Int. J. Heat Mass Transfer. Vol. 24, No. 4, pp. 611–620, 1981
Printed in Great Britain

0017-9310/81/040611-10 $02.00/0
Pergamon Press Ltd

HEAT AND MASS TRANSFER OF A LIQUID DROP EVAPORATING INTO A FLOW OF GAS CAPABLE OF CONDENSING

P. I. Lebedev, S. S. Rybanin and L. N. Stesik
Chernogolovka Branch of the Institute of Chemical Physics of the U.S.S.R. Academy of Sciences, U.S.S.R.

(*Received* 25 *June* 1979)

Abstract—Results of experimental investigation of a liquid nitrogen droplet evaporating into a flow of carbon dioxide, helium, nitrogen and water vapour and of a diethyl ether droplet evaporating into a flow of water vapour at atmospheric pressure are reported. The gas flow temperature varied from 20 to 400°C. The Reynolds numbers ranged from 3 to 600, the Prandtl numbers, from 0.3 to 1.0 and the heat- and mass-transfer parameter, from 1.5 to 15. Both volumetric and surface condensation of the ambient gas have been detected. It has been established that in the case of volumetric condensation the heat-transfer rate described by the Stanton number is related to the Peclet and Prandtl numbers and the heat- and mass-transfer parameter as

$$St = \frac{2\ln(1+B)}{B \cdot Pe}(1 + 0.276 Pe^{1/2} Pr^{-1/6}).$$

A conclusion has been made that heat and mass transfer is the process which limits volumetric condensation.

NOMENCLATURE

a, thermal diffusivity;
B, $= \dfrac{h_e - h_s}{h_s - h_d}$, heat- and mass-transfer parameter;
C, weight concentration;
c_p, specific heat at constant pressure;
d, diameter of a droplet;
d_f, diameter of quartz filament;
D diffusion coefficient;
h, enthalpy of a unit mass;
L, evaporation heat;
$\dot{m}$, mass flow;
Nu, $= \dfrac{\alpha d}{\lambda}$, Nusselt number;
Pe, $= \dfrac{ud}{a}$, Peclet number;
Pr, $= \dfrac{\mu}{\rho a}$, Prandtl number;
Q, condensation heat;
Q_s, heat flux to the droplet;
Q_f, heat flux to the droplet through the quartz filament;
R, curvature radius of the droplet at the forward stagnation point;
Re, $= \dfrac{\rho u d}{\mu}$, Reynolds number;
Sc, $= \dfrac{\mu}{\rho D}$, Schmidt number;
Sh, $= \dfrac{\beta d}{D}$, Sherwood number;
St, $= \dfrac{Q_e}{\rho u(h_e - h_s)}$, Stanton number;
S, surface area of droplet;
T, temperature [K];
t, temperature [°C];
u, gas flow velocity.

Greek symbols
α, heat-transfer coefficient;
β, mass-transfer coefficient;
δ, distance between the condensation front and the droplet surface;
λ, thermal conductivity;
μ, dynamic viscosity;
ρ, density;
τ, time;
ϑ, non-dimensional rate of droplet evaporation.

Subscripts
d, droplet;
e gas flow;
f, quartz filament;
s, droplet surface.

INTRODUCTION

A KNOWLEDGE of the laws governing the process of evaporation from a drop of liquid is essential for the solution of involved engineering problems facing a designer of various power plants, for the understanding and management of various technological processes occurring, for example, in the production of a number of substances in chemical reactors. A close scrutiny of separate minute details of the process of evaporation of drops is also important to solve imminent problems of preventing and fighting pollution of the environment.

A considerable amount of research, both experimental and theoretical [1–9], has been devoted to the problem of evaporation of liquid droplets. However, the knowledge of evaporation of droplets in chemically reacting media is far from being complete. The explanation lies in the extreme complexity of the processes occurring in such systems. For this reason, the study of separate aspects of the process taking place under such complicated conditions is undoubtedly of great interest.

A non-dimensional analysis of heat- and mass-transfer equations shows that the process of evaporation from a droplet is characterized by the Sherwood and Nusselt numbers which depend on the Reynolds, Schmidt or Prandtl numbers and the heat- and mass-transfer parameter, i.e.

$$Nu = Nu(Re, Pr, B)$$

or

$$Sh = Sh(Re, Sc, B). \qquad (1)$$

Studies of the laws governing evaporation from a liquid droplet in an inert gas flow were initiated by the works of Frössling [1], Ranz and Marshall [2]. The first accurate measurement of the rate of evaporation from a droplet placed in a gas flow was made by Frössling. He experimented with drops of water, aniline and nitrobenzene suspended in an air flow above the wind tunnel outlet hole. The gas flow velocity varied from 0.2 to 0.7 m/s and the Reynolds number, from 2.3 to 1280. Under these conditions the droplet evaporation was found to be most accurately described by the relationship

$$Sh = 2(1 + 0.276\,Re^{1/2}Pr^{1/3}). \qquad (2)$$

In the experiments conducted by Ranz and Marshall, a droplet of water on the tip of a microburet was placed in an air flow. The gas flow temperature varied from 20 to 220°C and the Reynolds number did not exceed 200. The results are in good agreement with equation (2).

A comprehensive analysis of the early analytical and experimental studies of evaporation from a liquid droplet is given in the book by Fuks [3].

Rowe, Claxton and Lewis [4], having analyzed more recent experimental data pertaining to heat and mass transfer of a sphere in a flow with $Re < 2000$, obtained the relationship

$$Nu = 2 + 0.69\,Re^{1/2}Pr^{1/3}. \qquad (3)$$

Further studies of a drop evaporating into a gas flow were aimed at elucidation of the effect of various flow parameters on the rate of evaporation. Thus, Blinov and Dobrovol'skaya [5] investigated the effect of temperature on a tetrabromidifluorethane droplet evaporating in an air flow. The air temperature varied from 40 to 750°C and the Reynolds number, from 25 to 500. The data obtained are described by relation (2) with an accuracy of $\pm 10\%$.

In one of the recent studies on droplet evaporation Yuen and Chen [6] presented the data on water and methanol droplets evaporating into the flow of air with the temperature of the latter within 150–960°C. The purpose of this work was to determine the effect of temperature on heat transfer. A droplet specimen of about 6.5 mm in diameter was placed into the air flow the velocity of which varied from 2.4 to 11.4 m/s. The experiments were carried out for the Reynolds number range from 200 to 2000. The results obtained are fitted by the following relationship

$$Nu(1 + B) = 2 + 0.6\,Re^{1/2}Pr^{1/3}. \qquad (4)$$

Note that in all the works quoted above the heat- and mass-transfer parameter which determines the intensity of evaporation did not exceed 0.5, while an increase of B had a considerable effect on droplet evaporation. On the one hand, it leads to an increase in the enthalpy difference between the flow and the droplet surface and to intensification of evaporation. On the other hand, intensification of evaporation increases the flow of matter from the droplet surface thus impeding an increase in the heat-transfer rate. From this point of view, for the systems with a high heat- and mass-transfer parameter, as is the case of a hydrocarbon fuel droplet evaporating during its combustion in an oxidizing flow ($B \sim 6$–7), the following relationship, suggested by Spalding [7] and refined by Agoston, Wise and Kosser [8], is more acceptable and physically justified

$$\frac{\dot{m}}{\dot{m}_0} = 1 + 0.276\,Re^{1/2}Pr^{1/3} \qquad (5)$$

where

$$\dot{m}_0 = \frac{4\pi r\lambda}{c_p}\ln(1 + B)$$

is the evaporation rate in the absence of convection.

Thus, even at small values of the heat- and mass-transfer parameter no relationship has been obtained which would unambiguously describe the process of drop evaporation. And as to the B's much in excess of unity and the occurrence of condensation of the surrounding medium species, thus far there have been almost no experimental data available [9]. However, investigation of this process and elucidation of the basic laws governing it are needed to, for example, understanding and calculation of such a practically important case as combustion of a metal particle in an oxidizing medium [10].

In order to investigate all the aspects of the process which comprises evaporation, heat and mass transfer and condensation, acting simultaneously, the present authors have made a detailed study of a cryogenic liquid droplet evaporating into a CO_2- and water vapour containing (i.e. capable of condensing) flow over wide ranges of the heat and mass transfer parameter and the Peclet and Prandtl numbers.

EXPERIMENTAL APPARATUS AND TECHNIQUE

In investigating evaporation of a drop into a medium capable of condensing, a droplet of liquid nitrogen was placed into a gas flow of a rectangular velocity profile, constant composition and tempera-

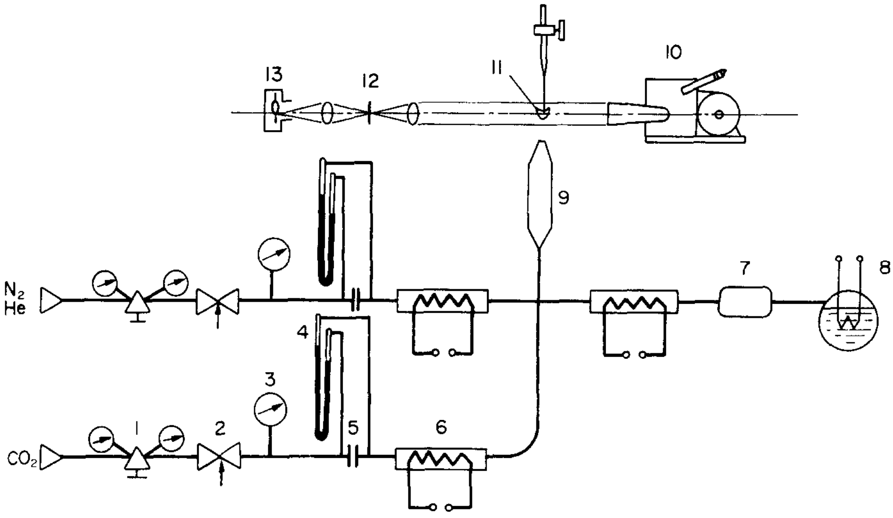

FIG. 1. A schematic of the experimental set-up: 1, reducing valve; 2, fine adjustment valve; 3, standard pressure gauge; 4, U-shaped pressure gauge; 5, flow rate diaphragm; 6, heater; 7, receiver; 8, evaporator; 9, Vitoshinsky nozzle; 10, cine camera; 11, evaporating droplet; 12, optical system; 13, mercury lamp.

ture. The schematic of the experimental set-up is shown in Fig. 1. The rectangular velocity profile of the gas flow was produced by the Vitoshinsky nozzle 20 mm in diameter [11]. The carbon dioxide and nitrogen (or helium) flows were adjusted separately. Their magnitude was preset by the flow rate restrictors regulated by valves of fine adjustment and determined by standard and U-shaped pressure gauges. Water vapour was introduced into the gas flow from an evaporator which was a glass vessel filled with distilled water into which a Nichrome spiral was immersed. Passage of an electric current through the spiral initiated liquid boiling and water vapour formation. A 2-l. receiver was used to compensate for flow fluctuations. Measurements of the gas flow velocity by a platinum hot-wire anemometer with a 20 μm dia., 4 mm long filament have demonstrated a high stability of velocity and the absence of fluctuations.

The gas mixture was heated up to 400°C by Nichrome heaters. The gas temperature was measured with a 50 μm dia. platinum–platinum rhodium thermocouple at the Vitoshinsky nozzle outlet.

A droplet of liquid nitrogen was suspended in the gas stream on a thin quartz filament 40–50 μm in diameter and 10–50 mm in length, at the end of which a small glass ball 300–400 μm in diameter was soldered. The droplet was held at a distance of 17 mm away from the nozzle exit in the core of the upward gas flow. The liquid nitrogen droplet was evaporated at room temperature ($t_e = 20°C$) into a carbon dioxide–nitrogen (or helium) mixture with the CO_2 concentration by weight equal to 1.0, 0.75, 0.5, 0.33, 0.1, 0.05, 0.0. At the temperature of the gas flow being 200°C, the concentration of carbon dioxide in a mixture with nitrogen was 1.0, 0.5 and 0.0. The temperature of 200°C was also used in the study of droplet evaporation into a nitrogen–water vapour flow, with water vapour concentration being 1.0 and 0.5, and into a water vapour–carbon dioxide mixture. At $t_e = 400°C$ concentration of carbon dioxide in a mixture with nitrogen was 1.0, 0.5 and 0.0. The gas flow velocity varied from 0.03 to 2.5 m/s. The initial size of the liquid nitrogen droplet varied from 1.0 to 1.5 mm and depended on the quartz filament thickness and the glass ball diameter.

Droplet evaporation was recorded by a "Pentazet-35" motion picture camera with the survey frequency of 140 and 300 frames/s and the use of the shadowgraph method. The evaporating droplet was illuminated by a parallel beam of light produced by a mercury lamp, two lens condensers and an aperture. The camera was calibrated by filming a metal rod of known diameter. The magnification factor was 7.

Each experiment commenced with setting the required gas and water vapour flow rates and measuring their temperatures. Next to this, the Vitoshinsky nozzle was closed with a gate (not shown in Fig. 1) which diverted the gas stream from the droplet. Suspension of a liquid nitrogen droplet from the glass ball was achieved following the technique suggested by Pereverzev [9]. It is this: a clean dry glass funnel (60–70 mm high, about 20 mm in diameter in the upper part, with an about 0.5 mm dia. tip bent at a right angle to the axis) is first immersed into the Dewar flask filled with liquid nitrogen. On having been cooled down to the liquid nitrogen temperature, it is taken out still full of liquid nitrogen. The latter escapes the funnel through a tip as a thin fuming jet which is directed onto the glass ball at the end of the quartz filament. After a period of time ($\sim$5–7 s) during which the glass ball is cooled down to the liquid nitrogen temperature, a liquid nitrogen droplet is formed on its surface. The moment the droplet is formed the gate in the Vitoshinsky nozzle is opened and the camera is turned on.

Evaporation went on for 0.3–2.0 s depending on the conditions of experiment. Each experiment was run twice. From 100 to 300 motion pictures featuring droplet evaporation were taken in each one experiment, 10 to 15 of which were measured, i.e. the magnitudes of a few chords (minimum seven) intercepted on the droplet vertical axis were determined. From these data, assuming that the droplet is a body of revolution, the surface area of the droplet, its volume and the diameter of an equidimensional sphere (effective diameter d) were calculated. The results of calculations were used for plotting the dependence of the droplet surface area on time $S(\tau)$, which was then approximated by the least square method. The approximation equation gave the derivative of the droplet surface area with respect to time $\mathrm{d}S/\mathrm{d}\tau$, which, together with the effective diameter d, were used to calculate

$$St = \frac{\rho_d L_d}{4\pi \rho u d(h_e - h_s)} \cdot \left|\frac{\mathrm{d}S}{\mathrm{d}t}\right| \tag{6}$$

the nondimensional rate of droplet evaporation

$$\vartheta = \frac{\rho_d c_p}{8\pi\lambda} \cdot \left|\frac{\mathrm{d}S}{\mathrm{d}t}\right| \tag{7}$$

and the Reynolds and Peclet numbers.

In the calculations performed, thermal conductivity λ, heat capacity c_p and the gas viscosity μ were assumed to be equal to the average of their values in the flow and at the droplet surface. The value of each of these parameters in the gas flow was calculated from the formulae given in [13, 14].

When calculating the difference between the enthalpies in the surrounding fluid and at the droplet surface, it was assumed that

$$h_e - h_s = c_p(T_e - T_d) + CQ \tag{8}$$

where C is the concentration of the substance capable of condensing, T_d is the drop temperature which, under the conditions of vigour evaporation, was assumed to be equal to the boiling temperature of the droplet substance.

The experimental data obtained were all processed on an electronic computer.

In evaluation of the accuracy of the experimental data obtained in [12], it was revealed that the error in determining the Stanton number was 8%, the nondimensional evaporation rate, 6%, and the Reynolds number, 10%, the latter being mainly due to averaging of the Reynolds number in every experiment over its values at the beginning and at the end of evaporation. The error in measuring the ratio between the condensation front distance from the droplet surface at the forward stagnation point and the curvature radius at this point, δ/R, amounted to 8%.

Table 1. Effect of the quartz filament diameter on the liquid nitrogen droplet evaporation rate (ϑ^*, evaporation rate in a carbon dioxide flow, ϑ^{**}, evaporation rate in a nitrogen flow)

d_f(μ)	ϑ^*	ϑ^{**}
300	9,6	4,0
100	7,8	3,5
43	7,3	3,3
0	6,9	3,2

Since a droplet of liquid nitrogen was not isolated but suspended from a glass ball, particular attention was given to the thermal effect of the quartz filament and glass ball on evaporation. In a steady state, the energy equation for an evaporating droplet is of the form.

$$Q_e + Q_f = \dot{m}(h_s - h_d) \tag{9}$$

where h_s and h_d are the enthalpies of the gas and liquid. The effect of heat addition through the quartz filament can be neglected when

$$\frac{Q_f}{Q_e} \ll 1.$$

That the magnitude of Q_f could be evaluated, the rate of droplet evaporation was measured with different diameters of the quartz filament, d_f (Table 1). The evaporation rate corresponding to $d_f = 0$ was obtained by means of extrapolation.

Since in the majority of experiments the quartz filament diameter was 40–45 μm, then for $d_f = 43$ μm one can obtain from the data of Table 1 that

$$\frac{Q_f}{Q_e} \simeq 0.05$$

when a droplet of liquid nitrogen evaporates into a carbon dioxide stream at 20°C and

$$\frac{Q_f}{Q_e} \simeq 0.03$$

when it evaporates into a nitrogen flow at the same temperature. Thus, heat addition through the filament has a small effect on the evaporation rate and the error introduced is within experimental error. Radiative heat transfer was neglected.

EXPERIMENTAL RESULTS

Figure 2 presents typical shadow pictures of a droplet of liquid nitrogen in a flow of gaseous nitrogen (Fig. 2a) and in a flow of carbon dioxide mixed with nitrogen (Fig. 2b and c). Evaporation of the droplet in the CO_2–N_2 flow was accompanied by accumulation around it of the CO_2 condensation products. In a shadow picture these look like a grey mist surrounding the droplet. Depending on the magnitude of CO_2 concentration and the flow velocity, condensation had

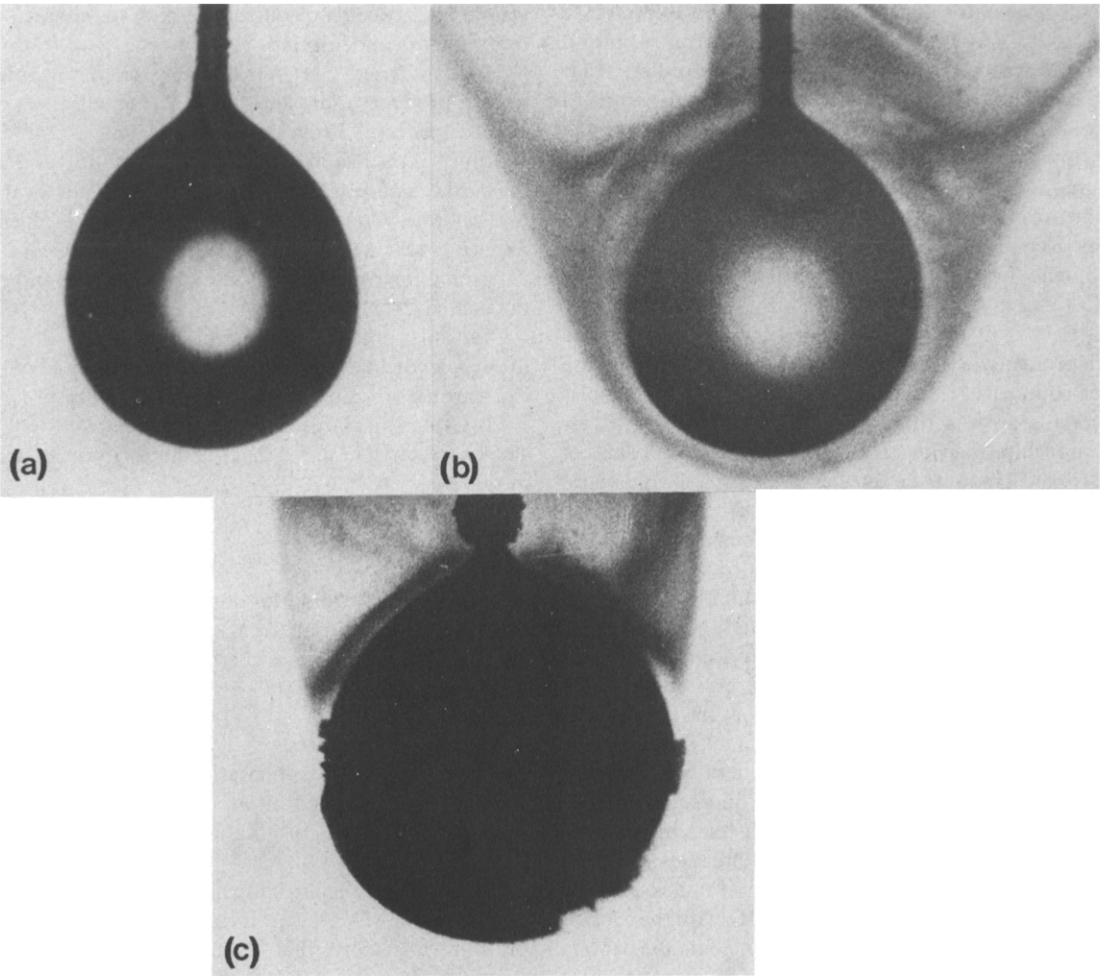

FIG. 2. Liquid nitrogen droplet in a flow of : (a) nitrogen; (b, c) carbon dioxide mixed with nitrogen.

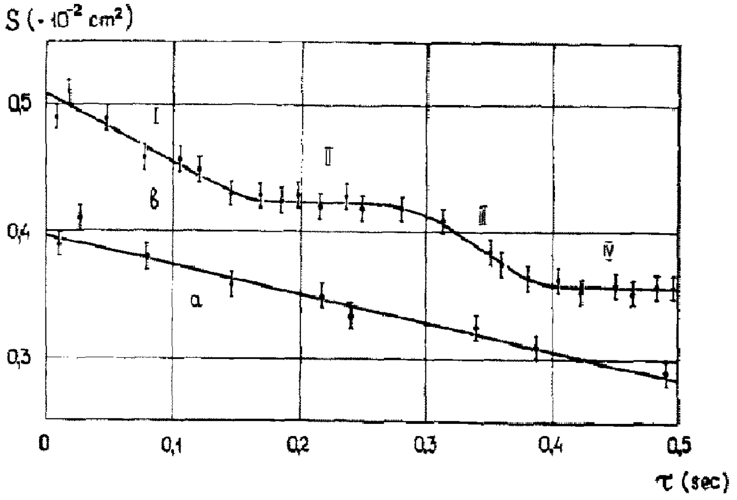

FIG. 3. Time dependence of the droplet surface area: (a) condensation in the volume of the flow, $\rho u = 0.95$ kg/m^2 s; (b) condensation on the droplet surface, $\rho u = 2.9$ kg/m^2 s.

both volumetric and surface character. In the first case (Fig. 2b), CO_2 condensation front is sharply visible on the upstream side of the droplet and the droplet itself is transparent as evidenced by a light spot in the center of its picture. In the second case (Fig. 2c), no condensation front is observed and only a tail of condensation products is visible in the wake of the droplet; the droplet is opaque and its upstream side is covered by a condensed carbon dioxide film. These are convincing indications of the surface condensation of CO_2.

Each of these two regimes had a corresponding time dependence of the droplet evaporation rate. In the case of volumetric condensation, a change in the droplet surface area is rather well described by linear relationship (Fig. 3a). In the other words, the process of droplet evaporation in the presence of volumetric condensation obeys the Sreznevsky law: $dS/d\tau$ = const. In the second case, the relationship between the surface area and the time is much more complex. At the beginning the droplet is transparent and a graph of its surface area vs time gives a straight line (Fig. 3c, segment I), but as evaporation proceeds, the CO_2 condensate particles make their appearance on the droplet surface and subsequently coat the frontal part of the droplet by a continuous film (Fig. 2c). The droplet becomes opaque and the tail of condensation products in its wake becomes less dense. The rate of change of the surface area with time diminishes (segment II). This is followed by breakaway of the condensate film from the surface and increase of the surface area change rate (segment III), with the droplet being still opaque. Then, a new film coats the droplet (segment IV). A sequential process of formation and breakaway of the condensate film recurs until the droplet evaporates completely. This evaporation pattern can be explained by frustration of the volumetric condensation and its transition on to the droplet surface due to the characteristic time of heat and mass transfer, τ_{hm}, becoming comparable with the characteristic time of condensation, τ_c.

The condensed CO_2 film forming on the droplet surface produces a drastic change in the entire evaporation process. From the data obtained, only a qualitative conclusion can be drawn as to the fact that the surface condensation decreases the droplet evaporation rate. Complete elucidation of this problem requires such methods which would allow accurate determination of the condensate film structure and of the coated droplet geometry.

Transition of condensation from the volume around the droplet on to the droplet surface was observed only in a pure carbon dioxide flow at room temperature (t_e = 20°C) at rather large Reynolds numbers ($Re \sim 600$). The characteristic time of heat and mass transfer was in this case

$$\tau_{hm} = \frac{d^2}{a \cdot Nu^2} \simeq 10^{-4}\ \mathrm{s}.$$

The facility did not allow for observation of the process of such transition in mixtures of carbon dioxide with nitrogen and other gases, therefore the main part of our experimental data relates to volumetric condensation.

The results of the present study allow us to conclude that the volumetric condensation has a considerable effect on droplet evaporation. For illustration, Fig. 4 gives the droplet evaporation rate as a function of the Reynolds number at different concentrations of CO_2. It can be clearly seen from this figure that volumetric condensation of CO_2 can increase the droplet evaporation rate more than twice. Indeed, when the Reynolds number is constant, an increase of CO_2 concentration in the flow first up to 10% and then up to 50 and 100% results in the increase of the droplet evaporation rate by a factor of 1.4, 1.7 and 2.2, respectively.

In order to change the conditions of heat and mass

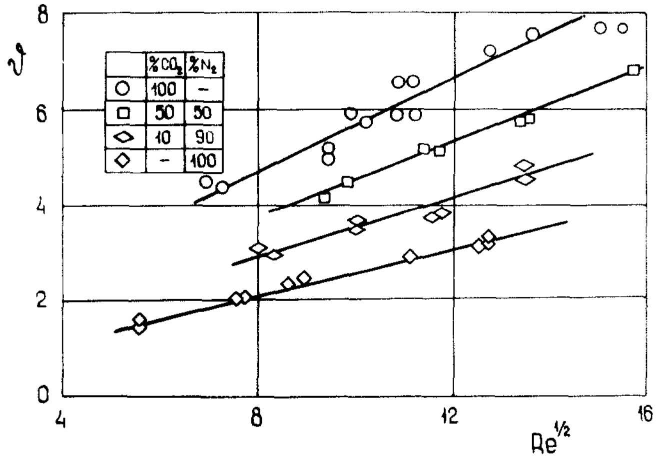

FIG. 4. Non-dimensional rate of droplet evaporation as a function of the Reynolds number (t_e = 20°C).

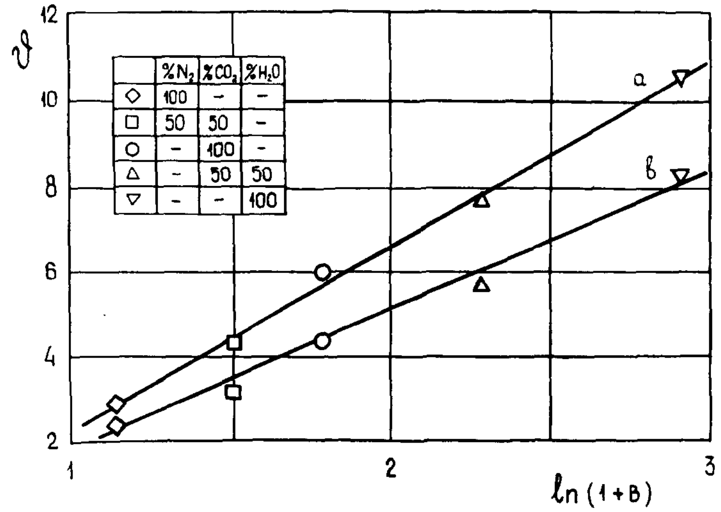

FIG. 5. Dependence of the nondimensional rate of droplet evaporation on the heat- and mass-transfer parameter; (a) t_e = 200°C; Re = 57; (b) t_e = 200°C, Re = 27.

transfer between the droplet and the gas flow and to study the effect of temperature on evaporation in the presence of condensation, the gas flow was heated up to 200 and 400°C. At 200°C, evaporation of a liquid nitrogen droplet in water vapour flow was studied. Unfortunately, in this case we failed to obtain sharp pictures of the condensation front. This is likely to be due to weak scattering of light by the water vapour condensation products which could not be recorded with the instruments employed. But the liquid nitrogen droplet remained transparent and no foreign inclusions appeared on its surface throughout its evaporation in the flow of water vapour. This and also comparisons with evaporation of a liquid nitrogen droplet in a CO_2 and water vapour flows indicate that condensation of water vapour under the conditions studied is volumetric.

Investigation of a liquid nitrogen droplet evaporating into a water vapour flow made it possible to considerably expand the range of the heat- and mass-transfer parameter which in the given system equals ~15. In other cases, as in a nitrogen flow of the same temperature, the value of this parameter is only ~2, and in a carbon dioxide flow, ~5.

A rather clear representation of the evaporation rate and its dependence on the parameters of heat and mass transfer between the droplet and the gas flow is furnished by the dependence of the evaporation rate on $\ln(1 + B)$ at the constant Reynolds number and flow temperature (Fig. 5). Note that under these conditions

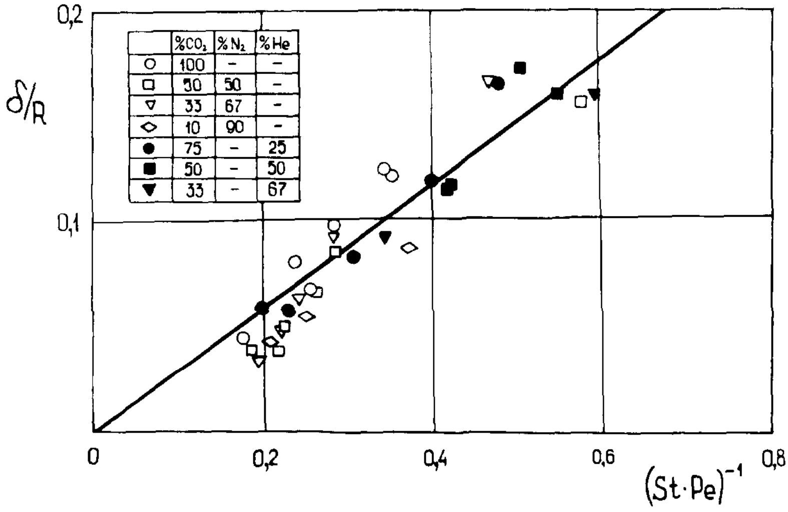

FIG. 6. Effect of the heat- and mass-transfer rate on the position of condensation front.

an increase in B is due to a change in the amount of the condensate substance in the gas flow only.

A parameter very important for understanding droplet evaporation in the presence of volumetric condensation is the position of condensation front with respect to the droplet surface. Therefore, the distance between the condensation front and the droplet surface at the forward stagnation point, δ, was measured in processing of the experimental results. It was established that an increase in the velocity of the gas flow at its constant composition and temperature leads to a decrease in δ, while an increase in carbon dioxide concentration under constant conditions of flow passage, to an increase in the distance between the condensation front and the droplet surface. It seems to be due to the fact that with an increase in the evaporation rate and CO_2 concentration the flow of substance from the droplet surface increases. In Fig. 6, the ratio of the distance δ to the droplet curvature radius at the forward stagnation point is presented as a function of $(St \cdot Pe)^{-1}$. The experimental data given in this figure refer to the liquid nitrogen droplet evaporation in the flow of carbon dioxide mixed with nitrogen and helium at 20°C and are well correlated by the relationship

$$\frac{\delta}{R} = \frac{0.296}{St \cdot Pe}. \tag{10}$$

When the liquid nitrogen droplet evaporates into a flow of carbon dioxide, nitrogen and water vapour, the Prandtl number is close to unity. Thus, for a CO_2 flow at $t_e = 20°C$, it is 0.77, at $t_e = 200°C$, 0.69, and at $t_e = 400°C$, 0.61. For a nitrogen flow at 20°C it is 0.84 and for a water vapour flow, 0.96. To expand the Prandtl number range, helium was introduced into the flow. An increase of helium concentration in the gas flow up to 100% made it possible to decrease the Prandtl number down to 0.31.

The use of a cryogenic liquid, liquid nitrogen ($T_d = 77K$), as an object of study of droplet evaporation in the medium capable of condensing could impart to the evaporating process the specific features typical of such low-temperature fluids only. To get rid of doubt and to prove universality of the results obtained, a series of experiments has been carried out with evaporation of a droplet of diethyl ether, with the boiling temperature of 35°C, in water vapour flow. The gas temperature was 130°C and the weight concentration of water vapour mixed in the flow with nitrogen was 0.1, 0.25, 0.33, 0.5, 0.75 and 1.0. Just as in the case of a liquid nitrogen droplet evaporating into water vapour, the pictures featuring evaporation of the ether droplet failed to show a clear-cut condensation front. But the appearance of the droplet and the linear dependence of its surface area on time indicate that in this case too a volumetric condensation of water vapour persisted throughout the evaporation process.

A total of 600-plus experiments has been conducted with liquid nitrogen evaporating from a droplet into a flow of carbon dioxide, nitrogen, helium and water vapour and with a diethyl ether droplet evaporating into water vapour flow. Based on the results obtained for the volumetric condensation, it can be said with confidence that in this case the droplet evaporation is

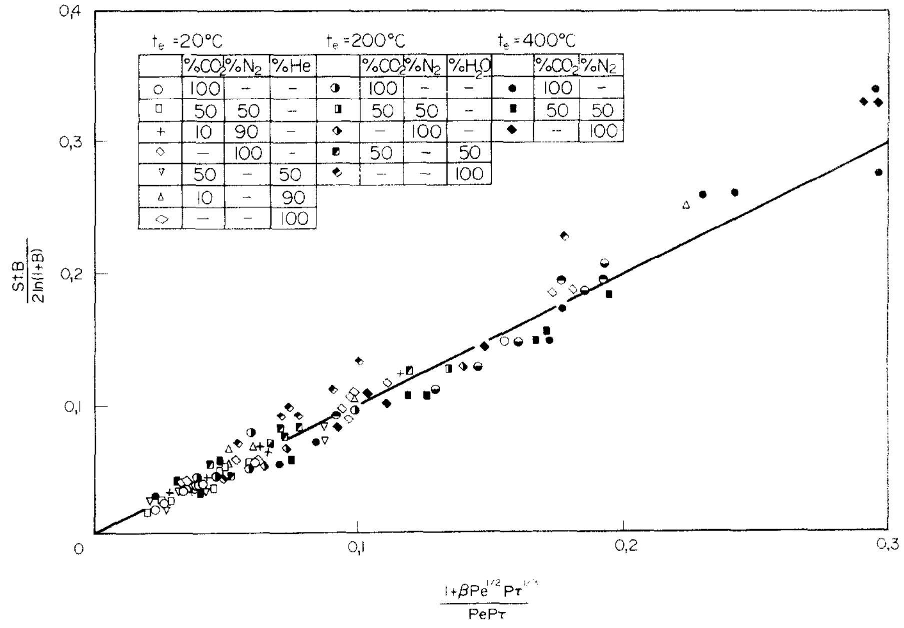

FIG. 7. Dependence of $(St \cdot B)/2\ln(1+B)$ on the Prandtl and Peclet numbers. Points ◓ and ◒ denote evaporation of a diethyl droplet in a flow of water vapour at concentrations 1.0 and 0.5, respectively ($t_e = 130°C$).

best described by the relationship

$$St = \frac{2\ln(1+B)}{B\cdot Pe}(1+0.276\,Pe^{1/2}Pr^{1/6}). \quad (11)$$

As an illustration of this conclusion, Fig. 7 shows a plot of $(St\cdot B)/2\ln(1+B)$ vs $(1+0.276\,Pe^{1/2}Pr^{-1/6})/Pe$. Here, only a portion of all experimental results is given because of almost no spread in the data in the region of small values of the group $(1+0.276\,Pe^{1/2}Pr^{-1/6})/Pe$ and because these furnish complete information on the range of change of the basic experimental parameters and on the degree of scatter in the experimental points.

Thus, in the presence of volumetric condensation the droplet evaporation process obeys the same law as the simple evaporation of a droplet and evaporation of a hydrocarbon fuel droplet during its burning in an oxidizing flow. In other words, the rate of liquid droplet evaporation is determined by the intensity of heat and mass transfer alone irrespective of whether it is due to the temperature difference between the gas flow and the droplet or the heat of condensation of the surrounding substance.

CONCLUSIONS

1. In the present paper, a liquid nitrogen droplet evaporating into a flow of carbon dioxide or water vapour mixed with nitrogen and helium and a diethyl ether droplet evaporating into a flow of water vapour mixed with nitrogen have been used to study the laws governing evaporation of droplets in a medium capable of condensing.

2. Two different regimes of droplet evaporation have been discovered depending on the nature of condensation in the surrounding medium. With condensation occurring in the volume of the flow around the droplet, the surface area of the latter decreases linearly with time. With condensation taking place on the droplet surface, the dependence of the surface area on time is non-linear.

3. In the case of volumetric condensation, the relations have been obtained for calculation of the droplet evaporation rate which are given in terms of the dependence of the Stanton number on the Peclet and Prandtl numbers and the heat and mass transfer parameter. A dependence has also been obtained of the ratio between the distance of the condensation front from the droplet surface and the curvature radius at the forward stagnation point of the droplet on the Stanton and Peclet numbers. These dependences indicate the limiting action of heat and mass transfer on droplet evaporation in the presence of volumetric condensation.

Acknowledgements—The authors want to express their gratitude to the undergraduate students N. S. Galibin and A. A. Gorin for their assistance in carrying out this meticulous work.

REFERENCES

1. N. Frössling, Über die Verdungzung Fallenden Tropfen Gerlands *Beitr. Geophys.* **52,** 170–216 (1938).
2. W. E. Ranz and W. R. Marshall, Evaporation from drops—I–II, *Chem. Engng Progr.* **48,** 161–146 (1952).
3. N. A. Fuks, *Evaporation and Growth of Drops in a Gaseous Medium.* Izd. Akad. Nauk SSSR, Moscow (1958).
4. R. N. Rowe, K. T. Claxton and J. B. Lewis, Heat and mass transfer from a single sphere in an extensive flowing fluid, *Trans. Instn Chem. Engrs* **43,** T14–T31 (1965).
5. V. I. Blinov and L. P. Dobrovol'skaya, On temperature effect on droplet evaporation in an air flow, *J. Engng Phys.* **23**(4), 686–691 (1972).
6. M. C. Yuen and L. W. Chen, Heat-transfer measurement of evaporating liquid droplets, *Int. J. Heat Mass Transfer* **21**(5), 537–542 (1978).
7. D. B. Spalding, The combustion of liquid fuels, in *Fourth International Symposium on Combustion,* pp. 847–864. William and Wilkins, Baltimore (1953).
8. G. A. Agoston, H. Wise and W. A. Rosser, Dynamic factors affecting the combustion of liquid spheres, in *Sixth International Symposium on Combustion,* pp. 708–717. Reinhold, New York (1957).
9. P. I. Lebedev, V. Ya. Pereverzev, S. S. Rybanin and L. N. Stesik, Droplet evaporation in a medium capable of condensing, *Dokl. Akad. Nauk SSSR* **219**(1), 120–123 (1974).
10. P. F. Pokhil, A. F. Belyaev, Yu. V. Frolov, V. S. Logachev and A. I. Korotkov, *Combustion of Powder Metals in Active Media.* Nauka, Moscow (1972).
11. C. Witoszynski, *Vortrage dem Gebiete der Hydro-und-Aerodynamik.* Berlin (1927).
12. G. L. Squires, *Practical Physics.* McGraw-Hill, London (1968).
13. R. S. Reid and T. K. Sherwood, *The Properties of Gases and Liquids.* McGraw-Hill, New York (1966).
14. N. B. Vargaftik, *Handbook of Thermophysical Properties of Gases and Liquids.* Nauka, Moscow (1972).

TRANSFERT DE CHALEUR ET DE MASSE POUR UNE GOUTTE LIQUIDE S'EVAPORANT DANS UN ECOULEMENT DE GAZ CONDENSABLE

Résumé—On présente des résultats expérimentaux sur une gouttelette d'azote liquide qui s'évapore dans un écoulement de gaz carbonique, d'hélium, d'azote et de vapeur d'eau de même que, sur une gouttelette d'éther diethylique d'évaporant dans un écoulement de vapeur d'eau à la pression atmosphérique. La température des gaz en écoulement varie entre 20 et 400°C. Le nombre de Reynolds est compris entre 3 et 600, le nombre de Prandtl entre 0,3 et 1 et le paramètre de transfert de chaleur et de masse entre 1,5 et 15. Les condensations volumique et surfacique du gaz ambiant ont été détectées. On a établi que dans le cas de la condensation volumique le transfert de chaleur décrit par le nombre de Stanton est lié aux nombres de Péclet et de Prandtl et au paramètre de transfert de chaleur et de masse par

$$St = \frac{2\ln(1+B)}{BPe}(1+0{,}276Pe^{1/2}Pr^{-1/6}).$$

On conclut que le transfert de chaleur et de masse est le mécanisme qui limite la condensation volumique.

WÄRME- UND STOFFÜBERGANG AN EINEM FLÜSSIGKEITSTROPFEN BEI DER VERDUNSTUNG IN EINE STRÖMUNG AUS KONDENSIERBAREM GAS

Zusammenfassung—Es wird über die Ergebnisse einer experimentellen Untersuchung zur Verdungstung eines Tröpfchens aus flüssigem Stickstoff in Strömungen aus Kohlendioxid, Helium, Stickstoff und Wasserdampf und eines Diäthyläther-Tröpfchens in eine Wasserdampfströmung bei atmosphärischem Druck berichtet.

Die Temperatur der Gasströmung wurde von 20 bis 400°C variiert. Die Reynolds-Zahlen lagen im Bereich von 3 bis 600, die Prandtl-Zahlen im Bereich von 0,3 bis 1,0 und die Wärme- und Stoffübergangsparameter im Bereich von 1,5 bis 15. Es wurde sowohl homogene Kondensation als auch Oberflächenkondensation des umgebenden Gases beobachtet. Im Fall der homogenen Kondensation wurde festgestellt, daß der Wärmeübergang, der durch die Stanton-Zahl beschrieben wird, in folgender Form mit der Peclet-Zahl, der Prandtl-Zahl und dem Wärme- und Stoffübergangsparameter verknüpft ist:

$$St = \frac{2 \ln (1+B)}{B \cdot P} (1 + 0{,}276\, Pe^{1/2}\, Pr^{-1/6}).$$

Es wurde der Schluß gezogen, daß der Wärme- und Stoffübergang die Grenzen der homogenen Kondensation bestimmt.

ТЕПЛО- И МАССОПЕРЕНОС ПРИ ИСПАРЕНИИ КАПЛИ ЖИДКОСТИ В ПОТОКЕ ГАЗА, СПОСОБНОГО КОНДЕНСИРОВАТЬСЯ

Аннотация — Приводятся результаты экспериментального исследования испарения капли жидкого азота в потоке углекислого газа, гелия, азота, паров воды и капли диэтилового эфира в потоке паров воды при атмосферном давлении. Температура потока газа изменялась от 20 С до 400 С. Диапазон изменения числа Рейнольдса составлял 3 ÷ 600, числа Прандтля 0,3 ÷ 1,0, а параметра тепло- и массопереноса 1,5 ÷ 15. Обнаружены как объемная, так и поверхностная конденсация газа окружающей среды. Получено, что в случае объемной конденсации интенсивность теплопереноса, характеризуемая числом Стантона, связана с числами Пекле и Прандтля и параметром тепломассопереноса следующим соотношением:

$$St = \frac{2 \ln (1 + B)}{B \cdot Pe} (1 + 0{,}276\, Pe^{1/2} Pr^{-1/6}).$$

Сделан вывод о том, что лимитирующим процессом в случае объемной конденсации является тепло- и массоперенос.