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WOOD AND SOLID FUEL HEATING IN NEW ZEALAND

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ABSTRACT

A new method for in-situ monitoring of solid fuel burners has been developed that is cheap and easy to install and calibrate. This method was used to monitor 244 solid fuel burners in houses, estimating their heat output at 10 minute intervals. Nationwide solid fuel use was shown to be 20% of residential energy consumption, four times higher than the official statistics, and is the dominant fuel source for space heating in New Zealand.

Keywords: Wood, Coal, Solid Fuel, Household Energy End-use Project (HEEP), Space Heating.
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INTRODUCTION

Although there have been large reductions in wood and coal use due to air pollution concerns and by competition from other fuels, even in developed countries solid fuel is still a major source of heating. In some countries wood (and more recently processed wood such as wood pellets) is seen as an environmentally preferable fuel choice. New efficient wood burners have been developed while inefficient and polluting open fires have been largely phased out or banned altogether in many locations.

Despite the obvious importance of solid fuel as a domestic energy source, there has been little research into its energy use. Most research has been to gain information on the sources of air pollution and is largely restricted to surveys or interviews, or the monitoring of particulate and pollutant emissions. Such surveys can rely on the house occupants to estimate the use by volume or weight of wood – in terms of number of pieces or number of baskets, or quantity of wood acquired for the heating season.

In New Zealand, Lamb (2005) used written diaries for the house occupant to report the weight of wood or coal burned during a two week period in winter of houses in Christchurch. Wilton (2005) conducted a nationwide survey of solid fuel use, using a similar methodology. They both used Lamb’s (2005) same fixed log and basket weights, which is questionable as the log and basket weights in Christchurch (one city) may not be the same as in other parts of New Zealand. Christchurch has a relatively cold climate, so if the log and basket weights are higher than average this might lead to an overestimate of national wood fuel use.

Whilst occupant self-reported wood use can give a rough estimate of the quantity of wood (provided the data collection is designed and implemented well), it is difficult to convert this to accurate estimates of space heating energy output for four main reasons: 1) The volumetric energy content of wood varies widely by species, and since most self-report studies use volume (e.g. a basket) the species needs to be known if accurate estimates are to be made. If the weight of wood is known, the net energy content per kg varies little between species for dry wood (Isaacs et al, 2005; sec 6.6). 2) The moisture content has a large effect on the net heat output and this is usually unknown, even if the wood is considered well seasoned. 3) The actual efficiencies of solid fuel burners in use will not always be the same as under laboratory conditions, particularly if the burner is run at low heat outputs, operated poorly, or has not been well maintained. 4) Some occupants do not provide reliable estimates of wood use. Together, these factors make the calculation of heat output from self-reported wood use highly inaccurate.

Measuring the energy input or output of a wood burning appliance in-situ is difficult and it appears that few researchers have attempted it. Modera and Sonderegger (1980) developed a method to measure the in-situ efficiency of fireplaces by maintaining constant temperatures with electric heating balancing fireplace heat output fluctuations, and monitoring air infiltration (natural and forced) and environmental parameters. A heat balance calculation was used to calculate the net efficiency of the fireplace (including infiltration losses forced by the fireplace), which ranged from 5.8% to 31.5%. The net efficiency of open fireplaces was found to be 5.8% to 6.6%, with higher efficiency for partially and fully enclosed fireboxes.
Modera, Wagner and Shelton (1984) developed a relatively simple method for monitoring the heat output of a stove using only one temperature sensor – either a radiometer or surface temperature. In this method the correlation between the stove temperature and the heat output was established, and this correlation predicted the heat output with an accuracy of about ±20% over the full range of the stove. The heat outputs were measured with the stove installed in a room-size calorimeter. To use this method in actual houses would have to rely either on a laboratory calibration of a similar unit, or on a calibration in the house, possibly using the techniques developed by Modera and Sonderegger (1980).

This method was further developed by Modera (1986) to be applicable for stove models that were not tested in the calorimeter. An equation using the stove surface area, ambient temperature, and one or more representative surface temperatures was derived to predict the heat output of the stove (Equation 2). Comparison with calorimeter measurements demonstrated that the method underestimated the heat output by on average 8%, and a variation between stoves of 15%, based on testing of four stoves.

This method and householder reporting was then used to monitor wood use in 100 homes in the Hood River Conservation Project (Tonn and White 1989). The average annual heat outputs were 6,680 kWh before and 4,820 kWh after retrofit. Comparison of the household reports of wood use and the monitored wood use indicated that the householder reporting was unreliable, with a poor correlation (~0.15) found between reported cords of wood used and energy output. This shows that self-reported wood use is an inaccurate way of estimating energy output, which matched our experience (Isaacs et al, 2005; sec 6.6).

Wood stove usage was monitored in the End-Use Load and Consumer Assessment Program (ELCAP), using thermocouples to determine if the stove was in use or not. Only the frequency of use was monitored, with no information recorded on the heat output (Pratt et al 1993).

**METHOD**

At the time of the Household Energy End-use Project (HEEP) pilot program (1995–1997) the various methods used by other researchers were investigated, but none offered a reasonably inexpensive, reliable and accurate method that could be quickly installed. Modera’s (1986) method was tried, but this was unsuccessful as the calculated heat outputs apparently exceeded the calorific value of the wood used.

In some of the early HEEP pilot houses, Industrial Research Limited undertook in-situ efficiency calibrations on some burners (Sloecklein and Isaacs 1998). The house occupant was asked to keep a written record of the fuel use, which could then be used to calculate the heat output using the calibrated efficiency. Typical pieces of wood were weighed and designated as small, medium or large, and baskets of wood similarly weighed. A thermocouple data logger was also connected to the wood burner (usually in contact with the flue) to monitor the burner use. It was hoped that the wood burner temperature would relate to the wood use.
Unfortunately the method had many uncertainties that would not have been found in laboratory testing. The accuracy of the log books was not as high as hoped and the weight estimates were not helpful, and the wood species and moisture content was usually not known. This eventually became a semi-manual process, comparing logbooks with the monitoring. The results were not acceptable and the cost of the efficiency calibration was too high for large-scale use.

At the conclusion of the pilot program we did not have a suitable method for determining solid fuel energy use. It was decided to continue with log books and burner surface temperature monitoring in the hope that a suitable analysis method could be developed.

Several further attempts at analysis were made over the ensuing years, with none being fully successful (Stoecklein et al 2001). The final breakthrough came with the convergence of several other analyses in HEEP. The simple thermal model that was used previously was refined, and more experience gained in how to cope with poorly quantified loads such as solar gains. Good estimates of the unmonitored heating were therefore possible. The quality of the monitored data was also enhanced by an improved thermocouple and data logger calibration process, and data inspection.

**ESTIMATING UNMONITORED HEAT LOADS**

The unmonitored heat loads were estimated by using the room or house as a calorimeter. If the U-value and thermal mass of the room are known, and the internal and external temperatures are measured, then the net energy input to the room or house can be estimated. By subtracting the monitored energy input, and making allowances for internal gains (e.g. hot water standing losses and metabolic gains), the difference at night time (i.e. no solar gains) can be attributed to the solid fuel burner.

The U-value and thermal mass were calculated from using ALF3 (Stoecklein and Bassett 1999). House plan details, construction type, climate, window and wall areas, and insulation levels were input into ALF3 which calculated an overall envelope loss including infiltration losses. Generally the whole house was used, as energy loads cannot normally be localised to specific rooms, although a smaller zone could be used for calibration e.g. top storey only. The internal temperature was usually a simple average of the two living room and one bedroom measurements. Where appropriate, a floor weighting was applied if the bedroom areas were much larger than the living room areas, but this was decided on a case-by-case basis and documented in the analysis.

The internal loads were usually calculated from the overall total load for the house (including gas and electricity) minus the hot water load. The internal load then had metabolic loads added (based on the occupants’ age and sex, time spent in the house, and bedtimes), and hot water standing losses (if the cylinder is located within the thermal envelope). In some cases, other particular loads may have been removed from the whole house energy use e.g. garage or spa pool. Again, this was carried out on a case-by-case basis.

These parameters were then used to make estimates of the missing heat load using the STEM (Short Term Energy Monitoring) methodology (Shorrock, Henderson and Brown, 1991) which treats the house as a thermal circuit with one heat loss element and one heat storage element. The process is described in detail in (Stoecklein and Isaacs 1998) and Stoecklein et al (2001).
The STEM modelling equation is:

\[ q_{\text{heat}} = UA \cdot (T_{\text{in}} - T_{\text{out}}) + mC_p \left( \frac{\partial T_{\text{in}}}{\partial t} \right) \]

Equation 1

where:

- \( q_{\text{heat}} \) = Heat delivered to house interior by internal gains and heating (W)
- \( UA \) = Whole house heat loss coefficient (W/°C)
- \( T_{\text{in}} \) = Interior air temperature (°C)
- \( T_{\text{out}} \) = External air temperature (°C)
- \( mC_p \) = Thermal mass of the house (Wh/°C)
- \( \frac{\partial T_{\text{in}}}{\partial t} \) = Rate of change of interior air temperature (°C/hr).

**ACCURACY OF ESTIMATION OF UNMONITORED HEAT LOADS**

To estimate the accuracy of the calibration process, all the HEEP houses with large monitored heaters (e.g. natural gas heaters) were put through the same type of processing. The results for one house are shown in Figure 1. The top plot of the figure is from the 10 minute monitored data. It has a lot of scatter as the heater is controlled by switching on and off a large burner and the house also has a gas instant water heater, which when subtracted from the total gas use creates further scatter. To estimate the slope of missing heat load to measured heat load, the data are aggregated in 100 W bins as shown in the lower plot. The fitted line is from a least squares linear regression with each point weighted by the number of points in each bin, fitted to all the data points. The slope of this line is 0.85, so the missing heat load is 85% of the monitored heat load. The monitored heat load is a gross energy, and the net heat output of a gas heater would be 80–90% of that figure, so a slope of 0.85 is good. As the method works acceptably for the monitored heating fuels, it is reasonable to assume that it will work for unmonitored solid fuel load.

![Figure 1: Test calibration of gas heated house – House 1.](image-url)
This process was repeated for a number of other houses, and the results compared to estimate the accuracy of this process (see Table 1). If the calibration is accurate and the fuel has 100% conversion efficiency into heat in the house, the slope will be equal to 1.

<table>
<thead>
<tr>
<th>House</th>
<th>Gas heater slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.85</td>
</tr>
<tr>
<td>10</td>
<td>0.67</td>
</tr>
<tr>
<td>11</td>
<td>0.64</td>
</tr>
<tr>
<td>12</td>
<td>0.72</td>
</tr>
<tr>
<td>13</td>
<td>0.81</td>
</tr>
<tr>
<td>14</td>
<td>0.43</td>
</tr>
<tr>
<td>17</td>
<td>0.52</td>
</tr>
<tr>
<td>19</td>
<td>1.13</td>
</tr>
</tbody>
</table>

Table 1: Calibration slopes

The average slope of the gas heaters is 0.72 ± 0.22, using the sample standard deviation (SD). The precise efficiency of these gas unit heaters is unknown, but likely to be around 80%. Assuming it is 80%, the average of the calibration slopes is 0.9 ± 0.1 (SD of the mean), which is not significantly different from 1. This demonstrates that there is not a large systematic bias caused by the calibration process. The standard error in the calibration for a single heater is ± 0.18 or ± 20%.

CALIBRATION OF SOLID FUEL BURNERS

The calibration data for the solid fuel burner from House 2 is presented as an example (Figure 2). A plot of the 10 minute solid fuel temperature shows the correlation with the missing load. Interestingly it is very close to linear, despite the theoretical fourth order dependence of radiant heat output on temperature. This may be due to the relatively small range of absolute temperature (from about 350K to 600K), and the fact that the thermocouple measures flue temperature which may not be in a direct relationship to the firebox temperature, or to the convective heat output of the burner. A few solid fuel burners do show some curvature, and for these a second order polynomial was fitted.

The solid fuel calibration slope was taken from a weighted linear regression fit of the data grouped according to the solid fuel temperatures in 10°C bins, using only data from 50°C and above. The intercept was then adjusted so that the output of the solid fuel burner is 0 W at 17.5°C – a typical average indoor ambient temperature during winter heating periods. For the example in Figure 2 the parameters were – 92.1 + 11.0× MonitoredTemperature. For this burner, the maximum 10 minute average heat output was about 3.5 kW.

NET TO GROSS CONVERSION EFFICIENCIES

HEEP uses gross energy data, so the net energy output estimates need to be converted. Table 2 gives the assumed conversion efficiencies (Isaacs et al 2006):
Efficiencies of modern enclosed burners are often tested at 60–70% or higher. The average label efficiency of the HEEP monitored wood burners was 63% on low, 68% on medium, and 64% on high. The average space heating efficiency of solid fuel burners approved by Nelson City Council is 71%. Since most solid fuel burners in HEEP are not the new, clean air-approved types, the low efficiency setting of the basic type was used, and de-rated slightly to 60% to reflect lower efficiency in use at low heat outputs.

**DIFFICULT HOUSES**

As is usual with field experiments, some difficulties were encountered. A few houses give a very poor correlation between the solid fuel temperature and the missing load calculated for the whole house. This can be due to the other energy uses in the house being large compared to those in the room with the solid fuel burner. The way to solve this problem is to use the room that the solid fuel burner is located in, rather than the entire house, and to only include metered loads that are known to be released in this room. This in effect uses one room as a calorimeter, rather than the whole house. In most instances a satisfactory calibration could then be performed.

**COMPARISON WITH MODERA (1986)**

For a selection of solid fuel burners the calculations using the equation of Modera (1986) (Equation 2) were compared to the outputs calculated using the HEEP method:

\[
Q = A_s \left\{ \varepsilon_s \sigma \left( T_s^4 - T_a^4 \right) K' \left( \frac{T_s - T_a^{9/3}}{T_s + T_a^{2/3}} \right)^{0.41} \right\}
\]

Equation 2

Where:
- \( Q \) = Total heat flow from the surface (W)
- \( \sigma \) = Stefan-Boltzmann constant, 5.67×10^{-8} W/m²K^4
- \( A_s \) = Surface area of the burner (m²)
- \( \varepsilon_s \) = Emittance of surface
- \( T_s \) = Absolute temperature of surface (K)
- \( T_a \) = Absolute temperature of ambient surroundings (K)
- \( K' \) = Dimensional constant: value = 15.9 W/m²K^{0.92}

This equation, when plotted with typical values for the temperatures and a realistic emissivity of 0.8, gives the plot of heat output per m² versus temperature in Figure 3. This plot has pronounced curvature, which was not seen in most of the HEEP calibration curves. Only 20% of the HEEP calibration curves were fitted with second order polynomials, usually with only modest curvature, and 80% using the heat output as a linear function of the temperature.

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1 [www.nelsoncitycouncil.co.nz/environment/air_quality/burners_approved_table.htm](http://www.nelsoncitycouncil.co.nz/environment/air_quality/burners_approved_table.htm)
A variety of HEEP solid fuel burner heat outputs were compared to the method of Modera (1986). In general, Modera’s method gave an overestimate of the heat output, with larger overestimates for larger heat outputs due to the non-linear heat output. A typical example is given in Figure 4. HEEP usually monitored flue temperatures, which are usually lower than firebox surface temperatures, so the actual estimates using Equation 1 should be even higher. Several adjustments were made to try to reconcile the estimates. Reducing the solid fuel burner flue temperature for calculation (as a set fraction of the difference between ambient and flue temperatures) reduced the difference between the two methods (Figure 4 ‘Low Temperature’ points). At a value of about 0.7 times the (flue – ambient) temperature the curvature was reduced somewhat, and the overall average heat output was much closer. Removing the radiant heat term reduces the curvature, however the heat output then becomes an underestimate (Figure 4 ‘Low Temperature, no radiant’ points).

The difference seems likely to be due to the typical solid fuel burner in HEEP and the types of stoves used by Modera (1986). The stove types used by Modera (1986) assumed that the stove was a simple firebox with the firebox as the main radiant and convective heating surface. Most of the solid fuel burners found in HEEP are double burners, which use an efficient double burning combustion process that may lead to a larger variation of temperatures between surfaces than a single burning process. The ceramic lined firebox is also surrounded by a separate steel box separated by an air cavity. This traps some of the radiant heat in the cavity, giving a lower surface temperature to the exterior, which is safer for people and for fire risk, and allows smaller clearances to combustible materials and acts as a convective cavity. Most enclosed wood burners also have a window which radiates some heat directly. These differences may mean that the assumption of Modera (1986) that a single temperature can be used to characterise the burner surface is invalid and a more complex model may be required.

It appears that the HEEP solid fuel burners are, in general, producing a larger fraction of their heat output as convective heat than the wood stoves used by Modera (1986) and with a lower radiant external surface temperature. Using a lower surface temperature in Equation 1 in some way compensates. However, the actual physics of the heat transfer process may not be described properly by this equation.
RESULTS

The average annual energy consumption of HEEP houses that use an enclosed solid fuel burner was 4,500 kWh. Some houses have more than one solid fuel burner but generally the second one (often an open fire) is used infrequently. Open fires may have very high gross energy consumption as their efficiency is very low (see Table 2).

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy per appliance (kWh)</th>
<th>SE</th>
<th>Energy per house (all houses) (kWh)</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open fire</td>
<td>995</td>
<td>285</td>
<td>100</td>
<td>36</td>
</tr>
<tr>
<td>Enclosed burner</td>
<td>4,480</td>
<td>415</td>
<td>2,075</td>
<td>256</td>
</tr>
</tbody>
</table>

Table 3: Annual gross energy input by appliance type

There are major differences in energy consumption by region, as shown in Table 4. The warm and cool clusters are small towns and rural areas, split at 900 heating degree days base 15°C, and together represent roughly half of New Zealand households. Energy consumption of solid fuel is much higher in colder climates, as solid fuel burners are both more common and more intensively used.

The average energy consumption of solid fuel for all houses is 2,150 kWh ± 250 kWh per year. This is about 20% of all domestic energy consumption (electricity, gas, LPG, and solid fuel). The Energy Data File *Energy Supply and Demand Balance June Year 2004* (MED 2005) estimated solid fuel use (coal + wood = 2.9 PJ) at 5% of energy consumption in domestic buildings. The HEEP results have been used to update these national statistics so solid fuel is now 14% of domestic energy use (MED 2006; Isaacs et al 2006). More than half of all New Zealand residential space heating is from solid fuel.

<table>
<thead>
<tr>
<th>Location</th>
<th>Heating degree days, base 15°C</th>
<th>Energy per household (kWh)</th>
<th>SE</th>
<th>Energy per household using solid fuel (kWh)</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auckland</td>
<td>670</td>
<td>810</td>
<td>230</td>
<td>2,690</td>
<td>650</td>
</tr>
<tr>
<td>Hamilton/Tauranga</td>
<td>930</td>
<td>1,160</td>
<td>440</td>
<td>2,740</td>
<td>860</td>
</tr>
<tr>
<td>Wellington</td>
<td>1,120</td>
<td>240</td>
<td>100</td>
<td>850</td>
<td>290</td>
</tr>
<tr>
<td>Christchurch</td>
<td>1,470</td>
<td>1,220</td>
<td>390</td>
<td>2,440</td>
<td>670</td>
</tr>
<tr>
<td>Dunedin/Invercargill</td>
<td>1,730</td>
<td>1,870</td>
<td>630</td>
<td>3,740</td>
<td>940</td>
</tr>
<tr>
<td>Warm cluster</td>
<td>670</td>
<td>1,830</td>
<td>290</td>
<td>3,520</td>
<td>440</td>
</tr>
<tr>
<td>Cool cluster</td>
<td>1,240</td>
<td>3,980</td>
<td>710</td>
<td>5,320</td>
<td>880</td>
</tr>
</tbody>
</table>

Table 4: Variation of gross annual solid fuel energy consumption by location

Roughly 5% of the total amount of solid fuel consumed is used in open fires, which are very inefficient and much more polluting than enclosed wood burners. However, a high proportion of open fires are not used, or used only a few times per year.

An enclosed wood burner can put out large amounts of heat, typically around 15 kW for a mid-sized burner. However, the HEEP monitored heat outputs are much lower – typically in the 0.5 to 4 kW range and two-thirds of enclosed solid fuel burners never exceeded a 10 minute averaged 4 kW output. This is lower than the rated minimum heat
output, and the efficiency of these solid fuel burners at this heat output is likely to be lower than typical test results with higher pollution levels. Recently introduced clean air requirements for solid fuel burners may be compromised by being used at such low heat outputs.

CONCLUSIONS

A practical method of estimating net heating energy has been developed and demonstrated to work with an accuracy of about ±20% by calibration against monitored gas and electric heating under normal, occupied house operation. For solid fuel burners the monitoring uses a single thermocouple plus monitored temperature and energy data, with house physical parameters based on a site survey. This method has been implemented on a large scale and it has been found that the installation and calibration time for each solid fuel burner is 30-60 minutes. The method failed in only a small percentage of cases.

The calculation method of Modera (1986) has been shown to overestimate the heat output of modern solid fuel burners, due possibly to their different design. As a single temperature was used to predict the heat output, it seems possible that different equations could now be developed based on the physical characteristics of the burners. The wide variation in solid fuel burner designs, the effect of the double burning chamber and the patterns of use makes the development of a similar model outside the scope of this study.

Occupant self-reported wood use surveys do not give reliable estimates of heat output, particularly if sub-seasonal data are required. Field monitoring based on our new method gives more reliable estimates, energy time-of-use information and quantifies the heat output. Generally the heat outputs are well below the levels used for laboratory testing.

One result of this work has been changes to the official New Zealand Government energy statistics. Solid fuel heating now accounts for about 20% of domestic sector energy consumption, so important that a change in policies is now required to ensure its contribution is included in long-term energy policy and planning.

REFERENCES


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