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Wood stove combustion air retrofits: A low cost way to increase energy savings in dwellings

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ABSTRACT

In Europe, wood-fired stoves remain as major renewable household heating and emission sources. This study focused on improving the performance of a wood stove (natural draft) traditionally used in Portugal by the adoption of alternative combustion air retrofits. Additionally, the performance of a new pellet stove (forced-air) was determined to investigate the highest achievable goal for solid-fuel stoves. In the wood stove, an outer chimney component was installed around the existing chimney to allow the vertical admission of outdoor air that was preheated before entering the combustion chamber. This measure increased the thermal efficiency of the wood stove from 62% to up to 79%. Another component was used to administrate secondary air to the wood stove reducing the carbon monoxide emissions by 39% to 2808 mg Nm^{-3}. The two retrofits enhanced a more stable heat release from the wood stove, which reached a thermal efficiency 11% lower than that achieved by the pellet stove. This research suggests that retrofitting stoves with chimney components that allow the admission of combustion air can substantially increase energy savings in dwellings. Further efforts should focus on improving the interplay between the outdoor air and secondary air admission to achieve higher emission reductions at low-cost.

1. Introduction

Fireplaces and conventional wood stoves (WSs) continue to be used as reliable and renewable heating systems in Europe [1] and other cold and temperate climate zones. According to the World Health Organization (WHO), in several locations in Europe, North America, China and other regions, residential wood combustion is a major source of ambient air pollution [2]. Worldwide, families might continue to use biomass fuels in their homes as long as wood fuels will be available at a relatively low cost [3]. In Europe, Mudgal et al. [4] reported that there are more than 65 million inefficient fireplaces and solid-fuel stoves. Although traditional solid-fuel fired local space-heating systems are considered major sources of fine particulate matter ($PM_{2.5}$) and greenhouse gas emissions, efficient wood-fired stoves can be considered as important renewable residential energy sources in the region [1,5].

On this background, in Europe, strict regulations on the performance of new solid-fuel local space heaters (e.g. wood stoves) acquired in countries bellowing to the European Union might be established by 2022 [6]. The upcoming legislation aims the achievement of significant carbon monoxide (CO) and $PM_{2.5}$ emission reductions by 2030 associated with the utilization of fireplaces and solid-fuel fired stoves. The European Commission estimates such reductions to be higher than 18% in relation to the emissions registered for 2010. Although, it is also predicted that the implementation of the new regulations might have much lower impacts on energy savings than on the mitigation of those emissions. The impact on energy savings is estimated to reach by 2030 levels in the order of 5% (41 PJ) in relation to the year 2010. Here, it is important to point out that the Ecodesign requirements [6] for solid-fuel fired stoves are mainly focused on establishing strict emission thresholds for new appliances, rather than being targeted to regulate the performance of already existing installations.

1.1. Wood combustion appliances

Experimental investigations conducted by Calvo et al. [7] described the operating conditions during the combustion of pine wood in a marketed European cast-iron stove. Three stages that describe the wood combustion process were characterized, namely: (i) a first stage of fuel heating and drying without the existence of a visible flame; (ii) a second stage characterized by the devolatilization, ignition and combustion of volatiles and char, during which a visible flame was observed (approximately 5 minutes after igniting the fire); and a third stage, identified by the combustion of the char. Another experimental study conducted by Ozgen et al.

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[8] described the formation of fine particulate matter compounds, stating that larger particles are thought to be primary soot particles emitted during the flaming combustion phase and coated by condensing semi volatile organic species in the diluted and cooled flue gas. In this case, the soot formed in the flaming phase is a result of incomplete and inefficient combustion of wood associated with poor mixing conditions in the combustion chamber. A study conducted by Vicente et al. [9] tested the admission of combustion air at the secondary combustion zone through a single air inlet, in order to promote the secondary combustion of organic volatile matter and soot during the flaming phase. Sornek et al. [10] tested the emission of CO in a modern wood-fired fireplace-stove with an additional heat accumulation unit. This study showed the effectiveness of an automatic system used to control the combustion air admitted to the combustion chamber through independent air-inlets installed at the bottom, rear and front side of the stove. In this case, the additional improvements allowed a better distribution of combustion air and flue gases in the combustion chamber, contributing to the reduction of the CO emissions to levels below the Ecodesign threshold of 1500 mg Nm^{-3} [6]. Obaidullah et al. [11] have also showed that a modern 10 kW wood-fired stove marketed in Belgium equipped with a system of secondary air inlets and a baffle plate with vermicular insulation material in the surface at the top of the combustion chamber could reach CO emissions lower than 1185 mg Nm^{-3}.

1.2. Wood stoves in dwellings

Concerning the interplay of wood stoves with dwellings, previous investigations conducted in Scandinavia by Gustavsson et al. [12] on the life cycle assessment on primary household energy usage highlighted that the use of biomass in dwellings have a great potential to reduce net carbon dioxide equivalent (CO_{2e}) emissions in relation to the use of fossil fuels. Beyond that, the authors stated that the use of heat-recovery systems in buildings might substantially contribute to increase energy savings in Swedish dwellings by reducing primary energy demands and net CO_{2e} emissions associated with space-heating. Here, the reduction of the carbon footprint could be even lower if locally available biomass fuels would be used for direct (local) space heating purposes. However, in Norway, Georges et al. [13] reported, through a building simulation study, issues concerning the thermal performance of modern cast-iron wood-fired stoves when heating single-family homes with low heat demands, associated with the risk of overheating. In this perspective, Carvalho et al. [3,14] have showed, through a literature review and infield measurements, that even modern Danish wood-fired stoves tend to overheat dwellings with low heat requirements. On this background, heat exchangers and combustion air inlets could be conceived to improve the real-world performance of wood stove installations in order to enhance more stable heat transfer conditions in dwellings. Beyond focusing on the energy conversion efficiency and emissions from wood stove appliances, in the future, WSs should be designed to better interplay with building elements and avoid undue atmospheric pollutant emissions and energy losses, including those associated with the intake of combustion air from the indoor environment [3].

Recent investigations have worked on developing high performance solid biofuels, combustion appliances and associated components to increase energy savings in modern housing and reduce atmospheric emissions associated with wood heating. In Denmark, Illerup et al. [15] tested and supported the development of a digital device to regulate the primary and secondary combustion air admission (automatic air-staging) in a modern Danish wood stove. This upgrade resulted in substantial reductions on both the particulate matter and CO emissions in relation to the values obtained for certified stoves typically acquired in the Danish market. The emission factors determined for the upgraded stove were below the upcoming Ecodesign requirements (e.g. 5 g kg_F^{-1} for $PM_{2.5}$). In France, Limousy et al. [16] showed through laboratory experiments that spent coffee grounds can be used as an alternative biofuel in the form of crop-residue briquettes in a marketed wood stove to achieve high performance standards according to the French Green Flame label [17]. Furthermore, the scientific review conducted by Carvalho et al. [3] reported that wood pellet stoves (PSs) usually have an higher thermal efficiency than manually fed WSs. In the Iberian Peninsula, Carpio et al. [18] conducted a study on the impacts of using biomass-fired boilers on the energy rating and carbon dioxide (CO_2) emissions from dwellings, showing a remarkable decrease of up to 95% of CO_2 emissions when using biomass for space-heating, as compared to fossil fuels, with the economic savings being as much as 88%.

1.3. Retrofitting wood stoves

Despite of their high performance, wood pellet-fired stoves and gas boilers are usually less economically viable than manually fired WSs as stated in feasibility studies conducted by Kruse [19] and Carvalho [20] addressing certain economic scenarios in Portugal, due to the relatively high capital and operating costs associated with the acquisition of new appliances, the maintenance of electric components and the accessibility to suitable fuel supply chains. In this context, this study considers that mid and low income dwellings might face difficulties to acquire new stoves in a short-term. Thus, the present research focus is on retrofitting components that can be installed in existing wood stove installations as alternative solutions to reduce wood fuel use in dwellings and atmospheric pollutant emissions, increasing the economic feasibility of residential wood combustion.

Beyond the studies described along the literature review, few studies aimed to characterize the differences in the performance (thermal efficiency and emissions) of wood stove installations typically used today in European households, including associated retrofitted configurations of wood stoves sold in the market. On this background, the present research was targeted to evaluate the effect of retrofitting interventions with alternative combustion air admission components that can be used to improve the performance of wood stoves traditionally used in existing installations in Southern European countries at a relatively low-cost. In the present study, an outer chimney installed around the existing chimney of a traditional wood stove was tested as a system that allowed the vertical admission, at the top of the external chimney, of atmospheric air to the interior of the combustion chamber of the stove. The intervention functions as an additional heat-recovery system that can be installed in dwellings equipped with conventional wood stoves. Beyond that, the admission of secondary air to the combustion chamber was also tested as a measure to reduce atmospheric pollutant emissions from the wood stove. The performance and economic viability of the two low-cost wood stove retrofits was then compared with that achieved by the adoption of an ultimate wood pellet stove technology and upcoming Ecodesign emission requirements.

2. Materials and methods

The present experimental study was conducted in a combustion test facility at the University of Aveiro adapted to evaluate both the thermal efficiency and emissions of a manually fired wood stove and test two modified configurations of that stove. The combustion tests in the wood stove aimed to simulate, typical operating conditions applied by users in dwellings in Portugal, taking into account previous studies conducted by Carvalho et al. [20,21]. The