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AUTOMATED, INTELLIGENTLY MODULATING STOVES (AIMS) TO REDUCE RESIDENTIAL SPACE HEATING EMISSIONS

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ABSTRACT

Residential wood combustion represents 0.5% of the United States' primary energy consumption yet is responsible for over one-third of the primary PM2.5 emissions nationwide. Cordwood stoves are a class of residential space heating devices with significant prospects for emissions reduction. Emissions from woodstoves are a result of incomplete combustion due to poor mixing, low chamber temperatures, low residence times of the fuel/air mixture, and/or an overall lack of available oxygen. These challenges are further exacerbated by user-error, producing more real-world emissions than what certification testing may suggest, as most devices on the market rely on manual controls for air supply and refueling. To combat this, we have envisioned an intelligent stove that utilizes a minimal set of measurement sensors and a heuristic control strategy to actively modulate incoming air to enhance stove combustion performance, thereby eliminating user-error as a factor for emissions production. Critical performance metrics such as the heat release rate, instantaneous stove efficiency, combustion stoichiometry and wood moisture content can all be estimated using combinations of the stove temperature, weight and airflow rates. These parameters are then used in a feedback control algorithm to optimize the variable application of combustion air as well as reduce the burden on the operator by providing recommendations for refueling and replacement of components through automated, intelligent decision-making. Results from preliminary experiments have exhibited trends between the airflow velocity and stove temperatures, as well as demonstrated the reliability of low-cost sensors such as strain gauges and K-type thermocouples in producing repeatable measurements.

KEY WORDS: Cordwood, Woodstove, Automation, Emissions, Particulate Matter, Low-cost sensors, Biomass, Combustion, Space heating

1. INTRODUCTION

Wood combustion is one of the oldest forms of space heating, persisting and evolving throughout human history. Today, modern forms of wood-based space heating consists of wood-fired hydronic heating devices and woodstoves. In the residential sector, these devices along with other uses of wood combustion are responsible for less than a percent of the United State's primary energy consumption but are the largest source of the nation's primary PM2.5 emissions [1, 2]. With residential wood combustion only growing in popularity in the Northeastern United States [3], there exists a need to develop new techniques to reducing emissions in this sector. Many technological advances have been made in wood-based space heaters throughout the years that have aided in emissions reduction. Pellet stoves and boilers rely on pre-processed fuels and are automatically fed, which adds a layer of control and allows for more consistent combustion. However, most cordwood

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stoves on the market remain reliant on manual intervention and utilize fuel that can differ in species, geometry, and moisture content. Differences in fuel characteristics [4] combined with operator error encourages incomplete combustion due to inadequate air supply and improper refuelling. Nyström et al determined that proper operation and avoidance of unfavorable burn conditions itself is of higher importance than fuel species in reducing emissions [5]. These factors alone produce more emissions than what is encountered during certification testing, and thus the real-world emissions may be orders of magnitude higher than what is predicted using currently allowable upper limits defined by the United States' Environmental Protection Agency. As a result, lowering emissions from cordwood stoves in particular is of primary importance as these devices continue to become more prominent as a form of residential space heating.

Much effort has already gone into reducing emissions from cordwood stoves. While several modeling approaches have been utilized, as described by a review study by Koraiem and Assanis [6], the physical phenomena are extremely complex and processes operate over different time scales. For example, a wood log takes minutes to fully go through pyrolysis, while turbulence variations take place over fractions of a second. Modeling the surface reactions, fluid flow, and gas reactions each accurately is difficult, and approximations or empirical relations are often used to reduce computational demands. However, a complete, state-of-the-art model has not yet been developed to address all components of wood combustion, and as a result much of the improvements in the field have been limited to experimental studies. A common approach is the development of secondary and tertiary air flow paths in modern stoves to allow for the introduction of additional oxygen during certain periods of operation to enhance performance and reduce emissions. Carvalho et al investigated low-cost retrofit devices that introduce pre-heated alternative secondary air for older devices [7] and found an increase in thermal efficiency from 62% to 79%, as well as reduced emissions. Their findings showcase the magnitudes of the effects secondary air optimization has on stove performance. However, stove manufacturers differ greatly in their placement of primary and secondary air inlets, and developing a retrofit device compatible with a variety of existing stove models may be cumbersome. Another retrofit study performed by König et al incorporating heat exchangers and exhaust fans found improvements in emissions as well, but found that combining the two approaches can lead to adverse interactions and increased PM emissions [8]. This indicates that there is a delicate balance that must be maintained for devices, and is difficult to maintain without additional feedback mechanisms. Furthermore, woodstoves are known to have wide range of values for performance and emissions depending on operating conditions, making it difficult to have a one-size fits all solution if the solution is not adaptive [9]. Additional techniques, such as utilizing porous ceramics in the combustion chamber [10], have found a 20% decrease in PM emissions, attributed an increase in volatile compound interactions. Furthermore, catalytic combustors are often used as a secondary emissions measure, but are limited by high flue-gas temperature requirements [11].
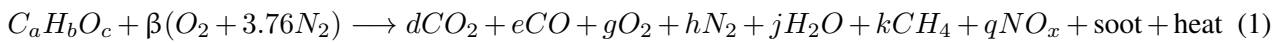
Many existing methods work well to reduce emissions in their given setup, but are often inflexible in that they either only affect a specific combustion regime, or are difficult to be adapted to a variety of existing and new stove designs. One approach by Illerup et al attempts to automatically control combustion air into a woodstove using the room and stack temperatures in combination with the oxygen concentration measured in the stack as process parameters [12]. While this method found an optimal oxygen concentration for minimum emissions, it relied on higher cost methods to determine oxygen concentration, such as hand held gas analyzers. This creates a cost barrier for market adoption, as the cost of these devices well exceeds the cost of a woodstove. Lower cost electrochemical sensors may be used, but their cross-sensitivity and survival in the harsh flue environment may prevent them from being viable options. A need thus exists for automated applications to identify a minimal set of sensors to characterize combustion performance that does not rely on laboratory grade measurement tools.

This manuscript focuses on the development of an intelligent stove that can actively modulate incoming air to enhance stove combustion performance using low-cost sensors in an effort to reduce emissions. Modulation of forced air has already been utilized in other space heating applications [13] and is promising for improving thermal output. A microcontroller then processes the data and actuates the relevant tools, such as a DC servo connected to air damper or small variable speed axial fan, to modulate the combustion airflow according to

the algorithm. This acts to ensure the inlet airflow is high enough to supply adequate oxygen and encourage more complete combustion throughout all burn phases, especially during start-up and burn out phases which are known to produce more emissions [14]. With this, a heuristic control strategy can reduce operator error and reduce the occurrence of unfavorable burn conditions. Determination of a minimal set of sensors required is the prime focus of this investigation. The proposed parameters to be measured are the stove weight, flue gas and jacket temperatures, and airflow.

2. THEORY OF OPERATION

Emissions from wood combustion arise due to variety of different mechanisms. The majority of emissions however may be attributed to incomplete combustion due to a lack of available oxygen, poor mixing, low residence times of the fuel-air mixture, and low chamber temperatures, which influences the rates of intermediary reactions [15, 16]. Rather than focus on a series of intermediary reactions, wood combustion may instead be approximated using the chemical reaction described by Eqn.(1).

$$C_aH_bO_c + \beta(O_2 + 3.76N_2) \longrightarrow dCO_2 + eCO + gO_2 + hN_2 + jH_2O + kCH_4 + qNO_x + \text{soot} + \text{heat} \quad (1)$$

There thus exists a defined amount of oxygen relative to fuel consumed required to ensure complete combustion. By measuring the stove weight in real time, we can compute how quickly fuel is consumed by the appliance and therefore how much oxygen is required at a given instance. This deviates from traditional stove performance, where an operator may "set and forget" the inlet air control, thereby over or under oxygenating the fuel throughout the combustion process. There is an optimum required oxygen supply rate to achieve a specified excess air-ratio, defined by Eqn. (2), that may be determined and prescribed for favorable combustion. For example, existing studies show a higher excess air ratio results in lower CO emissions [17] and as a result this derived parameter may be utilized in the algorithm's decision-making matrix.

$$EA = \frac{\beta_{\text{actual}}}{\beta_{\text{stoichiometric}}} \quad (2)$$

By incorporating an airflow measurement, the algorithm can determine how much air is being supplied and whether or not this amount is sufficient. However, further indicators are required to determine how much oxygen is sufficient. The best available indicator of this is the combustion chamber temperature. Yet, direct measurement of the combustion chamber temperature is difficult due to sensor longevity in such a harsh environment. For this, the flue gas and jacket temperatures are utilized as proxy measurements to help identify the combustion regime, as other authors have demonstrated acceptable ranges for different species [18].

A typical burn consists of an initial torrefication phase, where the drying and devolatilization of the fuel occurs, followed by pyrolysis in oxygen deficient areas, gasification, and eventually, full combustion. The initial drying phase may be determined through fitting the stove weight curve on the fly, as other authors have identified an initial linear decrease in mass during this phase [19]. In principle, the combination of this fundamental set of parameters could then be used to estimate the initial moisture content of the wood according to Fig. 1 and alert the operator for future runs if the fuel charge utilized was too wet or dry, as well as provide recommendations for refuelling events. Further specifications of the combustion regime will then make use of the flue and jacket temperatures, with certain thresholds corresponding to corresponding to different phases of the burn process. A layout of the aforementioned sensors is illustrated in Fig. 2 and is used as a basis for our design.

Item	Sensor	Sensor Type
①	stack temperature	K-type Thermocouple
②	jacket temperature	K-type thermocouple
③	stove mass	Strain gauges x4 on feet
④	air mass flow rate	blade-based anemometer
Derived parameters		
❺	d③$/dt$	total wood burning heat release
❻	① + ④	heat loss through stack
❼	❺ − ❻	heat release to room
❽	❼ / ❺	real-time efficiency
❾	d①$/dt$ + ②(after refuel)	wood water content
❿	④ + ❺	combustion stoichiometry
Control Options		
primary (& secondary, if equipped) air control actuator		
low-voltage (12 V DC) induced draft fan on chimney top		

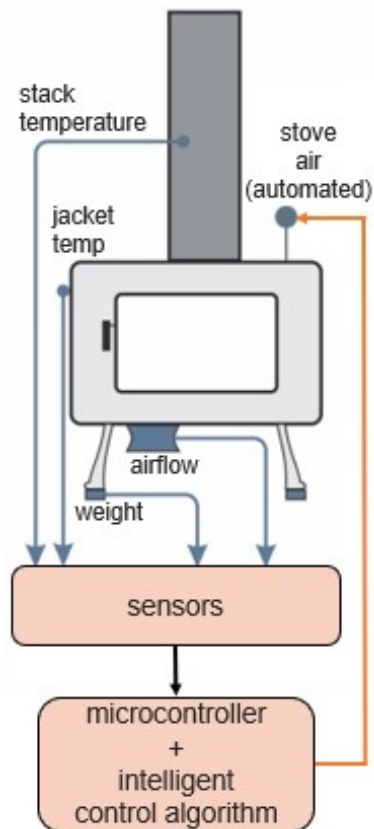Fig. 1 Fundamental parameters and their derived performance characteristics.

Fig. 2 Schematic of experimental test cell.

3. METHODS AND PROCEDURES

The experimental setup consisted of an instrumented Englander 30-NC cordwood stove with a firebox volume of 0.1 m^3 (3.5 ft^3) and stack diameter of 15.24 cm (6 in). Primary air was controlled through the use of a manual push rod located at the front of the stove next to the ash box with secondary air routed through small perforated holes at the top of the combustion chamber. Two 1/8" standard K-Type thermocouples accurate to $\pm$ 2.2 °C were utilized to measure the flue gas temperature in the stack and the stove jacket temperature. The stove weight was measured utilizing 8 50-kg strain gauge load cells with 0.1% Full-Scale accuracy attached to a flat board mounted at the bottom of the stove and processed through a 24-bit analog-to-digital converter (ADC), as in Fig. 3. The current setup utilized a high-cost, high-temperature vane anemometer (Hontzsch ZS25/25-350GFE/500/p10/ZG4) in the stack and assumes continuity to calculate the inlet air supply, with intent to replace with a lower-cost sensor on the inlet side in future iterations of the setup. An Arduino Mega was configured to interface with the sensors and output the data via serial communication to a PC to record the data. Fig. 4 showcases the sensors and setup mid-test, where a visible flame can be observed.

Tests begin by fully opening the air inlet control and placing a small amount of crumpled newspaper in the center of the stove. Kindling and small pieces of wood are then placed around the paper in a pyramid configuration. The starter fuel is then ignited and the door closed such that the interior handle makes contact with the outer side of the stove when rotated. This acts to provide a constant exterior inlet area into the combustion chamber during the startup phase. Fuel is then added as the fire progresses, with the last initial charge added as the flue gas temperature hits 176 °C (350 °F). The fuel door is then closed and the primary air inlet adjusted to the desired burn rate, which was approximately 3.6 kg (8 lb) per hour during the steady-state burn phase. An additional refuelling took place at one hour into the experiment, as well as adjustment of the inlet air control at the 150 minute mark. The refueling event occurred to showcase that the data collected during this phase is distinct from those collected during cold-start, which will be critical for algorithm development as each phase will require different air control strategies. The fuel was then allowed to burn completely until the jacket temperature began to approach ambient temperatures, at which case the experiment was concluded.
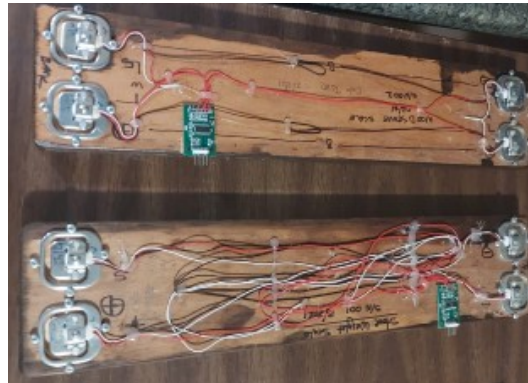
Fig. 3 Full-bridge strain gauge configuration.

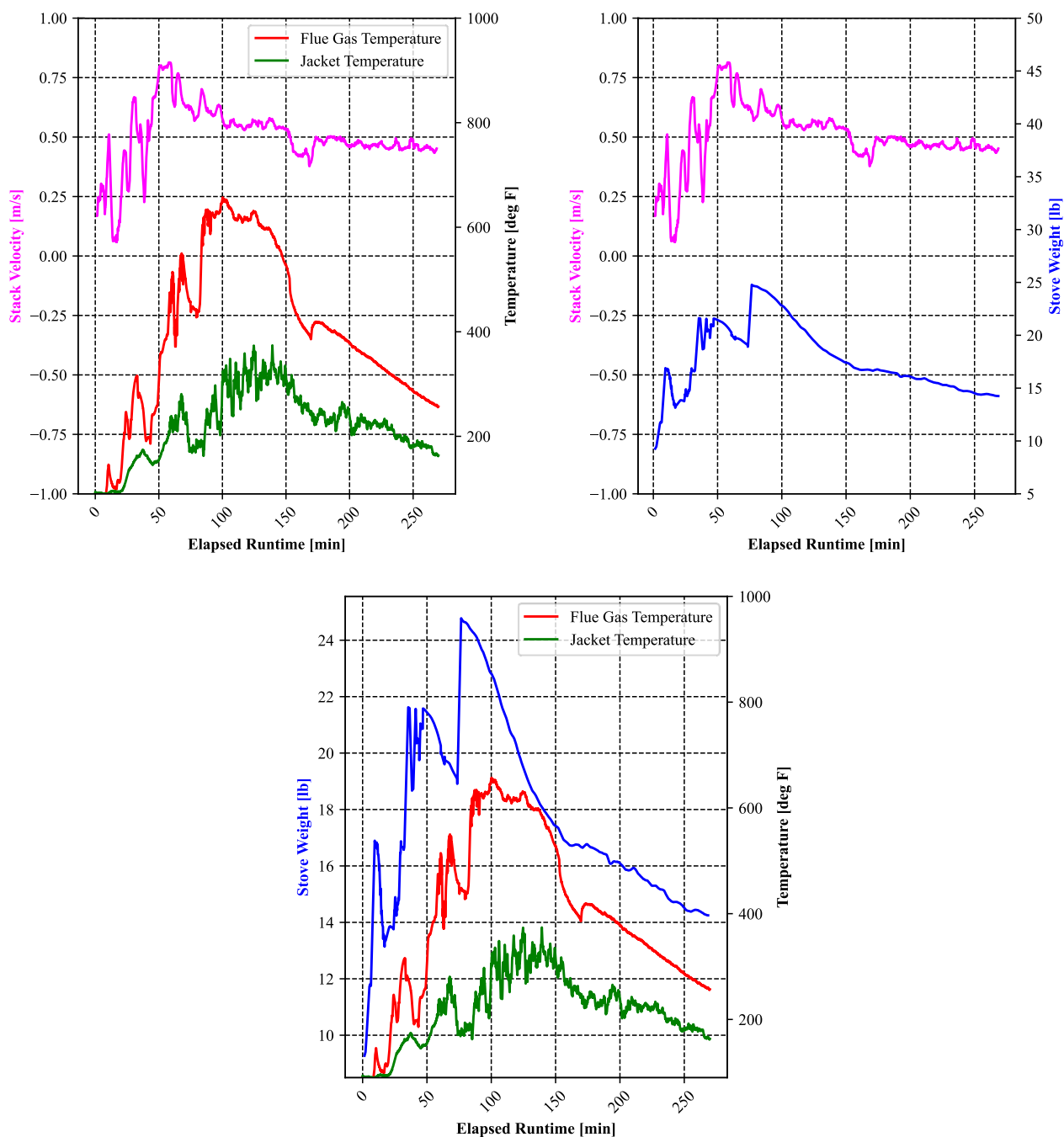**Fig. 4** Annotated fully-instrumented experimental setup.

4. RESULTS

Fig. 5 Stack velocity, stove weight, and stove temperature trends over a representative burn case.

The traces in Fig. 5 unveil simple yet powerful relationships between the minimal set of parameters selected. Flue gas and jacket temperatures appear to trend together, albeit with some initial lag-time. This shift in response time is likely due to the layers of insulation between the combustion chamber and jacket, which slows down the heat transfer rate, whereas the flue gas is a more direct measurement. There is also more granularity with the flue gas temperature measurement, which may show changes in behavior that the jacket temperature may otherwise not predict. Therefore, decisions that require fast response time are likely best suited to utilize the flue gas temperature. However, the jacket temperature is still important for determining operation mode,

as the flue gas temperature on its own is not enough. For example, a rapidly increasing flue gas temperature may be indicative of a cold start-up or refuelling phase. When combined with the jacket temperature, it is clear that when combined with a jacket temperature close to ambient, this would be categorized as a start-up phase, while when the jacket temperature is steady and hot, it is a refuelling phase. Experimental records and stove weight data verify this determination from temperatures alone.

Similarly, the stove weight measurement brings additional information. When fuel consumption begins to slow and flue gas temperatures decrease below a certain threshold, a smouldering or burnout case may exist. Additionally, the slope of the weight curve in conjunction with the flue gas temperature may be used to indicate the drying phase and estimate the initial moisture content of the wood. This phase distinction is important as it may impact the amount of air required to be supplied to the combustion chamber as compared to a steady-state burn due to the difference in the apparent mass change (water or fuel). This is also critical for the determination of other performance characteristics, such as the heat release rate and eventual heat output to the room.

Furthermore, while the airflow will require further studies for optimization, it is clear that there is sufficient bandwidth in velocity measurements within the system to utilize it as one of the primary variables to design our algorithm upon. A clear drop in velocity occurs as combustion enters the burnout phase, and high burn rates trend with higher velocities. However, further investigation must be performed into lower-cost alternatives, as the stack environment requires resilient sensors to survive and increases cost. A low-cost inlet air supply measurement is suggested with careful consideration on the pressure drop imposed by the measurement device as to not dramatically alter the draft in the system.

5. CONCLUSIONS

An initial investigation into the validity of a selected set of minimal parameters for determining stove operation was performed. An experimental test cell was constructed using a series of low-cost sensors where applicable. The following are major takeaways from this study:

- Strain gauges were found to produce consistent relative measurements of the stove weight.

- Flue gas and jacket temperatures together may differentiate between cold start-up and refuelling phases.

- Air velocity was shown to change in large enough increments over the duration of a burn to be utilized as a control parameter.

- Low-cost micro-controller prototyping boards such as the Arduino Mega may be utilized in conjunction with analog-to-digital converters to provide the necessary resolution for measured parameters.

Overall, the key finding from this investigation is that the minimal set of measurements prescribed allows for the determination of operating mode, and is promising for computing performance characteristics and recommendations for operators.

Future work consists of determining the optimal inlet supply airflow measurement device, incorporating actuators to control the supply air, developing the control algorithm, measurement of emissions, and verifying low-cost options with high-precision devices. The inlet supply airflow may be measured in the future by a small vane anemometer with low pressure drop. Tests incorporating the variable actuation of the supply air must be formed, through the use of low-cost DC servos or axial fans. Algorithm development may progress from heuristic control methods to more advanced techniques, such as the incorporation of machine learning tools. Emissions and stove weight measured through laboratory grade tools will be required to be performed in order to validate the effectiveness of the proposed solution.

ACKNOWLEDGMENTS

NOMENCLATURE

| PM2.5 | Particulate Matter | ($\#/cm^3$) | EA | Excess Air Ratio | |
| $\beta_{stoichiometric}$ | stoichiometric airflow | (mols) | β_{actual} | actual airflow | (mols) |

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