to change the airflow.

5.3.2 Turbulence

The effect of turbulence on emissions was not modelled, except by the calibration factor calVolatiles. Turbulence is extremely important to the mixing of the smoke and the oxygen, so that the gases can burn well and produce fewer emissions. A CFD package would be required to model this turbulence effect as in the shopping mall fire simulation (Markatos, 1983).

5.3.3 *Pyrolysis rate*

The pyrolysis rate is a very complex set of reactions and the following list attempts to show the factors that effect it that were not modelled by this project.

- The pyrolysis rate can be exothermic or endothermic depending on the type of pyrolysis reactions that are occurring.
- The chemical reactions will have an Arrhenious dependence on temperature. However, it was assumed in this model that the mass transfer of the pyrolysis processes was the rate determining step so that the pyrolysis rate was proportional to temperature.
- Convection heat transfer changes the log temperature. The cooler pyrolysis gases and water vapour exit the wood, which causes a cooling effect on the wood closer to the surface.
- Wood composition. The three major components of wood; cellulose, hemi-cellulose and lignin all have different pyrolysis rates.
- Diffusion of pyrolysis gases into the centre of the wood, which then condense back into solids and liquids. This effect slows the pyrolysis rate at the start and increases it later on when the centre of the wood becomes hot enough for the condensed volatiles to re-vaporise.

Much work has been completed (DiBlasi, 1993), (Kanury, 1970) on the affect these processes have on wood pyrolysis rates. It was concluded that to try and model all these factors would take too much time away from more important modelling. Therefore the pyrolysis rate was simplified and made proportional to both the wood mass and temperature:

5.3.4 *Radiation modelling*

The radiation heat transfer used in the model is not as perfect as it could be. There are some sources of radiation that were not modelled due to insufficient time and understanding.

1. Radiation heat transfer from gases. Certain gases including water vapour and carbon dioxide absorb and emit thermal radiation. This is the cause of the greenhouse effect and in a wood burning heater can create non-negligible heat flows. The replacement for this effect was to increase the convection heat transfer coefficients so that the air temperatures were correct. This should be an adequate replacement, but it means that convection heat transfer coefficients can not be calculated from other parameters e.g. Reynold's number, Prantl number.
2. Re-radiation from grey body surfaces. Grey bodies, which are nearly all materials, reflect part of the radiation that they receive. This means that the radiation between more than two surfaces becomes very complicated. A technique was found in Mills (1998), that showed how to calculate all the radiation heat transfer with re-radiation, but for some reason when this was tried using EES, the results obtained were not correct so this technique was removed and a simplification of the radiation

heat transfer was made. It was assumed that there was no re-radiation, with the amount of radiation between two surfaces being calculated from the smallest emissivity of the two.

3. There are many equation methods to calculate radiation shape factors, but it was felt that the time required to implement these equations for the complex geometry of a wood burning heater would be too large and that it would nearly require another research project to complete. Also complicating this task is that the log, charcoal bed and flame size change throughout the run. One attempt to model the log size decreasing was very successful and remained throughout the model. This method was that the shape factor for the radiation flowing from the charcoal bed to the logs was calculated from the area of the logs divided by the area of the logs at the start. This meant that when the logs burn out and loose surface area, the amount of radiation into them from the charcoal bed decreases. To make up for this decrease, the radiation from the charcoal bed to the inside walls of the heater was increased by the same amount. For every other area of the model the radiation shape factors were estimated and then refined to match the results of the Masport LE2000 heat transfer test, therefore providing the best estimation that can be hoped for without the huge effort of calculating all the shape factors from text book equations.

5.3.5 Log Geometry

Early on in the modelling process the modelling of the log size and shape was considered extremely important, with the burn-rate thought to be very dependent on the shape and layout of the logs inside the firebox. This is true, as logs at the front of the firebox receive the most oxygen so burn faster. The logs on the bottom layer are hotter, from the charcoal bed, but have less oxygen than the logs on the top so will be more prone to smouldering. Both these effects show how log geometry and location plays a key part in the burning of logs in a wood burning heater. Fortunately for this project, the emissions test procedure show that the logs must be arranged in a certain manner inside the firebox. Therefore, from Model 5 onwards all the wood logs were assumed to burn at the same rate and have the same mass. This kept the problem simpler, smaller and quicker for EES to solve.

5.3.6 Convection heat transfer coefficients

During Model 17 all the convective heat transfer coefficients were calculated using equations obtained from Mills (1998). There were equations for almost any situation of heat transfer e.g. hot horizontal plate facing upwards, vertical plate with natural convection. The applicable equations were added to the model and this produced some interesting results. The coefficients were close to the estimates that had been used previously, but were all slightly lower. It was thought that this is due to the lack of modelling the gaseous radiation (Section 5.3.4).

Since the equations for the coefficients were often very complicated, they upset EES's solving process quite often and they also didn't provide any easy means with which to calibrate the model to the actual data. Because of these two reasons it was decided to remove these equations and return to the estimations, with the added knowledge that some of the coefficients should be slightly decreased from where they were in the previous models.

When returning to the estimations of the coefficients the same coefficient was used for all outer surfaces. This was done to make the model easier to calibrate, but is not correct. For example, some surfaces are better at removing heat than others. An example of this is that a hot surface will loose more heat if it is facing upwards so that the hot air will move more quickly away from the surface than if it is facing downwards where the hot air will want to stay on the surface and therefore let less heat off the surface. The need to calibrate the model means that the same heat transfer coefficient must be used for all outer surfaces. The theory was that to obtain the correct surface temperatures as found in the Masport LE2000 heat transfer experiment, the heat transfer from the surface used the same coefficient for each surface and the surface temperatures were refined by changing the internal heat flows of the heater so that the model and the experimental data match.

5.3.7 CFD modelling

CFD modelling could be very useful instead of this model or as an extension of it. CFD modelling the airflow through a pellet burning boiler has recently been completed by (Musil, 2003). This work produced good results and shows that CFD is effective when modelling the combustion and heat transfer processes of wood burning. The author used CFD in fourth year Chemical and Process Engineering Research at the University of Canterbury. This gave a good indication of the complexities involved in using CFD, which is why it wasn't tried for this project. The main problem with CFD would be the use of it by the end user. This is because changing the geometry in CFD is the hardest task and this is what the end-user will want to do to improve the heater's design.

One section of the problem where CFD may be useful is in the design of the primary air deflector and baffle positions. The design of these two parts is interlinked and if it is not done correctly large amounts of primary air can bypass the combustion chamber and enter directly into the baffle chamber (above the baffle). If the inlet air doesn't have enough velocity the draught of the baffle chamber easily overcomes its momentum or if it is directed in the wrong direction it can bounce off the glass door into the path of the exiting gases. Applied Research Services Ltd often change the design of the deflector and baffle in order to improve the heaters. It is comparatively easy to change, compared with insulation, door size etc.

5.4 Material Properties

Material properties for the heater are extremely important when using this model. The model requires the user to know the density, specific heat, thermal conductivity and emissivity of the materials they wish to use in their heater. The author has determined material properties for the most commonly used materials, namely steel, firebrick, promat and glass. These values were found from (Perry, 1997) and (Mills, 1998), while the properties of the wood, ash and char were found from (Shelton, 1983) and (Tillman, 1987). If the user wishes to find values for a new material, it can be reasonably difficult to find the correct material properties in any textbook. The best idea is to ask the manufacturer of the material for this information.

For the modelling, many material properties had to be found. This lead to some interesting findings, one being that the conductivity of charcoal is lower than the best building insulators. The conductivity of charcoal was found to be 0.05 W/m K (Shelton, 1983) compared to steel (50 W/m K) and kaowool insulation (0.1 W/m K). Heat shields were also found to be better insulators than firebricks. This is because heat shields require two convective heat transfer terms, which generally provide more resistance than conduction heat transfer. In fact most good insulators work by having many air pockets to increase the convective heat transfer required. Heat shields have far less heat mass than firebricks so firebricks are still required for the start-up part of the run. This is because at the start-up the logs are cold, which cools the heater down, which leads to poor combustion conditions. Heat mass is required to keep the heater hot at the start of a burn so combustion starts well.

5.5 Future use of Model

Because Applied Research Services Ltd is a testing company to many different manufacturers they must remain neutral and therefore can not become involved in the actual design of any wood burning heaters. The model will be used by the staff at Applied Research Services Ltd to determine any quick changes that are able to be made before the next test to improve that heater so that it passes the emissions and efficiency targets. In affect Applied Research Services Ltd only tune the heaters instead of changing their design. These tuning changes could be:

1. Primary and Secondary air areas.
2. Deflector and Baffle design.
3. Firebrick size, thickness and material.
4. Baffle size, thickness and material.
5. Wetback size.

As you can see there are only five areas to change on the heaters. This means that the model is slightly limited when it is used by Applied Research Services Ltd to only tune the heaters. The model could become a great help for the initial design of the heaters, designing the correct dimensions for the heater and its air inlets and outlets.

Because of the calibration needed for the model to be used successfully, it is still reasonably difficult to use. Detailed instructions on how to calibrate the model can be found in the Instruction Manual

(Appendix 1). The model does not include a graphical user interface so the heater parameters are added into a table, with the help of diagrams also found in the Instruction manual. The main reason the model is hard to use is that there is no real distinction from the user section of the model to the equations that define the model. This is a great help if the user has time to understand the equations used in the model, so can manipulate these to better model their individual heater i.e. if their heater has a bay window they may consider increasing the shape factors to the door, because of the door's concave shape. This feature could become particularly important if the user wished to model a different style of heater, other than the five standard types that the model has been adapted for. If for instance a heater was designed with a completely steel door so that no radiation exits through it, the user could modify the equations for this type of heater. Unfortunately it is hard to see another user becoming familiar enough with the model to be able to make such changes and to keep the model working. Problems such as keeping the right degrees of freedom in the model and making sure that equations do not produce mathematical errors e.g. divide by zero can be extremely difficult to keep under control. The solution to this problem, while the model is used by Applied Research Services Ltd, will be to stay in contact with the author and when a need for changing the model equations arises the author can be contracted to perform these duties.

5.6 Preliminary Model results

Some very interesting results were found by using the model on the two heaters mentioned previously. The two tests were an investigation of the heat output distribution from the Masport LE2000 and an investigation into the effect of secondary vs primary air for the Hewitson Lady Kitchener.

The results of the heat output distribution for the Masport LE2000 were:

- Over 50% of the heat output exits out the front of the heater, either from the front walls or radiation from the flame and charcoal embers that transmits the glass.
- Approximately 20% of heat output is from the exposed flue. The loss of this heat output is the main reason for insert heaters having a lower efficiency than free standing heaters.
- When extra insulation was added to the side walls, the total output only slightly decreased (2%). The loss in heat leaving through the sides was made up by the increase out the front because of the higher firebox temperatures. The emissions for the design with more insulation were much less (approximately half) that of the standard design. This shows that for this heater a large decrease in emissions can be made for only a slight decrease in efficiency, by adding insulation.
- When the firebox door was changed to an insulated wall that did not let radiation transmit through it, the firebox temperatures increased dramatically and the log pyrolysis rate increased too much. This lead to high emissions because there was too much smoke to be burnt. This shows that there is a limit to the amount of insulation designed into heaters.

The results for the secondary vs primary air test for the Hewitson Lady Kitchener were:

- Increased secondary air had no effect on emissions. The extra oxygen helped combustion, but the extra cooling of the cold air harmed combustion. The two processes cancelled each other out so that emissions stayed the same.
- This heater had a large wetback and top wall area. The top wall area was large because there were large fins on its inner surface. The conversion of volatiles was calculated for three different areas; Lower half of firebox, Upper half of firebox and above the baffle. The average conversions were approximately 95% for both the lower and upper half of the firebox but only 56% for the air section above the baffle. This was because the temperature in the baffle section was much lower than in the firebox because of the cooling effects of the top wall and wetback. This could be improved by adding an extra combustion section before the upper chamber, so that the heat removed from the wetback and top wall do not affect the combustion process.

5.7 Optimum Efficiency for a wood burning heater

One of the more interesting articles read in the literature review was an explanation of the optimum efficiency possible for a natural draught heater. The flue gases from a wood burning heater must be greater than 200°C to cause an adequate draught and prevent the build-up of creosote in the flue, which is condensed smoke and is the cause of chimney fires. There also needs to be more than twice the oxygen as required for stoichiometric combustion. These two numbers are all that is required to calculate an efficiency figure for a wood burning heater, by the stack loss method. This gives an efficiency of approximately 80%, which is the limit for the efficiency of wood burning heaters. Pellet burners obtain efficiencies of over 90% because of their exceptionally low flue gas temperatures (can be less than 100°C). This is fine for pellet burners because they produce much less smoke so chimney fires are not so much of a problem and they use blowers to suck the air through the heater so the lack of draught is not a problem. This example shows that there is a definite limit to efficiency of these heaters and it is not, like most people would think, 100 % but 80%.

Another area where there is a limit to a heater's performance is in its emissions. The emissions test measures the emissions of a heater once it is completely heated and a good ember bed has been established. This is close to perfect conditions and in a real life situation the fire is lit cold, where combustion conditions are particularly bad. This leads to a large amount of emissions and if a heater is used for only six hours, the start-up emissions can contribute over half the total emissions. This could lead to the conclusion that the design of the heater has a very small influence on the emissions of a wood burning heater and that how the heater is operated is far more important. This conclusion is also made in (Shelton, 1975).

5.8 Heater design recommendations

After determining equations for the model and using this model on a number of heaters, several recommendations can be made for the design of better performing wood burning heaters.

5.8.1 Turbulence

Turbulence is very important in order to mix the smoke and oxygen together for complete combustion. Therefore, when designing a wood burning heater turbulence creation must be an important consideration. Turbulence can be increased by designing high velocity inlet air, using baffles to direct the gases in different directions. Another idea may be to create vortices with the primary air and flue gases. Vortices are highly turbulent and the mixing of the smoke and oxygen would be excellent. This technology is used in large scale wood combustion and could easily be transferred to domestic wood burning heaters.

5.8.2 Heat Transfer

The major problem when designing a wood burning heater is that good combustion requires high temperatures which means that heat flows from the combustion chamber should be kept to a minimum. The role of the wood burning heater is to heat the home so heat must be removed from the heater at some stage. One area where this could be accomplished is from the flue pipe. Once the gases are in the flue, they have finished combustion so do not need to be kept hot. Therefore as much heat can be taken from the flue pipe as is possible. The only limit here is that the flue gases need to be kept at a reasonably high temperature, over 150°C, so that natural draught continues to suck the gases through the heater.

The heat output from the flue pipe could be increased by using forced convection. This would be accomplished by using a fan to blow air across the flue. A better idea would be to increase the area for convection heat transfer by applying fins to the flue pipe. This would increase the heat output and therefore efficiency of the heater without harming emissions.

5.8.3 Combustion air pre-heating

Heaters exist where the air required for combustion is preheated from the hot flue gases or firebox walls. The inlet air into the heater has a major cooling effect upon the heater, which harms both the efficiency and emissions of the heater. However there is a limit to how hot the firebox can get, where the pyrolysis of the logs proceeds too quickly for limited airflow to keep up (section 5.6). With this in mind, it may not be a great idea to pre-heat the primary air as the primary air will heat the wood logs and create this effect. The secondary air should be as hot as possible as the secondary air is directed into the flames where heat is required for good combustion and there are no side effects from this extra temperature.

5.8.4 Primary air versus Secondary air

Primary air is inlet air that is directed into the charcoal ember bed and logs to produce heat and start the pyrolysis reactions in the wood. It is only the primary air that determines the burn-rate of the heater, not the secondary air. Secondary air is directed into the flames of the fire to provide extra oxygen for the smoke combustion phase of the burning. Secondary air is only needed near the start of a run, when the pyrolysis reactions are at their peak and large amounts of smoke are being created. There is no need for secondary air after the smoke combustion is finished and all it then does is to cool down the heater and decrease its efficiency. Primary air is required throughout the entire run but it could be decreased after the first moments of the run, because at this point the pyrolysis process should be slowed so that the smoke combustion process can catch up.

The ultimate system would be where the primary air flow is used to control the rate of burning and would be controlled by the heater user. The secondary airflow would be highly pre-heated and be computer controlled to keep emissions down. This kind of technology could easily exist but the system would be expensive as well as needing electricity so that it wouldn't work in a power failure. These two reasons are why wood burning heaters are so popular.

5.8.5 Excess Air

The loss of efficiency of a wood burning heater is nearly all in the heat of the flue gases exiting the flue and into the outside environment. A small proportion of the loss of efficiency is the un-burnt fuel, which is the emissions of the heater. If the heater design can give less air flowing out the flue then the energy of this air would be less and efficiency would improve.

Oxygen is required for stoichiometric combustion of the wood and this is obtained from air, which is only 23% m/m oxygen so we are already loosing optimum efficiency because the remaining 77%, mainly nitrogen, is only carrying heat out of the heater and into the outside environment, therefore lowering efficiency. There is also extra oxygen that enters the heater above the stoichiometric oxygen required. This excess air can become very large near the end of a run, after the wood has been fully broken down by the pyrolysis reactions and only charcoal remains. Four or five times the air required for stoichiometric combustion can be supplied at this point, which is a large waste of energy as this extra air must be heated and all this heat is removed up the flue.

Another loss of air is primary air that by-passes the combustion zone and flows straight into the baffle chamber (Fig.8). This can be fixed by careful design of the primary air deflector and baffle position.

6 Conclusions and Recommendations

A computer model has been produced that successfully models the performance of a wood burning heater undergoing the emissions test of AS/NZS 4013:1999. The model calculates all results of the emissions test as well as extra information that is not available from the emissions test including:

- excess air
- heat output breakdown, radiation versus convection as well as the region where the heat is emitted from.
- combustion conversions for each combustion zone
- internal temperatures

The computer model is for use by the wood heater testing company Applied Research Services Ltd to tune heater designs so that they may pass the emissions and efficiency standards. The design factors that will be changed include:

- primary and secondary air areas.
- deflector and baffle design.
- firebrick size, thickness and material.
- baffle size, thickness and material.
- wetback size.

The model does not include every process that affects a heater's performance and it also makes a number of assumptions that are not always correct under different conditions. This means that the model requires the use of calibration factors to model the processes that are not adequately modelled. An example of a process not modelled is the radiation shape factors changing as the flame and log dimensions change. The model assumes that the shape factors are the same throughout a run but in reality the size of the flame has a large impact on where it radiates to. These calibration factors can be found from one emissions test on a given heater design on high airflow setting. The average values for flue temperature, heat output, efficiency, wetback heat output and emissions are used to change the five calibration factors so that the model produced similar average values.

Many of the processes not modelled in this project require the use of computational fluid dynamics (CFD). CFD would be needed to model the mixing processes of the smoke and oxygen as well as the distribution of inlet air between the charcoal ember bed and logs. A large amount of work would be required to operate this CFD model especially when changing the geometry of the heater.

If more time was available a CFD model would have been used to model the design of the primary air deflector and baffle position. The proper design of these two heater sections stops inlet primary air from bypassing the combustion zone and being sucked straight above the baffle where it is of no use and only cools the heater, therefore reducing its efficiency and increasing emissions. CFD modelling could help well in this problem and the use of the model would not be too complex as there are only two or three design changes that are possible so the changes to the CFD geometry will not be overly complicated.

The model is still reasonably difficult to use, particularly in the calibration phase of the modelling. Because of this when the model is to be used at Applied Research Services Ltd, the Author will be employed part time to run the model. Because of the author's better understanding of the intricacies involved in the model the time taken to model each heater should be much shorter and the results should be better as fewer mistakes will be made in the use of the model.

In the future it is proposed that the model may be sold as a software package to heater designers and for this a user-friendly graphical interface would need to be created so that a user with less experience with the model could still operate it.

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Appendix 1: Model Instructions

Applied Research Services Ltd owns the rights to the model. If one wishes to use the model, Applied Research Services Ltd can be contacted at:

Applied Research Services Ltd
P O Box 687
Nelson
New Zealand
applied@ts.co.nz
03 547 7347

A1.1 Model Selection

Five models were created so that the model could be used for as many different styles of heater as possible. The five models were Standard, Radiant, Hewitson, Ethos and Insert. All models have the possibility of adding a wetback above the baffle.

Standard	Heat shields and an outer shell, Top heat shield that lets air out, secondary air taken from between heater walls and heat shield.
Radiant	No heat shields or shell
Hewitson	Standard with no heat shields but an insulating outer shell
Ethos	Standard plus Inlet air preheating
Insert	Radiant model plus a convective flow from under the heater and out over the top of the heater. Flue temperature is the same as the baffle air temperature.

A1.2 Entering heater dimensions

Heater dimensions are all entered into the parametric table. To get to the parametric table in EES, click on the  icon. Below is a list of the names used in the model and an explanation of what these names represent on a heater.

Nlogs	Number of logs used in the test
mlstart	Mass of logs used in test
Llog	Length of logs used in test
xwstart	Water content of logs
XApatest	Primary air inlet area used in test
XApahigh	Primary air inlet area on high
XApalow	Primary air inlet area on low
XAsa	Secondary air inlet area
Dflue	Diameter of flue
Dflueo	Diameter of outer flue (Ethos only)
Linlet	Height of inlet air pre-heat ducts that duct air from the flue to the inlet (Ethos only)
LOwidth	Total width of heater

LOheight	Total height of heater side heat shields
LOdepth	Total depth of heater
LIwidth	Width of firebox
LIheight	Height of firebox
LIdepth	Depth of firebox
Atwholes	Area of holes in the top heat shield
Lbaffleheight	Distance between top of baffle and top wall
Lbaffle	Length of baffle, from back wall
xb	Thickness of baffle
Ldoorwidth	Width of door glass
Ldoorheight	Height of door glass
xd	Thickness of door glass
Lbrickheight	Height of firebricks
Lbrickwidth	Width of firebricks
Nbricks	Number of firebricks
xfb	Thickness of firebricks
XAst	Area of the connection between the firebox floor and the stand
Lstandheight	Height of stand
xfluew	Thickness of flue wall
xhs	Thickness of heat shield and outer shell
xwall	Thickness of side and back walls
xtop	Thickness of top wall
xfl	Thickness of floor
Atopribi	Area of fins on the inside of the top wall
Atopribo	Area of fins on the outside of the top wall

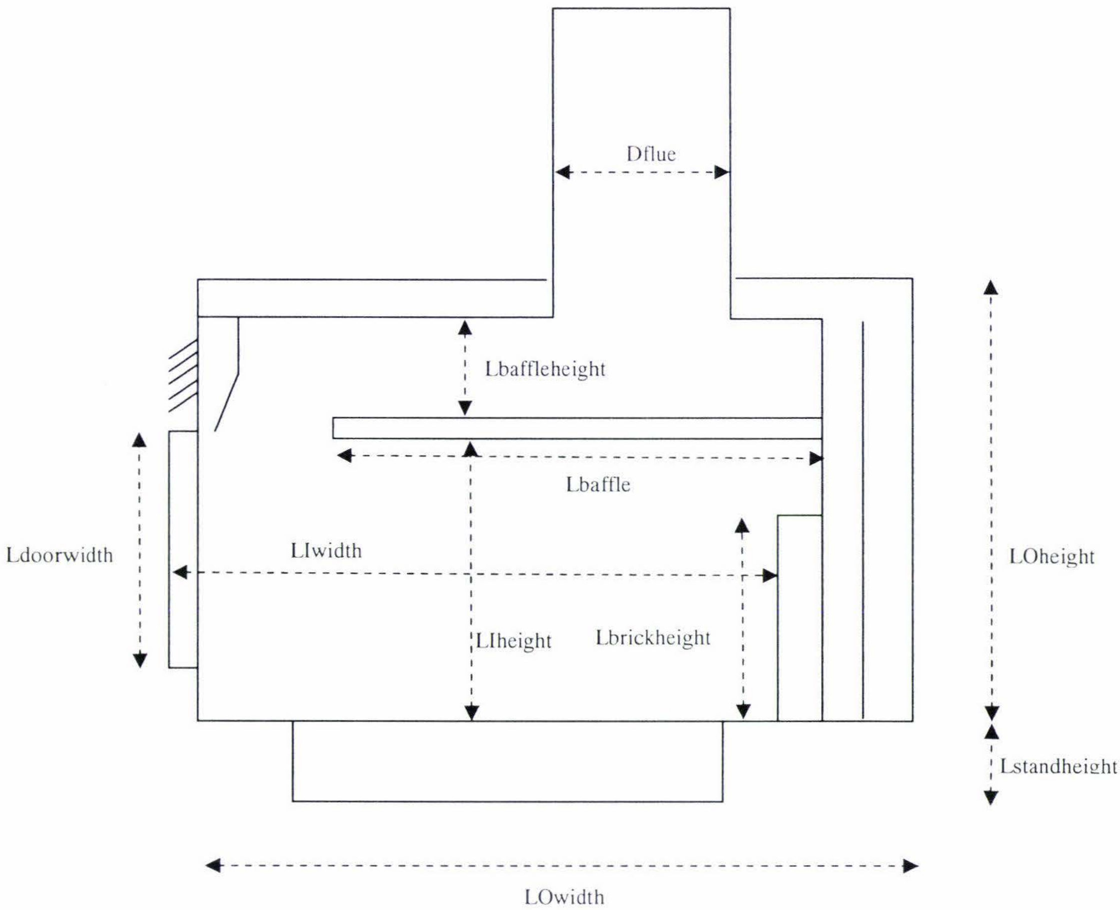


Figure 30: Dimensions of Heater as used in model

A1.3 Entering Material Properties

Once the dimensions of the heater have been entered into the parametric table, material properties should be entered in the equations window. Click on the symbol to get to the equations window. After the functions, start temperatures and the calibration factors are the material properties. The properties required for the model are Emissivities (e), Specific heats (Cp), Densities (Den) and Conductivities (k). The properties of seven materials have been determined already so that if the heater uses these materials the user can use the name of these materials rather than obtaining the numbers from other sources. These materials are steel, glass, firebrick, promat, kaowool, CVB (Ceramic vacuum board) and Tiles.

Each heater section must be supplied with all four material properties. Below is a list of the names used for the heater sections and a diagram showing what they represent.

fb	Firebricks
b	Baffle
tw	Top wall
fl	Floor
hs	Heat shield (Sides and back)
ths	Top heat shield
sh	Shell

st	Stand
flue1w	Flue wall, half the way to 2m
fluew	Flue wall, upper half of flue up to 2m

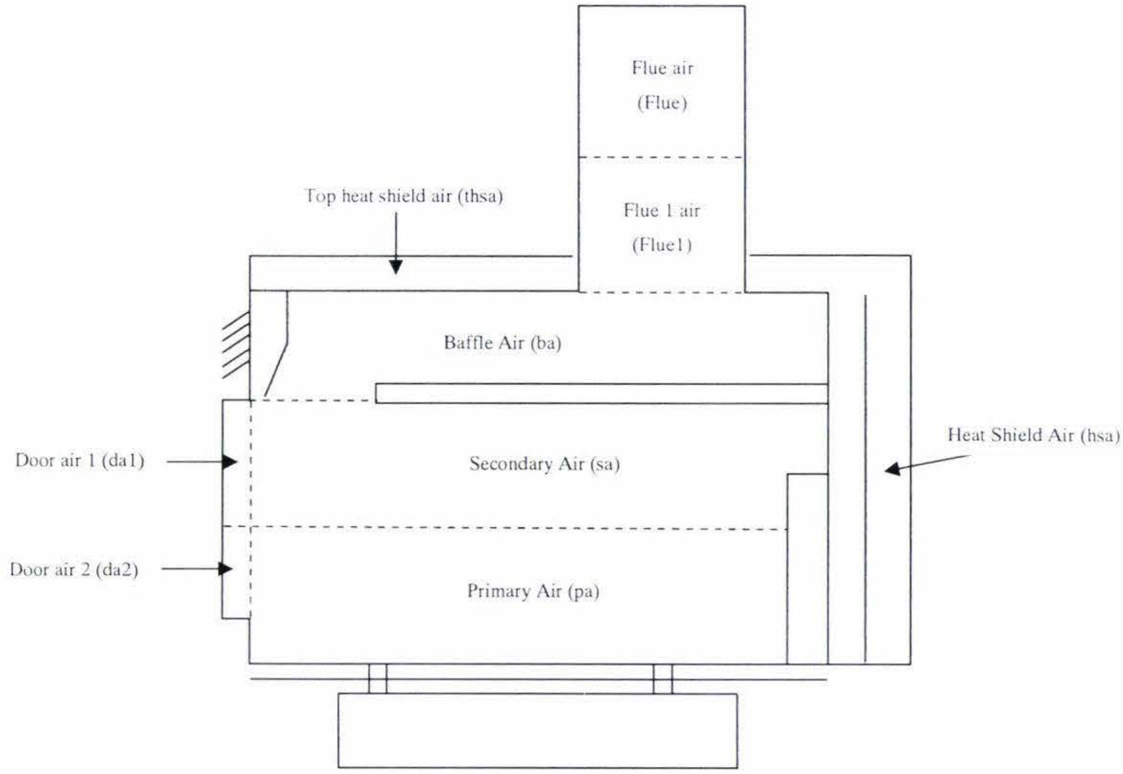


Figure 31: Air section naming convention for the final model

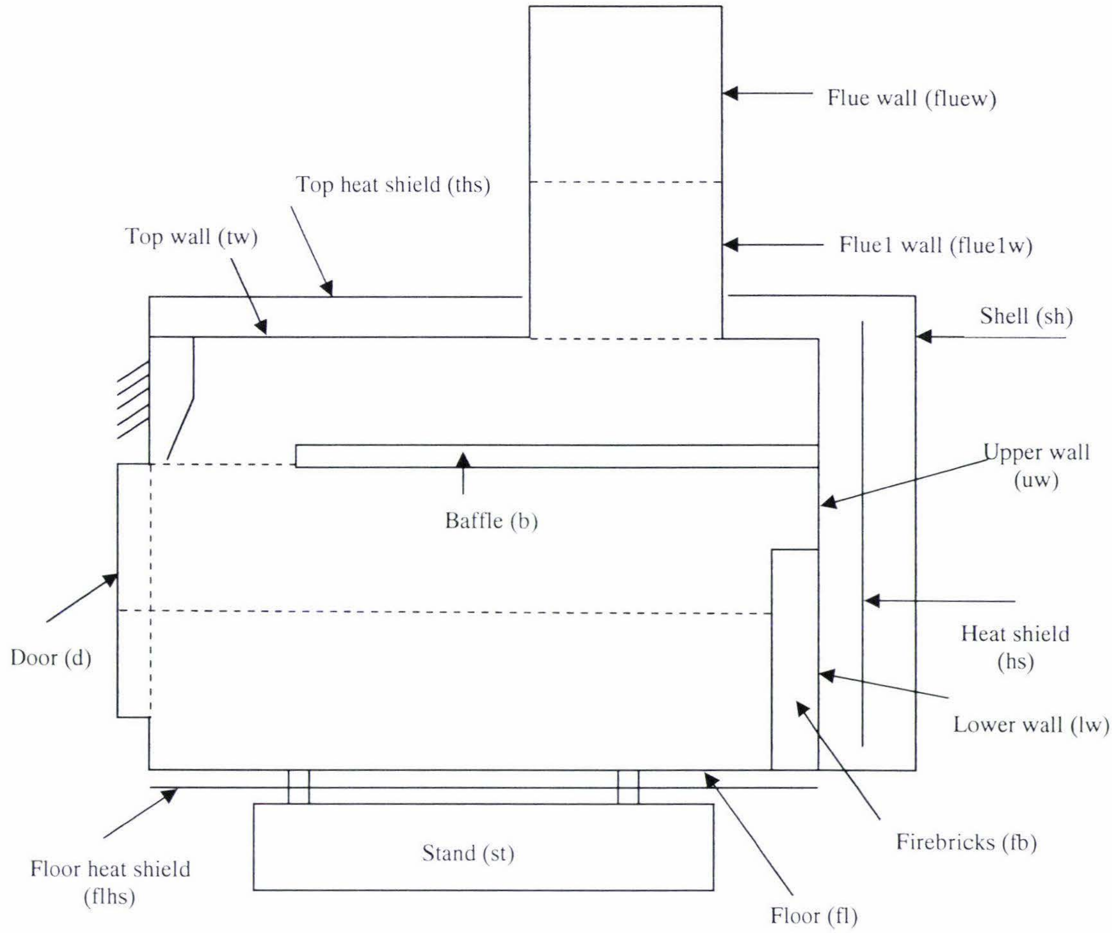


Figure 32: Heater solid sections naming convention for the final model

A1.4 Running the model

Once heater dimensions are input into the parametric table and material properties into the equations window, click the  button to start the solving process. On the Pentium 366Mhz computer used to develop this model the time taken was approximately 10 times less than the actual run time. Therefore after around 10 minutes the solver will stop, claiming that an error has occurred. This error is used to stop the model when the net mass of the heater falls below zero, which is when the normal emissions test finishes.

A1.5 Results explanation

There are two locations that results of the run can be obtained. The first is the solution window, which shows the values of all the variables at the end of the run. Click to obtain the solution window. Averages of the important results e.g. Output, Flue Temperature are found at the top of this sheet because they start with aa. These results cannot be saved so the user can use the results sheet located in the excel spreadsheet "Heat Transfer" to record these values. One of the more important results from the model is the variable aaDT, which gives the maximum temperature difference of all the heater sections between the start and finish. This shows if the heater has reached a steady state. It is very important for the heater to reach steady state as if the heater has not reached steady state the results can be misleading because of the heat stored in the heater. For more information about altering the model to obtain steady state see the section below called "Start temperatures".

The other location for results is the integral window, which shows how some variables have changed over the entire run. One can add variables to this window, before solving, by adding the variable name to the list at the bottom of the equations window. The integral table can be copied and pasted into Microsoft Excel simply using the Microsoft clip-board. Sums, Standard deviation, minimum and maximums can be obtained from the integral table by right clicking on the column heading.

Beware that once anything is changed in the equation window all the results are lost from the solution and integral tables.

A1.6 Graphing

The variables in the integral table can be graphed by clicking the button. A window pops up and one simply selects the integral table from the table pull down menu and then selects what variables to plot. More than one variable at a time can be plotted on the y-axis. To view the graphs that are created click on the button. These graphs are stored in the EES file forever

A1.7 Calibration

Because the model does not model some important features of wood burning heaters (e.g. turbulence, air pathways) calibration factors are required so that the one model can model all types of heaters. There are five calibration factors, calRate, calVolatiles, calIncreaseOutput, Kflowhigh and Kflowlow.

calRate increases the rate of pyrolysis as well as the rate of char combustion. Change this value if the run time needs to be increased or decreased.

calVolatiles increases the rate that the smoke burns with the oxygen thus decreasing emissions. Increase calVolatiles to decrease the emissions. This calibration factor is really a measure of how good the mixing between the smoke and the oxygen is. This calibration only has a small effect on the other results (Other than emissions), so should be changed last.

calIncreaseOutput increases all the parameters that increase the output and decreases all the parameters that decrease the output. Examples are that the shape factor from the flame into the room is increased when calIncreaseOutput is increased. Obviously this parameter is used to increase the output. This also decreases the flue gas temperatures and therefore the burn-rate because of a decrease in draught.

calWetback increases the convection heat transfer coefficient for the wetback. This increases the heat output of the wetback.

calBypass is the bypass ratio for the primary air. The fraction of bypass flows straight into the bypass while the remaining air flows down the door and into the primary air section. Increase this to decrease flue temperature and increase emissions.

Kflowhigh controls the rate of airflow into the heater when it is on the high setting. The airflow into the heater is given by this constant multiplied by the flue draught.

Kflowlow controls the rate of airflow into the heater when it is on the low setting. When a medium setting is used a linear interpolation of Kflowhigh and Kflowlow is used.

When calibrating one should look for the following results and compare these with the emissions test results. All calibration apart from Kflowlow should occur on the high airflow setting.

Output, Wetback, Flue temperature, Burn-time, Efficiency, Emissions

A1.8 Start Temperatures

In order to use the model, start temperatures for every section of the heater must be provided to the model. This is done my running the model twice. The first time one uses the standard start temperatures and records the temperatures at the end of the model on the results sheet. These temperatures can be found at the bottom of the results sheet as they start with zzT. The temperatures can then be used on the actual run. This procedure is similar to the pre-test on the actual emissions test where a test is run before the actual tests in order to get the heater up to temperature. The procedure may have to be run twice so that the heater is at the same point at the start and finish of the run. One can tell if it is in the same position by looking at the variable aaDT. If aaDT is zero then the heater is in exactly the same position at the finish as it was at the start. It is recommended that the above procedure is repeated until aaDT is less than 5°C.

A1.9 Variable symbols

In order to keep track of all the equations and variables used in the model, a system of naming the variables was used. The first letter or letters represents what type of variable it is, e.g. A for surface area, T for temperature. Below is a list of all variable types used in the model.

A	Surface area	[m^2]
D	Diameter	[m]
DP	Pressure drop	[Pa]
DT	Temperature difference	[°C]
e	Reaction extent or emissivity	[kmol],[]
F	Mass flow-rate	[kg/s]
FV	Volumetric flow-rate	[m^3/s]
h	Heat transfer coefficient	[kW/ m^2 C]
M	Mass	[kg]
Q	Heat content	[kJ]
qr	Heat flow-rate	[kW]
sf	Radiation shape factor	[]
T	Temperature	[°C]
U	Velocity	[m/s]
V	Volume	[m^3]
XA	Cross-sectional area	[m^2]
x	Fraction	[]

Following this is the name of the object that this variable represented. The objects used in the model are shown below.

A1.10 Section Names

ba	Baffle air (Firebox air above baffle)
b	Baffle
c	Charcoal (Charcoal bed at the base of the firebox, assumed to cover entire floor)
d	Door
f	Flame
fb	Firebrick
fl	Floor
flhs	Floor heat shield
flue	Upper half of the air inside the flue, below 2m
flue1	Lower half of the air inside the flue, below 2m
flue2	From 2m to the top of the flue, 4.7m high
fluew	Wall surrounding flue air
flue1w	Wall surrounding flue1 air
flue2w	Wall surrounding flue2 air
G	Pyrolysis gases (Smoke)
hs	Heat shield
l	Log
lw	Lower wall (Sides and back)
pa	Primary air (Lower half of the firebox air)
r	Calorimeter room air
rw	Calorimeter room walls
sa	Secondary air (Upper half of the firebox air)
tw	Top wall
uw	Upper wall (Sides and back)
w	Water
i	Inside (Closest to the logs)
o	Outside

The variables were combined together, with the variable symbol first, followed by the names.

The heat flow fate from the flame to the top wall would be: qrftw

The water content in the log section 1 would be: xl1w

A1.11 Heat transfer spreadsheet

To help the end-user's understanding of the heat transfer system in the model, a graphical representation of the system has been made inside the spreadsheet "Heat transfer.xls". All heater sections are listed horizontally and vertically and where there is heat transfer, the square where the two sections intersect is coloured. Red is radiation, blue is convection, yellow is conduction and green is heat inlet or outlet flows.

A1.12 Convection Heat Transfer Coefficients

hin	Internal convection heat transfer coefficient. Used for convection to firebox air from logs, charcoal, firebrick inside surface, upper wall inside surface, baffle inside surface. Increases with air-flow because of the extra turbulence causing better heat transfer.
hout	Convection heat transfer coefficient from all outer heater surfaces into the calorimeter room. Examples are the flue wall to the room and the shell to the room
hflue	Convection heat transfer coefficient from the upper sections of the heater into the flue gases. This coefficient is used for the baffle air and the flue air.
hhs	Used for convection to or from heat shields that are generally in stagnant air, therefore this coefficient is less than the others
hd	Used for the convection from the door to the door air.

A1.13 Radiation shape factors

If one wants to change the radiation shape factors they can be found in the equations window, close to the top of the window. The shape factors use the naming convention mentioned above and start with sf. For example the shape factor from the flame (f) to the inside of the baffle (bi) would be sffbi. The shape factors into the room are the same as the shape factors into the door so these have di at the end of their names e.g. from top surface of charcoal bed (ci) to the room and door is sfcidi. Note that the sum of the shape factors from each surface can not exceed one.

Appendix 2.1 Heat Transfer

Firebricks side and back. Heat shields side, back, floor. Baffle. Thin outer shell. Stand. Air can flow out of top heat shield. Secondary air is preheated between firebox walls and shell

			Wood					Firebricks		Air							Walls												Heat shields							Room	
Radiation	42	1																																			
Convection	25	2																																			
Conduction	10	3	f	ci	co	l	ash	fbi	fbo	pa	sa	ba	flue1	flue	da1	da2	bi	bo	uwi	uwo	lwo	di	do	twi	two	flo	flue1w	fluew	hsa	hs	thsa	ths	flhs	sh	st	r	rw
77	77	77	7	8	1	6	1	6	1	0	2	2	1	1	1	1	4	1	3	2	2	1	2	1	2	2	3	2	2	1	1	2	3	2	2	1	0
Wood																																					
Flame	0	f																																			
Coals inside	1	ci	1																																		
Coals outside	1	co		3																																	
Logs	2	l	1	1																																	
Ash outside	1	ash			3																																
Firebricks																																					
Side inside	3	fbi	1	1		1																															
Side outside	1	fbo						3																													
Air																																					
Primary	3	pa		2		2		2																													
Secondary	0	sa																																			
Baffle	0	ba																																			
Flue1	0	flue1																																			
Flue	0	flue																																			
Door air 1	0	da1																																			
Door air 2	0	da2																																			
Walls																																					
Baffle inside	5	bi	1	1		1		1			2																										
Baffle outside	2	bo										2					3																				
Upper inside	6	uwi	1	1		1		1			2						1																				
Upper outside	1	uwo																	3																		
Lower outside	1	lwo							3																												
Door inside	8	di	1	1		1		1							2	2	1		1																		
Door outside	1	do																				3															
Top inside	2	twi										2						1																			
Top outside	1	two																						3													
Floor outside	1	flo					3																														
Flue1 wall	1	flue1w											2																								
Flue wall	1	fluew												2																							
Heat shields																																					
Air	2	hsa																		2	2																
Heat shield	3	hs																		1	1								2								
Top Heat shield air	1	thsa																							2												
Top Heat shield	3	ths																							1		1				2						
Floor heat shield	1	flhs																								1											
Shell	2	sh																											2	1							
Stand	2	st																								3							1				
Room																																					
Room	7	r																					2				2	2				2	2	2	2		
Room walls	14	rw	1	1		1		1									1		1				1				1	1				1	1	1	1	2	

Add horizontals and subtract verticals

Appendix 2.2 Bernoulli

This spreadsheet was used to determine the equations required to model the airflow using bernoullis equation
Solver was used to change the primary air flow (blue) so that the pressure drops due to friction equaled the draft pressure.

M	28.964	
R	8314	
Tinside	20	
Toutside	20	
Height	4	

Primary Air 7.44E-07

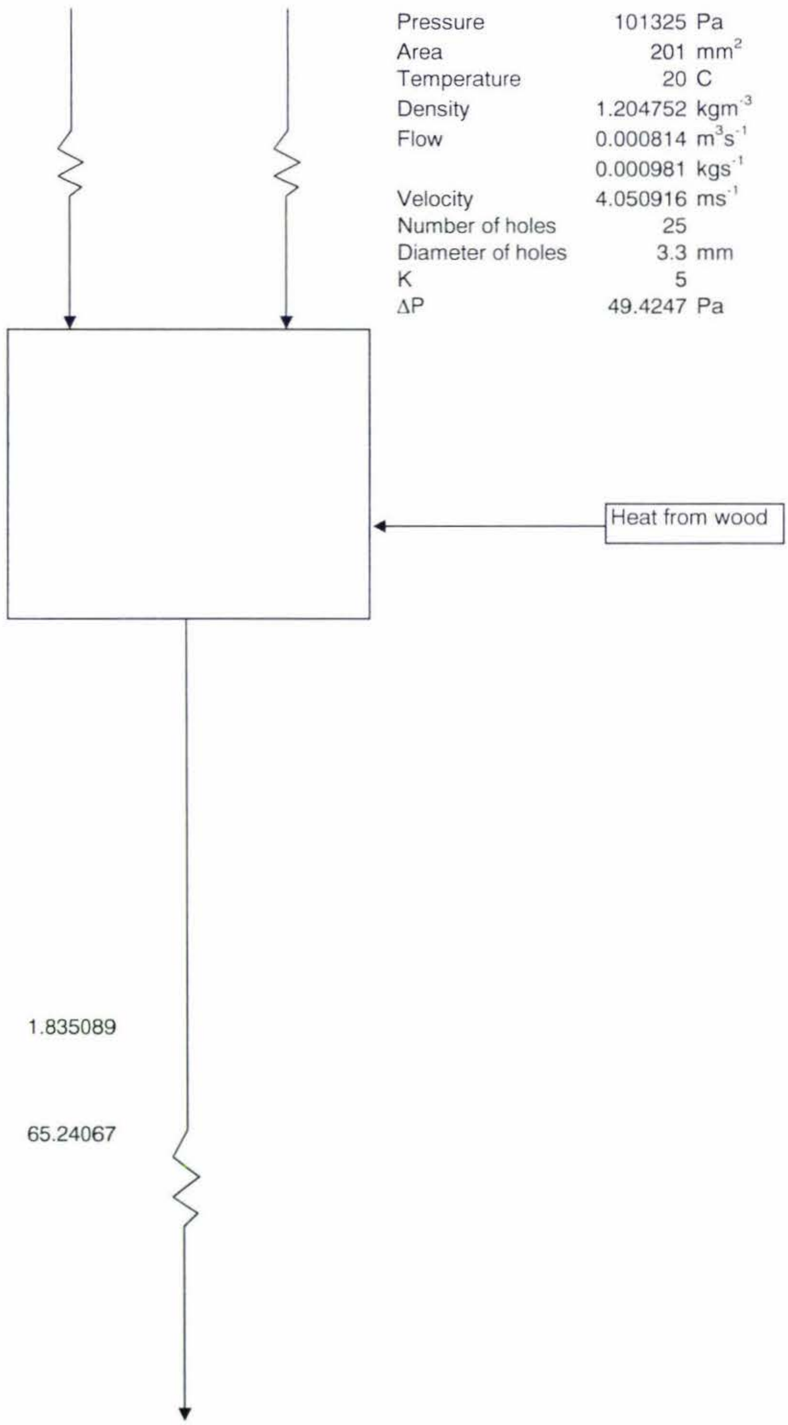
Pressure	101325	Pa
Area	1856	mm^2
Temperature	20	C
Density	1.204751597	kgm^{-3}
Flow	0.006863421	m^3s^{-1}
	0.008268717	kgs^{-1}
Velocity	3.697963831	ms^{-1}
K	6	
ΔP	49.42470475	Pa

Secondary Air

Pressure	101325	Pa
Area	201	mm^2
Temperature	20	C
Density	1.204752	kgm^{-3}
Flow	0.000814	m^3s^{-1}
	0.000981	kgs^{-1}
Velocity	4.050916	ms^{-1}
Number of holes	25	
Diameter of holes	3.3	mm
K	5	
ΔP	49.4247	Pa

Firebox

Burn-rate	0.000944444	kg/s
Heat from wood	3.137187083	kW
Temperature	299.768199	C
Density	0.615990962	kgm^{-3}
Flow	0.016549125	m^3s^{-1}
	0.010194112	kgs^{-1}
Cpair	1.1	kJ/kg K
Pressure	101275.5753	Pa



Firebox outlet

Pressure	101275.5753	
Area	4000	mm^2
Temperature	299.768199	C
Density	0.615990962	kgm^{-3}
Flow	0.016549125	m^3s^{-1}
	0.010194112	kgs^{-1}
Velocity	4.137281339	ms^{-1}
K	3	
ΔP	15.81596546	Pa

Theoretical Draft

Flue T	200		
	17.9662168	Pa	1.835089

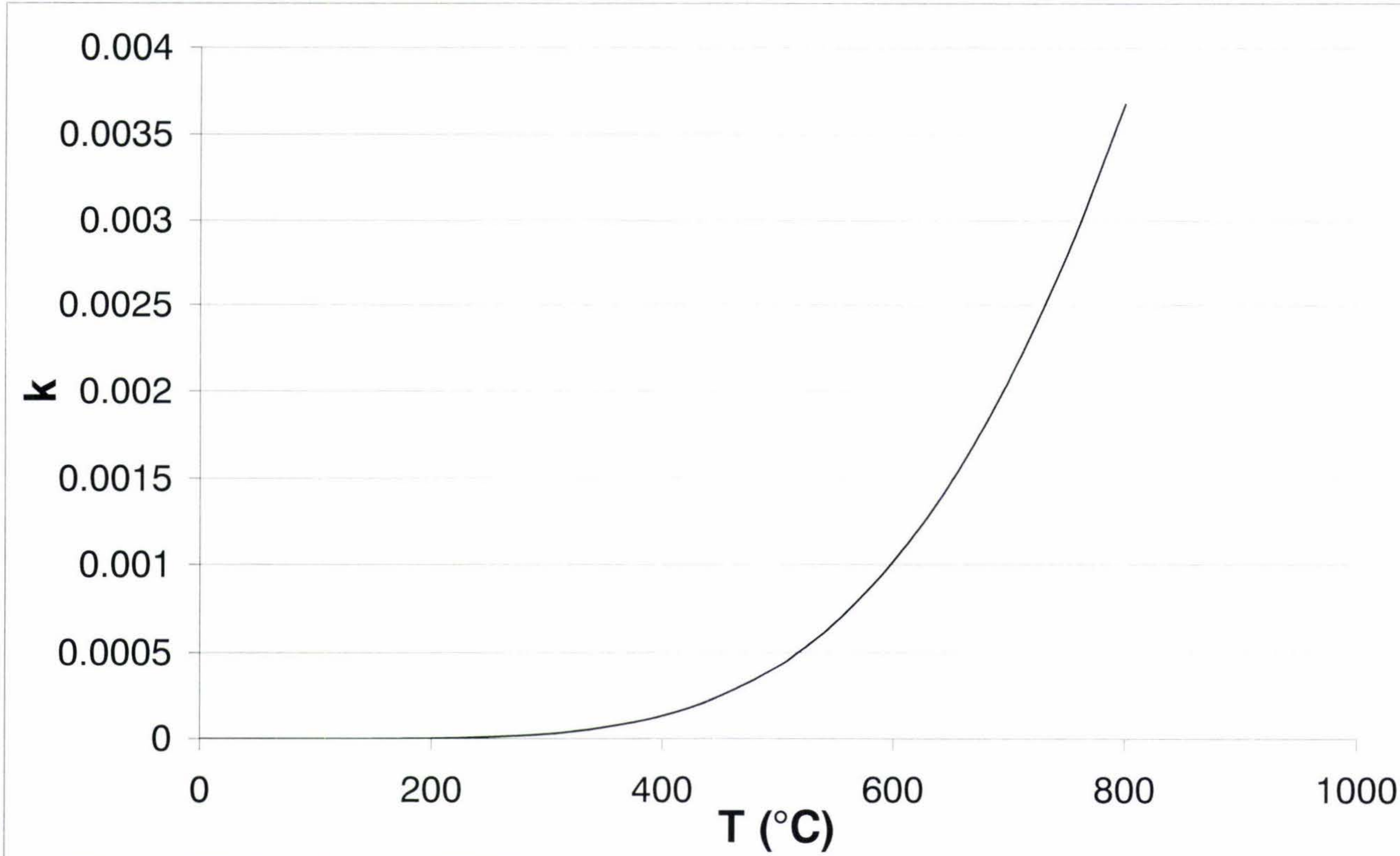
Flue pipe

Pressure	101259.7593	Pa	65.24067
Area	17671	mm^2	
Temperature	315	C	
Density	0.599940366	kgm^{-3}	
Flow	0.01699187	m^3s^{-1}	
	0.010194112	kgs^{-1}	
Velocity	0.961543426	ms^{-1}	
K	3		
ΔP	0.83202648	Pa	

Exit

Pressure	101277.7255	Pa
Ambient Pressure	101277.7255	Pa
Difference	7.44301E-07	

47.27445

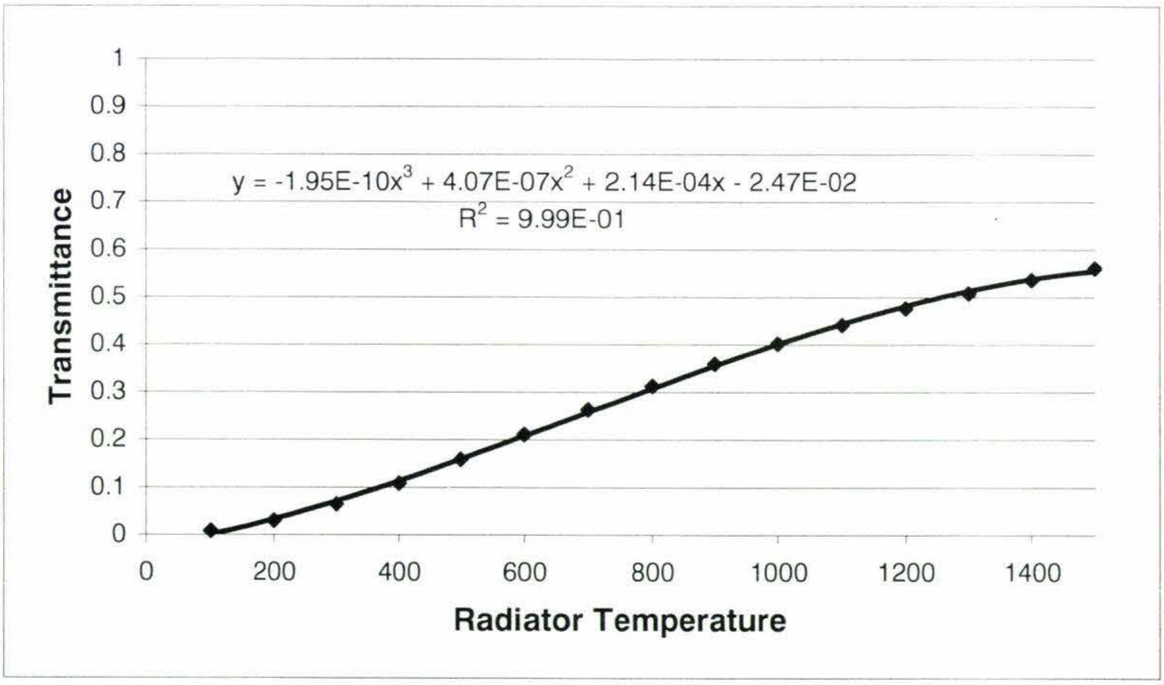

0.004
0.0035
0.003
0.0025
k
0.002
0.0015
0.001
0.0005
0
0
200
400
600
800
1000
T (°C)

Appendix 2.4 Transmittance

The program BBRAD was used to calculate the % first and %second
This spreadsheet calculates an equation for transmittance through a wood heater's door with respect to temperature of radiator

Convert	2400	cm^{-1}
	4.166667	μm
Trans 0-2.8	80%	
Trans 3.3-4.2	50%	

T(C)	% First	% Second	Trans
1500	63.7	10.29	0.56105
1400	60	11.22	0.5361
1300	55.87	12.22	0.50806
1200	51.29	13.26	0.47662
1100	46.24	14.34	0.44162
1000	40.71	15.37	0.40253
900	34.76	16.3	0.35958
800	28.48	16.99	0.31279
700	22.06	17.27	0.26283
600	15.79	16.88	0.21072
500	10.09	15.52	0.15832
400	5.43	12.97	0.10829
300	2.23	9.23	0.06399
200	0.58	4.96	0.02944
100	0.06	1.54	0.00818

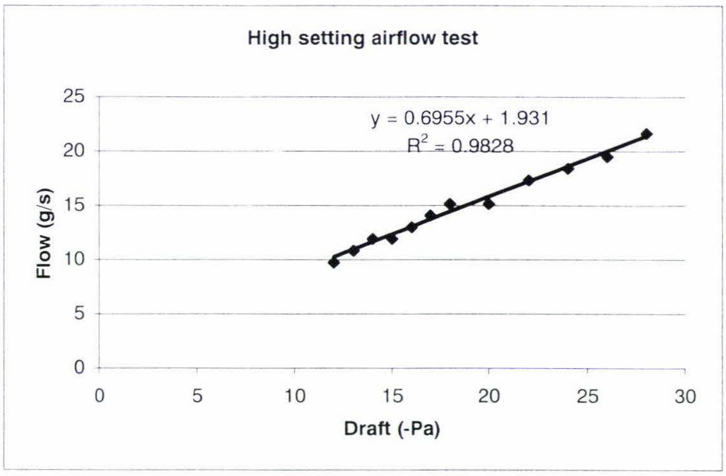


Appendix 2.5 Flow measurements

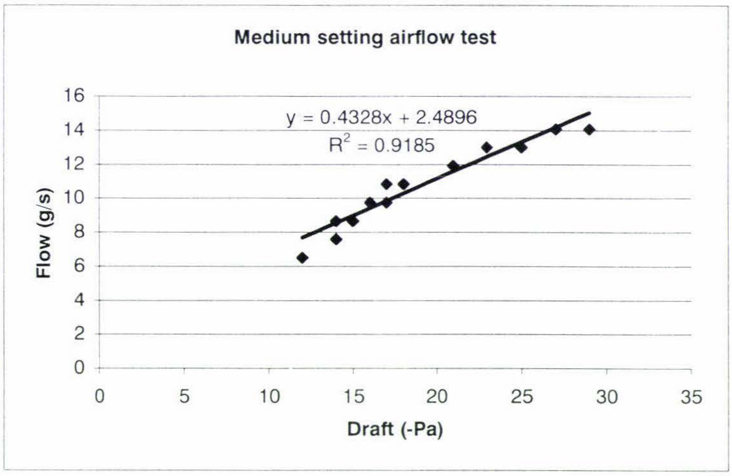
This spreadsheet was used to record the results of the experiment with the objective of determining the relationship between draft and flow.

Primary area	high	0.0013
	med	0.0008
	low	0.0003
Secondary area		0.0003
Flue area		0.0177
Density		1.2

High Measurements					
Voltage	Flow			Ppa	Pflue
	ft/min	m/s	g/s	(Pa)	(Pa)
150	90	0.4596	9.7462	10	12
160	100	0.5107	10.829	11	13
170	110	0.5617	11.912	12	14
180	110	0.5617	11.912	14	15
190	120	0.6128	12.995	15	16
200	120	0.6128	12.995	15	16
210	130	0.6639	14.078	16	17
220	130	0.6639	14.078	16	17
230	140	0.7149	15.161	17	18
240	140	0.7149	15.161	17	18
200	140	0.7149	15.161	20	20
210	160	0.8171	17.327	22	22
220	170	0.8681	18.409	24	24
230	180	0.9192	19.492	26	26
240	200	1.0213	21.658	28	28

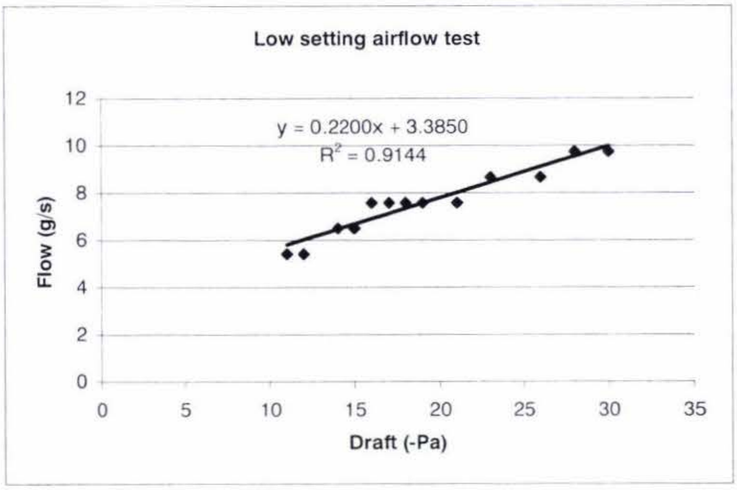


Medium Measurements					
Voltage	Flow			Ppa	Pflue
	ft/min	m/s	g/s	(Pa)	(Pa)
150	60	0.3064	6.4974	10	12
160	70	0.3575	7.5803	12	14
170	80	0.4085	8.6633	13	14
180	80	0.4085	8.6633	14	15
190	90	0.4596	9.7462	15	16
200	90	0.4596	9.7462	16	17
210	100	0.5107	10.829	16	17
220	100	0.5107	10.829	17	18
230	100	0.5107	10.829	17	18
240	100	0.5107	10.829	17	18
200	110	0.5617	11.912	21	21
210	120	0.6128	12.995	24	23
220	120	0.6128	12.995	26	25
230	130	0.6639	14.078	28	27
240	130	0.6639	14.078	30	29



Appendix 2.5 Flow measurements

Low Measurements					
Voltage	Flow			Ppa	Pflue
	ft/min	m/s	g/s	(Pa)	(Pa)
150	50	0.2553	5.4145	11	11
160	50	0.2553	5.4145	12	12
170	60	0.3064	6.4974	14	14
180	60	0.3064	6.4974	15	15
190	70	0.3575	7.5803	16	16
200	70	0.3575	7.5803	17	17
210	70	0.3575	7.5803	17	17
220	70	0.3575	7.5803	18	18
230	70	0.3575	7.5803	18	19
240	70	0.3575	7.5803	18	19
200	70	0.3575	7.5803	22	21
210	80	0.4085	8.6633	24	23
220	80	0.4085	8.6633	26	26
230	90	0.4596	9.7462	29	28
240	90	0.4596	9.7462	32	30



	XA	Kflow
High	0.0016	0.6955
Med	0.0011	0.4328
Low	0.0006	0.22