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Research Paper

Experimental analysis of fouling rates in two small-scale domestic boilers

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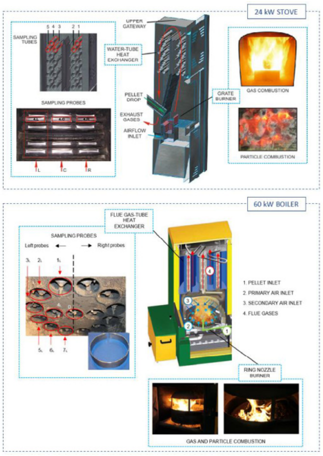
HIGHLIGHTS

- The fouling rates of 24 kW water-tube and 60 kW fire-tube boilers were experimentally obtained.
- Sampling probes were placed at different locations of the heat exchangers during the tests.
- Commercial wood pellets were used as fuel.
- The particulate matter (PM) and flue gas composition were studied.

GRAPHICAL ABSTRACT



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ABSTRACT

Fouling is a topic of interest in almost all heat production systems. A noticeable fall in thermal efficiency can be caused by accumulated fouled matter, especially in those surfaces where heat exchange takes place. In this research, two domestic-scale commercial pellet boilers were studied (a 24 kW water-tube boiler-stove and a 60 kW fire-tube boiler). Sampling probes were placed in both heat exchangers to measure the deposition rate. Commercial wood pellets were used as fuel. A series of tests were carried out under the same operating conditions. Average fouling rates (F_R) of 7–12 g/m^{2}h in the water-tube boiler-stove and 3–5 g/m^{2}h in the fire-tube boiler were measured. The variation of these fouling rates with the position in the boiler side was also analyzed. In addition, measurements of the particulate matter (PM) concentration and flue gas composition were made during the tests. A correlation between the CO emissions and the collected solid particulate (SP) matter was obtained for each case of study. PM values of 110–280 mg/Nm^3 were measured for the water-tube boiler and 13–135 mg/Nm^3 for the fire-tube boiler. An SP size distribution study provided evidence for the large amount of ultrafine particles in domestic biomass combustion systems.

1. Introduction

Energetic efficiency studies and renewable energy developments have gained attention, thanks to the generalized concern about global warming [1]. Related to these issues, contemporary laws try

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Abbreviations: CFD, computational fluid dynamics; PM, particulate matter; SP, solid particle.

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to guarantee the performance of engines, devices and machines all along their service life. The amount of research studies analyzing the degradation and efficiency losses of the equipment during their lifetime [2] has grown. Understanding the mechanisms involving deterioration, fouling formation and deposition is very important in this field.

In the particular case of heat production systems (furnaces, boilers …), fouling or slagging problems are of interest, especially in those surfaces where heat exchange takes place. There, the sum of the accumulated fouled matter creates an insulating layer (low thermal conductivity) that reduces the global heat transfer coefficient to the working/heating fluid [3]. As a consequence, the thermal efficiency will fall, leading to an increase in exploitation costs and pollutant emissions [4]. In some cases, this gas-side fouling is accompanied by corrosion, or even erosion, by the impact of particulate matter (PM).

Traditional small-scale or domestic biomass boilers have low efficiency, are highly pollutant, and have small automation systems [5]. Although modern plants have solved or, at least, somehow minimized the greatest part of these problems, those facilities are still important particulate matter generators [6]. It is commonly thought that the fouling of heat exchangers strongly depends on the deposition of airborne particles [7]. The mass concentration, size distribution and composition of aerosol contained in flue gases are supposed to strongly determine the fouling rate.

The formation of PM, either from organic or inorganic origins, involves complex processes that are not fully understood. The appearance of organic solid particles (soot) can be simplistically understood as the by-products of hydrocarbon fragments (non-burnt) that can coagulate and condensate, ranging from millimeters to ultrafine particles (nm). If these particles are not consumed in fuel-lean flame zones, they will normally remain in the flue gas stream. Inorganic particles sweep a similar range, but their origins are inorganic ash compounds volatilized into flue gases or dragged by the entrained combustion air. In general, in biomass small-scale systems, PM emissions are on the order of 10–70 mg/Nm^3, and as combustion conditions are poorly controlled, the composition is believed to be dominated by particles from incomplete combustion (soot) and condensable organic compounds (COC). The size distribution may be bimodal or unimodal depending on the sampling port positioning [8].

All airborne particles may come into contact with cold surfaces, and depending on the conditions, they can stick to the surface, creating a foulant (insulating) layer. Depositions over surfaces subjected to direct flame radiation are referred to as slagging, whereas the term fouling is applied to deposits in the convection passes. However, in both cases, the processes will be governed by transport mechanisms and the sticking probability (propensity).

Transport mechanisms can be divided into those affecting large and medium scale particles (mm) and those boundary layer-controlled mechanistic deposition models that only affect submicron particles [9]. Within the first group, inertial impaction is the main force involved. Large mass particles dragged by the airflow are not able to follow the stream lines, impacting into the surfaces, mainly in the upstream face. In the second group, deposits are collected both windward and leeward. The different mechanism depends on the properties suffering a gradient that generates transport across the boundary layer. In the case of condensation and diffusion, the mass concentration gradients are the active principles, whereas in thermophoresis temperature is the key [10]. In this last scale, the Brownian and eddy diffusion deposition rates (micro turbulence effects) should also be taken into account [9].

Once the particles have been transported to the surface, they may or may not stick depending on the arriving conditions. There exist a number of works dealing with this issue [11,12], and several parameters should be studied to determine the impacting conditions. In general, one of the most important parameters is the particles' velocity (quantity and angle of impact). The kinetic energy will determine if the particle sticks or rebounds, generating erosion (shedding). The other key variable is the state of matter. The higher the melting fraction in both contact bodies, the higher the sticking propensity. Finally, all the physical properties of the surfaces in contact are also of great importance, such as the roughness, hardness, and shape.

Several assays are currently being carried out to analyze and characterize the biomass fouling effects in pilot-plants and on large-scale real facilities. Li et al. [13] experimented with three different types of biomasses in a 25 kW down-fired combustor and distinguished four deposition periods following the trend of a "fast-slow-fast-slow" process. The effect of the cofiring biomass and coal on ash deposition was examined by Robinson et al. [14], resulting in a possible way to mitigate some of the fouling difficulties related to high-fouling biofuels. Wang et al. [15] studied the effect of additives for preventing ash fouling. Pronobis [16] also studied the influence of biomass co-combustion on the fouling of boiler convection surfaces. Boiler cleaning mechanisms are also being studied to control this fouling. Romeo and Gareta [17] presented the activation of sootblowing as a control strategy. In another study, Naganuma et al. [18] proposed a surface treatment on tubes through the use of a thermal spray technique. In addition, some numerical analysis and CFD models were developed [19–22]. Theis et al. [23] obtained experimental data to validate CFD deposition models.

Few studies give numerical data on fouling rates. Theis et al. [24] found deposition rates between 20 and 160 g/m^{2}h depending on the biofuel burned. An entrained flow reactor was used during these experiments. In a second part of this investigation [25], the deposits' chemistry was studied. The effect of the probe surface temperature on the deposition rate was also evaluated [26], and a dependency on the fuel mixture burned was found. In a review about ash-related issues in biomass combustion, Hupa et al. [27] reported deposition rates between 2 and 22 g/m^{2}h when two different types of bark were blended with rice husk on an entrained flow reactor. The deposition rates increased as the bark percentage in weight increased. Teixeira et al. [28] determined fouling rates of approximately 10–20 mg/m^{2}h for coal and wood pellet blends and approximately 10–50 mg/m^{2}h when coal is mixed with olive cake. When oil-palm empty-fruit-bunch was burned in a 150 kW$_{th}$ pilot-scale combustor, Madhiyanon et al. [29] reported deposits mass fluxes between 160 and 182 g/m^{2}h depending on the temperature experiments. Jensen et al. [30] conducted experiments in two straw-fired plants and reported that deposits in the range of 15–160 g/m^{2}h formed in the furnace and between 2 and 25 g/m^{2}h in the superheaters. Bashir et al. [31] measured deposit formation rates of approximately 33–41 g/m^{2}h in 105 MW and 250 MW biomass fired boilers. Hansen et al. [32] reviewed a number of large grate-fired and suspension-fired boilers with biomass and found similar levels of fouling (0–100 g/m^{2}h). Table 1 summarizes the deposition rates obtained from the literature.

However, there is little knowledge on commercial small-power domestic heating systems because of a lack of experimental data. The aim of the present work is to produce useful data from two different small-scale commercial boilers. One of them is a boiler-stove with a power of 24 kW and a water-tube heat exchanger. It is not the archetype of a domestic type but presents certain advantages to measure the deposition velocity in the water-tube heat exchanger. The second one is a 60 kW fire-tube boiler. The results will include detailed data about the particulate matter concentration and the flue gas composition, as well as a broad range of relevant parameters.