Cyclones as PM_{10} and $PM_{2.5}$ emission measurement classifiers

J. Hemerka, M. Braniš & P.Vybíral
Faculty of Mechanical Engineering,
Czech Technical University in Prague, Czech Republic

Abstract

Two cyclone classifiers D = 78 and 32 mm for emission measurement of particle fractions PM_{10} and $PM_{2.5}$ were developed at our department as a part of R&D activities. Verification tests of the cyclones were generalized in the form of criteria relations $Stk_m = f(Re)$. These relations tell us how the cyclone classification ability given by the value of Stokes number Stk_m for the aerodynamic cut size $a_{1,m}$ changes in dependence on the sample volume flow rate V of the gas generalized by Reynolds number Re.

By a subsequent analysis of both non-dimensional criteria relations the dependances of the sample volume flow rate on the gas temperature V = f(t), where cyclones classify as PM_{10} and $PM_{2.5}$ classifiers, were derived for both dry air and flue gases from combustion of lignite and hard coal in the usual range of excess combustion air coefficients and vapour contents.

From the individual dependences V = f(t) for both cyclones it follows that :

- The dependance of V (m^3/h) on gas temperature t (°C) is significant.
- Dependances V = f(t) for dry air and combustion flue gases significantly differ (from 12 to 13%).
- For coal combustion the differences of the corresponding volume flow rates depend on the flue gas composition and differ in the range of several percent. Differences between volume flow rates for hard coal and lignite combustion are not very significant.

In all mentioned cases, the corresponding volume flow rates for gas temperature up to 200°C change in the range from 2 to 6 m^3/h (usual sample volume flow rates in emission measurements) and the cyclones D = 78 and 32 mm can be thus used as PM_{10} and $PM_{2,5}$ emission classifiers.

Keywords: emission measurement, PM_{10} and $PM_{2,5}$ fraction, cyclone separator.

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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. 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 the introduction of measurement of emissions with graded sampling – measurement of PM_{10} and $PM_{2..5}$ fractions – into practical use. Present Czech legislature on emission control is concerned only with the emission limits of total solid state pollutants (TSP), i.e. concentration of all solid state particles without considering their grain size.

The present paper brings information on the research of cyclone classifiers for emission measurement, which classify particles at usual sample gas flow rates from 2 to 6 m^3/h and a current temperature range up to 200°C in compliance with requirements defined by the PM_{10} and $PM_{2.5}$ fraction.

2 Design of cyclone classifiers for emission measurement

During sampling of solid state particles from a carrier gas a particle classifier is inserted between the sampling probe and the final filter. The task of the classifier is to separate particle fractions of particular sizes from the sample. The basic characteristic of every classifier is the dependance of grade efficiency E on the aerodynamic particle size a_1 – function $E(a_1)$. The level at which a particle is captured with grade efficiency E = 0.5 is designated as the cut size $a_{1,m}$. PM_{10} and $PM_{2.5}$ classifiers are classifiers, where $a_{1,m}$ = 10 μm and $a_{1,m}$ = 2.5 μm and the dependance $E(a_1)$ is in the form of a sharp "S – curve".

2.1 Design of PM_{10} cyclone classifier

Assessment of the main dimensions of the cyclone separator was based on an assumption that for geometrically similar cyclones the separating ability E can be described by function E = f(Stk), where Stk is Stokes criterion which is a decisive parameter for particle separation in cyclones. Stokes criterion for the magnitude of cut size $a_{1,m}$ is defined as

$$Stk_m = \frac{{a_{1,m}}^2 1000}{18\,\eta} \frac{v_D}{D} \qquad (1)$$

where v_D (m/s) is the characteristic velocity in the cylindrical chamber of a cyclone with diameter D expressed by

$$v_D = \frac{4\,V}{\pi\,D^2} \qquad (2)$$

The concept of the cyclone was based on the value of $Stk_m = 1.05.10^{-3}$ given by Smith *et al* [1] for a SRI-I type cyclone.

The cyclone was originally designed at our department according to a requirement from industry to design a preseparator of coarse fractions a > 20 μm (a_1 > 30 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. From the viewpoint of separation the cyclone was designed for the most unfavourable case in the range of the above sample flow rates and gas temperatures. The main dimension of the cyclone - cylinder diameter D = 78 mm - was determined by calculation from equation (1), where $a_{1,m} = 15.10^{-6}$ m, $V = 3\ m^3/h = 8.333.10^{-4}\ m^3/s$ and $\eta = 26.3.10^{-6}$ Pa.s (corresponds to dry air temperature 200°C). The remaining dimensions were derived by geometrical similarity from the original dimensions of the SRI-I type cyclone and are apparent from fig. 1.

Our preliminary laboratory tests indicated that the cyclone D = 78 mm could serve in current conditions of emission measurements as a PM_{10} classifier and this was the reason why the cyclone was subjected to other more detailed tests.

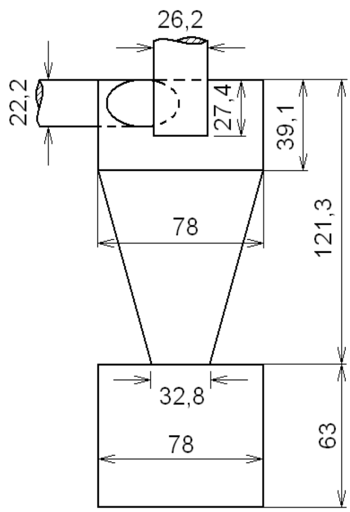

Figure 1: Main dimensions of the cyclone D = 78 mm.

2.2 Design of $PM_{2.5}$ cyclone classifier

Based on equations (1) and (2) and experiments with the cyclone D = 78 mm, a cyclone D = 35 mm, geometrically similar to the cyclone D = 78 mm, was first designed as a $PM_{2.5}$ classifier. However laboratory tests with this type of a cyclone did not give satisfactory results. For this reason a URG type of cyclone was chosen for further design. The URG type has a tangential inlet with a rectangular cross-section and a longer cylindrical part and thus has higher grade efficiencies compared with the SRI type cyclone. Preliminary experiments with commercial URG type cyclones D = 18 mm and D = 22 mm together with findings of our previous experiments with the SRI type cyclone D = 35 mm led to an original design of the cyclone with a D = 32 mm diameter of the cylindrical part. The main dimensions of the cyclone are shown in fig. 2.

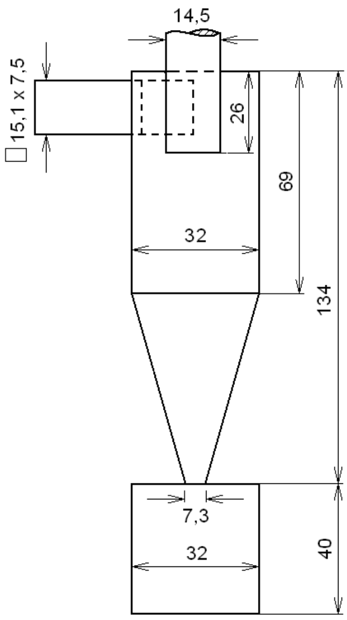

Figure 2: Main dimensions of the cyclone D = 32 mm.

3 Verification tests

Changes of the separating ability of the cyclone with varying flow rate V performed in laboratory conditions can be generalized in the form of the dependence of Stokes criterion Stk_m (related to the aerodynamic cut size $a_{1,m}$) on Reynolds number Re [2].

According to (1) and (2) the value of Stk_m can be expressed as

$$Stk_m = \frac{a_{1,m}^2 1000}{18\eta} \frac{4V}{\pi D^3} \tag{3}$$

and Reynolds number Re is defined as

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

In equations (3) and (4) ρ (kg/m^3) is the gas density and η (Pa.s) is the dynamic viscosity of the gas.

Cyclone performance tests were performed in the laboratory dust rig in the range of sample flow rates V = 2 – 6 m^3/h for cyclone D = 78 mm and V = 1.5 – 6 m^3/h for cyclone D = 32 mm. Dependances of grade efficiency E on the aerodynamic particle size a_1 (functions $E(a_1)$) were determined by the standard „capture – outlet" method, where dust samples for determination of corresponding oversize cumulative distribution curves were taken from the discharge hopper of the cyclone and from the end filter. Particle size analyses of the dust samples were 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.

Due to the fact that in the range of small particles, where values of grade efficiency E should theoretically approach zero but the found dependances $E(a_1)$ did not reach zero values, the functions $E(a_1)$ were corrected in the range of small particles into the form of an „S – curve"- $E'(a_1)$. Hence for further calculations of Stk_m corrected values of the aerodynamic cut size $a'_{1,m}$ are used.

3.1 Results of verification tests with cyclone D = 78 mm

Results of 14 laboratory tests with the cyclone D = 78 mm in the range of sample flow rates V = 2 – 6 m^3/h are expressed in the form of criteria dependance Stk_m and Re in fig. 3.

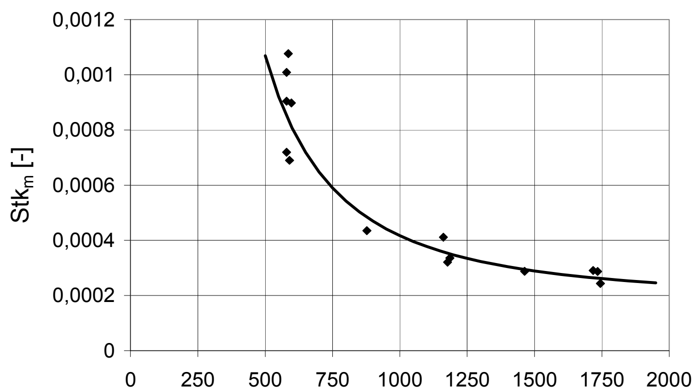

Figure 3: Dependance of Stk_m on Re for cyclone D = 78 mm.

The found dependance of Stk_m on Re can be best expressed in the form

$$Stk_m = 0.00018 + 127.\mathrm{Re}^{-1.91} \tag{5}$$

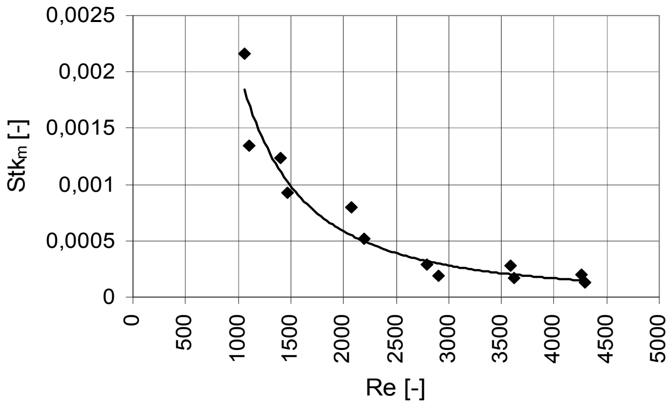

Figure 4: Dependance of Stk_m on Re for cyclone D = 32 mm.

3.2 Results of verification tests with cyclone D = 32 mm

Similarly, results of 14 laboratory tests with the cyclone D = 32 mm in the range of sample flow rates V = 1.5 – 6 m^3/h are expressed in the form of criteria dependance Stk_m and Re in fig. 4.

The dependance of Stk_m on Re can be best expressed in the form

$$Stk_m = 559.\mathrm{Re}^{-1.81} \tag{6}$$

4 Use of cyclone D = 78 mm as a PM_{10} classifier

Verification tests of a cyclone D = 78 mm generalized in the form given by relation (6) makes it possible to determine for what temperatures and for what flow rates the cyclone D = 78 mm can be used as a PM_{10} emission classifier (condition $a_{1,m}$ = 10 μm). If criteria Stk_m and Re in eqn. (6) are substituted with their definitions (3) and (4) respectively we obtain

$$\frac{4V}{\pi D^3} \frac{a_{1,m}^2 1000}{18\eta} = 0.00018 + 127\left(\frac{4\,V\,\rho}{\pi\,D\,\eta}\right)^{-1.91} \tag{7}$$

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

4.1 Cyclone D = 78 mm as PM_{10} classifier for dry air

In further processing of results it is assumed that the gas is dry air and current relations are used for functions ρ = f(p,t) and η = f(t). The calculation is performed for standard pressure 98 kPa in such a way that $a_{1,m}$ is set equal to 10.10^{-6} m and by iterating a dependance of the volume flow rate of air V (m^3/s) on the temperature of air t (°C) for which the cyclone can be used at 98 kPa as a PM_{10} emission classifier is obtained. The found dependance V = f(t) can be expressed by a polynomial of the 2nd degree in the form

$$V = 7.10^{-6}\,t^2 + 0.011\,t + 2{,}35 \tag{8}$$

where V is for practical reasons expressed in m^3/h. According to this relation 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.

4.2 Cyclone D = 78 mm as PM_{10} classifier for flue gases from coal combustion processes

For a different gas than dry air the use of the cyclone as a PM_{10} classifier differs from (8) and a similar relation V = f(t) can be derived from (7) by the same procedure as for dry air by means of relevant values of ρ = f(p,t) and η = f(t) for the particular gas.

In the Czech Republic a cyclone can be used as a PM_{10} emission classifier mainly for flue gases from coal combustion processes.

In calculations designers of boilers prefer to use kinematic viscosity ν (m^2/s) rather than dynamic viscosity η (Pa.s) and therefore equation (7) can be rewritten using relation η = ν. ρ in the form

$$\frac{4V}{\pi D^3}\,\frac{a_{1,m}^2\,1000}{18\nu\,\rho} = 0.00018 + 127\left(\frac{4\,V}{\pi\,D\,\nu}\right)^{-1.91} \tag{9}$$

Determination of the flue gas density ρ (kg/m^3) follows from the expression of the density of wet flue gas at standard conditions ρ_N (kg/m^3) and from state equation

$$\rho_N = \rho_{d,N}\,\omega_d + \rho_{w,N}\,\omega_w \tag{10}$$

$$\rho = \rho_N\,\frac{p}{p_N}\,\frac{T_N}{T} \tag{11}$$

In eqn. (10) $\rho_{d,N}$ (kg/m^3) and $\rho_{w,N}$ (kg/m^3) are densities of dry flue gas and water vapour under standard conditions and ω_d (1) and ω_w (1) are volume ratios of dry flue gas and water vapour in wet flue gas.

The value of the density of dry flue gas $\rho_{d,N}$ (kg/m^3) depends on the fuel composition and can be accurately determined by means of stoichiometric calculations of combustion equations or by calculation from the known dry flue gas composition. In a simplified way $\rho_{d,N}$ (kg/m^3) can be determined according to the fact that the density of dry flue gases depends above all on an excess of combustion air, expressed by an excess combustion air coefficient α (1) which influences the actual value of CO_2 in flue gas and depends less on the fuel composition. According to [3] for the determination of $\rho_{d,N}$ (kg/m^3) it is possible for lignite combustion to derive the expression

$$\rho_{d,N} = 1.293 + 0.004938\ CO_{2,act} \tag{12}$$

where $CO_{2,act}$ (1) gives the actual volume ratio of CO_2 in flue gas. Similarly, for the hard coal combustion the expression can be derived for $\rho_{d,N}$ (kg/m^3)

$$\rho_{d,N} = 1.293 + 0.004929\ CO_{2,act} \tag{13}$$

The simplified calculation of the actual flue gas density ρ (kg/m^3) consists of steps as follows:

- choice of used coal, hard coal or lignite, which determines the maximum value of CO_2 in flue gas, $CO_{2,max} = 0.1915$ for lignite or $CO_{2,max} = 0.1880$ for hard coal [3],
- choice of the value of the excess combustion air coefficient α (1) or the volume ratio of O_2 in flue gas and calculation of α as $\alpha = 0.21/(0.21 - O_2)$,
- determination of $CO_{2,act}$ (1) from the equation for ideal combustion $CO_{2,act} = CO_{2,max}/\alpha$,
- calculation of $\rho_{d,N}$ (kg/m^3) by means of equation (12) or (13),
- choice of the value of water vapour in wet flue gas ω_w (1) and atmospheric pressure p (Pa),
- calculation of ρ_N and ρ (kg/m^3) by means of equations (10) and (11).

The flue gas kinematic viscosity ν (m^2/s) can be according to [4] determined as

$$\nu = M_\nu\ \nu_{mean} \tag{14}$$

where ν_{mean} (m^2/s) is the kinematic viscosity of the flue gas with mean gas composition ($\omega_w = 0.11$and $CO_{2,mean} = 0.13$) and M_ν (1) is the correction factor which depends on the actual value of ω_w (1) in wet flue gas and gas temperature. The value of ν_{mean} (m^2/s) is a function of the gas temperature and from data in [4] can be expressed as

$$\nu_{mean} = \left(1.10^{-4}\, t^2 + 0.0795\ t + 11.9\right).10^{-6} \tag{15}$$

The value of correction factor M_ν (1) lies in a narrow range 0.95 – 1.0 [4].

Determination of the dependence of the sample volume flow rate on the gas temperature V = f(t), where the cyclone at the pressure p (Pa) classifies as a PM_{10} classifier, is performed by an authorized software [5].

Analysis of equation (9) by means of software [5] was performed for a real range of the excess combustion air coefficient α (1) and the content of water vapour in wet flue gas ω_w (1) for lignite and hard coal combustion. For lignite combustion α (1) ranged from 1.2 to 2 and ω_w (1) from 0.10 to 0.25 and for hard coal combustion α (1) ranged again from 1.2 to 2 and ω_w (1) from 0.08 to 0.15.

In figures 5 and 6 are plotted as examples dependances V = f(t) for combinations of α (1) and ω_w (1) for lignite and hard coal combustion which lead to maximum (ω_w = 0.10, α = 1.2) and minimum (ω_w = 0.25, α = 2.0) values of the volume flow rate of the sample. In figures 5 and 6 the dependences V = f(t) for dry air are added for comparison.

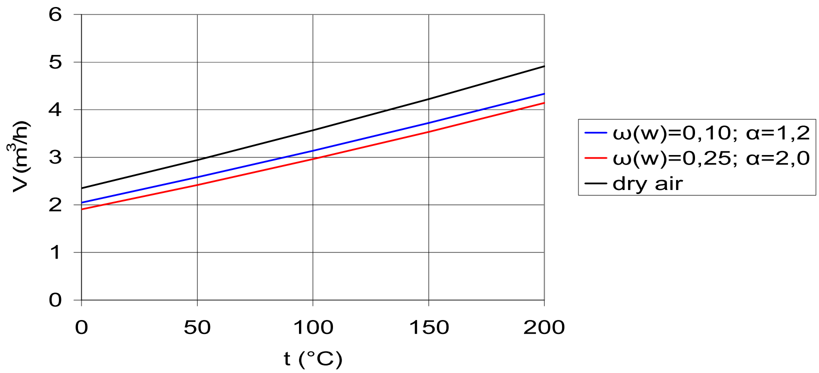

Figure 5: Range of dependances of V = f (t), where the cyclone D = 78 mm for lignite combustion serves as a PM_{10} classifier.

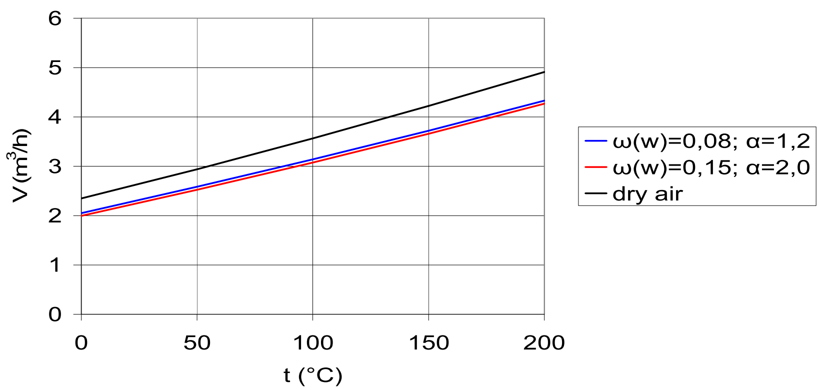

Figure 6: Range of dependances of V = f (t), where the cyclone D = 78 mm for hard coal combustion serves as a PM_{10} classifier.

From both diagrams it follows that the cyclone D = 78 mm can serve as a PM_{10} classifier in combustion processes at flue gas temperatures up to 200°C in the real range of sample volume flow rates from 2 to 6 m^3/h.

5 Use of cyclone D = 32 mm as a $PM_{2.5}$ classifier

Results of measurement with the cyclone D = 32 mm, expressed by equation (6), were processed by the similar way as results with the cyclone D = 78 mm.

5.1 Cyclone D = 32 mm as $PM_{2.5}$ classifier for dry air

Processing equation (6) for dry air, where the cyclone D = 32 mm classifies as a $PM_{2.5}$ classifier, leads to dependance of V (m^3/h) on temperature t (°C) in the form

$$V = 8.10^{-6}\, t^2 + 0.0133\, t + 2.575 \tag{16}$$

According to this relation the required flow rate through the cyclone V increases from the value 2.58 m^3/h at 0°C to 5.56 m^3/h at 200°C.

5.2 Cyclone D = 32 mm as a $PM_{2.5}$ classifier for flue gases from coal combustion processes

For flue gases from coal combustion processes the Eq. (6) was rewritten into the form

$$\frac{4V}{\pi D^3}\,\frac{a_{1,m}^2\, 1000}{18\,\nu\,\rho} = 559\left(\frac{4\,V}{\pi\, D\, \nu}\right)^{-1.81} \tag{17}$$

The processing of eqn. (17) by means of software similar to [5] was performed in the same range of values of the excess combustion air coefficient α (1) and the content of water vapour in wet flue gas ω_w (1) as in the case of the cyclone D = 78 mm. The results are presented in figures 7 and 8.

In figure 7 dependances of V = f (t) are plotted for lignite combustion and combination of the excess combustion air coefficient α (1) and the content of water vapour in wet flue gas ω_w (1) which leads to the maximum (ω_w = 0.10, α = 1.2) and minimum values (ω_w = 0.25, α = 2.0) of the sample flow rate V (m^3/h). In figure 8 similar dependances of V = f (t) are plotted for hard coal combustion. Again, for comparison the dependence V = f (t) for dry air is plotted in figures 7 and 8.

From diagrams in figures 7 and 8 it follows again that cyclone D = 32 mm can serve as a $PM_{2.5}$ classifier in combustion processes at flue gas temperatures up to 200°C in the real range of sample volume flow rates from 2 to 6 m^3/h.

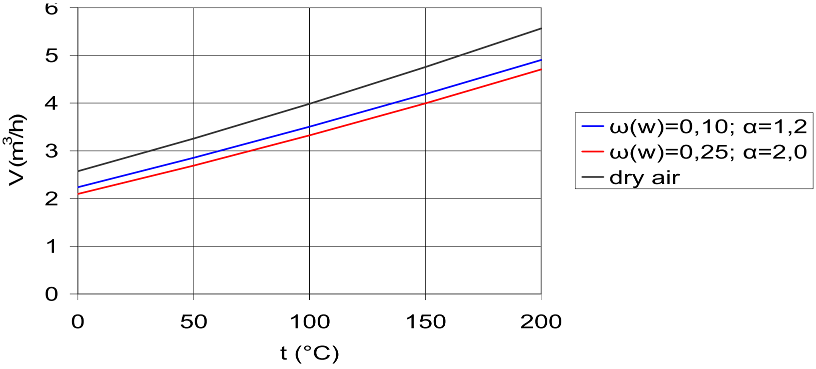

Figure 7: Range of dependances of V = f (t), where the cyclone D = 32 mm for lignite combustion serves as a $PM_{2.5}$ classifier.

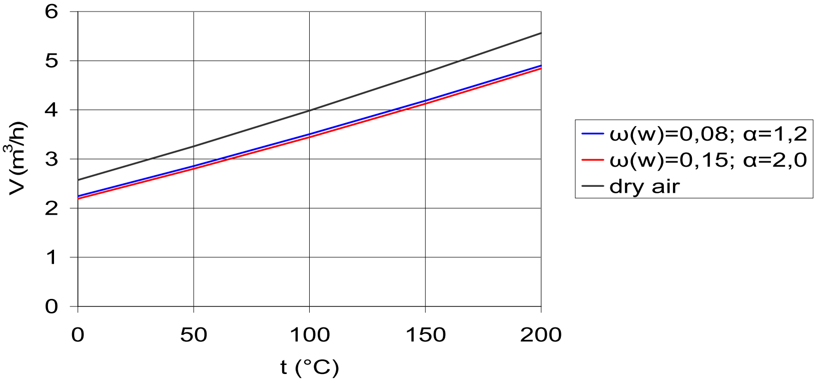

Figure 8: Range of dependances of V = f (t), where the cyclone D = 32 m for hard coal combustion serves as a $PM_{2.5}$ classifier.

6 Conclusion

Two cyclones D = 78 and 32 mm for emission measurement of particle fractions PM_{10} and $PM_{2.5}$ were developed at our department. Verification tests of the cyclones were generalized in the form of criteria relations Stk_m = f(Re). By a subsequent analysis of the criteria relations dependances of the sample volume flow rate on gas temperature V = f(t), where cyclones classify as PM_{10} and $PM_{2.5}$ classifiers, were derived for dry air and flue gases from combustion of lignite and hard coal in the current range of the excess air combustion coefficient and vapour content.

From the individual dependences V = f(t) for both cyclone follows:

- In the given case the dependence of V (m^3/h) on the gas temperature t (°C) is significant.

- Dependances V = f(t) for dry air and combustion flue gases differ significantly (from12 to 13%).
- For coal combustion the differences of the corresponding volume flow rates depend on the flue gas composition and differ in the range of several percents. Differences between volume flow rates for hard coal and lignite combustion are not very significant.
- For both cyclones and in all analysed cases the corresponding volume flow rates for gas temperatures up to 200°C change in the range from 2 to 6 m^3/h, usual for emission measurements, and the cyclones D = 78 and 32 mm can be thus used as PM_{10} and $PM_{2,5}$ emission classifiers.

Acknowledgement

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