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EFIKASNOST MERA ZA SMANJENJE EMISIJA PRAŠKASTIH MATERIJA IZ PROCESA SAGOREVANJE BIOMASE

EFFICIENCY OF PARTICULATE MATTER EMISSION REDUCTION MEASURES FROM BIOMASS COMBUSTION

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Čvrste čestice (PM) emitovane iz procesa sagorevanja biomase sadrže čestice sa prečnikom u rasponu od 1 nm do 100 μm. Tar, koksni ostaci, leteći pepeo, elementarni ugljenik (EC) koji nisu potpuno sagoreli, primeri su PM-a. Nije svaka tehnologija za kontrolu čestica pogodna za sve potrebe. Među faktorima koji utiču na izbor su veličina čestica, potrebna efikasnost izdvajanja, protoka gasa, dozvoljeno vreme između čišćenja, detaljna priroda čestica i prisustvo tara u dimnim gasovima. Efikasnost tehnologija za kontrolu emisija čestica u velikoj meri zavisi od veličine čestica. Sistemi sa skruberima imaju neke prednosti u odnosu na elektrostatičke filtre (ESP) i vrećaste filtre. Fokus ovog rada su skruberi. Skruberi su manji i kompaktniji od vrećastih filtera ili ESP-a. Imaju niže kapitalne troškove i uporedive operativne i troškove održavanja (O&M), što ih čini pogodnim za upotrebu u manjim instalacijama, odnosno u instalacijama sa termičkim kapacitetom manjim od 1 MW. U skruberima se čestice uklanjaju iz dimnih gasova pomoću kapljica vode različitih veličina. Čestice se uklanjaju putem interakcije između kapljica i čestica. Prilikom kontakta, čestice se kvase i nose kapljicom vode, čime se postiže njihovo uklanjanje. Što se više kapljica formira, proces će biti efikasniji. Stoga, poželjno je da kapljice budu male. Mlaznice manjeg prečnika će proizvesti manje kapljice, ali će takođe rezultirati većim padom pritiska, trošeći više energije. Kako se efikasnost povećava smanjenjem veličine kapljica, posledično efikasnost se povećava sa povećanjem pada pritiska u sistemu.

Ključne reči: *biomasa; čvrste čestice; emisija; mere redukcije; skruber*

The PM emitted by biomass contains particles with a diameter range of 1 nm to 100 μm. Tar, char, flying ash, residues, elemental carbon (EC), and black carbon (BC) that would not burn completely are examples of PM. Not every particle control technology suits every need. Among the determining factors are the particle's size, required collection efficiency, gas flow size, allowed time between cleanings, the detailed nature of the particles, and the presence of tars in the flue gas. The effectiveness of particle control technologies strongly depends on the particle size. Wet scrubber systems have some advantages over electrostatic precipitators (ESPs) and baghouses. This paper focus on wet scrubbers, they are smaller and more compact than baghouses or ESPs. They have lower

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capital cost and comparable operation and maintenance (O&M) costs, which makes them suitable for use in installations with an installed thermal capacity of less than 1 MW. In scrubbers, particles are scrubbed out from the flue gas by water droplets of various sizes, depending on the type of scrubber used. The particles are removed by collision and interception between droplets and particles. Upon impact, the particles are wetted and carried by the water droplet, thus affecting removal. The more droplets that are formed, the more efficient the unit will be. Therefore, the droplets must be small. Smaller-diameter spray nozzles will produce smaller droplets but will also result in higher pressure drops, consuming more energy. Since efficiency increases as the droplet size decreases, efficiency increases with increasing pressure drop.

Key words: *biomass; particulate matter (PM); emission; reduction measure; scrubber*

1. Introduction

Globally, an estimated nine million premature deaths are linked to environmental pollution, which is about as many deaths as from cancer. Nearly half of these deaths are attributed to fine particles released during indoor biomass fuel emissions. Although a high proportion of the global population relies on using biomass for its energy demands, the consequences of exposure to ambient particles from biomass combustion for human health have only been poorly investigated. In developed countries residential biomass combustion is also a major source of particle emission, gaining in popularity as a renewable CO_2 neutral energy source [1]. As one important energy source, the burning of biomass fuels contributes to approximately 10% of the total energy from solid fuels, but this percentage varies largely among different regions [2]. Woody biomass and other biogenic fuels with moderate moisture content are mainly used in combustion processes to generate heat and to a less extent electricity. Combustion technologies are available in a broad range from a few kW for residential heating and cooking up to the size range of more than 100 MW applied in thermal power plants usually operated for combined heat and power (CHP) production [3]. Automated biomass combustion systems greater than 70 kW were usually equipped with particle removal mostly by electrostatic precipitators or for larger plants also by fabric filters. For residential wood combustion smaller than 70 kW, regulations are also becoming more stringent. Their effect on the ambient air is, however, uncertain, since the operation of manual wood combustion devices has a strong impact on the pollutant formation and real-life emissions can significantly exceed the emissions under type-test conditions [4].

2. Particle formation during biomass combustion

PM emissions (TSP) from biomass combustion are categorised into coarse fly ashes and aerosols (Figure 1). While a major share of ashes formed during biomass combustion is found as so called bottom or grate ash, a minor portion of ash particles is entrained from the fuel bed with the flue gas and forms the coarse fly ashes. Depending on the flow conditions in the furnace and the boiler, coarse fly ash particles are partly precipitated in these plant sections while the remaining part forms the coarse fly ash emissions. These coarse fly ash emissions are usually in a particle size range between some µm up to about 200 µm [5]. The particles mainly consist of refractory species such as Ca, Si, Mg as well as smaller amounts of K, Na and Mn bound as oxides, sulphates or phosphates. In residential biomass combustion systems coarse fly ashes usually only provide minor contributions of up to 10 wt% to the total particulate emissions. Moreover, due to their comparably large particle size, they are not respirable and therefore of almost neglectable relevance regarding health effects. Therefore, coarse fly ash emissions have not been considered in this paper.

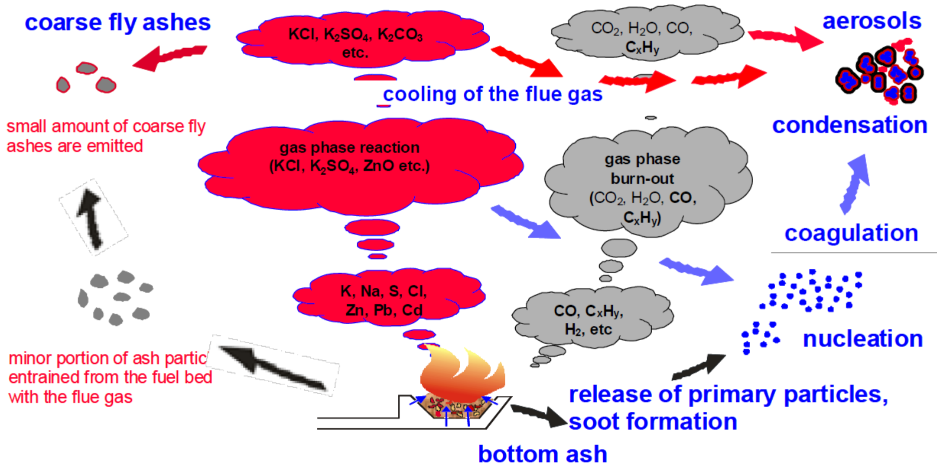

Figure 1: Particle formation during residential biomass combustion

The formation of aerosols (fine particles with a diameter <1 µm) is much more complex. Aerosols can be categorised into inorganic as well as carbonaceous particles, whereas carbonaceous aerosols are divided into soot particles (elemental carbon) and particles consisting of organic compounds. Inorganic aerosols represent a fraction which is mainly influenced by the chemical composition of the fuel used. Volatile ash forming elements such as K, Na, S, Cl as well as easily volatile heavy metals (*e. g.* Zn, Pb) contained in the fuel are released into the gas phase during combustion. By gas phase reactions different compounds (alkaline metal sulphates, chlorides and carbonates, heavy metal oxides, *etc.*) are formed. As soon as one of these compounds becomes supersaturated, which could happen either due to the excessive formation of the respective compound or due to the cooling of the flue gas in the boiler, gas to particle conversion by nucleation and condensation processes takes place. Carbonaceous aerosols on the other side are formed by the condensation of organic vapors which are a result of an incomplete gas phase burnout as well as by an incomplete oxidization of soot particles [6].

3. Particle control technologies

Not every particle control technology suits every need. Among the determining factors are the particle's size, required collection efficiency, gas flow size, allowed time between cleanings, the detailed nature of the particles, and the presence of tars in the flue gas. The following rules of thumb may be helpful in selecting particle control technologies for biomass combustion applications [3]:

- Sticky particles (*e. g.* tars) must be collected in a liquid, as in a scrubber, or in a cyclone, bag filter or an electrostatic filter whose collecting surfaces are continually coated with a film of flowing liquid. There must also be a way to process the contaminated liquid thus produced.
- Particles that adhere well to each other but not to solid surfaces are easy to collect.
- Those that do the reverse often need special surfaces, *e. g.* Teflon-coated fibers in filters that release collected particles well during cleaning.
- The electrical properties of the particles are of paramount importance in electrostatic filters, and they are often significant in other control devices where friction-induced electrostatic charges on the particles can aid or hinder collection.
- For non-sticky particles larger than about 5mm, a cyclone separator is probably the only device to consider.

- For particles much smaller than 5mm one normally considered electrostatic filters, bag filters and scrubbers. Each of these can collect particles as small as a fraction of a micron.
- For large flows the pumping cost makes scrubbers very expensive; other devices are preferable.
- Corrosion resistance and dew point must always be considered.

While Figure 2 presents typical particle (fly ash) size distribution from biomass combustion, Figure 3 shows, the effectiveness of particle control technologies strongly depends on the particle size. Table 1 summarizes the main characteristics of PM separation devices.

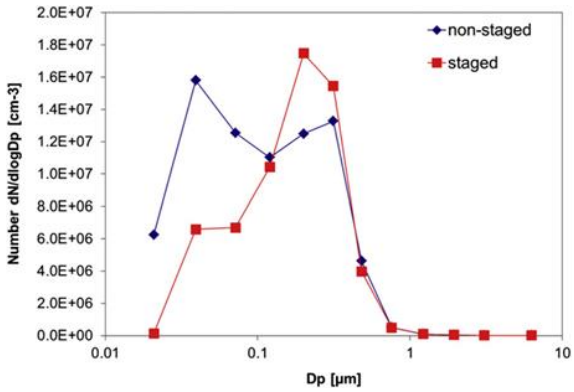

Fig. 2 Particle (fly ash) size distribution [7]

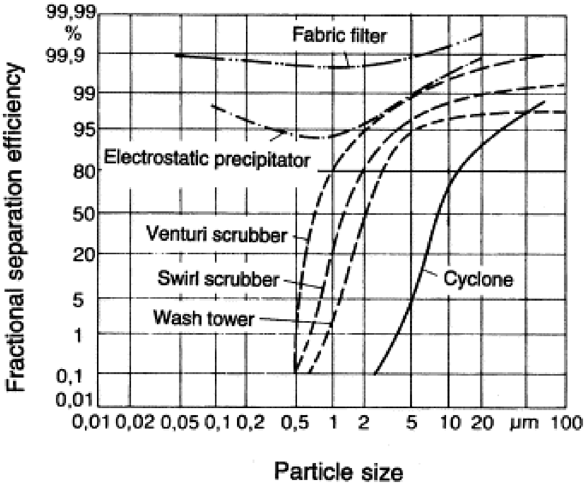

Fig. 3. Particle collection efficiencies of conventional gas cleaning systems [8].

As presented in Table 1 scrubber systems have the highest efficiency for removal of PM. Scrubber removal efficiency is influenced by the capacity of each single water droplet to collect particles by using one or more of the scrubbing mechanisms, which are diffusion, interception and inertial impaction. Diffusion is a particle capture mechanism based on Brownian motion and it is the dominant scrubbing mechanism for small particles (diameter lower than 0.1 µm), since small particles attain a high diffusion coefficient. Even if the trajectory of a particle does not depart from the streamline, a particle may still be collected through the interception mechanism if the particle passes within one particle radius from the droplet surface. Interception is the main mechanism for capturing particles with dimensions between 0.1 µm and 1 µm. Finally, inertial impaction is the predominant removal mechanism for scrubbers with particles larger than 5 µm, since it is influenced by droplet and particles size as well as their relative velocity. Fig. 1 clearly shows that common scrubbers, like Venturi or Swirl scrubbers as well as washing towers, have relatively high PM removal efficiency (over 95%) for PM size above 2-5 µm, diameters which are too high for biomass boiler flue gas. Bubble-column wet scrubbers represent a promising and interesting alternative for nanoparticle collection. In fact, starting from the first theory of absorption of particles in gas bubbles during their rise through a liquid (developed in the ’60s) and coming to the more recent experimental studies, it has been demonstrated that the most predominant mechanism of PM removal in bubble-column scrubber is diffusion. So, a bubble-column scrubber, if opportunely supported by bubble micronization, has the potential to be competitive in terms of nanoparticle removal if compared with fabric filters and ESPs. However, few studies on bubble-column scrubbing of particles have been reported and none of them deal with the application in a real scale plant [10].

Table 1 Characteristics of PM separation devices, such as particle size, efficiency, costs and disadvantages [9]

PM separation technology	**Collection Efficiency**	**Optimized for PM (µm)**	**Equipment, operating and maintenance costs**	**Main disadvantages**
Cyclones	95% (dp > 10 µm)	> 10	Low equipment, operating and	High efficiency only on coarse particles
	80% (dp < 5 µm)		maintenance costs	
Fabric filters	40% (dp <3 µm) 99% (dp > 0.5 µm)	> 0.5	Low equipment costs, high operating	Rapid clogging of the filter
	95% (dp < 0.5 µm)		and maintenance costs	
ESPs	95% (dp > 0.8 µm)	> 0.8	High equipment and operating costs	High investment costs for ESP adaptation to residential
Washing towers	85% (dp < 0.8 µm) 90% (dp > 5 µm)	> 5	Low equipment, operating and	applications and sophisticated control and safety systems High efficiency only on large particles
	50% (dp <3 µm)		maintenance costs	
Venturi scrubbers	70–99% (dp > 1 µm)	> 1	Low equipment and maintenance	High pressure drop and electric energy consumption
	50% (dp <1 µm)		costs, high operating costs	
Tray scrubbers	97% (dp > 5 µm)	> 5	Low equipment and operating costs,	Clogging of the plates
			high maintenance costs	
Packing scrubbers	99% (dp > 2 µm)	> 2	Low equipment, operating and	Possible uneven airflow distribution
Bubble scrubbers	50% (dp <1 µm) 95% (dp > 2 µm)	> 2	maintenance costs Low equipment, operating and	Difficult bubble micronization
	70% (dp < 2 µm)	< 0.1	maintenance costs	
	90% (dp < 0.1 µm)			

4. Conclusion

This paper delves into the effectiveness of various reduction measures aimed at decreasing particulate matter (PM) emissions generated during the process of biomass combustion. Specifically, it highlights the comparative advantages of wet scrubber systems over alternative technologies such as fabric filters and electrostatic precipitators (ESPs). The performance of wet scrubbers in collecting particulates is influenced by several factors, including the size distribution of the particulates and the specific type of scrubber used. Through meticulous design optimization, wet scrubbers can achieve a separation efficiency exceeding 99% for sub-micron particles, which are particularly challenging to capture. Several key operating parameters significantly impact the efficiency of wet scrubbers. These parameters include the particle size distribution of the PM, the velocity or flow rate of the gas stream, the ratio of liquid to gas within the system, the distribution of droplet sizes within the scrubber, as well as the operational temperature and the pressure drop across the system. However, a notable drawback of wet scrubbers is the correlation between increased removal efficiency and a higher pressure drop across the system. This increased pressure drop can lead to higher operational costs and energy consumption, presenting a trade-off between efficiency and cost-effectiveness.

5. Acknowledgment

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6. Reference

[1] **Merk R, Heßelbach K, Osipova A, Popadić D, Schmidt-Heck W, Kim GJ, Günther S, Piñeres AG, Merfort I, Humar M.** Particulate Matter (PM2.5) from Biomass Combustion Induces an Anti-Oxidative Response and Cancer Drug Resistance in Human Bronchial Epithelial BEAS-2B Cells. *Int J Environ Res Public Health. 2020* Nov 6;17(21):8193. doi: 10.3390/ijerph17218193. PMID: 33171923; PMCID: PMC7664250.

[2] *** World Bioenergy Association (WBA), Global bioenergy statistics 2021, https://www.worldbioenergy.org/global-bioenergy-statistics/

[3] **van Loo, S. and J. Koppejan (eds.)**: The handbook of biomass combustion and co-firing, 2nd edition, Earthscan, London (UK), 2008, ISBN 978-1-84407-249-1

[4] **Nussbaumer, T. (Ed.)**: Technical report on behalf of the IEA Bioenergy Task 32, 17 July 2017, Zurich 2017, ISBN 3-908705-33-9

[5] **Brunner T.**, 2006: Aerosols and coarse fly ashes in fixed-bed biomass combustion. PhD-thesis, book series “Thermal Biomass Utilization”, Volume 6, Graz University of Technoloy. ISBN 3-9501980-2-4

[6] **J. Kelz, T. Brunner, I. Obernberger, P. Jalava, M.-R. Hirvonen**. PM emissions from old and modern biomass combustion systems and their health effects

[7] **Michaël Becidan, Dusan Todorovic, Øyvind Skreiberg, Roger A. Khalil, Rainer Backman, Franziska Goile, Alexandra Skreiberg, Aleksandar Jovovic, Lars Sørum,** Ash related behavior in staged and non-staged combustion of biomass fuels and fuel mixtures, *Biomass and Bioenergy, Volume 41,* 2012, Pages 86-93, ISSN 0961-9534,https://doi.org/10.1016/j.biombioe.2012.02.005.

[8] **Fritz H, Kern W.** *Reinigung von Abgasen* (Flue gas cleaning). Vogel, Würzburg, 1990

[9] **Augusto Bianchini, Marco Pellegrini, Jessica Rossi, Cesare Saccani,** Theoretical model and preliminary design of an innovative wet scrubber for the separation of fine particulate matter produced by biomass combustion in small size boilers, *Biomass and Bioenergy, Volume 116,* 2018, Pages 60-71, ISSN 0961-9534, https://doi.org/10.1016/j.biombioe.2018.05.011.

[10] **Augusto Bianchini, Francesco Cento, Luca Golfera, Marco Pellegrini, Cesare Saccani,** Performance analysis of different scrubber systems for removal of particulate emissions from a small size biomass boiler, *Biomass and Bioenergy, Volume 92,* 2016, Pages 31-39, ISSN 0961-9534, https://doi.org/10.1016/j.biombioe.2016.06.005.