PROCEEDINGS

RESIDENTIAL WOOD & COAL COMBUSTION

SPECIALTY CONFERENCE

- PREFACE
- RESIDENTIAL WOOD COMBUSTION
- IMPACTS OF WOOD COMBUSTION ON AMBIENT AIR QUALITY
- IMPACTS OF RESIDENTIAL COMBUSTION PROCESSES ON INDOOR AIR QUALITY

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AIR POLLUTION CONTROL ASSOCIATION
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PROCEEDINGS

RESIDENTIAL WOOD & COAL COMBUSTION

SPECIALTY CONFERENCE

EDITED BY

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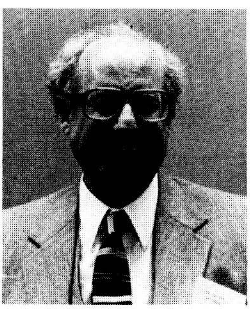

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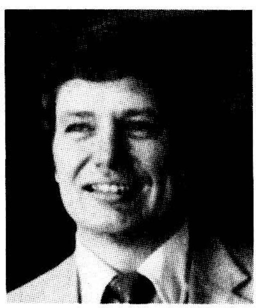

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A Specialty Conference On:

RESIDENTIAL WOOD
& COAL COMBUSTION

March 1 and 2, 1982, Louisville, KY

CONFERENCE PROGRAM

Sunday, February 28, 1982 Registration

Monday, March 1, 1982 Registration

SESSION I - Residential Wood Combustion - Environmental Assessment and Control Technology
Session Chairman: Michael C. Osborne - U.S. EPA

"TECHNIQUES FOR ACHIEVING MORE COMPLETE COMBUSTION IN WOOD STOVES"
John Allen - Battelle Columbus Laboratories

"EFFECT OF FUEL AND COMBUSTION DESIGN ON PERFORMANCE OF DOMESTIC WOOD-FIRED APPLIANCES"
A. C. S. Hayden - Canadian Combustion Research Laboratory

"EMISSIONS MEASUREMENT OF RESIDENTIAL WOOD STOVES (BOX CATALYTIC AND ADD-ON DEVICES)"
Roy Neulicht - Del Green Associates

EUROPEAN ACTIVITIES IN SOLID FUEL FIRED HEATING:
Werner Martin - Integrated Energy Systems

BREAK

SESSION II - Residential Coal Combustion - Efficiency and Emissions
Session Chairman: Robert E. Hall - U.S. EPA

"RESIDENTIAL STOVE EMISSIONS FROM COAL AND OTHER ALTERNATIVE FUELS COMBUSTION"
John Cleland - Research Triangle Institute

"MEASUREMENT TECHNIQUES AND EMISSION FACTORS FOR HAND-FIRED COAL STOVES"
Dennis R. Jaasma - Virginia Polytechnic Institute and State U

"PERFORMANCE OF DOMESTIC COAL STOVES"
A. C. S. Hayden - Canadian Combustion Laboratory

"CHARACTERIZATION OF EMISSIONS FROM RESIDENTIAL COAL STOVES"
Cedric Sandborn - VT Dept. of Water Resources & Envir. Engineering

LUNCHEON

TRADE SHOW

Tuesday, March 2, 1982

SESSION III - Impacts of Wood Combustion on Ambient Air Quality
Session Chairman: Robert K. Stevens - U.S. EPA

"WINTER HEATER STUDY"
Robert I. Imhoff - Tennessee Valley Authority

"RADIOLABELED CARBON MEASUREMENTS USED IN ESTIMATING IMPACT OF VEGETATIVE BURNING"
Dr. Lloyd Currie - National Bureau of Standards

"SMOG CHAMBER STUDIES RELATED TO WOOD SMOKE"
Dr. Richard Kamens - University of North Carolina

"A NATIONAL ASSESSMENT OF AIR QUALITY IMPACTS OF RESIDENTIAL FIREWOOD USE"
Dr. F. W. Lipfert - Brookhaven National Laboratories

BREAK

SESSION IV - The Impact of Residential Combustion Processes on Indoor Air Quality
Session Chairman: D. J. Moschandreas - IL Institute of Tech.

"IMPACT OF RESIDENTIAL WOOD COMBUSTION APPLIANCES ON INDOOR AIR QUALITY"
Roy Neulicht - Del Green Associates

"WOOD COMBUSTION EFFECTS ON INDOOR AIR QUALITY"
Joseph Zebranshy - Geomet Technology, Inc.

"INDOOR AIR EMISSIONS FROM RESIDENTIAL COMBUSTION"
Craig Hollowell - Lawrence Berkeley Laboratories

"INDOOR EXPOSURE TO PARTICULATES IN HOMES WHICH USE WOOD FOR HEATING"
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Barbara O. Beck - Harvard School of Public Health

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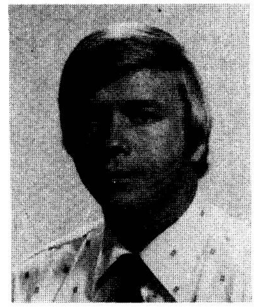

Michael C. Osborne
Technical Program Chairman

For a variety of reasons, residential wood and coal combustion has become extremely popular in recent years. As of 1981, wood- and coal-burning equipment is projected to have penetrated almost 20 million U.S. households and is expected to continue growing at a rate of about one million units per year. Based on current emissions assessments, residential wood and coal combustion could significantly impact ambient air quality in the years ahead. Many believe that these emissions can be substantially decreased by upgrading the combustion characteristics of wood and coal stoves. The purposes of this conference were to: 1) identify the environmentally significant pollutants emitted from residential wood and coal combustors, 2) assess potential emission control approaches, 3) determine current and projected ambient impacts, and 4) establish the effects of wood and coal combustion on indoor air quality.

TECHNIQUES FOR ACHIEVING MORE COMPLETE COMBUSTION IN WOOD STOVES

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Secondary combustion has been shown previously to be very effective in reducing air pollution emissions from wood stoves, especially when it can be maintained such as during operation at high burning rates. In this study, several techniques have been investigated to promote effective secondary combustion in a small air-tight box stove operating at low burning rates. The design of the secondary air inlet system, quantity of secondary air admitted, and thermal insulation of the stove were studied experimentally. Carbon monoxide and total hydrocarbon emissions were monitored simultaneously in the gasses leaving both the primary and secondary combustion zones.

Air in-leakage thru joints in the primary chamber resulted in lower emissions, but prevented stove operation in a controlled manner at low burning rates. The thermal insulation of stove walls was relatively ineffective in promoting secondary burning, as primary air bypassing the burning wood cooled the combustion products to temperatures where additional burning was quenched. The carbon monoxide emissions from the primary combustion zone were more effectively consumed in the secondary combustion zone than the unburned hydrocarbons.

TECHNIQUES FOR ACHIEVING MORE COMPLETE COMBUSTION IN WOOD STOVES

I. Introduction

Increased usage of wood as a residential heating fuel has resulted from the rising prices of other fuels and public skepticism as to reliability of normal fuel supplies. This increase has occurred with the widespread impression that wood burning is environmentally clean. Increased wood use is being encouraged by DOE, equipment manufacturers, and many environmentalists, all with a very limited technology pertaining to emission factors, and even less technical basis for reducing emissions. In many instances the residential stove manufacturers and operators are adopting stove designs and operating practices conducive to increased emission factors. This accentuates the environmental significance of the increased quantity of wood burned residentially.

As a means of reducing these objectionable emissions from the use of wood for residential heating, five alternatives have been identified. These include the following:

(1) Prevention of emissions formation in fuel magazine
(2) Prevention of emissions formation in combustion region
(3) Destruction of emissions in primary burning zone
(4) Destruction of emissions in secondary burning zone
(5) Add-on systems for emission control.

Of the five methods, the first three can be aided by burning well seasoned wood at a relatively high rate. Method 5 includes the recently introduced catalytic stoves and is not discussed in this report.

The application of Method 4 is the focus of this study. The purpose of the research was to investigate the effects of various modifications of commercial stoves as a means of improving the secondary combustion.

Secondary combustion is the combustion of the fuel materials not completely burned in the primary combustion or immediate vicinity of the wood. These materials can result from quenching of the primary combustion products or from pyrolysis of wood without burning downstream of the primary combustion region. This secondary combustion is achieved by mixing the gases from the wood and from the primary combustion with suitable oxygen at a temperature sufficient to ignite the mixture or sustain burning to completion. In some stoves this is attempted directly above the burning wood and in other stoves the primary combustion zone is separated from the secondary combustion zone by a physical barrier, with the secondary air entering at a different location than the primary air. For secondary combustion to take place the gas composition must be within the flammability limits of the gases.

In actual practice the secondary combustion is hindered by the following:

- Mixing rate and turbulence are limited in natural draft stoves.

- Temperatures in the secondary zone are often below that required for ignition due to excess air and stove wall quenching.

- Rate of secondary air supply is not controlled to provide the optimum amount required during the various combustion phases.

As a result secondary combustion is often intermittent and not sustained for any length of time in most conventional stoves. The effectiveness of catalytic stoves in sustaining secondary combustion is being investigated by a number of researchers.

II. Experimental Program

Laboratory Facility

The principal stove used for this study was a small box stove made in this country. It has a relatively large rectangular chamber above the horizontal baffle which could be readily modified as desired for secondary combustion studies. It was equipped with shielded aspirated thermocouples at the inlet and outlet of the secondary combustion chamber formed by the baffle. By forming the radiation shield into a rake type of sampling probe extending across the chamber, a representative gas sample for analysis was obtained through the same probe. This provided an increase in the sensitivity of monitoring the secondary combustion.

In selecting the placement of the rake probe, a temperature profile of the combustion gas entering the secondary chamber was made by traversing the chamber with a thermocouple. The graphical results of this experiment for the four vertical levels and ten horizontal points at the rear edge of the baffle opening are shown in Figure 1. Based on this profile, position No. 3 was chosen for sampling, with six equally spaced horizontal sampling ports.

The box stove and stack were mounted together on a platform which permits weight loss (burning rate) measurements during operation. Two gas sampling probes were installed. One as described above was between the primary and secondary combustion chamber at a level determined to be representative of the gas flow pattern. The second was a similar rake type of probe which was installed immediately downstream of the secondary combustion chamber just as the gas entered the flue pipe. Heated gas sampling lines were installed with two heated pumps located adjacent to the stoves. A glass wool filter trap (insulated) was installed immediately before the pump inlet to prevent damage to the pumps. Two flexible heated lines extended from these pumps to the instrument room where the gas compositions were continuously monitored. The gas sample lines, pumps, and flexible heated lines were maintained at 400 F by individual temperature controllers. Temperatures were also manually monitored by thermocouples with a digital readout.

Inside the instrument room, the gas flow from each line was split into another heated line leading to a heated Total Hydrocarbon Analyzer (THC) and into a gas cooling/trapping system leading to inorganic analyses instruments. A schematic of the overall sampling system along with the data acquisition and data reduction system interfaces is shown in Figure 2. This system represents a highly effective method for sampling and analysis of wood stove emissions. The system was used for a large number of tests with only minor problems. Sample line plugging was never a problem as long as the glass wool traps were changed and ice was kept in the gas cooling system. The computer program for data reduction was developed by Battelle and provides continuous one-minute parameter checks and emission calculations. All data are stored in engineering terms for subsequent computer graphic presentations on the same system.

Experimental Procedure

The experimental program on the box stove included a total of 32 test burns. Of these tests, ten represented "background burns" on the box stove in which usable data were not collected. The remaining 22 burns included six "baseline" tests. These tests were designed to establish typical and also some atypical characteristics of the stove in an as-purchased condition. An additional 16 tests were performed on the box stove to examine the effect of various modifications on the stove flue gas emissions.

The wood used for these tests was all split, seasoned white oak. Two different lots of wood were used, one which was approximately 10 percent moisture and a second which was approximately 18 percent moisture (as determined by average weight loss after drying in a 220 F laboratory oven). In each case the appropriate moisture value was entered in the computer data reduction program.

The average amount of wood charge for the small box stove tests was 6.8 lb (actual) which represents 4.9 lb/ft^3 of combustion volume.

In conducting the tests, all instruments were first calibrated for zero and span. A fire was built in the stove and allowed to burn while the sample lines and pumps were being heated. The computer program was initiated by entering background information such as wood charge, moisture, scan interval, barometric pressure, wood type, and monitoring instrument identifications.

When the wood had burned to glowing coals, the sample pumps were started and flow rates adjusted. This allowed flushing and conditioning of the system. The data acquisition was then programmed to initiate sampling at a set time. At approximately 2 minutes prior to test initiation, the balance was zeroed and all sample flow rates and line temperature were checked. At exactly 60 seconds prior to test initiation, the stove door was opened and the preweighed charge of wood was placed in the stove. The wood, which consisted of triangular splits, was placed in a position such that two pieces were side by side with the "interior point" of the split facing down (in the coals). The third piece, when included, was placed on top of these two pieces with the bark face down.

The door was closed with the primary air supply fully opened. The data processor initiated the sampling at the preset time while the operator monitored the stack temperature via a digital readout from a thermocouple. When the stack temperature reached 400 F, the air supply was adjusted to the test design conditions. This procedure was necessary to assure that combustion had been initiated and thus did not require opening the door to check the fire. Usually the stack temperature reached the 400 F point in 2 to 3 minutes, but in a few tests 10 minutes was required. In the event of continued low stack temperatures or serious equipment failure, this data acquisition was stopped and the test was repeated using a new charge of wood according to the method described.

While this method provided a generally reliable single batch test procedure without any in-test adjustments or wood additions, it did present one significant problem. The design of the computer program required that the time for the test be entered into the pretest program. This time was estimated by the operator and generally was sufficient such that only about 2 to 3 percent of the wood charge weight remained at the completion of the test. Occasionally during poor burn or slow burn conditions, the remaining weight was higher, thus not representing a complete cycle, but probably eliminating only the lowest emission level of the cycle. No attempt has been made to adjust any of the calculated average values for this problem.

Description of Stove Modifications and Observed Results

The background tests on the small box stove indicated that minimal, if any, control of the air distribution within the stove was achieved by the existing air regulators on the stove door. As a result, a modification as shown in Figure 3 was constructed. This diverter plate was designed to direct the air to either the primary combustion chamber or the secondary combustion zone as controlled by the stove regulators. This plate was used in all reported tests.

Summary of Data

Table I presents the averaged emission factors observed for the various modes of stove operation. The emission factors were calculated as the average mass rate of CO or THC divided by the mass rate of wet wood burning. The hydrocarbon rates were those indicated by flame ionization detector instrumentation, calculated (and calibrated) as methane. The true emissions would be actually higher, realizing that all hydrocarbons do not reach the instrument, and all those that do are not uniformly measured by the instrument. The numbers are considered to be representative of total hydrocarbon emissions, and suitable for comparison purposes.

Air Tight Stove

Although the stove was sold as an "Air Tight", it was discovered that the total air flow could not be controlled due to excessive air leakage. As a result all of the seams and joints of the stove were sealed with furnace cement. This apparently provided a significant amount of control in the total quantity of air supplied but not in the internal distribution. Modification A refers to the un-sealed stovebody. In tests 5 and 6 the internal bypass was left open and the secondary air vent in the door was closed. Thus all secondary air was supplied by leakage. This is identified by L on the table.

Secondary Air Control System

After the small box stove was modified by sealing all joints and cracks for better air control, an additional modification included installing a secondary air distributer into the combustion gas inlet to the secondary zone. The secondary air distributer consists of a 1/2-inch stainless steel tube with equally spaced perforations along a single line. An air flow monitoring orifice was positioned upstream of this distributer. A needle valve allowed control of air flow into the secondary combustion zone and the direction of air injection was controlled by rotating the tube. This is "B" modification and installation is shown in Figure 4.

During low rate burning in the box stove, the effect of direction of the secondary air injection was observed while maintaining a constant secondary air flow of 0.09 lb/hr. The stove primary air system was operated normally, but the conventional secondary air inlet in the door was shut. The air diverter plate was in place inside the stove door to more effectively distribute the primary air to the primary burn zone. For these tests, compressed air was used for secondary air supply to permit accurate measurement and control.

The results of these tests for four injection directions are shown in Table II. In this case "out" is the horizontal position into the gas flow, "down" is the vertical position into the gas flow, "up" is vertical position towards the top of the stove, and "in" is direction of flow into the flue pipe.

The results indicated that introduction of the secondary air was most effective when injected in a direction counter to the flow of the incoming combustion gas, particularly when injected in the horizontal direction. Only this orientation caused a change in gas composition as shown on Table II indicating secondary combustion. It should be recognized that the controlled secondary air constituted less than 1 percent of the total supply of air. As there was always sufficient oxygen available, the effects of this air injection were, therefore, primarily associated with increased mixing.

Two monitored burns were then conducted (tests 7 and 8) using the controlled secondary air distributer in the counter flow orientation. The results were encouraging with very controlled burns (even stack temperature 400 to 500 F) and moderate to low emissions factors and excess air levels.

The secondary air injection system was further evaluated by increasing the volume of air supplied. The air supply was increased (tests 10 and 9) to 1.4 and 1.7 times respectively the volume used previously. Air was introduced at the same position as used in the previous tests. The secondary air was again supplied as compressed air.

The preliminary results indicate that there may be a maximum level for the secondary air introduction. At high flows of secondary air there was indication of dilution and quenching; therefore, the increased mixing at the higher air flows may not be an advantage. At low to moderate flows, there appears to be a short time period during a burn when reduced THC and CO emission factors (lb/Klb wood) were obtained, corresponding to an increased temperature in the secondary zone (at 20 to 30 minutes into the burn time). It was not demonstrated conclusively that the secondary air distributer improved overall combustion of hydrocarbons, but an improvement in control of the burn rate and air regulation was demonstrated.

Thermal Insulation

The results of previous tests by Allen and Cooke[1] and Poirot and Sanborn[2] indicated that the temperatures of both the combustion air and the burning zone are important for improved combustion. A recent paper by Thornton et al[3] examined the pyrolysis and combustion of model compounds and wood gas to identify the effect of various parameters on the processes. The results indicate that a temperature of 1100 to 1200 C (2000 to 2200 F) is required for complete combustion (defined as <3 percent of input carbon as CO and <0.5 percent as C_1 and C_3 organics). An examination of the data from the experiments conducted on this program demonstrated that this temperature regime was never really attained. The data from Poirot and Sanborn's test show that secondary zone temperatures rarely exceed 800 F (425 C) even with preheated secondary air. On the previous Battelle program, extensive secondary burning was observed when gas temperatures above 800 F were obtained.

As a means of improving secondary combustion, a third modification was tried in this program which included an insulated secondary combustion chamber in the box stove. This is referred to as modification C.

For these tests, the secondary chamber of the box stove was insulated with ceramic wool wrapped and taped to the outside of the metal. The purpose of these parametric tests was to increase the secondary zone temperature as a means of improving combustion. In tests 11 and 12, the stove was run with high levels of excess air (both primary and secondary). Total excess air ranged between 400 and 1000 percent with wood burn rates between 3 and 5 lb per hour. In both tests, there was a minimal difference between emission factors for CO and THC from the primary and secondary zones. In both tests, gas temperatures in either combustion zone rarely exceeded 500 F. In test 12, there was one instance of the stack temperature exceeding 500 F with a corresponding lower secondary zone emission factor for CO and THC. In this instance, at approximately 33 minutes into the test, secondary CO was between 46 and 59 lb/Klb wood, secondary THC was between 12 and 13 lb/Klb wood, while primary CO was between 57 and 62 lb/Klb wood and primary THC was between 15 and 16 lb/Klb wood. These numbers suggest that some minimal secondary combustion might have been attained when temperatures exceeded 500 F, but it was not sustained for any length of time. The stack gas temperature did drop back to 350 to 450 F after this short period.

An additional test was conducted (test 13) which included the same insulated secondary chamber, but with the controlled and directed injection of secondary air. Compressed air was metered into the secondary chamber at approximately 0.1 lb/hr (68 F) through a distributer directly above the primary zone inlet into the secondary chamber. The air was directed through the equally spaced holes in the direction opposing the flow of incoming combustion gas (horizontal and front facing). In test 13, the burning was very stable. During this test, the average combustion gas temperature entering the secondary zone was 498 F with a high temperature of 567 F. As shown in Table II, the average O_2 in the primary chamber effluent was lower (16.1 percent) while the average CO_2 was higher. Similarly, the secondary effluent showed lower O_2 with higher CO_2. The THC emission factors appeared lower (<50 lb/Klb wood) in the graphic presentation, but the average concentrations for CO (percent) and THC (ppm) showed little difference and actually were slightly higher. The results indicated that overall combustion was improved, but not necessarily by increased secondary combustion.

Internal Primary Chamber Insulation

The next tests were conducted with interior insulation of the primary combustion chamber walls with ceramic wool, and also firebricking the inside stove hearth. This modification, D, is shown in Figure 5. It was hoped that the insulation would increase the gas temperatures by reducing heat loss to the stove walls, and also the firebrick would raise the fire closer to the secondary zone. For this modification, the firebrick was