Woodstove Comparative Testing to Determine Fuel Savings with the Use of a Thermoelectric Fan to Maintain Thermal Comfort

Viqar Haider, Mojtaba Pourvash, Dale Schnurr,
Caframo Ltd.
Wiarton, ON Canada N0H 2T0

Richard Culham, Peter Teertstra
Department of Mechanical & Mechatronics Engineering
University of Waterloo
Waterloo, ON Canada N2L 3G1

ABSTRACT

An experimental study is presented that provides credible evidence that the use of a thermoelectric fan on a wood stove reduces the amount of fuel required to maintain a prescribed level of thermal comfort. Test procedures and protocols based on existing standards and norms have been incorporated into a test facility that allows for a detailed examination of the dynamic heat transfer characteristics associated with woodstove operation in a controlled environment. Experimental results are validated using numerical simulations that further substantiate that the test findings show that the use of a thermoelectric fan during woodstove operation provides an average fuel saving of 14% for a range of test conditions studied while maintaining user comfort levels over extended periods.

INTRODUCTION

Rising fuel costs have increased the demand for efficient, solid fuel appliances as well as the associated consumer products that promise to enhance and improve the thermal performance of these appliances. These enhancements and improvements are ultimately designed to reduce fuel consumption and operating costs. Most wood stove manufacturers suggest that fuel usage can be improved, by installing a blower or a fan to redistribute the heat trapped at the back of the stove thereby improving the conditions for convective heat transfer. This will result in a more uniform heating of the room that feels more comfortable to occupants.

A review of existing standards and methodologies determined that there are no commonly accepted standard tests for conducting comparative testing of solid fuel appliances and associated consumer products, in “real life” conditions. The existing methodologies are primarily legislative driven and are directed at determining burn rates and/or stack emissions. The development of comparative testing procedures for wood stoves in “real life” situations is very complicated, as the operation of wood stoves is dynamic and steady state conditions are rarely achieved and measured values constantly change. Therefore, analyzing data to determine comparative results becomes very complicated due to the variability of the data.

In developing a standardized test methodology to properly address this situation; existing standards including “ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy”[1] “EPA Method 28 Certification and Auditing of Wood Stoves”[2], and “ISO 7730:2005, Ergonomics of the Thermal Environment”[3] were used as guidelines.

TESTING PROCEDURE

The main focus of this testing is to determine the amount of fuel that could potentially be saved by maintaining a comfortable thermal environment for occupant through comparative testing with and without a thermoelectric fan. Most wood stove manufactures and consumers anticipate that a fan-assisted woodstove leads to improved thermal performance based on the fact that forced convection heat transfer induced by a fan, redistributes the warm air that is trapped around the wood stove, as well as the stagnant warm air at the top of the room. However, few studies have been performed in a controlled study to substantiate this belief. To investigate improved thermal comfort, ASHRAE Standard 55-2004 [1] guidelines was referenced in designing a controlled test facility in which air temperature, humidity and velocity sensors were installed to evaluate the thermal comfort level. The test facility, thermal environment, testing methodology and procedures are outlined as follows.

Test Facility

The test facility used in this study consists of a 9.75 meters long by 6.4 meters wide by 2.4 meters high room, constructed to local building code, within an existing structure. There is a 30.5 centimeter air gap on three sides of the test facility, between the existing structure and the outside of the test facility walls. The walls and ceiling are insulated to an R12 and R20 level, respectively. Outside air is conditioned by an air ventilation system, which is equipped with a heater and capable of circulating the conditioned outside air and maintaining a specified temperature between the test facility wall and the existing structure. The test facility is heavily instrumented with temperature sensing, weight measurement and airflow velocity sensors at locations recommended by the ASHRAE Standard [1]. A computerized data acquisition system is used to log and save the data. Figure 1 depicts the test facility layout.

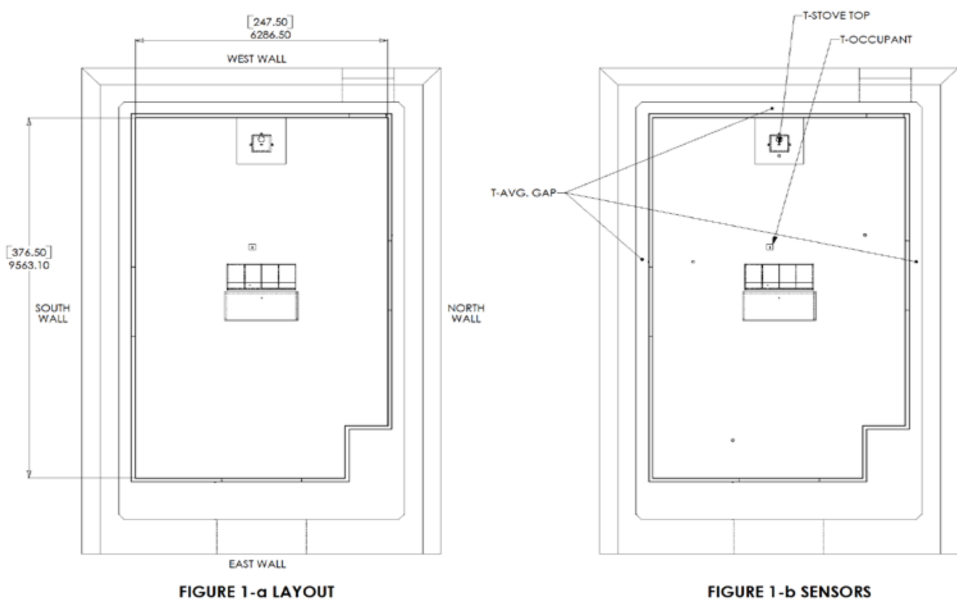

Figure 1 Test Facility Layout

As shown in Figure 1, a wood stove (Drolet Pyropak E.P.A. [4]) is placed by the west wall of the test facility. A couch was placed 3 meters in front of the stove; where the occupant Operative Temperature (T_o) is obtained.

Per ASHRAE Standard 55-2004 [1], T_o can be calculated with sufficient approximation as the mean value of air and mean radiant temperature, where relative air speed is small (<0.2 m/s) or where the difference between mean radiant and air temperature is small (<4 °C) [1]. Air temperature at the position of occupant is measured at four different heights; 0.1 m, 0.6 m, 1.1 m, and 1.7 m. These locations are at the ankle, knee and sitting/standing head positions of occupant. The mean air temperature is the average of temperature readings at these locations. Mean radiant temperature is defined as the temperature of a uniform, black enclosure that exchanges the same amount of thermal radiation with occupant as the actual enclosure [1]. To obtain radiant temperatures, a black box is placed at the head level of occupant above the couch with T-type thermocouples attached to all its faces. The mean radiant temperature is the average of these thermocouple readings. The operative temperature is then calculated from:

$$T_o = \frac{(T_a + T_r)}{2} \qquad (1)$$

where T_a and T_r are air and radiant temperatures, respectively. In addition, air temperature in other parts of the test facility was measured at 1.1 m and 2.0 m from all test facility walls and the four air gaps between the test facility and existing structure. Surface temperatures at mid point locations on the inside and outside of all walls as well as the ceiling and roof were recorded. The wood stove top, back and sides and chimney surface temperatures were also measured and recorded. Static pressure of the flue gasses in the chimney was also measured.

Test Facility Heat Loss calculation

As an index of thermal comfort, a room temperature of 22.5 °C was selected for occupant with a metabolic rate of sedentary or near sedentary and a medium clothing insulation.
The heat loss of the test facility was calculated based on the air temperature of the gap and final room temperatures of 0 °C and 22.5 °C, respectively. The power needed to raise the room temperature from initial 0 °C to 22.5 °C in a given time can be calculated from Equation 2.

$$Q = \frac{mC_p \Delta T}{t} \qquad (2)$$

where m and C_p are mass and specific heat at constant pressure of the air, t is the time interval and ΔT is the difference between the gap temperature and final temperature of the room. By substitution for the appropriate terms, the total required energy is estimated at 1152 W.

To calculate the heat loss for the test facility, thermal resistance of the walls, the two windows, and the ceiling must be evaluated. Table 1 shows the calculated values of these thermal resistances with their associated areas.

Table 1. Thermal Resistance of Test Facility Boundaries

Boundaries	Thermal Resistance (m^2 °C/W)	Area (m^2)
Walls	2.406	78.8
Windows	0.176	4.5
Ceiling	3.952	62.5

The transmission heat loss through the test facility boundaries can be calculated according to Equation (3).

$$Q_{Tr} = \frac{A \Delta T}{R} \qquad (3)$$

where A, R and ΔT, are the area, thermal resistance, and the difference between room and the gap temperatures, respectively. Substituting values for walls, windows, ceiling and ΔT in Equation 3 yields:

$$Q_{Tr} = \frac{78.8x22.5}{2.406} + \frac{4.5x22.5}{0.176} + \frac{62.5x22.5}{3.952} = 1662W \tag{4}$$

Heat loss through the floor slab is through perimeter and is evaluated using Equation 5:

$$Q_{floor} = U'P\Delta T \tag{5}$$

where U', P, and ΔT are edge coefficient, floor perimeter, and the difference between room and the ground temperatures, respectively. Heat loss through the floor is evaluated at 1799 W, assuming an edge coefficient of 2.47 W/m°C for the floor with minimum insulation and a ground temperature of 0 °C. The total transmission heat loss will be the summation of heat loss through the boundaries of the facility is:

$$Q_{Tr} = 1662 + 1799 = 3461\,W \tag{6}$$

The total heat loss is equal to the transmission heat loss plus the heat loss due to infiltration according to Equation 7.

$$Q_T = Q_{Tr} + Q_I \tag{7}$$

where, Q_I is the infiltration heat loss that is caused by the air exchange between the test facility and outside. Assuming one air exchange per one hour, the infiltration heat loss would be equal to 1152 W. Substitution for appropriate terms in Equation 7 would yield the total heat loss in the test facility.

$$Q_T = Q_{Tr} + Q_I = 3461 + 1152 = 4613\,W \tag{8}$$

Numerical Analysis of the Test Facility

To calculate and evaluate the impact of using a thermoelectric fan on a wood stove on the thermal environment of the test facility, a computational fluid dynamics analysis was performed. FloEFD Pro 9 ™, a commercial CFD package by Mentor Graphics [5]was used to simulate the test facility real case scenarios with and without a fan. The CFD images in Figure 2 clearly show that the warm air is more evenly distributed when a thermoelectric fan is used. In Figure 2a, when no fan is used, the warm air rises directly to the top, where it spreads out and stays at the top of the room. In Figure 2b however, when a fan is used warm air is pushed lower into the room by forced convection and mixes and distributes the warm air evenly.

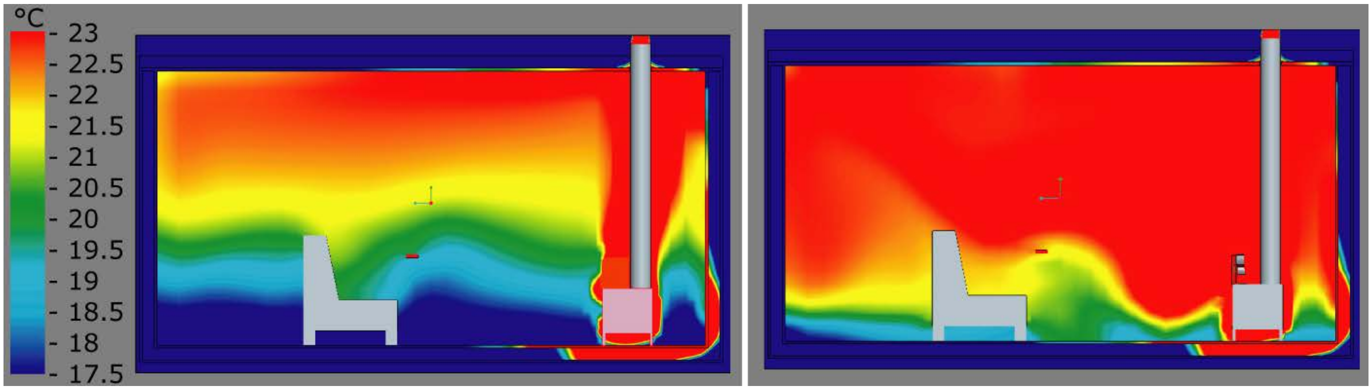

Figure 2 *CFD Image of Test Facility with a) no fan and b) with a fan*

Woodstove Comparative Testing to Determine Fuel Savings with the Use of a Thermoelectric Fan to Maintain Thermal Comfort

Test Procedure

A new test protocol was developed as the objective for this investigation was unique. There have been a number of studies performed on wood stoves, but they are designed to evaluate wood stove burn rates and stove efficiency or stack emissions. However, there was no previous work designed to evaluate fuel savings where a specified thermal comfort for occupant was being maintained, using a thermo electric fan.

It is important to note that fuel savings subject of this study is not directly related to the efficiency of wood stoves. The net space heat lost to the outside ambient is the same whether or not a fan is used under the same environmental conditions. The use of a fan does not change the stove heat output, but it does circulate and distribute the warm air throughout the room. In other words, a thermoelectric fan draws the stagnant warm air from the top and back of a stove and forces it to the middle of the room. The enhanced forced convection heat transfer causes occupants to experience a more comfortable room temperature. This results in; less fuel reloads over the extended use of the wood stove.

It was important to design a test procedure that reflected real life scenarios, as close as possible. The intent of this investigation was to create a test method that could capture the true behavior of occupants trying to utilize the stove to achieve and maintain thermal comfort. With this consideration, long tests were designed in which the testing technician tried to maintain T_O at 22.5 °C. To accomplish this, the wood stove was started with a fixed amount of kindling and pretest ignition fire, with additional fuel loads during transition from initial test facility temperature to the prescribed room temperature, after which the test run would start. Wood fuel would only be added when the remaining fuel in the stove reached a minimum mass of 1 kg. The testing technician was allowed to control temperature by adjusting the air damper setting. In doing so, air to fuel ratio would change resulting in a change in burn rate thus affecting stove heat output. The stove was placed on an electronic scale and the mass of existing or consumed wood could be calculated at any instance of time. All data were electronically acquired by a computer data acquisition system. Upon test completion, raw data were processed to determine total consumed wood for the duration of the test and when divided by the time, burn rate in kg/hr were estimated. The burn rates were further normalized with respect to ΔT, to account for the difference in temperature gradients. A detailed description of the test procedure and data analysis can be obtained from Caframo Ecofan Fuel Usage Test Procedure document [6]

For the test protocol, EPA Method 28 for Certification and Auditing of Wood Heaters [2] was used as a general guideline. There were deviations; one of which was the type of fuel. The fuel used in this study was bark free untreated two-year air dried furniture grade white ash, as compared to Douglas fir used in EPA method 28 [2].

At the beginning of each test, 19 mm x 19 mm x 380 mm white ash (1.0 kg) is consumed for kindling, followed by 50 mm x 50 mm x 225 mm white ash (2.25 kg) for pre-ignition, and 50 mm x 100 mm x 380 mm white ash (3.25 kg) for fuel loads. All burn rates were in the category 2 of EPA method 28 (0.8 to 1.25 kg/hr).

The moisture content of wood fuel was measured by a moisture meter before placing it in the stove's firebox. The wood fuel used in this study had a moisture level ranging from 18 to 23%. The mass of moisture was deducted from the total mass to yield the wood dry mass.

An initial fuel usage test procedure was developed and several iterations of testing were competed before the procedure was finalized. The evolution of the test protocol is briefly explained in the following section.

Woodstove Comparative Testing to Determine Fuel Savings with the Use of a Thermoelectric Fan to Maintain Thermal Comfort

Evolution of Wood Stove Fuel Usage Test Protocol and Procedure

Phase I: As specified by EPA Method 28, the objective of this phase was to standardize the pretest ignition procedures. Pretest ignition is required to ensure that a uniform charcoalization of the test fuel bed is achieved prior to loading test fuel charge. The pretest ignition consisted of loading crumpled newsprint, 1.0 kg of kindling and a pretest fuel load of 2.25 kg. The pretest ignition is allowed to burn until the fuel weight is consumed to approximately 20 – 25% of the weight of the test fuel charge. Stove operations and room temperature characterization was monitored and documented. At the end of this phase the pretest ignition procedure was updated and finalized.

Phase II: Test facility was brought to an initial condition of 10 °C and ambient outside relative humidity. Once pretest ignition was completed, the wood stove was charged with a single test load (3.25 kg) at a pre-set combustion air setting. Room temperature and stove operation were monitored and documented. Several tests were conducted at different combustion air settings and resulting burn rates. It was determined that the desired comfort level of 22.5 °C could not be achieved with a single fuel load from an initial room condition of 10 °C. Test procedure was revised to incorporate multiple fuel loads.

Phase III: This Phase was similar to Phase II, however, multiple fuel loads of 3.25 kg were added at set time intervals and a preset combustion air setting. Room temperature and stove operation were monitored and documented. Several tests were conducted at different combustion air settings and resulting burn rates. It was determined that the desired comfort level of 22.5 °C could be achieved with multiple fuel loads, however, as the test progressed the fuel loads were not being fully consumed during the prescribe time intervals and the wood stove became over filled with coals in various stages of combustion. After two consecutive fuel loads, additional fuel loads could not be added and combustion was becoming smothered at lower combustion air settings.

Phase IV: Testing multiple fuel loads of 3.25 kg were used, with a preset combustion air setting. However, additional fuel loads were only added when the total weight of fuel left in the Wood Stove was 1.2 kg. This ensured that there was sufficient room for the next fuel load to be added to the wood stove and that there was uniform combustion. Test runs were typically 7 to 10 hours in duration, and the desired thermal comfort temperature was achieved. However, it was determined that the resulting room temperature varied significantly due to the cyclic nature of the burn rate, the size of the fuel load (3.25 kg), and environmental influences. An analysis of the data collected determined that due to the significant variation in temperatures the data could not be used for fan/no fan comparisons. The analysis also determined that a majority of the test time and fuel consumed were used to bring the test facility from initial conditions of 10 °C to 22.5 °C. As a result actual test times at the desired comfort temperature were too short.

Phase V: Testing procedure was revised to reduce the fuel load (50 mm x 100 mm x 380 white ash weighing approximately 1.25 kg), with additional fuel loads only added when the total weight of fuel left in the wood stove was 1.2 kg and combustion air settings were pre-set. The test facility initial conditions were modified from 10 °C to 21 °C, to minimize time to transition from initial conditions to desired thermal comfort temperature. Environmental conditions for February and March indicated unusually warmer day time temperatures than normal. The dynamics of the environmental conditions significantly influenced the heat loss from the test facility and ultimately resulted in significant variation in test facility room temperature. An analysis of the data collected, determined that due to the significant variation in day time temperatures, the data could not be used for valid fan/no fan comparisons.

Woodstove Comparative Testing to Determine Fuel Savings with the Use of a Thermoelectric Fan to Maintain Thermal Comfort

Phase VI: Testing was initiated in the evening and conducted through the night time. During the night environmental conditions tend to be more stable and outside temperatures are lower and more consistent. Testing procedures consisted of the reduced fuel loads, with additional fuel being added when the total weight of fuel left in the wood stove was 1.0 to 1.2 kg. In this phase, the testing technician was allowed to adjust the combustion air setting, as required to maintain a stabilized thermal comfort temperature. To compensate for unusually warm seasonal temperatures and to ensure consistent heat loss rates from the test facility; the thermal comfort temperature was defined as 22.5 °C above the stabilized air gap temperature.

RESULTS AND DISCUSSIONS

In January and February 2010, a large number of tests were conducted. However, not all the test runs could be considered in the data analysis. Some of the earlier tests were designed to characterize the wood stove and testing protocol. The test data that could be compiled and processed for thermal comfort and fuel usage interpretation is listed in Table 2. Some of these test runs are integrated continuous runs covering both fan-no fan conditions. Others are independent test pairs performed either on the same day or one day apart covering either fan or no fan condition. The results of the tests are shown in Table 2.

Table 2. Fuel Usage Test Runs

Test #	Fan	Time (hrs)	Stove Top Temp (°C)	Avg. T_O (°C)	Avg. T_{airGap} (°C)	ΔT (°C)	Fuel Burnt (Dry) kg/hr	Fuel Burnt per °C	Potential Savings Using a Fan, %
1a	No	3.00	227.6	22.2	0.8	21.4	1.339	0.063	14
1b	Yes	3.00	204.0	22.3	1.4	20.9	1.123	0.054	
2a	No	3.00	213.7	22.4	1.1	21.4	1.196	0.056	10
2b	Yes	3.00	191.3	22.5	1.0	21.6	1.082	0.050	
3a	No	3.00	197.4	22.5	2.6	20.0	1.141	0.057	14
3b	Yes	3.00	197.0	22.3	2.7	19.8	0.963	0.049	
4a	No	4.00	179.5	22.5	3.8	18.9	1.092	0.058	28
4b	Yes	4.00	189.5	23.4	2.9	20.8	0.872	0.042	
5a	No	2.33	234.7	22.4	0.6	22.1	1.293	0.058	17
5b	Yes	2.33	206.4	22.2	0.8	21.8	1.050	0.048	
6	No	6.00	224.5	27.1	6.1	21.1	1.210	0.057	6
7	Yes	6.00	207.8	27.1	5.7	21.8	1.171	0.054	
8	No	8.00	215.4	26.5	6.6	20.8	1.245	0.060	15
9	Yes	8.00	209.6	27.3	5.5	22.1	1.135	0.051	
10a	No	3.00	241.4	27.7	5.8	22.4	1.411	0.063	12
10b	Yes	3.00	198.1	27.4	6.2	21.5	1.189	0.055	
11a	No	4.00	179.4	24.4	3.0	21.6	1.003	0.046	11
11b	Yes	4.00	178.4	23.9	3.0	21.2	0.979	0.042	

Table 2 shows a consistent trend of fuel savings from 6% to 28% with an average of 14.1% for the test runs with a thermoelectric fan. In analyzing the data, it is important to note the improvement that is seen in individual test pairs since they had comparable test conditions. The large degree of variability in percentages of improvement for different test pairs could be due to many uncontrolled variables inherent to unsteady nature of wood burning process. Environmental changes such as outside temperatures, humidity, barometric conditions might have contributed to the variability of the data since the individual test pairs were done over a wide range of meteorological conditions.

But a greater source of data variability is the way the wood stove was operated in the course of the experiments. Since the main criteria was to maintain the comfort temperature around 22.5 °C, the operator may have had to change the air damper setting a number of times in any given test run. Obviously, changing the air damper setting would change air to fuel ratio and that in turn change the fuel burning rate and efficiency accordingly. Change of the air damper setting is a means of controlling and maintaining temperature and reflects the real life scenario of wood stove operation. In the absence of an automatic control system, the occupant changes the air setting to reach a desirable thermal comfort. It is evident from the data that the occupant behavior to maintain a thermally comfortable environment seems different when a fan is used on the wood stove. Use of a fan provides a higher and more uniform comfort temperature, thus the occupant would tend to run the stove at a lower air damper setting. At lower settings, a more complete combustion takes place and efficiency of the burn increases. This result in less reloads of wood fuel over an extended use of the wood stove.

Wood fuel saving is not the only advantage of using a fan with wood stoves. A fan would create a thermal environment that is more pleasant and comfortable to occupant. ASHRAE Standard [1] has a number of scales for measuring local temperature discomfort, one of which is Vertical Air Temperature Difference. According to ASHRAE Standards [1], thermal stratification that results in the air temperature at the head level being warmer than the ankle may cause thermal discomfort [1]. In evaluating the Vertical Temperature Difference, the temperature at the ankle level could not be used since it had been observed that temperature sensing assembly at this level had touched the floor at some point and use of these values would have skewed the results. Alternatively, temperature at the knee level was used instead. Figure 3 compares the Vertical Temperature Difference for the fan/no fan condition in different test pairs. As it is evident, the Vertical Temperature Difference is less with a fan in all of the conducted tests. The difference is between 0.2 °C to 0.9 °C with an average of 0.5 °C. It must be noted that the difference would have been even more had the ankle level temperature been used in the evaluation of the Vertical Temperature Difference.

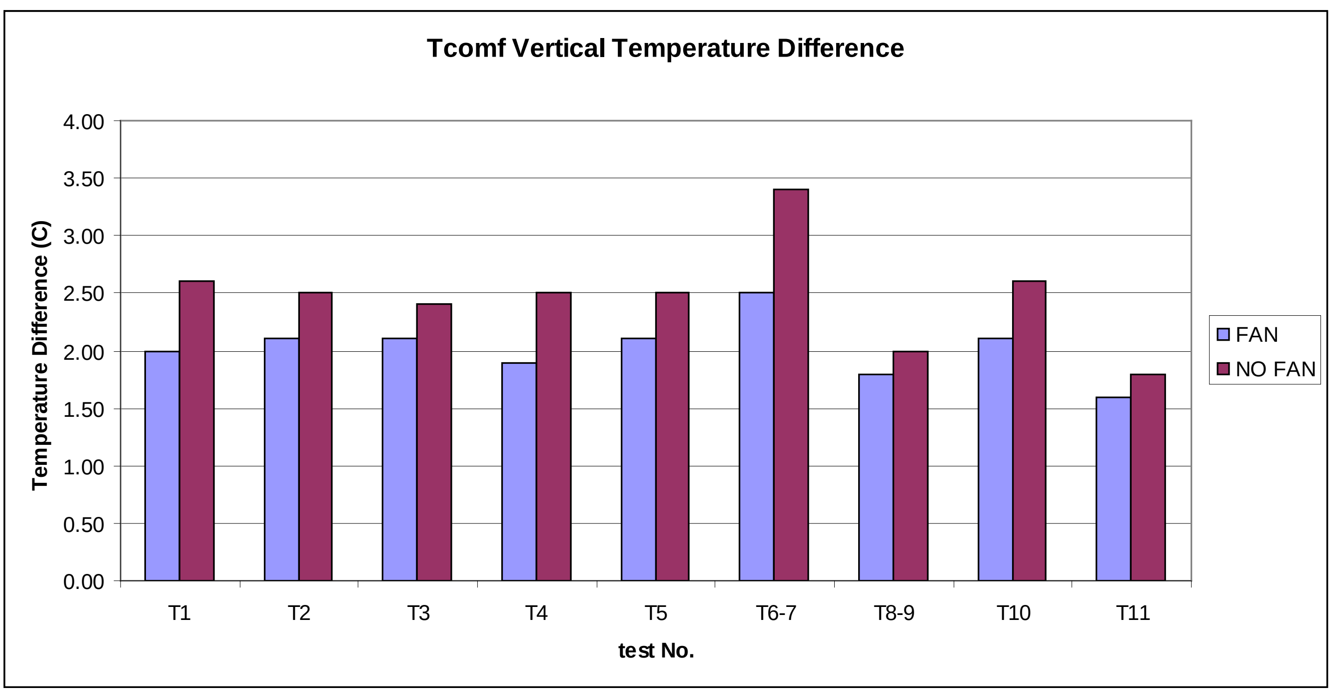

Figure 3 ***Vertical temperature differences at occupant operative temperature with and without fan***

Woodstove Comparative Testing to Determine Fuel Savings with the Use of a Thermoelectric Fan to Maintain Thermal Comfort

This investigation establishes strong indications that use of a fan on a wood stove saves fuel and improves thermal comfort of occupant. However, to provide a more accurate quantitative measure of the fuel saving and thermal comfort, further studies are needed. The authors intend to design and conduct improved experiments in the fall of 2010 to adequately quantify advantages of using a fan when used with a wood stove. The new experiments will be conducted in a test facility with improved controlled environment that allows for below 0°C settings.

CONCLUSION

Test results shown in the preceding section of this report strongly suggest improvement in fuel saving and occupant thermal comfort when a thermoelectric fan is used with wood stoves.

In all the tests, a consistent and considerable percentage in fuel saving is reported when the thermo electric fan is used with the wood stove. The fuel saving is from 6% to 28% with an average of 14.1%. The large variability seen in the fuel saving between the experiments was expected. However, the test pairs are comparable since they were conducted in the same time frame and similar environmental conditions.

There is also a strong trend and indication that use of a thermoelectric fan improves the environmental thermal comfort. In every test, the Vertical Temperature Difference between occupant head and knee is less when a fan is used. The difference is from 0.2 °C to 0.9 °C with an average of 0.5 °C. The difference would have been even greater if the difference had been evaluated between occupant head and ankle.

NOMENCLATURE

A = area
C_p = Specific heat of air at constant pressure
m = Mass of test facility air
P = Perimeter
Q = Energy
R = Thermal Resistance
t = time
T_a = Air Temperature
T_o = Occupant Operative Temperature
T_r = Radiant Temperature
ΔT = Temperature gradient between test facility final and initial
U' = Edge Coefficient

Subscripts

a = air
air gap = air gap between the test facility and the original structure
floor = floor of the test facility
I = infiltration
o = operative
r = radiant
T = total

REFERENCES

1. ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy, American Society of Heating Refrigeration and Air Conditioning Engineers, Inc.

2. Method 28, Certification and Auditing Wood Heaters. Emission Measurement Center, CFR Promulgates Test Methods, U.S. EPA Technology Transfer Network, February 2000.

3. ISO 7730:2005(E), Ergonomics of the Thermal Environment, Third Edition 2005-11-15.

4. Drolet Pyropak E.P.A. Wood Stove Manual, published by Stove Builder International Inc., 1700, Leon-Harmel, Quebec City (Quebec), Canada G1N 4R9

5. Mentor Graphics®, Head Quartered in Wilsonville, Oregon, http:www.mentor.com

6. Ecofan Fuel usage Test Protocol, revision 6, Caframo Limited, June 2010.