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Research Paper

Experimental study on the fouling behaviour of an underfeed fixed-bed biomass combustor

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HIGHLIGHTS

- Determination of the fouling rates in a small-scale biomass underfed fixed-bed combustor.
- A water-refrigerated sampling probe was placed in the cross-flow.
- Deposition rates fluctuated between 7 and 28 g/m^2 h using commercial wood pellet.
- Collected matter was divided into deposited and attached.
- A photogrammetric procedure was used to determine the fouling profile around the sampling probe.

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ABSTRACT

One of the most important problems occurring in biomass combustion is the appearance of fouling on heat exchangers which reduces the efficiency and lifetime of the facility. In this experimental work, wood pellets were burned in a small-scale biomass underfed fixed-bed combustor (12 kW_{th}) using low primary to secondary air ratios (15/85, 20/80, 25/75, 30/70). A water-refrigerated sampling probe was placed in the cross-flow above the bed to measure the fouling layer build-up rates. The water temperature inside the tube was varied between 20 and 95 °C. This research proposes a test methodology to mimic the behaviour of a real heat exchanger of a commercial boiler.

The measured deposition rates fluctuated between 7 and 28 g/m^2 h. A greater amount of total airflow, an increase in the primary air inlet and a lower water temperature increased the deposition mass. In addition, the deposition rate decreased with time and did not appear to follow a linear pattern, which likely indicates that after a strong initial fouling rate, removal and collapse mechanisms begin to counter-balance the arrival of particles, which stabilizes the fouling layer.

1. Introduction

The growing concern about global warming has led to numerous studies related to energy efficiency and renewable energies [1]. In the particular case of small-scale biomass boilers, these boilers have traditionally been linked to low efficiency, high pollutant emissions and small automation systems [2,3]. Although modern facilities have resolved or at least in some way, minimized most of the issues, these facilities still generate significant amounts of particulate matter (PM) [4–7] and gaseous emissions [8–10]. The formation of slagging is also one of the most challenging problems faced by these facilities [11–13]. Apart from the obvious handicaps of PM and gaseous emissions as pollutants, the ash accumulation and unburnt matter over different surfaces of the boiler's heat exchangers (fouling and slagging) reduce the global heat transfer, which minimizes the yield of the plant and causes serious problems of corrosion and erosion [14–19].

The size distribution, mass concentration and composition of the particulate matter greatly influence fouling. Numerous studies have analysed the ash deposition on heat exchanger tubes and its relation with the aforementioned parameters [20–22]. Nielsen et al. [22] performed a chemical analysis of the deposited mass, which showed that the primary constituents are Si, Ca and K and also contains minor amounts of K, P, Cl and S. Baxter et al. [23] demonstrated that one of the elements, K, results in a greater tendency of fouling, and Teixeira et al. [24] corroborated these results, claiming that the presence of KCl or K_2SO_4 in the deposits results in a high tendency for fouling. Regarding the chemical composition, two layers with different chemical compositions can be distinguished in the deposited layer [20,25,26]. Theis et al. [17,27]

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Nomenclature

$\dot{m}''_{air}$	total air mass flow (kg/m^2 s)
$\dot{m}''_1$	primary air mass flow (kg/m^2 s)
$\dot{m}''_2$	secondary air mass flow (kg/m^2 s)
$\dot{m}''_{att}$	attached mass (kg/m^2 s)
$\dot{m}''_{dep}$	deposited mass (kg/m^2 s)
$\dot{m}''_f$	burning rate (kg/m^2 s)
$\dot{m}''_{tot}$	total mass (kg/m^2 s)
S_R	slag ratio
T_{in}	water inlet temperature (°C)
T_{out}	water outlet temperature (°C)
T_g	gas temperature (°C)

Greek symbols

φ	air staging ratio $(\dot{m}''_1/\dot{m}''_{air})$

Abbreviation

DL	detection limit
PM	particulate matter
wp	wood pellet
wt	% weight
XRF	X-ray fluorescence

showed that a non-linear deposition pattern occurs due to the physicochemical interactions that take place. Other parameters involved in the deposition are the boiler geometry and operating conditions [19]. Several studies have focused particularly on the probe surface temperature as an operating parameter using straw, peat, bark, saw dust, corn and coal [16,18].

Deposition in the tubes' surfaces is caused by different transport mechanisms, which can be divided into two groups depending on the size of the particles that are involved in them. In the first group, for particles larger than 10 μm, inertial impaction is the primary force; this mechanism is strongly related to the size, geometry and density of the particles and occurs because large particles are unable to follow the streamlines and thus, impact the windward surface of the heat exchanger. The second group includes medium- to small-sized particles, where the deposits are distributed evenly over the entire surface. The primary cause of thermophoresis is the thermal gradient; however, diffusion is produced by the mass concentration gradient [16,19,28]. The last group contains the smallest particles, which are affected by eddy and Brownian diffusion [29,30]. Once the particles reach the heat exchanger surface, deposition occurs to a greater or lesser degree depending on the magnitudes of different factors, such as the angle of impact, kinetic energy or state of matter. The roughness, hardness and shape of the surfaces also have an important role in the stickiness of this matter [31].

Several studies have investigated the deposition problems, which have not only focused on small-scale burners [21,32] but also on large-scale boilers [15,33]. Although data comparison is extremely difficult and should be handled carefully, it is useful to perform such studies in laboratory-scale facilities, where operative parameters are easier to control. In Table 1, data from several studies performed in a pilot laboratory-scale combustor are presented. Heinzel et al. [34] evaluated the fouling rates in an air-cooled sampling probe for straw, pure coal and via co-combustion of coal and different biomasses, where values between 5 and 103 g/m^2 h were obtained. Theis et al. [27] obtained deposition rates values between 20 and 160 g/m^2 h depending on the fuel used. Hupa et al. [35] used an air-cooled probe and studied the fouling rates and obtained values between 2 and 22 g/m^2 h. Teixeira et al. [24] performed co-combustion with wood pellets and coal in a water-cooled sampling probe with fouling rates between 10 and 20 g/m^2 h. Madhiyanon et al. [20] studied the fouling rate for an oil palm empty-fruit bunch in an air-water-cooled probe with deposition rates between 160 and 182 g/m^2 h. To reduce the effects on

Table 1
Fouling rate studies in a biomass pilot laboratory-scale combustor.

Pilot laboratory-scale combustor					Fuel	Fouling rate (g/m^2 h)	Reference
General characteristics			Sampling probe				
Bed type	Feeding	Power	Refrigeration	Temperature			
Fluidized	Continuous-top feed	300 kW	Air	Air-cooled	100% Coal	12.8	[34]
					100% Straw	103	
					Co-combustion with coal:		
					25% Straw	17.9	
					25% Miscanthus sinensis	44.90	
					25% Beech	5.10	
					25% Oats	52.60	
					25% Sewage sludge	52.30	
Entrained flow reactor	Continuous-top feed	–	Air	Surface probe	Peat	20	[27]
					Bark	80	
					Straw	160	
Fluidized	–	–	Air	Gas temperature close to the sampling probe	Eucalyptus bark with rice husk	2–22	[35]
Fluidized	By gravity from the top	$\sim$75 kW	Water	Gas temperature close to the sampling probe	Co-combustion: wood pellet and coal	10–20	[24]
Grate-fired	Continuous-top feed	150 kW	Water and air	Gas temperature close to the sampling probe	Oil palm empty-fruit bunch	160–182	[20]
Fluidized	Continuous-top feed	30 kW	Air	Surface probe	Different coals	1.3; 2.0; 2.2 and 4.5 g deposit/kg fuel	[21]
					Red oak wood	0.04 g deposit/kg fuel	
					Switchgrass	0.4 g deposit/kg fuel	
Fluidized	Continuous-top feed	25 kW	Air	Surface probe	Saw dust	0.31–0.57 mg/min	[16]
					Wheat straw	0.27–2.62 mg/min	
					Corn stover	0.19–3.03 mg/min	