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Project Summary

Control of Emissions from Residential Wood Burning by Combustion Modification

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An exploratory study is described of factors contributing to atmospheric emissions from residential wood-fired combustion equipment. Three commercial appliances were operated with both normal and modified designs, providing different burning modes: up-draft with a grate, up-draft with a hearth, cross-draft, downdraft, and a high-turbulence mode utilizing a forced-draft blower. Fuels were naturally dried commercial oak cordwood, commercial green pine cordwood, oven-dried fir brands, and naturally dried oak cut into reproducible triangles. Continuous measurements of stack gases included O_2, CO_2, CO, NO, SO_2, and total hydrocarbons (FID) as an indication of the total organic species in the stack gases during batchtype operation. Several combustion modification techniques were identified which have an appreciable effect on emission factors and, therefore, can be developed and applied to reduce emissions in consumer use. The more promising design modifications include: preventing heating of the wood inventory within the stove, focusing the air supply into the primary burning area with high turbulence, and increasing the temperatures in the secondary burning regions of the appliances.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The study reported in this document was initiated to explore the combustion modification techniques that might be applied beneficially to wood stoves, and more specifically to identify those techniques which show promise of providing a significant improvement in emissions when adequately developed and applied. The focus of the effort is on naturally drafted, hand-fired radiant stoves, as these constitute the majority of units used extensively for residential heating.

The combustion in wood stoves, and the resulting emissions, can be modified in many ways. In this experimental program several modifications were made in stove operation in attempts to correlate specific changes in emissions with each of several specific combustion modifications. Synergistic effects of several simultaneous modifications were not specifically sought. However, each set of tests conducted to demonstrate the effects of a specific modification necessarily depends on the other design and operating conditions in use at the time. The effects of a specific modification under different design and operating conditions can only be assumed, and the synergistic effects determined by inference.

Table 1. Summary of Wood Combustion Research Reviewed

Performing Laboratory	Project Focus
Monsanto Research Corporation	Extensive analysis of residential wood stove emissions
California Air Resources Board	Residential and laboratory tests on free standing stoves
Bowdoin College	Measured particulate emissions at low burn rates using a dilution tunnel
Canadian Combustion Research Laboratory	Continuous monitoring of gas emissions including efficiency measurements of different stove designs and fireplaces at low rates of burning
Auburn University	Measured stove performance and safety, focusing on efficiency measurements
Argonne National Laboratory	Measuring emission factors for residential wood stoves
Tennessee Valley Authority	Evaluation of several wood stoves including particulate and gas emission and efficiency calculations
Virginia Polytechnic Institute	Studies of catalytic-bed after-burners and staged combustion
National Bureau of Standards	Basic study of detailed characterization of emissions and their formation
Thermocore, Inc.	Measurement of air supply configuration effects in stove design
New York University (Plattsburgh)	Studies on thermostatic control development and stove design focused on particulates
Vermont Environmental Control Agency	Ambient emission studies focusing on particulates in the atmosphere
Institute of Man and Resources	Particulate and limited gas measurements for 10 central systems using wood for residential heating
U.S. EPA, Industrial Environmental Research Laboratory (RTP), Combustion Research Branch	Continuous measurement of gas emissions and comparison of stack sampling and dilution tunnel sampling during several phases of burning cordwood and pellets used as fuels
Del Green Associates	Just starting an emission measurement program using six stoves to determine reasonable standards for emissions, to develop a simplified testing procedure, and to evaluate the effects of fuel moisture
OMNI Environmental	An emission evaluation to establish baseline data on several new, commercially available stove designs

The modifications conducted in this laboratory program were of three types: stove design, fuel properties, and operator techniques. The uses of non-wood fuel and combustion additives were not considered. The use of processed wood, such as pellets, was also not considered, as this fuel can most effectively be burned in equipment specifically designed for its use.

Wood Combustion

The combustion of wood is generally recognized as involving three processes or phases: moisture evaporation, pyrolysis with subsequent space burning, and surface char burning. These processes occur successively at any local particle of wood, but in real combustion systems there is appreciable overlap resulting in all three processes occurring simultaneously within a combustion chamber loaded with wood. This overlap is especially significant when a reservoir of fuel is supplied within the combustion space for prolonged burning, as often occurs in stoves.

Types of Wood Combustors

Several options of air flow and fuel patterns within the stove have been adopted in commercialized designs. This study investigated up-draft airflow using a grate, up-draft using an impervious hearth, cross-draft, and down-draft through a grate. Also studied was a novel residential combustor design using forced-draft, highly turbulent combustion with additional design characteristics promoting low emissions.

Fuel Characteristics

Several types of wood were burned including commercially available air-dried oak cordwood, commercially available green pine, oven dried fir, and air-dried oak cut into reproducible triangles. The effects of piece size and dryness on emissions were found to be significant: extremely dry wood and small pieces resulted in high emissions of CO and hydrocarbons.

Operator Techniques

Stove operation at high burning rates was shown to result in reduced emissions of CO and organics as compared to low burning rates, and large inventories of wood in the combustion chamber reservoir also increase these emissions.

Current Research Summaries

This study included a review of current research programs related to wood stove emissions. Table 1 summarizes the programs and organizations performing wood combustion research including the emission measurements discussed in this study. There may be other studies unknown to the authors.

Conclusions

This laboratory program included an investigation of the effects of several independent variables on the atmospheric emissions averaged over complete burning cycles. Emissions were measured for CO and a total of organic species as indicated by total hydrocarbons (THC) measured by flame ionization detection. For a few tests, emissions of polycyclic aromatic hydrocarbons (PAH) and benzo(a)pyrene (BaP) were also measured by integrated gas chromatography and mass spectroscopy.

When burning air-dried oak at moderate rates, >4.5 kg/hr (>10 lb/hr), small differences were observed between up-draft burning with a grate and side draft burning modes in Table 2. The up-draft mode burning on a hearth resulted in lower emissions. When the side-draft stove was converted to the down-draft burning mode, the emissions were appreciably lower. Emissions from the novel high-turbulence wood burner were lower than those of conventional radiant wood stoves.

In the few tests involving measurements of specific PAH compounds from five different conditions of burning, the total PAH emissions varied from 11 x 10^{-3} g/kg wood for high-turbulence burning to 50 x 10^{-3} g/kg wood for down-draft burning. The emissions of BaP were found to be appreciably lower for down-draft and high-turbulence burning (0.04 and 0.05 x 10^{-3} g/kg wood, respectively) than from side-draft and up-draft burning (0.5 and 1.4 x 10^{-3} g/kg wood, respectively).

The emissions of CO and THC were observed to be much greater when lower burning rates were maintained, when large quantities of wood were charged at one time, and when small or oven-dried wood was burned. Emissions of both CO and THC were decreased by as much as a factor of 10 when effective secondary burning was obtained.

As a result of this study, several combustion modification techniques appear to be available to reduce the emissions from wood stoves, with varying degrees of probable effectiveness, and different levels of acceptability to residential stove builders and operators. These techniques are summarized in Table 3, noting whether modified stove designs, special operator techniques, or specific fuel characteristics are required. These conclusions indicate the more promising combustion modifications which should be developed in more detail to justify practice by stove users. In each category the modifications are presented in decreasing order as to their likelihood of being effectively implemented.

Table 2. *Atmospheric Emissions as Measured by Flame Ionization Detection*

Burning Mode	*Emissions — g emitted per kg wood as fired** CO	*Emissions — g emitted per kg wood as fired** THC
Up-Draft on Hearth	*33 to 37*	*8 to 19*
Up-Draft with a Grate	*200 to 400*	*32 to 42*
Side-Draft	*34 to 210*	*24 to 220*
Down-Draft	*4 to 110*	*5 to 56*
High-Turbulence	*~25*	*~5*

**≤g emitted per kg wood is equivalent to lb emitted per 1000 lb wood.*

Table 3. *Summary of Emission Control Techniques*

Factors Adversely Affecting Emissions	Approaches for Possible Improvements	Principal Modifications Required	Applicable to Existing Stoves?
Premature Pyrolysis in Wood Magazine Within Stove	1. Preventing heating of wood inventory	Design	No
	2. Feed wood frequently in small amounts	Operation	Yes
	3. Use large wood pieces, low surface-to-volume ratio	Fuel	Yes
	4. Burn moderate moisture content wood to retard pyrolysis	Fuel	Yes
	5. Burn devolatilized wood, charcoal	Fuel	Yes
Pyrolysis Rate in Primary Combustion Area Exceeds Local Air Supply Preventing Complete Combustion	1. Maintain high rate of primary air supply, with ensuing high burning rates	Operation	Yes
	2. Focus air supply into limited burning area to prevent widespread burning	Design	Retrofit
	3. Maintain high turbulence in active combustion region	Design	No
	4. Limit quantity of fuel in active burning area; i.e. approach fuel-controlled burning	Design	No
	5. Maintain high temperatures in active burning area	Design	Retrofit
	6. Avoid sharp and/or frequent reductions in air supply rate	Operation	Yes
Control of Emissions in Primary Burning Area	1. Provide high level of turbulence in burning area to promote mixing	Design	No
	2. Maintain high temperatures in burning area	Design	Retrofit
	3. Provide long gas residence time at the high temperatures	Design	No
	4. Duct pyrolysis products from magazine into burning area	Design	No
	5. Provide down-draft combustion, with bed area reduction to accomodate low burning rates	Design	No
Control of Emissions in Secondary Combustion Zone	1. Maintain high temperatures	Design	Retrofit
	2. Use heated secondary air	Design	No
	3. Increase combustible content of primary combustion products	Design	No
	4. Provide anxilliary combustion using an ignition source and/or supplementary fuel	Design (Operation)	No
Add-on Systems Affecting Emissions Reduction	1. Use catalytic afterburner	Design	Yes
	2. Use separately fueled afterburner	Design	Yes
	3. Add heat storage capacity to the system, permitting other modifications to be acceptable for consumer utilization	Design	Yes

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***Robert E. Hall** is the EPA Project Officer (see below).*
The complete report, entitled "Control of Emissions from Residential Wood Burning by Combustion Modification," (Order No. PB 81-217 655; Cost: $9.50, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650
The EPA Project Officer can be contacted at:
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