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MEASUREMENT OF SOLID PARTICLE EMISSIONS FROM OXY-FUEL COMBUSTION OF BIOMASS IN FLUIDIZED BED

Ondřej Červený*, Pavel Vybíral, Jiří Hemerka, Luděk Mareš

Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Environmental Engineering, Technická 4, 166 07 Prague, Czech Republic

* corresponding author: ondrej.cerveny@fs.cvut.cz

Abstract. The presented work summarizes the results of the measurement of solid particle emissions from an experimental 30 kW combustion unit. This unit has been used for the research of oxy-fuel combustion of biomass in a fluidized bed, which, when accompanied with carbon capture technologies, is one of the promising ways for decreasing the amount of CO_2 in the atmosphere. To implement a carbon capture system, it is first needed to separate various impurities from the flue gas. Therefore, the goal of this work was to identify solid particles contained in the flue gas.

Part of the apparatus used for this measurement was an ejector dilutor. To evaluate the results of this measurement, it is key to know the dilution ratio of the dilutor. For this purpose, a method for determining the dilution ratio of an ejector dilutor was proposed and experimentally verified.

Keywords: Oxy-fuel biomass combustion, solid particle emission, ejector dilutor, dilution ratio.

1. Introduction

As global warming is becoming an increasingly pressing issue, people are starting to look for new ways of decreasing carbon dioxide emissions. According to EPA [1], CO_2 is widely considered the most important anthropogenic greenhouse gas. Still, coal is one of the main energy sources and it contributes with approximately 40 % to the total energy production [2]. Replacing or cofiring coal with biomass fuels and utilization of carbon capture systems is one of the ways to reduce CO_2 emissions. We recognize two carbon capture systems: carbon capture and storage (CCS) and carbon capture and use/utilization (CCU). By combusting biomass with CCS or CCU system implemented, we can achieve negative or neutral CO_2 emissions, respectively [3].

The goal of this work was to identify solid particle emissions from the process of oxy-fuel biomass combustion in a fluidized bed. As a part of Research Center for Low-Carbon Energy Technologies project, this measurement was performed to get data for an efficient solid particle separation. This measurement took place on an experimental 30 kW combustion unit, which is shown in Figure 1. The fuel used for the experiment were spruce wooden pellets with 6 mm diameter.

A part of the apparatus is an ejector dilutor. To get the correct data from such a measurement, it is needed to know the actual dilution ratio of the dilutor. Although this ratio is provided by the manufacturer of the dilutor (in our case Dekati®), the real dilution ratio may differ. As stated in [5], the dilution ratio is influenced by the composition of the gas. Thus, when the nominal values of the dilution ratio are obtained using air, it is clear that these values will not be appropriate when diluting flue gas, as in our case. The composition of the gas may change the dilution ratio by 20 %, which would cause a quite significant error in the results. Specifically, the composition of the flue gas in our case was ca. 90 % CO_2, 6 % O_2 and some minor gases in the dry flue gas. Wet flue gas had around 40 % vol. water vapour content. This composition can be calculated using equations from [6], where the authors described the oxy-fuel combustion specifics. The secondary goal of this work was, therefore, to set and verify a method to obtain a more accurate dilution ratio for gases different from the calibration

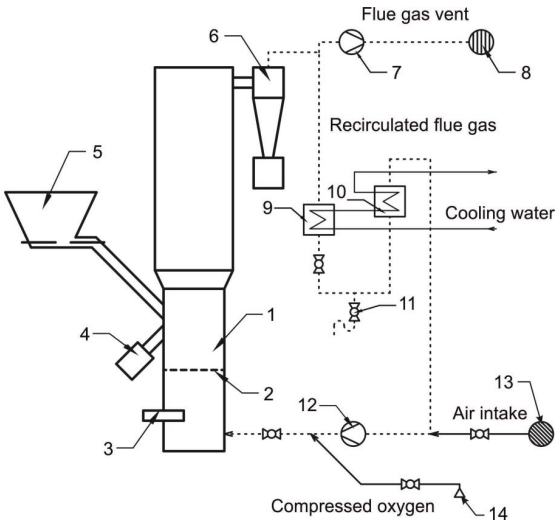

Figure 1. Scheme of the 30 kWth BFB experimental facility 1) fluidized bed region, 2) distributor of the fluidizing gas, 3) gas burner mount, 4) fluidized bed spill way, 5) fuel feeder, 6) cyclone separator, 7) flue gas fan, 8) flue gas vent, 9) and 10) water coolers, 11) condensate drain, 12) primary fan, 13) air-suck pipe, 14) vessels with oxygen [4].

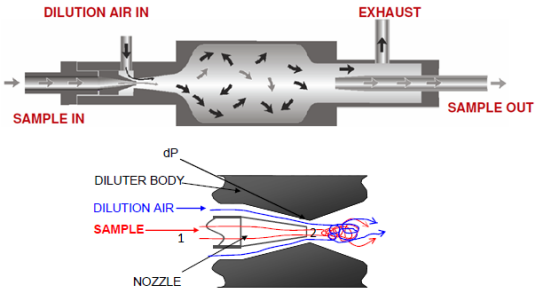

Figure 2. Operating principle of Dekati® dilutor [7].

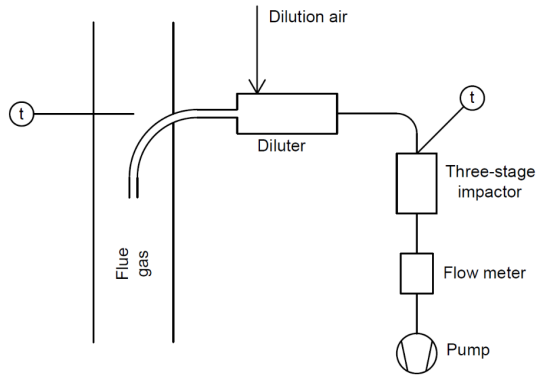

Figure 3. Scheme of experimental set-up of solid particle emission measurement.

gas. The operating principle of the ejector dilutor is shown in Figure 2. Pressurized dilution air enters the dilutor and is accelerated in the orifice ring, which causes a vacuum in front of the sample nozzle and the sample gas is sucked in. These two gases are mixed and then leave the dilutor.

2. Method

2.1. Solid particle emission measurement

To determine the properties of solid particles contained in the flue gas, we used the gravimetric analysis. The apparatus used was a three-stage impactor with an ejector dilutor, both from Dekati® company. The scheme of the experimental set-up can be seen in Figure 3. The impactor classifies the solid particles into three fractions, which are PM10, PM2,5 and PM1. The use of the dilutor provides a longer running time for each measurement. That is desirable, because the impaction plates of the impactor have a limited mass capacity, about 1 mg each. Additionally, it helps to avoid condensation of water vapour, which is useful here, because the flue gas from this combustion technology is specific for its high water vapour content (around 40 % vol.). The dilutor was heated up to the temperature of the flue gas in the vent (200 °C). The dilution air had an ambient temperature and was dried before feeding into diluter.

2.2. Correction of the dilution ratio for a gas of general composition

The following method is based on the theory of gas flow through a nozzle. To use it, we have to know the nominal dilution ratio (obtained with air) and the composition of the gas we are diluting. The method consists in comparing the air flow rate and the desired gas flow rate through the entry nozzle. The procedure is as follows. On the basis of the theoretically calculated air and gas flow rates, the air flow rate measured during the calibration is corrected to correspond to the case when the different gas would enter the nozzle under the same conditions (temperature and pressure). To calculate the mass flow rate through the nozzle, we use Saint-Venant-Wantzel equation [8] in the following form:

$$\dot{m}_s = K_s \times \rho_{s,1} \times A_{s,2} \left(\frac{P_{s,2}}{P_{s,1}}\right)^{\frac{1}{\kappa_s}} \times \left(\frac{2\kappa_s}{\kappa_s - 1} \frac{P_{s,1}}{\rho_{s,1}} \left(1 - \left(\frac{P_{s,2}}{P_{s,1}}\right)^{\frac{\kappa_s - 1}{\kappa_s}}\right)\right)^{\frac{1}{2}} \quad (1)$$

Index 1 in equation (1) indicates the point of entry into the dilutor, index 2 is the narrowest point of the nozzle – its outlet. ρ_s is the density, A_s flow cross section, P_s static pressure, κ_s Poisson's constant and K_s coefficient, which takes into account the internal friction and contraction of the flow. It follows from equation (1) that the flow rate depends on the composition, here expressed by density and Poisson's constant, and the state of the gas.

Mass flow rates obtained using equation (1) are first converted to volume flow rates and then their ratio is expressed:

$$VR = \frac{\dot{V}_{air,teor}}{\dot{V}_{gas,teor}}. \quad (2)$$

This calculated VR ratio is then used to convert the measured air flow rate to the desired gas flow rate:

$$\dot{V}_{gas} = \frac{\dot{V}_{air}}{VR}. \quad (3)$$

Now, with the knowledge of the gas flow V_{gas} and the dilution air flow V_{DA}, it is possible to determine the dilution ratio as given by equation (4):

$$N_{gas} = \frac{\dot{V}_{DA} + \dot{V}_{gas}}{\dot{V}_{gas}}. \quad (4)$$

By adjusting equations (3) and (4), an equation for a direct conversion between the dilution ratio with air N_{air} (nominal) and with gas N_{gas} can be obtained:

$$N_{gas} = (N_{air} - 1)VR + 1. \quad (5)$$

2.2.1. Experimental verification

To verify the method described in the previous section, an experimental measurement was performed using

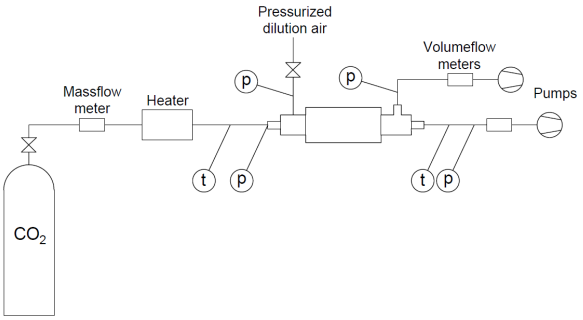

FIGURE 4. Scheme of the experimental set-up.

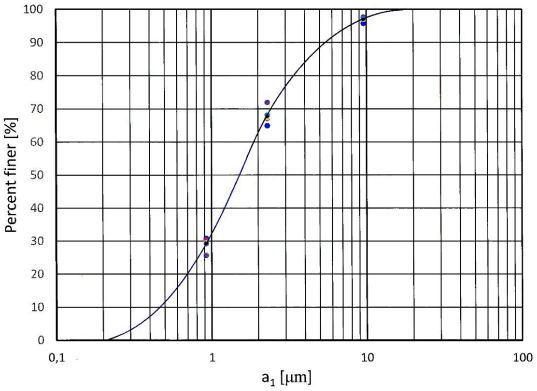

FIGURE 5. Particle size distribution curve.

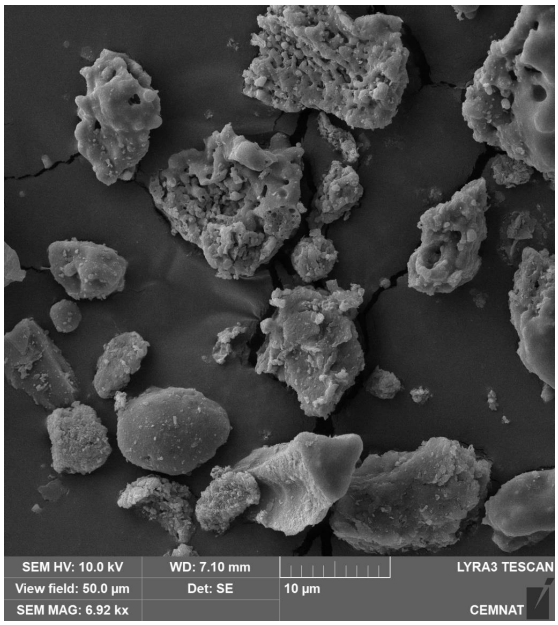

FIGURE 6. PM2,5 particles captured in the impactor.

carbon dioxide as the diluted gas. Dekati® dilutor in Figure 2 was used. The overpressure of the dilution air was set to nominal 2×10^5 Pa. The flow rate and pressure were measured at the sample inlet and both dilutor outlets. A heater preceded the sample inlet and the measurement was performed in the range from room temperature to a temperature of about 200 °C. This temperature was measured using a thermocouple placed in the gas stream before the entrance to the dilutor. The dilution air had ambient temperature during the whole experiment. The experimental set-up is shown in Figure 4. To calculate the flow rate according to equation (1), it is necessary to determine the static pressure $P_{s,2}$, which causes the suction of the sample gas. This can be achieved by blocking the sample inlet to the dilutor and measuring the static pressure there without the sample gas flowing in. Similarly, the dilution air flow rate V_{DA} can be determined, again, by blocking the sample inlet and measuring the two outlet flow rates of the dilutor.

3. Results and discussion

3.1. Solid particle emission characteristics

With the apparatus described, we performed five separated measurements and specified the concentration and particle size distribution in the flue gas. Cut-off diameters of the impactor were corrected according to temperature. The acquired particle size distribution is shown in Figure 5 with a curve plotted with the average values. Our results showed a relatively small mass median aerodynamic diameter of 1.6 µm. The solid particle concentration in the flue gas was found to be cca 30 mg/mN^3. It is important to add that these results were influenced by the fact that the flue gas goes through a cyclone before exhausting to the vent, as can be seen in Figure 1. According to different theories, the cut-off diameter of this cyclone was estimated to lay between 3 and 5 µm. That explains the relatively small median and concentration found.

Images of the particles captured in the impactor have been taken with an electron microscope. In Figure 6, there is an image of particles captured in the second stage of the impactor. This picture shows many particles larger than 2.5 µm, which should be the cut-off diameter of this stage. These particles correspond to particles penetrating from the previous stage.

3.2. Evaluation of the proposed method for dilution ratio correction

Experimental measurements with CO_2, the results of which can be seen in Figure 7, showed a very good agreement between the presented method and the experiment. The average value of the deviation between the measured and calculated values of the dilution ratio is, on average, about 1 % over the entire temperature course. The largest deviation was found at room temperature, where it reaches about 3 %. Figure 7 also demonstrates how a significant error can be caused by using the air dilution ratio N_{air} for a different gas. In the case of CO_2, the error is almost 20 %. The same figure also shows that the dilution ratio also varies with the sample gas temperature, which is another factor that should be remembered during field measurements.

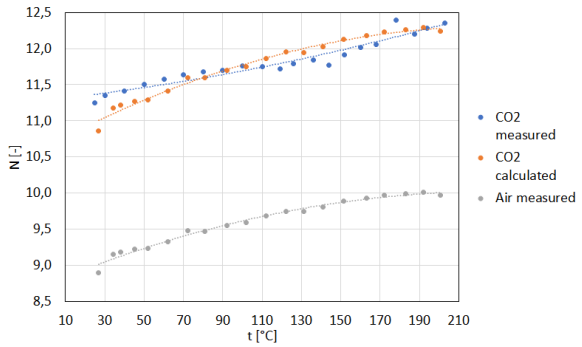

Figure 7. Values of dilution ratio obtained using the given method and experimentally by measurement as a function of sample gas temperature.

4. Conclusions

A measurement on the experimental 30 kW boiler during a biomass combustion in oxy-fuel regime was carried out to specify the solid particle emission present in the flue gas. We found a relatively small mass median aerodynamic diameter of 1.6 µm and a concentration of 30 mg/m$_N^3$. Both these values were affected by the presence of a cyclone at the outlet of the boiler. The results of this measurement will be used for the design of an appropriate precipitator for this combustion technology. To correctly interpret the data acquired during the solid particle emission measurement, there rose a need to specify the dilution ratio of the ejector dilutor we used for the measurement. Therefore, in this paper, we also proposed and experimentally verified a method for a correction of the nominal dilution ratio to fit the actual case during a field measurement. The experimentally obtained data differ from the proposed method by an average of about 1 %. This method could find good use wherever the sample gas composition differs from air (calibration gas) and the knowledge of accurate concentrations of the sample is important. Such cases might be, for example, boiler flue gases or car exhaust gases.

Acknowledgements

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