Development of a wood-fired cooking stove to incorporate a thermo-acoustic engine-generator unit

Ron Dennis[1], Keith Pullen[1]

Abstract

The provision of affordable electrical power in off-grid rural areas of developing countries is a major challenge but a vital element in the battle to reduce poverty. In response to this need, the SCORE project objective was to integrate a novel technology, thermo-acoustics, into a domestic cooking stove in order to produce an adequate level of electricity supply for families in developing countries whilst also providing efficient cooking. The unit is aimed at the majority of poorer families in developing countries that do not have access to electricity and have little hope of being connected to grid electricity in the near future. The electrical generation function is a vital driver in the adoption of low emissions stoves which significantly reduce health problems from smoke inhalation. This paper describes the design of the cooking part of the stove developed within the framework of the project.

Within the wood burning stove, heat released by combustion is first transferred to a thermo-acoustic engine (TAE) to generate electricity, and then to the cooking part. The paper describes the development of the design and construction of the stove to meet the above objectives. This has been progressed through extensive testing of prototype stoves and also through modelling of the heat transfer within the combustion chamber and also for the cooking part of the stove

The paper presents and compares the results from the test programme and heat transfer modelling and shows how the results are being used to achieve a stove design with an acceptable level of performance. It then concludes with a discussion of how this design might be produced in developing countries.

Keywords

Cook-stove, stove design, stove testing, heat balance for stoves, SCORE project

1 Introduction

This paper describes the development of the cooking stove component of the SCORE project described by Chen *et al* (1). The requirements of the stove are to provide heat to the thermo-acoustic Engine (TAE) to produce electricity and to give an acceptable level of cooking performance for families in developing countries. This is to be achieved with a reduction in fuel use as compared with traditional cooking stoves and minimising smoke emission which is a major cause of illness and death from respiratory problems with many existing stoves. It is also desirable for the stove to be operated and controlled in a similar way to existing stoves so that it is readily accepted by the target users.

The paper starts with a description of the experimental procedures and instrumentation that have been used to investigate and measure stove performance and then shows how the results have been evaluated to direct the development of the stove. This leads onto conclusions for the concept for the design of the stove and how this might be produced in developing countries.

[1] School of Engineering and Mathematical Sciences, City University, London

2 Development of stove design

2.1 Selection of design concept

The main specifications initially set for the SCORE stove were as follows:

i. Heat to the thermo-acoustic engine (TAE) 2kW to produce 100W output for up to 4 hours per day
ii. Boil 3 litre water in 15 minutes
iii. Wood consumption less than 1.4 kg/hr
iv. Low emissions
v. Reach 50% power in 20 minutes

The wood consumption is based on reducing the typical consumption for cooking stoves by 20%. A review of published information for wood stoves showed an average value of 1.2 kg per person per day (equivalent to about 200W per capita) which, assuming an average family size of 4.5 persons and cooking time of 3 hours per day, is equivalent to 1.8 kg/hr, Chen *et al* (1).

The average calorific value of wood at a typical moisture content of 15% is 16 MJ/kg, so a burn rate of 1.4 kg/hr produces 6.2 kW. Boiling 3l of water in 15 minutes requires 1.1 kW and with 2 kW to the TAE the required output is 3.1 kW and required stove efficiency 50%. The efficiency estimated by Baldwin (2) for a well- designed stove with a wood burn rate of 1.5 kg/hr is 30%, so the specifications for the SCORE stove are a considerable challenge, although Grover (3) estimates that an efficiency of 65% is possible.

In addition it was considered that the operation of the stove should be similar to existing practice in order for it to be readily acceptable to domestic users. The majority of improved cook stoves are based on the 'rocket stove' concept, Bryden *et al* (4), Winiarski (5), which uses an 'L' shape combustion chamber with a horizontal leg for input of wood and air and a vertical 'chimney' leg that creates buoyancy to improve inlet air flow and combustion efficiency. In this type of stove the heat is controlled by the feed rate of the wood with no other controls which is the procedure for traditional cooking stoves and is acceptable to users. This design concept was therefore selected for the stove developed for incorporation of the thermo-acoustic engine.

2.2 Initial stove design

The literature on stove design contains a number of papers describing the testing of improved wood-fired stoves and a report by the Approvecho Research Centre (6) gives an excellent review of the performance of a range of designs together with an evaluation of the design factors influencing their performance. However, papers on the detailed design of stoves and parameters affecting performance are few, Agenbroad *et al* (7). Among these, Sharma (8) reviews the pre-1993 work on the effect of design parameters, whilst Urban *et al* (9) describe a numerical analysis to improve a Plancha type stove. Other literature has been largely concerned with the wood-combustion process, for example Kausely and Pandit (10) and Agenbroard *et al*, (11). References (4) and (6) have been particularly useful in developing the stove design.

The main factor controlling the design layout of the stove was the incorporation of the TAE and the mode of heat transfer to this. It was clear from the comparison of the heat requirements for the TAE and cooking that the TAE would need to precede the cooking section. The initial concept was for the TAE to be located above the combustion chamber (CC) with heat radiated from the flame and combustion chamber walls to the TAE via a metal disc placed on top of the CC. The combustion gases would then be exhausted from the CC to pass through the cooking section.

The initial design layout is shown in Figure 1. The three main components, CC, cooking section and stove body are described in the following sections. In the design of the test stove for development, the TAE was simulated by a drum of water to provide a heat sink above the CC.

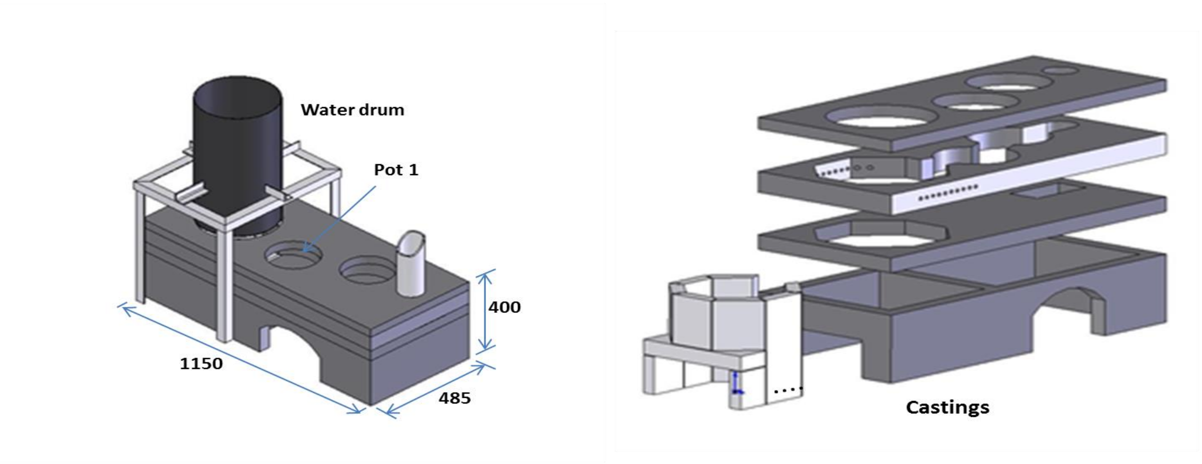


Figure 1. Stove design

2.2.1 Combustion chamber: the initial design was set by the TAE which requires a 300 mm diameter radiating disc at the top of the CC. Guidelines on rocket stove construction suggest making CCs from tiles cemented together to reduce risk of cracking when hot so the initial CC was made with eight tiles in the shape of an octagon to match the disc. It was decided to initially try this even though the cross-sectional area was much higher than recommended. Winiarski (5) recommends an area of 120 x 120 mm for a family stove, equivalent to diameter of 135mm, whilst Winkelmann (12) suggests a grate area of 3750 mm^2/kW, giving a diameter of 170mm for 6kW. The height of the CC needs to be sufficient to allow good mixing of the air and wood gases for efficient combustion and to limit cooling of the flame by the TAE above the CC whilst avoiding the loss of too much heat from the combustion gases to the CC wall. Winiarski (4) recommends around 3 times the diameter which for the recommended diameter of 135mm gives a height of 400mm. Since the temperature of the TAE would be considerably higher than a cooking pot a CC height of 330mm was chosen to maximise heat transfer. For rapid heating and hot combustion the thermal mass of the CC needs to be as low as possible. Initially tiles were made of a 50/50 mix of fireclay and vermiculite but it was found that the inner surface was damaged by the flame so a change was made to tiles with a 20mm thick layer of pure fireclay mounted on a 20mm backing of the mixture used for the stove body, 20% cement/80% vermiculite, which proved satisfactory.

To control the air flow into the CC a door is fitted at the entry to the horizontal leg with an adjustable window for the air. The door is opened to feed wood on top of the grate, 40mm above the floor of the

CC. The entry part of the grate is covered by a stainless steel sheet so all the air has to pass under and then up through the grate and burning wood. The cover is heated by conduction from the fire and preheats the air to around 500K to increase the temperature of the combustion flame. This also controls the burning of the wood to the section above the open grate at the base of the CC.

An alternative option for the preheating of the inlet air was initially tested in which the air inlet was through holes in the top of the outer casing around the CC (see Figure 1), then down the outer surface of the CC to be preheated and passing through holes at the base of the CC to enter the CC from under the grate. However, tests showed the preheating of the air was largely negated by cooling of the CC wall and so this option was abandoned. In any case it would only work with an air gap between the CC and outer casing and this was subsequently filled with insulation to reduce heat loss from the CC.

Only a primary air supply was initially included as the rocket-stove concept is claimed to provide a good draw and effective mixing of the air to achieve efficient combustion.

The combustion gases exhaust from the CC through a rectangular opening 100 x 70 mm at the top of the CC below the disc to then pass through the cooking section.

2.2.2 Cooking section**:** surveys of households in Nepal and Uganda, Sanchez *et al* (13) showed a preference for a stove that could heat at least two cooking pots, with at least one for primary cooking and one for simmering. Since cooking is done with gases that have already supplied considerable heat to the TAE it was considered that only two pots would be feasible. For the same reason the most efficient mode of heating would be needed to achieve the very tough specification of boiling 3 litres in 15 minutes. It was therefore decided to use recessed pots which would allow the hot gases to flow over the maximum surface area of the pots. However, this introduces some disadvantages. Firstly, the pots needed to be a good fit in the top of the recessed holes to limit leakage of combustion gases. The pot handles caused additional problems with this. Secondly, only cylindrical pots could be used and the sizes of the pots have to be matched to the stove. Although some form of shroud-type seal might allow smaller pots to be used in a recess the larger gap between the pot and hole would significantly reduce the efficiency of heat transfer.

The pots used in testing have been stainless steel, 20 cm diameter x 10 cm deep with the bottom surface and 6 cm of the periphery in contact with the hot gases. In choosing the gaps around the pot a balance is needed between maximising gas velocity to achieve good convective heat transfer without causing a pressure loss that might affect the flow of air needed for efficient combustion. Initially gaps of 10 mm under the pot and 20 mm around the periphery were chosen.

2.2.3 Stove body**:** the following criteria were considered in the design of the stove body:

i. Low thermal mass to minimise heat absorbed by the body
ii. Robust to resist any vibration transmitted from the TAE
iii. Readily produced in large numbers to a good degree of accuracy for fitting of the TAE and cooking pots

It was decided to cast the body in sections in plywood moulds from a lightweight mixture of vermiculite and cement (80/20%) and this gave a strong and durable mixture of specific gravity 0.7. The method was successfully reproduced in making a batch of 17 demonstration stoves in Kenya. However, for larger batches more durable moulds would be needed.

3 Testing

3.1 *Test set-up and instrumentation*

It was necessary to carry out laboratory testing in an area with a fume extraction system to exhaust the flue gases from the stove chimney and remove any leaking combustion gases. Since work on the stove was carried out in a different area the stove was assembled onto a trolley to allow it to be easily moved. The test rig set-up is shown in Figure 2. The relative height of the trolley and inlet to the extractor duct allowed a chimney height of 2.55 m. The height of the chimney is important in creating the buoyancy to draw air through air and combustion gases through the stove. Commercial wood stoves seem to recommend a minimum height of 3 to 4 m so the test set-up might be considered low. However, no problems were found with air flow during the testing.

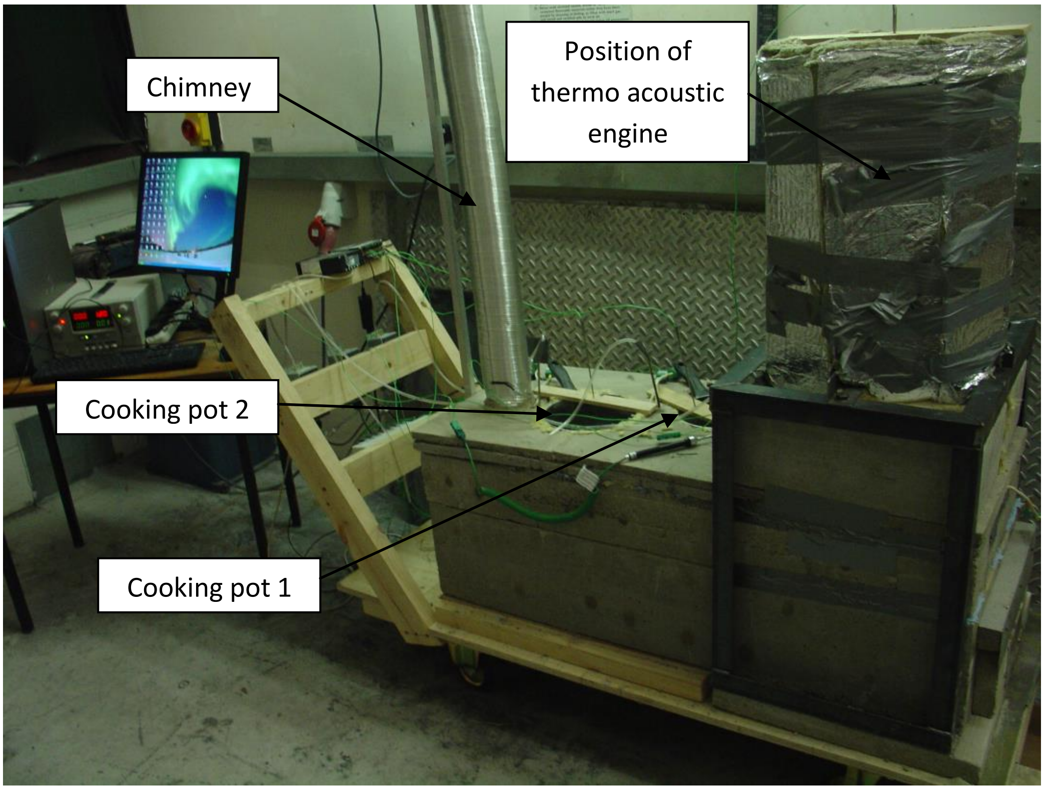


Figure 2. Stove experimental test rig

The instrumentation used for the tests is illustrated in Figure 3 and included 20 thermocouples as listed in Table 1.

Table 1. Location of thermocouples

Combustion chamber		1: Mid-front outer	2: Mid-font inner	3: Top-side outer	4: Top-side inner
		5: Mid-back outer	6: Mid-back inner	7: Base-side outer	8: Base-side inner
Flame		9: Lower – 110mm above grate	10: Upper – 290mm above grate		
Disc		11: Front	12: Side	13: Centre	14: Back
Cooking section	**Gas**	15: Entry Pot 1	17: Between pots	19: Exit Pot 2	
	Wall	16: Entry Pot 1	18: Between pots	20: Exit Pot 2	

All these thermocouples were logged at 30 second intervals. In addition, three manually read thermocouples were used to record the water temperature in the drum and two cooking pots.

For pressure, three differential pressure transducers were used to measure the pressure drop of the gas through the cooking section, sensor one at entry to Pot 1; sensor two between pots; sensor three at exit from Pot 2. These had a full-range setting of 25 Pa to measure the very low pressure expected of around 15 Pa.

A flue gas analyser placed before exit to the chimney to measure the composition of the flue gas emissions and evaluate the efficiency of combustion. Finally, a hot-wire anemometer was used to measure the velocity of the inlet air to the combustion chamber. This was traversed across the inlet window to obtain the average velocity and the air flow rate.

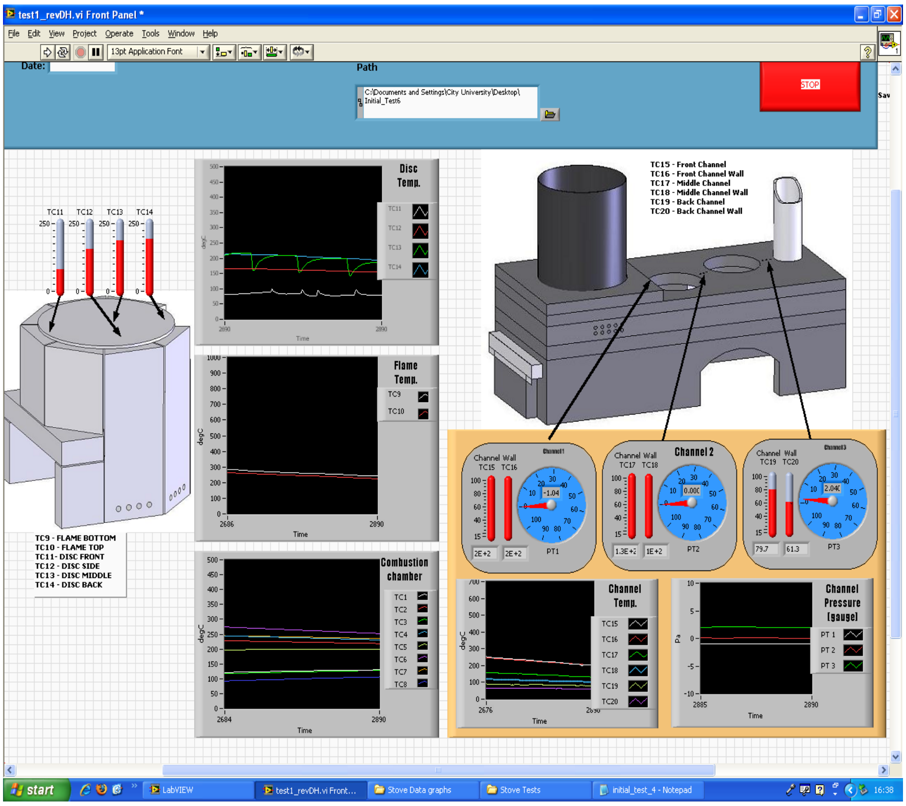


Figure 3. Instrumentation

3.2 Testing procedure

Tests were carried out over a one hour cycle using normally 1.5 kg of wood fed in at a regular interval. The wood used was ash tree type of around 250mm length and 60mm section to allow the stove door to be kept closed to control the air flow into the stove through the adjustable window. The moisture content of the wood was measured and kept as uniform as possible. Water levels in the drum and pots were recorded at the beginning and end of the tests to measure any evaporation. Over 50 tests have been carried out to date with many repeat tests to check findings. The results presented in the next sections have been checked by at least two tests

4 Test results for first prototype

Initial tests suggested that the grate area was too large as suspected and it was found difficult to achieve strong combustion at the required wood feed rate of 1.5kg/hr. The maximum flame temperature achieved was 825K and average disc temperature 475K. The latter is far below the estimated disc temperature of 1025K needed to radiate 2 kW to the TAE, Lawn (14). Even at a wood feed rate of 2.5kg the maximum temperatures reached were only 900K for the flame and 700K for the disc as shown in Figure 4.

Tests with a smaller CC of equivalent diameter 140mm (Figure 4) showed that a flame temperature of 1000K was achieved at a wood feed rate of 1.5kg/hr but the average disc temperature decreased to 600K due to the reduced view factor for radiation. It was therefore decided to try a conical CC to reduce the grate area whilst maintaining full exposure to the 300 mm disc at the top of the CC.

The other significant factor noted from these initial tests was the large temperature variation across the disc with the front of the disc being about 120K cooler than the rear where the combustion gases are exhausted to the cooking section. This suggests there is also considerable heat transfer to the TAE via convection from the gases. The heat transfer achieved was 0.64 kW, 32% of the target.

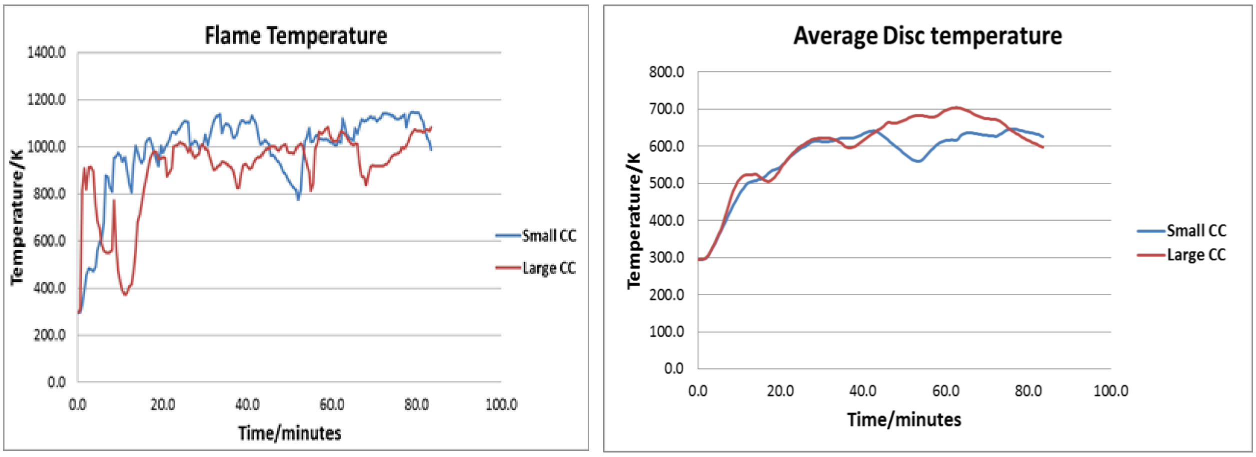
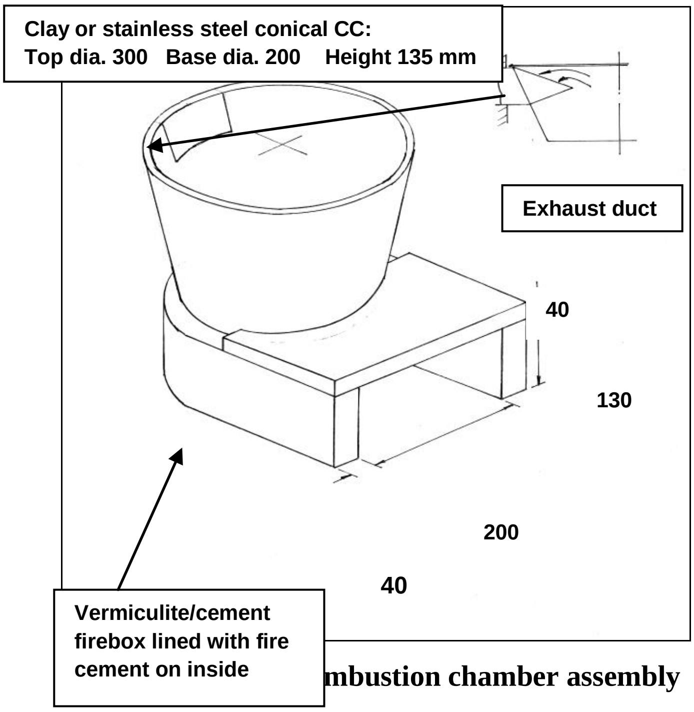


Figure 4. Comparison of temperatures achieved with large and small CCs
(Note wood burn rate for large CC of 2.5 kg/hr and small CC 1.5 kg/hr)

5 Stove development

5.1 Combustion chamber development

Figure 5 shows the conical CC assembly that was tested next. Note also the exhaust duct fitted with the aim of forcing the gases to flow more uniformly over the disc to reduce the temperature variation across the disc. Two CC were tested, a clay pot of 10 mm wall thickness and a stainless steel cone rolled from 0.6 mm sheet. The space between the CC and outer casing was filled with insulating wool to minimise thermal mass.



mbustion chamber assembly

Figure 6 compares the average flame and disc temperatures for three CC, the initial large fireclay CC and conical CCs made from clay and stainless steel. The wood burn rates were 2.5 kg/hr for the fireclay CC and 1.5 kg/hr for the two conical CC. It is seen that there is little difference for the flame temperatures but for the disc temperatures the stainless steel CC gives a significantly higher rate of heating and reaches a higher temperature. Unfortunately the test on the clay CC was cut short because it cracked. However, the conical CCs show a marked improvement over the fireclay CC, achieving a higher disc temperature at 60% of the wood burn rate. Part of this was due to a more even temperature variation across the disc achieved by the exhaust duct, with the difference between front and rear reduced to about 70K.

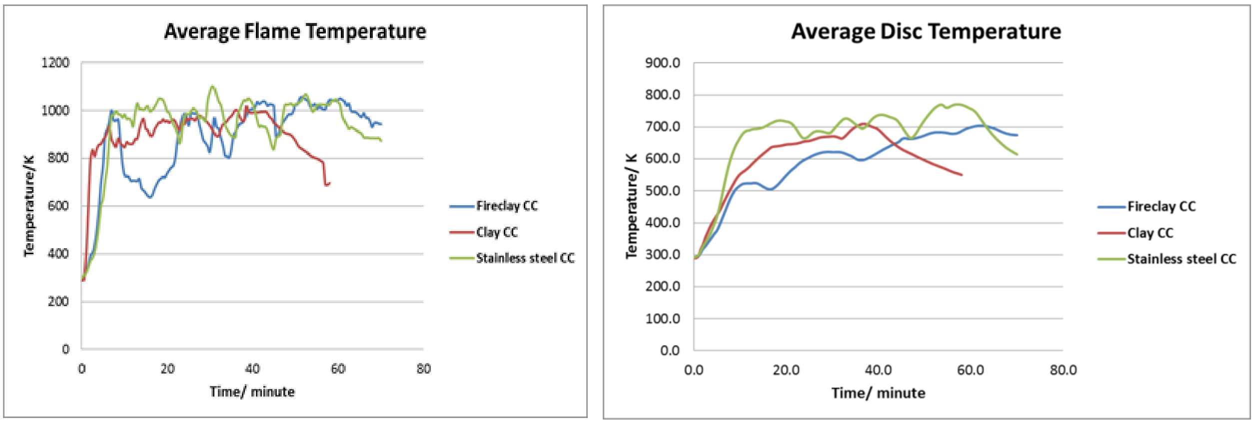


Figure 6. Comparison of temperatures for various combustion chamber materials

It may be noted from Figure 5 that the height of the CC has been reduced to 265 mm compared to 330 mm for the initial fireclay CC. The effect of this was investigated by adding in a cylindrical section at the base of the cone to increase the height to 330 mm. The effect of CC height on flame and disc temperatures is shown in Figure 7. This shows little difference in flame temperature once steady combustion has been achieved but a slightly higher disc temperature for the shorter CC. This indicates the reduction in height has not had a significant impact on combustion or cooling of the flame and has slightly improved heat transfer to the disc.

Subsequent tests were carried out with the stainless steel CC assembly as shown in Figure 5. Although stove performance had been significantly improved by changes to the CC and the heat flow to the water drum increased to 0.85 kW, the disc temperature was still considerably below that estimated to be needed to transfer 2 kW to the TAE. It was thought that this might be due to the cooling effect of the water drum which was reaching a maximum temperature of less than 320K in a one hour test. A baffle was therefore inserted between the disc and drum to check this. As seen in Figure 8 this significantly increased the disc temperature but had only a small effect on the average flame temperature. Also the heat flow to the tank was reduced by around 19% due to the reduced temperature difference between the disc and the flame and CC walls.

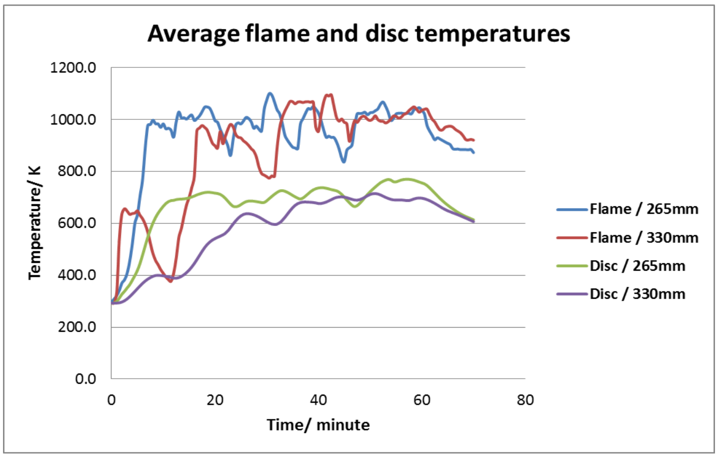


Figure 7. Effect of CC height on flame and disc temperatures

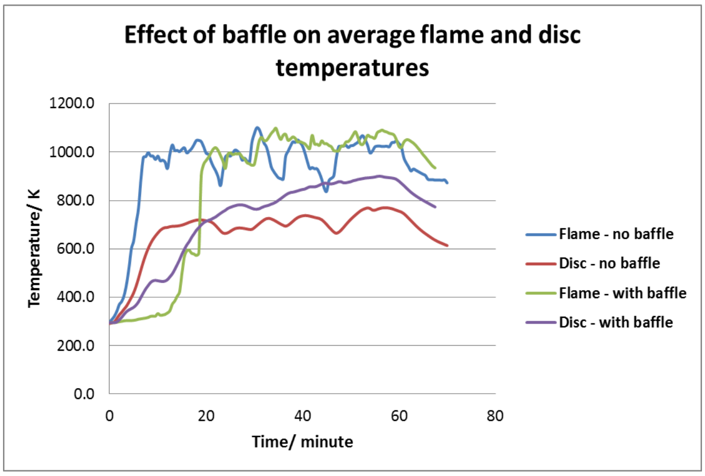


Figure 8. Effect of placing a baffle between the disc and water drum

5.2 Evaluation of stove performance

The efficiency of the stove over a one hour test based on the useful heat produced in the drum and cooking pots as a percentage of the heat input from the wood was measured as between 23% and 27%, only about one half of that required. A calorific value of [18.8 – 0.2.(% moisture content)] MJ/kg was assumed for the wood. A heat balance was therefore carried out to determine the losses at each stage of the stove based on the estimated heat content of the combustion gases. Figure 9 shows the heat content of the combustion gases calculated for various levels of excess air from the combustion equation for wood (stoichiometric):

$$1 \text{ kg wood} + 6.13 \text{ kg air} \longrightarrow 1.83 \text{ kg } CO_2 + 0.59 \text{ kg } H_2O + 4.71 \text{ kg } N_2$$

Figure 9 also shows that the gas temperature expected from burning wood with typical conditions of 15% moisture content, 100% excess air and 20% heat loss is around 1050K, the same order of magnitude as measured in the tests.

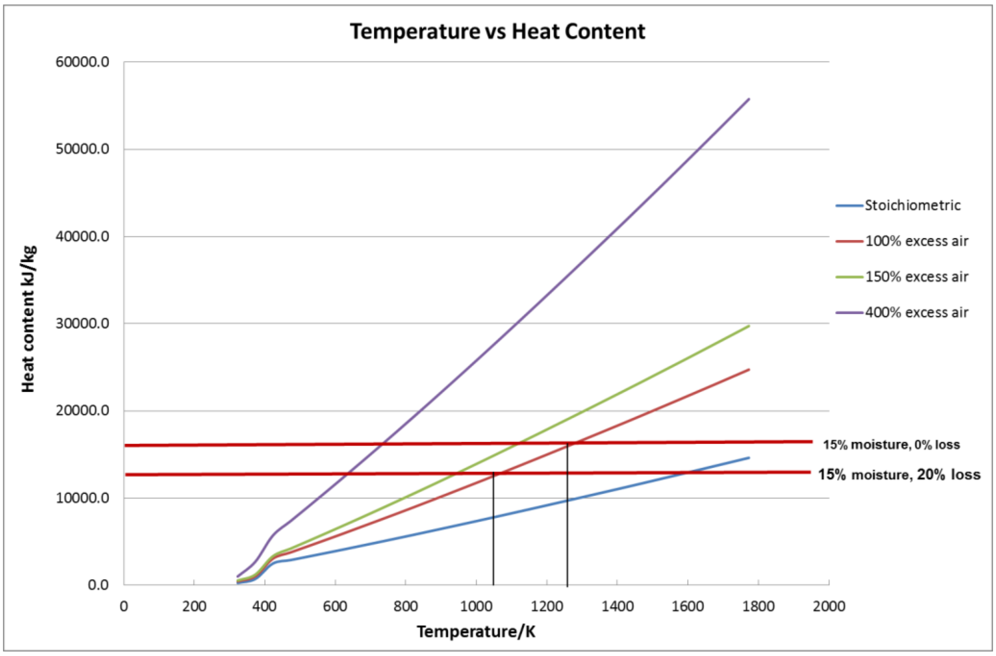


Figure 9. Heat content of gases from combustion of 1kg of wood

An algorithm derived from this analysis was used to estimate the heat content of the combustion gas and heat losses at different stages in the stove at half-minute intervals over a test run. The results are shown in Figure 10 and are similar to values estimated by Kausely and Pandit (10).

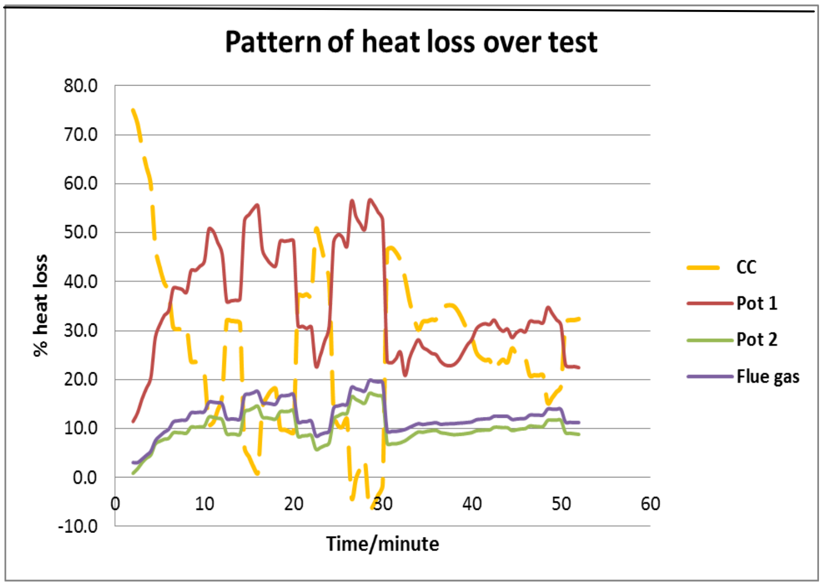


Figure 10. Pattern of heat loss from stove over test cycle

Additionally it was noted, that after an initial period of heating up the CC, the combustion process is quite efficient but variable. It is considered that this due to the batch feeding of the wood. When wood is added it tends to smother the flame reducing efficiency of combustion but then burns strongly and efficiently. It is possible that using longer lengths of wood and pushing them in would achieve a more uniform combustion process. There are also considerable heat losses in heating Pot 1 which seem to be related to the strength of combustion. It appears that when combustion is strong the heat transfer to Pot 1 is not efficient enough to transfer all the heat and losses increase. Heat losses at Pot 2 and to the flue are relatively low and follow the same pattern as Pot 1.

As an improvement, two vertical stainless steel ducts of cross-section 50 x 12 mm were fitted above the grate to feed inlet air to the upper part of the CC. Tests on stoves prior to this modification are labelled Test Series A and after, Test Series B. The other change for Test Series B was to reduce the gap around the pots from 20 to 10mm to try to improve the heat transfer to the pots.

The results of an analysis of heat losses at various positions along the stove is given in Table 2 for Test Series A and Test Series B. For Test Series A, the small difference between the heat loss in combustion, indicated by the upper flame temperature, and the total heat loss in the CC suggests that combustion is also occurring towards the top of the CC. This is also suggested by the fact that sometimes the temperature of the exhaust gas was higher than the upper flame temperature. It seems possible that the air and wood gas were not mixing well enough to achieve efficient combustion in the CC and combustion might be improved by directing heated air to the upper CC to combine with the unburnt gases. In response to this, the modifications previously described, Test Series B, were made and the results shown in Table 2 suggest this had a significant effect, improving overall combustion efficiency to 80%. Results in Table 2 also show this also produced a significant improvement and with the time to boil 2 l of water in Pot 1 reduced from 27 to 18 minutes.

Table 2. Examples of heat balance for two series of tests

Component of heat loss	% of Input Heat Loss		Explanation
	Series A	Series B	
Combustion	25.8	30.2	Heat from wood – gas heat at top flame temp
1 CC	26.0	21.5	Heat from wood – gas heat at CC exit – heat to drum
2 Pot 1	29.2	23.6	Gas heat before pot – heat after pot – heat to Pot 1
3 Pot 2	10.5	6.0	Gas heat before pot – heat after pot – heat to Pot 2
4 Flue gas	12.9	20.2	Gas heat to flue
Total loss	78.6	71.5	Losses 1 to 4
Useful heat	20.9	29.5	Heat to drum + heat to pots
Total check	99.5	101.0	Total loss + useful heat

5.3 Analysis of losses

Table 2 shows that 30.5% of the total heat loss occurs in the combustion section, 41.4% in the cooking section and 28.1% in the flue gas, indicating that a significant increase in stove efficiency is potentially achievable by reducing heat loss and improving heat transfer in the cooking section.

5.3.1 Heat losses in cooking section: this comprises heat absorbed in the stove body, heat lost from walls of stove and heat lost from the cooking pots. Table 3 shows a summary of the analysis of heat losses based on measurements of the temperature profile of the stove body under steady state conditions.

Table 3. Summary of heat losses in cooking section of stove

Component of heat loss	Value	Comment
Total heat loss over 1 hr test	6.25 MJ	From gas temperatures
Heat absorbed in stove body	3.29 MJ	53% of total occuring mainly during initial heating up of stove
Rate of total heat loss at steady state	1.67 kW	From gas temperatures
Heat transferred to walls of cooking section by convection and radiation	0.92 kW	Estimate assumes h = 20W/m^2.K as for cooking pots and emissivity of gas = 0.1
Heat loss from cooking pots	0.42 kW	Evaporation is included in heat to cooking pots and this estimates convection from the water surface based on cooling rate results
Conduction through stove body	0.74 kW	

Heat loss from cooking pots: this was measured over a 20 minute cooling period of the stove gave the following data on heat loss from the cooking pots:

Heat loss = heat input from gases (291W) + drop in water temperature (106W) – evaporation (22W)
= 375W; (Note there was some heating of gases from the embers of the fire)

Based on the average water temperatures during the cooling period the heat transfer coefficient for convection from the surface of the water (all other surfaces are recessed in the stove) is $98W/m^2.K$. This value has been used to estimate the losses by convection from the water surfaces in the cooking pots during the steady-state part of the test. They are clearly a significant portion of the overall heat loss from the cooking section.

Heat balance: considering the fluctuating temperatures and assumptions made in the analysis there is reasonable agreement between the measured heat lost from the gases (1.67 kW) and the estimated loss of 1.34 kW comprising that transferred to the stove body (0.92 kW) and that lost from the cooking pots (0.42W). Also the heat transfer into the stove body compares well with the conduction through the body (0.74kW). However, the heat loss from the outer wall of the stove does not seem to fit in with this heat balance. The steady-state temperature profile measured on the outer walls indicates a coefficient of 40 $W/m^2.K$ would be needed to account for the convection component of a 0.75kW loss by convection and radiation to the surrounding air. This is very high compared to the expected range of 5 – 25 $W/m^2.K$ (16). 41% of the heat is lost from the top surface of the stove around the cooking pots where the surface temperature reaches 80^oC.

***5.3.3 Heat transfer in the cooking section*:** if heat losses in the cooking section are reduced by improved insulation there will be an increase in gas temperature and unless heat transfer to the cooking pots is also improved part of the benefit will be lost to higher flue gas temperatures. A heat transfer model indicates that the limiting factor is the surface area of the cooking pots in contact with the gases. A ribbed hotplate with increased contact area has therefore been investigated. This comprises an aluminium heat sink with 19 ribs, 25mm deep. The results shown in Figure 11 compare the two methods of heating.

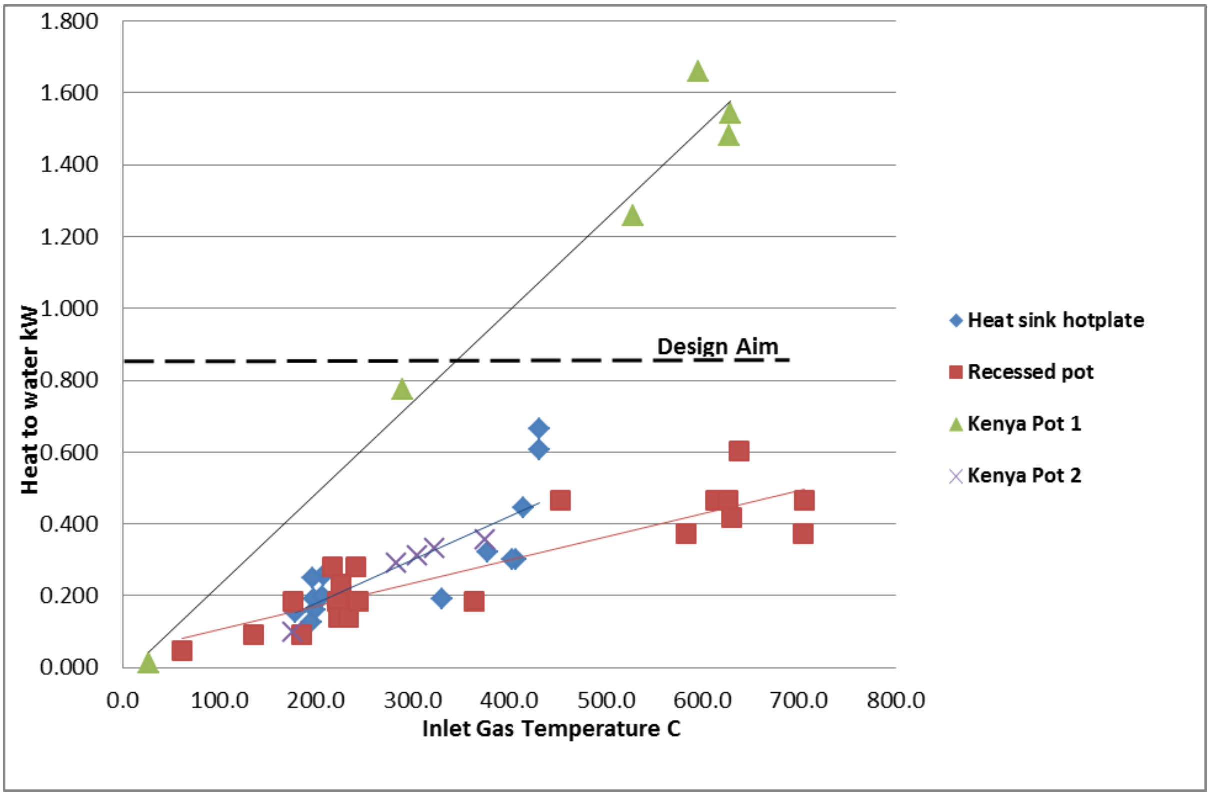


Figure 11. Heat transfer rates in cooking

The results show a significant increase in heat transfer rate for the hotplate compared to the recessed pot even though the transfer is now indirect via conduction through the hotplate and the heat transfer model still shows that the limiting factor is the transfer from the gas into the hotplate. The hotplate has other advantages in completely enclosing the gases and allowing a range of cooking pot sizes to be used. However, it adds significantly to the cost of the stove.

Figure 11 also shows results from a test on one of the stoves undergoing trials in Kenya. Pot 1 is a recessed pot directly above the combustion chamber while Pot 2 is recessed in a similar layout to the City stove. Comparing the results for the two pots shows the considerable heat input from radiation from the flame and combustion chamber. The higher heat input for Pot 2 compared to the recessed pot in theCity stove is due to a larger pot size, 300 mm diameter compared with 200 mm diameter.

5.4 Review of progress

Table 4 compares the performance of the stove achieved to date with the target specifications. Further progress needed is to increase CC temperatures to increase heat flow to the TAE and to improve heat transfer to the cooking pots.

Table 4. Comparison of performance achieved against target

Performance criterion	Target	Achieved to date
1 Heat to TAE	2 kW	1.08 kW
2 Boil 3l of water	15 minutes	27 minutes
3 Reach 50% power – 90% temperature	945K in 20 minutes	895K in 25 minutes
4 Wood consumption reduced 20%	< 1.4kg/hr	1.5 kg/hr
4 Low emissions	Minimise smoke	Achieved with chimney
5 Stove efficiency	50%	29.5%

CC temperature: Figure 9 indicates the principle means of increasing CC gas temperatures is to minimise the excess air level. However, care is needed in this as it can lead to incomplete combustion and high levels of Carbon Monoxide. Figure 12 shows a summary of results from the test programme showing that the CO level rises rapidly below around 80% excess air and this might be set as the lower limit.

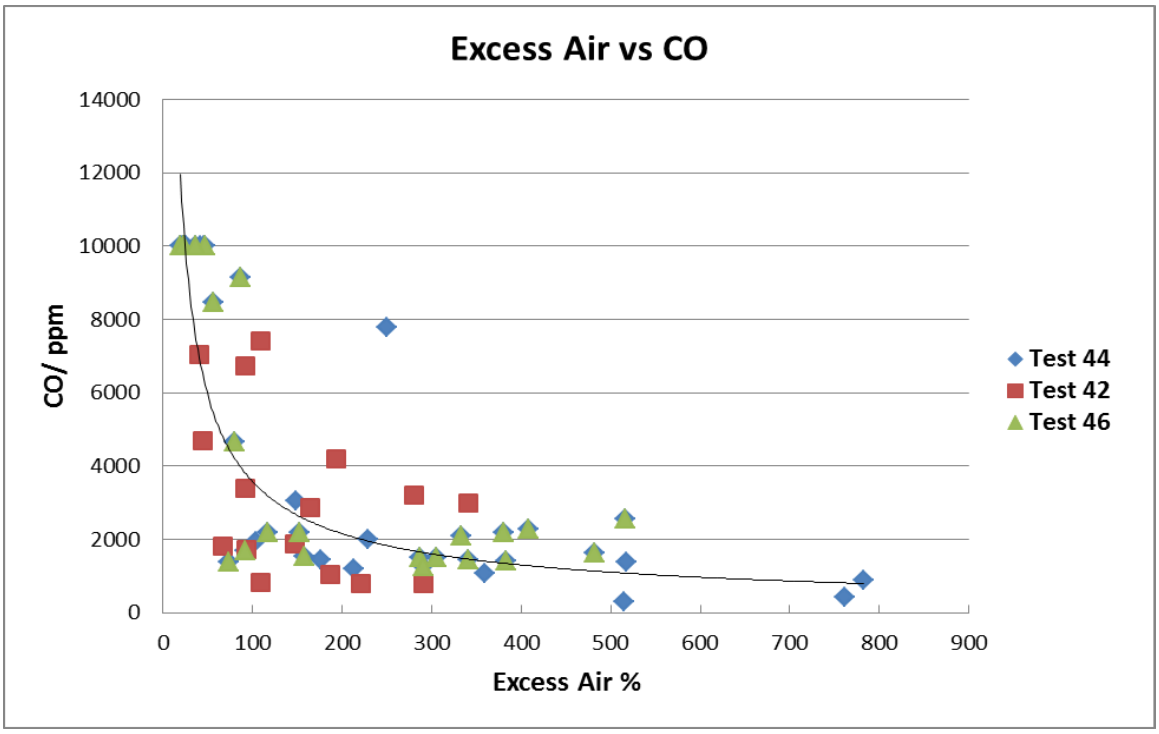


Figure 12. Relationship between excess air and CO emmissions

Another possibility to improve combustion is to incorporate a small fan to improve air flow ino the CC. The Approvecho Research Centre (6) report tests on stoves incorporating a fan greatly improved combustion and reduced emissions due to improved mixing of air and gases in the CC. However, this was on stoves without a chimney the same level of improvement may not be achieved on stoves with a chimney where air flow is improved by the bouyancy effect of the chimney. Some preliminary tests have been carried out but no conclusive results obtained so far.

Cooking: reducing the gap around the pots significantly improved the heat transfer but any further reduction is likely to lead to an excessive pressure drop that reduces the flow of air into the stove. Although the recessed pot gives the most direct method of heating it has the disadvantage of requiring a specific shape and size of pot to match the recess. Analysis shows the limiting factor on heat transfer to the pot is the surface area in contact with the gases for convection. A solution to overcome both these drawbacks is to use a hotplate that both encloses the gases and allows more flexible cooking and a wide range of cooking utensils. Figure 11 shows that heat transfer can be improved with a hotplate but a gas temperature of over 800°C is still needed to achieve the design aim of boiling 3l of water in 15 minutes. This cannot be achieved with cooking following the TAE and it appears the only solution is to divert some of the combustion gases directly to the cooking section.

6 CONCLUSIONS ON STOVE DESIGN

This paper has described the development of a stove in which the main mode of heat transfer to the TAE is by radiation. It is estimated that flame temperatures of around 1150K are needed to achieve the target heat flow of 2 kW, a considerable challenge for the combustion of wood at an acceptable burn rate. Average temperatures reached to date are around 1075K and it is considered that this is approaching the maximum that can be achieved in a low-cost domestic stove burning wood of different varieties, shape and size. Even so if the 1.1 kW heat transfer to the TAE produces an electrical output of 50 W this will be a major achievement with considerable commercial potential.

A second stove is also being developed in which the heat transfer to the TAE is mainly by convection so flame temperature is not as critical. However, for both stoves achieving cooking rate targets is a problem because at least 20% of the combustion heat has already been taken out by the TAE. Test results and analysis indicate that heat transfer to the cooking pots is limited by the surface contact area between the combustion gases and the pot and that an indirect heating method using a hotplate with a much larger contact area could improve the heat transfer. This would also have other major advantages in allowing a wider range of cooking pot shapes and sizes and other modes of cooking.

The design concept developed for a production stove is likely to comprise three main sections:

1. An inner heat resistant shell of low thermal mass comprising combustion chamber and ducts leading to heat sink hot-plates. At present a stainless steel combustion chamber is being used but this may not be durable for long-term use and some form of ceramic or fireclay tiles may be needed, keeping these as thin as possible.
2. A thick layer of lightweight insulation to limit heat loss. Although natural materials such as wood ash, rice husk ash or pummice rock might be used, supplies may not be adequate for large-scale production and it may be better to import rockwool. This can withstand temperatures to around 800K so that a layer of ceramic wool or fibre board may be needed around the hottest sectons of the stove
3. An outer robust and durable casing that gives the stove an attractive appearance. Since this will be well insulated from the inner shell thermal mass will not be an issue and low-cost concrete blocks may be used, cast to the required shape.

7 References

1 Chen BM, Riley PH, Abakr YA,Pullen K, Hahn DB, Johnson CM. *Design and Development of a low-cost, electrically generating cooking SCORE stove.* Proc. Inst. Mech. Eng, Part A, Journal of Power and Energy, JPE-12-0123R1 (to be revised)

2 Baldwin SF. *Biomass Stoves.* VITA, Virginia, USA, 1952

3 Grover PD. *Cost Estimate of Dream Stove for Asia*. www.repp.org/discussiongroups/resources/stoves/Grover/paper-grover.htm

4 Bryden M, Still D, Ogle D and Maccarty N. *Designing Improved Wood Burning Heating Stoves*. Aprovecho Research Centre, USA, October 2005

5 Winiarski L. *Design Principles for Wood Burning Cook Stoves.* Aprovecho Research Centre, USA, June 2005

6 Approvecho Research Centre *Test Results of Cook Stove Performance.* Prepared for Partnership for Clean Indoor Air, 2010

7 Agenbroad J, DeFoort M, Kirkpatrick A. and Kreutzer A. *A Simplified Model for Understanding Natural Convection in Biomass Cooking Stoves – Part 1: Set-up and Validation.* Energy for Sustainable Development 2011, 15 (2), 160-168

8 Sharma SK. *Improved Solid Biomass Cooking Stoves: A Development Manual.* Field Document No 44, 1993, FAO Regional Wood Energy Development Programme in Asia

9 Urban GL, Bryden KM and Ashlock DA. *Engineering Optimisation of an Improved Plancha Stove.* Energy for Sustainable Development 2002, VI(2), 9-19

10 Kausely SB, Pandit BP. *Modelling of Solid Fuel Stoves.* Fuel 89, 2010, 782-791

11 Agenbroad J, DeFoort M, Kirkpatrick A. and Kreutzer A. *A Simplified Model for Understanding Natural Convection in Biomass Cooking Stoves – Part2: With Cook Piece Operationand the Dimensionless Form.* Energy for Sustainable Development 2011, 15 (2), 169-175

12 Winklemann HG. *Wood Burning.* FAO, Rome, 1955

13 Sanchez T, Dennis R and Pullen K. *Cooking and Lighting Habits in Rural Nepal and Uganda*. Proc. Inst. Mech. Eng, Part A, Journal of Power and Energy, JPE-12-0132R1. (to be revised).

14 Lawn C J. SCORE Review 2010. Internal project report

15 The Engineering Toolbox. www.EngineeringToolbox.com

to Proc. Inst. Mech. Eng, Part A, Journal of Power and Energy, JPE-12-0123R1 (to be revised) and of Ref 13 to refer to Proc. Inst. Mech. Eng, Part A, Journal of Power and Energy, JPE-12-0132R1. (to be revised).

Acknowledgments

The SCORE project is funded by EPSRC, the UK Engineering and Physical Research Council (Grant number EP/E044468/1)