Bulgarian Chemical Communications, Volume 49, Number 3, (pp. 589 – 594) 2017

Characterization of aerodispersed systems with increased concentration according to the kinematic viscosity and mass density of their aerosol phase

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Received October 28, 2016; Revised March 22, 2017

Aerodispersed systems, hereinafter referred to as aerosols are an integral part of the natural environment of man. Such are the condensation clouds and fogs, dust clouds in deserts and those caused by volcanic activity. Aerosols are widely used in industry, agriculture, medicine, military science. Therefore, the study of their properties is an essential necessity. If the concentration of their aerosol phase is increased, they possess certain physical properties similar to those of liquids, for example the ability to flow.

The current work offers a laboratory method for the determination of the kinematic viscosity and mass density of concentrated aero dispersed systems formed in a limited volume. This method is based on measuring the time required for a certain amount of aerosol to flow out through a calibrated outlet pipe under the influence of its own hydrostatic pressure. This method uses the Poiseuille's law and the equation of continuity. The time needed for the aerosol to flow out is determined by monitoring its upper borderline "aerosol–air" using a laser system and photoelectric sensors and is based on the scattering of laser light by the aerosol.

Keywords: aerosols, kinematic viscosity, mass density, limited volume, laser beam scan

INTRODUCTION

Dispersion state is the ground state of matter, because most of the substance of the universe is in powder form. We find this thought in the preface to the Russian edition of the Reist monograph [1]. Today, although that statement is disputed, no one can deny the important role of aerosols in human life. Here at terrestrial conditions, we are daily confronted with the wide variety of aerosols – eg. starting from atmospheric aerosols (clouds, fog), on which depends the life of organisms and ending with household aerosols (smoke, dust, steam).

The term "aerosol" is proposed by Donian in the end of World War I [2]. Independently Schmauss used the same term and the first article in which the word "aerosol" was used belongs to him [3].

The aerodispersed systems also called aerosols are mixtures of suspended solid or liquid particles (dispersed phase) in a carrier gas often air [1, 2, 4, 5]. An object of study are aerodispersed systems having a particle diameter of the disperse phase in the range of 1 nm to 1 mm [4]. For the researchers in this area the case when the size of the particles is between 10 nm and 100 μm is of greatest interest [1]. In cases when the particles are smaller, i.e., tent to molecular dimensions their study is the subject of molecular physics. When the size of the particles is significantly larger, the aerosols have a very short life because of the rapid sedimentation and their study is of no interest. Also depending on the dispersibility the nature of the laws describing aerodispersed systems is also changing [4].

It's obvious that investigating the aerodispersed state of matter is essential for human activity. Therefore, in the middle of the twentieth century a new science was established – Nanoparticle Aerosol Science and Technology (NAST) [6]. It evolved on the foundations laid by numerous scientists working in different areas. The aerosol science history edited by Preining and Davis [7], casts a glance at the events, people and organizations which transformed the aerosol science to the internationally acknowledged state it has today in scientific communities.

Today, in the early 21st century the object of study of aerosol science is comprehensive – from the environment in which the humanity lives and works to space (meteorite, interplanetary and galactic dust) [2]. Broadly speaking, the subject of study are the characteristics and laws of the behavior of aerodispersed systems. Their gas medium is characterized by parameters such as temperature, pressure, free path of molecules etc. Most often it is air whose composition and properties are studied to the highest level. Special interest is provoked by the fact that the properties

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of aerosols differ from those of air, where they are formed. The properties of aerosols are largely determined by the dispersed phase – size, shape and composition of particles [1]. In polydispersed aerosols the functions of size distribution and particle mass are also important.

Aerosols are generally characterized by several basic macrophysical parameters. Among them the mostly applied in practice are the viscosity and mass density. They determine the behavior of aerosols in physical reactions taking place in the industry, radiation balance on earth, agriculture, health effects, light scattering, etc. Therefor these two parameters applied to concentrated aerodispersed systems are examined in this study. This type of aero systems is also known as Aerodispersed Systems of Limited Volume (ASLVs).

The concept for ASLVs was introduced for the first time by Fuchs [4] in studying the denotation of aerosol systems formed under laboratory conditions in opened containers, where the volume was limited by the walls of the container and a horizontal aerosol–air border. This condition was described first by Regener [8] and can also be observed in nature too, for example, mist in a valley field [4].

We carried out the ASLVs kinematic viscosity and mass density measurements, that are based on the presence of hydrostatic pressure (in these systems) and take place in the case of the aerosol's flowing out from the container (in which it has been formed) through a calibrated pipe in the bottom of the container. Assuming that the stream flows under the Poiseuille's law, we derived a set of equations for the kinematic viscosity and mass density of ASLV [9–11].

BASIC EQUATIONS AND EXPERIMENTAL SETUP

Figure 1 shows our experimental setup [9, 11, 12]. The aerosol is formed in a chamber for initial aerosol formation 2. Using peristaltic pump (smoking machine) 3 the aerosol is transfered to aerosol chamber 1 (of section *S*) through tube 4 (about 35s, until full). The calibrated exit tube 5 of length ℓ and diameter 2*r* is closed (not shown). When opened, the aerosol starts to flow out and the upper borderline aerosol–air descends. The laser beam (laser 6, mirror 7) travels by the cylinder‘s longitudinal axis. Photosensors 8 register only the lights scattered by the aerosol in horizontal direction (90°). The signals are processed by electronic block 9, which consists of DC amplifiers, triggers and a logical unit. A Personal Computer 10 records the moment of crossing the upper aerosol–air border line through each of the photosensors. The final results are processed, visualized and recorded.

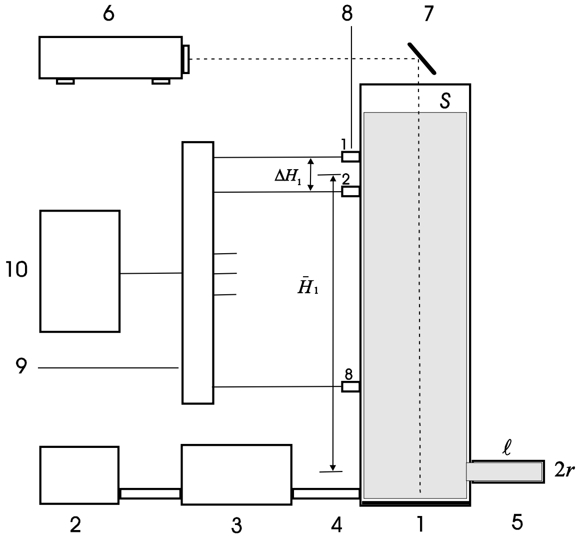


Fig.1. Scheme of the experimental setup: where 1 is an aerosol chamber, 2 container for initial aerosol formation, 3 peristaltic pump, 4 entry to the chamber, 5 calibrated exit tube, 6 laser, 7 mirror, 8 photo sensors, 9 electronic block, 10 PC.

To determine the position of the upper aerosol borderline in the course of time, we used the method of laser light scattering at angle of 90° with respect to the beam followed by detection of the scattered light using photosensors [13]. The methods related to using laser light for scanning have shown their advantages long ago [14]. Therefore in our study we used those methods and further developed them. This led to significant reduction of the setup uncertainty 5% and allowed the use of optoelectronic device [13].

In our setup we used a transperant Polymethyl methacrylate (PMMA) cylinder, 30 mm in diameter as an aerosol chamber. The exit tube's (also made of PMMA) length is $\ell = 30$ mm and has a diameter $2r = 8$ mm. The installation constant is $b = 4.65 \times 10^{-5}$ m^2/s^2.

In the presented experimental setup the flow changes direction by 90° when moving from the aerosol chamber to the calibrated exit tube. Therefore determining the Stokes number St in this case is of interest. The Stokes number is the ratio of the stop distance (the product of the characteristic time τ and the fluid velocity u_o) to a characteristic length scale of the flow L. [15]

$$\mathrm{St} = \frac{\tau u_0}{L} = \frac{D_p^2 \rho_p C_c u_0}{18 \mu L} \qquad (1)$$

In (1) D_p is the particle diameter, ρ_p the particle density, C_c the slip correction factor and μ the gas viscosity (air).The Stokes number is $\approx 10^{-4}$–10^{-6} <<

1, therefore the particles are accurately following the change in direction of the flow.

We use 8 sensors (phototransistors), spaced of 30 mm from each other, the first one being 30 cm above the exit tube. After filling the chamber, we let the aerosol stay for 1 min (time retention t_r) before the outflow. We used a He–Ne laser with unpolarized light and power of 5 mW for scanning the aerosol border line.

The aerosol flows in a laminar manner according to Poiseuille's law. The Reinold’s number when the aerosol is flowing out through the calibrated exit pipe is Re ≤ 1. The stream inside the aerosol chamber has Re << 1 and these sedimentation of the individual particles $\mathrm{Re} \approx 10^{-7}$.

If we examine the case in which the upper aerosol–air borderline descends from the level of photosensor 1 to the level of photosensor 2 for a time Δt_1. The volume change V_1 of the aerosol is

$$V_1 = S\,\Delta H_1\,. \qquad (2)$$

For the same ammount of time (Δt_1) the volume V_2 of aerosol that flows out trough the calibrated exit pipe, according to Poiseuille’s law is

$$V_2 = \frac{\pi r^4 \nabla p}{8\eta_1 \ell} \nabla t_1\,. \qquad (3)$$

Because of the aerosol’s incompressibility and the principle of continuity we can assume that $V_2 = V_1$.

The pressure difference Δp is caused by the aerosol’s own hydrostatic pressure. If we assume that during the period in which the aerosol flows between two neighbouring photosensors (in the order of few seconds) the aerosols density will be roughly constant, than the hydrostatic pressure should be

$$\Delta p = \rho_1 g \bar{H}_1\,. \qquad (4)$$

After equalizing equations (1) and (2) and taking in account equation (3), we obtain the kinematic viscosity of ASLV in the form

$$\nu_1 = b\,\frac{\bar{H}_1}{\Delta H_1}\,\Delta t_1\,, \qquad (5)$$

where $b = \pi r^4 g/8S$.

We obtain the same values for the kinematic viscosity of ASLV in cases when the aerosol–air border line is passing through all the other photosensors. For example, in the case of complete flow out of the examined aerosol through all of the eight photosensors (the time required for the aerosol to travel the distance between photosesors 1 to 8 is 8 to 60 seconds, depending on it’s concentration) we will get 7 (roughly equal) values for it’s kinematic viscosity. They can be used as an essential physical parameter discribing the aerosol in the moment of measuring.

Unlike liquids, the viscosity and density of aerosols are constantly changeing over time, because of the undergoing processes of sedimentation, coagulation, evaporation through the aerosol–air border, precipitation on the walls of the chamber, etc. Therefore, it is logically to express the aerosols parameters as a function of time. Thereby we obtaing the following summarized equation for determining the kinematic viscosity of aerosols (ASLV) by the fluid flow method

$$\nu(t) = \frac{\eta(t)}{\rho(t)} = b\,\frac{\bar{H}}{\Delta H}\,\Delta t\,. \qquad (6)$$

According to the well-known Einstein’s equation for the dynamic viscosity of dispersed systems [16]

$$\eta = \eta_0(1+2.5\varphi)\,, \qquad (7)$$

where η is the dynamic viscosity of the dispersed system, η_0 the dispersed medium (air) and φ the volume fraction of the dispersed phase. For the total volume of the aerosol particles (in the case of tabacco smoke) in 1m^3 we get $\approx 10^{-6}$ m^3. Therefore $\varphi \approx 10^{-6}$. We can then neglect the second term in equation (7) to obtain $\eta \approx \eta_0 = 1.80 \times 10^{-5}$ Ns/m^2 [17].

We can assume that the last assessment can be applied to other ASLVs systems we examined. If η is replaced by η_0 in equation (6), one obtains the following equation for the mass density of the aerodispersed phase

$$\rho(t) = \frac{\eta_0}{\nu(t)} = \frac{1}{b}\frac{\Delta H}{\bar{H}}\frac{\eta_0}{\Delta t}\,. \qquad (8)$$

Equation (8) allows us to determine the density of the aerosol phase ρ if we assume that the dynamic viscosity η of the aerosol system is roughly equal to the dynamic viscosity of air η_0 ($\eta \approx \eta_0$) and we measure the time Δt needed for the upper border line to decrease with ΔH.

EXPERIMENTAL RESULTS

We conducted measurements of the kinematic viscosity and mass density of different ASLVs under laboratory conditions – smoke from different types of cigarettes, smoke produced by sublimation and condensation of solid and liquid substances and also screening smokes. The aerosol’s phase particles have a very small size and vastly high concentration. Indeed their parameters vary to some extent, depending on the conditions of their formation.

The results of the kinematic viscosity and mass density of several types of aerosols (ASLVs) we have obtained are shown in Table 1. Each of the results listed is an average of 7 experimentally obtained viscosity values (for 7 different volumes of the aerosol) and t_r = 1 min. The experiments were carried out under standard laboratory conditions and atmospheric pressure of 970–980 hPa. On line 6 we have shown, for comparison, the kinematic viscosity and density of air at 20°C and normal atmospheric pressure [17].

From the results shown, it is clear that the kinematic viscosity of the limited volume aerosols is one or two orders higher than the one of air. Similarly the values of mass density are one or two orders of magnitude smaller.

In Figure 2 are shown the relations of kinematic viscosity (1-a) and the mass density of the aerosol phase (1-b) of ASLVs of the retention time (t_r) from 0 min (when the aerosol is released to flow immediately after filling the aerosol chamber) to 10 min, at 1 min intervals. We used smoke produced by burning cigarettes of different brands (we show only 3) using a peristaltic pump. Moreover, we had the opportunity to fill the aerosol chamber with each cigarette three times. From the 8 photosensors are obtained 7 values. That`s why any point of the graph corresponding to a certain retention time is determined based on 21 values. Relations after results aproximation, give us the reason to consider them as linear, but with fluctuations exceeding the relative error of 5%.

The resulting relationships show that the smoke of cigarettes with lower tar content and better quality filters has a lower density, in analogy with the higher viscosity (in the case Stuyvesant). The reduction of density, similarly the increase in viscosity with the increase of t_r is caused by the loss of mass in the process of evolution. We received similar dependencies with other tested cigarette brands.

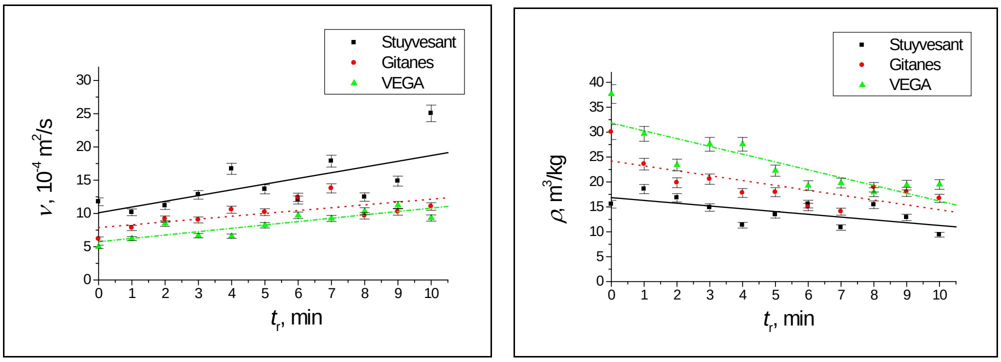
We propose to characterize the change of density (also similarly viewed the change of viscosity) of the aerosol system according to the t_r by different volumes (heights from the bottom of the container), using a *density distribution function* (the same concerns the viscosity distribution function) defined by the following equation

$$f_i = \frac{W_i}{\Delta\rho_i} = \frac{N_i}{\sum N_i}\frac{1}{\Delta\rho_i}\ , \qquad (9)$$

where N_i is the number of the values obtained experimentally in the range $\Delta\rho_i$, ΣN_i is the total number of values. $\Delta\rho_i = \Delta\rho$ = const are the steps in density change (the same for viscosity) that are constant in our experiment. We call this function (f_i) *spectrum of the condition of the aerosol system*. This is a common feature of ASLVs and includes a set of all density values (number 231). They were obtained during its evolution.

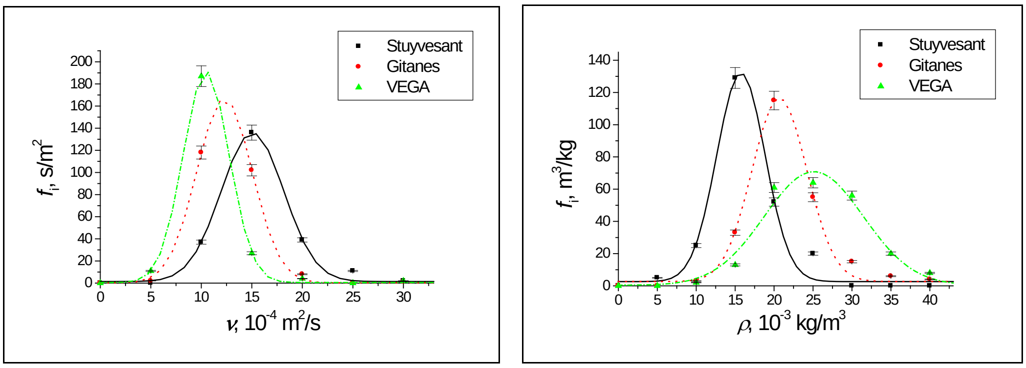
Table 1. Values of thekinematic viscosity and mass density of several types of aerosols (ASLVs) obtained by the described method

	Aerosol type	ν, 10^{-4} m^2/s	ρ, 10^{-3} kg/m^3
1	Cigarette smoke – Stuyvesant	14.4 ± 0.8	14.1 ± 0.4
2	Cigarette smoke – Gitanes	10 ± 0.3	19.3 ± 0.5
3	Cigarette smoke – VEGA	8.3 ± 0.3	24 ± 0.8
4	Paraffin vapour	3.9 ± 0.2	46 ± 1.4
5	Screening smoke – white	5.3 ± 0.2	33 ± 1.4
6	Air (at 20°C)	0.15	1200



(a) (b)

Fig. 2. Change of viscosity ν (a) and density ρ (b) of ASLVs when the retention time t_r increases.



(a) (b)

Fig.3. Spectra of state obtained from the values of the kinematic viscosity (2-a) and the mass density of the aerosol phase (2-b) of ASLVs, obtained from the smoke of three brands of cigarettes.

Table 2. Parameters of the spectrums of the status obtained from the values of the mass density of the aerosol phase, characterizing ASLVs

	Parameters		Cigarettes	
		Stuyvesant	Gitanes	VEGA
1	$\bar{\rho}\,(10^{-3}\ kg/m^3)$	14.1	19.3	24
2	$\sigma_\rho\ (10^{-3}\ kg/m^3)$	0.26	0.34	0.47
3	$\rho_{min}(10^{-3}\ kg/m^3)$	2.8	7.1	6
4	$\rho_{max}\,(10^{-3}\ kg/m^3)$	24.7	38.4	57.7
5	$f_{i-max}\ (m^3/kg)$	130	118	64
6	$\rho_{0.5}\ (10^{-3}\ kg/m^3)$	6	8	17

Figure 3 presents the spectra of condition derived from the values of the kinematic viscosity (2-a) and the mass density of the aerosol phase (2-b) of ASLVs, obtained from the smoke of the three brands. The smoke of a single cigarette can fill the measuring chamber three times and having 8 photosensors we obtain 7 values. We worked with retention times from 0 to 10 min, at 1 min intervals. Therefore, in our case the resulting values are 231. We show for clarity only approximations with the Gauss curve.

The resulting correlations indicate that the spectrum of density of the aerosol phase (2-b), corresponding to the smoke of cigarettes with lower tar content and better filters is shifted to the right, in the direction of the smaller density values. Similarly to the spectrum of the viscosity is obtained shift to the left (2-a), in the direction of larger values of viscosity. Such dependencies we received with other tested cigarette brands.

Parameters of the spectrums of the status obtained from the values of kinematic viscosity and mass density of the aerosol phase, can be used to characterize each ASLV. Table 2 (for example, only the mass density of the aerosol phase of the three brands) shows these basic parameters of the spectra of the state – the average mass density $\bar{\rho}$, corresponding mean square error σ_ρ, minimum ρ_{min} and corresponding maximum ρ_{max} value of the entire array (231 values). On the fifth and sixth row are presented the maximum of the density distribution function $f_{i\text{-}max}$ (equation (9)) of the relevant spectrum and its corresponding half-width $\rho_{0.5}$.

DISCUSSION AND CONCLUSION

The current paper, offers a method for determining the kinematic viscosity and mass density of concentrated aerodispersed systems formed in a limited volume (aerosol chamber) ASLVs. This method is based on the measurement of the time needed for a certain amount of aerosol to flow out through a calibrated pipe under the impact of its own hydrostatic pressure. The volume of the flowing aerosol is determined by scanning the upper border aerosol–air. This measurement is performed using a laser beam scan and a photoelectronic circuit, on the basis of light scattering. Poiseuille's law and the continuity equation are applied. Two equations for the determination of kinematic viscosity and mass density of concentrated aero dispersed systems have been obtained, based on the experimentally measured flow out time.

In result of the processes of coagulation and sedimentation within them, the density of the aerosol phase is constantly decreasing. This leads to reduction of the hydrostatic pressure and after a certain period of time the flow of the aerosol stops. The preliminary results show that this method is applicable to a period of time of the evolution process in relation to the moment of their production in order of 10 to 15 minutes. Most of the experiments we conducted in our experimental setup were using smokes from various types of cigarettes and evolution time of up to 10 minutes. We also investigated the influence of external factors, such as electric and magnetic fields. The data we obtained for the smoke's kinematic viscosity is in the range (3–65) × 10^{-4} m^2/s and the resolution is $\Delta\nu = 0.15 \times 10^{-4}$ m^2/s. Similarly for the mass density of the aerosol phase we got (3–60) × 10^{-3} kg/m^3 and the resolution is $\Delta\rho = 0.15 \times 10^{-3}$ kg/m^3. The relative error is 5%.

Results also show that after the examination of the change of two parameters in the process of evolution of the aerodispersed systems and construction of the spectra of the condition, this method can be used to create a new type of ASLVs characterization. The presented experimental data obtained with the use of cigarette smoke proves the potential of the method.

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ОХАРАКТЕРИЗИРАНЕ НА АЕРОДИСПЕРСНИ СИСТЕМИ С ПОВИШЕНА КОНЦЕНТРАЦИЯ ПО КИНЕМАТИЧНИЯ ВИСКОЗИТЕТ И МАСОВАТА ПЛЪТНОСТ НА АЕРОЗОЛНАТА ИМ ФАЗА

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Получена на 28 октомври 2016 г.; коригирана на 22 март 2017 г.

(Резюме)

Настоящата статия предлага метод за определяне на кинематичния вискозитет и масовата плътност на концентрирани аеродисперсни системи, формирани в ограничен обем (аерозолна камера) – ASLVs (Aerodispersed Systems of Limited Volume). Този метод се основава на измерване на времето, необходимо за изтичане на определено количество аерозол през калибрирана изходна тръба под въздействието на собственото му хидростатично налягане. Определянето на обема на аерозола, който изтича, става посредством проследяване на горната граница аерозол–въздух. Проследяването се осъществява с помощта на лазерен лъч и фотоелектронна схема, на базата на разсейването на светлината. Прилагат се законът на Поазьой и уравнението за непрекъснатост. Изведени са две уравнения за определянето на кинематичния вискозитет и масовата плътност на концентрирани аеродисперсни системи на базата на експериментално измерване на времето на изтичане.