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# Effect of air staging on fine particle, dust and gaseous emissions from masonry heaters

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## ABSTRACT

There is a need to decrease the detrimental particle and gaseous emissions from residential wood combustion appliances. One encouraging alternative is to stage the air supply which improves the combustion conditions in small appliances. In this study, two types of combustion technologies were studied in conventional masonry heaters (CMH) and modern masonry heaters (MMH). Air staging in the MMHs considerably reduced the particle and gas emissions. The greatest reduction was observed in gaseous and particulate organic emissions. Methane emissions were reduced by 74%–91% and carbon monoxide by 26%–81%. The reduction of fine particle mass (PM<sub>1</sub>) was 14%–58%. Elemental carbon (EC, i.e. soot) emission increased in small combustion appliances but declined in large appliances. In addition, dust (TSP, Total Suspended Particulate matter i.e. Dust) emissions from hot flue gas were compared with the fine particle mass emissions from diluted sample. PM<sub>1</sub> emissions measured from diluted flue gas were 1.1–4.4-fold as compared to TSP collected from hot flue gas. This may be attributable to the fact that organic vapors partially had penetrated into the TSP filter in a gaseous form whereas when they were diluted, semivolatile species condensed on the particles. It can be concluded that air staging is an effective way to reduce gaseous and organic emissions from batch combustion appliances. Particle emission measured from diluted flue gas represents a more realistic results than TSP (hot sampling), because in dilution, also the organic fraction of the particle emissions is taken into account.

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## 1. Introduction

Fine particles (PM<sub>2.5</sub>: Particle mass below aerodynamic size of 2.5 μm) are the most important pollutant present in the outdoor air [1]. The impact of airborne particles on health

varies, ranging from mild, short-lived symptoms to the onset or worsening of chronic conditions, even premature death [2,3].

Residential wood combustion (RWC) has been claimed to be a major source of fine particle mass emissions, particulate polyaromatic hydrocarbons (PAHs) and certain gaseous

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pollutants such as volatile organic compounds (VOCs) throughout Europe [4–7]. Recent results from RWC studies have shown that poor operational practices increase clearly fine particle emissions [8–10]. In addition, the proportion of organic fraction, emissions of PAH compounds and genotoxicity of particles all increase under poor combustion conditions [11–15]. In contrast, in complete combustion conditions (e.g. pellet boilers), the fine particles are composed mainly of alkali metal compounds and trace elements [16–21]. In masonry heaters and stoves, fine particles include organic and elemental carbon [8,10,22], which are the main compounds emitted by conventional appliances such as sauna stoves [23,24]. The EU has decreed that there will be an increase in the use of renewable energy, up to 20% of the total energy consumption by 2020. Implementation of this decision will require an increased utilization in all kinds of wood-based energy which is likely to increase the emissions originating from RWC appliances.

There is a need to decrease the particle and gaseous emissions from RWC appliances due to their health effects. The emissions from RWC appliances can be decreased with primary (combustion technologies [19]) and secondary means (reduction technologies [22,26,27]). Particularly in small scale appliances, there is the potential to decrease emissions by improving the combustion technology. The basic prerequisites to achieve complete combustion are the good mixing of secondary air and partly oxidized pyrolysis gases and provision of an appropriate temperature, oxygen supply and residence time to allow flue gas oxidation [28–30]. Good mixing reduces the amount of air needed, providing lower excess air ratios and higher combustion temperature and increasing of the degree of efficiency. Inadequate mixing in the combustion chamber may lead to either high emissions of incomplete combustion or low combustion temperatures due to high excess air ratios.

In conventional heat storing appliances, the only way to control the combustion process is to try to prevent too quick devolatilization of the fuel batch. That is very important, especially in the closed combustion appliances (e.g. old wood log stoves), where the sizes of air intakes are restricted. As a result, smoldering combustion conditions are typically encountered for example in old wood boilers without heat-storing tanks [31]. This is also the case in appliances where the storage of heat is not possible, e.g. in light metal stoves [32] because they often operate in conditions with restricted air in attempts to slow down the heating. Particularly in masonry heaters, which have been described well in our previous studies [8–10,24,25] the control of the fuel devolatilization rate is important. In these heaters, wood is combusted in a relatively short period of time and at a high power. Due to efficient energy storing, one can achieve a high combustion rate without excessively increasing of flue gas temperature or decreasing the efficiency. However, the temperature of firebox walls increases from batch to batch, which accelerates the devolatilization of wood fuel from batch to batch. The prevention of a high fuel devolatilization rate is not straightforward and typically in conventional appliances one also encounters increases in particulate and gaseous emissions from batch to batch [24]. In the worst case scenario, this leads to smoldering combustion conditions [8].

In practice, effective mixing of the pyrolysis gases and air and satisfactory residence time can be achieved by the staging of the air supply [20]. In modern combustion appliances, the combustion air is supplied evenly in three stages to the firebox or burners. The primary air supply regulates the fuel devolatilization rate, whereas the secondary and optional tertiary air supplies oxidize the released combustion products (i.e. secondary combustion). The introduction of the heated secondary air into the top of the primary combustion chamber further enhances the ignition of the combustion gases. However, complete secondary combustion is difficult to achieve in a batch-wise process of wood log combustion because the combustion conditions vary remarkably during different combustion phases. The formation of the pyrolysis gases begins very quickly, when the wood batch is ignited or added to the firebox. This can be seen as peaks in the gaseous emissions after the addition of new fuel if the combustion gases have not enough time to burn completely [24].

In RWC, the mass and chemical composition of particle emissions are strongly dependent on the measurement technique being used. Many factors can influence the deposition of the particles to be sampled e.g. electric forces, gravitational settling, thermophoresis, diffusion and impaction, as described by Brockmann [33]. In addition, isokinetic sampling is needed if one wishes to sample large particles. Isokinetic sampling is less important for smaller particles, since these are less influenced by inertia. In general, particles smaller than 1  $\mu\text{m}$  behave like a gas, i.e. they follow the gas flow even in the sharp bends of the sampling line [33].

The most widely used methods can be roughly divided in dilution based techniques (e.g. Refs. [23,34–36]) and methods, where the particulate mass emission is measured directly from hot, undiluted flue gas (e.g. Ref. [37]). The regulations and emission limits presently applied in some countries e.g. Germany and Austria, are usually based on Total Suspended Particulate matter (TSP) (or shortly Particulate Matter, PM; generally Total Dust) from hot flue gas taking also account of large particles. Thus, the determination of TSP from the undiluted flue gas enables the comparison of the results with the appliance testing and certification. Since large particles have a tendency to impact or settle in the sampling lines and most diluters have bends and complex structures, the collection of TSP from dilution methods is in practice impossible. With respect to the health risk of PM emissions, knowledge about the thoracic fraction ( $\text{PM}_{10}$ ) or fine particles ( $\text{PM}_{2.5}$ ) is, however of greater relevance [1].

The most important question in the sampling of particles in RWC is how much the sampler collects organic material [38]. If the particle sample is collected from hot, undiluted flue gas, then condensable organic vapors partially penetrate through the filter in gaseous form. The dilution of the flue gas decreases the temperature and partial vapor pressures of organic vapors and this cause the semivolatile species to condense on the particles due to the exponential dependence between the saturation vapor pressure and temperature [9]. In general, by using dilution, a certain fraction of the organics condenses and is collected although there are several unclear factors (e.g. dilution ratio and dilution air temperature) that affect the dilution processes. Dilution is also used for several other reasons, e.g. simulation of ambient conditions [39]. In

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