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BEHAVIOUR OF A WATER DROP ON A ROTATING NON-WETTABLE TUBE

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ABSTRACT

The study described in the present paper has been undertaken as a step towards clarification of the behavior of condensate droplets on a horizontal rotating tube. This behavior is difficult to determine during dropwise condensation because the drops are constantly changing their weight and shape. In the present study, individual water drops of predetermined weight on the outside of a rotating tube have been studied with the aid of VTR. The falling velocity of the drop on the surface has been calculated as a function of its location on the surface. The adherence time of the droplet and the force balance during detachment are discussed.

1. INTRODUCTION

It is well known that the behavior of condensate drops influence the heat transfer of dropwise condensation. Thus, the authors investigated the relation between the behavior of condensate drops and the heat transfer on the static horizontal tube in the previous paper (HOSOKAWA et al.,1983,1986). From the results of these studies, it was found that departing drops caused two significant effects, i.e, sweeping and covering effects.

In regard to the effect of the centrifugal force on the heat transfer, TANASAWA et al.(1976) and NAKATA et al.(1975) have experimentally studied it with using a small condensing surface. As a result, it was recognized that the rate of the heat transfer was increased and the behavior of condensate drops was influenced by the centrifugal force. Authors have investigated the relation between the behavior of falling drops and the heat transfer on a comparatively wide surface (HOSOKAWA et al.,1990).

This study has been undertaken to clarify the behavior of condensate drops on a rotating horizontal tube under dropwise condensation. It is difficult to clarify the behavior of condensate drops on a condensing surface, because of their constantly changing weight and shape. Therefore, in air, the behavior of a water drop with a constant weight on a rotating non-wettable tube is investigated using a video-tape recorder. In particular, the velocity and the location of a falling drop on a rotating tube are calculated. Moreover, the adhering time to the surface and the detachment force on a falling drop are discussed.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 1 shows the experimental apparatus. Three teflon tubes (1) were used for a test surface and these outer diameters D are 20.1, 62.3 and 101.6 mm. A water drop was carefully dropped on the top surface of the steady rotating tube and the mass M of the drop was beforehand measured by a electric balance. The behavior of the falling drop was recorded with a video-camera (10). The velocity and the location of the falling drop were measured by using the VTR.

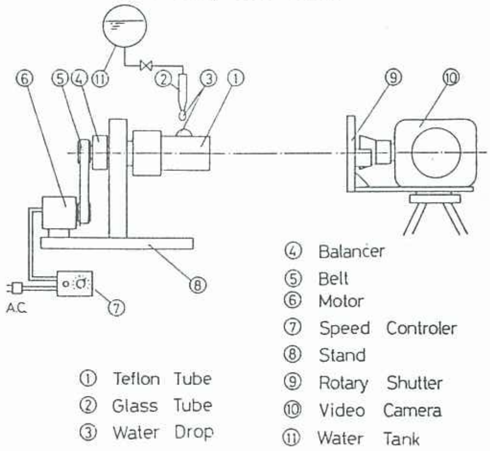

Fig.1 Experimental apparatus

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Contact angle

A contact angle θ_c influences the behavior of a drop. First of all, the values of θ_c are measured for static drops on a teflon surface. As shown in Fig.2, we impose the transparent sheet which is drawn concentric circles on the picture of a drop and obtain the values, r, h, about the circle of which the segment most overlapped with the contour of the drop. Substituting values, r, h, in Eq.(1), θ_c is obtained. The averaged value is 83.7 .

$$\theta c = \cos^{-1}(h/\gamma) \quad \cdots\cdots(1)$$

3.2 Behavior of a water drop

Figure 3 shows one example of the behavior of a drop corresponding with a time t. The test tube is counter-clockwise revolved and N is a revolution number. Symbol α is an angle from the top of the tube. When N increases, the behavior of a drop is sketched in Fig.4. Froude number Fr is defined as the following equation.

$$Fr = D/(2g) \cdot (2\pi N/60) \quad \cdots\cdots(2)$$

where, g is a gravitational acceleration.

From Figs.3 and 4, the location of drops which fall from the tube is $\alpha \fallingdotseq 120°$ except extremely large N. As increasing N, an adhering time of a drop is shorter and a falling velocity becomes larger. Occasionally, we observe that a drop is stopped at the surface and is revolved with the rotating tube. As a result, the behavior of a drop can be discussed by a velocity, a location of a falling drop, an adhering time and a detachment force from a test tube.

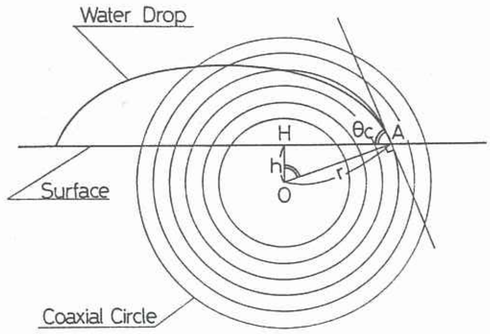

Fig. 2

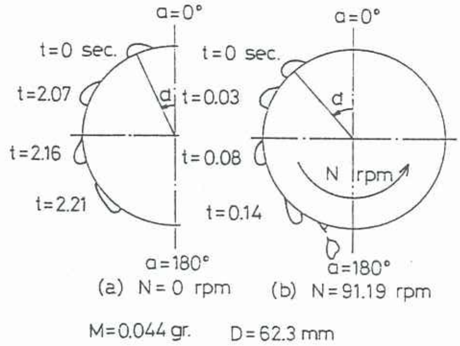

Fig.3 Sketch of a falling drop corresponding with a spent time

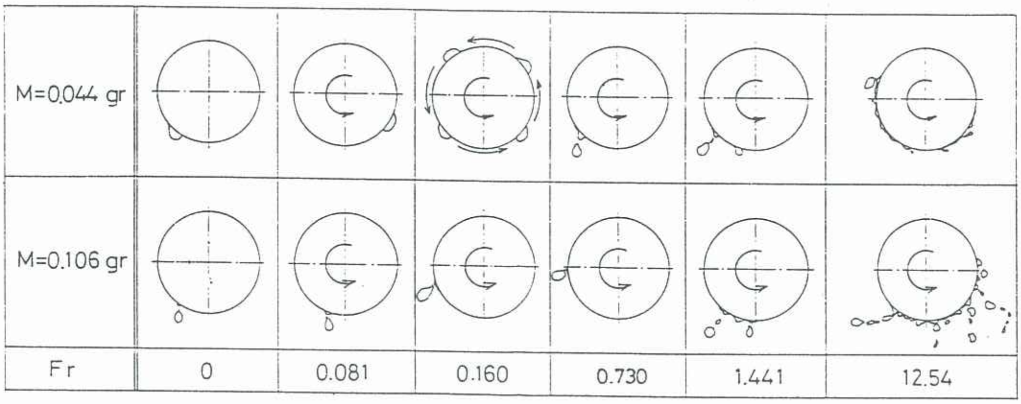

Fig.4 Sketch of a falling drop (Froude number changes.)

3.3 Velocity of a falling drop

Figure 5 shows the relation between a velocity U of a drop and an inclination angle α . In a low velocity, U shows an averaged value at an interval of $\alpha \fallingdotseq 5°$. When a nearly maximum velocity, U shows an averaged value at an interval of $t \fallingdotseq 0.03$ sec.. As shown in Fig.5, the distribution of U shows three tendencies corresponding to Fr. In $Fr \lesssim 0.081$, a drop yields the maximum velocity at $\alpha \fallingdotseq 120°$ and stops at $\alpha \fallingdotseq 240°$. In a value of $Fr \fallingdotseq 0.160$, a drop has the minimum velocity at $\alpha \fallingdotseq 270°$. When over $\alpha \fallingdotseq 270°$, the velocity gradually increases and repeats the former distribution. In $Fr \gtrsim 0.290$, the maximum velocity shows at $\alpha \fallingdotseq 120°$ and just then a drop falls from the tube.

Above results were obtained by changing a revolution number N. When D and M are changed, the velocity distribution shows the same characteristic as N changes. It is found that the velocity distribution has three kinds from these results. That is, a drop stops at the surface, rotates with a periphery velocity and falls from the tube. When a drop does not fall from the tube, we calculate the velocity U on the tube surface and the effect of N on U is discussed.

In this case, we propose the model of a velocity distribution as shown in Fig.6 and there are 4 velocity regions on the rotating tube. The velocity for I and III regions is equal to the periphery velocity U_0 . The velocity for II and IV regions is calculated by the following method. KAWAI (1966) presented a kinematic equation of a drop moving on an inclined flat surface.

$$M \cdot dU/dt = M \cdot g \cdot \sin\alpha - \sigma \int_0^b (\cos\theta_R - \cos\theta_A) \cdot db - R \quad \cdots\cdots(3)$$

where, σ is a surface tension,
b is a diameter on a contact surface,
θ_A and θ_R are contact angles of foremost and hindmost.
R is a force of a frictional resistance against motion.

Applying Eq.(3) to the kinematic equation of a drop on a rotating tube, the following equation of the velocity U is obtained.

$$U = (C_1/C_2 + \pi D \cdot N/60) \cdot \exp(-C_2 t) - C_1/C_2 \quad \cdots\cdots(4)$$

where,

$$C_1 = \left\{ \sigma \Delta\Theta_{co} k_1 k_2 \frac{f(\theta_m)}{U_{RC}} + \frac{\pi^2}{8} k_1{}^4 f(\theta_m)^4 \mu \right\} \frac{1}{M^{2/3} \rho^{1/3}}$$

$$C_2 = -g \sin\alpha + \left\{ \sigma \Theta_0 k_1 k_2 f(\theta_m) - \left(\sigma \Delta\Theta_{co} k_1 k_2 \frac{f(\theta_m)}{U_{RC}} + \frac{\pi^2}{8} k_1{}^4 f(\theta_m)^4 \mu \right) \frac{\pi DN}{60} \right\} \frac{1}{M^{2/3} \rho^{1/3}}$$

ρ is a density,
k_1 and k_2 are constant,
$\Delta\Theta_{co} = \Theta_c - \Theta_0$,
$\Theta = \cos\theta_R - \cos\theta_A$,
Θ_c is the value of Θ at the state of a tailless drop which has a critical velocity,
Θ_0 is the value of Θ at the state of a departing drop which is just going to move,
U_{RC} is a critical velocity of a tailless drop,
μ is a viscosity,
$f(\theta_m) = 2 \cdot \sin\theta_m / ((1-\cos\theta_m)^2 (2+\cos\theta_m))^{1/3}$
θ_m is a mean contact angle.

Data for the calculation in Eq.(4) are the same values as those in the reference (KAWAI,1966). σ =0.0739 N/m, Θ_0=0.305, Θ_c =1.4, k_1 =1.0, k_2 =0.666, ρ =958 kg/m^3, g=9.81 m/s^2, θ_m =90°.

The critical velocity U_{RC} in Eq.(4), which is influenced by the surface condition, effect on the behavior of a drop. But U_{RC} is not measured because of the complex unsteady phenomenon. Figure 7 shows the velocity distributions with a parameter U_{RC} . As U_{RC} increases, the maximum velocity of U becomes large and a stop location of a drop is a small angle. The calculated results qualitatively agree with that of Fig.5. In U_{RC} ≒15 cm/s, the calculated results are good agreement with experimental results.

3.4 Location of a falling drop

We discuss a fall location when a drop falls just from a tube. Figure 8 shows the relation between the fall location α_c and Froude number Fr. Regardless of M, a drop falls at a smaller angle as Fr increases. In Fr>1, α_c decreases sharply with increasing Fr. When M increases, a drop falls easily from the tube. The other hand, in the case of a small M, a drop stops at a surface and its stop location α_s is marked with a symbol □ in Fig.8. Each experimental value is an averaged value of 5 times and these values disply the both of the maximum and minimum values. The difference of the two values is small. When D is changed, we can obtain the same results in D=62.3.

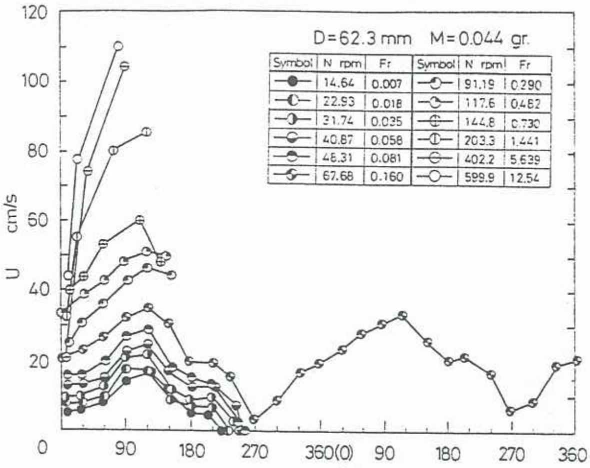

Fig.5 Distribution of a velocity U
(D and M are constant.)

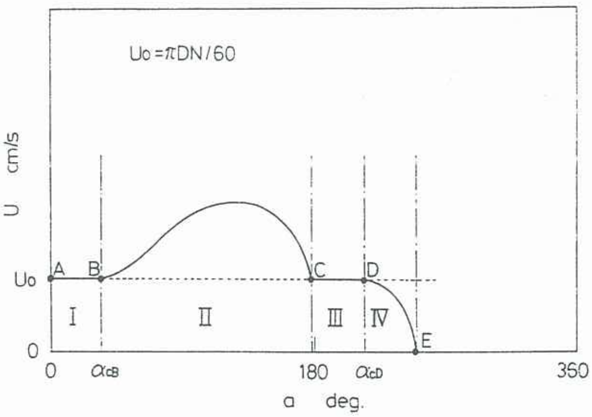

Fig.6 Calculation model of a velocity U

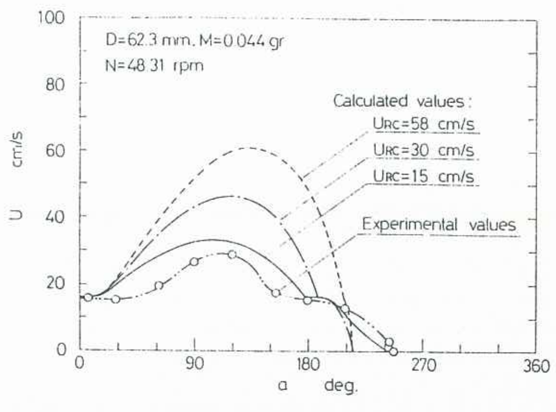

Fig.7 Distribution of a velocity U with a parameter U_{RC}

3.5 Adhering time of a falling drop

Figure 9 shows the relation between an adhering time T and Froude number Fr. An adhering time T is defined as a required time for a drop to fall from a tube. In the region of a small Fr, the time T shows a small value as Fr increases. And T gradually decreases with larger Fr. We are almost able to obtain the same results in other tube diameters.

3.6 Detachment force of a water drop

We judge a detachment force F in Eq.(5) when to detach an adhering drop from the tube.

$$F = M \cdot g \{ \cos(180-\alpha) + 2U/(g \cdot D) \} \quad \cdots\cdots (5)$$

It is assumed that the detachment force F is composed of the centrifugal and gravitational forces in this paper.

Calculated results which are obtained from Eq.(5) are shown in Fig.10. When a drop do not fall from the tube, the maximum value of F is about 0.5 mN regardless of Fr. When a drop falls from the tube, the value of F exceeds 0.5 mN and becomes a larger value with increasing Fr. These same results are obtained in the other cases of D=20.1 and 101.6 mm.

4. CONCLUSIONS

The following conclusions can be drawn:

1) The velocity distribution which is characterized by Froude number has three types. Experimental results are agreement with calculated results in a critical velocity $U_{RC} \fallingdotseq 15$ cm/s.
2) When a water drop falls from a tube, a fall location and an adhering time are small as Froude number increases.
3) When a water drop does not fall from a tube, the maximum value of a detachment force shows about 0.5 mN regardless of Froude number.

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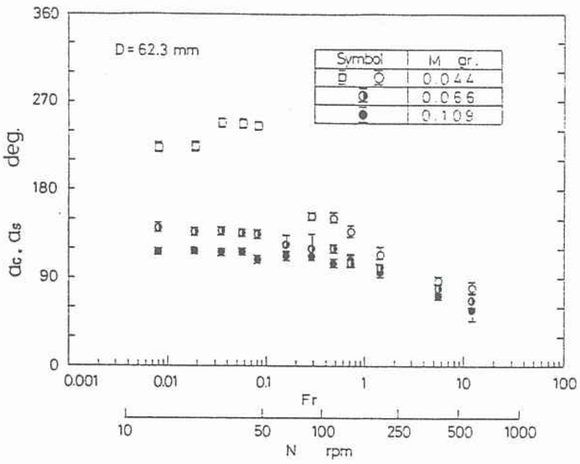

Fig.8 Relation between a fall location α_c and Froude number Fr

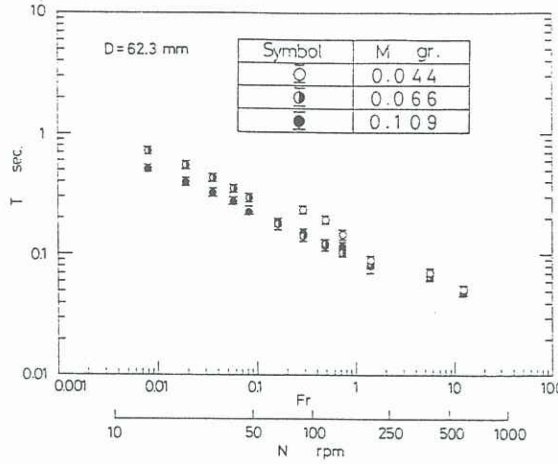

Fig.9 Relation between an adhering time T and Froude number Fr

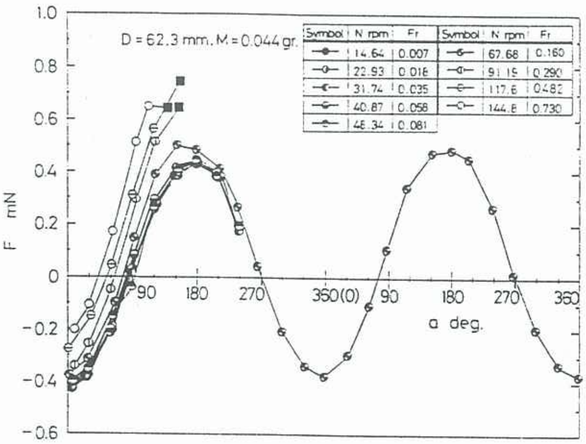

Fig.10 Distribution of a detachment force F