Journal of Engineering Physics and Thermophysics, Vol. 66, No. 6, 1994

ANALYSIS OF THE INFLUENCE OF DROP DIAMETERS ON THE INTENSITY OF HEAT TRANSFER IN DROPWISE CONDENSATION

A. S. Gavrish, V. G. Rifert, and
A. I. Sardak

UDC 536.423

An analysis of the contribution of drops of different sizes to the intensity of heat transfer is performed for dropwise condensation of water vapor on a surface that is stimulated by fluorine-containing disulfide. The fraction of the heat-exchange surface and the lifetime of different classes of drops for specified values of the temperature difference are determined. A comparison with the results of other investigators is made.

As is well known, a change in the regime of condensation from film condensation to dropwise condensation makes it possible to substantially intensify heat transfer. A fairly large number of works are concerned with studying dropwise condensation (DC). Some of them, for example, [1, 2], are of a purely applied nature and seek to determine average heat-transfer coefficients and to study methods for producing a stable DC. A second direction of the works (see, for example, [3–5]) is studying the mechanism of the process. Thus, in [4] efforts have been made to establish a universal size distribution function for drops, knowledge of which is needed to calculate heat transfer. In this connection primary importance is given to calculating heat transfer through individual drops of different sizes [3, 5] and hence to answering the question of what drop sizes make a decisive contribution to the average heat transfer in DC.

The development of the DC process is of a nonstationary nature in the general case. However, with a certain degree of arbitrariness we can distinguish the so-called "cycle" of DC [3–5]: the development of drops from some incipient size R_{cr} to a separating size R_{sep} with subsequent removal of them from the heat-exchange surface. In this case calculation of R_{cr} by the procedure of [3, 4] shows that its value varies with a change in the temperature difference $\Delta t = t_s - t_w$ and amounts to fractions of a micron. The separating radius of drops R_{sep} in condensation of a practically stationary vapor is, according to [4], equal to several millimeters. The same order of magnitude of the values is also confirmed by our experimental investigations [6, 7].

At the same time the entire spectrum of drop sizes from R_{cr} to R_{sep} can be divided into a series of classes [5] that are characterized by the growth rate, lifetime, average size $\overline{R}_{dr}$, and heat-transfer coefficient.

Investigations of heat transfer in DC in the presence of fluorine-containing disulfide performed by us earlier [6, 7] enabled us to establish that the condensation curves $\alpha = f(\Delta t)$ or $\alpha = f(q)$ have a maximum under the following conditions: the pressure is atmospheric, the mass concentration of hydrophobicizing agent is 5 g/m^2 of the heat-exchange surface, the temperature difference $\Delta T = 0.8-1.1$ K, the vapor velocity $W_v \leq 2$ m/sec, and there is no condensate overflow or uncondensed gases. The condensation occurred on flat and concave brass surfaces (the latter is the inner surface of a horizontal tube) that correspond to classes of roughness 7–9 (the range of the arithmetic mean deviation of the surface profile is 1.25–0.15 μm). A deviation of Δt from the optimum value upward or downward causes a decrease in the heat-transfer coefficients.

The DC process was photographed with a Hitachi photographic and video cameras via an optical microscope with an image magnification from 50 to 262. The radius of the smallest visible drops amounted to 0.5–1 μm.

Based on the results of video recording and photography of condensation of a vapor at atmospheric pressure and $\Delta t = 0.4-4^{\circ}$C we obtained a plot of the size distribution function for the drops (Fig. 1). As the figure shows, the data of the present investigation are in good agreement with the results of [4, 5]. The separating size of the

Kiev Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 66, No. 6, pp. 668-672, June, 1994. Original article submitted June 10, 1992.

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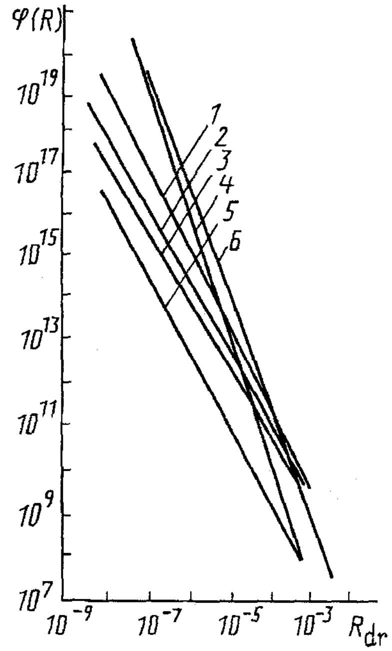


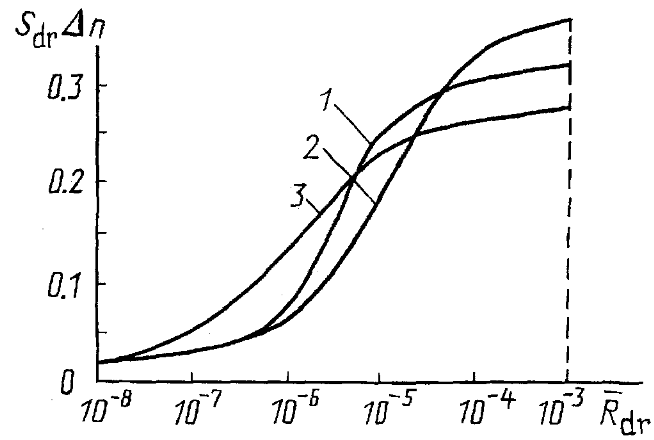


Fig. 1. Drop size distribution functions obtained by different authors for P_{atm}: 1) data of [4] for $\Delta t = 1^{\circ}C$; 2) the same for $\Delta t = 5^{\circ}C$; 3) the same for $\Delta t = 10^{\circ}C$; 4) data of [5]; 5) data of [3]; 6) data of [6, 7] for $\Delta t = 0.4-4^{\circ}C$. φ, $1/m^3$; R_{dr}, m.

Fig. 2. Fraction of the heat-exchange surface occupied by drops of each class: 1) $\Delta t = 1^{\circ}C$; 2) 0.4; 3) 4.

drops established experimentally is equal to $R_{sep} = (1-2) \cdot 10^{-3}$ m, which is in agreement with calculated values determined by V. P. Isachenko's procedure [4]. For the same temperature differences the critical radius of nucleation calculated according to [4, 5] amounted to $R_{cr} = 5 \cdot 10^{-8}-5 \cdot 10^{-7}$ m.

Condensation was considered on a surface much larger in size than the separating diameter of the drops. Then, knowing the drop size distribution function $\varphi(R)$, it is easy to calculate the number of drops of a given class on the heat-exchange surface Δn $[1/m^2]$ and, subsequently, having determined the area of the drops, the fraction of the heat-exchange surface that is occupied by them:

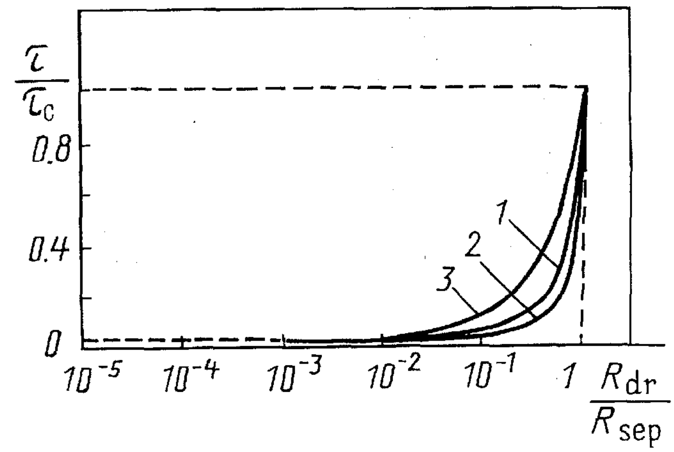
$$(S_{dr}\,\Delta n)_i = \int_{R_{min}}^{T_{max}} f(R_{dr})\, dR_{dr}\,, \tag{1}$$

where R_{min} and R_{max} are the minimum and maximum sizes defining the given class of drops. After summation over all classes of drops, in the limit as $R_{cr} \to 0$ we obtain

$$\overline{S_{dr}\,\Delta n} = \int_{R_{cr}}^{R_{sep}} f(R_{dr})\, dR_{dr} \to 1\,. \tag{2}$$

Figure 2 shows dependence (1) plotted based on results of experimental investigations for three values of the temperature difference. From the data it follows that most of the area is occupied by drops of radii above 1 μm, i.e., the spectrum of drop sizes $\overline{R}_{dr} = 1 \cdot 10^{-6}-1 \cdot 10^{-3}$ m is spread, in the final analysis, on more than 90% of the heat-exchange surface.

On the other hand, the question of the "lifetime" of the drops is very substantial. On the basis of frame-by-frame processing of video- and photomaterial we obtained a plot that reflects the development of drops in time in the conventional DC cycle (Fig. 3). The ratio of the current time τ to the total time of the cycle τ_c is laid off as



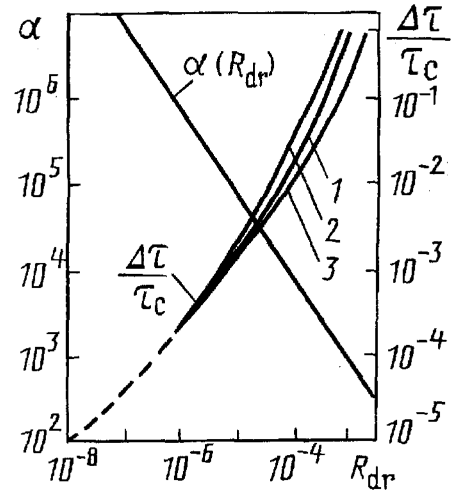


Fig. 3. Development of drops in time in the conventional cycle of dropwise condensation: 1) $\Delta t = 1°C$; 2) 0.4; 3) 4.

Fig. 4. Estimate of the heat transfer and lifetime of drops: 1) $\Delta t = 1°C$; 2) 0.4; 3) 4.

ordinates on the plot. The time of removal of drops from the heat-exchange surface τ_{rem} is small compared to the time of their growth to R_{sep}: $\tau_{rem} \le 0.01\tau$ of growth, and new incipient drops form immediately in place of a departing drop. This served as a simplifying premise, and τ_{rem} was not involved in calculating the total time of the cycle.

The cycle time τ_c decreases as the temperature difference increases: whereas at $\Delta t = 0.4°C$ it is equal to 10 ± 1 sec, at $\Delta t = 4°C$ it is equal to 1 ± 0.1 sec. Knowing intermediate radii between R_{cr} and R_{sep} obtained by analyzing videoimages using a still, it is useful to plot the development of drops in the DC cycle (Fig. 3). In dimensionless coordinates we give curves that average the values of the current time of the cycle τ/τ_c as a function R_{dr}/R_{sep} for different Δt.

Using the model of heat conduction in a drop of [3, 5], we can estimate the heat-transfer coefficient characterizing one or another class of drops $\alpha_{dri} = C(\lambda_l/\overline{R}_{dri})$, where the value of the constant is taken as $C = 1.5$. Figure 4 presents a plot of α as a function of R_{dr}. With increasing size the heat transfer of the drops decreases and their "lifetime" on the heat-exchange surface increases. The relative lifetime for each class of drops was determined from the difference in the values of the times that correspond to the limiting maximum and minimum sizes defining the given class of drops. This difference referred to the entire time of the DC cycle is

$$\frac{\Delta\tau^i}{\tau_c} = \frac{\tau^i_{max} - \tau^i_{min}}{\tau_c}. \tag{3}$$

The analysis performed enabled us to consider the basic factors that describe the average heat transfer in DC over time and space, i.e., the fraction of the area occupied by drops of different sizes, their relative lifetime, and the estimate of heat transfer for different classes of drops. Through these factors many other factors are taken into account indirectly, such as the frequency of drop formation, which is determined by the time factor.

It is evident that the larger the fraction of the surface occupied by drops of a certain class and the longer their lifetime the larger the contribution to the intensity of the process. By making up the dimensionless complex $A = S_{dr}\Delta n\Delta\tau/\tau_c \cdot \alpha_{dr}/\alpha_f$ (α_f is the heat-transfer coefficient in film condensation for specified Δt, calculated by the Nusselt formula) from the above quantities, we can determine the contribution of all classes of drops to the total average heat transfer of the process as a whole (see Table 1).

As Table 1 shows, the largest values of the parameter A for $\Delta t = 1°C$ correspond to drops with $\overline{R}_{dr} = 10^{-5}$ m. The more so since the heat-transfer coefficients for these drops (Fig. 4), too, are closest to the average heat transfer of the process determined in the course of experimental investigations (Table 1). The percent

TABLE 1. Determination of the Contribution of Drops of Different Sizes to Heat Transfer

Δt, °C	$\bar{R}_{dr}$, m	$S_{dr}\Delta n$	$A\cdot 10^3$	Contribution to heat transfer A_i, % $\sum_{i=1}^{m} A_i$	$\bar{\alpha}$ (4)	α_{exp} [6, 7]	Error $\lvert\bar{\alpha}-\alpha_{exp}\rvert/\alpha_{exp}$, %
1.0	10^{-3}	0.35	7.6	8.73	100145	100451	0.3
	10^{-4}	0.31	19.1	22.05			
	10^{-5}	0.25	46.1	53.23			
	10^{-6}	0.06	11.1	12.82			
	10^{-7}	0.03*	2.8	3.17			
0.4	10^{-3}	0.43	7.1	12.29	54867	73582	25.4
	10^{-4}	0.34	14.5	24.97			
	10^{-5}	0.16	25.9	45.21			
	10^{-6}	0.06	9.7	16.95			
	10^{-7}	0.01*	0.32	0.57			
4.0	10^{-3}	0.27	13.1	12.39	80651	71931	12.1
	10^{-4}	0.26	56.2	47.70			
	10^{-5}	0.24	36.2	28.31			
	10^{-6}	0.14	10.1	9.14			
	10^{-7}	0.07*	2.5	2.29			
	10^{-8}	0.02**	0.14	0.13			

*Values obtained on the basis of assessing the data of photomicrography at the resolution limit of the optics.

** Values obtained by approximation.

estimate of the contribution of the drops to the heat transfer from a calculation for each i-th class of drops is also given here for different Δt.

For a temperature difference of 1°C a decisive contribution to the average intensity of the process is made by drops with sizes of about 10^{-5} m, which occupy 25% of the heat-exchange surface. The contribution of the drops of this class to the heat transfer also remains substantial for other values of the temperature difference (see Table 1). The conclusion obtained by us is in agreement with concepts of Graham and Griffith [9], who determined that drops whose diameter does not exceed 40 μm occupy 23% of the surface at atmospheric pressure and make a decisive contribution to heat transfer.

Knowing the percent contribution of each class of drops to the heat transfer, the number of classes involved in the heat transfer m_i, and their corresponding heat-transfer coefficients α_{dri}, it seems possible to determine the average heat transfer of the process $\bar{\alpha}$:

$$\bar{\alpha} = \frac{\sum_{i=1}^{m}\left[\frac{A_i}{\sum_{i=1}^{m} A_i}\alpha_i\right]}{m_i}. \tag{4}$$

The results of a calculation for three values of Δt are given in Table 1, where a comparison with the heat-transfer coefficients α_{exp} obtained experimentally in [6, 7] is also given. We observe good agreement of the data. The difference between the calculated and experimental values of α for $\Delta t = 0.4^{\circ}C$ is explained by the effect of the error of experimental determination for the temperature at small temperature differences. As the temperature difference $\Delta t = t_s - t_w$ increases, the development of drops in time accelerates, R_{sep} decreases, and the number of drops on the heat-exchange surface increases; in this case the determination of time characteristics is made difficult.

In general the above procedure for calculating the average heat transfer in DC makes it possible to describe experimental results sufficiently accurately. It is evident that the analysis performed for a particular process can also be applied to other cases of DC, as demonstrated by the nature of the well-known size distribution functions for drops (see Fig. 1).

NOTATION

α, heat-transfer coefficient, $W/(m^2 \cdot K)$; λ, thermal conductivity, $W/(m \cdot K)$; q, heat flux density, W/m^2; t, temperature of the medium, $^{\circ}C$; R, drop radius, m; Δn, number of drops; $\varphi(R)$, size distribution function for drops, $1/m^3$; S_{dr}, area of a drop, m^2; $S_{dr}\Delta n$, fraction of the heat-exchange surface; τ, time, sec; A, dimensionless complex that characterizes the contribution of different classes of drops to the heat transfer in the dropwise condensation process. Subscripts: sep, separating; cr, critical; s, saturation; c, cycle; g, growth; rem, removal; w, wall; dr, drop; atm, atmospheric; f, film condensation; i, i-th class of drops; max, maximum; min, minimum.

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