An Investigation of Skirts

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Introduction

It is generally known that skirts are an effective way to increase the heat transfer to a cooking pot. A skirt is a vertical sleeve, usually of metal, that forces the hot gases from the fire to flow closely around the sides of the pot.

It is generally believed that skirts increase the heat transfer by forcing the hot gases from the fire to flow close to the sides of the pot. This is correct, but there are other reasons why a skirt may be effective under a variety of conditions. These reasons include:

1. The classic reason, that skirts force the gases to flow next to the sides of the pot, increasing heat transfer. Under some conditions without a skirt the hot gases flow under the bottom of the pot, radially outward, and then may shoot away from the pot. Clearly, in this situation the hottest gases are not passing near the sides of the pot and skirts will help greatly. Under other conditions, the hot gases rise naturally close to the sides of the pot and skirts will offer lesser benefits under these conditions. At the present, we do not know why the gases sometimes rise along the sides of the pot while under other conditions they do not.

2. The skirt will pick up heat from the flowing gases and radiate some of this heat to the sides of the pot. As a rule of thumb, this accounts for about 1/3 of the heat transfer to the sides of the pot. Skirts can be insulated on the outside, which increases the temperature of the inside of the skirt and increases the heat transfer.

3. Prevention of radiative heat loss from the sides of the pot. The sides of the pot are at about the same temperature as the contents of the pot, and this is usually warmer than the environment. The sides of the pot will radiate a certain amount of heat to the environment and this is lost from the contents of the pot. While this may appear to be the same physical mechanism as reason 2 above, we distinguish it as a separate mechanism because if all you wanted to do was to prevent radiative heat loss from the pot, you could simply insulate the pot.

4. Cutting of excess air. This applies when the gas flow path through the stove and skirt is closed, that is, when all the air that enters the stove flows under the pot and up through the skirt. In this case the presence of the skirt slows the flow of gas through the stove (unless the skirt is very loose) reducing the excess air and allows the gas to get hotter. The extra temperature of the gas forces more heat to flow from the gas to the pot all over the pot, on the bottom as well as the sides.

Figure 1: The basic burner being used as a simulated open fire.

In each test the primary measured quantity was the total heat transfer rate to the pot. This was measured by using a known quantity of water and by measuring the initial and final temperatures of the water, and the time the heat was turned on. The pot had a lid to prevent evaporation, and convective and radiative losses from the pot were minimal. The test was stopped well before the boiling point was reached. During each test the power level at the fire is constant. Typically, 2 levels of power were used, corresponding to "low" and "medium" power.

Unique Skirt Design

The skirt used in these tests was a unique skirt that was developed for testing purposes but which had features that might be useful for field work. It is generally believed that the gap between the skirt and the sides of the pot should be uniform, and thus keeping this gap uniform is very important. (This will be investigated further in a later section.) The test skirt included about 30 small legs built into the inside of the skirt, and when the skirt was wrapped and clamped tightly to the pot with a band clamp (hose clamp) these 30 legs all touched the pot. See Fig. 2. Each of the legs had been previously adjusted and locked at the correct length +/- 0.25 mm, thus the gap was set at this distance. There were several sets of legs with lengths of 8, 10, 12, and 14 mm, and the legs could be switched out fairly quickly between tests.

Test Results-Open Fire (3-Stone Fire)

For the simulated open fire the burner shown in Fig. 1 was used directly under the pot. The top of the burner was 76 mm (3 inches) below the bottom of the pot. The burner was centered under the pot by eye.

Several tests were done with the 10 mm skirt in which the bottom level of the skirt was varied. It was found that the heat transfer was better with the bottom of the skirt 50 mm (2 inches) below the bottom of the pot than with the bottom of the skirt 25 mm below the bottom of the pot. The same conclusion is probably true for other gaps, though this was not tested. It is likely that, if the test had been done outdoors with a crossbreeze, the increased "hangdown distance" would improve the performance of the pot. Therefore, all open fire tests were done with the 50 mm hangdown distance.

The results for the open fire tests are shown in Fig. 3. The skirt clearly helps the heat transfer, but the optimum gap is not clear. The conventional wisdom that a 10 mm gap is the optimum appears to be generally correct.

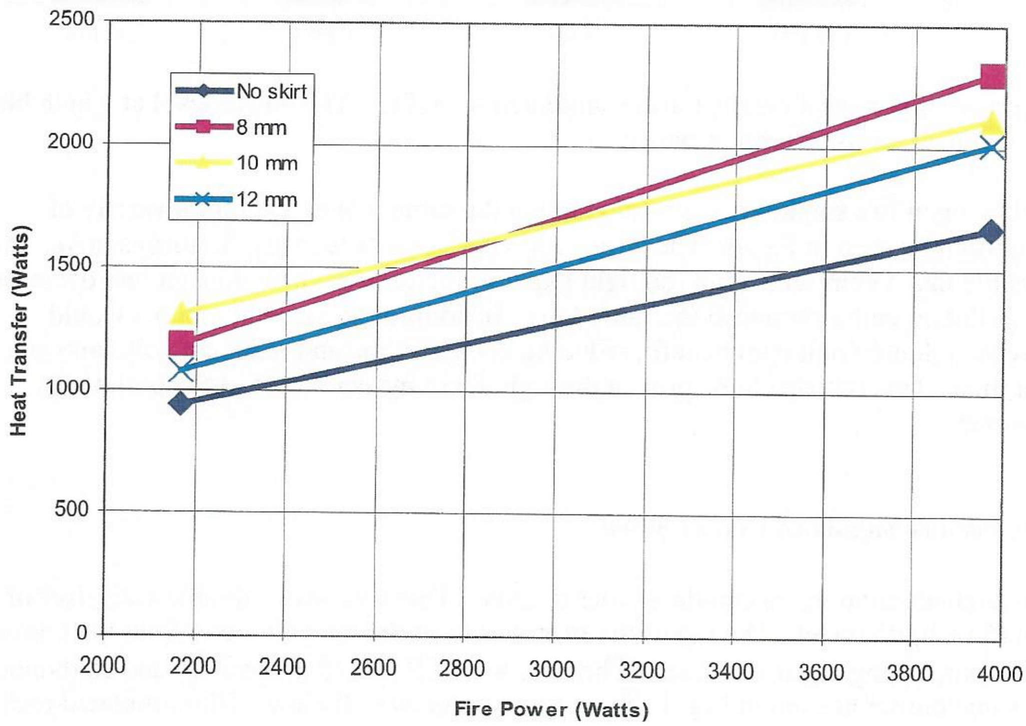

Figure 3: Heat transfer results for the simulated open fire.

The skirt will also have an effect on the pollutant formation. If one is cooking indoors without a chimney, it may not be good to reduce fuel usage at the expense of increased pollutant formation. Using natural gas as a fuel makes the pollutant formation different from using wood as a fuel, but an attempt was made to determine the pollution forming

Figure 5: Simulated rocket stove. The burner inside the duct (riser) is the same burner shown in Fig. 1.

The heat transfer to the pot was measured without the skirt for a variety of power levels. For two of these power levels the pot was insulated along the sides and the test was repeated. This allows an estimation of the portion of the heat passing into the pot through the bottom. About 85% of the heat transfer was through the bottom of the pot for the simulated rocket when there is no skirt.

After the bare pot was tested the heat transfer was tested again with a skirt, using 3 different gaps. In each of these 3 tests, 2 power levels were used, low and medium. In all tests the skirt hung down below the pot by the same amount.

For the simulated rocket stove the results are shown in Fig. 6. The presence of the skirt makes a significant difference to the heat transfer. All 3 gap distances gave about the same results, with the 10 mm gap being slightly better than the others.

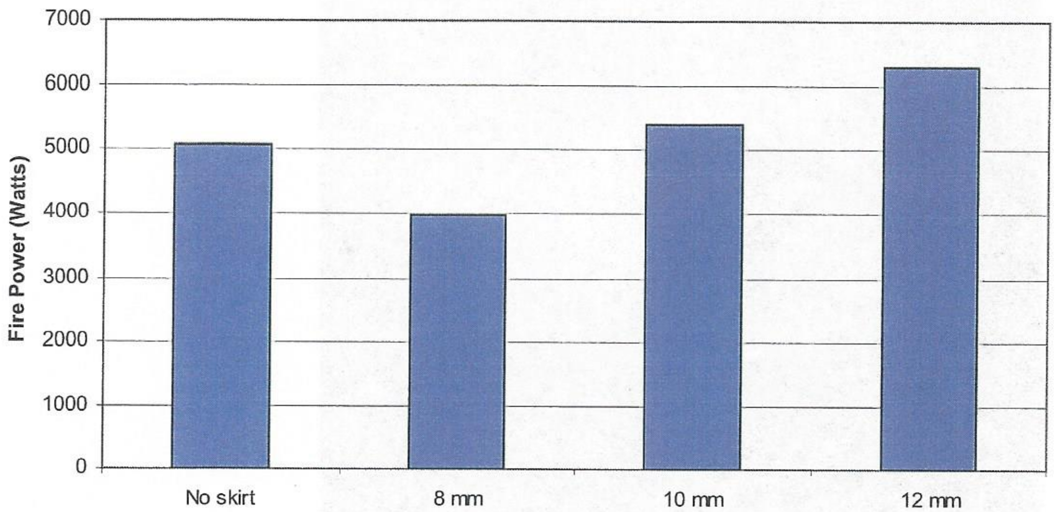

Figure 7: The minimum fire power level at which smoke is observed, simulated rocket stove.

With a skirt this mixing is delayed, however the gases are cooled in the skirt (especially the tighter skirt) and the pollutant formation is a function of the speed of the cooling. In this case, more of the heat in the gases goes into the pot than without a skirt, hence there is an increase in heat transfer. It is possible that a pot and a skirt that is not too tight the pot would give better heat transfer and lower pollution per unit of fuel burned.

In many cases it was noted that the soot collected heavily on the pot while the inside of the skirt was nearly perfectly clean. Small particles have a tendency to travel down the temperature gradient, and will thus collect on the coolest surface. Or, it could be that at the start of the test, water vapor condensed on the side of the pot, soot collected in the liquid, and never left once the pot got hot and the water evaporated.

Test Results-Chinese Rocket Stove

The 3rd cooking method tested was the Chinese rocket stove, shown in Fig. 8. Due to the limited size of the firebox a different gas burner was used, but it was based on the same ideas as previous burners. The stove was warmed for 5 minutes before the start of the actual tests, because in the first few minutes of operation a considerable amount of heat goes into the body of the stove. The body of the stove is ceramic, which is insulative but still has significant mass.

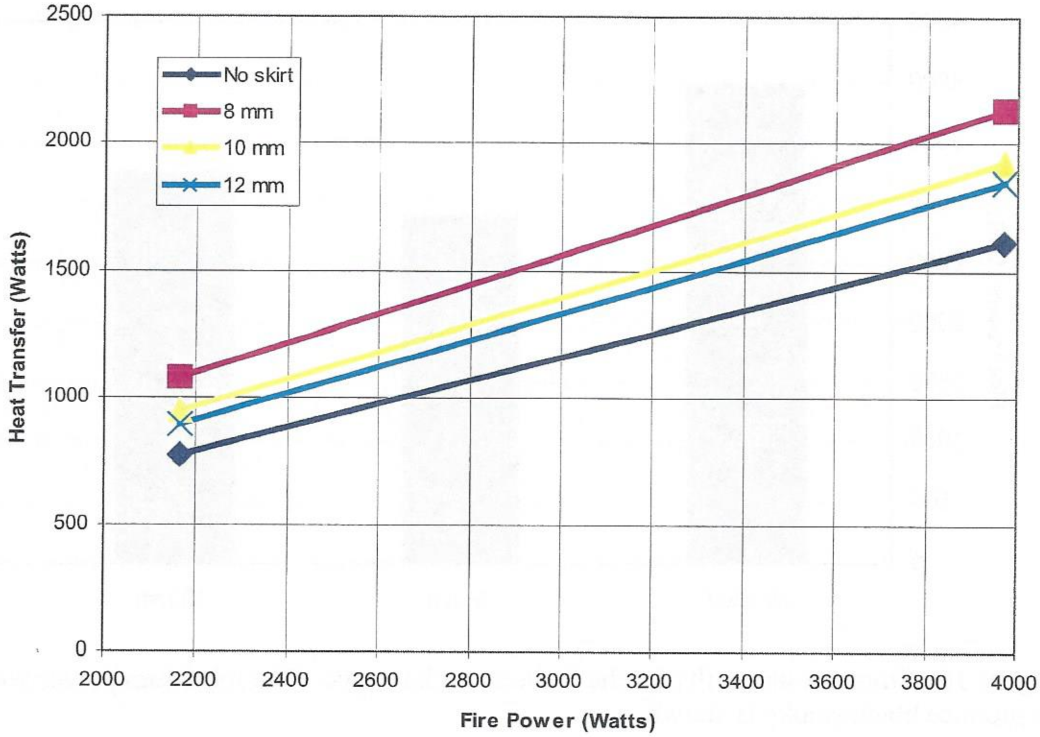

Figure 9: Heat transfer results for the Chinese rocket stove.

The results for the heat transfer tests are shown in Fig. 9. This situation was different from the other test situations in that there was a closed path for the gas to flow through the stove, under the pot, and through the skirt. Adding a tight skirt is likely to reduce the excess airflow through the stove leading to hotter combustion and higher heat transfer all over the pot, including the bottom of the pot. In this situation, using a tighter skirt reduces the excess air more than a looser skirt, and will always lead to increased heat transfer. The heat transfer is increased for all of the first 4 reasons given in the introduction to this report. If one is interested only in increasing heat transfer, tighter skirts are better for this stove.

The smoke test results for the Chinese rocket stove are given in Fig. 10. Again, reducing the skirt gap led to increased smoke production, but the bare pot also gave significant smoke. The mechanism of soot and smoke formation is probably similar to that of the simulated rocket stove described above.

In other tests the opposite is true, the temperature at the bottom edge of the skirt is fairly high, suggesting that hot air from the fire is moving radially outward under the skirt's bottom edge. This results in some energy loss, however this effect may be a good thing in the following sense. The gases flowing across the bottom of the pot are not uniform in temperature. There are cool gases right next to the bottom of the pot (call this layer 1) very hot gases some distance away from the bottom (call this layer 2) and then gases of diminishing temperature as you go farther from the bottom of the pot (call this layer 3). To some extent these gases will separate, with layers 1 and 2 passing up the skirt but with some of layer 3 passing up the skirt and some of it passing under the skirt. With some of the hot gas passing out and under the skirt some energy will be lost, but the average temperature of the gases going up the skirt will be increased, possibly leading to better heat transfer. Of the energy available in the gas at the bottom of the skirt, a significant fraction (usually the majority) will not be transferred to the pot. The heat transfer is limited by the temperature of the gas, not by the amount of energy in the gas.

In a limited number of tests the skirt temperature was measured at 2 locations opposite each other on the skirt. Again, the temperatures were highly asymmetric, but the temperatures were generally high enough to support the idea that there is significant radiation from the skirt to the pot.

Computational Fluid Dynamics in Cook Stove Research

Computational fluid dynamics (CFD) is an increasingly used tool in the area of engineering research. It offers many benefits over traditional experimentation, but has limitations that need to be kept in mind for its use to be of the greatest benefit. For our research with cook stoves, CFD has really proven to be instrumental in confirming our intuitions and experimental results. It has also shown us possible directions for the design of better cook stoves, skirts, and pots.

Perhaps the greatest (and most noticeable) advantage of using CFD is the reduction in time to gather data. To set up a cook stove, with proper arrangement of the burner and other objects, takes well over an hour. Running an experiment can take around 20-30 minutes, and putting away experimental equipment increases the time spent. CFD tests for the work being done on cook stoves took no longer than 25 minutes, and on more simplified cases less than 10 minutes. There is the initial investment of designing the mesh and setting model boundary conditions which can be somewhat time consuming, but this needn't be repeated for a series of similar tests. For example, simple changes in the mesh can be handled in just a minute or two, allowing another range of tests to be run off the same base mesh.

Taking measurements also tends to add to the time needed for real-world experiments, but there is also the aspect of ease of measurement. It is extremely difficult to place a thermocouple in a 10 mm gap between a pot and skirt, let alone obtain enough readings to approximate a temperature profile. In CFD, the program allows the user to choose which qualities should be incorporated into the model. Whichever qualities are selected

CFD Results

An overview of the results obtained through the many CFD trials will be helpful in demonstrating these advantages and limitations. For all CFD experiments described here the power level was 3250 W, somewhat below the medium power tests used in the physical model results. The exit temperature from the "stove" was 773 K, or 500°C, similar to that seen in the physical test at 3250 W. Details of the CFD models and of the experiments are contained in Ref. 1.

Heat Flux (in Watts)	Skirt distance from Pot, W			No Skirt
	5 mm	10 mm	15 mm	
Bottom Convective	365	366	367	367
Bottom Radiative	33	33	33	33
Net Bottom	398	399	400	400
Side Convective	82	321	351	321
Side Radiative	35	160	103	-46
Net Side	117	481	454	274
Total (side and bottom)	515	880	854	673

Table 1: Predicted heat transfer to various surfaces of the pot with and without skirt placed at various distances from cook pot. In this case, the skirt was 127 mm (5 inches) tall and its bottom edge is aligned slightly above the bottom of the pot. Positive sign indicates heat transfer into pot.

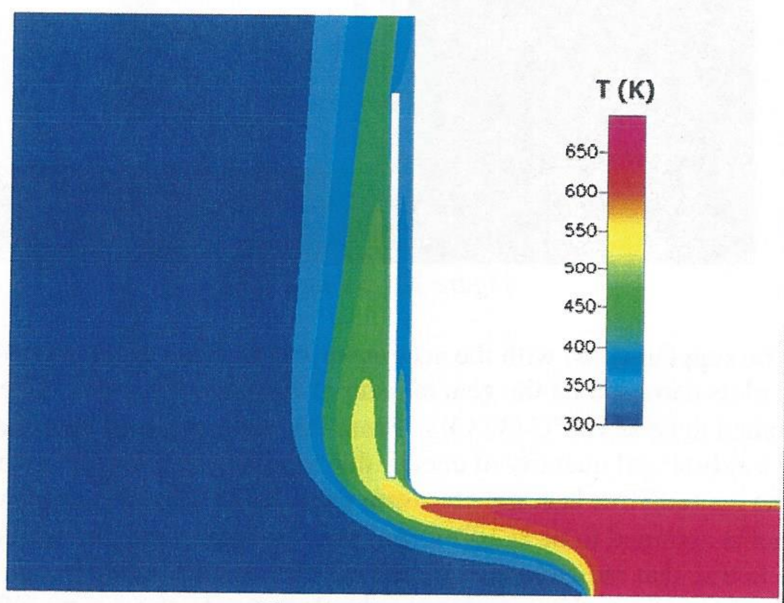

Figure 11: 5 mm skirt

heat transfer to the bottom of the pot. However, the 5 mm skirt actually forces most of the flow of hot gas away from the pot, leading to significantly reduced heat transfer even when compared to an unskirted pot. The 10 mm skirt captures the most radiative energy, but still loses some convective energy (evidenced by the 15 mm skirt's comparatively larger convective transfer). The 10 mm skirt is thus the best choice of the three designs, and understanding of the reasons for this (reduced obstruction of flow balanced with proximity to trap radiative transfer) enable one to apply these principles in future designs.

The total heat transfer to the unskirted pot was calculated to be 673 W, of which 59% went through the bottom. The total heat transfer in the physical test under nearly identical conditions was 883 W, of which 85% was through the bottom. The calculated radiant heat transfer to the bottom of the pot was small. All of these numbers appear in Table 1. Heat transfer from the hot gas was included in the model, but was probably underestimated. Had this factor been included more properly, the radiant heat transfer to the bottom of the pot, the proportion of the heat transfer through the bottom of the pot, and the total heat transfer to the pot would have all increased, bringing them more into accordance with the physical experiment. The heat transfer on the sides of the pot, which is our primary interest in this report, will be largely unaffected by this factor.

Heat Flux (in Watts)	Skirt distance from Pot, W			No Skirt
	5 mm	10 mm	15 mm	
Bottom Convective	337	360	366	367
Bottom Radiative	91	63	40	33
Net Bottom	428	423	406	400
Side Convective	191	373	366	321
Side Radiative	93	195	130	-46
Net Side	285	569	496	274
Total (side and bottom)	713	992	902	673

Table 2: Predicted heat transfer to various surfaces of the pot with and without skirt placed at various distances from cook pot. In this case, the skirt was 165 mm (6.5 inches) tall and its bottom edge is aligned with the mouth of the chimney, 32 mm (1.25 inches) below the bottom of the pot. Positive sign indicates heat transfer into pot.

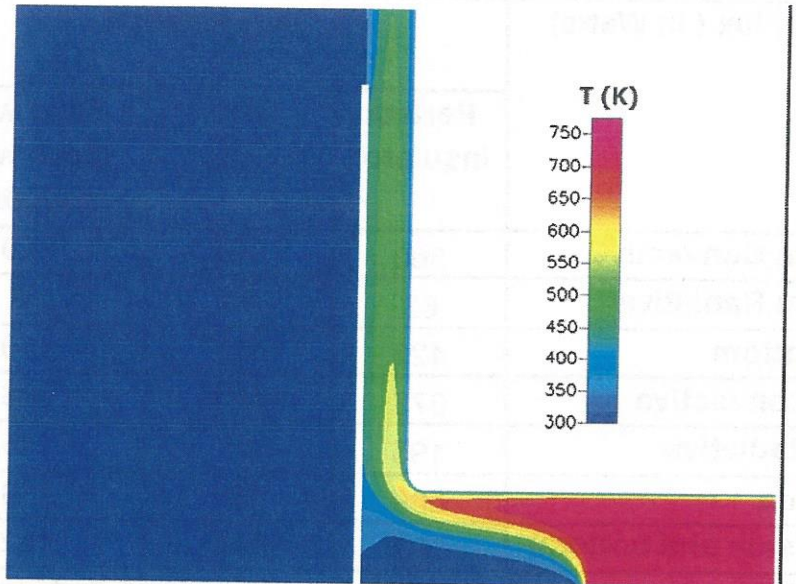

Figure 16: 15 mm skirt

In the table and figures above, a similar trend is seen when the skirt is lengthened to start level with the top of the stove riser (32 mm or 1.25 inches below the bottom of the pot) and 'catch' more of the gas leaving the stove to direct it to the pot. Again, the 10 mm skirt is the best choice, as the 5 mm skirt again forces flow away from the pot, and the 15 mm skirt fails to capture the radiative energy available.

With a tight skirt the hot gas is seen to flow under the skirt and away from the pot, while for the loose skirt the cool ambient air flows under the skirt and towards the pot and stove. This is similar to the experimental trend observed and described in the previous section.

Table 2 also begins to answer a question regarding convective heat transfer to the sides of the pot. Without the skirt, the hot gases will more or less rise along the side of the pot, transferring some heat to the pot sides by convection. With the skirt more heat may be transferred because the gases are forced to move closer to the side of the pot, but is there really much difference.

The results given in Table 2 says that without the skirt the convective heat transfer to the sides of the pot will be 321 W, while with the skirt the convective heat transfer will be 377 W, not a lot greater. The big difference is in the radiative heat transfer, 195 W with the skirt against –46 W without. Again, since the pot is hotter than the environment and radiation passes easily through gases, the hot pot will always lose heat by radiation to the cooler environment.

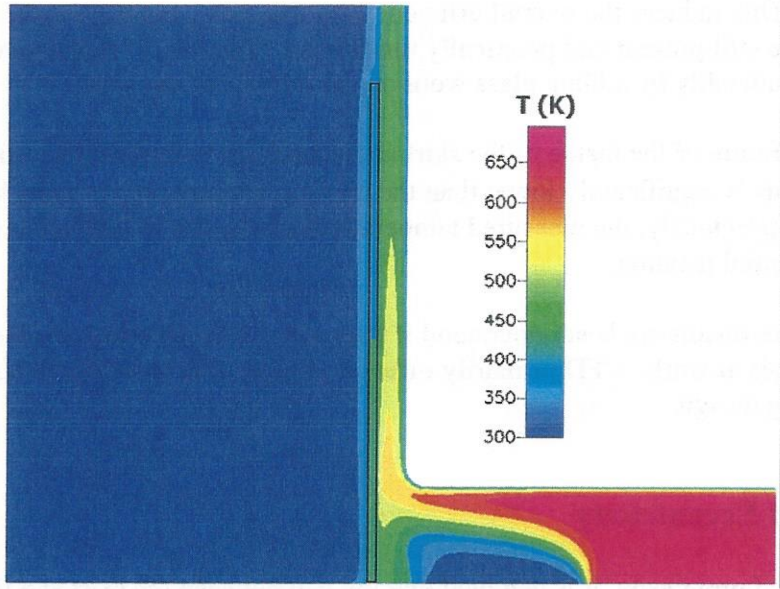

Figure 18: 10 mm skirt, steel skirt

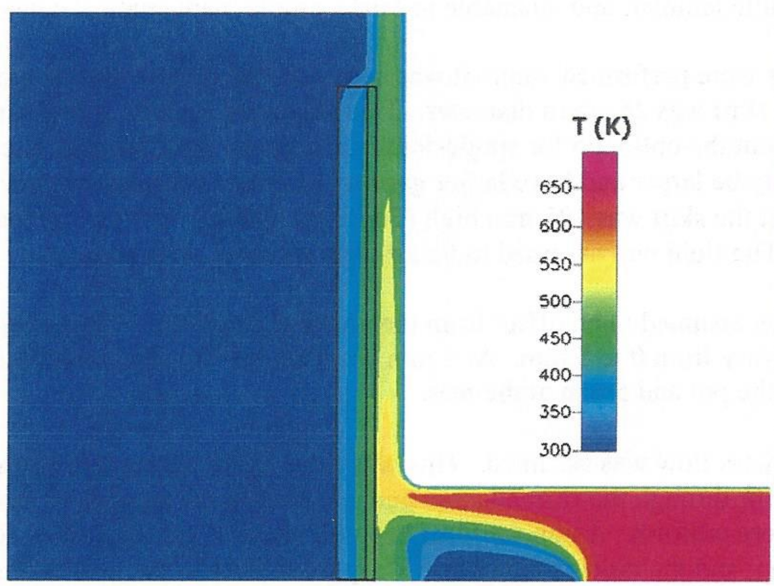

Figure 19: 10 mm skirt, steel skirt with glass wool backing

The table and figures above demonstrates the effect of differing materials of skirts. The previous results (Figs. 11-16) were obtained through modeling the skirt as perfectly insulated, so all radiative energy was reflected back to the pot and none was conducted through the skirt. Modeling the skirt as steel, as well as steel with glass wool insulation, provides a more realistic look at the potential benefits of skirts. Looking at the heat transfer values, one can see that the only significant differences come from radiation energy. Changing the perfectly insulated skirt to highly conductive steel allows heat to be conducted through the skirt and then radiated and convected away from the outside of gas before it exits from the top of the skirt, and at the top of the skirt the gas is only slightly warmer than the pot.

Figure 20 shows the mass flow distribution and exit temperature as a function of the angle around the pot. The angle of 0 or 360° is the front of the pot with the largest gap. The angle of 180° is the rear of the pot with the smallest gap. The inlet temperature difference was assumed to be 300°C, and the mass flow was about 4 g/sec. These conditions are comparable to the conditions described at the medium power level of about 4000 Watts in the physical tests previously described.

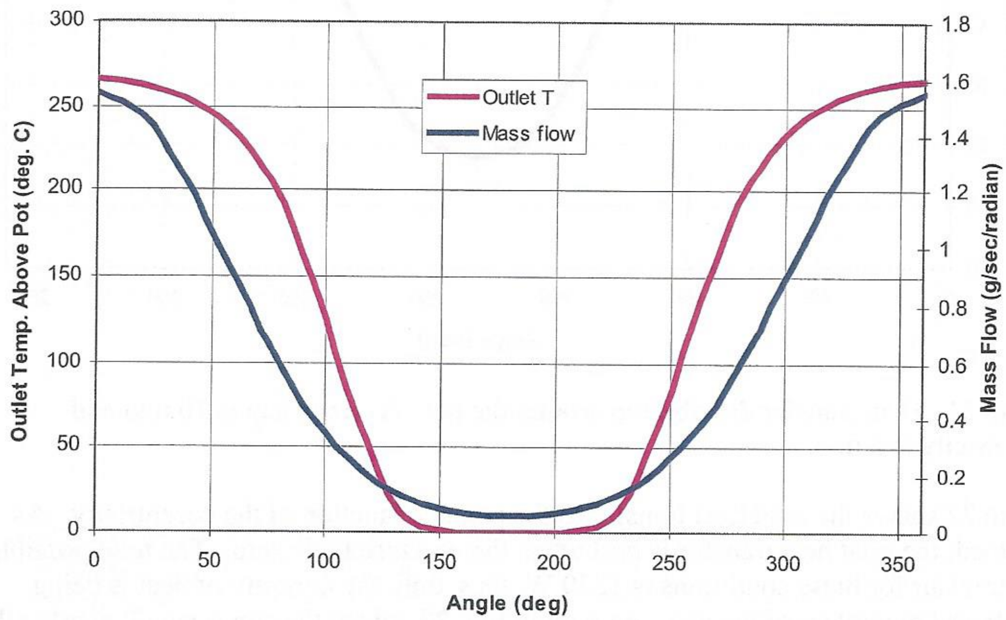

Figure 20: The mass flow per unit angle around the pot and the gas exit temperature (above the pot temperature) around the pot. Eccentricity is 5 mm and the average gap is 10 mm. Gap is largest at the front of the pot, 0°. Inlet gas temperature is 300° C above the pot temperature.

One can see that there is very little mass flow at the rear of the pot. The heat transfer is very good, and thus almost all of the available heat has been pulled out of this portion of the gas. The exit temperature here is almost the same as the pot temperature.

At the front of the pot there is much more mass flow, but the heat transfer is not as good. Some heat has been pulled out of the gas by the time it exits and the exit temperature difference is lower than 300°C, but the exit temperature difference is still quite high, indicating that not all of the available heat was removed from the gas.

Figure 21 shows the heat transfer distribution around the pot, in Watts per unit of angle around the pot. It is highest at a moderate gap, where the gap is large enough to allow good mass flow but small enough to allow good heat transfer. For comparison purposes,

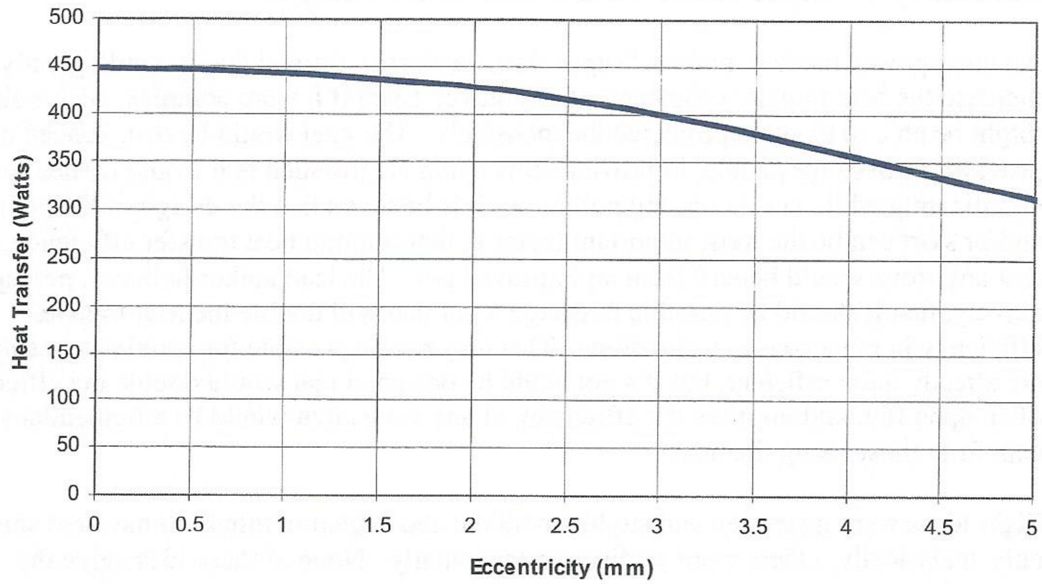

Figure 22: Total heat transfer as a function of eccentricity between the pot and the skirt. Medium power conditions roughly corresponding to the conditions of the 4000 W tests in the previous section.

Figure 23 shows the same type of results for a condition comparable to the lower power tests described earlier. This would be approximately simmering conditions, and are roughly the lowest power level that can be maintained when burning wood. The total power available in the skirt is 556 W. Again we see that the best heat transfer is when the eccentricity is 0.

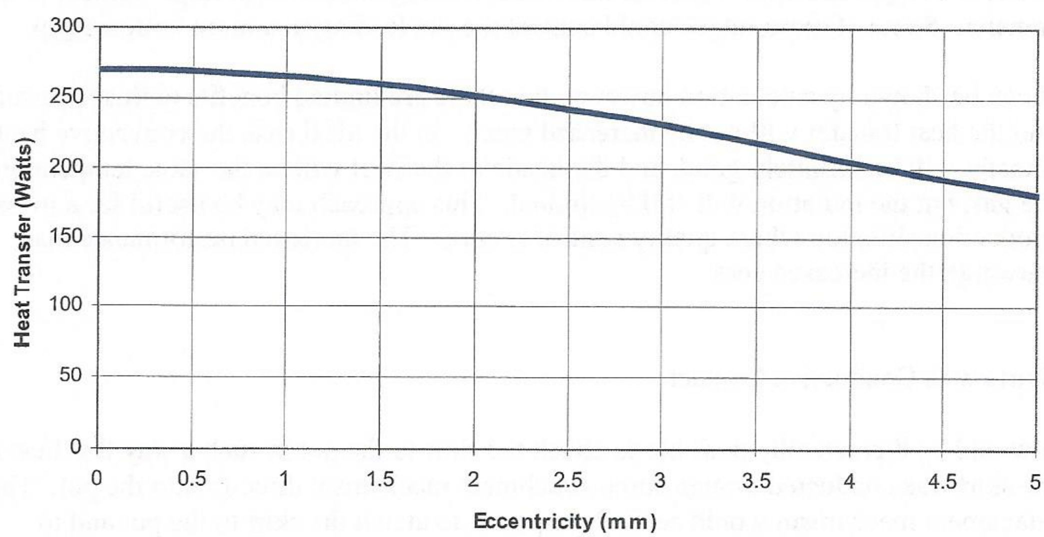

Figure 23: Heat transfer as a function of the eccentricity between the pot and the skirt. This is for the low power conditions described earlier.

extremely conductive heat would not be transferred effectively to the pot. Even with the best conductors available (copper) the skirt would need to be very thick, the attachments would need to be very thick, and the attachments would need to be brazed or welded to the pot. This method seems extremely expensive.

Triangular Skirt Channels

With an ordinary skirt the channel is uniform, an annulus with a gap of about 1 cm extending uniformly all around the pot. With the flow being laminar there is limited mixing, the gas that starts out close to the pot stays close to the pot, giving up its heat readily. The gas that starts out far from the pot stays far from the pot, giving up its heat poorly. Half of the gas is closer to the pot than the average, and half is farther away than average.

A skirt with triangular passages would not be too difficult to build. See Fig. 24. More than half of the gas would be closer than average to the pot, and the gas that was farther than average would be close to the points of the triangle and would give up heat readily to the skirt, which could then be radiated to the pot.

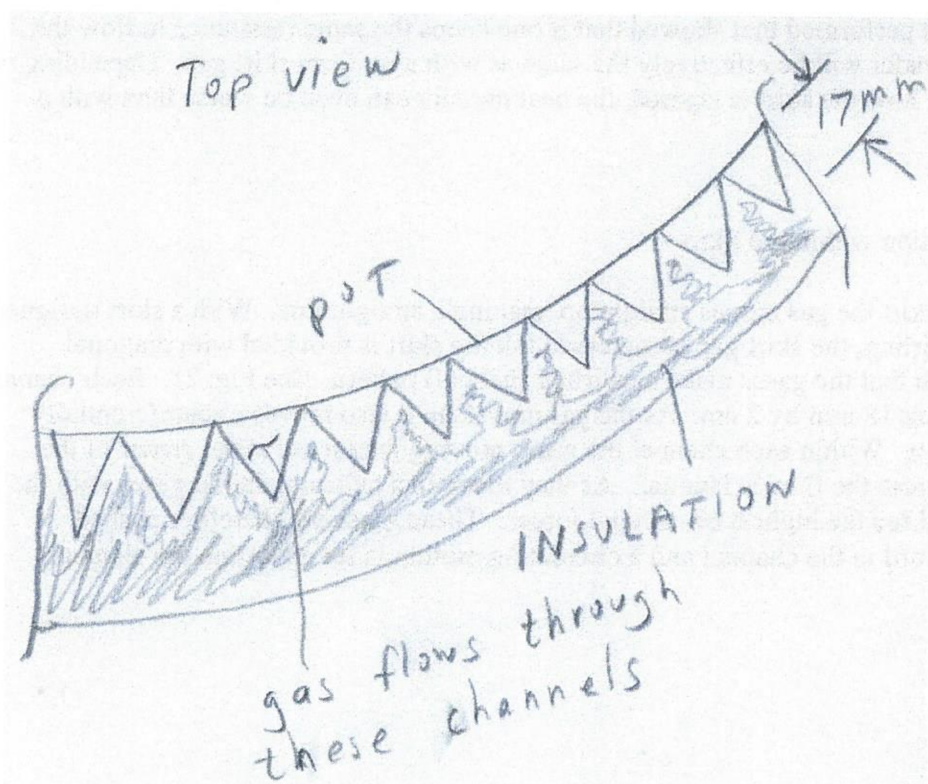

Figure 24: Sketch showing a top of a section of a skirt with triangular flow channels instead of the usual annual flow channel.

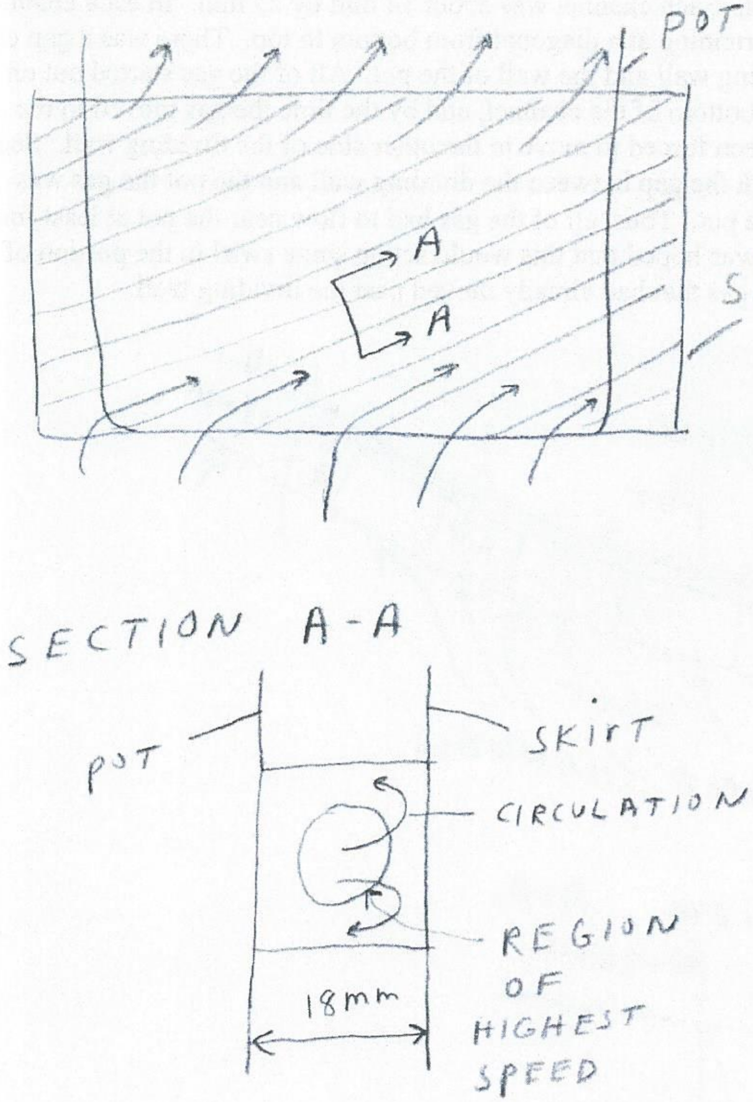

Figure 25: Sketch showing a skirt with channels that force the gases to make a swirling (helical) pattern around the pot. Section A-A shows how the gases circulate within a single channel.

Such conditions have been studied. Ref. 3 gives data that is useful for design. It was determined through calculations that a prototype should be built and tested. The results of the experiment were almost identical to a normal skirt with 1 cm gap.

Multi-channel Skirts with Swirl

As mentioned before, with laminar flow the gas that starts out near the pot stays near the pot and the gas that starts far from the pot stays far from the pot. In an attempt to upset this situation a multi-channel skirt was developed, where there was a multitude of vertical

A prototype was built and tested. To get the same flow as an ordinary skirt with a 1 cm gap a slightly larger gap needed to be used in the multi-channel skirt, about 14 mm. The results of the test were very similar to ordinary skirts.

Multi-channel skirts with slots or perforated metal

Here, two ideas were built and tested together, as they were similar in construction. In the first idea, the skirt was divided into a series of channels as shown in Fig. 27. For each channel the gas first moves up, then is forced to pass through the slot of width a. After passing through this slot the gas moves very close to the pot wall for a significant time.

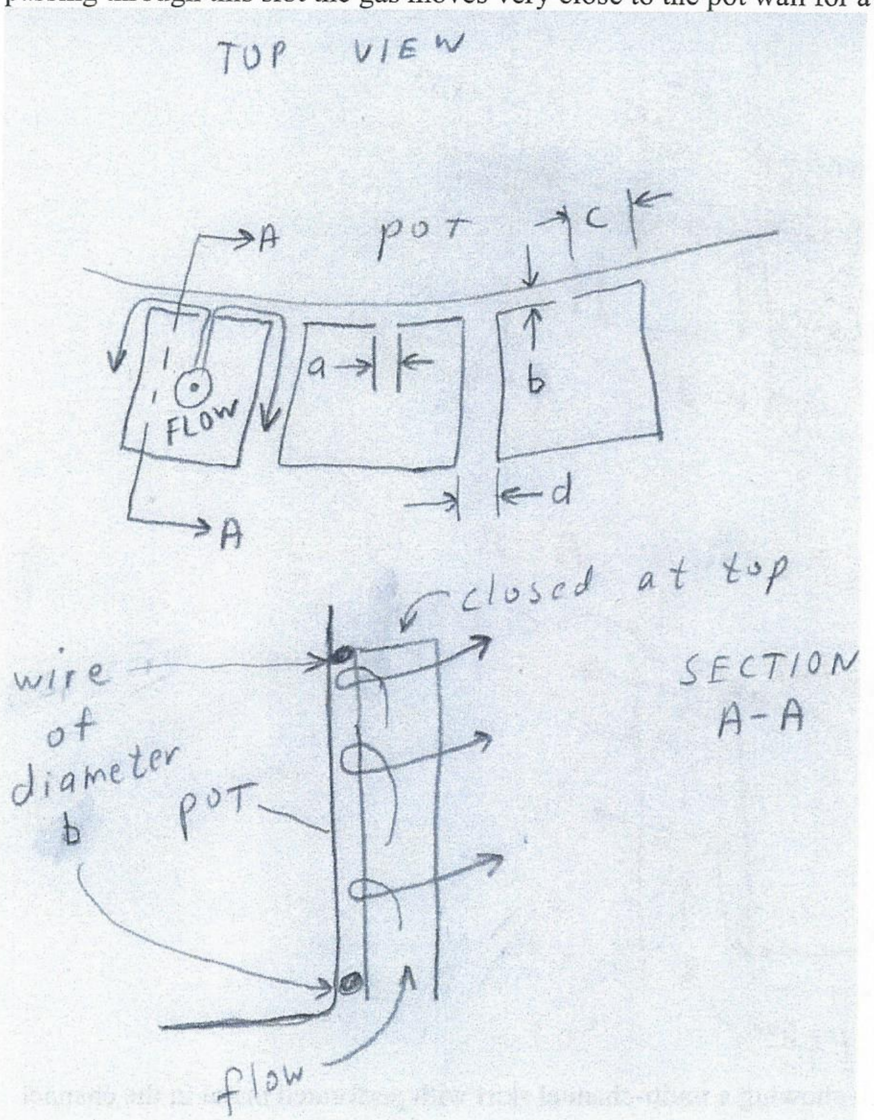

Figure 27: Sketch of a multi-channel skirt with slotted channels.

heat transfer. This idea is shown in Fig. 28. Further, the perforated metal will absorb heat by convection and will radiate significant heat to the pot. Again, a wire of diameter b is wrapped around the pot, and dimension b will be small but not too small. Dimension d is about equal to 2b to keep the flow area equal. Dimension c must not be too large to keep the pressure drop down, and c was about 25 mm.

A single-channel prototype of each of these ideas was built and tested in small scale by attaching one channel of each type to a pot of hot water and passing a known flow rate of room temperature air into the channel through a tube. The temperature of the air coming out of the channel along the side of the pot was measured. The system that had the warmest air leaving the system was the superior system, and heat transfer coefficients could be estimated as a function of mass flow. It was determined that the perforated metal system was significantly better than the single slot system.

A full size prototype was built and tested with the perforated metal system. The results were that it was generally not a lot different than a regular skirt. One test, with low power and a simulated rocket stove performed fairly well, giving a 60% improvement over the pot with no skirt (significantly better than an ordinary skirt) but all other tests with this setup gave results similar to an ordinary skirt. Since this design is much more complex than an ordinary skirt, it seems to be not worth pursuing.

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3. Ibid, pp. 5.84-5.92.

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