Temperature and Heat Flux Distributions Around a Pot

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Introduction

Omega Engineering makes a small heat flux sensor, a thin device about 25 mm by 25 mm with 40 embedded thermocouples, which puts out a voltage proportional to the heat flux through the device. This device was used to perform a series of experiments designed to begin to answer the following questions:

1. In a cooking pot that is being heated, where does the heat enter the pot, the bottom center, bottom edges, the sides, or uniformly?

2. How much of the heat is transferred through radiation vs. how much of the heat is transferred through convection?

3. Can one measure the temperature distributions in the gas around the pot, and can anything be learned about the heat transfer from these temperature distributions?

4. Can the heat flux sensor be used to determine the effectiveness of skirts?

Heat flux is defined as heat flow per unit area, and the units are Watts/m^2. Another concept is heat flow, which is the total amount of heat being moved, in Watts. Heat flow is the integral of the heat flux over the total area, or in other words, the average heat flux times the total area.

In science, it is often useful to compare the conclusions and results with conclusions drawn from other measurements. If the measurements are consistent, this gives us confidence that the measurements are accurate. If the measurements are not consistent, the results may be reported, but the inconsistencies must also be pointed out. In this report, a rigorous effort will be made to find inconsistencies, both within the data that was measured, and in comparison with other data that was previously measured.

Test Methods

All tests were done on a “standard” pot, provided by Aprovecho. This pot had a base diameter of about 9 5/8 inches (240 mm) and the majority of the pot was blackened either by black paint or by soot for all tests. In some tests, the sensor was covered by a piece of shiny aluminum tape, so that the radiative and convective heat fluxes could be separated. In the tests with the blackened surface, the same aluminum tape was used, except that the tape was either painted or sooted over. This way, the heat transfer resistance of the tape was the same in both cases.

The sensor puts out a voltage proportional the heat flux. A multimeter was used to measured this voltage, which was typically in the tens of millivolts.

In all tests the pot contained about 4 liters of water, except in tests where the temperature rise of the water was being measured, in which case the pot contained precisely 4 liters of water. In most cases, the tests were short, usually less than 10 minutes. The water was always well below boiling. Since the temperature difference between the flame and the pot will be about the same regardless of the temperature of the water (and thus of the pot) the heat flux will change only slightly with the temperature of the water.

The sensor was located in one of 4 positions:

1. At the center of the pot bottom.
2. With the sensor on the pot bottom as close as possible to the edge of the pot without getting onto the curve at the edge of the pot (about 100 mm from the center).
3. About halfway between the previous 2 locations (about 50 mm from the center of the pot).
4. On the side of the pot about 37 mm up from the bottom.

All distances mentioned are to the center of the sensor, and as mentioned previously, the sensor was about 25 mm by 25 mm. See Figs. 1and 2 for photos of the sensor and its attachment to the pot.

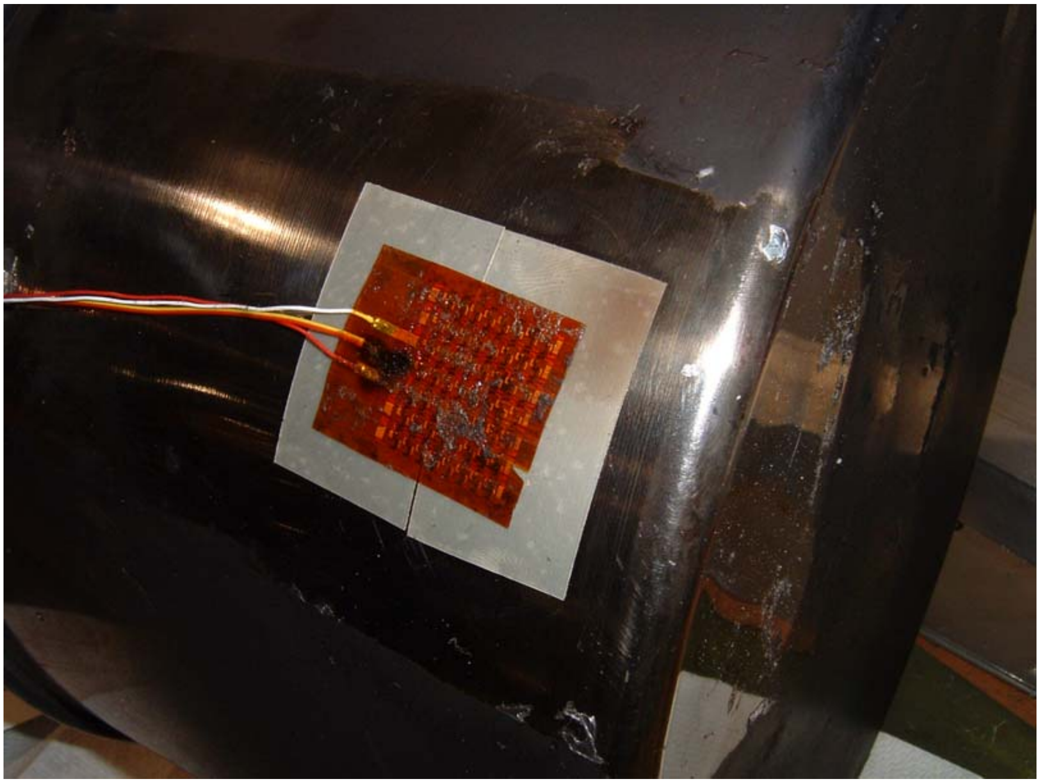

Figure 1: The heat flux sensor after attachment to the pot with high-temperature double-sided tape.

Figure 2: The heat flux sensor after being covered by reflective tape.

Two sets of test were done, the first set with an unskirted pot and the second set to determine the effects of a skirt. The skirted tests will be described in more detail in a later section.

For the unskirted pot, tests were done under 3 conditions. The first was using a simulated wood flame under medium power conditions. The simulated wood flame was a natural gas flame burning in a low speed, completely non-premixed manner, such that the character of the flame was similar to a wood flame. This method was descried previously (Ref. 1) and was chosen since the power of the flame could be easily measured and controlled. The flame was primarily yellow, and sooting could be produced under certain conditions, much like as wood flame. See Fig. 3 for a photograph of the burner with a typical flame.

Figure 3: The simulated wood flame. The flame has a "tongued" appearance due to the camera flash.

The burner was in a 12-inch (305 mm) tall by 5 inch (125 mm) diameter single wall duct with an open bottom . This simulated a rocket-type stove. The bottom was open to allow easy airflow, and the gap between the top of the duct and the pot bottom was equal to ¼ of the duct diameter (1 ¼ inches or 31 mm). The firepower level was 3250 Watts (medium power). Gas flow was controlled and measured using a rotameter, with a correction applied since the rotameter was calibrated for air rather than natural gas.

The second test condition was the same as above except at high power, 5417 Watts.

The 3rd condition was using a Fisher burner at the medium power level. Since the Fisher burner produced a much more concentrated flame than the simulated wood burner, the burner had to be farther than normal from the bottom of the pot, about 8 ¼ inches (206 mm) to keep the heat flux sensor from overheating when it was at the middle of the pot. As will be described later, the results from the Fisher burner tests were not consistent, and will be reported here in only a limited way.

Preliminary testing showed that it was necessary to have absolutely no air gaps around the sensor. As such, high temperature double-sided tape was used to stick the sensor to the pot bottom, and the aluminum tape (either shiny or blackened) was applied directly over the sensor. While these layers of tape added a little to the heat transfer resistance of the sensor, the effects on the overall results appear to be minimal.

The heat flux sensor has a built-in thermocouple that serves 2 purposes. The first is to monitor the temperature of the sensor, as the sensor has a temperature limit of 400° F (204° C). The other purpose was that the sensor is somewhat temperature dependant, and a correction factor must be applied to the heat flux based on the temperature of the sensor. The correction factor is supplied by the factory, as is the individually-measured calibration factor for this sensor.

It was difficult to move the sensor once it was in place, therefore the test sequence was organized such that the sensor would not need to be moved much. Still, the sensor was damaged after tests at the bottom edge location and before it was moved to the side location. However, there was a strong correlation between the sensor temperature and the heat flux. Plotting of 6 cases where the sensor temperature, the water temperature, and the heat flux were all known approximately simultaneously gave a nearly perfect straight line fit between heat flux on the ordinate and the difference in temperature between the sensor and the water on the abscissa. In an approximate sense, the sensor temperature serves as the heat flux sensor, at least when testing under uniform conditions. The heat flux noted later in this report for the side of the pot was measured using only the sensor temperature. This measurement should be good enough to draw general conclusions, though not as good as the direct heat flux reading.

The heat from the simulated wood flame will not be symmetric, since the burner is a pipe with a length about equal to the duct diameter. Some preliminary tests were conducted that showed that, away from the center of the pot, the heat flux was reduced was on the parts of the pot farthest from the burner, and highest when the sensor was along the burner. All tests afterwards were done with the sensor at a 45° location.

General Observations

It was observed that under all conditions, the output voltage varied considerably. Fig. 4 shows the heat fluxes at 5-second intervals for a medium power simulated wood test with the sensor near the outer edge of the bottom of the pot. There were higher frequency variations within these variations. These were noted at all positions at all power levels, using 2 different multi-meters. Fluctuations appear to be relatively larger at the larger power levels, that is, at low power the fluctuations will be smaller, but at higher power the fluctuations will not only be larger due to the increase in power, but the fluctuations will be a larger proportion of the power level. There also appear to be sensor temperature fluctuations on a similar time scale. All of this suggests that these are true variations in heat flux, not measurement errors.

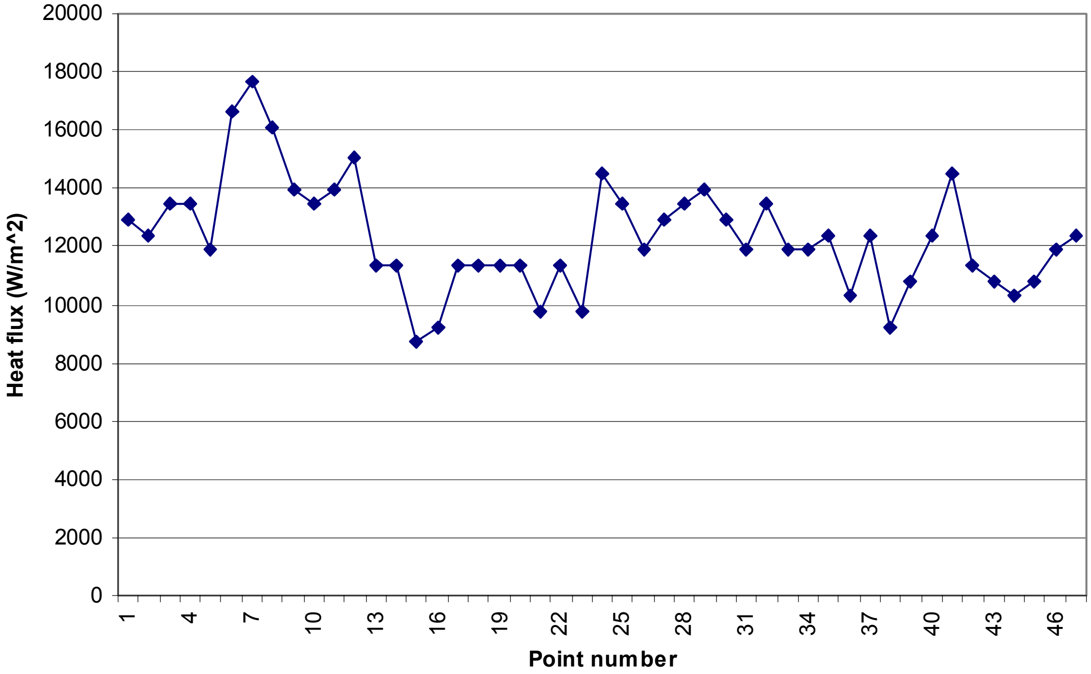

Figure 4: The variation in heat flux with time. Each point is a 5-second interval. This is with the simulated wood stove, medium power level, and the sensor near the edge of the bottom of the pot.

The average of the above measurements is 12,335 and the standard deviation is 1892, or 15% of the average. At higher power levels, the deviation seems to be an even greater percentage of the average. One can see in the above graph that the maximum flux is nearly 18,000, or about 43% higher than the average, while the minimum is about 8600, or 70% of the average.

Separation of Radiation From Convection-Theory

The radiative and convective heat transfer can be theoretically separated by considering the following. The measured heat flux at a point (or over the small surface area of the sensor) is given by the following equation:

$$q''_{measured} = q''_{conv} + \alpha q''_{incident} - \varepsilon\sigma T^4 \quad \text{(Eq. 1)}$$

where:

$q''_{measured}$ = total heat flux measured by sensor

q''_{conv} = convective component of heat flux

$q''_{incident}$ = radiative heat flux impinging on surface

α = absorptivity of surface

ε = emissivity of surface

σ = Stefan-Boltzmann constant, 5.67 E-8 W/m^2K^4

T = absolute surface temperature

The third term on the right side of the above equation represents the emission from the surface and will generally be small, but should be included to get the best accuracy. The second term above represents the radiative contribution to total heat flux, and the first term is the convective heat flux. It is assumed that the blackening agent, either soot or high temperature black paint, will have no conductive resistance to heat flux, which should be a good assumption since the layer is very thin.

The gray body assumption should be valid in this case. All radiation is long wavelength, and the shiny and black surfaces chosen tend to have constant emission/absorption properties over a wide range of wavelengths. With these assumptions, $\alpha = \varepsilon$, and both of these numbers are constant. This number will be close to but a little below 1 for the blackened surface, and close to but a little above 0 for the shiny surface. The numbers used were 0.98 for the blackened surface and 0.1 for the shiny surface.

The quantities in Eq. 1 are measured twice, once under blackened conditions and once under shiny conditions. Combining the 2 sets of values for Eq. 1, the following mathematical steps are performed:

$$q''_{measured,black} - q''_{measured,shiny} = (\alpha_{black} - \alpha_{shiny})q''_{incident} - \sigma(\alpha_{black}T^4_{black} - \alpha_{shiny}T^4_{shiny}) \quad \text{(Eq. 2)}$$

$$q''_{incident} = \frac{q''_{measured,black} - q''_{measured,shiny} + \sigma(\alpha_{black}T^4_{black} - \alpha_{shiny}T^4_{shiny})}{\alpha_{black} - \alpha_{shiny}} \quad \text{(Eq. 3)}$$

Once $q''_{incident}$ is known it is multiplied by the appropriate α to get the radiative heat flux. Equation 1 would then be used to get the q''_{conv}. Note that the sum of the radiative and convective heat fluxes will be slightly larger than the measured heat flux, since a small amount the heat is emitted (the 3rd term on the right side of Eq. 1). The ratios of the radiative heat flux to total heat flux, and convective heat flux to total heat flux can then be calculated directly.

Results of Tests on Unskirted Pot

The results are given in Figs. 5-7 for the 3 cases of interest. The horizontal axis is the “area enclosed”. In each graph, the points at 0, 0.0095, 0.036, and 0.074 square meters are the directly measured points, the remainder of the distribution is assumed.

A few words are in order about the use of area as the horizontal axis. A given point on the horizontal axis represented the amount of pot area between the center of the pot and the measured point. The 0 point is the center of the pot. The measurement point about halfway between the center and the outer edge is the 0.0095 square meter point because that is the area of the circle bounded by that radius. The measured point near the edge of the pot is at 0.036 square meters because that is the area bounded by that radius. The total bottom area of the pot is about 0.047 square meters. The effective area of the side of the pot was assumed to be about 0.057 meters. On the graphs below this is the abrupt change in heat flux at the corner. The heat flux is not expected to be the same on the side of the pot as it is on the bottom of the pot, even if the points of measurement are both very close to the corner.

Area was used as the horizontal axis rather than radial distance for several reasons. One reason was as a way of combining the effects of the pot sides and the pot bottom. Also, the horizontal axis gives a visual cue as to how much area is seeing what level of heat flux. For example, one sees that even though the flux through the side of the pot is low, the side of the pot has significant area, such that the total heat flow through the side of the pot is significant. On the other hand, even if the heat flux is very high close to the center of the pot, there is not much area there, so not much actual heat flow.

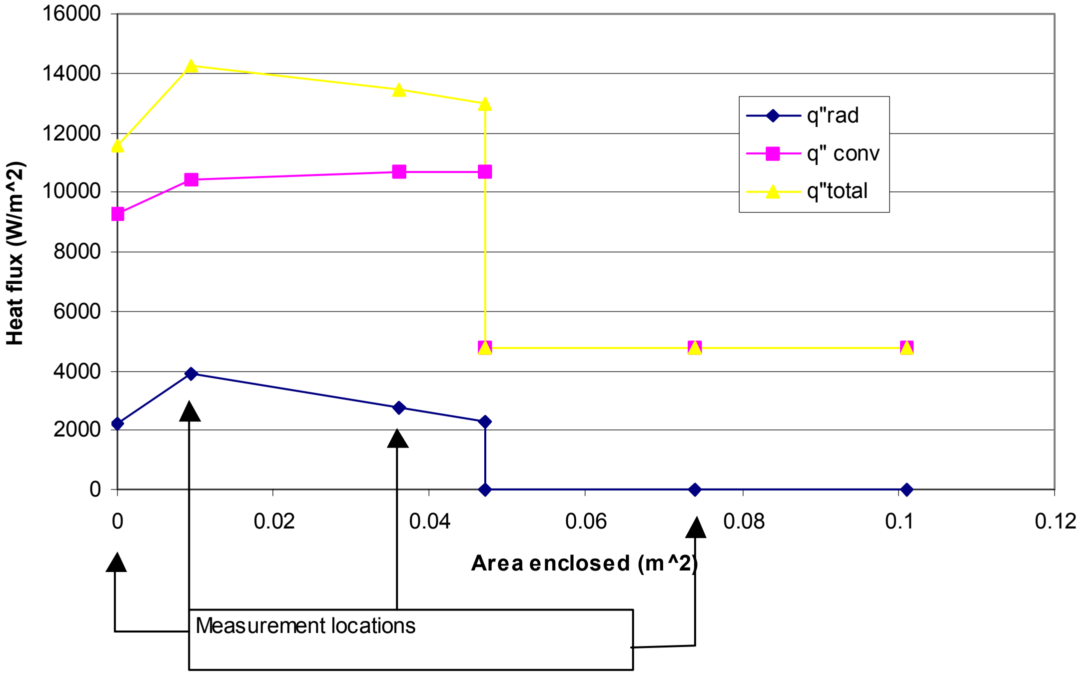

Figure 5: Heat flux for the medium power, simulated wood case.

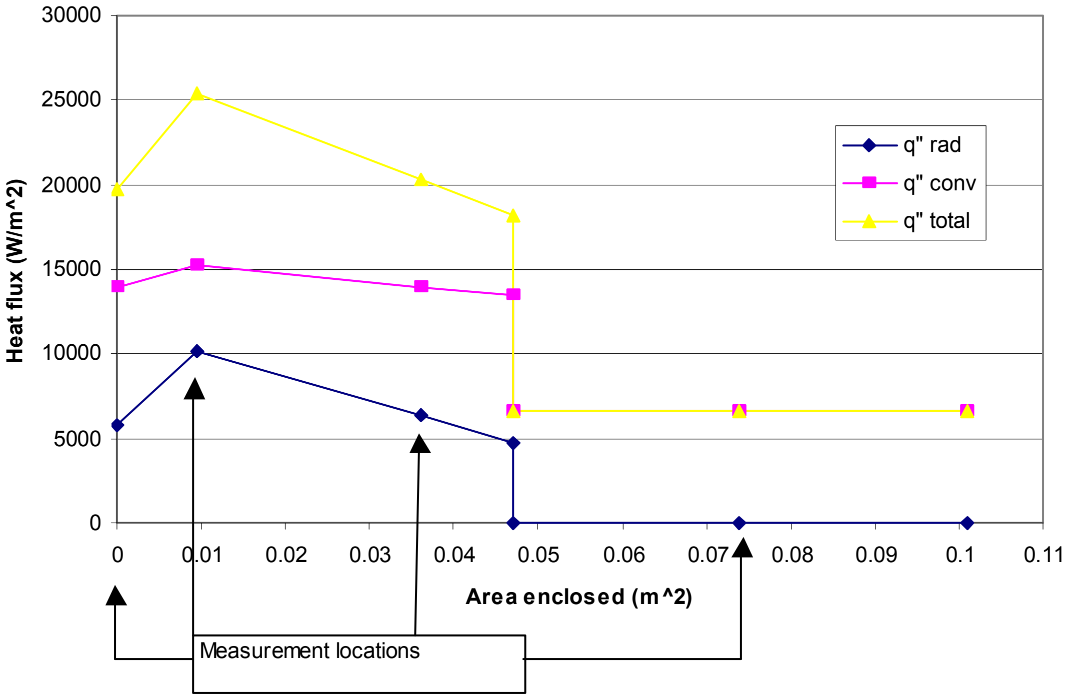

Figure 6: Heat flux distribution for the high power simulated wood case.

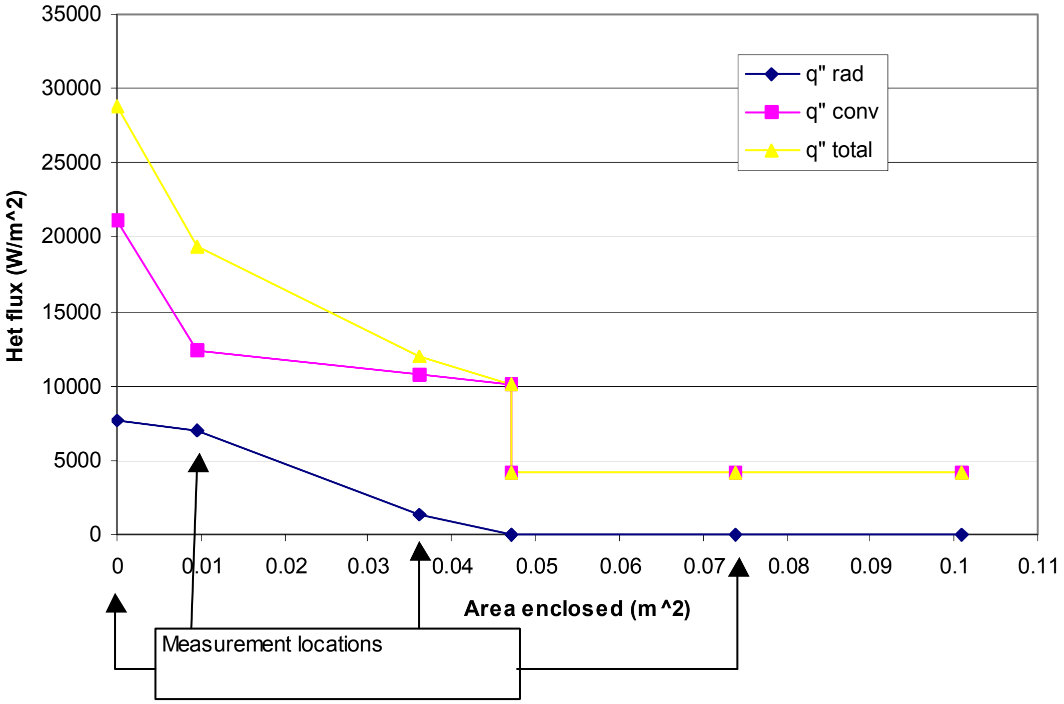

Figure 7: Heat flux distribution for the Fisher burner, medium power case.

Further, the total heat flow to the pot is simply the area under the curve in the above graphs, and this is easy to visualize and calculate.

In the above graphs we see that the radiative component of heat flux is the minority of the heat flux, but is still significant. With a true wood flame, the radiation would probably be even stronger in the center of the bottom of the pot, that is the part that "sees" the hot coals. There were no hot coals in the simulated stove.

It was assumed that the radiative component of the heat flux to the side of the pot will be very small for an unskirted pot, and is assumed to be zero. The side of the pot sees no hot surfaces, and sees only a thin layer of hot gas. As described in the section on experimental methods, by the time the sensor was moved to the side of the pot it was malfunctioning, which limited the accuracy of the measurements in this area. The heat flux measurements on the side of the pot should be accurate enough to present as a total, but not accurate enough to distinguish the difference between radiative and convective heat flux, especially since the radiative component is so small.

Even with the very clean burning blue Fisher burner flame the radiation was a significant fraction of the total heat flux. This goes against the idea that only hot soot particles (which produce the yellow color of a wood flame) radiate significant heat. As a side experiment, an infrared thermometer (a non-contact thermometer) was pointed along a horizontal line at the middle of the 8 ¼ inch plume of blue flame coming from the Fisher burner with no hot surface directly behind the flame. The temperature reading was 330°

F (166° C) which confirms that there is significant radiation coming off the flame, but it is unknown at this time exactly how this temperature correlates with radiative heat flux. The optical thickness of the flame in this direction would be smaller than that seen by the bottom of the pot. Optical thickness is a parameter that is the product of the emission per unit volume times the length of gas that is emitting.

We see that for the Fisher burner the heat flux is concentrated in the center of the pot. This would be expected given the appearance of the flame. One would typically use a Fisher burner much closer to the pot bottom, but this would overwhelm the sensor when it was at the center of the pot.

In all cases the bulk of the heat transfer is through the bottom of the pot rather than the sides, even though more than half of the area was on the sides of the pot. This was with an unskirted pot, and the effects of a skirt will be discussed in a later section. With the Fisher burner about 25% of the heat went through the sides of the pot. For the simulated wood stove at medium power about 32% of the heat went through the sides of the pot, and at high power about 28% went through the sides of the pot.

Comparison of Calculated Total Heat Flow to Heat Flow From Overall Heat Balance

One key element of the engineering discipline is that results should be correlated and checked against each other. Once the heat flux was measured as a number of points on the pot, the total heat flow could be estimated by finding the area under the curves in Figs. 5-7. This total heat flow could be compared to the heat flow directly measured by measuring the temperature rise of the water. In this case, the true "area" of the side of the pot subjected to heat transfer is difficult to estimate. Since the heat flux to the side of the pot is generally much less than through the bottom, this estimation of the area of the side of the pot is not critical.

For the simulated wood flame, there was good agreement between the estimated heat flow from the flux sensor and the heat flow directly measured, within about 5%. For the Fisher burner, however, the sensor-estimated heat flux was 50% greater than that which was directly measured. The reasons for this discrepancy are unknown. It could be that the concentrated flame from the Fisher burner makes it difficult to estimate the true heat flux distribution from only 4 points of data. Alternately, the heat flow around the bottom of the pot may not have been axi-symmetric due to the pot bottom not being perfectly level, and the flux sensor might have been on the high flux side. Hence, results for the Fisher burner should be taken as qualitative only.

Temperature Distributions

Attempts were made using a shielded thermocouple to measure the temperature near the heat flux sensor at 3, 6, 9, and 12 mm from the surface. It was hoped that this distribution could be correlated to the convective component of heat flux, and that something could be learned about boundary layers and the details of the heat transfer process.

Unfortunately, the predicted convective heat flux based on the measured temperatures was far from the measured heat flux from the sensor. The predicted heat flux was a factor of 5 to 10 times too small. The predicted heat flux was determined by 2 completely independent calculations, one based on the average temperature gradient from the 3 mm point to the surface, and the other based on the measured boundary layer thickness. Given such poor agreement, the results will not be given here, as all measured temperatures are suspect.

The Effects of a Skirt

A second set of tests was done to determine directly the effects of a skirt. All previous tests were done on an unskirted pot. The tests described here were performed as follows. A short skirt was made that was tall enough to cover the sensor mounted on the side of the pot, but not a lot more. For each test, after the device had heated up the skirt was lifted so that it no longer covered the sensor, hence the sensor heat flux would be as if no skirt were present.

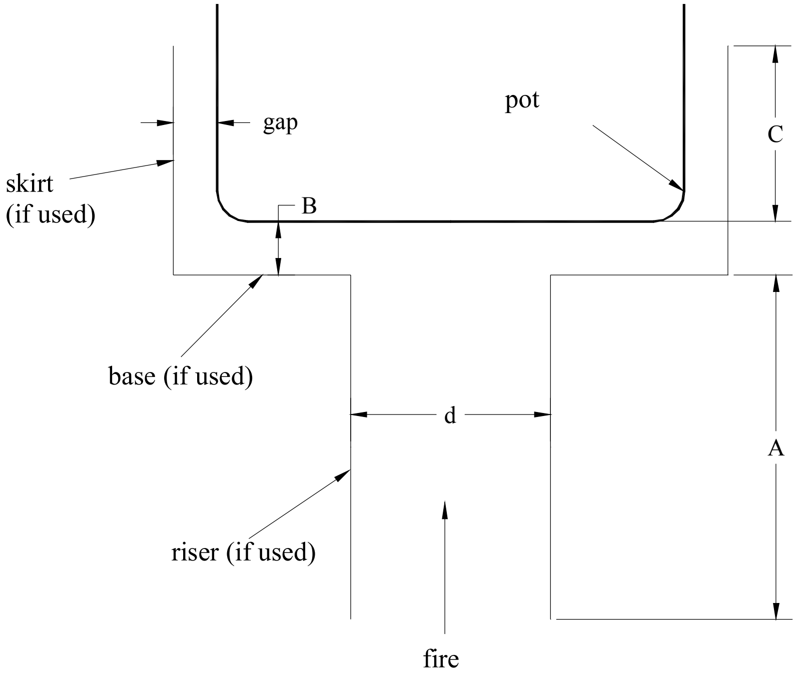

Figure 8: Overall layout of the simulated stove with skirt. Dimensions are given below.

For these tests the dimensions were as follows.

A = 12 inches = 305 mm
d = 5 inches = 125 mm
B = 1 ¼ inches = 31 mm
Gap = 0.45 inches average = 11 mm
C = 2 ¾ inches = 69 mm

The average gap around the pot was about 0.45 inches (11 mm). The inside of the skirt was blackened, and the outside was insulated by a layer of aluminum foil. The foil should greatly reduce conduction through the skirt and radiation from the skirt. While it is not a perfect insulator, it should reduce heat loss through the skirt to a small value.

The 12 inch riser was present, along with the same gas burner as with the other set of tests reported on, however the top of the riser was partly blocked. Without this blockage the top of the riser formed the minimum cross section for flow, at 19.6 square inches (126 square centimeters) which is the area of the 5-inch diameter duct. The flow area for these tests was reduced to about 10.6 square inches (68 square centimeters). The reasons for this was that it was found previously (Ref. 1) that the heat transfer is a strong function of the gas temperature, and the gas temperature is a strong function of the amount of combustion air flowing through the stove. The flow area of the skirt was less than 19.6 square inches, hence, if the top of the stove had not been blocked, the amount of air flowing through the stove was have increased when the skirt was lifted.

At the time of these tests the sensor was not measuring heat flux, so the heat flux had to be inferred from the difference between the sensor temperature and the bulk water temperature. As described previously, it was found that the measured heat flux was closely correlated to this temperature difference, so this technique should be good enough to make general conclusions.

There was also a base between the riser and the skirt, parallel to the bottom of the pot, and this was at a distance of 1 ¼ inches from the bottom of the pot.

Four conditions were tested, medium (3250 W) and high power (5417 W) and with the sensor covered by either shiny or blackened tape. The results are:

	Med. Pow. Shiny tape	High Pow. Shiny tape	Med. Pow. Black tape	High Pow. Black tape
With skirt	7800	10,100	8800	10,500
Without skirt	2100	2400	1100	1200

We see that the skirt makes a large difference in the heat flux, and that this conclusion is valid for both shiny and blackened tape. This implies that a significant portion of the heat transfer is through convection, rather than radiation from the inside of the hot skirt.

The heat flux in all 4 of these tests without a skirt is considerably less than what was measured on the side of the pot in the first set of tests. The reason for this difference is unknown, though it should be noted that the overall test configuration was somewhat different.

Comparison With Previous Research

In Ref. 1 it was said that the skirt made little difference unless it was tight enough to reduce the air flow through the stove so as to make the gases hotter. It was also reported that the benefit of the skirt was mainly in the radiation from the inside of the skirt. Both of these conclusions are not consistent with the findings in this study. This study shows the skirt makes a large difference in local heat transfer, even when the skirt is loose enough that it doesn't block the air flow. This study shows that the improvement also applied when the pot surface is shiny, hence the increase in heat transfer is not all radiative. This study made use of a more direct measurement method, hence conclusions in this study should be more accurate. Still, the effects of the skirt are not fully understood.

Another area where Ref. 1 is inconsistent with the previous results in that in Ref. 1 a set of tests was reported where 3 different sized pots were tested under the same conditions. In those tests it was found that the size of the pot made little difference to the amount of heat absorbed, which would imply that most of the heat went through the center of the bottom of the pot. That is contradictory to the current results, which show that for the simulated wood flame, the heat flux is fairly even over the bottom of the pot. Again, the reasons for the differences are unknown, but the research reported here is a more direct measurement method, which should be better.

One difference between the tests reported on in Ref. 1 concerning the effects of pot size and the current tests is that the tests in Ref. 1 simulated an open fire, with the pot far enough above the flame to minimize sooting. This means the fire was unconfined over a long vertical distance, which would entrain a lot of cool air. The current tests involved a burner in a duct, which would entrain much less outside air. Still, the reasons for the differences between tests are not understood.

Conclusions

The limited testing reported here allows several conclusions to be drawn.

1. More heat is transferred by convection than by radiation, but radiation is an important component of heat transfer.

2. For a skirtless pot, the bulk of the heat goes through the bottom of the pot.

3. The skirt gives a large increase in the heat transfer through the sides of the pot.

4. For the simulated wood flame, the heat flux is fairly uniform through the bottom of the pot; there is no outstanding hot spot on the bottom of the pot.

Reference:

1. A Report on Some Heat Transfer Experiments, Dale Andreatta, presented at the 2005 ETHOS Conference, Seattle ,Washington, www.repp.org/discussiongroups/resources/stoves/Andreatta/Cookstove%20Efficiency%20Report-January%202005.pdf

Appendix-Tips For Using the Heat Flux Sensor

It is expected that others might want to get the Omega heat flux sensor and perform their own experiments. This section is to provide some informal tips for doing so.

The heat flux sensor is available from

Omega Engineering Inc.
One Omega Dr.
PO Box 4047
Stamford, CT 06907-0047
800 826-6342
www.omega.com

The part number is HFS-4. The cost is around $130.

The most critical factor in use of the heat flux sensor is that the heat flow through the sensor must be as direct as possible, and must be in an area where the sensor itself will not have large effect on the heat flow path. In other words, the sensor has a certain resistance to heat flow, it must be used in a place where there is already great resistance to heat flow, such that the added resistance of the sensor doesn't have much of an effect. This means the sensor must be attached to the outside of the pot, not the inside. The heat transfer coefficient on the outside of the pot is much lower than the inside, since the thermal conductivity of gases is much lower than that of liquids.

The sensor must be firmly attached to the pot so as to give a very good heat flow path. At the same time, this ensures that the sensor won't get much hotter than the liquid in the pot. The method I used is as follows. Attach to the pot some double sided high-temperature tape. One good type is sold by:

McMaster Carr
(Los Angeles Sales number) 562 692-5911
Item # 77215A13

This tape is expensive, about $60 for 36 yards, but will withstand the high temperatures that the sensor will see, and will also peel off fairly easily with little residue. For removing residue, acetone and a little rubbing will remove any paint or tape residue I've come across.

After the tape is applied to the pot, the sensor is applied to the tape, as seen in Fig. 1. If one is only interested in total heat flux, the pot may be used as is, and since the sensor is firmly held to the surface of the pot, the pot will keep the sensor below its 400° F temperature limit. (Actually the sensor can go above 400° for short periods of time.) The sensor may get blackened with soot, though this can usually be wiped away easily.

If one wants to study radiation and convection separately, as in this study, aluminized tape must be applied over the sensor. A high temperature tape is needed. Some forms of aluminum tape are plastic tape that are coated with a shiny surface. These do not withstand high temperatures. The kind of tape to use is the kind that is aluminum metal, covered on one side with adhesive.

In retrospect, a different procedure should have been used for attaching the aluminum tape. Two pieces of tape should have been used, one cut precisely to cover the sensor but nothing else, and a second piece to hold down the sensor leads. This would eliminate the possibility of the tape conducting heat parallel to the pot surface and around the sensor.

One might question the need for the double sided tape between the pot and the sensor. In a preliminary experiment, the double sided tape was not used, and since the sensor itself is not sticky, a small gap opened up between the sensor and the pot. This gap reduced the heat flow by a factor of about 4.

One might permanently attach the sensor to the pot using a number of conductive adhesives. These should work well, though they might make it impossible to remove the sensor. Ultimately, it would be best to use a single pot with multiple sensors, permanently attached. This would eliminate the need for removing sensors, but more importantly it would allow the taking of data from multiple places at the same time, which is important when working with a wood fire, which is never constant. (The natural gas flame used for these tests is much easier to control so as to burn at a constant rate, and to be constant between tests.)

The sensor can be removed, but must be carefully cut from the pot using something like a razor blade. There is a limited number of times the sensor can be cut from the pot before it starts to get cut up. Experiments must be planned carefully. My sensor was applied and removed 4 or 5 times and then tore, making the heat flux function unusable.

To use the sensor a good voltmeter or multimeter can be used to read the voltage output of the sensor. For stove types of conditions, the output is usually 20-60 mV, which is easily measurable by a number of instruments. There appears to be a lot of fluctuation in the measurement (see Fig. 4) even under the steady conditions of a Fisher burner. This seems to be actual fluctuation in the heat transfer, since the temperature of the sensor fluctuates as well.

When measuring heat flux, the temperature of the sensor should also be monitored and recorded. There are 2 reasons for this. First, the sensor should be prevented from going much over its 400° F limit (which is also the temperature limit of the grade of tape available from McMaster Carr). The second reason is that there is a small correction factor that must be applied to the sensor, based on its temperature. This correction graph will be on the certification sheet that comes with the sensor.