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The use of infrared irradiation to stabilize levitating clusters of water droplets

Leonid A. Dombrovsky [a,*], Alexander A. Fedorets [b,c], Dmitry N. Medvedev [b]

[a] Joint Institute for High Temperatures, NCHMT, Krasnokazarmennaya 17A, Moscow 111116, Russia
[b] Tyumen State University, Semakov 10, Tyumen 625003, Russia
[c] Institute of Thermophysics, Lavrentiev prosp. 1, Novosibirsk 630090, Russia

HIGHLIGHTS

- Theoretical estimates of heating of water droplets by infrared radiation are presented.
- The droplet size variation with time at different radiation power is studied experimentally.
- The radiation power required to stabilize sizes of levitating droplets is found.
- Possible use of microwave irradiation to solve the same problem is estimated.

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ABSTRACT

Theoretical estimates based on the Mie solution for single droplets show that infrared irradiation of droplet clusters levitating over the heated water surface prevents the ordinary growth of droplets and subsequent coalescence of the droplet cluster with water layer. As a result, this irradiation can be used to stabilize the levitating clusters for a long time. This prediction is confirmed in the paper by a series of experiments with obtaining the required power of infrared irradiation. The resulting stable droplet clusters are considered as an appropriate laboratory model of atmospheric droplets to study biochemical processes in the droplets of natural mists and clouds. Possible use of sub-millimeter electromagnetic radiation to reach a similar stabilization effect is also analyzed in the paper.

1. Introduction

The levitating droplets which form the clusters of regularly positioned spherical droplets above the heated water surface were observed for the first time more than ten years ago [1]. The behavior of the levitating single droplets and droplet clusters in the upcoming flow of vapor of various liquids and entrained air has been studied experimentally and the laboratory observations appeared to be useful for understanding this specific phenomenon [2–5].

Following recent suggestions by the authors [6,7], the present stage of the work can be treated as a transfer from passive observations to managing the process. The main objective of the present paper is to stabilize levitating droplet clusters in time and avoid their coalescence with water substrate. This can be reached by preventing the growth of single droplets due to predominant steam condensation on their surface. It seems obvious that independent external heating of water droplets can be used to increase their evaporation and reach a desirable balance between evaporation and condensation over the droplet surface. The radiative heating is an appropriate way because it does not disturb directly the flow around the droplet. The wide-range infrared heating of droplet clusters was chosen in the present paper as the simplest way. At the same time, the possible use of sub-millimeter electromagnetic radiation is also discussed in the paper.

The motivation of the work on stabilization of levitating clusters of water droplets is to make the laboratory conditions as closer as possible to the physical conditions in natural mists and clouds with the only important difference: the temperature of droplets in laboratory clusters is much greater than that in the present-day atmosphere of our planet. The latter is expected to enable one to arrange detailed laboratory investigations of biochemical processes in atmospheric water droplets in the case of a relatively hot atmosphere. A discussion of the role of biochemical processes in possible biogenesis on our planet is beyond the scope of the

* Corresponding author. Tel.: +7 910 408 0186.
E-mail address: ldombr@yandex.ru (L.A. Dombrovsky).

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Nomenclature

a	droplet radius
c, d	coefficients introduced by Eq. (10)
C	cross section; function introduced by Eq. (17)
e, E	components of electric field
x	diffraction parameter
m	complex index of refraction
n	index of refraction
p, P	absorbed radiation power
q	radiative flux
Q	efficiency factor
r	current radius
R	radius
S	surface area of droplet; function introduced by Eq. (17)
t	time
T	temperature
u	velocity
W	radiation power
y, z	independent variables in Eq. (10)

Greek symbols

α	absorption coefficient
δ	thickness of radiating layer
ε	emittance
κ	index of absorption
λ	wavelength of radiation
μ	cosine of polar angle
θ	polar angle
ρ	density
σ	electrical conductivity
τ	optical thickness
ψ, ζ	Riccati–Bessel functions

Subscripts

a	absorption
el	electrical
g	glass plate
h	heated region
IR	infrared
L	laser
n	normal
r	radial component
s	scattering; low-frequency
tr	transport
w	water
λ	spectral
θ	polar component
φ	azimuthal component
∞	high-frequency

present paper, but the authors believe that laboratory work with relatively stable and hot levitating droplets will give new important possibilities to solve specific biochemical problems.

2. Theoretical estimates of total absorption of infrared radiation by water droplets

In contrast to recent paper [5], the analysis of absorption of a wide-range infrared radiation by water droplets typical of levitating clusters cannot be based on the geometrical optics approximation because of insufficiently large diffraction parameter $x = 2\pi a/\lambda$ over the wavelength range. Therefore, one should use the rigorous Mie theory [8–10]. The classical Mie solution gives complete information on the interaction of a plane electromagnetic wave with a homogeneous spherical particle, including the near-field region and the electromagnetic field inside the particle. The last possibility will be also used in subsequent analysis. In the present section, the only integral characteristic of the far-field solution is considered. It is the so-called efficiency factor of absorption introduced as follows [8–10]:

$$Q_a = C_a/(\pi a^2) \quad (1)$$

where C_a is the absorption cross section of a particle with radius a. The dimensionless value of Q_a depends not only on the diffraction parameter x but also on the complex index of refraction $m = n - i\kappa$, where n is the index of refraction and κ is the index of absorption. The spectral optical constants, n and κ, of pure water are well known in a wide wavelength range [11–13]. The fragments of these spectral dependences for the infrared range of radiation sources used in experiments of the present paper are shown in Fig. 1.

It goes without saying that absorption and scattering of visible and infrared radiation by water droplets is important in numerous applications. One can remember the known problems of atmospheric optics and thermal regime of the Earth atmosphere [14–16]. The analysis of radiative heat transfer in presence of water droplets is important for calculations of fire suppression by water sprays and protection of industrial installations and other facilities from the fire radiation by water mists and curtains [17–24]. Attenuation of solar irradiation from cloudless atmosphere by a layer of

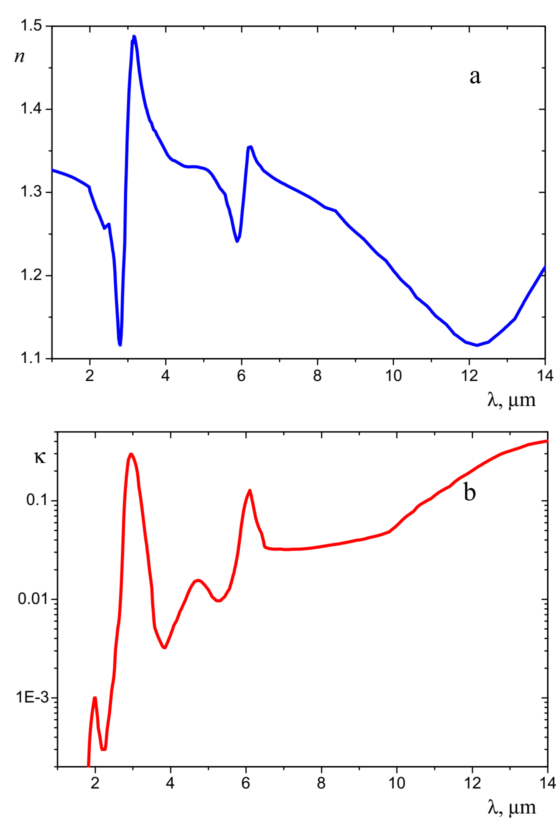

Fig. 1. Infrared indices of (a) refraction and (b) absorption of pure water.