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Reduction of particulate matter concentration in stove with biomass combustion

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Abstract

Particulate matter concentration in ambient air is increasing in many European countries. Higher concentration of those emissions has harmful influence on human health. There are various sources of those particles – traffic, industry, volcanoes and also small heat sources with biomass combustion. Small heat sources are relatively big source of pollution because they are not monitored and not controlled, so especially during heating season they produce large amount of pollutants. To decrease particulate matter emission it is necessary to capture particles before their leaving from source into the ambient atmosphere. There are various ways how to do it, but it is important to find effective and not very cost solution, which can be applied. In this work was paid attention to construction changes in flue gas path where huge amount of solid particles can by captured. Those construction changes can be applied in simulation program where it is possible to observe. After comparison of various versions of changes is chosen one, which has the best result according to the simulations. To find out if those changes are helpful for particulate matter concentration reduction it is necessary to do comparative measurement with an original construction and a changed construction. The measurements help to evaluate if the assumptions of construction changes reduce particulate matter concentration.

Keywords: biomass, particulate matter, gravimetric method

Streszczenie

Zmniejszenie stężenia pyłu w piecu ze spalania biomasy

Koncentracja pyłu zawieszonego w otaczającym powietrzu stale rośnie w wielu krajach Europy. Wyższe koncentracje tych emisji mają toksyczny wpływ na zdrowie ludzi. Cząstki pyłu zawieszonego pochodzą z wielu różnych źródeł: transportu, przemysłu, działalności wulkanów, a także małych źródeł ciepła - ze spalania biomasy. Niewielkie źródła ciepła są stosunkowo dużymi źródłami zanieczyszczenia, bo nie są monitorowane i kontrolowane, więc szczególnie w sezonie grzewczym produkują dużą ilość zanieczyszczeń. Aby obniżyć emisję pyłu zawieszonego konieczne jest wychwytywanie cząstek pyłu, zanim wydostaną się one do otaczającej atmosfery. Są różne sposoby wychwytywania tych cząstek, ale najważniejsze jest znalezienie efektywnego i niezbyt kosztownego rozwiązania, które mogłoby być stosowane w praktyce. W artykule położono nacisk na zmiany konstrukcyjne w przewodach spalinowych (spalinowodach), gdzie duże ilości cząstek pyłu mogą być wychwytywane. Wpływ zmian konstrukcyjnych może być symulowany programem komputerowym, który daje możliwość obserwowania torów ziaren pyłu. Po porównaniu różnych wersji zmian została wybrana jedna, która daje najlepszy wynik według symulacji komputerowej. Aby sprawdzić, czy te zmiany będą pomocne w redukcji stężenia pyłu zawieszonego konieczne będzie wykonanie pomiarów porównawczych z oryginalną i zmienioną wersją konstrukcji. Pomiary te pomogą ocenić, czy założone zmiany konstrukcyjne zredukują stężenia pyłu zawieszonego.

Słowa kluczowe: biomasa, pył, metoda grawimetryczna

1. Introduction

Very important factor that influence human health is air quality. Air quality is also assessed on the basis of particulate matter concentration. There is in many European countries growing trend of particulate matter concentration in ambient air. Pollution is coming into the air inter alia also from combustion processes of solid fuels and biomass. Stream of burnt gas drags solid particles as soot, fly ash and tar to the ambient air [1].

Biomass boilers and small combustion installations could be potentially a significant source of various pollutants. They are not controlled and not monitored and therefore they can produce large amount of pollution. Small combustion installations are a common source of energy used in heating all over the world. It is estimated that small combustion installations can produced from 20% even to 90% of total particulate matter emission in winter heating season [2] [3].

With regard to reduce particulate matter emission from small heat sources and improve air quality are used various ways of their reduction. The devices which produce particulate matter emissions are connected with filters, external separators, catalysts, etc. Cost for implementation and operation can significantly financially charged consumers and also usually maintenance of those devices can be difficult. In order to obtain better solution are researching ways which will decreasing particulate matter production enough and at the same time will be costly as least as possible. Construction changes of combustion appliances can satisfy the following conditions. Construction changes can be realized in a combustion chamber or in a flue gas path. There was attention focused on flue gas path, where particulate matter can be captured.

2. Particulate matter pollution

Particulate Matter (PM) is a widespread air pollutant consisting of a wide range of materials mixture of solid and liquid particles arising from a variety of sources. PM is generally categorised on the basis of the particle size. The most frequently used metric is PM10, i.e. particles with a diameter less than 10 micrometres. Concentrations of PM2.5 (i.e. particles with a diameter less than 2.5 μm) are also becoming more important. Both short-term and long-term exposure to ambient levels of PM is consistently associated with ill-health effects. PM2.5, often called fine PM, also comprises ultrafine particles having a diameter of less than 0.1 μm. In most locations in Europe, PM2.5 constitutes 50–70% of PM10. Particulate matter with size between 0.1 μm and 1 μm in diameter can remain in the atmosphere [4], [5].

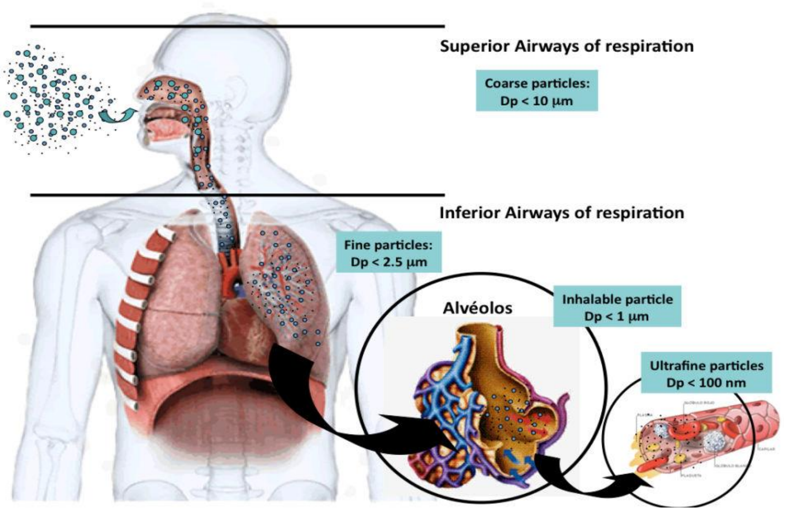

Fig. 2.1. Local impacts of particulate matter [6]

Small particles are able to get into the lungs and the smallest one into the alveolus and into the blood stream (Fig. 2.1.). Particulate matter pollution can cause or aggravate cardiovascular and lung diseases, heart attacks and arrhythmias, affect the central nervous system, the reproductive system and cause cancer. The outcome can be premature death. It can affect animals in the same way as humans. Affects plant growth and ecosystem processes.

It can cause damage and soiling of buildings and also reduced visibility. It can lead to changed rainfall patterns. Deposition can lead to changes in surface albedo (the ability of the earth to reflect radiation from sunlight). Epidemiological studies attribute the most severe health effects of air pollution to PM. The evidence base for an association between PM and short-term as well as long‑ term health effects has become much stronger. Recent long-term studies show associations between PM and mortality at levels well below the current annual World Health Organization (WHO) air quality guideline level for PM2.5 (10 µg/m3). This corroborates earlier scientific evidence, and the WHO has therefore suggested that exposure to PM — even in very small amounts — causes adverse health effects (WHO, 2006a, 2006b, 2013). The latest study from the World Health Organization (WHO, 2013) links long-term exposure to fine particles PM2.5 with cardiovascular and respiratory deaths, as well as increased sickness, such as childhood respiratory diseases [1].

2.1. Particulate matter reducing

It is very necessary to trap solid particles before their leaving into the air. To the effect are used various devices for disposal of pollutant, that are called separators. This type of devices are placed between devices that products pollution and their outlet into the ambient air. A carrying medium together with pollution are flowing through this device where are particles of pollution separated [7].

The same function can has the flue gas path with tunnel labyrinth, which has special shape and size. Built-in tunnel labyrinth works as a separator. It can captured particles in one place where is biggest change of the flue direction.

3. Simulation

Computational fluid dynamics (CFD) is tool which uses numerical methods to simulate fluid flow. It allows us to solve various problems with mass, heat and momentum transfer, interaction between solid and fluid etc. The CFD is very convenient way of optimization and solving different physical processes because it is economical and safety. As well as there is possibility to simulate particulate matter`s flow in combustion appliances.

Velocity profile, pressure profile or particulate matter flow profile is possible to obtain from the simplify model of combustion appliance. There is possibility to observe the behaviour of flow, turbulence etc. and also influence of construction changes on particulate matter flow by minimum cost. Modelling improves our understanding of fundamental process in the appliances and it may significantly reduce the “trial and error” development time needed if experiments only are used for construction optimization. Combination of modelling with experiments enables to improved construction with respect to reduce particulate matter emissions. There can be carried out parametric studies that reveal the relative influence of different combustion process and flow variables on emission levels and energy efficiency [8].

With regard to simplify the model of the flow as much as possible were taken into account more assumptions. The essential assumption is that in the model is no combustion and there is assumed just air flow with particles. The processes are time independent and there is consider gravity force, which has a major impact on the particulate matter separation in this case. Particles diameter is not determined just by one size. There are used various sizes to observe behaviour of the particles with different diameter. Other parameters as gravity force and barometric pressure are given as normally used values. The next aspect which simplify model is also minimum thickness of model, it is certain slice from observed area. It enables to divide model into more cells and so achieved more accurately results. During modelling it is needed to simulate various constructions of flue gas path and compare them. After comparison of trapped particles quantity in those various versions it is possible to choose the best one, which can capture more particles than original one. This version is subsequently made as real model and observes also in real conditions.

One of the simulation results is vector map (Fig.3.1.) that shows direction of flow inside the flue gas path. This vector map will be convenient for comparison with PIV (particle image velocimetry) method which will be mentioned later in the article. Also is obtained ideal particulate matter profile without interaction between particles (Fig.3.1.). It is possible to notice in the second figure – original construction, that particles above 30 micrometers are almost all captured, but smaller particles flow with flue gas into the ambient atmosphere. There is possible to observe that particles with diameter above 17 micrometers are captured ideally in one of the changed constructions.

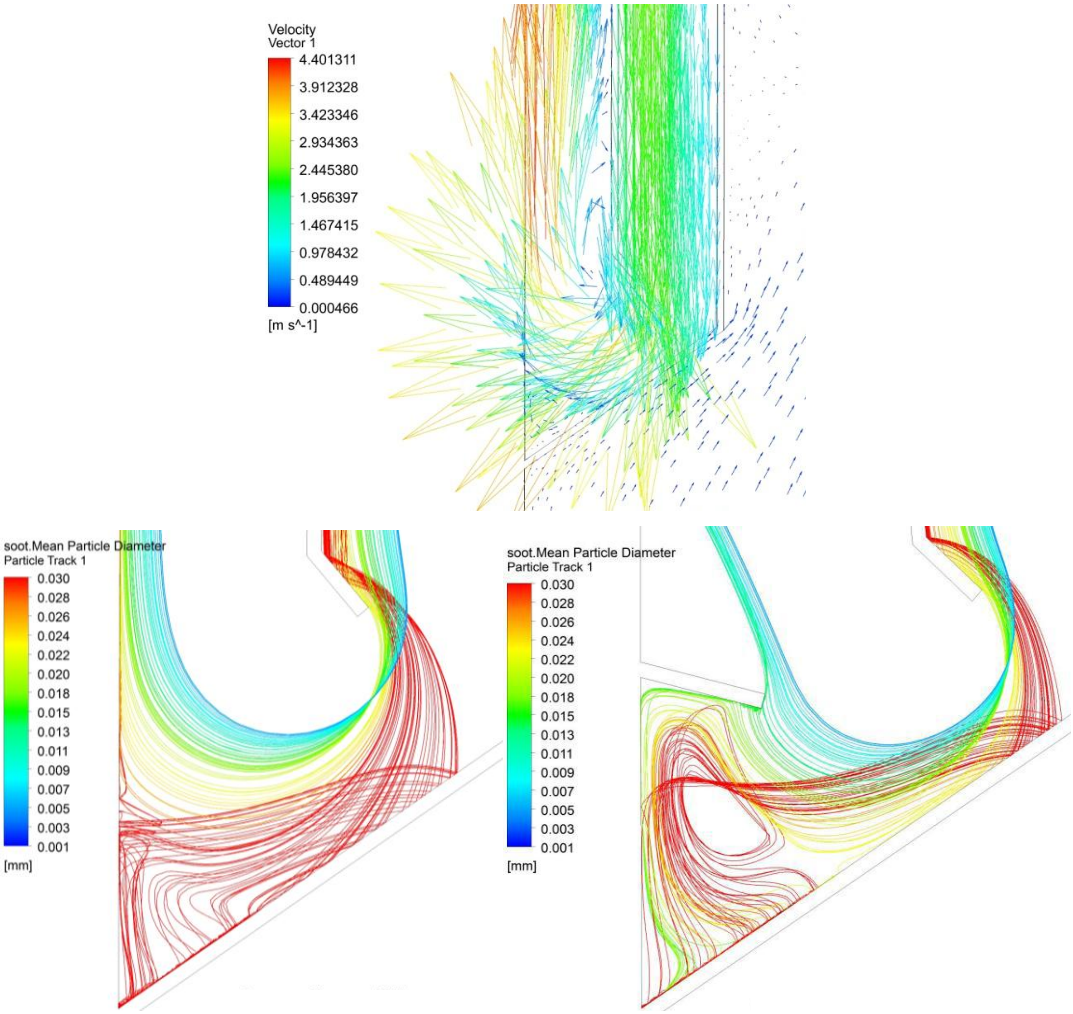

Fig. 3.1. Vector map, particulate matter layout from original construction and from changed construction

4. Verification

In order to verify the numerical results, Particle image velocimetry (PIV) method can be used to compare vector map from simulation and real vector map obtained from real model customized for visualization, and also the experimental measurements are required to find out influence in real construction. Two series of measurements are carried out on the heat source by gravimetric method – one with original construction and second series of measurement with changed construction.

4.1. Particle Image Velocimetry method

Particle Image Velocimetry (PIV) is a whole-flow-field technique providing instantaneous velocity vector measurements in a cross-section of a flow. Two velocity components are measured, but use of a stereoscopic approach permits all three velocity components to be recorded, resulting in instantaneous 3D velocity vectors for the whole area. The use of modern digital cameras and dedicated computing hardware, results in real-time velocity maps [9].

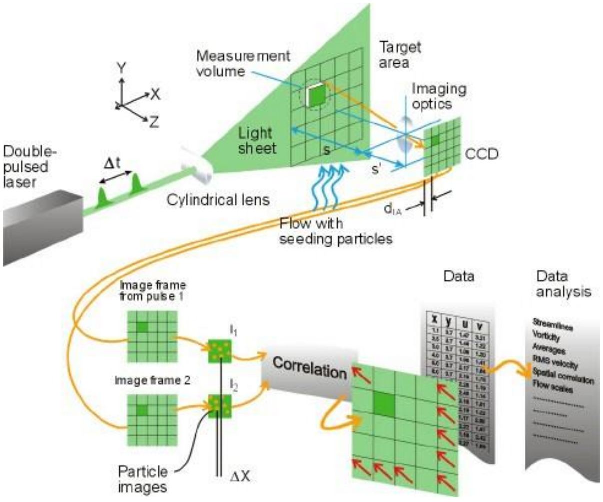

Fig. 4.2. PIV method scheme [9]

The experimental setup of PIV system typically consists of several subsystems. In most applications seeding particles have to be added to the flow. These particles have to be illuminated in a plane of the flow at least twice within a short time interval. The light scattered by particles has to be recorded either on a single frame or on a sequence of frames. The displacement of the particle images between the light pulses has to be determined through evaluation of the PIV records. In order to be able to handle the great amount of data which can be collected employing the PIV technique, sophisticated post-processing is required [10].

Principle of velocity measurement in fluid flow by PIV method is based on recording of particles movement in flow and subsequent evaluation of this motion. The seeding particles in the target area of fluid flow are illuminated by few short laser pulses with defined time difference. Positions of seeding particles are recorded on digital camera. The camera is able to capture each light pulse in separate image frames [11], [9].

Evaluation of those recordings is based on elementary equation:

$$velocity = distance / time \quad (4.1)$$

where distance is movement of particle in fluid flow per time interval (time) [11].

The images are divided into small subsections called interrogation areas. The interrogation areas from each image frame are cross-correlated with each other, pixel by pixel. The correlation produces a signal peak, identifying the common particle displacement. An accurate measure of the displacement - and thus also the velocity - is achieved with sub-pixel interpolation. A velocity vector map over the whole target area is obtained by repeating the cross-correlation for each interrogation area over the two image frames captured by the camera [9].

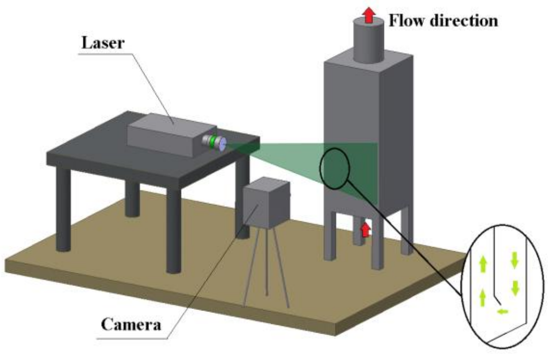

Fig. 4.3. Scheme of the experiment

According simulation model will be prepared real model from plexiglass for measurement by PIV method. For experiment is necessary to prepare the same condition as was set up in the simulation, it means to use approximately same temperature of air (as in simulation) and set up the same chimney draft. Position of devices for PIV measurement will be done according scheme of the experiment in Figure 4.3., where is possible to record fluid flow.

4.1. Gravimetric method

The measurement principle is to make multiple taking of samples during measurements by complex bleeding equipment by isokinetic conditions with gravimetric evaluation. Very important in this method is that samples of burnt gas and particulate matter are taken isokinetically. It means that flow speed of gasses in a jet of bleeding pipe have to be the same as velocity of the flow in the chimney in order the sample was representative. The base of this method is to determinate mean concentration of particulate matter emission by manual taking of samples from certain time cross section of measurement and its consistent gravimetric interpretation. Taking of representative sample is realized by bleeding pipe with proper shape right from stream of flue gas. This method is based on the weight difference of membrane filter before and after sampling. The measurement range by this method is from 0,1 to 2 000 mg/m^3. The smaller measured concentration is, the more uncertainty we can expect.

Gravimetric method accuracy is depending, extensively on accuracy of meeting isokinetic criteria what is depending on accuracy of velocity measurement of burnt gas in the measuring division. Velocity of burnt gas is measured by Pitot tube based on measurement of differential pressure difference. Problem may occur when the velocity of burnt gas in the small heat sources is approximately 2 m/s. It means approximately 3 Pa by measuring of differential pressure. This value is going up and down around level of measurement uncertainty of differential pressure [12].

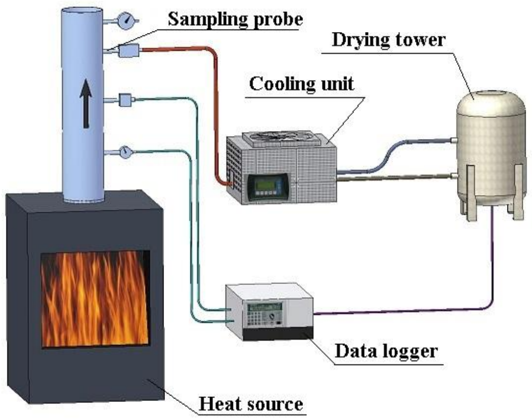

Fig. 4.1. Gravimetric method scheme

Measurement of particulate matter concentration by gravimetric method is realized in real heat source according all needed conditions. As was mentioned, two series of measurement are needed. One with original construction which should capture certain amount of particles and second with changed construction which should captured more particles than the first one. Three measurements are done in every series. Results are in Table 4.1.

Table 4.1. Measurement of two different constructions

Particulate matter concentration mg/m^3	First construction	Second construction
First measurement	58,3	47,9
Second measurement	54,3	51,3
Third measurement	57,1	49,8
Average	56,5 mg/m^3	49,6 mg/m^3

Results show that change in construction influence particulate matter concentration. Second construction captured more particles and final average concentration in chimney is 49,6 mg/m^3 whilst first average concentration is 56,5 mg/m^3. But there are still needed more measurements.

5. Conclusions

Nowadays is high encouragement to replace fossil fuels for renewable energy sources in order to reduced amount of total pollution in air. Biomass is one of the alternatives, which is used for energy obtaining. The combustion of biomass is the most developed and the most frequently applied technology of energy conversion. Worldwide using of biomass combustion is unfortunately also accompanied by certain kind of pollutant production. During combustion are formed gaseous and particulate matter pollutants. Particulate matter pollutants are getting into the air with flue gases where they have negative influence on the environment and human health. To capture those particles before they leave heat source seems to be one of ways how to reduce total pollution by minimum cost. Using of simulation helps to reduce needed time for finding out optimal construction of flue gas path and PIV method helps to make sure, that results from simulation are real and we can rely on them.

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