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CYCLONE AS A PM_{10} EMISSION CLASSIFIER

CYKLON JAKO KLASYFIKATOR EMISJI PM_{10}

A b s t r a c t

The author of the article deals with the problems of graded emissions sampling – PM_{10} fraction. He introduces the results of cyclone ø 78 mm checking measuring as PM_{10} classifier. On the dusty testing line the criteria dependence $Stk_m = f(Re)$ was found out which indicates the change of cyclone separation abilities depending on volume flow rate. By analysis of this dependence it was stated that it is possible to use cyclone ø 78 mm as PM_{10} classifier at solid particles emissions measurement in the range of common temperatures of 0 up to 200 °C and common flow rates of exhausted sample of 2 up to 6 m^3/h.

Keywords: emissions measurement, solid particles classification, PM_{10} fraction, cyclone

S t r e s z c z e n i e

Autor artykułu przedstawia zagadnienie klasyfikacji emitowanych pyłów dla frakcji PM_{10}. Przedstawiono wyniki dla cyklonu ϕ 78 mm pracującego jako PM_{10} klasyfikator. Dla linii charakterystycznej $Stk_m = f(Re)$ wykazano wpływ wydatku objętościowego przepływającego gazu na zdolność separacyjną cyklonu. Analiza tej zależności pozwala stwierdzić, że jest możliwe stosowanie cyklonu ϕ 78 mm jako klasyfikatora cząstek stałych frakcji PM_{10} w najbardziej rozpowszechnionych przedziałach stosowania; temperatur od 0 do 200 °C i przepływu gazu od 2 do 6 m^3/h.

Słowa kluczowe: pomiar emisji, klasyfikacja cząstek stałych, frakcja PM_{10}, cyklon

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1. Introduction

Concentrations of fine dust particles in ambient air in the Czech Republic and on a global scale are given in the form of PM_{10} and $PM_{2,5}$ particle fractions. PM_{10} and $PM_{2,5}$ are particles which pass during sampling through a classifier which has a 50% separation efficiency for aerodynamic particle diameters 10 µm and 2,5 µm. Contamination of ambient air with fine dust particles, which represents a serious health hazard for the population and its established relation with sources of solid state pollutants, calls for introduction of measurement of emissions with graded sampling – measurement of PM_{10} and $PM_{2,5}$ fractions – into practical use. Present legislature on protection of atmosphere focused on sources of pollutants is concerned only with the emission limits of solid state pollutants, i.e. concentration of all solid state particles without considering their grain size. The present paper brings information on research of a cyclone classifier which samples particles at standard exhaust gas flow rates and a standard temperature range in compliance with requirements defined by the PM_{10} fraction.

2. Concept of cyclone classifier

When sampling solid state particles from a gas a particle classifier is inserted between the sampling probe and the final filter. The task of the classifier is to separate from the sample particle fractions of particular sizes. The basic characteristic of every classifier is the dependence of grade efficiency E on the particle size a – function E (a). The level at which a particle is captured with grade efficiency E = 0,5 is designated as cut size a_m. In the field of air pollution control the requirement for separation of particles is given in the form of aerodynamic particle size a_1. Aerodynamic particle size classified with grade efficiency E = 0,5 is designated as cut size a_{1m}. For emission measurements a cyclone can be used as a classifier where particles are separated by centrifugal force.

The cyclone used for the experiments was originally designed at the Faculty of Mechanical Engineering (CTU in Prague) according to requirements from industry as a preseparator of coarse fractions a > 20 µm in samples of emissions in an assumed range of volume flow rates from 3 to 6 m^3/h and gas temperatures up to 200°C. The design utilized available experimental data on the performance of small diameter cyclones [1–5].

Assessment of the main dimensions of the cyclone separator was based on an assumption that for geometrically similar cyclones separating ability can be described by function $E = f(\mathrm{Stk})$, where Stk is Stokes criterion which is a decisive parameter for particle separation in cyclones. Stokes criterion for the magnitude of cut size a_m is defined as

$$\mathrm{Stk}_m = \frac{a_m^{\ 2} \cdot \rho_p}{18 \cdot \eta} \cdot \frac{v_D}{D} \tag{1}$$

where v_D [m/s] is the characteristic velocity in the cyclone with diameter D expressed by

$$v_D = \frac{4 \cdot V}{\pi \cdot D^2} \tag{2}$$

The concept of the cyclone was based on values of $Stk_m = 1{,}05\cdot10^{-3}$ given in references [1-3] for a SRI-I type cyclone. From the viewpoint of separation the cyclone was designed for the most unfavourable case in the range of the above flow rates $V_{min} = 3\ m^3/h = 0{,}8333\cdot10^{-3}\ m^3/s$ and least favourable temperature 200°C – in the calculation expressed by the dynamic viscosity of air $\eta = 26{,}3\cdot10^{-6}$ Pa·s. From the requirement for separation of coarse fractions $a > 20$ μm and the behaviour of function $E(a)$ (S–curve) a requirement was derived for $a_m = 10$ μm for particles with a density $\rho_p = 2200\ kg/m^3$.

The main dimension of the cyclone – diameter $D = 0{,}078$ m – was determined by calculation from relation (1). The remaining dimensions were derived by geometrical similarity from the original dimensions of the SRI-I type cyclone. The main dimensions of the designed cyclone are apparent from Fig. 1.

3. Aim of measurements

Assuming the value of Stk_m is constant and independent of the variation of the flow rate given by Reynolds number Re, from relations (1) and (2) it follows that both by an increase of the volume flow rate of the exhausted sample V or by reduction of the temperature t, i.e. reduction of viscosity η, the magnitue of cut size a_m is shifted towards lower values which improves the separating ability of the cyclone.

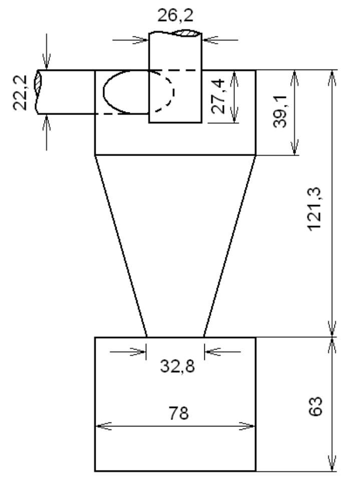

Fig. 1. Main dimensions of cyclone

Rys. 1. Główne wymiary cyklonu

In relation with the above trends and requirements in the field of measurement of emissions a proposal was put forward to test if a $D = 78$ mm cyclone would be appropriate for classification of the PM_{10} fraction in a real range of exhausted volume flow rates 2–6 m^3/h in emission apparatuses and temperatures of gases up to 200°C.

This performance job represents, from the viewpoint of separation, a rather different task than in the former one, since now it has to be proved that the cyclone in a real range of volume flow rates and gas temperatures can achieve the value $a_{1,m}$ = 10 μm as a classifier. The selected approach was experimental determination of the nondimensional relation $Stk_m = f(Re)$ and an analysis of this relation from the viewpoint of achievement the value $a_{1,m}$ = 10 μm.

4. Experimental stand and measuring method

Experiments were performed on a 4 m long horizontal experimental dust stand with an inner diameter 97 mm. Two variably classified power station fly-ashes with mass medians 9 and 12 μm were used as the experimental media. Concentrations of dust in dependance on the air flow rate through the stand are in the range 0,5–2 g/m^3.

The measurement 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 cut size of the cyclone O_c and assessment of the dependence of the fractional cut size on the size of a particle $O_f(a)$ on the basis of balance relations on the separator and assessment of the grain size of particles from relevant samples. More detailed information is available in the next section. A series of experiments performed in the necessary range of volume flow rates makes it possible to determine the nondimensional relation $Stk_m = f(Re)$.

Representative sampling of the aerodynamic mixture from the axis of the channel is performed with a 400 mm long direct sampling probe with a 8 mm probe head diameter connected to the cyclone inlet. The sampling probe with the head is driven through the end bend of the horizontal dust stand and the mouth of the sampling probe is located on the axis of the channel in a sufficient distance before the bend where the flow is undisturbed. When using a sampling proble with a 8 mm head diameter velocities in the channel axis and probe mouth (isokinetic sampling) in the range approximately 11–33 m/s correspond with the assumed range of flow rates through the cyclone 2–6 m^3/h.

The experimental sampling stand has a standard configuration and comprises a sampling probe with a head, the tested cyclone connected with a short joining piece to an end filter equipped with glass fibre filter paper and a 26 mm inner diameter flow rate measurement device with an orifice plate. The flow rate measurement device with an orifice plate is connected via a suction valve and a pulse damping vessel to a vacuum pump.

Measurement of relevant quantities and control of the exhausted volume for a variation of the pressure loss of the filter is performed by standard laboratory measurement methods.

5. Method of assessment of grade efficiency

Figure 2 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 simple balancing relations.

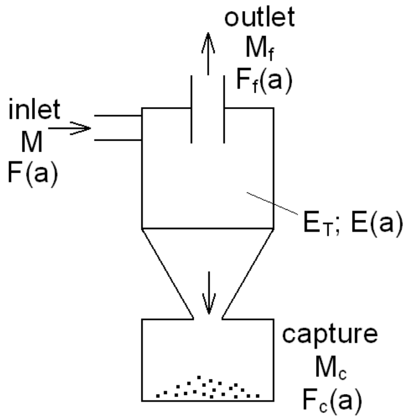

Fig. 2. Schematic diagram of a cyclone performing as a solid state particle classifier: M, M_c and M_f represent total mass flow rates in inlet, capture and outlet and $F(a)$, $F_c(a)$ and $F_f(a)$ repsesent corresponding oversize cummulative distribution curves

Rys. 2. Schematyczny rysunek cyklonu będącego klasyfikatorem cząstek stałych: M, M_c i M_f oznaczają całkowite masowe wydajności na wlocie, zatrzymane i na wylocie, zaś $F(a)$, $F_c(a)$ i $F_f(a)$ przedstawiają odpowiednie skumulowane krzywe rozkładu

Using the capture – outlet method, the fractional efficiency of particles E in the size range (a, $a+\Delta a$) can be derived as

$$E = \frac{\frac{E_T}{1-E_T}\Delta F_c}{\Delta F_f + \frac{E_T}{1-E_T}\Delta F_c} \tag{3}$$

where the total efficiency E_T is defined as a ratio of total mass flows in the capture section and in the inlet and differences of oversize cumulative distribution curves ΔF_c and ΔF_f correspond to particle size difference Δa.

Similarly by the inlet – outlet method, i.e. by application of oversize cumulative distribution curves $F(a)$ and $F_f(a)$ for grade efficiency E can be derived

$$E = 1-\left(1-E_T\right)\frac{\Delta F_f}{\Delta F} \tag{4}$$

For both relations, i.e. both for the capture-outlet (3) and inlet-outlet (4) method the following condition is fulfilled – for larger particles where the value ΔF_f first approaches zero, grade efficiency E approaches 1, i.e. to a value theoretically assumed for larger particles for the centrifugal separating principle.

Dust samples for determination of oversize cumulative distribution curves $F_c(a)$ are collected from the discharge hopper of the cyclone, for determination of $F_f(a)$ from the end filter and for $F(a)$ from the dust feed.

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

6. Performed measurements and results

Within the range of volume flow rates 2–6 m^3/h altogether 14 measurements were performed. The measurements performed either by the capture-outlet (3) or inlet-outlet (4) method led to the behaviour of function $E(a)$ in Fig. 3. In the range of fine particles where the grade efficiency should approach zero a certain non-zero value $E_{\min}$ was found and for smaller particles the grade efficiency again grew. This systematic error can be explained by a hypothesis that fine particles with a size below 1 μm are imperfectly dispersed in the dust feeder and move along the dust stand in clusters and from the viewpoint of separation behave like coarse particles. However when analyzing particle samples the dusts is first disintegrated in a supersonic bath and only after being perfectly dispersed the samples are 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.

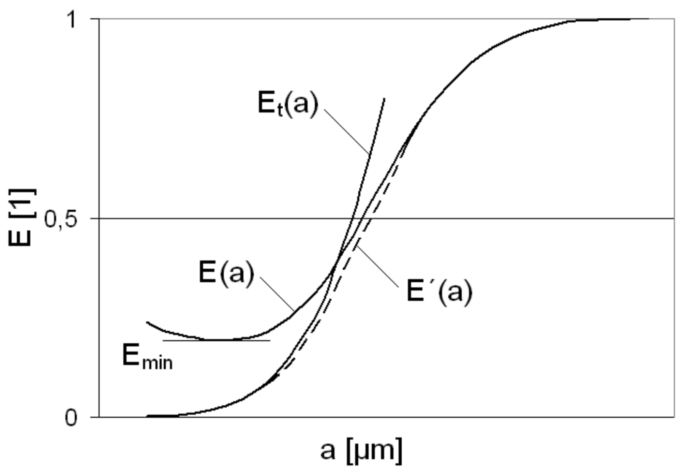

Fig. 3. Correction of function $E(a)$

Rys. 3. Poprawka funkcji $E(a)$

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 force and aerodynamic resistance assuming a simplified model of flow through the cyclone and quasistationary motion of particles at the separating surface [6]. This simplified model leads to the theoretical behaviour of $E_t(a)$ in the form $E_t = k{\cdot}a^2$ also shown in Fig. 3. The found behaviour of $E(a)$ for the range of larger particles and the theoretical behaviour of $E_t(a)$ for the range of smaller particles are a basis for plotting 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 $E^{'}(a_1)$ according to relation

$$a_1 = a \cdot \sqrt{\frac{\rho_p}{1000}} \tag{5}$$

where ρ_p [kg/m^3] is the particle density.

The method used for evaluation was that in which the value $E_{\min}$ for the found function $E(a)$ (and hence also correction) was minimum. In fact this meant that the capture-outlet method was applied for lower volume flow rates and the inlet-outlet method for higher volume flow rates.

Changes of the separating ability of the cyclone with varying flow rate can be generalized in the form of dependance of Stk_m on Reynolds number Re. In compliance with relation (1) by applying volume flow rate V, Stokes criterion Stk_m related to cut size $a_{1,m}$ is expressed in the form

$$\mathrm{Stk}_{\mathrm{m}} = \frac{a_m^{\ 2} \cdot \rho_{\check{c}}}{18 \cdot \eta} \cdot \frac{v_D}{D} = \frac{a_{1,m}^{\ 2} \cdot 1000}{18 \cdot \eta} \cdot \frac{v_D}{D} = \frac{a_{1,m}^{\ 2} \cdot 1000}{18 \cdot \eta} \cdot \frac{4 \cdot V}{\pi \cdot D^3} \tag{6}$$

and Reynolds criterion Re by applying volume flow rate V is expressed in the form

$$\mathrm{Re} = \frac{v_D \cdot D}{\nu} = \frac{v_D \cdot D \cdot \rho}{\eta} = \frac{4 \cdot V \cdot \rho}{\pi \cdot D \cdot \eta} \tag{7}$$

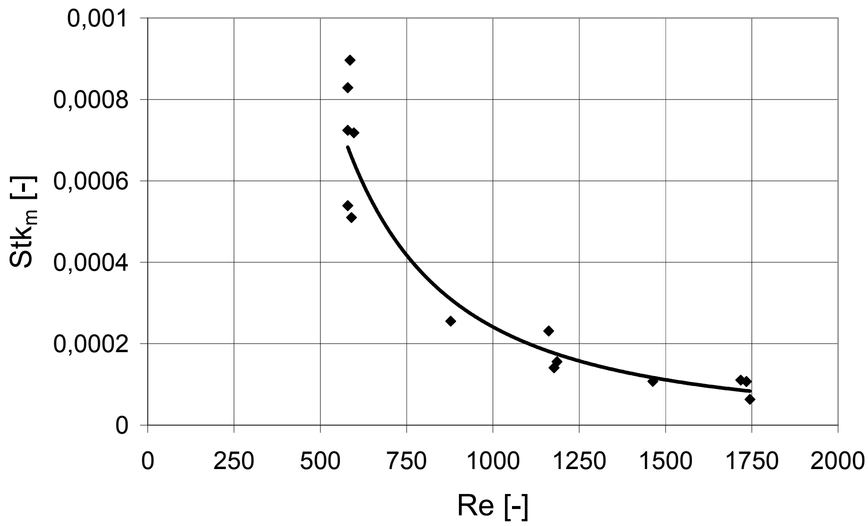

Fig. 4. Dependence of Stk_m on Re

Rys. 4. Zależność Stk_m od Re

In relations (6) and (7) ρ [kg/m^3] is the gas (air) density and η [Pa·s] the dynamic viscosity of the gas (air).

Results of measurements in the form of criteria Stk_m and Re are summarized in the form of dependence of Stk_m on Re in Fig. 4.

The found dependence of Stk_m on Re can best be expressed by the nondimensional dependence $\mathrm{Stk}_m = f(\mathrm{Re})$ in the form

$$\mathrm{Stk}_m = 0{,}00018 + 127 \cdot \mathrm{Re}^{-1{,}91} \tag{8}$$

7. Analysis of results of measurements – cyclone as a PM$_{10}$ emission classifier

Measurement of the grade efficiency of a cyclone generalized in the form given by relation (8) makes it possible to determine for what temperatures and for what flow rates a cyclone can be used as a PM$_{10}$ emission classifier. If Stk_m and Re in relation (8) are substituted with relations (6) and (7) respectively we obtain

$$\frac{4 \cdot V}{\pi \cdot D^3} \cdot \frac{a_{1,m}^2 \cdot 1000}{18 \cdot \eta} = 0{,}00018 + 127 \cdot \left(\frac{4 \cdot V \cdot \rho}{\pi \cdot D \cdot \eta} \right)^{-1{,}91} \tag{9}$$

In this relation we can observe quantities ρ and η which depend on the composition of the gas. Gas density ρ furthermore depends on state functions (temperature, pressure) and dynamic viscosity η is a function of temperature.

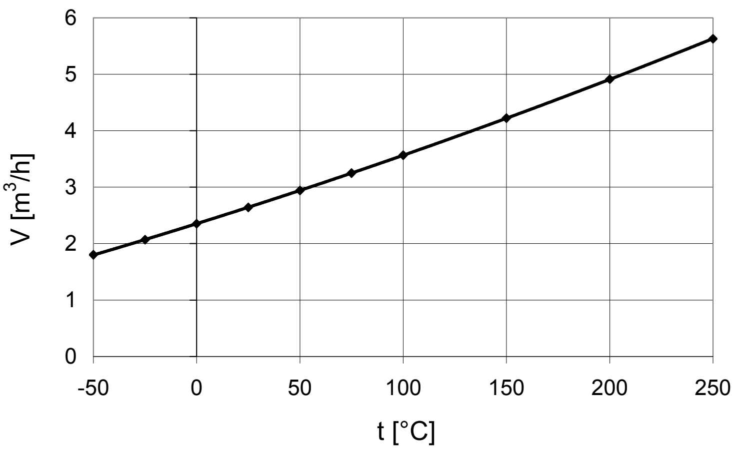

Fig. 5. Dependence of volume flow rate V m^3/h on the temperature of air t °C for cyclone D = 78 mm as a PM$_{10}$ emission classifier at a pressure of 98 kPa

Rys. 5. Zależność wydatku objętościowego V m^3/h od temperatury powietrza t °C dla cyklonu D = 78 mm jako klasyfikatora emisji PM$_{10}$ przy ciśnieniu 98 kPa

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 $\rho = f(p, t)$ and $\eta = f(t)$. The calculation will be performed for standard pressure 98 kPa in such a way that $a_{1,m}$ is set equal to $10 \cdot 10^{-6}$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_{10} emission classifier. This dependence is given in Fig. 5 and can be expressed by a polynomial of the 2nd degree in the form

$$V = 7 \cdot 10^{-6} \cdot t^2 + 0{,}011 \cdot t + 2{,}35 \tag{10}$$

8. Conclusions

The nondimensional relation $\mathrm{Stk}_m = f(\mathrm{Re})$ in the form (8) was experimentally determined on a dust stand and shows how the separation ability of a cyclone changes with the volume flow rate of the gas expressed by Reynolds number Re.

By analyzing this function it was found that a cyclone with a D = 78 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_{10} 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 (10). According to this relation or according to the relation in Fig. 5 the required flow rate through the cyclone V increases from 2,35 m^3/h at 0°C to 4,83 m^3/h at 200 °C.

For a different gas than dry air the usability of a cyclone as a PM_{10} emission classifier differs from (10) and by an analogous procedure to that with dry air can be derived from relation (9) according to relevant values of $\rho = f(p, t)$ and $\eta = f(t)$ for the particular gas.

It can be stated that in spite of the complexity of two-phase measurement and its evaluation the results obtained show good repeatability (identical experimental conditions) and at higher volume flow rates also good reproducibility. For minimum flow rates the results were more erroneous (the standard deviation reached approx. 12,5% of the respective mean value).

Symbols

a	–	particle size (diameter)	[m], [μm]
a_1	–	aerodynamic particle size (diameter)	[m], [μm]
a_m	–	particle cut size	[m], [μm]
$a_{1,m}$	–	aerodynamic particle cut size	[m], [μm]
p	–	gas pressure	[Pa]
t	–	gas temperature	[°C]
v_D	–	characteristic velocity in the cyclone	[m]
D	–	cyclone diameter	[m]
E	–	grade efficiency of separation	

E_T	–	total efficiency of separation	
M	–	mass flow rate of patricles in inlet	[kg/s]
M_c	–	mass flow rate of patricles in capture	[kg/s]
M_f	–	mass flow rate of patricles in outlet	[kg/s]
F	–	oversize cummulative part of particles	
V	–	volume flow rate of gas	[m^3/s]
Re	–	Reynolds number defined by (7)	
Stk_m	–	Stokes number defined by (6)	
ρ	–	density of gas	[kg/m^3]
ρ_p	–	density of particles	[kg/m^3]
η	–	dynamic viscosity of gas	[Pa·s]
Δ	–	difference of quantity	

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