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A specific uncertainty of sampling polydisperse particulate matter in gravimetric dust concentration measurements in conduits

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Abstract: A study of a simulation-calculation character has been undertaken in order to determine one of the uncertainty components of the gravimetric measurement of the mass concentration of total particulate matter in flue gas flowing through a conduit. This uncertainty component is attributed to the degree of representativeness of the isokinetic or anisokinetic sampling of polydisperse particulate matter in the situation when the granulometric composition and density of dust are not known in detail, which is common in routine dust emission field tests. In such cases, the quantitative description of this representativeness, being part of global measurement accuracy analysis, is either ignored or overestimated in practice. Well estimated, the uncertainty component in question is therefore needed for practical purposes. In the study reported here, many dusts of diverse particle size distributions have been simulated representing dusts actually occurring in typical places of dust removal plants, i.e. before and after the dust collectors. Definite aspiration characteristics, pertaining to a really existing and used sampling nozzle, have been applied for the calculations. Typical dust densities and isokinetic sampling rates have been adopted. Using the above, the total dust concentration error recorded for the simulated sample taken has been calculated. Based on the distributions of the obtained errors, the uncertainty (along with a necessary correction factor) of the measured concentration has been established as being dependent on the general type of dust, the dust density range, isokinetic rate, and nozzle size. The discussed measurement uncertainty component is estimated to be up to 12% and should be appropriately taken into account in measurement results of total dust concentration in ducts and stacks.

List of important symbols used

c	Total dust concentration in the conduit at the sampling point
c_f	Concentration of a given dust fraction in the conduit at the sampling point
c_{fs}	Concentration of a given dust fraction in the aspirated sample
c_s	Total dust concentration in the aspirated sample (measured concentration)
d	Equivalent free-falling (or sedimentation) diameter of a particle
d_{max}	Maximum particle diameter (for a given particle size distribution)
d_s	Inlet opening diameter of the entry nozzle
d_{50}	Mass median particle diameter (for a given particle size distribution)
f	Correction factor for the measured total dust concentration
H	Isokinetic rate
P	Aspiration efficiency
Stk	Stokes number
U	Relative expanded uncertainty (at a level of confidence of approx. 95%) of the measured total dust concentration due to the quantitatively unidentified sampling of the polydisperse dust
U_δ	Relative expanded uncertainty (at a level of confidence of approx. 95%) of the measured total dust concentration due to the quantitatively unidentified particle size distribution, as arising out of the simulation performed
U_μ	Relative expanded uncertainty (at a level of confidence of approx. 95%) of the measured total dust concentration attributed to the influence of gas viscosity

U_w Relative expanded uncertainty (at a level of confidence of approx. 95%) of the measured total dust concentration attributed to the influence of gas velocity
w Gas velocity in the conduit at the sampling point
x Mass fraction of a given dust fraction in the conduit
X Cumulative mass fraction of particles smaller than a given particle (cumulative undersize mass fraction)
δ Relative sampling error = Relative error between the measured total dust concentration and the actual total dust concentration (referenced to the measured concentration)
Δ_{max} Half of the range of all registered (calculated) values of sampling error
ρ Dust particle density
μ_o Gas absolute viscosity

Introduction

Gravimetric measurements of the amount of dust emitted from stationary sources, which mainly are technological processes, are common practice. Today, they are regulated by the international standards (ISO 2003, EN 2007, EN 2017). The basic quantity measured in flue gas plants, generally equipped with dust-removing devices, is the total dust mass concentration. This quantity is either the target control parameter itself or the basis for the determination of the dust mass flow rate (in addition to the volumetric flue gas flow rate), which is called the emission rate. For some time past, greater importance is attached to the best possibly to determine the uncertainty of the measurement results obtained using the gravimetric method. The overall, final uncertainty of the measured total dust concentration (formally called the expanded uncertainty now) is derived from uncertainty components. The quantitative identification of them, sometimes difficult, is strictly connected with the fact that the measurement procedure is complex and the conditions under which it is performed are not ideal, and it is also dependent on the skill and experience of the testing team. Let us present an orderly list of factors that determine the accuracy of the concentration measurement and that need to be identified quantitatively by appropriate partial uncertainties (or alternatively by corrections). It will allow one to better understand what are the locations and connections of the subject of the paper in this set of influencing factors. They are as follows:

(a) The representativeness of the averaged sample, which depends on the dust concentration and gas velocity profiles in the measurement plane, and the number of sampling points;
(b) The representativeness of sampling at one point of the measurement plane. It is the result of the following: (i) determined and maintained by different appropriate technical solutions applied, the degree of isokinetic sampling rate, i.e. the ratio of the mean gas velocity in the inlet opening of the entry nozzle (which can be called the sampling velocity) to the point velocity of gas in the conduit. (The target continuous and strict isokinetic conditions are difficult to maintain because of the conditions of the performance of the process plants and technical limits of the gravimetric samplers themselves. As a result, the above-mentioned velocity ratio is allowed, by standard regulations, to be in the range of 0.95–1.15.); (ii) the size of dust particles in the form of size distribution; (iii) the physical properties of both aerosol phases: the gas phase and the solid particles; (iv) the recognized velocity of the dust-laden gas in the conduit (in this case, the metrological properties of the suitable measuring instruments are of importance (e.g. Szulikowski and Kateusz (2009)); (v) the aerodynamic properties of the entry nozzle in the form of its aspiration characteristics (including the directional sensitivity); and, (vi) the reciprocal position of the entry nozzle and the direction of the gas flow, which optimally should be isoaxial;
(c) Potential losses (sedimentation) of the dust in the sampling line, upstream of the filter;
(d) The accuracy of the separation of dust on the filtration element, ensuing from the separation efficiency of the filtering material;
(e) The accuracy of weighing and the conditioning of the filter and other questions related to filter handling, transportation, etc.;
(f) The accuracy of determining the aspirated sample volume of gas for the actual and standard conditions, thus including measurement accuracies of the gas volume, temperature, pressure and chemical composition measuring devices;
(g) The accuracy of determining the oxygen concentration, whenever the dust concentration conversion to the reference oxygen content is required; and,
(h) The general, statistical randomness in the series of a few made measurements, resulting from the difficult technical conditions of performing a measurement in industrial conditions and the non-ideal stability of the technological process.

The factors (a) through (g) are quantified through Type B evaluation of uncertainty and together determine the accuracy of a single measurement result. Within Point (h), Type A uncertainty evaluation is applied, which is the method of statistical analysis (JCGM 2008, Piotrowski and Kostyrko 2012, ECA 2013, EMH 2013). Both aspects of representativeness, i.e. factors (a) and (b), function alike the factors (c)–(e), and they are the reason for the inaccuracy of the dust mass ascribed to the volume of the gas drawn in.

The most precisely recognized of the above specified component factors determining the accuracy of the measurement of the total dust concentration with the use of the gravimetric method, for the need of calculating the overall uncertainty, are the factors specified in Points (b)/(iii), (b)/(iv), (c)–(f), (g), and (h). The issue of the representativeness of the averaged sample (Point (a)) is not described in detail in regulations and guidebooks and does not happen to be included in the global analysis of uncertainty budget, despite the fact that the – hard to assess – uncertainty component pertaining just to this factor may be quite high (Kateusz 2018). In addition, the issue described in Point (b)/(vi) is hard to take into account in practice. The uncertainty associated with the issue of the representativeness of the single-point sampling (Point (b)), if at all taken into consideration, is usually adopted arbitrarily, without any detailed analysis.

The subject of the present study is the source of the error of the total dust concentration recorded for the sample, noted in Point (b)/(ii), which is the fact of the occurrence of the industrially generated dust in a conduit in the form of a mixture of many particle size fractions. The determination of the representativeness of sampling at a given point of the location of the entry nozzle in the measurement plane, i.e. establishing how the total dust concentration measured in the drawn gas sample differs from the one really occurring at that point of the conduit, is only possible if information about the differentiation of the particle size fractions is known. Taking into account the measurement data from Points (b)/(i), (b)/(iii), and (b)/(iv), calculating the total concentration measurement error and eliminating it through relevant correction is performed by utilizing the possessed precise (or at least estimated) knowledge of the aspiration characteristics of the entry nozzle (Point (b)/(v)). This characteristic is the dependence of the aspiration efficiency on two parameters of sampling: the isokinetic rate and the Stokes number. By the aspiration efficiency we mean the ratio of the mass of a given particle fraction in the aspirated volume of gas to the actual mass of the given fraction in the same volume of gas in the conduit. It is also possible, while using this ratio, to operate on fractional mass concentrations. These or related characteristics for the typical shapes of entry nozzles, which are more or less universal or practical, at the beginning experimental, later also calculation-based, have been prepared, used and cited since the fifties of the past century (Badzioch 1960, Belyaev and Levin 1974, Fuchs 1975, Durham and Lundgren 1980, Liu et al. 1989, Grinshpun et al. 1990, Szulikowski et al. 1994, Hinds 1999, Szulikowski 1999, Vincent 2007, Brockman 2011, to mention only a few).

Unfortunately, in measurement practice, it is common that there is a lack of detailed information considering the properties of the sampled polydisperse dust. In routine measurements being carried out for regulatory purposes, the dust in the drawn sample does not undergo a laboratory conducted particle size distribution and density analysis, because there is no requirement to do so in the standard procedure. The knowledge of the dust parameters in this case is, at best, only approximate, acquired from other (if available) comparative documentary sources, e.g., technical specifications or measurement reports, regarding similar technologies, and thus similar flue gases. In this situation, a precise calculation of the described error of total dust sampling is not possible, resulting in this error mostly being either ignored or replaced by a relevant uncertainty overestimated with the assumption of considering only the heaviest possible particles.

The above described wrong state of affairs (i.e. very rough or, most often, without an estimation of the sampling-related uncertainty) exists both in practice and in written sources (EN ISO 2002, ISO 2003, EN 2007, VTT 2007, EA 2011, EA 2013, NPL 2014, EN 2017). There are no reports on how measurement teams have to take account of the sampling error (in the value of the measured total dust concentration) with the absence of detailed dust characteristics data – by means of an appropriate uncertainty component. The intention to remedy this situation was a motive to undertake the study described in this paper.

The goal of the undertaken study, described in this work, is a proposition of a more precise and easy assessment of the possible error in question and, in consequence, the corresponding uncertainty component of the measured total dust concentration, i.e. based on possible *actual* size distributions of particles in specific situations, both before and after the dust-removing devices, with the essential, governing sampling parameters taken into account. The research conducted has a simulation-calculation character. Firstly, a series of artificial cumulative undersize distributions have been created, representing the whole range of dusts that actually occur in the flue gases (Subsection "Simulated cumulative particle undersize distributions"). For those distributions, while making use of definite aspiration characteristics, specific for existing entry nozzles of a certain gravimetric sampler (Subsection "Aspiration characteristics"), a calculation was performed – according to dependences appropriate for polydisperse particulate matter (Subsection "Calculation of the sampling error") – of the error of the simulated sampling runs. In these calculations, different dust densities and isokinetic rates were considered. Observation of numerous obtained error values allowed quantitative determination of the uncertainty of total concentration measurement due to non-ideally representative sampling of different fractions contributing actual dusts when they are not fully recognized.

Materials and methods

Simulated cumulative particle undersize distributions

The following four general cases (groups) of dusts present in industrial process flue gasses were adopted, representing typical, substantially varying from one another, cases of gravimetric measurement:

I. Coarse (coarse-grained) dusts in conduits before dust collectors,
II. Fine (fine-grained) dusts in conduits before dust collectors,
III. Dusts in conduits (ducts and stacks) after the medium--efficiency dust collectors, and
IV. Dusts in conduits (ducts and stacks) after the high--efficiency dust collectors.

As a rule, nucleation mode particulate matter (e.g., one created in arc furnaces) was not taken into consideration here, because the size of the particles in this case (below 1 μm) renders the sampling error extremely small resulting in the issue described in this article not taking place.

In general, the above gas-borne dust groups differ from each other in terms of the range of particle diameters, e.g., before the dust collectors or on the outlet of the technological devices, the largest particles can be expected with a sedimentation diameter of hundreds of micrometres. After the medium-efficiency dust collectors, e.g., cyclones, the largest particles may be around 30 μm in size, and after the high-efficiency dust collectors, e.g., bag filters or electrostatic precipitators, around 20 μm. Within a given group, dusts particles also differ in terms of particle diameter distribution – depending on the technological process, and as for Groups III and IV, also depending on the performance of the dust-removing device.

Over sixty real examples of graphic images of particle size distributions (in the form of cumulative mass undersize curves) of dusts generated in various technological processes and found in various places in gas cleaning plants have been set and compared, corresponding to Groups I–IV. These images are obtained from either laboratory analysis conducted on various occasions at the author's workplace or from the literature (among others, Jarzębski and Kapała 1976, Rutkowski 1989, Głomba 1990, Karcz et al. 1992, Laudyn 1996, Jędrusik and Świerczok 1997, Hławiczka 2001, Konieczyński et al. 2003, Botor 2003, Tapola 2003, Melaniuk-Wolny et al. 2006). The set comprises dusts in flue gases of the following technologies (in their different variations): fuel combustion (miscellaneous coal and boilers), steelmaking (arc furnace, blast furnace, converter, electroslag remelting, etc.), the cupola process, the ferroalloy production process, iron ore sintering, zinc ore dressing, zinc smelting, lead refining, clinker burning, woodworking, coal cleaning, and the coke-making process.

Within each Group I–IV, certain characteristic and most common cumulative undersize distribution shapes were chosen and described using simulation functions as follows: each distribution (see Fig. 1) is one curve showing, according to the common definition, the dependence of the cumulative mass fraction X (dimensionless quantity in the range of 0 to 1) of particles smaller than a given particle on the equivalent free-falling (or sedimentation) diameter d (in µm) of this particle. Each curve is described by a pair of two component polynomial functions: the left and right ones, meeting in the point of mass median (d_{50}, $X = 0.5$). Three different left functions were adopted A, B, and C as well as three right ones D, E, and F. They are the result of suitable approximations and represent the above described shapes of actual cumulative particle size distributions with a given median d_{50} and a given maximum diameter d_{max}. The left functions spread in the domain of $<0, d_{50}>$, while the right functions in $<d_{50}, d_{max}>$, with the $X(d_{max}) = 1$ as the adopted necessary approximation assumption. The notations of the left and right simulation functions for the normalized arguments, i.e. d_{nl} for the left functions and d_{nr} for the right, are as follows (the coefficients have been rounded up):

Left functions:

$$X(d_{nl})_A = 1.2827\, d_{nl}^4 - 1.2945\, d_{nl}^3 - 0.29832\, d_{nl}^2 + 0.81012\, d_{nl} \tag{1}$$

$$X(d_{nl})_B = 1.5283\, d_{nl}^5 - 2.0597\, d_{nl}^4 + 0.57646\, d_{nl}^3 + 0.27921\, d_{nl}^2 + 0.17573\, d_{nl} \tag{2}$$

$$X(d_{nl})_C = 3.6379\, d_{nl}^6 - 4.5925\, d_{nl}^5 + 0.25165\, d_{nl}^4 + 1.8320\, d_{nl}^3 - 0.74225\, d_{nl}^2 + 0.11316\, d_{nl} \tag{3}$$

$$d_{nl} = \frac{d}{d_{50}} \tag{4}$$

Right functions:

$$X(d_{nr})_D = 0.046708\,(\ln d_{nr})^5 - 0.38655\,(\ln d_{nr})^4 + 1.2375\,(\ln d_{nr})^3 - 1.9185\,(\ln d_{nr})^2 + 1.4794\,\ln d_{nr} + 0.50001 \tag{5}$$

$$X(d_{nr})_E = -0.000011306\, d_{nr}^6 + 0.00047214\, d_{nr}^5 - 0.0080525\, d_{nr}^4 + 0.071743\, d_{nr}^3 - 0.35355\, d_{nr}^2 + 0.93768\, d_{nr} - 0.14828 \tag{6}$$

$$X(d_{nr})_F = -0.0000074945\, d_{nr}^6 + 0.00028953\, d_{nr}^5 - 0.0045092\, d_{nr}^4 + 0.036309\, d_{nr}^3 - 0.16356\, d_{nr}^2 + 0.44995\, d_{nr} + 0.18153 \tag{7}$$

$$d_{nr} = \frac{9}{d_{max} - d_{50}}\, d - \frac{10 d_{50} - d_{max}}{d_{max} - d_{50}} \tag{8}$$

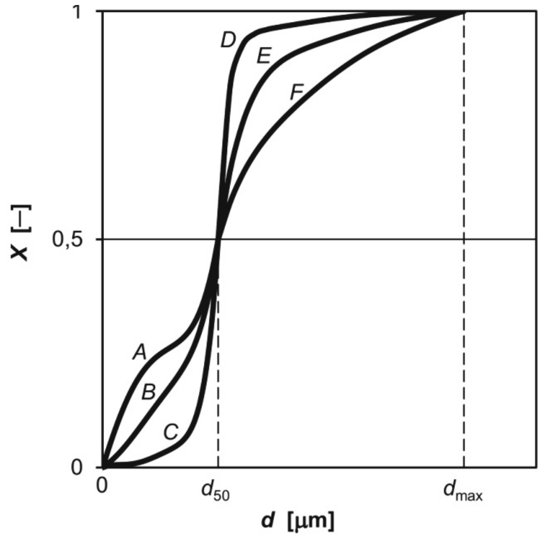

Fig. 1. The family of simulated cumulative particle size distributions $X(d)$: AF, BF, CF, AE, BE, CE, AD, BD, and CD, for a given median d_{50} and for a given maximum diameter d_{max}

All nine combinations of the above functions (1)–(3) and (5)–(7) have been built, yielding nine general shapes of dust particle size distributions, which can be labelled as AF, BF, CF, AE, BE, CE, AD, BD, and CD (Fig. 1). Those nine distributions constitute one family unambiguously defined by a particular and common pair of diameters (d_{50}, d_{max}). In each Group I–IV, three characteristic families of curves have been distinguished with the following pairs (d_{50}, d_{max}):

I:	$d_{50} = 40$ µm,	$d_{max} = 300$ µm
	$d_{50} = 120$ µm,	$d_{max} = 500$ µm
	$d_{50} = 200$ µm,	$d_{max} = 700$ µm
II:	$d_{50} = 4$ µm,	$d_{max} = 50$ µm
	$d_{50} = 22$ µm,	$d_{max} = 180$ µm
	$d_{50} = 40$ µm,	$d_{max} = 300$ µm
III:	$d_{50} = 4$ µm,	$d_{max} = 20$ µm
	$d_{50} = 8$ µm,	$d_{max} = 25$ µm
	$d_{50} = 12$ µm,	$d_{max} = 30$ µm
IV:	$d_{50} = 1$ µm,	$d_{max} = 14$ µm
	$d_{50} = 2.5$ µm,	$d_{max} = 17$ µm
	$d_{50} = 4$ µm,	$d_{max} = 20$ µm

As a result, each group of dusts covers 27 representative particle size distributions.

Aspiration characteristics

A certain gravimetric train with an automated function of maintaining isokinetic sampling conditions and with a pressure-balance-type sampling probe applied is produced in Poland. It has a thin-walled entry nozzle with a geometry consistent with standard regulations, which comes in a few variants of the inlet opening diameter d_s = 10, 13, 16, 20, and 25 mm. This nozzle was once the object of research carried out in the Department of Heating, Ventilation, and Dust Removal Technology of the Silesian University of Technology. Its aspiration characteristics were described in the form of a graph showing the discrete dependence of the aspiration efficiency on the Stokes number and the isokinetic rate (Szulikowski et al. 1994). This dependence was found based on the measurement-calculative (with the use of hot-wire anemometer technique) establishing of the gas velocity field in the region of the inlet of the entry nozzle, and then by the calculative establishing, based on the field mentioned, of the trajectory of the solid phase motion. At a later time, the discrete runs of the aspiration efficiency function were subjected to approximation (Szulikowski 1999, Kateusz and Szulikowski 2015), which resulted in the creation of the analytical version of the function expressed by Eq. 9 illustrated by Fig. 2. This formula was used in the described simulation research.

$$P = 1 + \left(\frac{1}{H} - 1\right)\left(1 - \frac{1 + a\mathrm{Stk}^{m}}{1 + b\mathrm{Stk}^{m+0.5} H^{n}}\right) - \frac{0.086\mathrm{Stk}}{\mathrm{Stk}^2 + 2.81\mathrm{Stk} + 0.358} \quad (9)$$

where P is the aspiration efficiency (Eq. 10), H is the isokinetic rate, Stk is the Stokes number (Eq. 11), and a, b, m, and n are the approximation constants, different in two H subranges.

$$P \overset{\mathrm{def}}{=} \frac{c_{fs}}{c_f} \quad (10)$$

$$\mathrm{Stk} = \frac{\rho d^2 w}{18 \mu_o d_s} \quad (11)$$

a = 0.026; b = 3.03; m = 0.473; n = 0.165 for H = 0.7–1,
a = –0.035; b = 1.51; m = 0.233; n = 3.08 for H = 1–1.3,

where c_{fs} is the fractional concentration of the dust particles with the diameter d in the aspirated sample (in the inlet opening of the entry nozzle), c_f is the fractional concentration of the dust particles with the diameter d in the conduit, ρ is the particle density, μ_o is the gas absolute viscosity, and w is the gas velocity in the conduit at the sampling point.

As for Eq. 9 and the former research mentioned above, which it originates from, it is worth paying attention to the following fact: for H = 1, the values of the aspiration efficiency P for the particles below a certain critical inertia (thus for small Stk numbers) turn out to be a little less than 1. They correspond to a very minute disturbance of the streamlines of gas flowing into the nozzle, and this disturbance is caused by a finite, very small thickness of the sharp edge of the slender inlet part of the nozzle, even during isokinetic sampling.

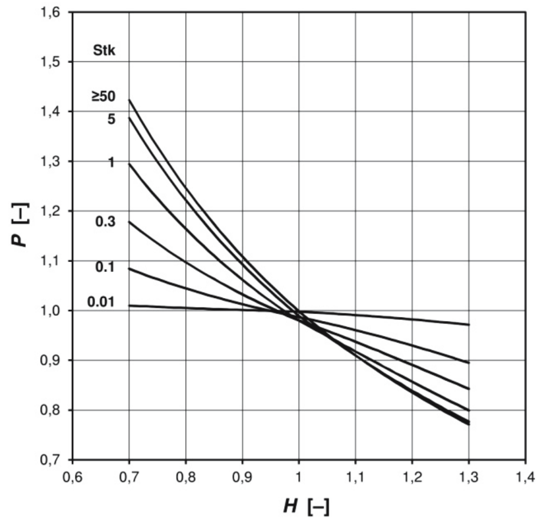

Fig. 2. Aspiration characteristics (of real entry nozzles) adopted for simulation calculations:
P – aspiration efficiency, Stk – Stokes number,
H – isokinetic rate

Calculation of the sampling error

The basis for the discussed calculations is the simulated knowledge of the particle size distribution of dust in gas flowing through a conduit, the parameters of the dust-laden gas, and the sampling itself.

The symbols are described as follows:

- c_s – total concentration in the aspirated sample (measured concentration),
- $c_{fs,i}$ – fractional concentration of the i-th fraction (with a representative particle diameter d_i) in the aspirated sample,
- c – total concentration in the conduit at the sampling point,
- $c_{f,i}$ – fractional concentration of the i-th fraction (with a representative particle diameter d_i) in the conduit at the sampling point,
- x_i – mass fraction of the i-th fraction (with a representative particle diameter d_i) of dust in the conduit, and
- i – order number of the dust fraction.

The following relationships occur:

$$c_s = \sum_{(i)} c_{fs,i} \quad (12)$$

$$c = \sum_{(i)} c_{f,i} \quad (13)$$

$$c_{fs,i} = P_i c_{f,i} = P_i x_i c \quad (14)$$

$$c_s = \sum_{(i)} P_i x_i c = c \sum_{(i)} P_i x_i \quad (15)$$

The measured total polydisperse dust concentration (occurring in the gas sample taken), c_s, differs from the actual concentration in the conduit c because of the specified efficiency of the sampling of the individual fractions P_i. We introduce a relative error of the total dust concentration measurement δ, which is, by assumption, referenced to the *measured* total dust concentration, which allows using the relative uncertainty also referenced to the measured concentration as the only one available. This error is called the sampling error here for simplification. Considering the above dependences, the following relation results:

$$\delta = \frac{c_s - c}{c_s} = 1 - \frac{c}{c_s} = 1 - \frac{c}{c \sum_{(i)} P_i x_i} \tag{16}$$

Out of it, the final equation (17) is derived, which is the key formula used in the simulation calculations:

$$\delta = 1 - \frac{1}{\sum_{(i)} P_i x_i} \tag{17}$$

Let us add a side note that, in real measurements, where the mass fractions in the taken sample $x_{s,i}$ are known, one should utilize the formula $\delta = 1 - \sum_{(i)} (x_{s,i}/P_i)$, which is equivalent to Eq. 17. In this situation, one can also, in the name of approximation, replace x_i with $x_{s,i}$ in Eq. 17. It is an absolutely acceptable approximation, not making any significant difference to the δ value obtained in this way.

It should be noted that the error that is described by Eqs. 16 and 17 is derived based on Formula 10 employing concentrations only when one, notionally separated, influence of anisokinetic conditions and particle inertia on the measured particulate matter mass concentration is under consideration. When a complete accuracy analysis of this concentration is performed, i.e. when the influence of the accuracy of the determination of the volume of the gas sample drawn is taken into account, the δ error is ascribed to the *mass* of the particulate matter present in the sample.

For the requirements of Eq. 17, each simulated size distribution was divided into 40 *i*-th fractions: 20 narrow fractions of equal width in the range of diameters from 0 to d_{50} and 20 other narrow fractions of equal width in the diameter range from d_{50} to d_{max}. Each fraction, with d_{i-1} and d_i at its ends, was assigned with a representative diameter $d_{r,i} = 0.5(d_i + d_{i-1})$. For the diameter $d_{r,i}$, Stokes number was calculated (according to Eq. 11) and finally P_i values (according to Eq. 10). All calculative fractions (d_i, d_{i-1}) had a small enough width (0.05 µm for the diameters d below 1 µm; 25 µm for diameters reaching 700 µm) that both the Stokes number and aspiration efficiency were practically the same for the individual values of d_i, d_{i-1}, and $d_{r,i}$. For the *i*-th particle fraction, from the polynomial curve of the cumulative composition (Functions 1–3 and 5–7), its mass fraction x_i was calculated as follows:

$$x_i = X(d_i) - X(d_{i-1}) \tag{18}$$

The calculations were performed for the following variables: three (out of five, which are described in Subsection "Aspiration characteristics") diameters of the inlet opening of the entry nozzle were chosen d_s: 10, 16, and 25 mm, and three variants of dust density values ρ encountered in the flue gas installations were assumed: 500 kg/m³, 1500 kg/m³, and 5000 kg/m³. They make for two density ranges: the rare 500–1500 kg/m³ and the common 1500–5000 kg/m³. They correspond to the ranges of the results of calculated sampling errors. For the actual samplings in industrial conditions, the values 0.95, 1.00, and 1.15 of the isokinetic rate H were accepted as typical. Numerous combinations of the above variables and, of course, of all the simulated dusts from Subsection "Simulated cumulative particle undersize distributions" were created.

A wide, real range of the viscosity of industrial flue gases was examined, i.e. roughly from 0.000016 N×s/m² to 0.000028 N×s/m². Calculation tests have been performed on the influence of viscosity on the error δ and the following result has been obtained. Adopting one mean value of viscosity, namely 0.000022 N×s/m², greatly simplifies the calculations, introducing discrepancies of the δ values that are small enough to be settled by an additional uncertainty component U_μ, which is equal to 0.1% for the δ values from –1% to 1% and 0.2% for the remaining δ values. A similar simplification has been done for the point velocity of gas w. Since each entry nozzle of a given diameter d_s operates on a definite range of the velocity w, the influence of the velocity on the error δ has been examined for individual nozzles. It turned out that, for a given diameter d_s, accepting one mean (median) velocity value from the nozzle-specific range greatly simplifies the calculations, introducing small enough discrepancies in the acquired δ values so that they can be settled by an additional uncertainty component U_w, equal to 0.4%. Nominal ranges of gas velocity and mean velocities (used for the calculations) are as follows for each entry nozzle:

For d_s = 10 mm, the gas velocity is 19–35 m/s, and the mean velocity is 27 m/s;

For d_s = 16 mm, the gas velocity is 7.5–14 m/s, and the mean velocity is 11 m/s; and,

For d_s = 25 mm, the gas velocity is 3–5.5 m/s, and the mean velocity is 4 m/s.

Results and discussion

The calculated sampling errors δ have been gathered in tables, according to the gravimetric dust measurement cases from Subsection "Simulated cumulative particle undersize distributions": coarse dusts in conduits before dust collectors, fine dusts in conduits before dust collectors, dusts in conduits after medium-efficiency dust collectors, and dusts in conduits after high-efficiency dust collectors, and a table for each of these cases was created in three different variants for three different H values. In a given table, the δ values are listed for a set of 27 different simulated particle size distributions, with two variants of dust density ranges ρ and with three variants of the entry nozzle diameter d_s. Due to the vastness of this material, only one exemplary table of the error δ results has been presented, namely for coarse dusts before a dust collector with the isokinetic rate of H = 0.95 (Table 1).

The following analysis of the error values δ was conducted. The results for an exemplary case of coarse dusts before dust collectors are presented in Table 2. Results were observed for a given H value, (e.g., in Table 1). For a certain value d_s and a certain range of ρ, a full variation range of 27 δ values was identified from the lower value δ_l to the upper δ_u (in Table 2, written as $\delta = \delta_l - \delta_u$). It turns out that this range was always asymmetric with respect to 0, with values both positive and negative, which means that a certain systematic error component occurs, and it originates from the asymmetry of the function $P = f(H, \text{Stk})$. It is included through a correction coefficient f corresponding to a mean value of error from its given range. It is calculated with Eq. 19:

$$f = 1 - \frac{\delta_u + \delta_l}{2} \tag{19}$$

What is left is the error dispersion around its mean value, within the range $\pm\Delta_{max}$:

$$\Delta_{max} = \frac{\delta_u - \delta_l}{2} \tag{20}$$

This dispersion has the character of a rectangular distribution, since all 27 simulative dusts are assumed to be equally probable. Thus, based on the value Δ_{max}, relative uncertainty U_δ has been calculated at a level of confidence of approximately 95% (with a coverage factor of 2) according to the formula valid also for rectangular distributions of error (JCGM 2008, Piotrowski and Kostyrko 2012, ECA 2013):

$$U_\delta = 2\Delta_{max} / \sqrt{3} \tag{21}$$

The uncertainty of the total dust concentration U has been calculated, with the above-mentioned additional uncertainties of the calculation method taken into account (the influence of which has proven to be, for the great majority of cases, unnoticeable).

$$U = \sqrt{U_\delta{}^2 + U_\mu{}^2 + U_w{}^2} \tag{22}$$

The results of the range of the error δ, the correction coefficient f, and the uncertainty U for the example of coarse dusts before dust collectors, for all three isokinetic sampling rates H, are presented in Table 2. Besides the two examined subranges of the dust densities 500–1500 kg/m³ and 1500–5000 kg/m³, additionally, δ, f, and U were established for the global range of density 500–5000 kg/m³ (the last column in the table). In addition, apart from three separately examined cases of the entry nozzle diameters, δ, f, and U were determined for the three diameters taken altogether (line entitled 'All the nozzles together'). In addition, δ, f, and U were established for a most general case, without dividing it into separate nozzle diameters, isokinetic rates, and subranges of the dust density (the last line in the table).

The complete presentation of the results of the performed calculations is provided in Table 3 and Figs. 3 and 4. Table 3 comprises the values of the coefficient f and uncertainty U for

Table 1. Relative error of total dust concentration δ for all simulated coarse dust particle size distributions before a dust collector, for different entry nozzle diameters d_s, medians d_{50} and particle densities ρ, with an isokinetic rate H = 0.95

d_s mm	d_{50} μm	ρ kg/m³	Error of total dust concentration δ, %								
			General shape of particle size distribution								
			AF	BF	CF	AE	BE	CE	AD	BD	CD
10	40	500–1500	3.30–3.82	3.36–4.21	4.00–4.54	3.21–3.78	3.53–4.17	3.90–4.50	3.07–3.73	3.40–4.12	3.77–4.45
		1500–5000	3.82–4.23	4.21–4.59	4.54–4.82	3.78–4.21	4.17–4.58	4.50–4.81	3.73–4.20	4.12–4.56	4.45–4.79
	120	500–1500	4.18–4.46	4.55–4.76	4.79–4.91	4.17–4.46	4.54–4.76	4.77–4.90	4.15–4.45	4.52–4.75	4.76–4.90
		1500–5000	4.46–4.67	4.76–4.88	4.91–4.96	4.46–4.67	4.76–4.88	4.90–4.96	4.45–4.67	4.75–4.88	4.90–4.96
	200	500–1500	4.44–4.64	4.75–4.87	4.90–4.95	4.44–4.64	4.75–4.87	4.90–4.95	4.43–4.64	4.74–4.87	4.89–4.95
		1500–5000	4.64–4.80	4.87–4.94	4.95–4.98	4.64–4.80	4.87–4.94	4.95–4.98	4.64–4.80	4.87–4.94	4.95–4.98
16	40	500–1500	2.45–3.15	2.61–3.45	2.89–3.81	2.21–3.03	2.38–3.33	2.66–3.69	1.93–2.87	2.09–3.17	2.38–3.54
		1500–5000	3.15–3.75	3.45–4.14	3.81–4.48	3.03–3.71	3.33–4.09	3.69–4.43	2.87–3.65	3.17–4.03	3.54–4.37
	120	500–1500	3.66–4.10	4.04–4.48	4.39–4.74	3.61–4.08	3.99–4.46	4.34–4.72	3.55–4.06	3.93–4.44	4.28–4.70
		1500–5000	4.10–4.43	4.48–4.74	4.74–4.90	4.08–4.42	4.46–4.73	4.72–4.89	4.06–4.41	4.44–4.73	4.70–4.88
	200	500–1500	4.07–4.38	4.45–4.71	4.72–4.88	4.05–4.38	4.43–4.70	4.70–4.87	4.02–4.37	4.41–4.69	4.67–4.89
		1500–5000	4.38–4.62	4.71–4.86	4.88–4.95	4.38–4.62	4.70–4.85	4.87–4.94	4.37–4.62	4.69–4.85	4.89–4.94
25	40	500–1500	1.42–2.19	1.44–2.32	1.53–2.55	1.06–1.92	1.08–2.04	1.17–2.28	0.69–1.60	0.71–1.72	0.80–1.96
		1500–5000	2.19–3.00	2.32–3.27	2.55–3.62	1.92–2.86	2.04–3.13	2.28–3.48	1.60–2.67	1.72–2.94	1.96–3.29
	120	500–1500	2.79–3.48	3.04–3.84	3.39–4.21	2.64–3.41	2.89–3.77	3.24–4.14	2.47–3.33	2.73–3.69	3.08–4.06
		1500–5000	3.48–4.01	3.84–4.40	4.21–4.68	3.41–3.99	3.77–4.37	4.14–4.66	3.33–3.96	3.69–4.35	4.06–4.63
	200	500–1500	3.41–3.93	3.77–4.32	4.14–4.62	3.34–3.91	3.70–4.30	4.07–4.60	3.26–3.87	3.62–4.26	3.99–4.56
		1500–5000	3.93–4.32	4.32–4.66	4.62–4.85	3.91–4.31	4.30–4.65	4.60–4.84	3.87–4.30	4.26–4.64	4.56–4.84

Table 2. Range of error δ, correction factor f, and uncertainty U of total dust concentration for the measurement before a dust collector, for coarse dusts

H	d_s mm	ρ = 500–1500 kg/m^3	ρ = 1500–5000 kg/m^3	Whole dust density range (500–5000 kg/m^3)
0.95	10	δ = 3.07% to 4.95% f = 0.960 U = 1.2%	δ = 3.73% to 4.98% f = 0.956 U = 0.8%	δ = 3.07% to 4.98% f = 0.960 U = 1.2%
	16	δ = 1.93% to 4.88% f = 0.966 U = 1.8%	δ = 2.87% to 4.95% f = 0.961 U = 1.3%	δ = 1.93% to 4.95% f = 0.966 U = 1.8%
	25	δ = 0.69% to 4.62% f = 0.973 U = 2.3%	δ = 1.60% to 4.85% f = 0.968 U = 1.9%	δ = 0.69% to 4.85% f = 0.972 U = 2.4%
	All nozzles together	δ = 0.69% to 4.95% f = 0.972 U = 2.5%	δ = 1.60% to 4.98% f = 0.967 U = 2.0%	δ = 0.69% to 4.98% f = 0.972 U = 2.5%
1.00	10	δ = –1.08% to –0.03 % f = 1.006 U = 0.7%	δ = –0.68% to –0.02 % f = 1.004 U = 0.6%	δ = –1.08% to –0.02 % f = 1.006 U = 0.7%
	16	δ = –1.80% to –0.01 % f = 1.009 U = 1.1%	δ = –1.21% to –0.04 % f = 1.006 U = 0.8%	δ = –1.80% to –0.01 % f = 1.009 U = 1.1%
	25	δ = –1.97% to –0.30 % f = 1.011 U = 1.1%	δ = –1.94% to –0.11 % f = 1.010 U = 1.1%	δ = –1.97% to –0.11 % f = 1.010 U = 1.2%
	All nozzles together	δ = –1.97% to –0.01 % f = 1.010 U = 1.2%	δ = –1.94% to –0.02 % f = 1.010 U = 1.2%	δ = –1.97% to –0.01 % f = 1.010 U = 1.2%
1.15	10	δ = –14.93% to –12.52 % f = 1.137 U = 1.5%	δ = –14.97% to –13.33 % f = 1.142 U = 1.0%	δ = –14.97% to –12.52 % f = 1.137 U = 1.5%
	16	δ = –14.85% to –10.95 % f = 1.129 U = 2.3%	δ = –14.92% to –12.28 % f = 1.136 U = 1.6%	δ = –14.92% to –10.95 % f = 1.129 U = 2.3%
	25	δ = –14.72% to –8.02 % f = 1.114 U = 3.9%	δ = –14.83% to –10.36 % f = 1.126 U = 2.6%	δ = –14.83% to –8.02 % f = 1.114 U = 4.0%
	All nozzles together	δ = –14.93% to –8.02 % f = 1.115 U = 4.0%	δ = –14.97% to –10.36 % f = 1.127 U = 2.7%	δ = –14.97% to –8.02 % f = 1.115 U = 4.0%
Irrespective of isokinetic rate (i.e. ranging in total from 0.95 to 1.15), nozzle diameter (i.e. ranging in total from 10 to 25 mm) and dust density (i.e. ranging in total from 500 to 5000 kg/m^3): δ = –14.97% to 4.98 %; f = 1.050; U = 11.5%				

Table 3. Range of error δ, correction factor f, and uncertainty U of total dust concentration, irrespective of isokinetic rate, entry nozzle diameter and dust density

Case	δ, %	f, –	U, %
Before a dust collector; coarse dust	–14.97 to 4.98	1.050	11.5
Before a dust collector; medium dust	–14.81 to 4.82	1.050	11.3
After a medium efficiency dust collector	–14.37 to 3.71	1.053	10.4
After a high efficiency dust collector	–11.79 to 1.78	1.050	7.8

the most general case, i.e. without dividing it to separate nozzle diameters, isokinetic rates, and subranges of the dust density. Fig. 3 graphically illustrates the continuous variation *f*(*H*) at different d_s's and *ρ*'s for all the cases of particulate matter, i.e. coarse dusts in conduits before dust collectors, fine dusts in conduits before dust collectors, dusts in conduits after medium-efficiency dust collectors, and dusts in conduits after high-efficiency dust collectors. Analogous variation *U*(*H*) is presented in Fig. 4.

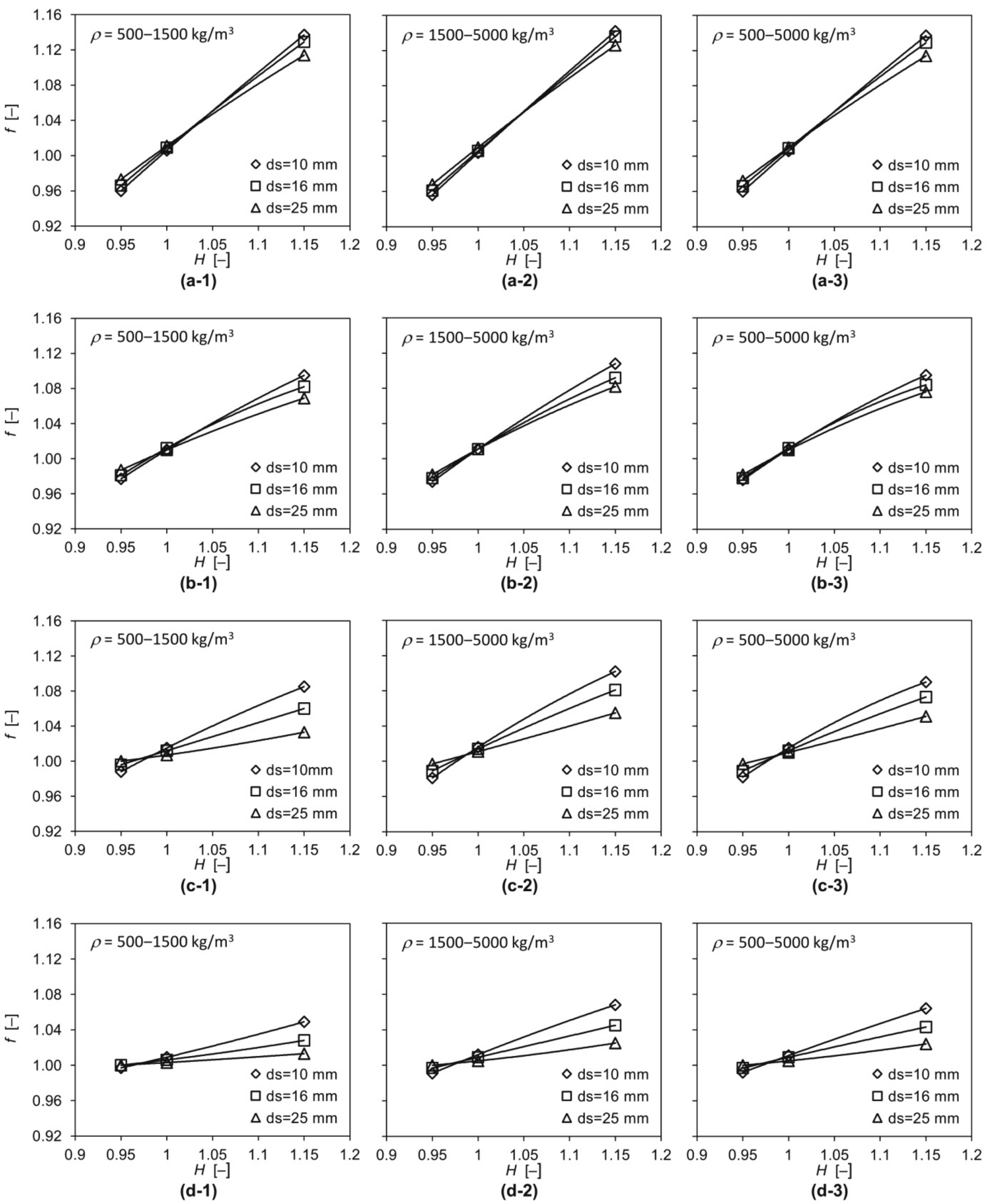

Fig. 3. Correction factor *f* for total dust concentration varying with the isokinetic rate *H*, at different entry nozzle diameters d_s: (1) Dust density from the range of 500–1500 kg/m³, (2) Dust density from the range of 1500–5000 kg/m³, (3) Dust density from the range of 500–5000 kg/m³, (a) Coarse dust in the flue gas before a dust collector, (b) Medium dust in the flue gas before a dust collector, (c) Dust in the flue gas after a medium-efficiency dust collector, (d) Dust in the flue gas after a high-efficiency dust collector

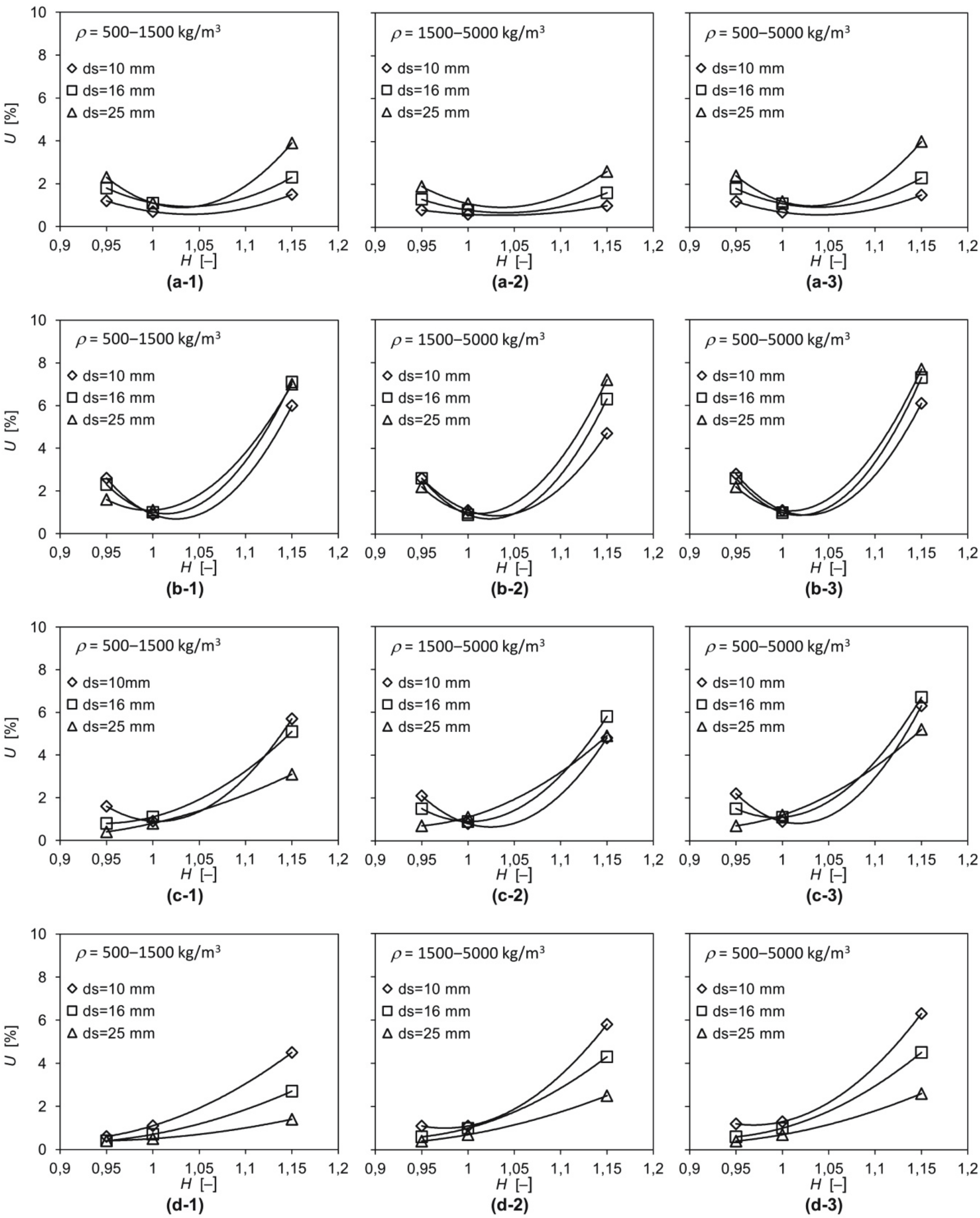

Fig. 4. Uncertainty U for total dust concentration varying with the isokinetic rate H, at different entry nozzle diameters d_s: (1) Dust density from the range of 500–1500 kg/m³, (2) Dust density from the range of 1500–5000 kg/m³, (3) Dust density from the range of 500–5000 kg/m³, (a) Coarse dust in the flue gas before a dust collector, (b) Medium dust in the flue gas before a dust collector, (c) Dust in the flue gas after a medium-efficiency dust collector, (d) Dust in the flue gas after a high-efficiency dust collector

A commentary to Fig. 4: according to theoretical considerations and all models of the aspiration characteristics, the maximum difference between the measured concentration and the actual one, at the anisokinetic sampling, occurs for the particles with the highest inertia. For practical reasons, particles may be considered as such if the Stokes number is greater than about 30 (at lower requirements of accuracy of such arrangements, this critical Stokes number may be even less). In that case, the curve of aspiration efficiency, dependent on the isokinetic rate, takes the shape of a hyperbole $P = 1/H$, and the correction coefficient is $f = H$. It can be seen in Fig. 3 that the obtained values of f are more realistic in comparison to the ones arising from the relationship $f = H$, which would be an exaggerated estimation with no data concerning the dust particle size distribution. Obviously, this is most visible for the fine polydisperse dusts, i.e. in the case of measurements done after the high-efficiency dust removal devices [Graphs (d)]. For example, for the density range of 500–5000 kg/m³, for a subisokinetic sampling $H = 0.95$, the obtained correction coefficient ranges from 0.992 to 1.000 (depending on the entry nozzle used), while the estimated, excessive downwards coefficient would be equal to 0.95. For a superisokinetic sampling $H = 1.15$, the obtained correction coefficient is 1.024–1.064, while the estimated, excessive upwards coefficient would amount to 1.15.

The general interpretation of the achieved results is as follows: if a given gravimetric measurement (performed with the use of entry nozzles mentioned in Subsection "Aspiration characteristics"), for which a precise identification of particle size composition and density of the gas-carried dust has not been made, results in obtaining a total dust concentration value c_s, this value needs to be corrected – in order to get the real concentration c, and the uncertainty due to the lack of above-mentioned data needs to be taken into account according to the following:

$$c = f c_s \pm U \qquad (23)$$

It is obviously the simplest way to look at this issue (i.e. as if other factors influencing the value c were not considered). In practice, one should reach the corrected concentration by the notation $c = f c_s$, and the uncertainty U discussed here should be included as a component of an entire uncertainty budget alongside other uncertainty components attributed to all other occurring factors.

Five examples of how Figs. 3 and 4 and Table 3 can be utilized are given below, together with a commentary of observed regularities.

(i) A sample of a dust-laden gas was taken from a conduit after a medium-efficiency dust collector, and the resultant isokinetic rate was equal to 1.12. Only one entry nozzle was used, and it had a diameter of 16 mm. The dust is known to have the density of the order of 2500–3500 kg/m³. Using Fig. 3 [Graph (c-2)] and Fig. 4 [Graph (c-2)] suitably enlarged, we find that the measured total dust concentration should be multiplied by a coefficient of 1.068, and an uncertainty of 4.0% should be introduced into the uncertainty budget.

(ii) A dust-laden gas was sampled from a conduit before a dust collector, and the resultant isokinetic rate was 0.95. Due to a quite non-uniform high gas velocity profile across the sampling plane, three entry nozzles were used: 10 mm, 13 mm, and 16 mm. The technology is known well enough to assume that the density of the emitted dust is at the level of 900–1200 kg/m³ and the dust itself is from the category of the coarse-grained dusts (with particles up to 500 μm and even bigger). When using a few nozzles, the following regularities appear, which were noticed in all of the prepared detailed table specifications: (1) the correction coefficient is, with a sufficient approximation, equal to the mean for all of the considered nozzles; and, (2) uncertainty is slightly higher than the highest uncertainty among all of the considered nozzles, i.e. by 0%–0.2% for the level of $U < 4\%$ and by 0.3%–1.8% for the level of $U = 4\%–8\%$. The following necessary coefficients and uncertainties were read off from two Graphs (a-1) in both figures, for the nozzles 10 mm and 16 mm, respectively: 0.960 and 1.2%; 0.966 and 1.8%. According to the above-mentioned regularities, it was established that $f = 0.963$ and $U = 1.9\%$.

(iii) The measurement plane was located in a stack. The dust-removing device, operating in the plant, is considered a high-efficiency one. The particulate matter is a mixture of different substances with diversified densities ranging from around 1000 kg/m³ to around 3000 kg/m³. One 20 mm entry nozzle was used for the measurements, and the isokinetic rate was maintained on an average level of 1.07. With use of the interpolation of curves for nozzles of 16 and 25 mm, Graphs (d-3) indicate that the correction coefficient is equal to 1.019 and the uncertainty component required for the uncertainty budget is equal to 1.8%.

(iv) If we assume that the gravimetric sampling is a method in general, then an analysis may be conducted in advance, even before a given measurement is performed. Therefore, let the object of interest be, for example, a fully isokinetic sampling with a chosen sampling place location in the dust removal plant, for example, after the medium-efficiency dust collectors, while the size of the nozzles and the density of dust is not considered. In this case, we can determine the parameters of sampling accuracy based on Graphs (c-3) and with the use of regularities from (ii). The graphs indicate that correction coefficients for all nozzles are equal to 1.015, 1.012, and 1.010, and the highest uncertainty equals 1.2%. Therefore, the final parameters are $f = 1.012$ and $U = 1.3\%$. Parameters established in this way correspond, with sufficient accuracy, to the calculated data contained in the line "All the nozzles together" in the table specifications.

(v) Let there be a similar analysis conducted as in (iv), but with an even greater degree of generalization, i.e. without the detailed anticipation of the dust density (in the range 500–5000 kg/m³) and the isokinetic rate (0.95–1.15), and which nozzle size would be in use. This analysis is a general assessment of the accuracy of the gravimetric method when there is a lack of detailed characteristics of the dust sampled. Based on the content of Table 3, we can state that the measured total dust concentration should be multiplied by a correction coefficient rounded to 1.05 and that the uncertainty component of 7.8%–11.5% should be taken as real, depending on the location of the sampling site.

Conclusions

1. The calculations conducted make it more realistic to perform the analysis of the particulate sampling accuracy in a conduit of a dust-removing plant in gravimetric

measurement in the common situation of lacking detailed information concerning the granulometric composition and density of the dust. In this situation, a correction of the measured total dust concentration is proposed to be applied along with introducing an uncertainty component due to the above-mentioned lack of data to the uncertainty budget.

2. A correction coefficient and uncertainty in the range of 0.956–1.142 and 0.4%–8%, respectively, were obtained. They are relevant to the simulated measurements and depend on the following: (a) the general classification of the dust in a flue gas, i.e. either as coarse-grained dust before a dust collector, or fine-grained dust before a dust collector, or dust after a medium- or high-efficiency dust collector; (b) the rough assessment of the dust density range; (c) adopting a certain isokinetic rate that took place during the measurement; and, (d) the size of the entry nozzle used. The calculations are valid for definite entry nozzles (geometrically consistent with standards) of a certain, actual existing gravimetric system. The above values of the discussed uncertainty component, resulting from generally incomplete knowledge of the granulometric composition and density of dust, are sometimes small and inconsequential. However, in other cases, the values are high and consequential and should be taken into account in the overall accuracy analysis of dust measurements in ducts and stacks.
3. Additional values of the correction coefficient and uncertainty component under consideration have been obtained for the sake of specific, broader analysis, i.e. for the undetailed assessment of the gravimetric sampling technique as a concrete method, by considering the entire potential real ranges of the isokinetic sampling rate (according to standards), dust density, and the size of the nozzles used (as the whole set). In these circumstances, one can use a correction coefficient equal to 1.05 and an uncertainty component of 10±2%.
4. The results, in the form of the correction coefficient f and the uncertainty component U, obviously depend on the utilized aspiration characteristics model $P = f(H, \mathrm{Stk})$ and on the method of simulating the particle size distributions. The investigation suggests that the sets of simulated dusts characteristics generated in this research are acceptable representations of conditions in dust-removing installations. One can imagine other analogous calculations with the same simulated dusts but with other aspiration characteristics (also appropriate for thin-walled standard entry nozzles) applied. Data obtained in this way, undoubtedly with similar values to those obtained by the described calculations, also will be a good base for a more reliable assessment of the sampling accuracy of a polydisperse dust in gravimetric measurement with limited knowledge of the dust characteristics.

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Specyficzna niepewność poboru pyłu polidyspersyjnego w grawimetrycznych pomiarach stężenia pyłu w kanałach

Streszczenie: Celem pracy było wyznaczenie składnika niepewności grawimetrycznego pomiaru masowego stężenia pyłu całkowitego w gazach odlotowych odpowiadającego za nie w pełni zidentyfikowany pobór pyłu mający miejsce, gdy nie są dokładnie znane: jego skład frakcyjny i gęstość. Wykonano obliczenia symulacyjne poborów próbki zapylonego gazu. Przyjęto zróżnicowane składy frakcyjne pyłów pogrupowane w cztery typy oddające realne pyły w instalacjach gazów odlotowych: I. gruboziarniste przed odpylaczami, II. średnioziarniste przed odpylaczami, III. za odpylaczami średnioskutecznymi, IV. za odpylaczami wysokoskutecznymi. Przyjęto, iż pobór próbki gazu realizowany jest przy pomocy końcówek aspiracyjnych o znanej charakterystyce zasysania. Obliczono wartości błędu stężenia całkowitego odnotowanego w pobranej próbce dla dwóch zakresów gęstości pyłu, przy zmiennych: stopniu izokinetyczności i średnicy końcówki aspiracyjnej. Na podstawie rozkładów uzyskanych wartości błędu ustalono niepewność pomiaru stężenia całkowitego uzależnioną od danych pomiarowych: zakresu gęstości pyłu, typu pyłu, stopnia izokinetyczności i wielkości końcówki aspiracyjnej. Wyznaczono także towarzyszący niepewności niezbędny współczynnik korekcyjny zmierzonego stężenia. Sporządzono graficzne postaci zmienności niepewności i współczynnika. Ich wartości odczytuje się w zależności od dysponowanych danych pomiarowych. Dla zidentyfikowanych pomiarów niepewność wynosi 0,4–8%. Dla metody grawimetrycznej jako całości, bez rozpatrywania szczegółowych przypadków pomiarowych, niepewność wynosi ok. 10±2%. Generalnie: w pomiarach grawimetrycznych zapylenia gazów odlotowych, w sytuacjach braku szczegółowych informacji o składzie frakcyjnym i gęstości pyłu można szacować składową niepewność pomiaru masowego stężenia pyłu całkowitego z tytułu braku powyższych danych na 0,4–11,5%, a więc w pewnych przypadkach na wysokim poziomie. Składnik ten powinno się wprowadzać do budżetu końcowej niepewności.