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.

5. Reducing the effects of crosswind. To our knowledge this has never been studied, but experiments in rooms with virtually no crossflow of air show highly asymmetric flame patterns. We believe that if there is a significant crosswind, as might be seen when cooking outdoors in even a gentle wind, most of the heat available will be swept away from the stove or fire. Skirts would reduce the effects of this crossbreeze, and the details of the skirt design would determine whether the skirt would have a large effect or a small effect.

6. Reduction in effects of fire asymmetry. As stated above, even in a room with negligible wind, the fire is often seen to be highly asymmetric, even with no apparent reason for asymmetry. There are a number of reasons why a fire might be asymmetric, and this has not been studied, to our knowledge. However, it would be likely that an asymmetric fire would not provide as large a quantity of heat transfer as a symmetric one, and that a skirt would tend to even out the flow of gas along the sides of the pot.

Testing Program

In testing for heat transfer, it is useful to have a very repeatable flame and then vary one parameter at a time. This was achieved by using a natural gas flame, and by metering and measuring the gas flow the power of the fire could be controlled and measured. By setting up the flame and pot (and sometimes a simulated or real stove in between) the conditions of the gases hitting the pot can be reproduced. Changing the design can be done in a systematic manner, changing one variable at a time.

Combustion is done in a low velocity fully non-premixed manner, in which the color and character of the flame appears very similar to a wood flame. See Fig. 1 for a view of the basic burner. This is a good way of testing the heat transfer situation, though perhaps not a good way to study pollutant formation. A number of tests of this type were performed, primarily during 2009, and this section is a description of those results.

The pot used for all tests was a 24 cm diameter pot made of ordinary (not stainless) steel with an enamel coating. The pot had a total capacity of slightly over 5 liters and is somewhat smaller than the standard pot that is usually used in water boiling tests. Since the goal was to see the effect of the skirt relative to the unskirted pot, minor differences between pots should not affect the overall conclusions.


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.

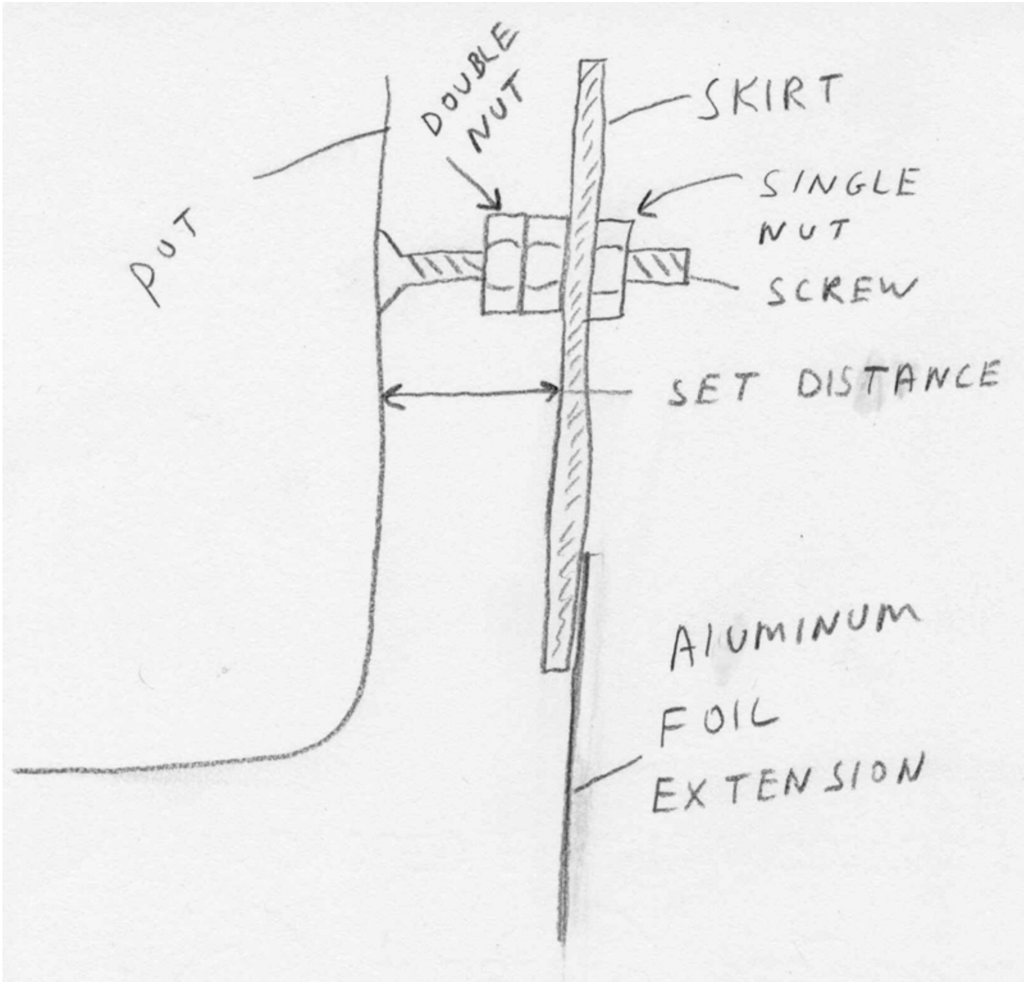

Figure 2: Sketch of the skirt, showing a typical leg which is used to set the skirt gap. Approximately 30 of these legs are used for the entire skirt. Skirt extension is also shown, which is used to adjust the height of the skirt.

The main part of the skirt was about 102 mm (4 inches) tall and made of steel sheet metal, but the total height of the skirt could be adjusted by adding an aluminum foil extender to the bottom of the sheet metal. If the sheet metal part of the skirt was held to the right gap, then the aluminum foil part would also be close to this gap. In all tests the skirt was insulated on the sides, although the insulation was somewhat different in different tests. In all tests it is believed that the insulation allowed negligible heat transfer, therefore the details of the insulation should not matter much.

Three sets of tests were done, each with a different cooking condition, an open fire, a simulated rocket stove, and a ceramic Chinese rocket stove with gas burner. Two or more power levels were used, corresponding to a range of cooking power levels from low power (generally just enough to keep a pot simmering with no lid) to medium power, in which the power of the fire was about 4000 W and the heat going into the pot was 1500 to 2000 W. Since the heat addition to the pot was already close to 2 kW, no “high” power tests were done.

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.

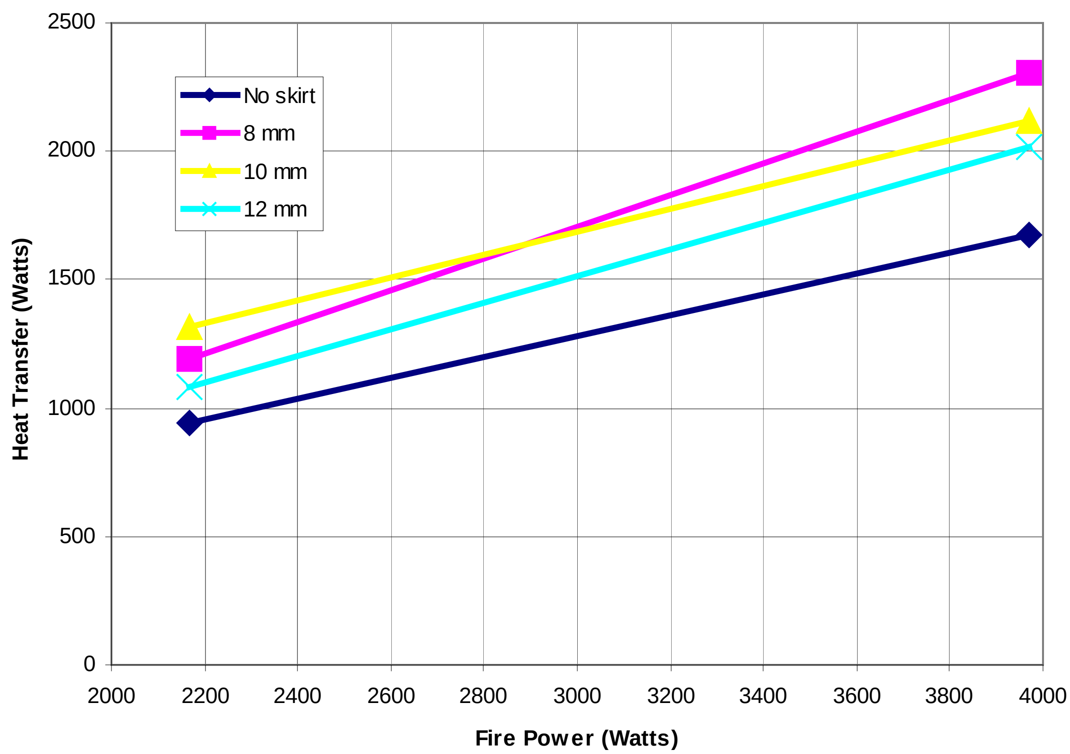

Figure 3: Heat transfer results for the simulated open fire.

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 tendency of a pot with a skirt. For each skirt design, the fire power level was turned up until black smoke (also known as soot or elemental carbon) was formed in small but steady amounts. This type of test is obviously somewhat subjective, but is at least a start into studying which pots are likely to cause more pollution.

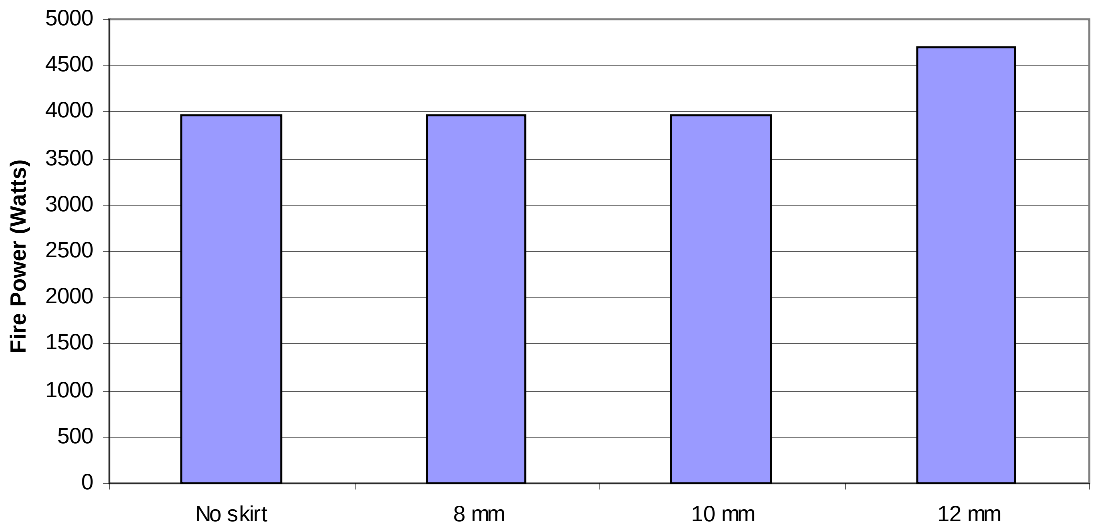

Figure 4. Smoke test results for the simulated open fire. The power level at which black smoke first begins to form is shown.

For the open fire smoke was created at much the same power level for a variety of conditions as seen in Fig. 4. The larger gap skirt has less tendency to form smoke. It is possible that a skirt with a not too tight gap will increase the heat transfer and decrease the pollutant emission rate at the same time. In addition to saving fuel, this would provide a double pollutant benefit, reducing cooking time and reducing pollutants per unit time. This remains to be proven through direct measurement of the pollutants, however.

Test Results-Simulated Rocket Stove

The next situation was a simulated rocket stove. This was with a double-wall riser of 127 mm (5 inch) diameter. The top of the riser was ¼ of the riser diameter from the bottom of the pot, giving equal flow area. The riser was 229 mm (9 inches) tall and contained the same burner as seen in Fig. 1. See Fig. 5 for an overall view of the simulated rocket.

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.

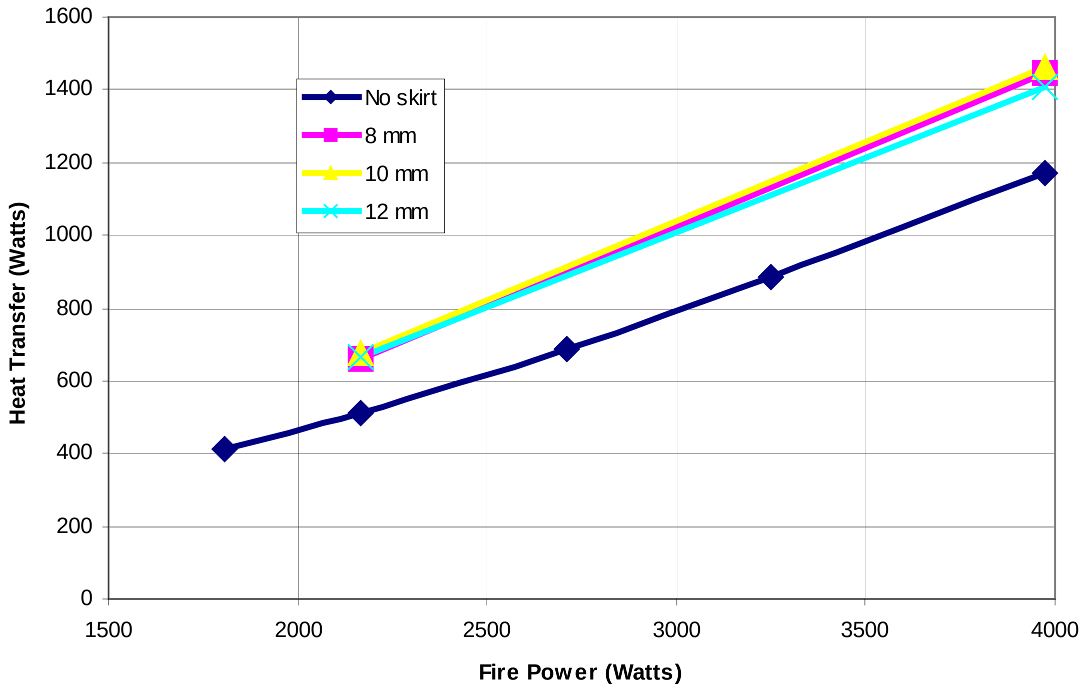

Figure 6: Heat transfer to the pot with and without a skirt. Simulated rocket stove.

Tighter skirts lead to increased pollutant formation, but the bare pot also tends to form smoke, as shown in Fig. 7. The mechanism of this pollutant formation is unknown, but the following is probably occurring. What causes soot (the same is generally true for other particulates and carbon monoxide) to be produced is that the combustion gases are not fully reacted, and they are cooled before they get a chance to react into carbon dioxide and water vapor. For the pot without a skirt hot gases which are not fully reacted mix rapidly with cooler air once the gases pass by the bottom of the pot. The unreacted hydrocarbons in the gas form soot before they can be turned into carbon dioxide or water vapor. Pollutant formation with an unskirted pot is a function of the speed of this mixing.

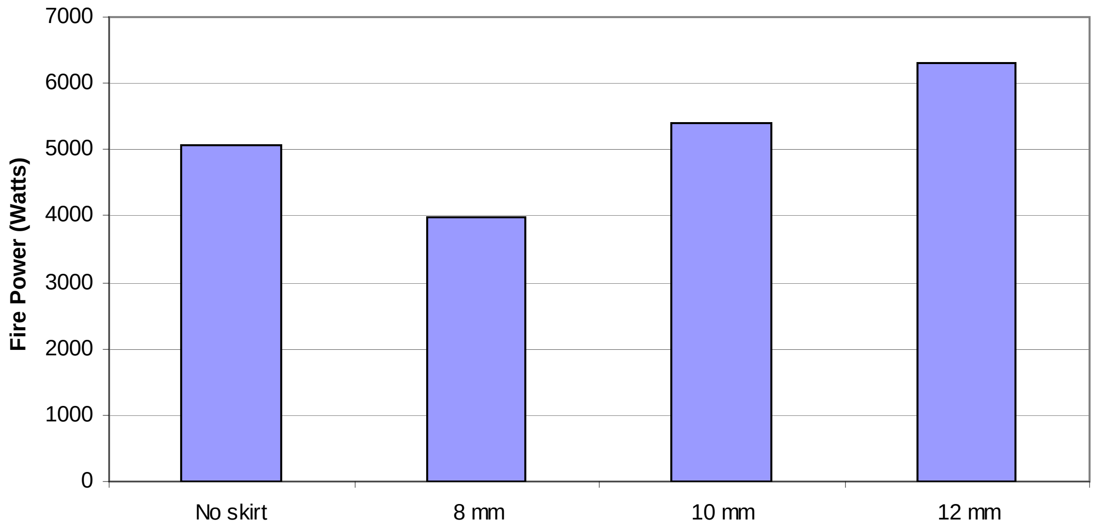

Figure 7: The minimum fire power level at which smoke is observed, simulated rocket stove.

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 8: Chinese rocket stove. For this test, a gas burner similar to that shown in Fig. 1 was placed in the area where the wood would normally burn.

In the baseline tests with no skirt and with the sides of the pot insulated, it was found that without a skirt virtually all of the heat flows through the bottom of the pot. With the pot sitting on the pot supports, there is a very narrow gap under the pot at the outer edge of the pot through which the gas will flow, and thus these gases will exit the stove with high radial speed. This is likely to pull the heat away from the sides of the pot, resulting in little heat transfer to the sides of the pot without a skirt. The heat transfer to the bottom of the pot is very good, and thus the overall efficiency of the stove is good, even without a skirt.

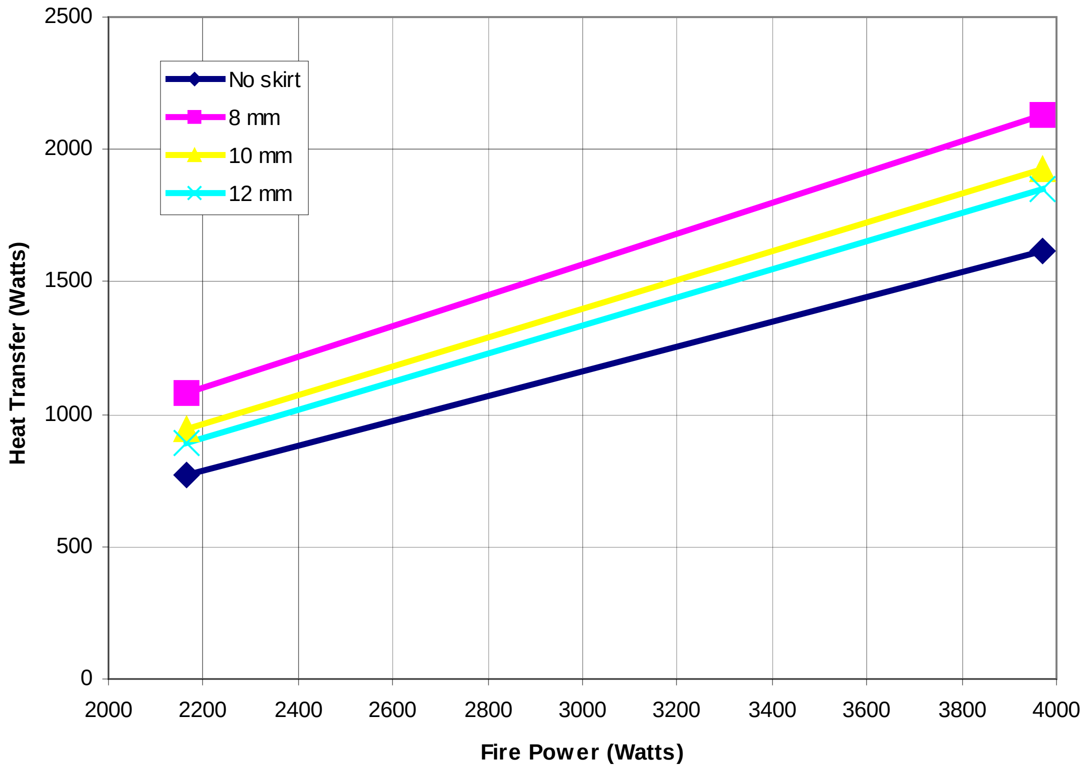

Figure 9: Heat transfer results for the Chinese rocket stove.

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.

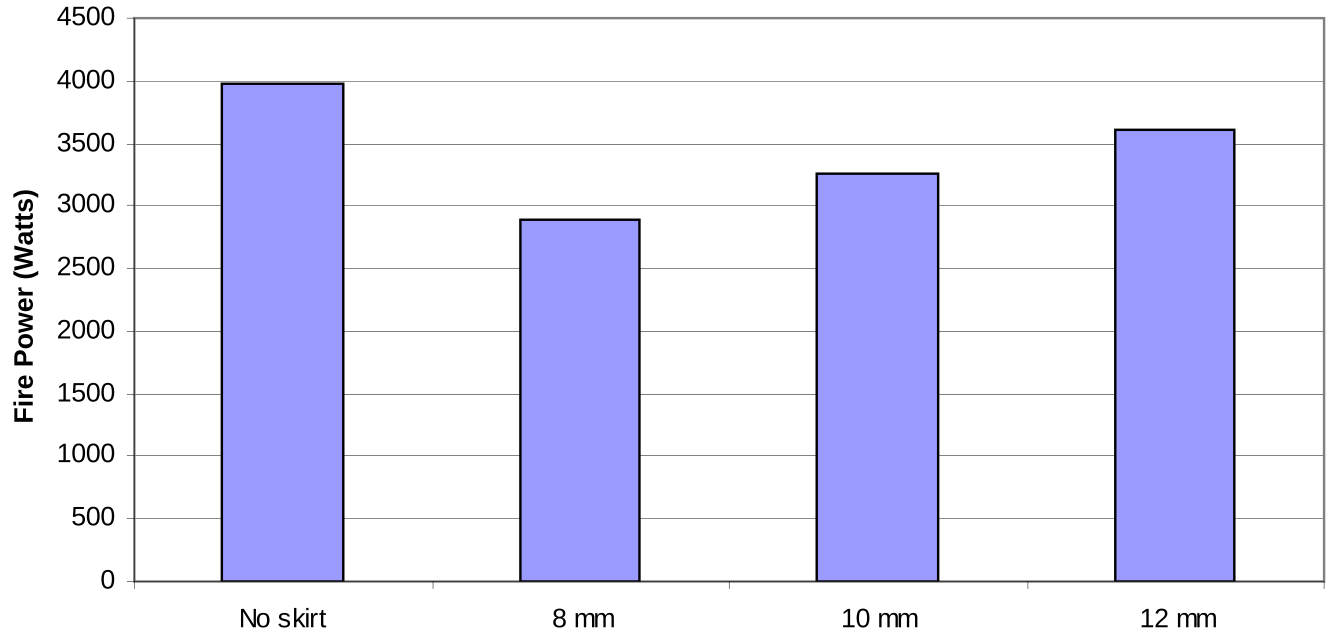

Figure 10: Smoke tests results for the Chinese rocket stove. The minimum power level to produce black smoke is shown.

Test Results-Patterns Observed

Throughout all of these tests, various temperatures were measured in the gas at the top or bottom of the skirt. In some tests the temperature of the skirt itself was measured. Various attempts were made to determine heat transfer coefficients, and all these measurements were in an attempt to determine WHY certain skirts worked better than others, in addition to merely determining THAT certain skirts worked better than others. Ultimately, the goal is to design skirts that work even better.

From this work, few clear patterns emerged. One pattern is that even when testing indoors the heat to the pot is highly asymmetric. There is no obvious asymmetry in the burner, and no significant crossflow of air in the room, so the cause of this asymmetry is unknown. The asymmetry varies from test to test, but during a single test it appears to be generally constant. It is believed that the presence of the skirt forces the gas flow to be somewhat more symmetric on the sides of the stove and probably on the bottom as well.

In cases where the bottom of the skirt was open (simulated rocket stove and open fire) the temperature of the air just under the bottom edge of the skirt was measured. In some cases this is nearly room temperature, suggesting that cool room air is flowing radially inward under the skirt and diluting to some extent the hot gases going up the skirt. When the skirt hangs down lower this tends to be the case.

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 are measured in the model. Thus, one can find the temperature, velocity and density of a gas *at any point* in the model, provided the user instructed the program to record that data. This saves a great deal of headache, and allows the user to observe phenomena that may simply not be observable in real-world experimental setups without the aid of advanced and expensive equipment.

Lastly, the use of CFD eliminates the possibility of error affecting results. In the workspace where we conducted experiments, there was a clear asymmetrical flow pattern in the hot gas from the burner, due to unforeseen and, as yet, unknown circumstances. In the computational model, the flow was modeled as perfectly axisymmetric, and the results reflect this. Human error is also eliminated, whether through approximated thermocouple readings, inaccurate length measurements, or the myriad of other error sources.

However, there are notable limitations to CFD that must be acknowledged for proper and responsible practice. While the time for conducting 2-D simulations was quite short, moving to 3-D simulations (used for more complex skirts such as those described in the last section of this report) increases the time necessary for a given run drastically. Instead of minutes, the time scale is now in days – meaning that traditional experimentation is more time efficient. The 2-D models used also neglected a certain type of turbulence modeling, which would have drastically increased computational time. The results of these tests demonstrate this lack of consonance with reality, but the researchers believe that such dissonance doesn't impact the validity of the results. The impressive capabilities of CFD also offer the temptation of treating it as a black box. The user can effectively treat the post-processed flux results as separate from the processes of fluid mechanics and heat transfer occurring in a given scenario. But it is those same processes that should inform and influence engineering design. The principle benefit CFD can offer should be considered as the qualitative information about the varying processes, not the exact numerical results presented. When one can look at a temperature or velocity profile and recognize how the flow responds to a given element in the model, this enables the user to modify a design accordingly. The numerical results CFD gives should not be regarded as absolute, but rather as supplements in engineering design.

Looking forward, CFD may be of use for modeling more complex skirt or pot designs that may not be easily manufacturable. For instance, one of the few 3-D simulations, run to investigate a potential super-skirt (the multi-channel skirt with slots described in the last section of this report) showed the flow of gas going outside the proposed skirt and away from the pot – demonstrating that, at the very least, significant changes to that design should be considered.

CFD has significant advantages that enable results to be obtained more accurately and with much less time than using traditional experimentation. However, there are limitations that need to be respected for responsible use of the software.

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.

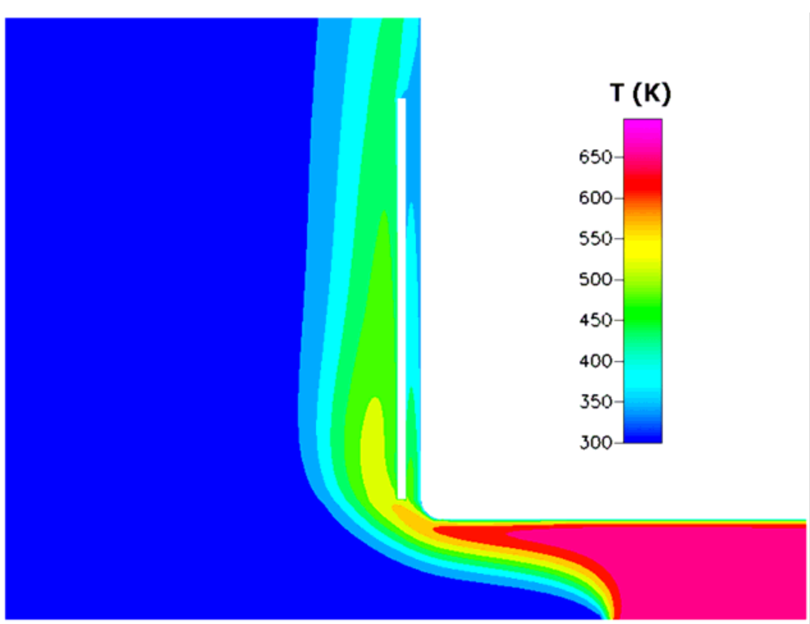

Figure 11: 5 mm skirt

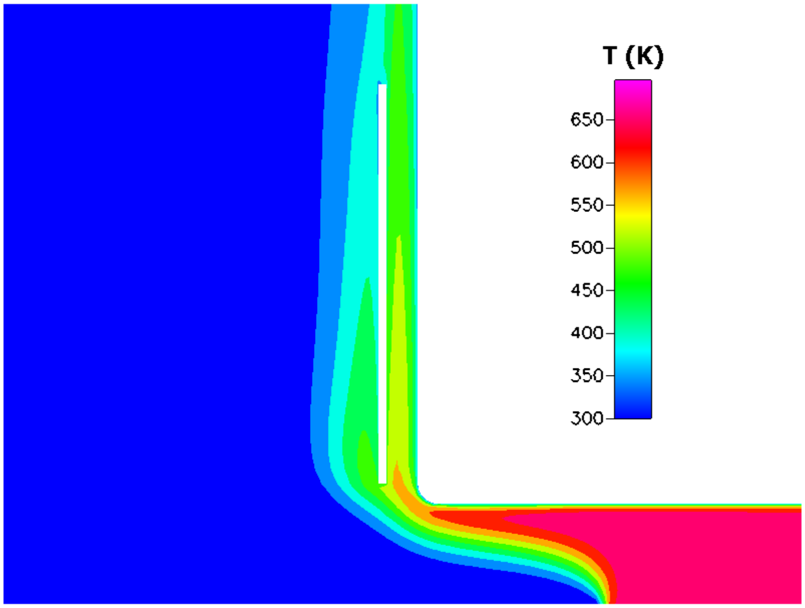

Figure 12: 10 mm skirt

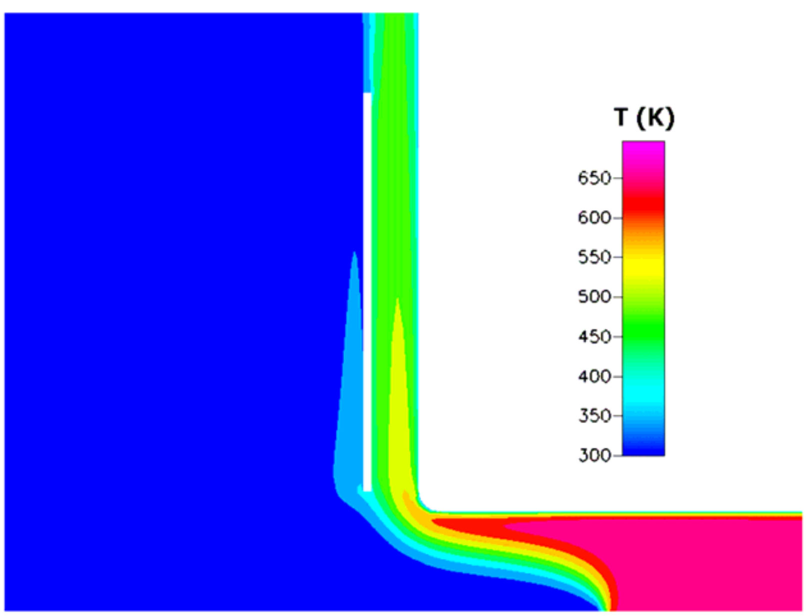

Figure 13: 15 mm skirt

Table 1 can be supplemented with the accompanying pictures (Figs. 11-13). The temperature plots demonstrate the general path of the flow of hot gas. The white area is the pot, assumed to be at 100°C (373 K). From the table, it can be seen that a pot without a skirt loses a substantial quantity of energy due to radiative energy being released to the ambient. The net radiative heat transfer form the sides of the pot is negative without a skirt. The pot is assumed to be at 100°C and radiates heat to the environment. The skirts added serve to trap that radiative energy, radiate heat directly to the pot, and improve convective heat transfer to the pot. Among the skirted pots, there is no difference in the 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.

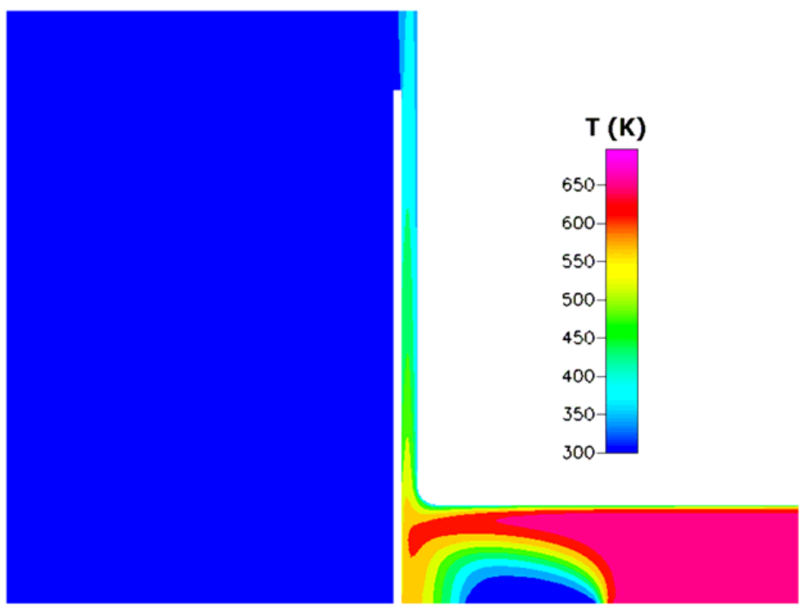

Figure 14: 5 mm skirt

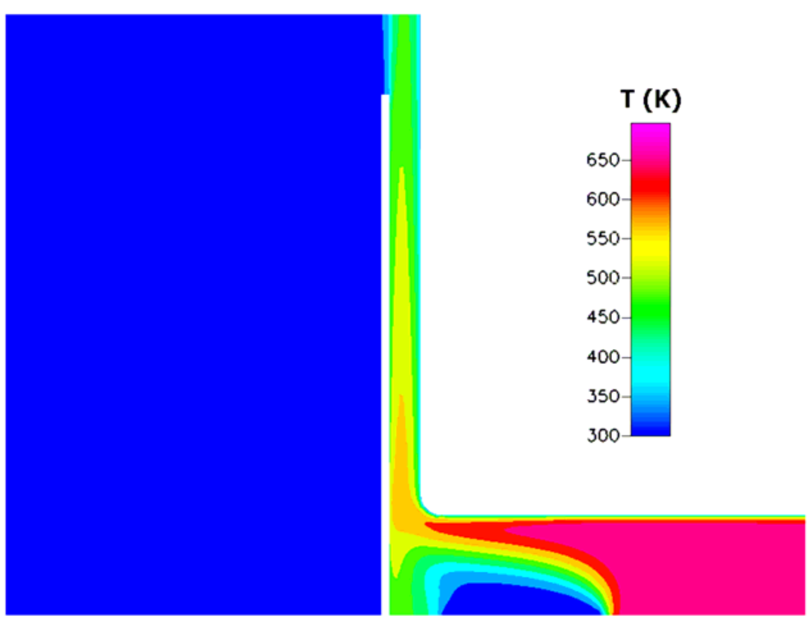

Figure 15: 10 mm skirt

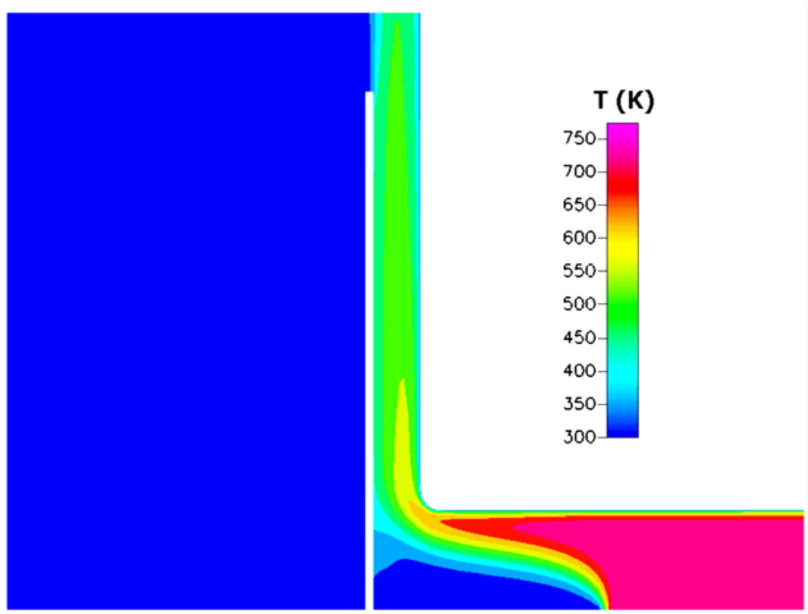

Figure 16: 15 mm skirt

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.

Heat Flux (in Watts)	Skirt Material			No Skirt
	Perfect Insulator	Steel	Steel with glass wool insulation	
Bottom Convective	360	361	360	367
Bottom Radiative	63	51	58	33
Net Bottom	423	412	419	400
Side Convective	373	363	368	321
Side Radiative	195	67	145	-46
Net Side	569	430	513	274
Total (side and bottom)	992	842	932	673

Table 3: Predicted heat transfer to various surfaces of the pot with skirts made out of various materials. In this case, the skirt was 165 mm (6.5 inches) tall and its bottom edge is aligned with the mouth of the stove, and it was placed at a distance of 10 mm from the pot. Positive sign indicates heat transfer into pot.

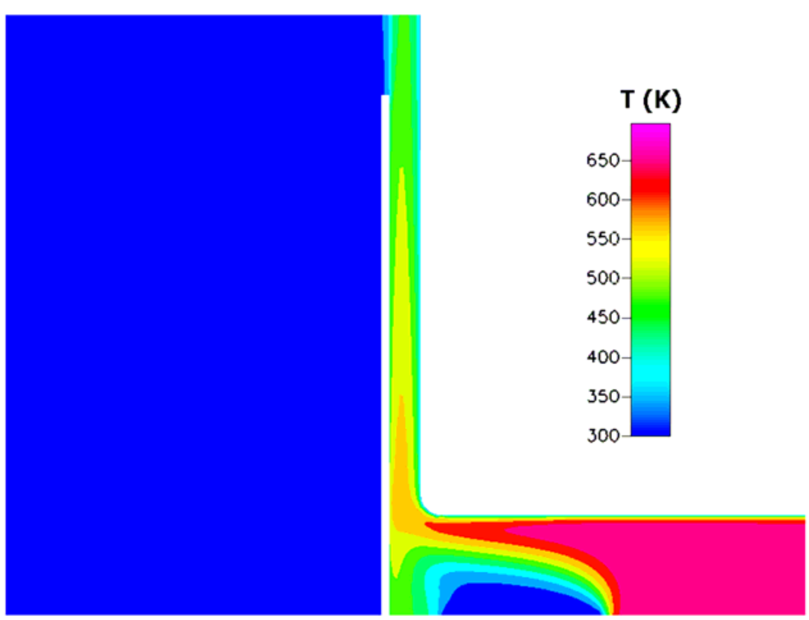

Figure 17: 10 mm skirt, perfectly insulated skirt

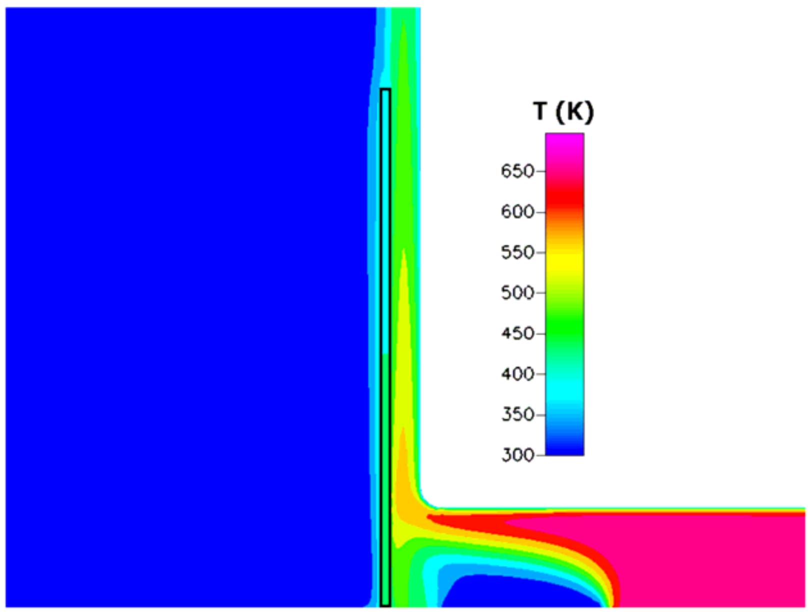

Figure 18: 10 mm skirt, steel skirt

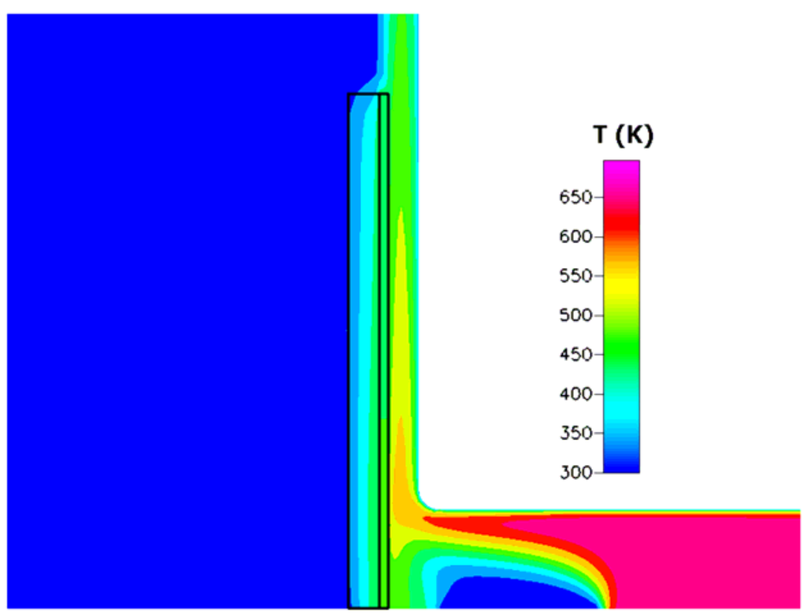

Figure 19: 10 mm skirt, steel skirt with glass wool backing

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 the skirt. This reduces the overall efficiency significantly, but the convective transfer benefits are still present and practically unaffected. The loss of radiative energy can be offset considerably by adding glass wool on the outside of the skirt.

The temperature of the inside of the skirt about halfway in in the CFD model is about 177°C. This is significantly lower than the measured temperatures seen, however, as reportedly previously, the measured temperatures are highly dependant on the circumferential location.

Again, these results are best understood if they are combined with an understanding of the processes at work. CFD primarily offers a glimpse into these processes, to inform engineering design.

Effects of Eccentricity

As described previously, it is believed that the gap between the skirt and the sides of the pot must be uniform around the pot to give best heat transfer. This was studied theoretically. The flow through the gap typically has a Reynolds number of about 400, making it quite laminar, and amenable to fairly simple mathematical analysis.

Calculations were performed where it was assumed that the pot was 24 cm in diameter and that the skirt was 26 cm in diameter. This leaves an average gap of 1 cm, which is typically about the optimum for single-family size pots. (Institutional size cooking pots will generally be larger and have larger gaps to give the necessary air flow.) It was assumed that the skirt was 125 mm high (5 inches) and that the flow moved strictly vertically. The fluid was assumed to be air with constant properties.

The skirt was assumed to be offset from the uniform condition. This eccentricity was assumed to vary from 0 to 5 mm. At 5 mm eccentricity, the gap would thus be 15 mm at the front of the pot and 5 mm at the rear.

A constant mass flow was assumed. This was done by assuming a pressure difference pushing the air through the skirt channel and calculating the mass flow that would occur if the gap were uniform. A non-uniform gap will allow larger mass flow for a given pressure drop, and the ratio of the uniform-gap mass flow to the non-uniform gap mass flow can be calculated as a function of eccentricity. The pressure drop was then adjusted to give the same mass flow for all values of eccentricity.

There is a strong tendency for the mass flow to be concentrated in the areas with the larger gap. The mass flow per unit of pot circumference will be proportional to the gap cubed. At the same time, for laminar flow the heat transfer coefficient will be inversely proportional to the gap. Thus, in the large gap section one has more mass flow but less heat transfer. In the areas with smaller gap, there is much less mass flow, but the heat transfer from this gas is very good. Almost all of the available heat is pulled out of the 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.

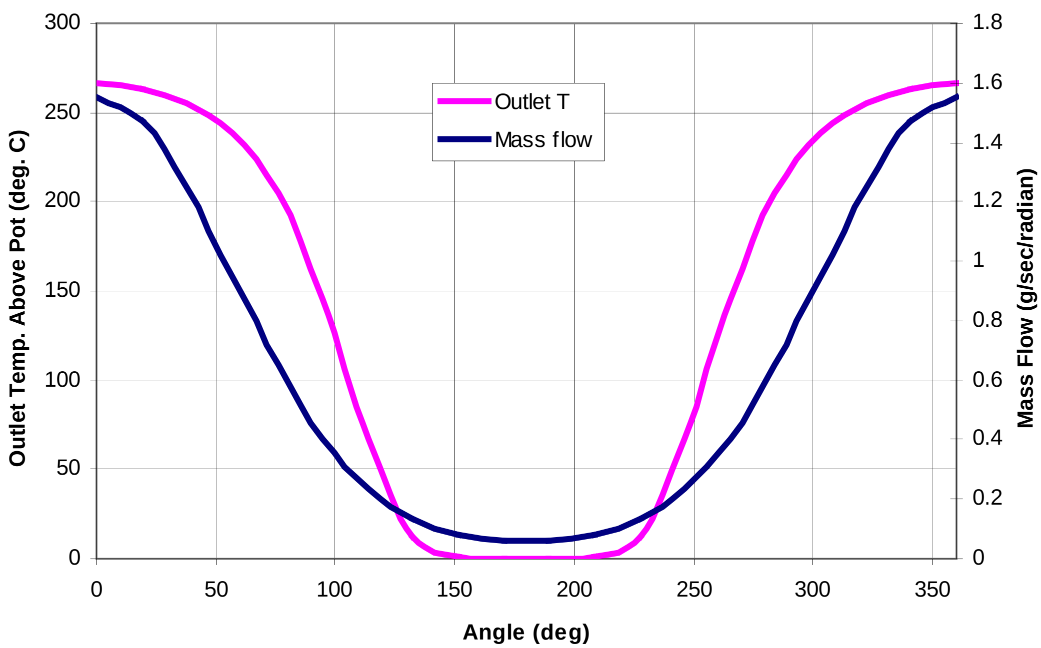

Figure 20: The mass flow per unit angle around the pot and the gas exit temperature (above the pot temperature) around the pot. Eccentricity is 5 mm and the average gap is 10 mm. Gap is largest at the front of the pot, 0°. Inlet gas temperature is 300° C above the pot temperature.

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, if the gap had been uniform the heat transfer would have been 71 Watts/radian, but with the eccentric gap the heat transfer is never this high. The best heat transfer occurs at an angle of about 90° or 270° where the gap is equal to the average gap of 10 mm. This may be a coincidence, however.

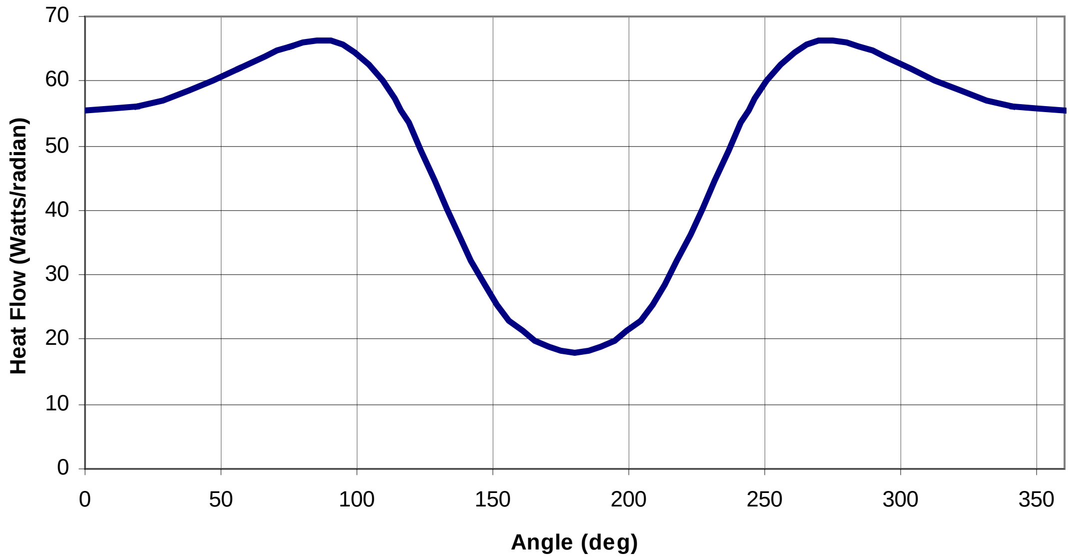

Figure 21: Heat transfer distribution around the pot. Average gap is 10 mm and eccentricity is 5 mm.

Figure 22 shows the total heat transfer to the pot as a function of the eccentricity. As expected, the total heat transfer is best when the eccentricity is zero. The total possible heat transfer for these conditions is 1250 W, thus, only the minority of heat is being transferred regardless of the gap. As seen in Fig. 20, where the gap is small, nearly all of the available heat is being pulled out of the gas.

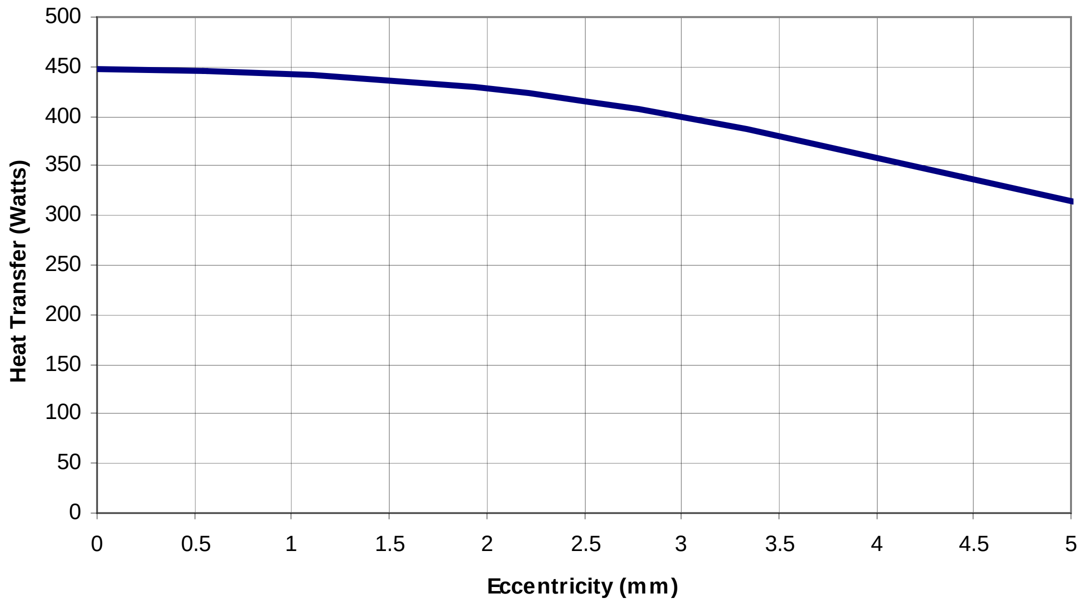

Figure 22: Total heat transfer as a function of eccentricity between the pot and the skirt. Medium power conditions roughly corresponding to the conditions of the 4000 W tests in the previous section.

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.

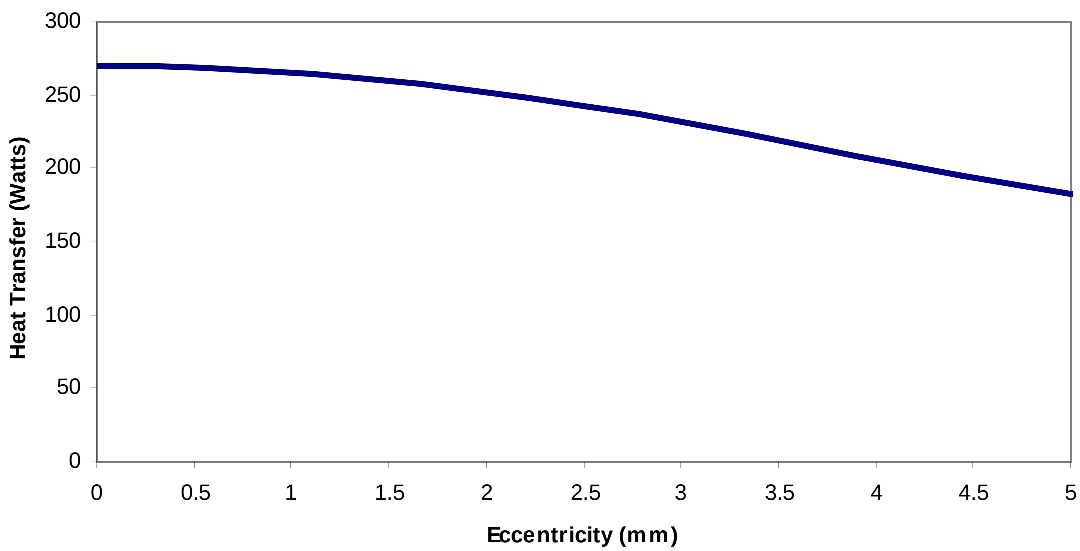

Figure 23: Heat transfer as a function of the eccentricity between the pot and the skirt. This is for the low power conditions described earlier.

Summary of Experiments into Other Skirt Designs

An attempt was made to make a “super skirt,” a skirt so formed that it would greatly increase the heat transfer efficiency of any stove. Even if it were complex, such a skirt might be able to be mass produced inexpensively. The goal would be that, instead of providing stoves for people, improved skirts could be provided that would reduce fuel use significantly while not increasing pollution. It is believed that the design of the pot and/or skirt can be the most important factor in determining heat transfer efficiency, and that any stove would benefit from an improved pot. The lead author believes, perhaps naively, that it should be possible to design a pot that will double the heat transfer efficiency in most common situations. This may not be possible for certain stoves that are already quite efficient, but if a pot could be designed that would double the efficiency of an open fire, and improve the efficiency of any stove, that would be a tremendous benefit to those using the pots.

Eight ideas were generated and studied with the above goal in mind. Some were studied only analytically, others were studied experimentally. None of these ideas give the required improvements, however.

Skirts with Ridges

There is significant radiation between the inside of the skirt and the pot. The inside of the skirt absorbs heat by convection from the flowing gas and radiates it to the pot. This heat transfer is significant, and could possibly be increased. The pot and skirt are already dark, so the radiation exchange will be as good as is possible, but if the inside of the skirt were made with ridges so as to increase the surface area, the convective heat transfer between the gas and skirt would be increased, leading to an overall improvement in heat transfer. Some of these ridges could contact the pot leading to a more uniform gap.

It can be shown by calculation however, that there are limited benefits to this approach, and the heat transfer will not be increased much. In the ideal case the convective heat transfer will be infinitely good, and the inside of the skirt will be the same temperature as the gas, but the radiation will still be limited. This approach may be useful for a mass production situation where quality control is good. The increased performance may outweigh the increased cost.

Skirts with Conductive Contact

It would be theoretically possible to attach the skirt to the pot in such a way that heat in the skirt was conducted though some attachment mechanism directly into the pot. The attachment mechanism would serve 2 purposes, to attach the skirt to the pot and to conduct heat from the skirt to the pot. This would at least double the heat absorbing area on the sides of the pot. The primary author of this work has done extensive work on finned pots. Calculations show that unless the skirt and attachment method were 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.

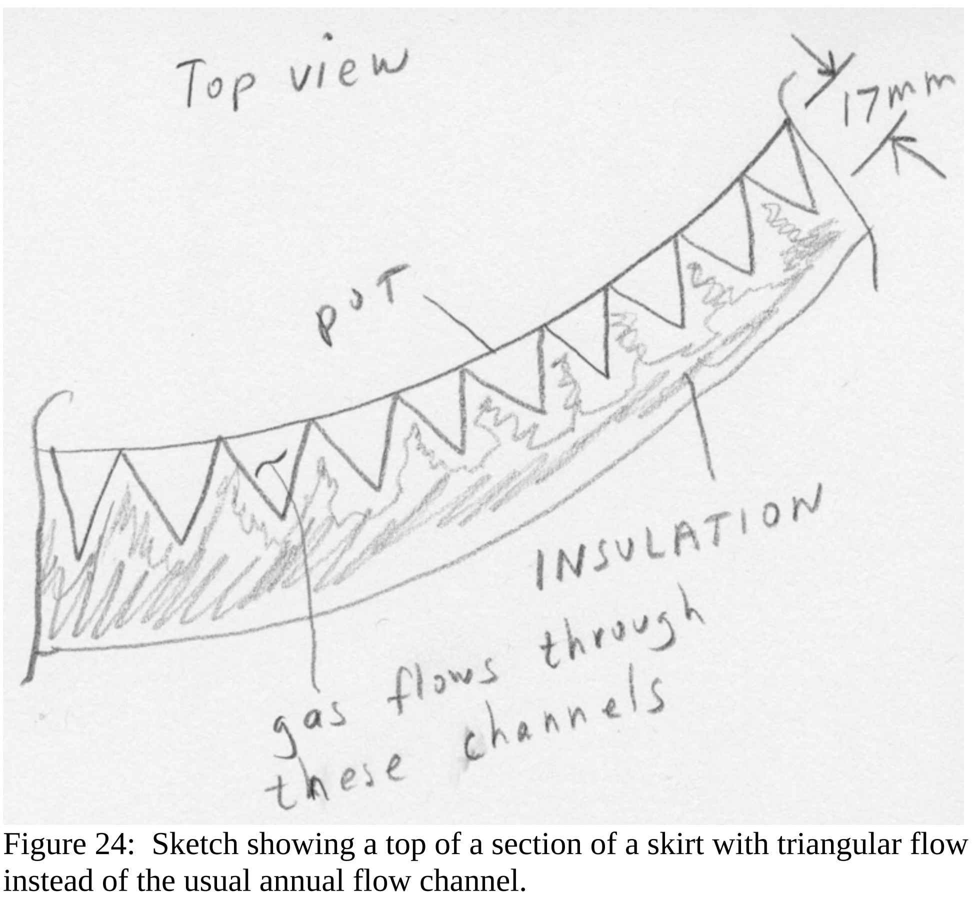

Figure 24: Sketch showing a top of a section of a skirt with triangular flow channels instead of the usual annual flow channel.

The pressure drop of such a system would be higher than a uniform skirt, and the 1 cm gap would need to be increased significantly such that mass flow wasn't restricted. An analysis was done based on information in Ref. 2. This shows that with triangular passages the gap must be increased to about 17 mm to give the same flow as an ordinary skirt with a 10 mm gap. This tends to decrease the heat transfer. Such a system with triangular passages achieves about the same heat transfer as a regular skirt with 10 mm gap.

Tapered Channels

As the gas flows through the skirt it cools and contracts, which decreases the velocity and decreases the viscosity. The downstream portions of the skirt could be made with a smaller gap, leading to better heat transfer in the downstream portion while still maintaining good flow. Measurements of ordinary skirts shows, however, that the temperature of the gas in the skirt is not decreased that much, therefore the gap could not be decreased that much, and therefore the heat transfer could not be increased that much. To maintain the same flow the gap at the bottom of the skirt would need to be increased, leading to worse heat transfer in that area.

Analysis was performed that showed that if one keeps the same resistance to flow the total heat transfer will be effectively the same as with a uniform skirt gap. Depending on the details of how the skirt is tapered, the heat transfer can even be worse than with a uniform gap.

Swirling Motion within the Skirt

In a normal skirt the gas moves straight up, making a straight line. With a skirt designed to induce swirling, the skirt gap is increased but the skirt is provided with diagonal channels such that the gases make a swirling (helical) pattern. See Fig. 25. Each channel might be about 18 mm by 2 cm. As the gas moves up it also moves circumferentially around the pot. Within each channel the gases moving fastest are at the center of the channel, because the flow is laminar. As they move in a helical path the gases with the highest speed see the highest centrifugal forces. These gases are therefore pushed radially outward in the channel and a circulating motion is set up within the channel.

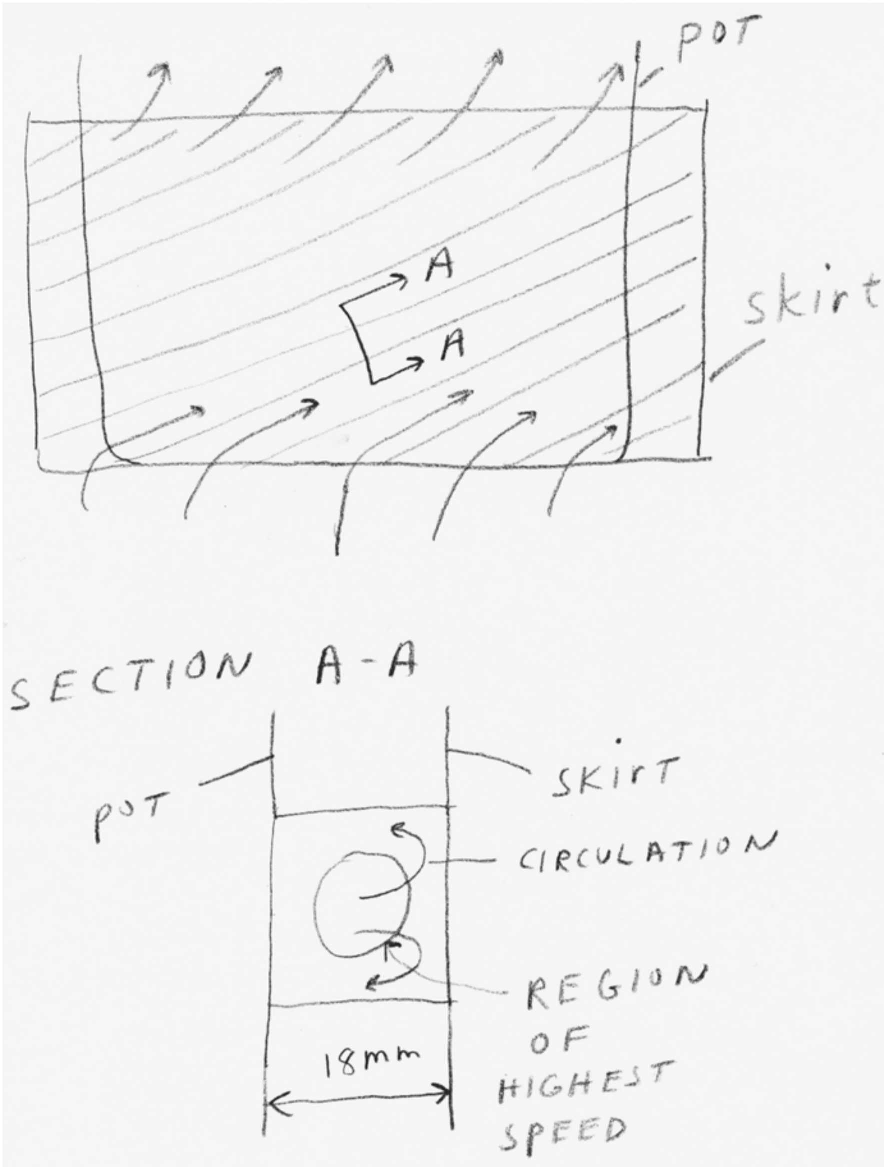

Figure 25: Sketch showing a skirt with channels that force the gases to make a swirling (helical) pattern around the pot. Section A-A shows how the gases circulate within a single channel.

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 channels built into the skirt. Each channel was about 14 mm by 25 mm. In each channel there was a dividing wall, running at a diagonal from bottom to top. There was a gap of 1-2 mm between the dividing wall and the wall of the pot. All of the gas started out on one side of the wall at the bottom of the channel, and by the time the gas moved to the top of the channel it had been forced to move to the other side of the dividing wall. See Fig. 26. In flowing through the gap between the dividing wall and the pot the gas was forced to move close to the pot. Thus, all of the gas had to flow near the pot at least for a short time. In addition, it was hoped that this would set up some swirl in the portion of the channel that contained gas that had already moved past the dividing wall.

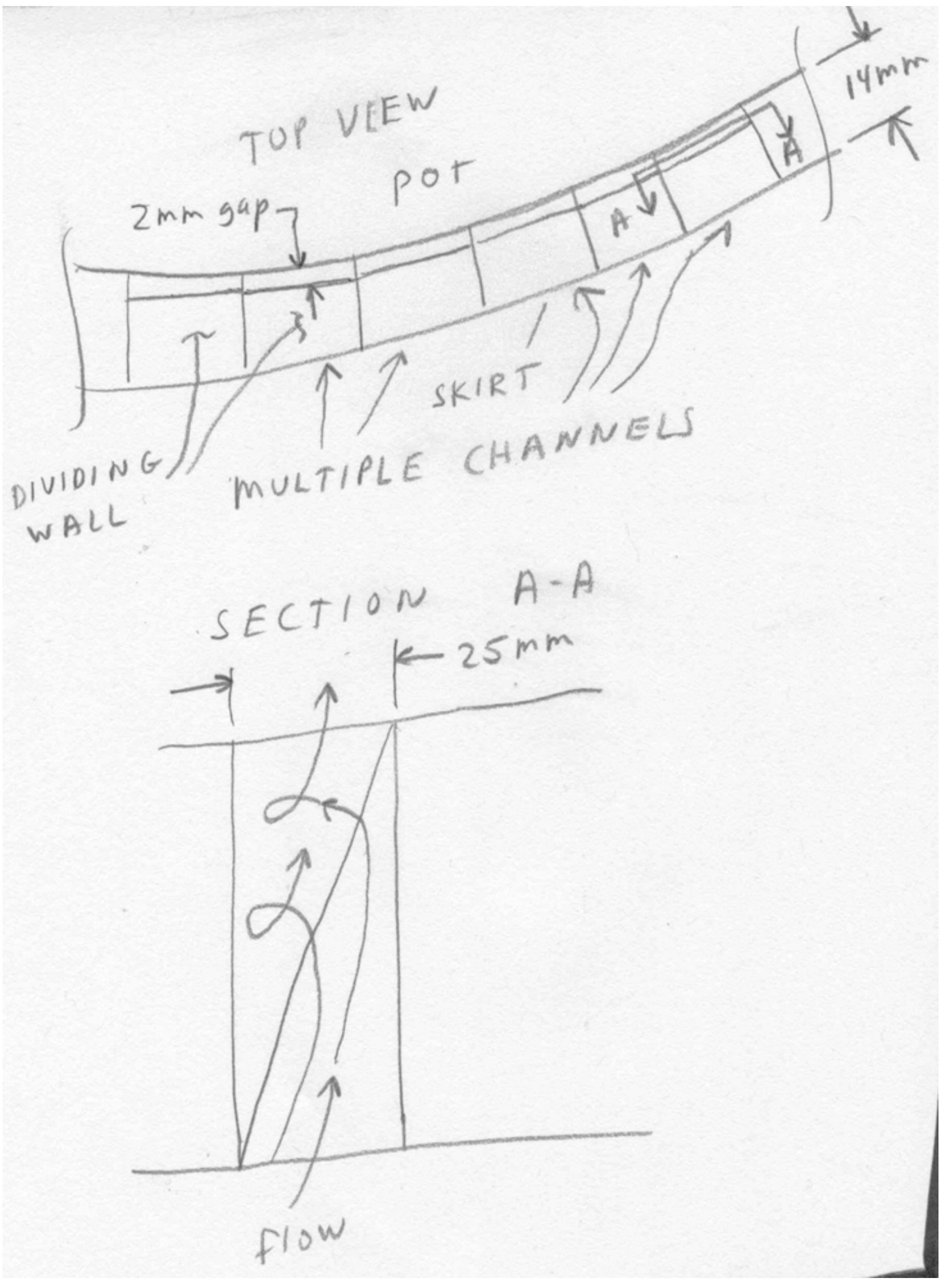

Figure 26: Sketch showing a skirt with multiple channels. In each channel the flow makes a swirling motion as it passes between the dividing wall and the pot.

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.

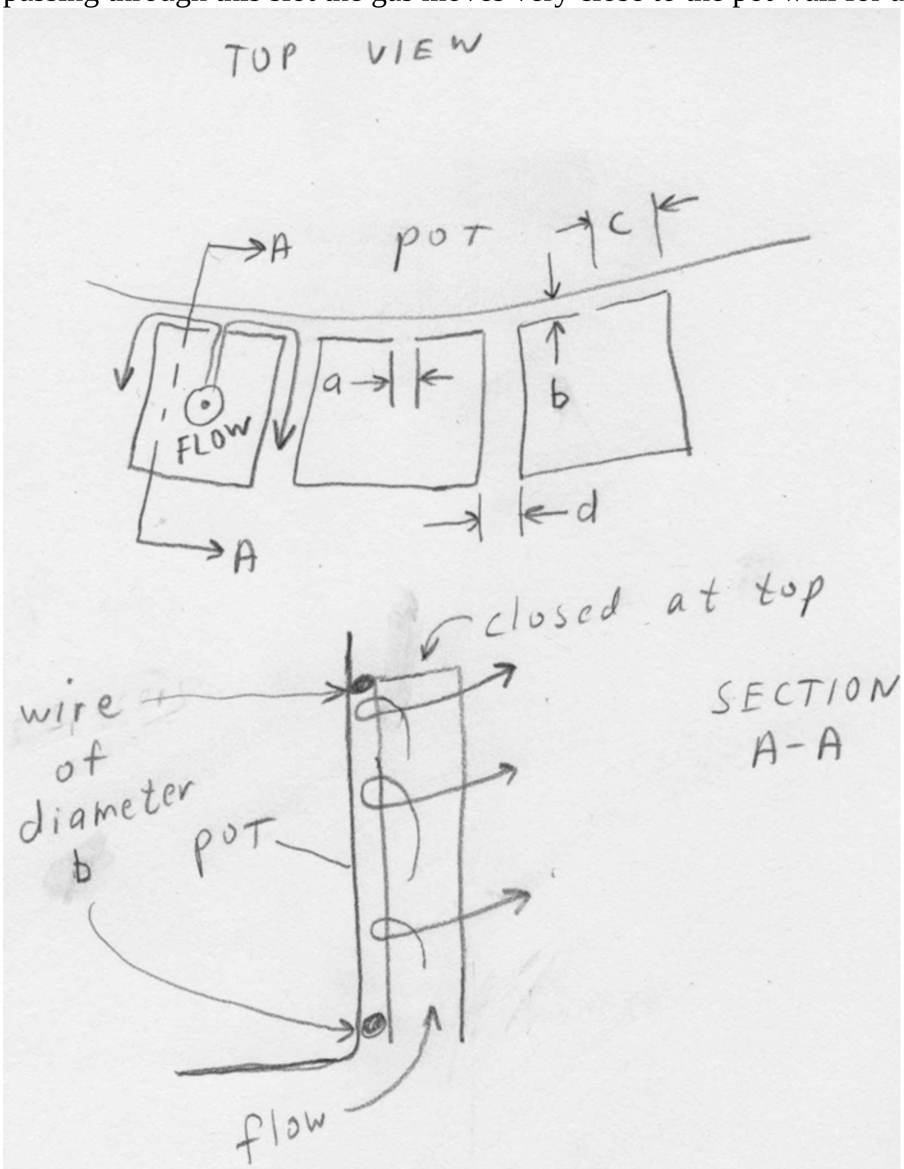

Figure 27: Sketch of a multi-channel skirt with slotted channels.

By keeping dimension b small good heat transfer can be achieved over most of the surface of the pot. By keeping dimension c small, the pressure drop can be minimized. By keeping dimension a and d about equal to 2b, the flow area will be uniform, and with perhaps one channel per 25 mm of pot circumference the flow will be about the same as with an ordinary skirt. Dimension b can be set precisely with a wire of diameter b around the pot.

The second idea was similar in that a series of channels was built. With this idea, the face of the channel toward the pot was made of perforated metal such that the hot gas passed through a series of jets impinging on the side of the pot, hopefully giving good

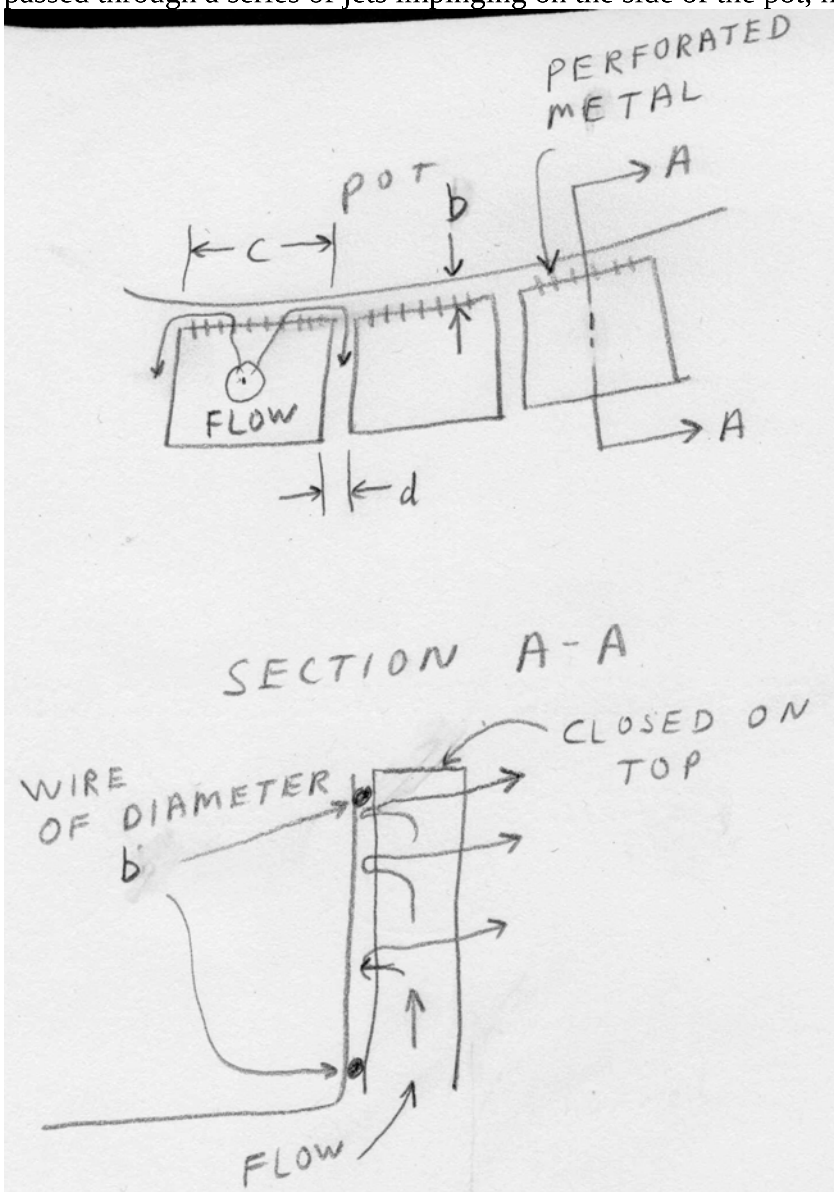

Figure 28: Sketch showing a multi-channel skirt with perforated metal in the channel wall facing the pot.

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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2. Handbook of Heat Transfer, Rohsenhow, Hartnett, and Cho, 3rd Edition, 1998, McGraw Hill, pp. 5.73-5.78.

3. Ibid, pp. 5.84-5.92.

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