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THERMAL STORAGE-MASS ENHANCES WOODSTOVE COMBUSTION AND REDUCES POLLUTION

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Abstract—Experiments were performed to study the effects of using a thermal storage-mass to enhance woodstove combustion-efficiency. The relation between thermal storage-mass spacing and combustion-zone temperature has been established. The results demonstrate that mass enhances combustion-efficiency. The stove may be operated at high temperatures that reduce pollution. Combustion-efficiency enhancement is inversely proportional to the mass spacing. The added mass moderates the frequency of room-temperature fluctuations without imposing a significant thermal lag, while providing a safety shield. However, use of the mass may cause a slight increase in energy consumption.

1. INTRODUCTION

Rising fuel costs have stimulated renewed interest in woodheating, as evidenced by the 1.5 $\times 10^6$ woodburning appliances that are now being sold each year.[1] In 1980, wood accounted for approximately 2.5% of the total energy consumed in the U.S., an amount comparable to the contributions from either nuclear or hydroelectric sources.[2] Between 0.25 and 0.5% of this energy was used for residential purposes.

During the last decade, a radically new breed of stoves was introduced. Although varied in appearance and basic design, they all incorporated a tightly sealed combustion chamber with a well controlled air supply. They are referred to as airtight stoves. These modern, airtight stoves with efficiencies of 50–60%, excellent temperature regulation and the ability to maintain burn cycles up to 8 hours, have overcome many of the traditional discomforts previously associated with residential woodheating.

However, these benefits are achieved by imposing a significant restriction on combustion-air supply. The fire is actually choked, lowering the combustion temperature and preventing complete combustion of the wood, especially its gaseous by-products. Operating the stove in this manner produces a cold fire. Correspondingly, if the air dampers are opened as wide as permissible, an oxygen-rich environment is provided which promotes a hot fire with higher combustion temperatures and less unburned material in the exhaust gases.

Recent studies have shown that cold fire operation has several distinct disadvantages to hot fire operation.[1–3] One disadvantage is increased creosote accumulation in the exhaust stack. As wood undergoes pyrolysis, it primarily decomposes into charcoal, volatile gases, CO_2, and H_2O. The volatile gases account for 30–60% of the potential energy available from the wood. However, the gas-ignition temperature is between 593 and 704°C.[2] A cold fire is less likely to yield these temperatures; hence, most of the gases escape unburned to the exhaust, where they cool and condense. The condensation coats the inside of the stack, then dries to a hard crust. This residue is creosote. Left unattended, the creosote accumulation will severely constrict the exhaust stack in a short period of time.

The most important aspect of creosote formation is that it presents a potentially dangerous fire hazard. Creosote is highly combustible. When it ignites, flue-gas temperatures exceeding 1093°C occur. The intense heat can warp prefabricated flues and severely crack masonry chimneys, necessitating costly repair. In addition, a house fire may be caused by heat conduction to the surrounding wood structure or burning exhaust debris falling on the roof. In 1981, 22,000 fires and 800 deaths in the U.S. resulted from fires caused by woodburning appliances.[4] Most of the fires caused by woodburning equipment start as chimney fires.

A second disadvantage of a cold fire is excessive pollution. In the absence of adequate air for combustion, large quantities of CO and smoke particles are emitted. Studies conducted in Montana, Oregon, Colorado, Maine, and Vermont have emphasized the magnitude of this problem in residential areas with a large concentration of woodburning appliances. The city council of Vail, Colorado, passed an ordinance in 1978 limiting each household to one woodstove or fireplace.[1] In addition, the preliminary conclusion of the Biomass Fuels and Air Pollution Project indicates that biomass fuel poses a greater pollution threat than oil or coal.[5]

Another disadvantage with cold fire operation is that the airtight stove becomes a major producer of polycyclic organic matter (POM), which contains carcinogens. In June 1980, the Monsanto Corporation completed an EPA-sponsored study, which showed that airtight woodstoves collectively produce more POM than all other sources combined. Also, tests demonstrated that POM production is a function of combustion temperature, which is closely related to oxygen supply. Limiting the combustion rate by reducing air supply increases POM emissions drastically.

In recent years, attempts have been made to overcome these problems. One method is to use a stove fitted with a catalytic combustor that is similar to the catalytic converter on an automobile. Its disadvantages include high initial stove cost, periodic combustor replacement and deactivation of the element if anything other than wood is burned, including flame-coloring dyes. Although combustors can be placed in the exhaust stack of stoves originally not fitted with the device, to do so may hamper combustion by adversely affecting the stove draft. Another method is to use a forced combustion air stove and store the excess heat in a water tank. The heat is distributed throughout the house by a piping system and heat exchangers. The stove now operates with complete combustion but it costs between $4,500 and $7,000.

An old alternative to these new technological approaches is to construct a large thermal storage-mass structure such as a masonry oven or a wall containing a stove or fireplace insert. This procedure allows the heating appliance to be operated with a hot fire but offers very poor temperature and heat regulation.

Since these proposed solutions are either expensive or plagued with disadvantages, it is likely that stoves will continue to be operated in the traditional cold fire mode. While providing the homeowner with an alternative to conventional space heating, a stove operated in this manner is a potentially dangerous substitute. A better solution may exist. With this goal, a two-phase investigation was conducted. In Phase I, a computer program to simulate a woodstove thermal mass storage system was developed by Zurigat and Ghajar.[6] In Phase II, a light thermal storage-mass was used to enhance woodstove combustion, as will now be described. The mass consists of concrete blocks, surrounds the stove on three sides and leaves the top and front fully exposed. The blocks are placed a specified distance from the stove and built up to the height of the stove (see Fig. 1).

Utilization of the mass provides several advantages over conventional stove operation.

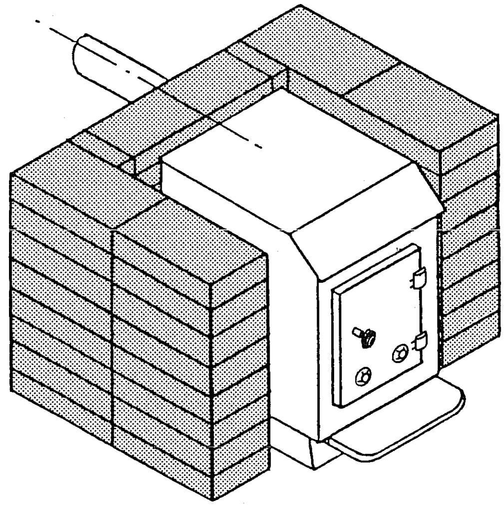

Fig. 1. Woodstove and the concrete thermal mass system.

These are: (a) increased combustion-efficiency during pyrolysis, which reduces creosote buildup, environmental pollution and POM emissions; (b) moderation in the frequency of room-temperature fluctuations without an extended thermal lag; (c) increased safety because the mass shields a large portion of the hot stove surface.

2. OBJECTIVES AND METHOD OF APPROACH

The main objective of this study was to investigate the effects of using a thermal storage-mass to enhance woodstove combustion. By comparing temperature histories, we (a) established the relation between mass spacing and combustion-zone temperature, (b) determined the combustion-efficiency, creosote condensation in the flue, moderation in the frequency of room-temperature fluctuations, and the effects of mass on energy use, (c) showed that the mass provides an effective safety shield. The investigation included: (a) determination of the temperatures to be monitored and a standardized test procedure, (b) construction of the apparatus, (c) collection and evaluation of the data.

3. EXPERIMENTAL SETUP

The apparatus included the stoveroom, stove, thermal storage-mass, temperature recorder, thermocouples, and scales. The single story room housing the stove was located within the Oklahoma State University Mechanical Engineering Laboratory. Its selection was based on a desire to duplicate, as closely as possible, an environment consistent with normal stove operation. The room, with its spacious dimensions and large window, closely resembled a typical living room, which is where residential stoves are usually installed.

The woodburning appliance was a simple, box-type, single-baffled, airtight stove (see Fig. 1). The stove measured $41.6 \times 49.0 \times 63.5$ cm. The firebrick was removed to simplify the computer simulation (developed in Phase I) and to be similar to popular, less expensive stoves. The stove was fitted with a grate to minimize shifting of the fuel as it was consumed. The storage-mass used around the stove consisted of solid concrete blocks with an approximate density of 2114 kg/m^3 (see Fig. 1). Concrete blocks were chosen because of availability and low cost.

The effects of the mass were evaluated by comparing temperature histories for mass and no mass operation. The temperatures were measured with 39 J and K-type thermocouples, having maximum temperature limits of 482 and 927°C, respectively.

The temperature of the combustion-zone is the single most important parameter affecting combustion-efficiency. This was demonstrated in tests for which many variables were investigated and the exhaust gases analyzed for completeness of combustion.[2] Since exhaust analyzing equipment was unavailable, the flame temperature was monitored to compare the relative effects of mass on combustion. Also, the exhaust pipe exit temperature was measured to monitor the potential for creosote condensation, which will be minimized, provided the exhaust gases stay above the 121–177°C range. Stove surface and mass outside wall temperatures were recorded to demonstrate that the mass acts as an effective safety shield.

All monitoring was conducted automatically using a 40 Channel Monitor Labs Datalogger Model 9302 capable of individual channel programming. For a detailed description of the apparatus, refer to Pilcher.[7]

4. TEST STANDARD

A test standard was developed based on the guidelines set forth by the Fireplace Institute.[8] No 3 builder grade Douglas Fir lumber was used as fuel. Based on the combustion chamber volume above the grate ($\simeq$0.113 m^3) and a medium size test fire (48.2 kg of fuel/m^3 of volume), the quantity of wood required per load was set at 5.44 kg. Firebrands were constructed of the lumber which had been finished to 1.9×1.9 cm strips, 25.4 and 45.3 cm long.

The very dry wood used in the tests had a moisture content of 8.6%. Low moisture content results in faster pyrolysis of the wood. This translates into a very quick burn cycle with major smoke and volatile gas generation occurring in the first part of the cycle. The expected characteristic burn cycle is shown in Fig. 2. Thus, the anticipated results from

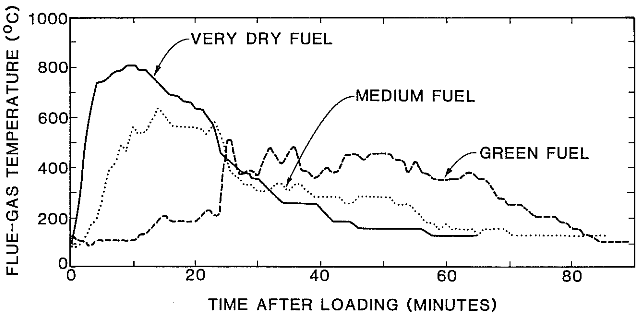

Fig. 2. Characteristic burn cycle based upon wood moisture content.[2]

using the mass will indicate higher combustion temperatures during this part of the cycle, which is where they are needed.

An indoor reference temperature of 20°C based on current government building regulations was selected. The tests were conducted by starting the fire, closing the door with the air dampers fully open, then periodically adjusting them to maintain the specified indoor temperature as closely as possible, a procedure which would occur in actual operation.

5. RESULTS AND DISCUSSION

A total of 17 tests were conducted in two-parts. Part I, a series of single load tests, was to determine the effects of mass spacing on combustion-zone temperature. Spacings were arbitrarily selected at 15.24, 11.43, and 1.27 cm. Part II was a series of extended tests, two loads each, performed with and without mass at the spacing from Part I which yielded the best combustion-zone temperature characteristics.

Several general trends were observed.

(1) Using the minimum mass spacing yielded the best combustion-zone temperature characteristics. The criteria for complete combustion is high combustion-zone temperatures during that part of the burn cycle where the volatile gases are released. For the dry wood used, fuel consumption occurs very quickly with most of the gases released at the beginning of the cycle (see Fig. 2). Test results indicated that the minimum spacing length of 1.27 cm best met this criteria (see Fig. 3). The lower spacing limit was imposed by an overhanging lip surrounding the top stove surface. Because a hot fire consumes the fuel very quickly, the combustion-zone temperature falls more rapidly in the latter stages of the test as the spacing is reduced.

(2) Thermal mass does enhance combustion-efficiency as implied by the combustion-zone temperature. The goal is to achieve combustion of the volatile gases which have ignition

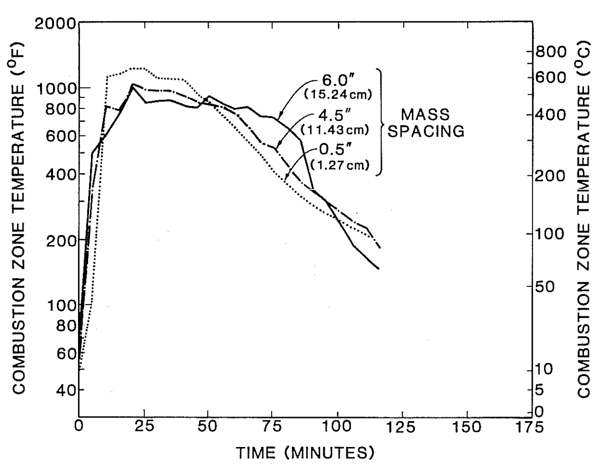

Fig. 3. Effect of thermal mass spacing on combustion-zone temperature.

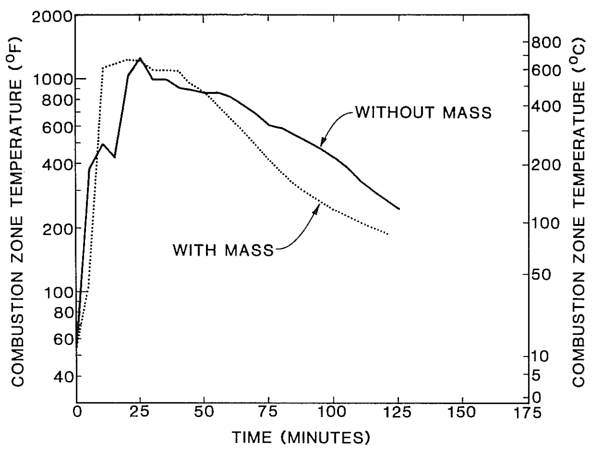

Fig. 4. Effects of thermal mass on combustion-zone temperature (short tests).

temperatures between 593 and 704°C.[2] Therefore, combustion enhancement is obtained when combustion temperatures greater than 593°C occur simultaneously with the volatile gas release, which must happen in the beginning stages of the burn cycle with dry wood (see Fig. 2). Results from short and long duration tests performed with one and two loads of wood, respectively, at the 1.27 cm mass spacing are shown in Figs. 4 and 5. The tests with mass met the criteria for a greater portion of the gas release stage than the tests without mass. Therefore, the general results implied that combustion-efficiency was increased when the mass was used. Thus, it follows that the effects of incomplete combustion (i.e., creosote formation, air pollution, and POM emissions) were reduced accordingly.

(3) Thermal mass does provide a slight decrease in the potential for exhaust gas creosote condensation based upon the stack exit temperature. The gases comprising the volatile gas mixture have different condensation temperatures ranging from 121–177°C. During part of the gas generating stage of the tests with mass, the temperature was greater than 121°C, but less than 177°C (see Fig. 5), indicating that the gases with the lower condensation temperatures would not condense. So, at least some decrease in the potential for condensation occurs. It is important to note that using the mass tends to enhance combustion-efficiency which reduces the volatile gas content of the effluent, thus, less creosote build up in the exhaust stack would occur, regardless of the exit temperature.

(4) Thermal mass helped reduce the frequency of room-temperature fluctuations without inducing an extensive thermal lag (see Fig. 6). The mass does absorb a significant amount of the heat flux, but not enough to detrimentally effect the time from initial startup until room temperature attains the test standard of 20°C.

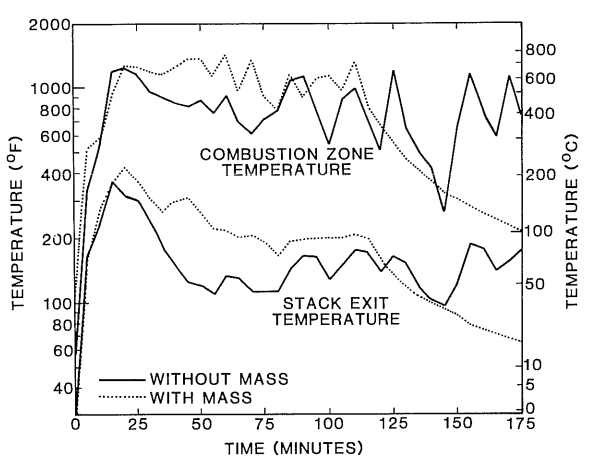

Fig. 5. Effects of thermal mass on combustion-zone temperature and stack exit temperature (long tests).

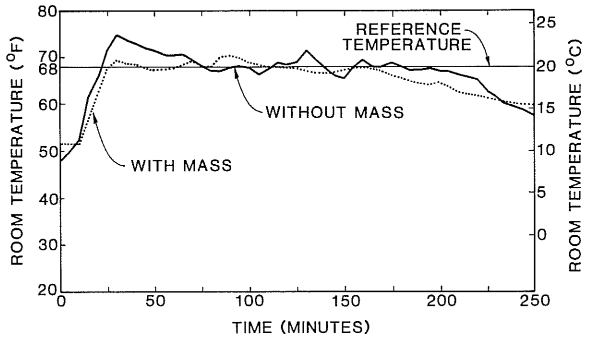

Fig. 6. Effects of thermal mass on room-temperature fluctuations.

(5) Thermal mass provided an additional safety feature because it shielded a large portion of the hot stove surface. During no mass operation the exposed surface reached temperatures in excess of 315°C (see Fig. 7). Although the surface temperature actually increases when the mass is used, the corresponding outside wall temperature of the mass is considerably less than the exposed stove-surface temperature would be under no mass operation.

(6) Thermal mass may result in a slight reduction of net heating efficiency. An examination of Fig. 6 reveals that for an equivalent amount of fuel consumed, the room-temperature reference level was maintained for a longer duration when the mass was not used. This seems contrary to expectations because the mass allows stove operation which promotes higher combustion-efficiency and heat release. However, the efficiency of heat transfer into the room is inversely proportional to combustion-efficiency (see Fig. 8). The opposing characteristics result because the driving force which enhances combustion, the plentiful air supply, moves through the system so fast that a large amount of the hot gases are swept out the exhaust stack. According to Fig. 8, overall efficiency of most woodburning stoves remains at approximately 55% regardless of operation.[2]

6. CONCLUSIONS

Despite the lack of exhaust-gas analyzing equipment, temperature comparisons showed the potential benefits from a thermal mass system similar to the one described in this paper. The harmful effects of woodstove pollution can only be reduced through complete combustion, which is primarily controlled by stove operation.

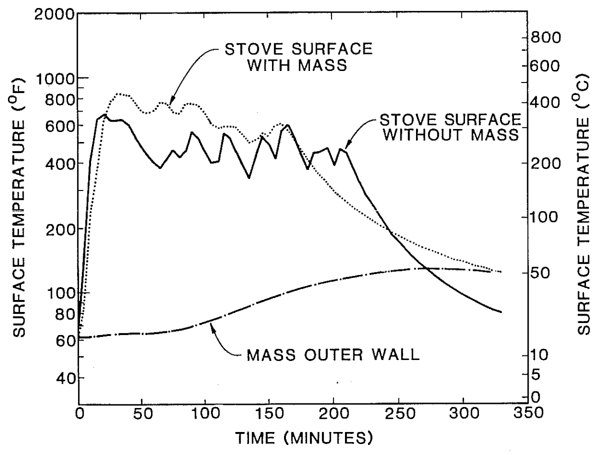

Fig. 7. Effects of thermal mass on stove-surface temperature.

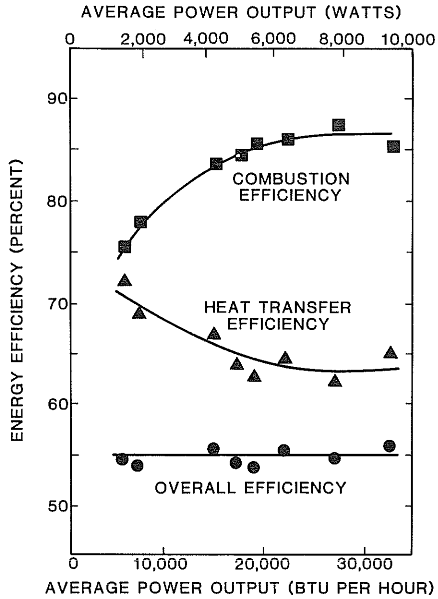

Fig. 8. Energy efficiencies vs. power output.[2]

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