Process Optimization for a Wood Stove with a Combustion Catalyst

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Abstract

Incomplete combustion of wood releases a substantial amount of carbon monoxide (CO), which is hazardous to human health. One retrofit option to reduce CO emission is the installation of a combustion catalyst. The operating condition of the catalyst affects its performance, hence particular attention is placed on the process optimization of wood stoves on improving the heating efficiency and decreasing the CO emission. In this study, a combustion catalyst was added into a wood stove that was modified with baseline features which included an airflow system (AFS) and dividers. The dividers increased the residence time of the combustion gases and slowed down the burn rate while the AFS provided better combustion gases mixing, and the combustion catalyst resulted in improved CO emission. Both the dividers and AFS features increased heating efficiency as well as CO emission. The configuration with AFS, dividers, and the combustion catalyst saw a decrease in time weight average CO (TWA-CO) concentration of 3682 ppm, a 25% decrease compared to the AFS and dividers configuration and simultaneously maintained the heating efficiency achieved from the AFS and divider configuration.

Keywords: wood stove, combustion catalyst, air flow systems, dividers, residence time, turbulence

1. Introduction

During wood combustion, specifically incomplete combustion, a substantial amount of CO is released into the air. Exposure to CO can be fatal since it deprives the body of oxygen and even when oxidized to CO\textsubscript{2}, it is still a greenhouse gas [1,2]. Limiting CO emissions can help protect human health as well as the environment. Additionally, standards for wood stoves emissions are being updated in various parts of Europe allowing for less CO emission [3].

New pellet stoves and wood stoves have improved performance compared to old wood stoves in order to meet these new standards [4]. Some ways that new stoves improve their performance compared to old wood stoves include better mixing of fresh air and combustion gases, sufficient amounts of oxygen inside the stove, and optimal temperature inside the stove. Many different retrofit modifications are also available to improve the performance of an existing wood stove. One promising retrofit modification is to install a combustion catalyst into the stove. The purpose of installing a combustion catalyst into the wood stove is to use small quantities of noble metals, usually platinum, palladium or rhodium, on the surface of the catalyst as oxidation sites to effectively oxidize pollutants, such as CO [5]. Installing a catalyst into a domestic wood stove/boiler is
a viable approach in reducing emissions because of its low complexity and high compatibility. Many studies have been done to determine the viability of using a combustion catalyst. For example, the study by Hukkanen et al. showed that using a combustion catalyst can reduce emissions by oxidizing CO [6]. The catalyst used was a set of three metal wire mesh nets that consisted of platinum and palladium, encircled by a steel frame for inserting and removing from the flue stack [3]. CO emissions were reduced by 21% during the whole combustion process, and by 79% during the burn-out (the end of combustion) stage [3]. Another study with platinum cerium palladium catalyst on a wood stove showed a greater reduction of 70% for CO [3]. When considering the viability of using a combustion catalyst, how the catalyst is operated can affect performance. Studies have shown that the performance of a combustion catalyst is affected by how it is operated which affects its heating efficiency and CO emissions [7]. Side reactions may also occur inside the catalyst and must also be considered. Kaivosoja et al. showed that the side reactions that occur in the catalyst can actually increase polychlorinated dibenzo-p-dioxins and polychlorinated dibenzo furans (PCDD/F) emissions [8]. Therefore when considering the benefits of using a combustion catalyst to reduce CO, other emissions should also be taken into consideration. Additionally, the composition of the catalyst can also affect its usefulness. The study by Sudhanshu Sharma and M. Hegde looked at how to produce a three way catalyst and how it performed [9]. The catalyst used in their study was a “Ce0.98Pd0.02O2-δ on γ-Al2O3,” the catalyst achieved 100% conversion of CO using a space velocity of 21,000 h⁻¹ and below a temperature of 245 °C [9]. Lastly, process of operating a catalyst inside the wood stove may further be optimized by installing additional features, such as a preheater for the catalyst or secondary air inlet, inside the wood stove to improve its performance.

In this study, four configurations of the wood stove were tested for the highest heating efficiency and lowest CO emission: the unmodified wood stove, the wood stove with dividers, the wood stove with AFS and dividers, and the wood stove with AFS, dividers, and catalyst. CO and O₂ concentrations and flue stack temperature $T_{\text{stack}}$ were measured during the burn tests and heating efficiency was calculated using the Stack Loss Method (SLM).

2. Material and Methods

2.1 Materials

![Overview of the testing station](image_url)

**Figure 1.** Overview of the testing station

The wood stove used is an all cast iron, updraft, front loading stove, it has a height/width/depth of 32/28.7519.5 in. and a maximum heat output of approximately 50,000 Btu/hr, dependent on how operated [9]. A Testo 330 Flue gas analyzer was used...
to measure CO, CO₂, and O₂ concentration, exhaust temperature, and draft in the flue stack through the gas analyzer port that was 3 ft above the top of the stove. The measuring range for CO was from 0 to 8000 ppm, with resolution of 1 ppm and accuracy of ± 10% of measured value; the measuring range for CO₂ was from 0 to 10000 ppm, with accuracy of ± 3% of the measured value; the measuring range for O₂ was from 0 to 21 vol.%, with resolution of 0.1 vol.% and accuracy of ± 0.2 vol.%. The measuring range for temperature was from -40°C to 1200°C, with resolution of 0.1°C and accuracy of ± 0.5°C when measured temperature is between 0 to 100 °C and ± 0.5% of the measured value at the rest of range.

Approximately 20 ± 1 lb of red oak wood was used for the burn tests. Each wood log was cut into pieces of 9 inches in length, weight ranging between 1 - 4.5 lb. Moisture content was measured by Delmhorst BD-10 Pin Analog Wood Moisture meter one day in advance of the burn test. The moisture content of all wood logs fell into the range of 8 ± 1%. Wood logs were stacked uniformly and equally in weight in both chambers during the burn tests.

2.2 Dividers

The dividers separated the firebox into two equal-sized chambers for fuel load and exhaust, allowing separate ignition and forcing longer path lengths of combustion gases. The dividers were made of stainless steel. The air inlet allowed air into the firebox from the bottom of the first chamber, and combustion gases had to travel through two sharp turns to reach the outlet. The addition of dividers improved the turbulence and mixing of combustion gases and increased the residence time inside the firebox.

2.3 AFS

![Figure 3. Diagram showing the components and airflow of the AFS](image)

The AFS was designed to increase the draft in firebox and thus increase the oxygen supply for complete combustion. The AFS was placed in the flue stack, above the gas analyzer port and injected a stream of fast moving air upwards by a blower through the venturi tube. The forced air inflow created a vacuum upstream in the flue stack and induced additional air intake in the firebox. Proof of concept experiments were done on a firebox model in lab to verify the induced draft. The additional air intake increased oxygen supply for complete combustion. It also resulted in a faster flow rate of combustion gases through the
firebox, which promoted better mixing in the stove.

2.4 Catalyst

A 2’’ × 5.66’’ honeycomb catalyst was obtained from FireCat Combustors, model Combustor ACI-43C. A small piece of the catalyst was taken for EDX analysis.

2.5 Burn Test

The wood stove was set up on a test stand (see Figure 1). The air draft inducer was used to regulate the air intake of the wood stove. Dividers were located inside the combustion chambers to be used to promote better mixing inside the wood stove as well as creating a secondary combustion. A combustion catalyst was installed along with a catalyst bypass arm control such that the catalyst could be inserted into and removed out of the direct path of the flue gas externally during the burn test in the back of the wood stove. Within the flue stack, Testo was inserted into the gas analyzer port to record CO and O₂ concentrations. The gas analyzer port was located three feet above the top plate of the wood stove. In addition, the mass of wood loaded into the wood stove was recorded using the scale on the test stand just below the wood stove in order to standardize the test duration. For the AFS+Dividers+Catalyst configuration, the catalyst was inserted into the wood stove when the outside wall temperature of the first chamber reached 200 °C.

Data was recorded for CO and O₂ concentration and flue stack temperature every five minutes through the gas analyzer port using Testo gas analyzer and LabVIEW. The test was terminated when the amount of wood dropped below 10% of the initial weight.

2.6 Heating efficiency

The heating efficiency was determined using the Stack Loss Method, which estimates the heating efficiency of the wood stove by the flue stack temperature and the mass of dry O₂, DO₂, inside the flue stack [11].

\[
DO₂ = 14.7365 \times \frac{O₂}{21%} + 15.731 \quad (EQ. 1)
\]

Which determines \( L_{DG} \) and \( L_{WG} \), where \( L_{DG} \) and \( L_{WG} \) are the dry gas heat and wet gas heat losses in the flue stack respectively:

\[
L_{DG} = 0.001033 \times DO₂ \times (T_{stack} - 70) \quad (EQ. 2)
\]

\[
L_{WG} = 9.482 + 0.004351 \times T_{stack} \quad (EQ. 3)
\]

The efficiency, HE, is then given by [11]:

\[
HE = 100\% - L_{DG} - L_{WG} - 1\% \quad (EQ. 4)
\]

Both O₂% and \( T_{stack} \) were measured during the burn test at a 5 minute interval.

2.7 Scanning Electron Microscope (SEM) for catalyst characterization

An SEM analysis was done to determine the composition of the catalyst used. The catalyst sample was taken from the catalyst by using metal pliers to chip off a piece of the catalyst. The sample was mounted on carbon tape and was spot coated with a 2 nm thick gold palladium coating to improve the conductivity of our sample. The SEM was done using a focused ion beam scanning electron microscope (ZEISS Crossbeam 340). During the SEM, eight different locations on the catalyst sample were observed. Electron images, EDS layered images, and a map sum spectrum was acquired for each of the eight locations.
3. Results and Discussion

3.1 Characterization of the Catalyst

Energy Dispersive X-ray Spectroscopy (EDS) layered images of the catalyst sample revealed how elements are dispersed along the surface of the catalyst.

Figure 4A-E. Electron Image from SEM test of catalyst, EDS layered images of Al, O, Na, and Ce respectively

Figure 4A showed an electron image of sampled location on the catalyst surface while EDS layered images of the location revealed how different elements were concentrated on the catalyst surface. At this location, O and Al could be found in most places on the surface of the catalyst. This leads to the conclusion that O and Al are part of the inert support of the catalyst. Meanwhile Na was concentrated in small clusters where Al and O was not present. This may be due to Na being introduced onto the catalyst surface as a contaminant and entering crevices along the surface of the catalyst. Very little Ce was found on the catalyst surface; however, figure 4E shows traces of Ce dispersed throughout the surface of the catalyst suggesting that it is part of the noble metal washcoat.

Figure 5. EDS analysis of the catalyst sample
Figure 5 showed that the catalyst sample had negligible amounts of many different elements. Some of these elements could be contaminants on the surface of the catalyst. For example, Fe might have originated from the metal pliers that were used to acquire the catalyst sample. Additionally, the sample was mounted using carbon tape, so carbon could have been introduced to the sample as well. While contamination may have been present on the surface of the catalyst, the presence of Ce, Al, and O suggests that the catalyst used in this test may be similar to the one used by Sudhanshu Sharma and M. Hegde which had a $\text{Ce}_{0.98}\text{Pd}_{0.02}\text{O}_{2-\delta}$ wash coat and a monolith consisting of $\gamma$-$\text{Al}_{2}\text{O}_{3}$ [9]. Since the composition of the catalyst used here is similar to the one used by Sharma and Hedge, the catalyst should also have similar characteristics, such as CO conversion rates.

![Figure 6. CO concentrations of tests with different configurations](image-url)
3.2 CO Emission and $O_2$ Concentration

The graphs of CO emission and $O_2$ concentration are shown above for each of the configurations and combustion phases are labeled with numbers and dash lines. Phase 1 and 2 are the start-up phases (ignition of the first chamber) of the AFS+Dividers configuration and Catalyst configuration respectively. Phase 3 and 4 represent the ignition of the second chamber for the AFS+Dividers configuration and Catalyst configuration respectively.

From the CO emission and $O_2$ concentration data (Figures 6 and 7), there were multiple sharp decreases during the burn. Comparing Figures 6 and 7, nearly every sharp decrease in $O_2$ corresponds to an increase in CO caused by the incomplete combustion of individual wood logs. The data from the AFS+Dividers, Dividers, and Catalyst configurations verified the conclusion where oxygen decreases can be observed between 50 - 70 minutes when the second chamber was reported to be flaming from visual observation and temperature monitoring. Incomplete combustion resulted in higher CO due to insufficient combustion time, low temperature, and poor mixing between oxygen and the combustion gases. The dividers addressed the problems of insufficient time and poor mixing by increasing the residence time and turbulence inside the firebox. The AFS increased draft into the firebox, generated more turbulence, and therefore assisted the combustion.

All three modified configurations showed three major trends: the start-up phase, second chamber ignition phase, and the burn-out phase. The start-up phase from 0 - 20 minutes had high CO emission (see Figure 6) from incomplete combustion caused by low temperature (cold start) of the
wood stove. The CO emission decreased as temperature of the wood stove increased. A significant increase in CO emission occurred at 40 - 80 minutes due to the start-up phase of the second chamber. Temperature decreased as the burn test reached the burn-out phase. This resulted in another increase of CO emission that was lower than the two start-up increases in CO emission due to less wood mass.

The unmodified wood stove had the lowest overall CO emission compared to the other three modified configurations. Additionally, it had a relatively high overall O₂ concentration due to the lack of dividers, which enabled more airflow despite the absence of AFS. Another reason for the high O₂ concentration was due to the unmodified stove having a high burn rate. Figure 7 showed that after 50 minutes into the test, O₂ concentration began increasing. This was because after 50 minutes, the burn test reached the burn out phase. The low CO emission from the unmodified test was because the unmodified stove reached higher temperatures than the other stove configurations which allowed for more CO to be converted into CO₂.

The dividers configuration had less CO emission than the unmodified stove after the ignition of second chamber (60 - 80 minutes) because the combustion in the second chamber acted as an afterburner for the emissions from the first chamber, converting CO into CO₂. Turbulence of combustion gases inside the firebox increased due to the introduction of dividers changing the pathway of air. The dividers also increased gases residence time inside the wood stove. The incomplete combustion caused by low temperature was most notable during the cold start phase of the tests. The addition of dividers created a second ignition which was a warm start due to the increased stove temperature. The O₂ concentration after the second chamber ignition (60-80 minutes) was lower than the case when the first chamber was ignited (20-40 minutes). Similarly, the CO concentration after the ignition of second chamber (60 - 80 minutes) was lower than after the ignition of the first chamber (20-50 minutes). However, the drawback was that the overall oxygen concentration was low when compared to the unmodified stove. In order to increase oxygen concentration inside the wood stove, the AFS was installed along with the dividers.

The AFS+Dividers configuration had higher CO concentration compared with the dividers and the unmodified configurations. Two peaks could be observed during 20 - 40 minutes and 60 - 80 minutes, which correspond to the ignition of two chambers. The induced airflow through the stove helped better mixing of combustion gases in the stove, but shortening the residence time of gases. The disadvantage could be resolved by adjusting the power of AFS during the burn-out phase, but for the consistency of burn tests, AFS was kept at the maximum power throughout the tests. The higher O₂ concentration, especially during 20 - 60 minutes, demonstrated the AFS was functioning as intended. Therefore, an addition of the catalyst could be used to oxidize CO.

The catalyst configuration had an overall lower CO emission than the AFS+Dividers configuration. The wall of the first chamber reached 200°C approximately 15 minutes into the test, at this time the catalyst was moved into the pathway of the gas inside the wood stove at this time. Approximately 40 minutes into the test, there was a drastic decrease in O₂ concentration in the wood stove. This is likely due to the second chamber igniting and the oxidation reaction occurring inside the catalyst. During this time, lower CO
emissions compared to the AFS+Dividers configuration were observed, likely due to oxidation of CO by the catalyst. However, the catalyst used during the test did not perform as well as the catalyst used by Sharma and Hedge. At 220°C, the catalyst used by Sharma and Hedge achieved 100% CO conversion, while the catalyst used in this test achieved a maximum drop in CO concentration of 2000 ppm or ~25% [9]. This could be due to the catalyst not being sealed properly allowing gases to travel out of the wood stove without having to go through the catalyst. Additionally, CO emissions during the burnout phase were stable at 3000 ppm suggesting the catalyst was not active during burnout phase. The TWA-CO for AFS+Dividers and Catalyst configuration were 4612 and 3682 ppm respectively. The 25% decrease confirmed the effectiveness and aligned with the literature data (21%) [3].

3.3 Heating Efficiency

Figure 8 showed an overall decreasing trend of the heating efficiency as a function of time. Phases of all configurations are labeled with numbers and dash lines. Phase 1 and 2 represent the start-up phase of the AFS+Dividers configuration and the Catalyst configuration respectively. Phase 3 and 4 represent the ignition of the second chamber for the AFS+Dividers configuration and Catalyst configuration respectively. Lastly, phase 5 represents the burn out phase of all configurations.

All three modified configurations showed an increase in heating efficiency at the onset of the second chamber, which
suggested dividers improve the heating efficiency of the wood stove. Meanwhile, the unmodified wood stove had lower heating efficiency when compared to each of the three modifications done. This is because there was no staged combustion in the unmodified stove and all of the wood was available for combustion at the beginning of the burn. It also further verifies the high temperature inside the flue stack of the unmodified configuration by equation 2 ~ 4 where high flue stack temperature corresponds to more CO oxidation and less heating efficiency. Therefore, combustion occurred at a much faster rate than staged combustion which decreased CO emissions but also decreased heating efficiency.

The increase in heating efficiency during the Dividers test compared to the unmodified configuration was due to staged combustion. Since not all of the wood was immediately available for combustion, the burn was prolonged, and maintained a higher heating efficiency. Figure 8 shows a jump in heating efficiency from 60-80 minutes into the test, this correlates to the second chamber of wood igniting during the test.

The AFS+Dividers and Catalyst configurations overlapped with each other throughout most time during the test, and their heating efficiency were higher than the unmodified and divider only configurations. The improved performance in efficiency was attributed to AFS as it increased the flowrate of gas into and out of the firebox, therefore lowered the temperature of the flue gas, which resulted in higher efficiency. The addition of a combustion catalyst caused additional exothermic reactions when oxidizing volatiles and CO. However, the Catalyst configuration did not produce significantly higher efficiency compared with AFS+Dividers, because the temperature of the flue gas had not reached the optimum temperature required for the catalyst. From the data, the catalyst had noticeable better heating efficiency from 100 minutes onward when compared to the AFS+Dividers configuration from the blockage of the catalyst.

4. Conclusion

From the results of testing different configurations of the wood stove, the AFS+Dividers configuration provided the best heating efficiency, but also emitted the most CO. The unmodified wood stove gave the lowest CO emissions, but also had the lowest heating efficiency. Using the catalyst with the AFS and dividers provided high heating efficiency while emitting significantly less CO than the AFS and dividers modifications. Therefore, using a combustion catalyst with an AFS and dividers would be the optimal configuration for retrofitting an old wood stove.

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References

[2] Environmental Protection Agency (EPA), Air Sources Emissions


