UDC 536.423.4

DROPWISE CONDENSATION—THE EFFECT OF THE CRITICAL SIZE OF DROP DETACHMENT (I)

滴状凝縮過程の実験的研究——液滴の離脱径の影響（I）

by Ichiro TANASAWA*, Jun-ichi OCHIAI*, Shintaro EN-YA*
and Yoshio UTAKA*
棚沢 一郎・落合 淳一・塩冶震太郎・宇高 義郎

1. Introduction

The authors have been proceeding with a research program on dropwise condensation whose objectives are to throw light on the basic mechanism of the process and to find a key to the application of this very efficient process to the practical heat exchanging devices. In the course of those research works, it has become clearer that the rate of drop growth due to coalescence and the distribution of drop size are the most important phenomenological factors controlling the average heat transfer rate over the condensing surface. These two factors relate each other very closely and each cannot vary independently. On clarifying the relation between these factors and the mechanism of heat transfer during dropwise condensation, it is necessary to know about the interrelation between the two factors.

On the other hand, the entire process of dropwise condensation is the combination of the cycles composed of nucleation of droplets, growth due to direct condensation, coalescence, and detachment from the surface. Hence, it is at the same time very important to observe and analyze each of these subprocesses.

The main object of the present study is to find the role of the critical size of drop detachment during the process of dropwise condensation. The critical size of drop detachment not only relates closely to the frequency of drop departure, but also is a representative parameter determining the drop size distribution. Thus, it is considered to be one of the most essential variables dominating the process of dropwise condensation.

The critical size of drop detachment is, to speak simply, determined from the balance between the adhesive force due to surface tension and the external forces. Up to now, the only procedure by which the critical sizes were varied experimentally was due to the change in the inclination of condensing surface (Citakoglu and Rose[1], Katsuta[2], Tower and Westwater[3], Tanasawa and Ochiai[4]). In these reports, however, the relation between the critical size and the coefficient of heat transfer was not shown explicitly (except 4)). Also, Tanasawa and Tachibana[5] stated in their study using the method of computer simulation that the heat transfer coefficient would be inversely proportional to (0.25∼0.35)-th power of the critical size, but they gave no experimental verification.

In the present study, the authors attempted to make the critical size smaller than in the normal gravity field on the earth by increasing the magnitude of resultant external force. The methods employed were; (1) raising the shear stress due to steam flow, and (2) placing the condensing chamber in the high acceleration field.

2. Experimental Procedure

As is stated above, the critical radius of drop detachment were to be changed by two methods: the steam shear stress and the high acceleration field. For the latter, the condensing chamber was settled on a centrifuge, whose detail will be shown later, and the centrifugal force generated by

---

* Dept. of Mechanical Engineering and Naval Architecture, Inst. of Industrial Science, Univ. of Tokyo.

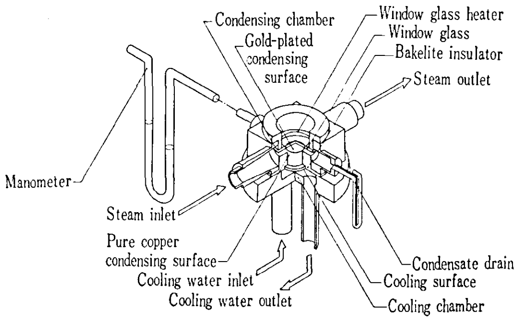

Fig. 1

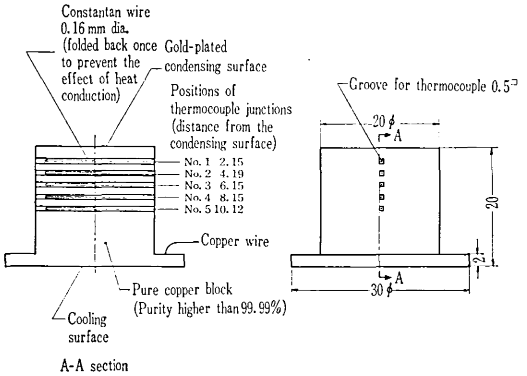

Fig. 2

rotation was utilized. Strictly speaking, the steam shear stress and the centrifugal force may have some different effects on the process of dropwise condensation. In the present report, however, the detailed discussion is omitted and the results are put in order taking the critical size as a chief parameter.

Figure 1 is a sketch of the condensing chamber. On designing and manufacturing the condensing surface, a care was taken of the precise measurement of the surface temperature and the heat flux. (For the explanation in more detail, see the previous report⁴⁾.) Chief improvements compared to the previous one were as follows: A cylindrical rod made of copper (purity higher than 99.99%) was used as the condensing surface. The rod was, first, split into two, then five grooves of 0.5 mm wide and 0.5 mm deep were cut into one side of the split surface, and constantan wires of 0.16 mm dia. were soldered just at the center of each groove. The wires were folded back once to prevent the effect of thermal conduction. Figure 2 shows the detail. Such structure was adopted in order to measure the locations of the thermocouple junctions very precisely. The surface on which the steam was to condense was gold-plated in place of applying an organic promotor, thus omitting troublesome application of the promotors and preventing the change in the surface condition.

In order to prevent the accumulation of non-condensable gases onto the condensing surface, the blowing-off method was used as before. The determination of the optimum steam velocity will be mentioned later.

Figure 3 is a sketch of the centrifuge by which the high acceleration field is generated. An arm is fixed on the upper end of a rotating shaft, and the condensing chamber is settled at the outermost end of the arm. The distance between the center of the condensing surface and the central axis of the shaft is 450 mm, and the revolution about 7.5 rev/sec can produce an acceleration about 100 times the normal gravity on the earth surface. The mechanisms for carrying steam and

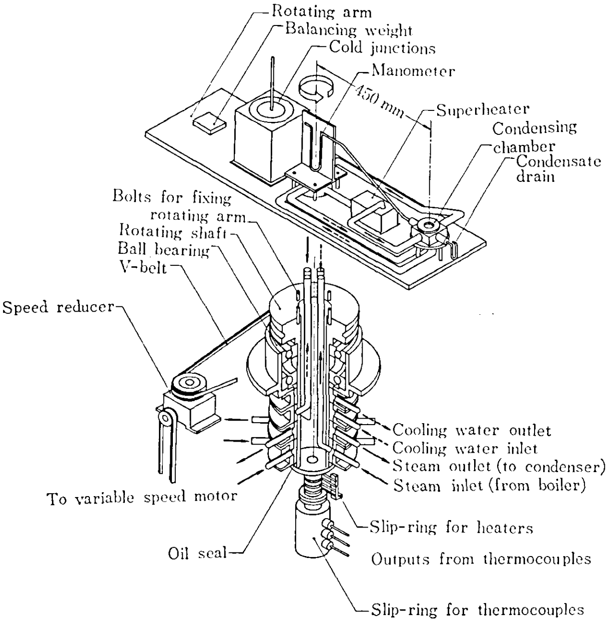

Fig. 3

cooling water to the rotating condensing chamber and for returning back again excess steam, condensate and cooling water outside were the parts most difficult in designing and manufacturing. In the present apparatus, several small chambers partitioned with oil-seals were made between the fixed and the rotating shaft, through each of which steam or water was transported. The outputs from the thermocouples for the surface temperature and heat flux measurement and the power inputs to the glass window heater of condensing chamber and to the steam superheater were transmitted through the slip-rings.

3. Experimental Results

3.1 Determination of Steam Velocity

As in the previous report the steam flow was to be utilized to blow off non-condensable gases accumulated near the condenser surface. The adequate steam velocity for the purpose had to be determined in advance. Figures 4 and 5 show the changes in the heat transfer coefficient and the critical size of drop detachment against the vapor velocity. The measurement of the critical size was carried out as before by taking motion pictures of the condensing surface with the speed of 100∼500 frames/sec. From Figs. 4 and 5, it is seen that the heat transfer coefficient decreases constantly (on the log-log graph) with the decrease of the steam velocity, while the critical size remains nearly constant where the steam velocity is smaller than 4 m/sec. From this fact the authors considered that the effect of non-condensable gases appeared for the steam velocity less than 4 m/sec and they decided to use the velocity higher than 5 m/sec.

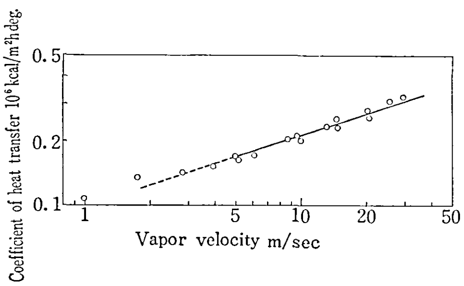

Fig. 4

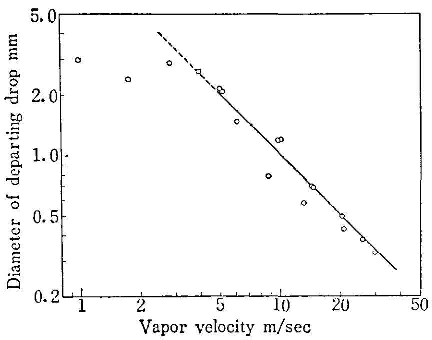

Fig. 5

3.2 Effect of the Steam Shear Stress

In Figs. 4 and 5 the data for the heat transfer coefficient and the critical diameter are plotted respectively against the steam velocity up to 31 m/sec. From these results the relation between the heat transfer coefficient and the critical diameter is obtained as shown in Fig. 6. If the least square method is applied to the points in Fig. 6, it results that the coefficient of heat transfer is inversely proportional to 0.35-th power of the critical diameter. This figure is a little larger than the one predicted by the computer simulation.

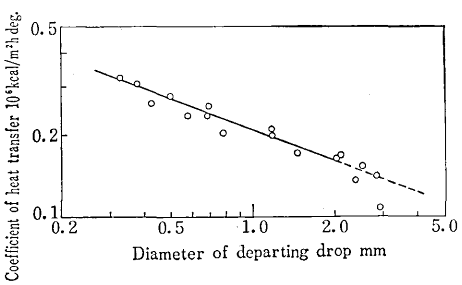

Fig. 6

3.3 Effect of the Centrifugal Acceleration

The data obtained up to now is for the rotational speed up to 4 rev/sec. The magnitude of the centrifugal acceleration generated from this revolution corresponds to 29 times the earth's normal gravity (provided it is taken as $g=980$ cm/sec^2). The change in the heat transfer

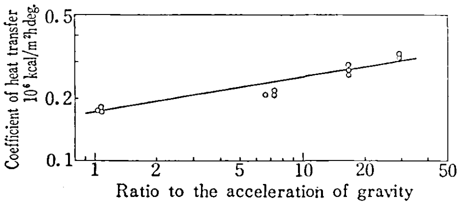

Fig. 7

coefficient within this range of acceleration is shown in Fig. 7. The steam velocity was maintained about 5 m/sec during the measurement and the heat flux was also kept almost constant. Since high speed motion pictures of the condensing process have not yet been obtained, the data on the critical diameters of departing drops are not available at present. However, it has been known that the tendency of the change in the heat transfer coefficient seen in Fig. 7 is fairly agreeable to the theoretical prediction by the authors.

(Manuscript received, December 24, 1973)

References

1) Citakoglu, E. and J. W. Rose: *Int. J. Heat Mass Transfer*, **12** (1969) 645.
2) Katsuta, K.: *Proc. 8th National Symposium on Heat Transfer* (in Japanese) (1971) 89.
3) Tower, R. E. and J. W. Westwater: *Chem. Engng. Symposium Series*, **66**, No. 102 (1970) 21.
4) Tanasawa, I. and J. Ochiai: *Trans. Japan Soc. Mech. Engrs.* (in Japanese) **38**, No. 316 (1972) 3193.
5) Tanasawa, I. and F. Tachibana: *Proc. 4th Int. Heat Transfer Conf.*, Vol. 6, Cs. 1.3 (1970)

(p. 41 よりつづく)

ク値 (cpm/mCi) は表2のように一次ガンマ線のエネルギーとその放出率の大きさに応じて変っている．^{99}Moのみピーク値が大きいのは，mCi 数の測定誤差によるものと考えられる．

さらに鉄の前面のカーボン煉瓦の厚さを変え，各線源ごとにピークの位置 (x の値) を求めると表3の結果が得られる．すなわちxの値が最も大きくなるのが，^{24}Naと ^{60}Co の場合はカーボン煉瓦の厚さ 12 cm のときで，^{46}Sc, ^{137}Cs, ^{192}Ir などでは 15 cm 前後である．これは測定の幾何学的配置とガンマ線エネルギーによって，カーボンのガンマ線吸収断面積が異なることによるものである．

4. むすび

以上の結果から鉄の前面にあるカーボン煉瓦の厚さを測定するには，図4のような較正曲線を作り，x がある値のときの散乱ガンマ線量 (cpm) から厚さを推定することもできるが，この方法では，カーボン煉瓦が厚くなると不正確となる．したがって複雑ではあるが，図8 b のようなぐらふを求めておき，そのピーク値からカーボン煉瓦の厚さを求めればかなり正確に求められる．

実験はカーボン煉瓦の厚さ 18 cm までしか行わなかつたが，表3のようにどの線源を用いた場合もピーク値が得られた．しかも引き算する前の無限厚のカーボン煉瓦からの比後方散乱ガンマ線量 (cpm/mCi) が，$x=4$～12 において 10000～500 cpm/mCi であるので，その標準偏差はほぼ 100～22 cpm/mCi である．したがってカーボン煉瓦の厚さ 18 cm までは十分測定可能である．

また一般に一次ガンマ線エネルギーが大きいほど厚いカーボン煉瓦の測定が容易となるが，^{60}Co, ^{137}Cs, ^{192}Ir を比較した場合でいえば，^{60}Co についで ^{192}Ir がすぐれている．また ^{99}Mo のように一次ガンマ線エネルギーが低い場合でも，カーボン煉瓦の厚さ 18 cm 程度まで測定できることは注目に値する．

(1974年1月9日受理)