EFFECT OF THE TEMPERATURE ON THE EVAPORATION OF LIQUID DROPLETS IN AN AIR STREAM

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Results are shown of a study concerning the evaporation of tetrafluorodibromomethane within a temperature range from −14 to +750°C.

It is well known that the evaporation rate of droplets depends very much on the temperature [1, 2, 6]. This temperature dependence has not been sufficiently well explored, however. The aim of our study was to close the gap.

The authors studied the evaporation of tetrafluorodibromomethane (Freon-114B-2). Its boiling point is 47°C, its melting point is −112°C, and its density is 2.18 g/cm^3.

Droplets of this substance were evaporated in an air stream whose velocity did not exceed 15 m/sec, while the temperature was varied from −40 to +750°C.

The test apparatus was simple. Air from a compressor was fed to a vertical cylindrical quartz or glass tube 1 mm long and 22 mm in diameter. At some distance from the tube end along the axis was placed a droplet specimen, suspended on a glass or quartz filament approximately 100 μ in diameter* and terminating into a spherical bead. The initial droplet diameter fluctuated between 1.5 and 2.0 mm.

Around the tube was wound a nichrome coil for electrically heating the air stream to the desired temperature. During low-temperature tests, part of the air was made to pass through a U-tube immersed in liquid nitrogen.

The air flow rate was measured with a rheometer, the air temperature was measured with a copper −constantan thermocouple in the low-temperature range and with a Copel–Alumel thermocouple in the high-temperature range.

The evaporating droplets were photographed with a mode "Konvas" cinema camera at a rate of 8-24 frames/sec. The photographs were then enlarged, whereupon the droplet size was determined according to the formula in [3] and the surface of droplets S was also calculated. The rate of change of the droplet surface S' served as the indicator of the evaporation rate.

The droplet temperature ϑ_d was also measured. For this purpose, in simultaneous tests a droplet was supported on the junction of a constantan–manganin thermocouple in the circuit of a mirror galvanometer with a matching resistor bank. The thermocouple wires were of different sizes: 30 and 100 μ respectively.

The tests were performed at the following air stream temperatures: −40, −30, −15, 0, +22, 100, 200, 300, 400, 600, and 700°C.

In Fig. 1a are shown tests results obtained at room temperature with droplets of various sizes and evaporating in an air stream of variable velocity. Some tests were performed with the tube terminating

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*A 0.4 mm (diameter) suspension was used in an air stream at temperatures from 600 to 700°C.

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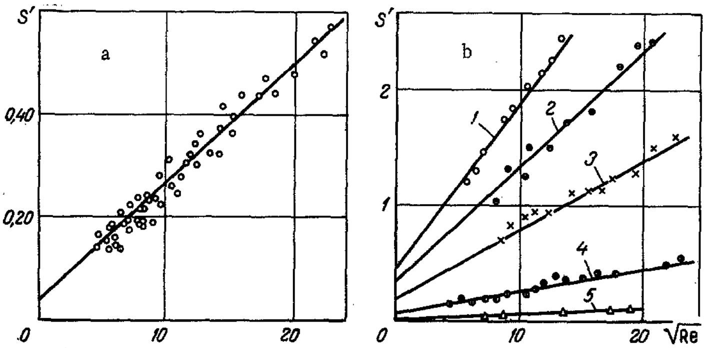

Fig. 1. Evaporation S' (mm^2/sec) as a function of √Re: a) for Freon droplets; b) for Freon droplets at air stream temperatures: 1) ϑ_s = 400°C; 2) 200°C; 3) 100°C; 4) 22°C; 5) −40°C.

into a Vetoshinskii nozzle [7]. The abscissas on the graph represent the square root of the Reynolds number referred to a droplet.

According to the graph, the evaporation rate at a given stream temperature is determined by the Reynolds number, namely:

$$S' = S_0'(1 + a\,\mathrm{Re}^{1/2}), \tag{1}$$

with S_0' denoting the evaporation rate at Re = 0. If we assume that

$$a = \beta\,\mathrm{Sc}^{1/3}, \tag{2}$$

then Eq. (1) becomes identical to the modified Frossling formula [4, 5].

In Fig. 1b are shown test results obtained at air temperatures from −40 to +400°C. The test points here represent averages of many measurements, a few tens of such measurements having been made in the experiment. According to the graphs, the test data for both high and low temperatures can closely enough be described by formula (1), with the error not exceeding a few percent. The straight line passes even through test points corresponding to the air stream temperature ϑ_s = 600 and 750°C.

The numerical values of S_0' (measured in cm^2/sec) and β according to formulas (1) and (2), respectively, as well as of the droplet temperature ϑ_d, are given in Table 1, which indicates that S_0' and ϑ_d increase with rising air stream temperature ϑ_s, while β is equal to 0.28 and almost independent of ϑ_d. This value for β agrees fairly well with values obtained for it by other authors studying the evaporation of droplets [5].

TABLE 1. Values of S_0', β, and ϑ_d at Various Air Stream Temperatures

ϑ_s, °C	—40	—30	—15	0	22	100	200	300	400	600	750
$S_0' \cdot 10^4$, test	0,87	1,4	2,24	3,3	6,0	16,4	29	34	44	67	90
$S_{02}' \cdot 10^4$, calc.	1,0	1,5	2,6	4,3	6,8	18	—	—	—	—	—
$S_{01}' \cdot 10^4$, calc.	1,0	1,5	2,7	4,6	7,5	23	—	—	—	—	—
ϑ_d, test	—43	—37	—29	—20	—12	8	14	—	—	—	—
ϑ_d, calc.	—45	—38	—29	—21	—13	7	19	—	—	—	—
$\beta \cdot 10^2$	28	27	25	28	28	30	28	26	27	28	30

TABLE 2. Saturated-Vapor Pressure of Freon at Various Temperatures

ϑ, °C	—71	—28,2	—18,5	0	5,5	9,7	15,6	22	23
p	0,1	37,6	41,4	116,5	145,7	177,3	224,6	301	311
ϑ, °C	25,5	29	33	37,7	41	43,5	46		
p	341	383	450	538	607	665	727		

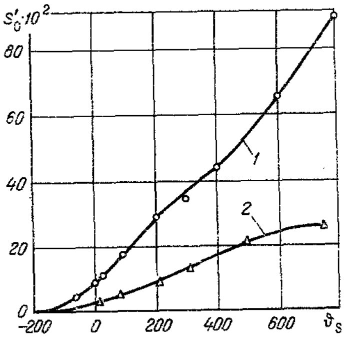

Fig. 2

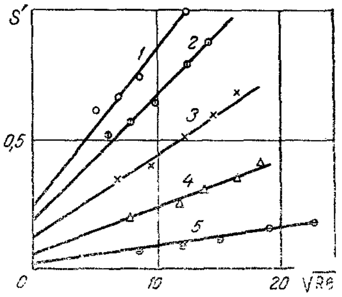

Fig. 3

Fig. 2. Evaporation rate S_0' (mm^2/sec) as a function of the air stream temperature ϑ_s for droplets of Freon (1) and water (2).

Fig. 3. Evaporation rate S' (mm^2/sec) as a function of $\sqrt{Re}$, for water droplets in an air stream at temperature: 1) 700°C; 2) 500°C; 3) 300°C; 4) 200°C; 5) 100°C.

The relation between S_0' and ϑ_s is presented graphically in Fig. 2.

Freon droplets ignite in an air stream sometimes at 750°C and always at $\vartheta_s > 750$°C.

In order to compare theoretical and experimental values of various parameters involved in the evaporation of tetrafluorodibromomethane droplets, it was necessary to measure the saturated-vapor pressure at various temperatures, the diffusivity D, and the heat of evaporation L of this substance. Results of these measurements are given in Table 2, with the pressure p expressed in millimeters of a mercury column. At temperature ϑ up to 23°C the pressure was measured statically, at temperatures $\vartheta > 23$°C it was measured dynamically. The accuracy of the pressure measurement at −71°C was 50%.

The diffusivity of Freon vapor into air was determined from data on the evaporation rate of tetrafluorodibromomethane from a vertical glass tube 8 mm in diameter, 7.1 cm^2/sec at 23°C.

The molar heat L of Freon evaporation was determined from measurements of the vapor pressure within the +9.7 to −23.2°C temperature range and from measurements of the quantity of heat necessary for evaporating a certain mass of liquid, evaluated then according to the Trouton–Pictet rule. The average value of L thus obtained was $6.4\cdot 10^3$ cal/mole ($2.68\cdot 10^4$ J/mole).

It is interesting to compare our test data with those obtained by Polishchuk in his study [1] of water droplets evaporating in an air stream within the 100–700°C temperature range.

In Fig. 3 we show our evaluation of Polishchuk's data. In that case too all points fit closely on straight lines not passing through the origin of coordinates but satisfying Eqs. (1) and (2) at β values within the 0.28–0.30 range.

Thus, the dependence of S' on Re is described by Eqs. (1) and (2) over a wide range of temperatures, for either water or Freon.

With the aid of the well-known Maxwell equation, it is not difficult to show that

$$S_0' = \frac{8\pi D\Delta c}{\rho}. \tag{3}$$

The values of S_{01}' and S_{02}' for Freon in Table 1 have been calculated according to formula (3). The diffusivity D was referred to temperature $\vartheta = (\vartheta_s + \vartheta_d)/2$ for calculating S_{01}' and to temperature $\vartheta = \vartheta_d$ for calculating S_{02}'.

At $\vartheta_d \le 100$°C the values of S_{01}' and S_{02}' in the Table agree fairly well with the test values, S_{02}' better than S_{01}'.

The test values of S_0' for water droplets were $2.7\cdot 10^{-4}$, $7.2\cdot 10^{-4}$, and $13.2\cdot 10^{-4}$ cm^2/sec at air temperatures 100, 200, 300°C and $\beta = 0.30$, 0.30, 0.28, respectively. The S_0' values calculated according to the Maxwell formula with D referred to the mean temperature are respectively $2.3\cdot 10^{-4}$, $6.6\cdot 10^{-4}$, and $13.2\cdot 10^{-4}$ cm^2/sec.

The calculated values agree fairly well with the test data.

The values of S_0' at $\vartheta_s = 500$ and 700°C are approximately 50% higher than those obtained in tests.

According to Fig. 2, the S_0' vs ϑ_s curve for Freon at air stream temperatures not above 500°C comes close to the $S_0'(\vartheta_s)$ curve for water, while at temperatures above 500°C the Freon curve rises sharply. One may speculate that this rise is due to an increase in the heat supply to a droplet through the quartz support. Calculations have shown, however, that the quantity of heat supplied to a droplet through the support does not exceed 5% of the heat used for evaporation, even at 750°C. At air stream temperatures above 500°C, apparently, radiation along with chemical processes and Stefan flux begins to play a significant role. Unfortunately, their effect could not be accounted for quantitatively, because the optical properties of Freon and the kinetics of its chemical conversions had not been studied yet, also because the temperature of very fast evaporating Freon droplets could not be reliably measured. The evaporation of droplets at a temperature near their boiling and ignition points must be still further and thoroughly studied, although some preliminary studies on this subject have already been reported in [6].

If the evaporation of Freon droplets is considered a quasisteady process, then for the range of moderate temperatures one can write

$$\mathrm{Nu}\,\lambda\Delta\vartheta = \mathrm{Sh}\,D\Delta c L. \tag{4}$$

With the Nusselt number Nu and the Sherwood number Sh calculated from existing formulas, with the value of D and L already determined, and with the temperature (ϑ) characteristic of the concentration c known, one can then find the temperature of a Freon droplet. The results of such calculations are given in Table 1, where a closed agreement between theoretical and experimental values will be noted.

At moderate temperatures of the air stream S_0' is a rather simple function of the droplet temperature T_d. Indeed, it follows from (4) that

$$S_0' = B\exp\left(-\frac{L}{RT_d}\right), \tag{5}$$

with coefficient B varying rather slightly with a change in temperature T_d. The curve of $\ln S_0'$ (ordinates) vs $1/T_d$ (abscissas) based on values taken from Table 1 for the −40 and +100°C temperature range is fairly close to a straight line. Here L = 6900 cal/mole with B assumed temperature dependent, and L = 7400 cal/mole with B assumed constant.

The test points obtained by Polishchuk for 100, 200, and 300°C also fit closely on a straight line, different from ours. In his case L = 1240 cal/mole.

NOTATION

S	is the surface area of a droplet;
S'	is the rate of change of droplet surface;
S_0'	is the rate of change of droplet surface at Re = 0;
ϑ_d	is the droplet temperature;
ϑ_s	is the air stream temperature;
β	is the coefficient;
L	is the heat of evaporation;
ρ	is the density;
D	is the diffusivity;
Δc	is the difference between vapor concentration at a droplet and in the medium;
λ	is the thermal conductivity;
Re	is the Reynolds number;
Sc	is the Schmidt number;
Sh	is the Sherwood number.

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