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Technologies for measurement and mitigation of particulate emissions from domestic combustion of biomass: A review

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ABSTRACT

Energy from biomass is becoming increasingly important as fossil fuel reserves diminish. The utilization of biomass is already prevalent in the domestic heating sector, but produces significant amounts of particulates that are detrimental to human health. Mitigation technologies are well-developed for large-scale applications, but that is not the case at domestic scale. This review evaluates the various technologies that are available for mitigation of emissions from domestic combustion. Various other technologies are presented too, including those from the vehicular emissions field. The most common methods are the use of additives and catalysts, but both techniques are of limited effectiveness. The most notable technology is probably small scale electrostatic precipitators (ESP) which are under development and have been shown to be effective in reducing emissions.

The effectiveness of mitigation technologies needs to be evaluated accurately through reliable particulate sampling methods. Some sampling methods can produce misleadingly low particulate emissions, indicating that mitigation technologies are not required, when this is not the case. Therefore, this paper also reviews the advantages and limits of different particulate sampling methods. Currently, different methods are used and most emissions are reported in terms of mass concentrations, which may not include the contribution from ultrafine particles. In particular, dilution sampling significantly affects particle emissions by promoting nucleation and condensation of volatile organic compounds. The resulting effect is an increase in formation of ultrafine particulates that are smaller in size, which are better represented by particle number measurements. However, varying methods and degrees of dilution are reported in the literature. The reporting of the particulate emissions (either in number or mass concentrations) is also too varied in its units, making comparison of emissions difficult. Thus, particulate sampling (and dilution) methods need to be standardized, as has been the case in vehicular emissions.

Contents

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1. Introduction

With diminishing stocks of easily-accessible fossil fuels [1], the use of renewable energy sources is essential to ensure the security and sustainability of energy supply. Biomass is a viable energy resource, and its combustion produces less net CO_2, SO_x and NO_x than fossil fuels [2,3]. Biomass is also abundant in supply, with an estimate of 159 Mtoe (million tonnes of oil equivalent) available in 2010 in the European Union from agricultural, forestry and waste-derived biomass, and is expected to increase to 186 Mtoe in 2020 [4]. If the supply chain of virgin biomass is properly managed, the biomass produces minimal net-CO_2 emissions, as the carbon emitted from its combustion is recycled through photosynthesis, with the energy stored in the chemical bonds of the replacement biomass [5,6]. Agricultural and forest residues are other forms of biomass that can be used with low net CO_2 emissions [7]. In the UK, half of all energy consumed is for domestic heating [8,9], and as the Renewable Heating Incentive (RHI) scheme (12.2 p/kWh to be paid out to eligible 2014 applicants [10,11] and 8.93 p/kWh for applicants from April 2015 onwards [12]) has started in 2015 for households who use biomass as fuel for heating [9,13], there is an expected increase in the utilization of biomass.

When biomass is burnt, a wide variety of chemical species are produced, including CO_2, NO_x, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAH) and particulates [14]. The emission of particulates from domestic combustion can be significant, as observed by Stedman and Derwent in their measurements of emissions from suburban locations in the United Kingdom[15]. Inefficient wood combustion can emit higher particulate emissions than fossil fuel burning [16,17], as much as a factor of 1.5, as reported by the European Environment Agency [18–20]. An example of emissions due to poor combustion is the use of low efficiency cooking stoves in developing countries, with emissions ranging from 1 to 68 mg/m^3 [21]. Particulate emissions are emissions of solid combustion particles, and are generally classified into those that are larger than particle diameters of 10 μm, and those that are smaller than particle diameters of 10, 2.5, and 1 μm which are known as PM_{10}, $PM_{2.5}$, and PM_1 respectively. In addition to these classifications, there is also the emission of "ultrafine" particles that are smaller than 0.1 μm.

All the aforementioned emissions pose a hazard to human health. Long-term exposure to particulates increases the risk of cardiopulmonary and lung cancer, while PM_{10} are known to cause asthma attacks [22]. The detrimental effects of ultrafine particles are even worse, as they are easier to inhale and are reportedly more toxic (e.g. higher polyaromatic hydrocarbon (PAH) content) than larger particulates [23–25]. For example, in China, it was reported that inhalation of particulates caused one million premature deaths per year [26,27]. More information on biomass combustion emissions, its origins and particulate formation mechanisms are presented in Section 3.1.

To reduce particulate emissions, the design of domestic heating appliances has been modified in recent years to improve the combustion efficiency [28]. They have increasingly been fitted with instruments that modulate the air – fuel ratio for emissions control [29]. One method is the use of "lambda probes", which detect the oxygen levels in the flue gas and control the air – fuel ratio in the combustion chamber, such that the oxygen level in the flue gas is minimal to ensure complete combustion in the boiler [30,31]. Another method of improving the combustion efficiency is the introduction of primary and secondary air into the combustion chamber to achieve a staged combustion process, in which the volatiles from incomplete combustion in the first stage are combusted in the second stage, thereby reducing the emissions further [16,29–33].

Modern boilers may adhere to the emissions limits imposed by regulations [34], but the additional technology and instruments render them more expensive. Older boilers that do not have these improved combustion technologies exhibit higher particulate emissions [35]. More stringent emission limits will be implemented in the future. For example, to be eligible for the payout from the RHI scheme in the UK, the particulate emissions from the boiler must be below 30 mg/MJ [11], while Germany will impose a 50 mg/Nm^3 (at 11% O_2) limit in 2015 [36]. In these situations, mitigating equipment is required for the clean-up of flue gas and for further emissions mitigation. Traditional particulate filtering equipment from gas streams includes cyclone separators, electrostatic precipitators (ESP), and bag filters. However, these methods are only cost-effective when used in large-scale heating applications where the amount of fossil fuel reduction is enough to cover the cost of the aforementioned technologies over a reasonable payback period. It has been reported that for domestic heating appliances (where the thermal output is lower than 200 kW), the savings from reduced fuel usage relative to the reduction in emissions do not warrant the use of such technologies [37]. Thus, there is a need to develop emission reduction technologies that are economical and cost effective at small-scale. Such methods are not widely reported in literature, and thus, this review intends to cover the various works that have been performed for domestic scale emissions mitigation, and to determine whether there are any available technologies which are, or are likely to become, economically beneficial. These are discussed in Section 3.2.

In order to determine the effectiveness of any mitigation measures, emissions must be accurately quantified. This task is complicated by the variety of available particulate sampling methods in literature, such as the European standard EN303-5 and EN13240 [16,38], NS3058/59, [39], BS/PD6463 and VDI2066 [31,40,41]. The measurement procedure outlined in EN303-5 is mainly meant for domestic boilers, while those of EN13240 and NS3058/9 are meant for domestic stoves. Some of these methods require the flue gas to be diluted and cooled before particles are sampled for, although in some investigations the dilution was not performed [31,33,42,43]. A different method may result in lower measured particulate emissions, and in the process negate the need for a mitigation system, when in reality harmful particulates continued to be released. From a health and safety perspective, this situation is worse than overestimation of the particulate emissions, which could at worst lead to "unnecessary" installation of mitigation technologies. Also, the variability in the approaches leads to results which are not easy to compare. Thus, the objective of the Section 3.3 is to review the different measurement methods to highlight their respective limits (or advantages). It will also be shown that possible future trends in the reporting standards for particulate emissions will have implications on the mitigation technologies in Section 3.2. This manuscript does not have a database on domestic biomass combustion technologies such as turbulators, lambda probes, etc. Such information can be found from Míguez et al. [29].