

Application of laser light scattering for determination of the border aerosol-air in a specialized physical laboratory setup

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Abstract. The current article examines the application of laser light scattering in a specialized laboratory setup. It is used for determination of the kinematic viscosity and mass density of Aerodispersed Systems formed in Limited Volume (High Concentration Aerosols) by the method of free flow out. The measurement chamber is first filled with the investigated aerosol. After a predetermined delay time the aerosol is allowed to flow out through a calibrated pipe with fixed size located few centimetres above the chamber's bottom. The lowering of the upper border aerosol-air is continuously scanned using a laser beam directed along the axis of the cylindrical chamber. The kinematic viscosity and mass density of the investigated aerosol phase are calculated by formulas obtained by the authors. The suggested application of laser light scattering led to higher accuracy of the determination the position of aerosol-air border, thence the certainty of this method. This improvement allowed the use of computer controlled optoelectronic setting. The use of laser light scattering significantly improves the method for determination of the kinematic viscosity and mass density of Aerodispersed Systems formed in Limited Volume.

1. Introduction

The aerosol phase of the Aerodispersed Systems formed in Limited Volume (ASLV) exerts additional hydrostatic pressure which causes aerosol flow through the horizontal tube above the bottom of the container (figure 1). In our previous papers [1-3], after applying the continuity equation and Poiseuille's law we come to the following formula for the kinematic viscosity of the aerosol:

$$\nu = \frac{\eta}{\rho} = -b \frac{\bar{H}}{\Delta H} \Delta t; b = \frac{\pi r^4 g}{8 \ell S} \quad (1)$$

where r is the radius of the horizontal tube, ℓ – its length, g – gravitational acceleration, S – the cross-section of the aerosol container, η – the dynamic viscosity, ρ – the density of the aerosol phase. The interval ΔH crossed by the lowering of the upper borderline for time Δt , \bar{H} is its average height with respect to the bottom of the container, The density ρ can be considered as the average density in the aerosol volume $V = S\bar{H}$, b – calculated equipment constant.



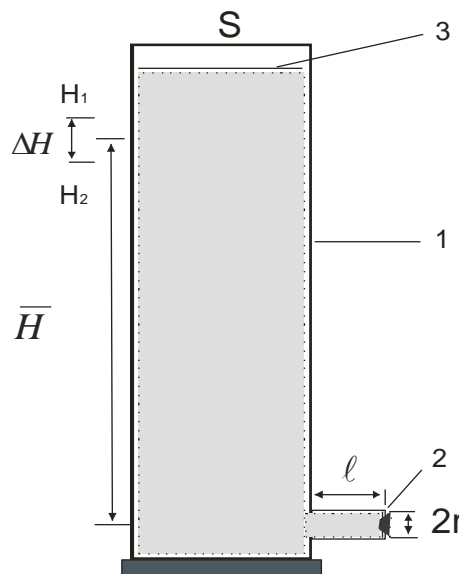


Figure 1. Schematic diagram showing (illustrating) the basis of the method for determination of the viscosity and the mass density of ASLV: 1– aerosol container, 2– calibrated exit tube, 3– aerosol-air border.

The equation (1) gives the possibility to obtain from a single experiment an array of values of the kinematic viscosity of the aerosol under investigation for different heights from the container bottom. The viscosity is specific for each type of aerosol and it can serve as its “individual characteristic” [4]. With the help of equation (1) we cannot determine separately the dynamic viscosity and the density of the aerosol, which change in the process of evolution of the system. This requires an assessment of the aerosol parameters, which will enable us to get additional information for the mass density ρ of the aerosol phase.

The most frequently used aerosol was cigarette smoke; it contains well-defined particles with a spherical shape, and it has been researched by authors [5, 6].

Einstein formula [7] for the dynamic viscosity of a dispersion system is well known:

$$\eta = \eta_0(1 + 2.5\varphi) \quad (2)$$

where η is the dynamic viscosity of the dispersion system, η_0 - of the dispersion medium (air) and φ is the ratio of the volume of the dispersion phase to the total volume.

The following assessment of parameters was made for the aerosol we used. The countable concentration of particles is $N \approx 10^{15} \text{ m}^{-3}$ [6]. The mean diameter of the aerosol particles measured with an electronic microscope is $D \approx 0.16 \times 10^{-6} \text{ m}$ [6]. For the total volume of aerosol particles in 1 m^3 we have $\approx 10^{-6} \text{ m}^3$, $\varphi \approx 10^{-6}$.

This allows us to disregard the second term in formula (2), i.e. $\eta \approx \eta_0 = 1.80 \times 10^{-5} \text{ N.cm}^{-2}$. Then the formula (1) transforms to [8–11].

$$\rho = \frac{\eta}{\nu} = - \frac{1}{b} \frac{\Delta H}{\bar{H}} \frac{\eta_0}{\Delta t} \quad (3)$$

Equation (3), makes it possible to determine the density of the aerosol phase ρ , after measuring Δt and \bar{H} .

Let's make a short theoretical analysis of the error we are making in our measurements. According to equation (1) after we apply the well-known method we come to the following equation for the relative error

$$\frac{\Delta \nu}{\nu} = 2 \frac{\Delta d}{d} + \frac{\Delta \bar{H}}{\bar{H}} + \frac{\Delta t}{t} + \frac{\Delta \ell}{\ell} + 2 \frac{\Delta D}{D} + \frac{\Delta(\Delta H)}{\Delta H} \quad (4)$$

In formula (4): $\Delta d/d$ is the relative error in the measurement of the exit tube diameter ($d = 2r$), $\Delta \bar{H}/\bar{H}$ – of the average height, $\Delta t/t$ – of the measured time interval, $\Delta \ell/\ell$ – of the measured length of the exit tube, $\Delta D/D$ – of the diameter of the measurement chamber ($S = \pi D^2/4$), $\Delta(\Delta H)/\Delta H$ – of the measured distance between level H_1 and H_2 .

The analysis of the individual relative errors shows, that the biggest part in the final error is due to the error of the measured time interval Δt . In practice it ranges from a second to several tens of seconds. The value of Δt depends on several factors – the viscosity of the aerosol, the size of the experimental setup (measurement chamber and the exit tube), the meteorological factors etc.

We have to keep in mind, that the aerosol-air border is not clearly outlined. Under day light (or the light of an electric bulb) it looks blurred due to the diffusion.

The scanning is usually made from one side (left or right) where the fluctuations are largest. This along with the blurred border leads to a significant error in the end result. Thus the accuracy of the measured time interval Δt significantly depends on the precise determination of the position on the horizontal aerosol-air border.

In order to resolve this problem, we referred to laser scattering. It has already been used for determination of the horizontal aerosol-air border by the authors of [12]. The scanning of the aerosol-air border was done visually. They have examined the natural lowering of the border caused by sedimentation. Its duration is in the order of several hours. The long period of this process assured them high accuracy of the end results, even in the case of visual scanning.

The scattering, reflection and absorption of light by the aerosols depend on the size, shape and nature of their particles and also on the wavelength of the incident light. Because of its large practical application the theory of light scattering has already been highly developed.

The theories of light scattering treat the particles of the dispersed aerosol phase (in approximation) as spheres of transparent isotropic dielectric. It is assumed that they scatter light incoherently, i.e. independently of each other. D. Sinclair [13] supposes, without evidence that in order to fulfil this assumption, the distance between the individual particles has to be at least 10 times (or even better 100 times) larger than their radius. Later it has been experimentally proven that with highly concentrated hydrosols [14] for incoherent scattering this ratio has to be larger than 3–4 times. As an exception this condition applies also to the case of extremely high concentrations of larger particles, because there the interference of light scattered by adjacent particles is usually negligible.

In this work by means of laser scattering we determine very precise the location of liquid-air border in containers filled with aerosol systems. As result of this the viscosity and density of the given aerosol systems could be characterised or compared better than the other visual methods.

2. Experimental equipment

To determine the position of the upper aerosol borderline in the course of time, we used the method of scattering of laser light under an angle of 90° with respect to the beam direction and detection of light with phototransistors [4, 8].

We assume that the scattering of the laser beam by aerosol particles of the size indicated above is described with the theory of Mie [6]. Since we used He-Ne laser with unpolarised light and power 5 mW, from the indicatrice of the dispersed light at an angle of 90° [6], there follows that the intensity of dispersed light is enough to be registered with phototransistors.

Figure 2 shows the scheme of the experimental equipment, where 1 is an aerosol container, 2 – container for initial formation of aerosol, 3 – peristaltic pump, 4 – entry to chamber, 5 – exit calibrated tube, 6 – laser, 7 – mirror, 8 – photosensors, 9 – electronic block, 10 – computer.

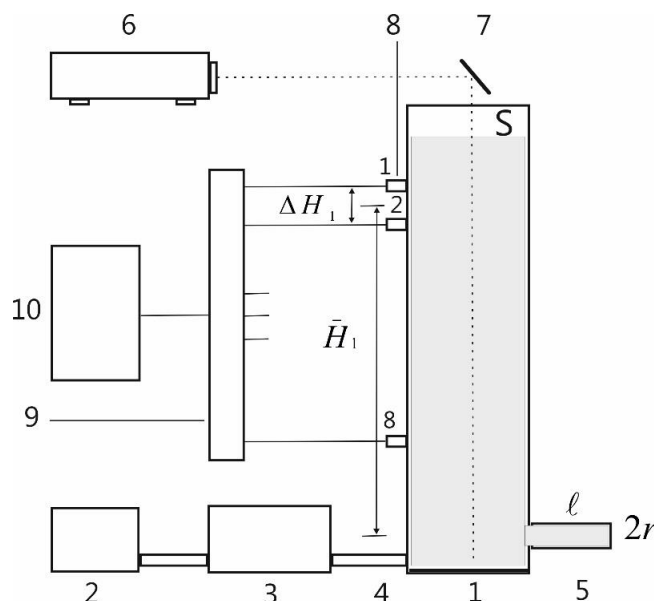


Figure 2. Scheme of the experimental equipment.

In our setup we used a transparent 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 calculated (1) installation constant is $b = 4.65 \times 10^{-5} \text{ m}^2 \text{ s}^{-2}$. The Stokes number is $Stk \approx 10^{-6} \ll 1$, 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 before the outflow.

3. Results and Discussion

The results of the kinematic viscosity of several types of aerosols obtained are shown in table 1. Each of the results listed is an average of 7 experimentally obtained viscosity values. The experiments were carried out under standard laboratory conditions and atmospheric pressure of 970–980 hPa. On line 10 in table 1 we have shown, for comparison, the kinematic viscosity of air at 20°C and normal atmospheric pressure [15].

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

Table 1. Values of the kinematic viscosity of several types of aerosols obtained by the described method.

	Aerosol type	$\nu, 10^{-4} \text{ m}^2 \text{ s}^{-1}$
1	Arda Cigarette smoke hard pack	6.0 ± 0.3
2	Arda Cigarette smoke soft pack	5.0 ± 0.3
3	Phoenix Cigarette smoke soft pack	4.7 ± 0.2
4	Paraffin vapour	3.9 ± 0.2
5	Glycerol vapour	10 ± 2
6	Ammonium chloride smoke	13.5 ± 0.6
7	Colophony resin smoke	9.6 ± 1.5
8	Screening smoke white	5.3 ± 0.2
9	Colored screening smoke red	13 ± 2
10	Air at 20°C	0.15

Table 2 shows the data we obtained for the mass density of the aerosol phase of several types of aerosols using the described method. Each of the listed values is an average of 7 measurements. On line 10 in table 2 we have shown, for comparison, the kinematic viscosity of air at 20°C and normal atmospheric pressure [15].

It is seen from the results shown that the mass density of the aerosols with limited volume is one or two orders lower than that of air. This fact is confirmed by the data for the kinematic viscosity of aerosols and air shown in table 1.

Table 2. Values of the mass density of aerosol's phase of several types of aerosols obtained by the described method.

№	Aerosol type	$\rho, 10^{-3} \text{ kg.m}^{-3}$
1	Cigarette smoke – Arda hard pack	30.6 ± 1.8
2	Cigarette smoke – Arda soft pack	37 ± 2
3	Cigarette smoke – Phoenix soft pack	38.5 ± 1.5
4	Paraffin vapour	46.6 ± 1.4
5	Glycerol vapour	22 ± 3
6	Ammonium Chloride smoke	13.5 ± 0.6
7	Colophony resin smoke	21 ± 2
8	Screening smoke – white	33.9 ± 1.4
9	Colored screening smoke – red	15 ± 2
10	Air at 20°C	1200

4. Conclusions

An important fact is that on the basis of laser light scattering an experimental setup was constructed for investigation of ASLV. Although the aerosol phase of ASLV has a much smaller density than the density of air at normal pressure and temperature, they flow out of the aerosol container like liquids a result of the additional hydrostatic pressure they possess.

The presented method based on laser light scattering and Poiseuille's law makes it possible to examine ASLV in the process of their evolution even in the case of application of an additional external impact on them – like electric, magnetic and/or acoustic fields.

In result of the processes of coagulation and sedimentation within them, the density of the aerosol phase is constantly decreasing. 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 min. The lowest density of the aerosol phase that can be measured using our method is in the order of $2.8 \times 10^{-3} \text{ kg m}^{-3}$.

The preliminary results have also shown that this method can be used for the development of a new type of characterization of the final product of the cigarette industry (cigarettes, cigars, cigarillos, pipe tobacco, filters), by determining and analyzing the parameters of their smoke.

Acknowledgements

INERA EU project Research Potential (FP7-316309-REGPOT-2012-2013-1) "Research and Innovation Capacity Strengthening of ISSP-BAS in Multifunctional Nanostructures" is acknowledged.

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