Physics Letters A 377 (2013) 1740–1744

Contents lists available at SciVerse ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Dropwise chains as the elements of water fog spatial structure

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ARTICLE INFO

Article history:
Received 1 February 2013
Accepted 3 May 2013
Available online 9 May 2013
Communicated by F. Porcelli

Keywords:
Water
Fog
Dropwise cluster
Dropwise chains
Debye radius

ABSTRACT

Video images of water fog drops were acquired under standard atmospheric conditions with weak turbulence of the environment. Pair correlation functions of the drops were performed and traces of the spatial arrangement of the drops inside the fog determined. The fog structure carriers are the drop chains with a fixed interdroplet distance. The possible influence of the drop chains on the shear viscosity and fog surface tension has been analysed.

1. Introduction

Recently, the scientific literature reported on observations of the spatial ordering of water drops in a type of water aerosol – dropwise cluster [1]. The dropwise cluster represents a one-layer space ordered structure, in which drops are located at the nodes of a hexagonal pattern. The diameter of the drops was of the order of tens of microns and the interdroplet distance was two to three times that of the drops' diameter. The structure formed spontaneously over a locally warmed water surface. In [2–4], we have made and then confirmed assumptions on the possible existence of volume ordered dropwise structures inside atmospheric clouds and fog. These structures are capable of influencing the physico-mechanical properties of clouds and fog. In particular, dropwise structures can raise the viscosity of clouds and fog, control convection within them and influence the speed of heat and mass transfer. However, experimental proof of the existence of the ordering of drops inside clouds and fog has still not been achieved.

The present project aims to find dropwise ordering in laboratory water fog. For this purpose, water fog was created over a wide range of temperatures inside a small vessel, video images of the fog drops in a certain plane (microscope object plane) were used to determine the drops coordinates and calculate pair correlation functions and based on this, conclusions were drawn on the degree of drop ordering.

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0375-9601/$ – see front matter
http://dx.doi.org/10.1016/j.physleta.2013.05.009

2. Experimental technique

The experiments with the water fog were carried out under atmospheric conditions close to standard. To create the fog we used an ultrasonic inhaler Vulkan-1 TY 1-720-0025-91 with power consumption of 130 Watts. The inhaler was supplied with a regulator for the fog generation intensity, a heater for the initial water and a fan regulating the output flow of fog from the device. To make a fog we used distilled water. The fog was supplied from the inhaler above, through a corrugated plastic tube 500 mm long with a 20 mm internal diameter, into a 50 mm high and 20 mm diameter glass measuring glass dish. The size of dish was selected empirically, such that the turbulent flows inside the dish faded within 3–5 seconds once the fog supply was interrupted. A specified time later, the fog inside the dish represented a hydrodynamically calm (the speed projection gradient on a horizontal plane less than 0.1 s^{-1}) translucent environment, in which water drops of some microns in size fell under gravity onto the bottom of the dish with a speed of about 10^{-3} m/s. The available period of observation of the fog, once it had been supplied to the dish, lasted some tens of seconds. The fog temperature was determined at the output of the corrugated plastic tube by means of thermometer with precision of $\pm 1\,^{\circ}$C.

Supervision of the fog drops was performed in a horizontal plane by means of a microscope МБС-1 with working distance of 65 mm. The microscope was focused onto the area located in the centre of the dish. The effective focusing depth of the microscope was determined experimentally by means of a mechanical micrometer with the measuring sensitivity of 1 micron. For this purpose, we placed on the microscope stage a glass slide with water drops that had fallen from the fog and then moved microscope vertically, registering its location; based on these data we determined the effective focusing depth. The focusing depth was 250 ± 10 microns, which exceeded, approximately by an order of magnitude, the minimum distance between the water drops inside the fog (about 30 microns).

The fog was lighted from beneath by means of a light-emitting diode. Registration of the video was performed with a MYscope 310M digital camera with image frequency of 30 frames s^{-1}. The relative error of measurement of time intervals was $\pm 1.7 \cdot 10^{-2}$ s. The absolute error of determination of the dimensions according to the video images was ± 0.5 px, which is equal to ± 1.1 microns.

A single drop in the dish moved downwards under the influence of gravity and friction forces. It was within the effective focusing depth of the microscope for a period of at least ten consecutive video images, or several tenths of a second, due to upward and downward variations depending on the fog temperature. When the fog temperature was lower than the environment air, the speed of drops of a fixed size was lower because of heating and movement of the fog upwards relative to the measuring dish. When the fog temperature was higher than the environment air, the speed of the drops was higher because of the cooling of the fog in the dish.

3. Measurement results

Fig. 1a represents a typical video image of the fog for 9 °C initial water temperature and Fig. 1b shows the graphical copy of this image. The drops have an identical radius of about 4.5 microns. The number of drops on the image is about 100; thus, drop concentration is $0.8 \cdot 10^8$ m^{-2} or as a volume value, $3 \cdot 10^{11}$ m^{-3}.

To identify the attributes of drop space ordering we constructed average pair correlation functions of drops at various temperatures. For this purpose, we selected randomly 10 video images from 300 consecutive video frames at a fixed temperature. For each video image, we calculated pair correlation functions of drops on the basis of $(dN/dr) \cdot r^{-2}$, where N is number of the drops' couples from the interval of interdroplet distances $(r, r + dr)$ at $dr = 2$ microns, r^{-2} is multiplier providing attenuation of the function at big r. Then, we calculated arithmetic-mean pair correlation functions (on the basis of 10 functions). Furthermore, we triple smoothed the received functions via calculation of a floating average on the basis of three points. Fig. 2 represents the average pair correlation functions for fog drops at 9 and 90 °C, curves *2* and *3*, respectively. Fig. 2 also shows average pair correlation functions of a hypothetical flat structure formed by casually located particles with concentration equal to the concentration of drops on the video image of the fog, $0.8 \cdot 10^8$ m^{-2} (curve *1*). The method of calculating curve *1* is the same as for curves *2*, *3*.

Fig. 2 demonstrates that the correlation function of particles casually distributed in the space (curve *1*), increases very quickly when $r \to 0$. Thus, the correlation functions of the fog drops (curves *2* and *3*) have maxima at interdroplet distance when $r =$ 20–30 microns and are equal to zero when $r \to 0$. Curves *2* and *3* also have weak maxima at a doubled interdroplet distance; thus, they contain attributes of the spatial ordering of water drops inside the fog. It should be noted that the location of the pair correlation function maximum is weakly dependent upon temperature. It can be substantially affected by the technical characteristics of the Vulkan-1 inhaler, as well as by the method of fog transportation to the dish, which in the present work was via the corrugated tube; obviously, this tube acts as a drops size separator.

The attributes of the fog drop ordering are more obvious on the graphics of pair correlation functions (Fig. 3, curve *1*), fitted by drops of a single image (Fig. 1). For the case in which the pair function was calculated based on the formula dN/dr, it was triple smoothed via calculation of a floating average on three points. The

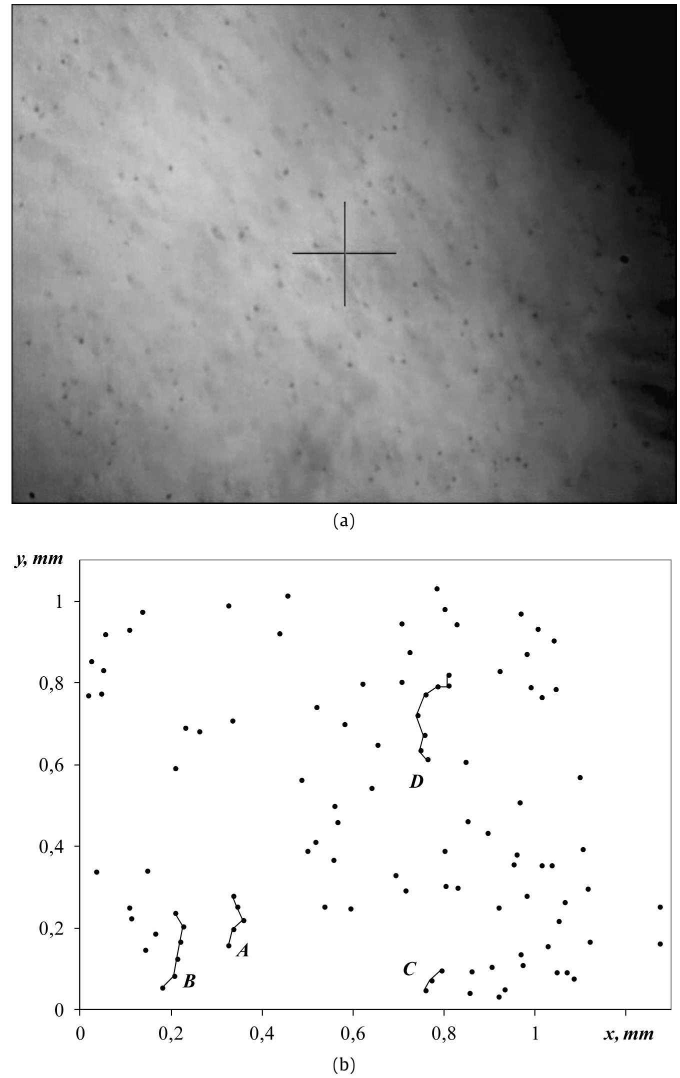

Fig. 1. (a) A typical video image of the fog for 9 °C initial water temperature and (b) the graphical copy of this image. Lines *A*, *B*, *C* and *D* connect drops whose relative space location was maintained for at least 0.5 s.

figure demonstrates not only the first and second maxima but also the maxima of higher orders.

The maxima of pair correlation functions is the responsibility of spatial drop structures inside the fog in the form of twisting and sometimes branched, drop chains with a fixed interdroplet distance. The longest drop chains in Fig. 1 are marked with the letters *A*, *B*, *C* and *D*. A frame-by-frame analysis of the video reveals that the drop chains do not collapse during their vertical movement within the focusing depth of the microscope, which is slightly more than 0.5 s; the actual existence of these chains, is apparently, much longer. In Fig. 3, curves *2*, *3* represent pair correlation functions of drop chains *A* and *B* containing 5 and 6 drops, respectively. Functions are calculated by the formulas similar to curve *1* in Fig. 3. These functions have clearly delineated maxima of the first and higher orders. Existence of clear peaks proves objectively drop ordering in the chains. When comparing curve *1* with curves *2* and *3*, an obvious correlation of their maxima can be seen. Thus, the existence of the chains with ordering to other water drops is an important structural property of the fog.

Drop chains *A* and *B* are characterised by various average interdroplet distances, which are equal to $r_A = 30$ and $r_B = 40$ microns, respectively. The mid-radiuses of the drops in the *A* and *B* chains also differ; $R_A = 4.1$ and $R_B = 4.6$ microns, respectively. Accuracy