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$PM_{2,5}$ Emission Classifier

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The contribution brings information on research of a cyclone classifier which samples particles at current exhaust gas flow rates V in the range of 2 – 6 m^3/h and temperatures t in the range of 0 – 200°C according to requirements defined by the $PM_{2,5}$ fraction.

The used approach for solution this task was experimental determination of the nondimensional relation $Stk_m = f(Re)$, which shows how the cyclone classification ability given by the value of Stokes number Stk_m for the aerodynamic cut size $a_{l,m}$ changes in dependence on the volume flow rate of the gas given by Reynolds number Re. Subsequent analysis of this relation from the viewpoint of achievement the value of $a_{lm} = 2,5$ μm for gas conditions which are common in emission measurements led to relation V = f(t), where the cyclone classifies as a $PM_{2,5}$ classifier.

1. Introduction

Concentrations of fine dust particles in atmosphere in the Czech Republic and globally are given in the form of particle fractions PM_{10} and $PM_{2.5}$. PM_{10} and $PM_{2.5}$ fractions are particles which pass during sampling through a classifier which gives a 50 % separation efficiency for aerodynamic particle sizes $a_l = 10$ μm and/or $a_l = 2,5$ μm.

$PM_{2.5}$ is also known as respirable particles because they penetrate the respiratory system further than larger particles and can reach the lungs. Exposure to fine $PM_{2,5}$ particles can cause many health problems and other environmental effects. Particularly combustion processes are sources of $PM_{2,5}$ fractions in atmosphere.

With respect to rising contamination of atmosphere with fine particles and its health effects and obvious relation between emissions and immissions there is an increasing demand to measure in emissions not only particle fraction PM_{10}, but also fraction $PM_{2,5}$.

2. Description of Cyclone Classifier

At emission measurements a cyclone can be used as a classifier when it is inserted between the sampling probe and filter. The task of the classifier is to separate from the sample particle fractions of particular sizes. The basic characteristics of every classifier is dependence of the grade efficiency E on the aerodynamic particle size a_l – function $E(a_l)$. The level at which a particle is captured with grade efficiency E = 0,5 is called the cut size a_{lm}. $PM_{2,5}$ classifier is the classifier, where $a_{lm} = 2,5$ μm.

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A design of the experimental cyclone $PM_{2,5}$ was preceded our previous research with cyclone D = 78 mm as PM_{10} classifier (Hemerka at al, 2008) that was of a SRI-I type with a circular cross-section tangential inlet.

The design of main dimensions of the cyclone separator was based on an assumption that for geometrically similar cyclones the separating ability can be described by uniform function E = f(Stk), where Stk is Stokes criterion which is a decisive parameter for particle separation in cyclones (Vincent, 1995).

However laboratory tests with the geometrically similar cyclone D = 35 mm that should be used as $PM_{2,5}$ classifier did not give us satisfactory results. From this reason a URG type of cyclone was chosen for further design. The URG type has the tangential inlet with rectangular cross-section and hence it has the higher grade efficiencies compared with the SRI cyclone type. Preliminary experiments with a commercial URG type cyclone together with findings of previous experiments with the SRI type cyclone led to an original design of the cyclone with D = 32 mm diameter of the cylindrical part. The main dimensions of the cyclone are shown in Fig. 1.

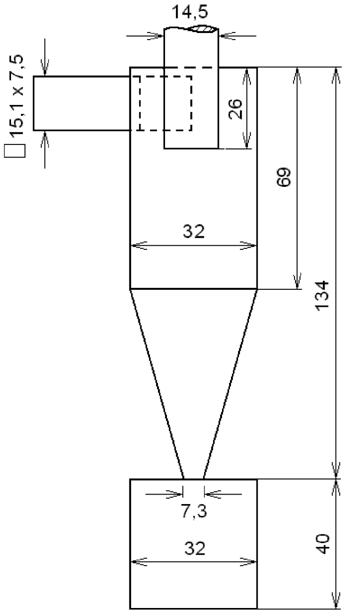

Fig. 1: Main dimensions of cyclone

3. Experimental and Evaluation Method

A sampling probe with a sampling head is inserted into the 4 m long horizontal dust line with an inner diameter 97 mm. The tested cyclone is connected with an end filter equipped with a glass fibre filter. From the end filter the sampled gas flows through the flow rate measurement device with an orifice plate, a pulse damping vessel equipped with a control valve and a vacuum pump (Fig. 2).

Two different polydisperse testing dusts with mass medians 5,4 and 6,4 µm were used for experiments. Dust concentrations in the line ranged from 0,2 to 0,7 g/m^3.

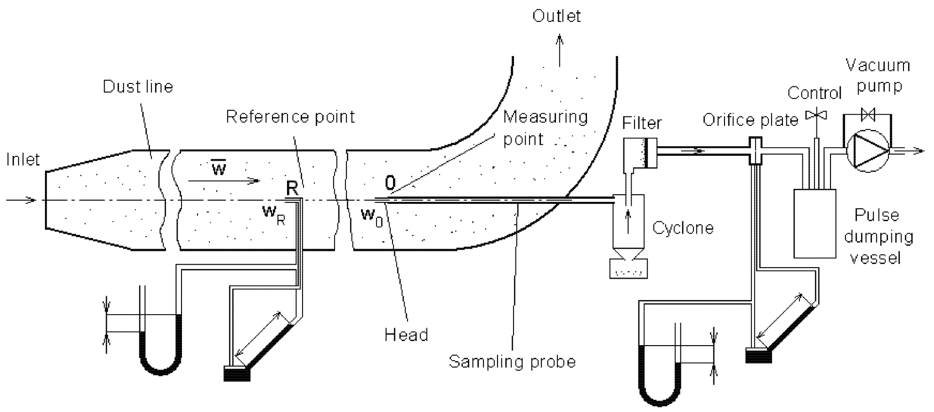

Fig. 2: Test rig

The measuring method of separating ability of the cyclone is based on isokinetic sampling of an aerodisperse mixture from the axis of the channel at a required volume flow rate and subsequent assessment of the total efficiency of separation of the cyclone E_T and assessment of the dependence of the grade efficiency on the size of a particle E(a) on the basis of balance relations on the separator and assessment of the grain size of particles from relevant samples.

Fig. 3 shows the schematic diagram of a cyclone performing as a solid state particle classifier. Particles entering the cyclone by the inlet are either separated and subsequently captured or pass through the cyclone and leave it by the outlet. Between the inlet, capture section and outlet there are valid simple total and fractional balancing relations.

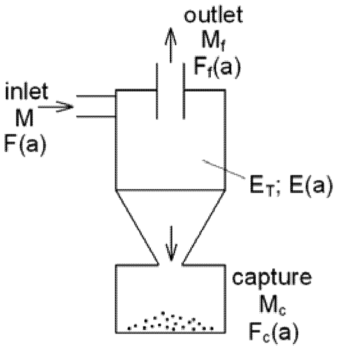

Fig. 3: Schematic diagram of a cyclone performing as a solid state particle classifier: M, M_c and M_f represent total mass flow rates in inlet, capture and outlet; $F(a)$, $F_c(a)$ and $F_f(a)$ represent oversize cumulative distribution curves

For determination of grade efficiency the capture – outlet method was used (Svarovsky, 1981). Dust samples for determination of oversize cumulative distribution curves $F_c(a)$ and $F_f(a)$ are taken from the discharge hopper of the cyclone and from the end filter.

Analysis of the grain size of particle samples from the capture section and outlet was performed by a Fritsch Analysette 22 laser analyzer which classifies particles into 62 size intervals ranging from 0,3 to 300 μm and the found number distribution of particle sizes is recalculated to the required distribution according to mass.

4. Measurements and Results

Altogether 14 measurements were performed in the range of volume flow rates 1,5 – 6 m^3/h (7 volume flow rates for each experimental dust). The measurements were evaluated by the capture – outlet method and the dependences E(a) were obtained in the form shown in Fig. 4. The problem of this curve form is that in the range of fine particles where the grade efficiency should approach zero a certain non-zero values E_{min} are found and for smaller particles the grade efficiency again grow.

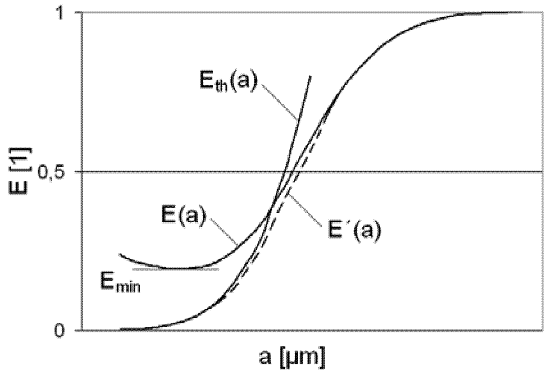

Fig. 4: Correction of the dependence E(a)

This systematic error can be explained by a hypothesis that fine particles with a size below 1 μm are not perfectly dispersed in the feeding device and move along the dust stand in clusters and behave like coarse particles. However laser analyzer first adjusts the dust sample in a supersonic bath and only perfectly dispersed sample is subsequently analyzed. For fine particles the assumption of equality of fractional mass flow rates is not complied with and evaluation of measurements in this range of particle sizes leads to systematic errors.

Limitation of the range of particle sizes starting from which particles in the cyclone are separated can be determined theoretically from the equilibrium of centrifugal and aerodynamic drag force assuming a simplified model of flow through the cyclone and quasi-stationary motion of particles at the separating surface. This simplified model leads to the theoretical behaviour of $E_{th}(a)$ in the parabolic form $E_{th} = k.a^2$ also shown in Fig. 4. The found behaviour of E(a) for the range of larger particles and the theoretical behaviour of $E_{th}(a)$ for the range of smaller particles are a basis for plotting the corrected function $E^{'}(a)$.

In order to be able to determine the values of cut size $a_{1,m}$ and in general to express the separating ability in the form of aerodynamic particle sizes a_1, the corrected function

$E'(a)$ must be recalculated to function $E'(a_l)$, where the density of aerodynamic particle sizes a_l is $\rho_l = 1000\ \mathrm{kg/m^3}$ (Vincent, 1995).

The capture – outlet method used for evaluation was that in which the values E_{min} for the found function E(a) (and hence also correction) were minimum. The test measurements showed us that the inlet – outlet and inlet – capture methods led to worse results.

Changes of the separating ability of the cyclone with varying flow rate can be generalized in the form of dependence of Stk_m (the Stokes criterion Stk related to the aerodynamic cut size $a_{1,m}$) on Reynolds number Re (Büttner, 1986).

Results of measurements are summarized in the form of dependence of Stk_m on Re in Fig. 5. The found dependence $Stk_m(Re)$ can be best expressed in the form

$$Stk_m = 0{,}000001 + 559.\mathrm{Re}^{-1{,}81} \qquad (1)$$

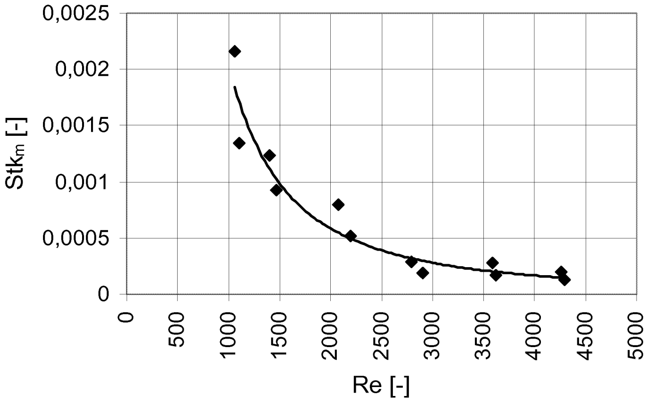

Fig. 5: Dependence of Stk_m on Re

5. Cyclone as a $PM_{2,5}$ Emission Classifier

Measurement of the grade efficiency of a cyclone generalized in the form given by relation (1) makes it possible to determine for what temperatures and for what flow rates the cyclone D = 32 mm can be used as a $PM_{2,5}$ emission classifier. If we express criteria Stk_m and Re in relation (1) according to their definition we obtain

$$\frac{4V}{\pi D^3}\,\frac{a_{1,m}^2\,1000}{18\eta} = 0{,}000001 + 559\left(\frac{4\,V\rho}{\pi D\,\eta}\right)^{-1{,}81} \qquad (2)$$

Quantities ρ and η depend on the composition of the gas. The gas density ρ furthermore depends on state quantities temperature and pressure and the dynamic viscosity η is a function of temperature.

In further processing of results it will be assumed for simplicity that the gas is dry air and current relations will be used for functions ρ = f(p,t) and η = f(t). The calculation will be performed for standard pressure 98 kPa in such a way that $a_{1,m}$ is set equal to $2{,}5.10^{-6}$m and by iterating a dependence will be obtained of the volume flow rate of air V on the temperature of air t for which the cyclone can be used at 98 kPa as a $PM_{2,5}$ emission classifier. The found dependence V = f(t) can be expressed by a polynomial of the 2nd degree in the form

$$V = 8.10^{-6}\, t^2 + 0{,}0133\, t + 2{,}575 \tag{3}$$

6. Conclusion

The nondimensional relation Stk_m = f(Re) in the form (1) was experimentally determined on a dust stand and shows how the separation ability expressed by Stk_m changes with the volume flow rate expressed by Reynolds number Re.

By analyzing this function it was found that a cyclone with D = 32 mm diameter, in the range of current temperatures of emission measurements 0 - 200°C and current flow rates of the exhausted samples 2 to 6 m^3/h, can be used as a $PM_{2,5}$ emission classifier. The calculation is performed for dry air and barometric pressure 98 kPa and leads to the function V = f(t) in the form of a polynomial of the 2nd degree – relation (3). According to this relation the required flow rate through the cyclone V increases from 2,58 m^3/h at 0°C to 5,56 m^3/h at 200 °C.

In the case of use of the cyclone as a $PM_{2,5}$ emission classifier for emission gases different from dry air the relation V = f(t) will be a little different and can be derived analogously as for dry air from the nondimensional relation Stk_m = f(Re) according to functions of density ρ = f(p,t) and viscosity η = f(t) for the particular gas.

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