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A REVIEW OF METHODS FOR ASSESSING THE EVAPORATION OF LIQUID DROPS UNDER VARIOUS CONDITIONS

Abstract. The article discusses methods for estimating the evaporation of liquid droplets under various environmental conditions. All estimation methods can be divided into three groups: evaporation of a stationary levitating drop, evaporation of a falling drop, and evaporation of a drop lying on a solid surface. The possibility of using the considered models and data in the design of local climate control systems is assessed.

Keywords: evaporation, drop, water vapor, surface, airflow.

Introduction. The problem of evaporation of liquid droplets is constantly studied by scientists all over the world due to a variety of practical tasks. Knowledge of evaporation processes of single droplets under various environmental conditions allows to design and improve technical cooling systems, microclimate installations, various energy and heating systems [3, 4, 26].

The purpose of this article is to review existing models for evaluating liquid droplet evaporation for further application in designing a local climate control system.

The first drop evaporation model was proposed by Maxwell in 1887 [4]. This model was very simple and was constructed under the assumption that the evaporation process is limited to vapor diffusion. Expression for calculation of vapor flux from the drop surface was obtained by integration of vapor flux equation from liquid surface and has the form:

$$j_w = 4\pi r_0 D_v \left(\rho_{vs} - \rho_{v0}\right) \quad (1)$$

where j_W is flux of number of vapor molecules from drop surface, r_0 is drop radius, D_V, ρ_{VS} and ρ_{V0} are vapor diffusion coefficient and its density on surface and in ambient gas.

This model is suitable only for stationary conditions, which are practically never met in reality, as the drop size inevitably changes during evaporation.

Based on the same assumptions as the Maxwell model, the Spalding model was built, which takes into account the change in droplet diameter over time. This model was called "law d²" and found wide application in practical calculations [4]:

$$\left(\frac{d}{d_0}\right)^2 = 1 - \frac{8D_V\rho_0}{d_0^2\rho_{ж}} ln\left(1+b_{1d}\right)t \qquad (2)$$

However, Maxwell and Spalding models describe only the functional dependence of drop size change with time and are applicable only to diffuse evaporation.

Hertz and Knudsen models are developed to describe the kinetic or free-molecular mode of evaporation [4].

$$I = \frac{1}{4}\pi r^2{}_p \frac{M}{RT}\sqrt{\frac{8RT}{\pi M}}\alpha_m\left(p_S - p_\infty\right) \qquad (3)$$

where α_m is the fraction of the number of falling vapor molecules condensing into the liquid phase, M is the molar mass of vapor, R is the universal gas constant

Given classical models can not solve all variety of practical problems of drop evaporation. Therefore, for each newly emerging problem researchers look for a suitable solution, as a rule, by experiment. Let's consider different approaches to estimation of evaporation of droplets.

Evaporation of a stationary droplet in an air stream.

The simplest case of evaporation of droplets immobile in relation to medium, which excludes influence of hydrodynamic factor, was considered by N. A. Fuchs [25]. He found that for sufficiently small droplets their motion is not reflected in the evaporation rate, i.e. the evaporation process is quasi-stationary.

In some works, evaporation of a stationary droplet in an air stream was studied for different droplet diameters at high temperatures of air or superheated steam [5; 15; 17, 22–24, 27; 29].

For example, it is noted in [29] that in most real cases evaporation of a droplet is significantly affected by conductive component of heat flow spent on heating or cooling to adiabatic evaporation temperature.

Studies of evaporation of a stationary droplet in an air stream were conducted by N. E. Shishkin, V. V. Terekhov, M. A. Pakhomov et al. [22–24].

In [22] evaporation processes of droplets in streams of different types were compared. It was found that during evaporation of a droplet in a vapor-gas flow, heat transfer is more intense compared to single-component vapor-droplet flow and single-phase vapor flow.

When studying droplets with diameter not more than 3 mm of pure liquids of water, ethanol and acetone suspended motionless in an aerodynamic channel in an air flow directed from below upwards, it was noted that the surface temperature of the droplets was non-uniform. Evaporation of droplets in a stationary medium (at an air temperature of 19.8 °C) was of a similar nature. It was found that for all pure liquids at the initial moments of time the droplet surface temperature was close to the adiabatic evaporation temperature [27]. In further studies [23], evaporation of a suspended droplet in a stream of hot (300 °C) air was investigated when the flow rate changed from 0 to 6 m/s. It was found that for water droplets the ratio $\frac{j_w}{p_0 V_0}$ (ratio of flow of evaporating liquid to initial mass) remains unchanged for a long time.

This data is of some interest for the design of microclimate systems, but in real conditions the droplet cannot remain stationary and the airflow will not be strictly vertical.

Evaporation of a falling droplet in an air stream.

Research on evaporation of the falling drop of liquid is of practical interest. Such researches were

carried out by Spiglazova A. S., Mezentsev A. V., Antonov A. S., Zhailaubaev J. D. et al. [1; 14; 16; 17; 21].

As a result of experimental studies in [17] for the movement of water droplets in a stream of hot gases (temperature above 1000 K), were established integral characteristics of the evaporation of droplets and droplet evaporation constants for the known models of heat and mass transfer. The obtained values can be used in practical calculations and numerical simulation of evaporation processes for the conditions of high-temperature cleaning of liquids, polydisperse fire extinguishing, etc.

In the work of Zhailaubaev Zh. [14] gives the basis for calculating the surface temperature of evaporating droplets for the entire period of nonstationary evaporation (when a vortex heat flow occurs), in which two stages are highlighted:

1 – propagation of thermal and concentration perturbations from the contact surface to the depth of the phases (the duration of the first stage of evaporation is equal to the contact time of the surface element with the gas phase and does not exceed 10^{-3}–10^{-4} s for atomized liquid droplets);

2 – stage of nonstationary evaporation, during which the resistance created by the gas phase to exchange processes remains constant. Temperature of liquid in the second stage approaches the value of adiabatic evaporation temperature, achievement of which is considered as the beginning of stationary evaporation of droplets.

Experiments carried out by the authors with suspended droplets 0.56 to 2.5 mm in diameter at air velocities up to 6.5 m/s allowed to obtain solution of the thermal conductivity equation from which the expression for calculation of evaporation rate was derived:

$$q = A(T_1)\cdot r + \varepsilon_K \cdot B\,(T_1)\cdot r^2 \qquad (4)$$

T – temperature; ε_K – thermal conductivity coefficient; r – current radius (coordinates); A, B – constants.

Despite the apparent simplicity of the considered model, its practical use requires a number of experiments to determine the calculated values of constants A and B.

In the work of Spiglazova A. S. [21] studied the influence of air resistance on evaporation of a falling drop. Analytical expressions were obtained for different ratios of evaporation rate and proportionality factor for the drag force. The use of these models in real conditions is difficult because of the difficulty of accurately assessing the conditions of resistance of the medium to the movement of the droplet.

The kinetics of evaporation of water droplets free-flying in an air stream was analyzed in [13] in order to formulate requirements for the optimal droplet size in an air-droplet mixture designed for cooling production equipment. The following features arise when droplets are forcibly injected into the air stream:

– the droplet expends its mass during evaporation until it disappears;

– small droplets that are in suspension are noticeably affected by viscous frictional forces and therefore their relative velocity in the air is low;

– a stable boundary layer of laminar type is formed around a droplet, which practically excludes the influence of convection and turbulence, so the diffusion of steam from the droplet surface into the ambient air occurs mainly at the molecular level.

Once in the air flow, the droplet very quickly reaches the psychrometric temperature, and further evaporation proceeds mainly at a steady temperature. It was found that the duration of existence of water droplets injected into the air stream is inversely proportional to their initial radius. For example, time of evaporation of a drop with initial radius $r_0 = 0.01$ mm in the flow is $\tau \cong 0.5\ s$.

Some authors [2, 20] investigated possibilities of influencing droplet evaporation processes by means of electric fields. In [2] influence of electric field on intensity of evaporation of levitating drops of liquid was simulated and empirical expression for calculation of time of complete evaporation for drops with size d = 4–5 mm was obtained:

$$t = 1.64f - 40.9, \quad (5)$$

where f is the relative humidity of the air.

It has been experimentally established that constant electric field of 3 kV/cm maximally intensifies processes of evaporation of water drop suspended in air flow.

Model (5) is notable for its simplicity and ease of use in practical calculations, however, this model is not suitable for calculations of microclimate systems as it was developed for evaporation of large drops only.

Comparison of evaporation processes of superheated and cold water was carried out by D. V. Marinichev [19], who found that fine atomization of superheated water with predominance of microdroplets with a diameter less than 3 microns can be achieved by using the technology of explosive boiling of strongly superheated liquid. It was proved that when superheated water is sprayed into an air stream at a velocity of up to 40 m/s, the droplet size distribution has a pronounced bimodal character. Atomizing water temperature of 220–240 °C about 65–70 mass percent of the droplets have diameter less than 3 microns, and the average diameter of large droplets is about 8 microns which is about 1.5–2.5 times less than atomizing cold water. When spraying with cold water (up to 150 °C) droplet size distribution remains unimodal. Data on the droplet size and nature of droplet distribution can be very useful in the calculation of microclimate systems.

Evaporation of droplets from a solid surface.

The process of evaporation of liquid droplets from various surfaces has been studied by many authors [16; 18; 20; 28; 30]. For the purposes of designing microclimate systems, processes of evaporation from surfaces are significant from the point of view that when spraying coolants into the air, a significant proportion of droplets inevitably settles on various surfaces and there continue to evaporate. Therefore further we shall consider results of researches of evaporation of liquid from surfaces of soil, leaves and various solid materials.

Many authors considering evaporation of water droplets from solid surfaces point out that:

– The evaporation rate increases with increasing surface temperature and is highly dependent on the roughness of the wall [30];

– evaporation of droplets smaller than 500 μm directly depends on the thermal conductivity of the substrate [28];

– changes in the electrokinetic potential of particles affect the evaporation of droplets [20]: an increase in the electrokinetic potential of particles leads to a change in the evaporation scenarios of a droplet located on a solid surface: the adhesion of the droplet to the underlying surface weakens, the droplet begins to move with a change in the surface shape, which leads to either acceleration or slowdown of evaporation.

A wide range of studies of evaporation from soil surface was carried out at Research Institute of Hydrometeorology (Uzbekistan) [6–11]. To estimate these processes, theoretical analysis of soil moisture evaporation process was made [11] based on equations of particle number balance and speed of their motion, mathematical dependencies between characteristic particle size of its area and volume were obtained [8]. In [9; 10], based on the generalized equilibrium equation and material balance of particles as well as the equations of hydrodynamics for a continuous medium and energy for air, a multiphase model of interaction between different kinds of underlying surface and air flows in the surface layer and upper atmosphere is analyzed. For these conditions the amount of vapor evaporating from a particle per unit time is calculated.

The problem of estimating the time of evaporation of raindrops and dewdrops from the surface of plant leaves was considered in [12]. To create microclimate systems in arid areas, it is important to be able to manage the time of evaporation of water from plant leaf surfaces. Thomson formula is used to estimate the dependence of saturated vapor pressure over a small droplet:

$$P = P_{\infty} e \frac{2M\sigma V_M}{aRT} \quad (6)$$

where M is the molecular mass, a is the changing drop radius, T is the thermodynamic temperature, V_M is the molar volume, σ is the surface tension of the liquid formed by vapor condensation.

From the above expression it can be concluded that the saturated vapor pressure over the convex surface of the droplets will be greater than over the flat one. Based on this statement the author [12] analyzed the evaporation time of a spherical droplet of small size lying on the surface of a solid body (sheet) at relative humidity f at temperature T:

$$t = \frac{RT\rho_{liq}^2 a_0^3 \left(2 - 3cos\theta + cos^3\theta\right)}{24DM\sigma\rho_{sat} f} \qquad (7)$$

θ – contact angle, ρ_{sat} – saturated vapor density, D – diffusion coefficient, r – drop radius, a_0 – initial radius.

An example of calculation of time of evaporation of a water droplet with initial radius a_0 = 0.1 mm evaporating from solid surface at contact angle θ = 120 degrees and temperature T = 293 K resulted in t = 325 hours. This result raises certain doubts about the adequacy of the proposed model. The approach suggested by the author is of interest, however, the model obtained obviously requires refinement.

Conclusion. Many of the considered computational schemes are in principle not stable in practical calculations, or give calculation results which are inadequate to the physical rules of substance movement in a gas flow.

Nevertheless, the data and models obtained by Balakrova S. B., Dokhov M. P., Shishkin N. E., Marinichev D. V. may be recommended (after clarification in real conditions) for calculation and design of microclimate systems based on atomization in the air of water droplets.

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