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RATE OF GROWTH OF DROPS DURING CONDENSATION

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Abstract—The growth of drops during condensation in direct contact between liquid drops and vapor was studied. An approximate correlation for this process was obtained from theoretical considerations. Experimental investigation of condensation of steam on water drops of three different diameters and with different initial subcooling of drops below the saturation temperature of steam was performed. High speed photography was used to analyse the growth of drops during condensation.

NOMENCLATURE

C_p, isobaric specific heat capacity;
D_i, initial drop diameter;
k, thermal conductivity;
r, local radius of sphere;
R, radius of the interface;
R_i, initial radius of drop;
T, temperature;
T_i, initial drop temperature;
T_s, saturation temperature;
ΔT, $T_s - T_i$, initial drop subcooling;
V, drop volume.

Greek letters
α, thermal diffusivity;
λ, latent heat of vaporization;
ρ, density;
θ, time.

INTRODUCTION

CONDENSATION in direct contact between vapor and liquid drops is used in mixing-type heat exchangers. As distinct from filmwise and dropwise condensation which have been studied widely, direct contact condensation has received little attention. Syhre [1] calculated the heat-transfer rate in condensation using the equation for heat conduction through a solid sphere. Brown [2] performed an experimental study of condensation of steam on a spray of water drops. For drops of 125–520 μ in size he obtained values of the heat-transfer coefficient up to 4800 Btu/hft^2°F, based on the overall heat balance. Weinberg [3] found experimentally that the heat-transfer coefficient for condensation on drops of 0·01–0·04 in. dia. had a mean value of 2400 Btu/hft^2°F. Although only a few experiments on condensation of steam on drops were performed, the results showed that heat transfer coefficients for this type of condensation are much higher than for filmwise condensation. An experimental investigation of the growth of a single drop during condensation does not yet appear to have been carried out. An approximate solution of the problem of growth rate of a drop was obtained at Moscow Energetics Institute [4]. This solution gives accurate results for the initial moment of time only.

THEORETICAL CONSIDERATIONS

In order to determine the amount of condensate formed, it is necessary to establish the rate of growth drops, d $(\rho V)/\mathrm{d}\theta$ or $\mathrm{d}R/\mathrm{d}\theta$. Only small

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drops will be considered, since they are known to behave as rigid spheres [5, 6].

The assumption will now be made that the process of vapor condensation can be treated as unsteady-state heat transfer to a solid sphere, with negligible resistance at the interface. The applicable differential equation is:

$$\frac{\partial T}{\partial \theta} = \alpha \left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \right) \qquad (1)$$

with boundary conditions

1. $T(r, 0) = T_i$ for $0 \leqslant r \leqslant R_i$; drop initially at uniform temperature
2. $R(R, \theta) = T_s$ for $\theta > 0$; drop surface immediately reaches saturation temperature
3. $\frac{\partial T}{\partial r} = 0$ at $r = 0$; symmetry
4. $k \left(\frac{\partial T}{\partial r} \right)_{r=R} = \lambda \rho \frac{dR}{d\theta}$; heat balance at the interface.

Since a solution to equation (1) with these boundary conditions has not yet been found, we use an approximate approach, considering that the heat flux at $r = R$ is the same as for a sphere with constant radius.

The appropriate temperature distribution is then:

$$T = T_s + (T_s - T_i) \frac{2R}{\pi r} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} \sin \frac{n \pi r}{R} \exp \left[- n^2 \pi^2 \frac{\alpha \theta}{R^2} \right]. \qquad (2)$$

Evaluating $(\partial T/\partial r)_{r=R}$, and inserting it into the heat balance at the interface yields:

$$\frac{d(R^2)}{d\theta} = \frac{4k(T_s - T_i)}{\rho \lambda} \sum_{n=1}^{\infty} \exp \left[- \frac{n^2 \pi^2 \alpha \theta}{R^2} \right]. \qquad (3)$$

This equation has been solved numerically, with $R = R_i$ at $\theta = 0$. Using these results, an expression which approximates the rate of droplet growth has been obtained:

$$\frac{R}{R_i} = 1 + \psi \sqrt{\left[1 - \exp \left(- \pi^2 \frac{\alpha \theta}{R_i^2} \right) \right]} \qquad (4)$$

where

$$\psi = \sqrt[3]{\left(1 + \frac{C_p(T_s - T_i)}{\lambda} \right)} - 1.$$

It will be shown that equation (4) accurately describes the experimentally observed growth rates. In the limit, when $\theta \to \infty$, it should be noted that

$$\frac{R}{R_i} = \sqrt[3]{\left(1 + \frac{C_p(T_s - T_i)}{\lambda} \right)}$$

which may also be obtained from an overall heat balance.

EXPERIMENTAL APPARATUS

An experimental apparatus similar to one built by Garner and Kendrick [9], was used for the photographic investigation of droplet growth. Steam was supplied from a boiler. It flowed through a cubical settling-chamber at low velocity (usually less than 0·2 ft/s). The steam was accelerated after the chamber through a nozzle, reducing the velocity nonuniformity. Two screens were mounted in a duct 4 in. apart to reduce turbulence. To further reduce the turbulence and obtain a flat velocity profile at the inlet of the working section, a contraction (designed by Fulford [10]) was built.

Upward flow of steam in the working section retarded the drops and made possible longer contact times. The square working section was made of perspex. Hot air was supplied between double walls to prevent condensation on the inner walls of the section. The drop producing unit was mounted at the top of the working section. Single drops of a certain size were produced by stainless steel hypodermic needles. Two needle diameters were used, 0·127 mm i.d., 0·254 mm o.d. and 0·0762 mm i.d., 0·178 mm o.d., in an attempt to obtain the smallest drops possible. Drops formed at the tip of the needle and after achieving a certain size detached and

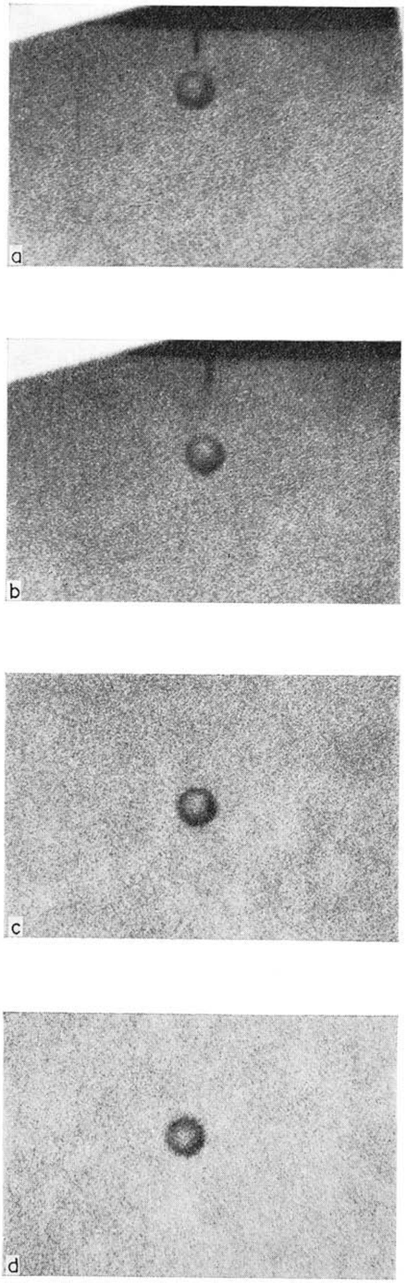

FIG. 1. Drop during condensation; $D_i = 1{\cdot}67$ mm, $\Delta T = 34{\cdot}4$°C;

(a) 0·0051 s after separation from hypodermic needle;
(b) 0·0097 s later; (c) 0·397 s later; (d) 0·792 s later.

fell through the working section. For different initial temperatures of drops, a water-cooled jacket was built around the nozzle. Steam and feed water temperatures were measured by thermocouple. Drops were photographed with a high speed camera, Hycam model K2004E, using back lighting. The number of frames per second was found to vary during the photographing and for different runs. It ranged from 2000–5000 frames per s. A milli-Mite timing light generator (model TLG-3) was used to mark the films every hundredth of a second.

RESULTS

Using the hypodermic needle of 0·254 mm o.d., drops of 1·76 mm dia. were produced. Five temperature differences, ΔT, between the saturation temperature of steam and initial temperature of the drop were realized. Heat transferred from vapor to water in the needle was shown to be negligible, by calculation. No condensation was observed on the needle. The drops were, of course, heated during formation. The increment of drop temperature during formation was calculated using an approximate correlation for heat flux, taking into account the variation of drop diameter during formation [8]. The 0·178 mm o.d. needle produced drops of 1·51 mm dia. Four temperature differences were investigated. After coating with a thin layer of glue for the final set of runs, drops of 1·67 mm dia. were obtained from this needle. Four temperature differences were investigated in this case.

Data for drop diameter during condensation were obtained by direct measurement of enlarged consecutive pictures developed from the films (projected by a photo-optical data analyser, model 224-A). The pictures were enlarged 40 times. Projected drop diameters were larger than 2 in., and a scale which permitted measurements to within 1/1000 in. was used. Photographs of a drop with initial diameter of 1·67 mm and $\Delta T = 34·4$°C are given in Fig. 1. Typical measured values of the ratios of radii of the drops during the process are illustrated in Fig. 2. The measured values are compared with equation (4), which can be seen to closely describe the experimental results. Investigated time of contact was not sufficiently long for the process to be completed.

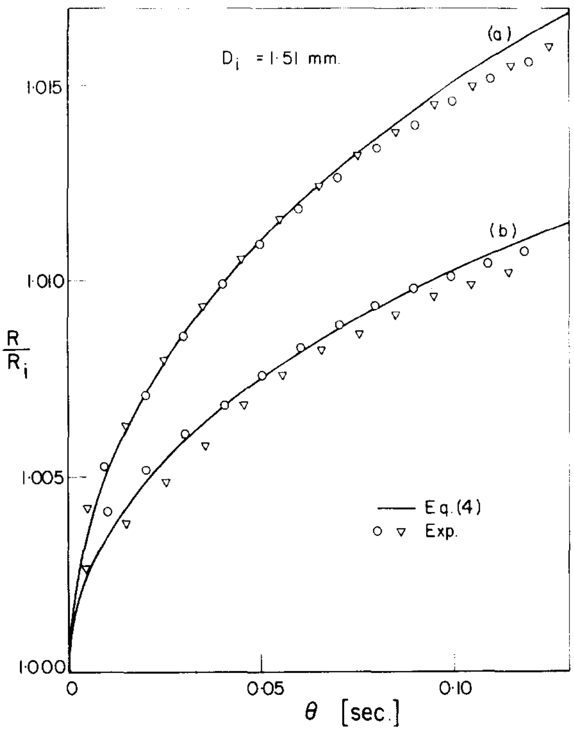

FIG. 2. Dimensionless radius of drop during condensation (a) $T_s = 99·1$°C, $\Delta T = 50·0$°C; (b) $T_s = 99·1$°C, $\Delta T = 33·7$°C.

CONCLUSIONS

The growth of drops during condensation of steam on water droplets has been experimentally investigated. Analysis of high-speed photographs led to accurate growth rate data. From theoretical considerations, an approximate correlation which agreed well with the observed experimental behaviour was obtained. Although the droplets produced in this investigation were somewhat larger than desirable, the successful correlation of the experimental data means that this analysis is now established for use at smaller diameters, such as are necessary for high rates of heat transfer in direct contact condensers.

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VITESSE DE CROISSANCE DE GOUTTES PENDANT LA CONDENSATION

Résumé—On considère la croissance des gouttes pendant la condensation dans le contact direct entre les gouttes liquides et la vapeur. Une loi approchée de ce processus est obtenue à partir de considérations théoriques. On a mené une étude expérimentale de la condensation de vapeur sur des gouttes d'eau de trois diamètres différents et pour différents refroidissements initiaux audessous de la température de vapeur saturante. On a utilisé la photographie ultra-rapide pour analyser la croissance des gouttes pendant la condensation.

WACHSTUMSRATE VON TROPFEN WÄHREND DER KONDENSATION

Zusammenfassung—Es wurde das Tropfenwachstum untersucht bei der Kondensation mit direktem Kontakt zwischen Flüssigkeitstropfen und Dampf. Aus theoretischen Betrachtungen für diesen Vorgang wurde eine Näherungsbeziehung abgeleitet. Experimentelle Untersuchungen über die Kondensation von Dampf wurden an Wassertropfen von drei verschiedenen Durchmessern und mit unterschiedlicher Anfangsunterkühlung der Tropfen gemacht. Für die Analyse des Tropfenwachstums während der Kondensation wurde die Hochgeschwindigkeitsphotographie verwendet.

СКОРОСТЬ РОСТА КАПЕЛЬ ПРИ КОНДЕНСАЦИИ

Аннотация—Исследовадся рост капелр при конденсации в условиях прямого контакта капель жидкости и пара. Для обобщения этого процесса применяется приближенное соотношение, полученное в результате теоретического анализа. Проведено экспериментальное исследование конденсации водяного пара на капельках воды трех различных диаметров и при различных степенях недогрева капель до температуры насыщения. Исследование роста капель при конденсации проводилось с помощью киносъемки.