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The effect of speed on the condensate layer on a cold cylinder rotating in a steam atmosphere

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A study has been made of the condition of the condensate layer on a plain cooled cylinder rotating in a steam atmosphere. Because the cylindrical surface was wettable, it was covered by what was essentially a film, from which, under the influence of centrifugal force, protrusions arose. The drainage of the film occurred by the growth and throwing off of these protrusions in the form of drops. The behaviour of the drops, the variation of their maximum size with speed, and their number per unit area were the subject of study.

1. Introduction

Condensate falling on the surface of a plain cylinder rotating about its polar axis will be thrown off the surface tangentially with an initial velocity of approximately $\frac{1}{2}D\omega$ and an initial radial acceleration of $\frac{1}{2}D\omega^2$, where D is the diameter of the cylindrical surface and ω is the angular velocity of its rotation. The cylindrical rotor surface could be either wettable by the condensate and be covered essentially by a film of condensate, or it could be non-wettable and be covered by discrete drops. Only the case of the film of condensate is studied here.

A study has been made by Matthews (1962) of the water layer on a rotating cylindrical surface on which steam was condensing. Because the cylindrical surface was wettable and rotating about its polar axis, it was covered essentially by a film or layer, in a field of uniform centrifugal force acting perpendicularly to the surface.

2. A condensate layer in conditions of uniform field force

A more familiar case of condensation in a field of uniform force perpendicular to the surface is that of condensation on the underside of a large horizontal flat plate in a field of gravity. Condensate collecting beneath such a plate will remain in a stable condition only while it is thin. As shown in figure 1 (*a*) fluid would flow down any pressure gradient caused by a disturbance into regions of lesser pressure and so form protrusions from the condensate. When the surface-tension force is exceeded by the weight of the protrusion, a neck will form in it, and a drop of fluid will break away. This is illustrated by the sequence of sketches in figure 1, which are derived from a study of drop formation by Tanasawa & Toyoda (1955).

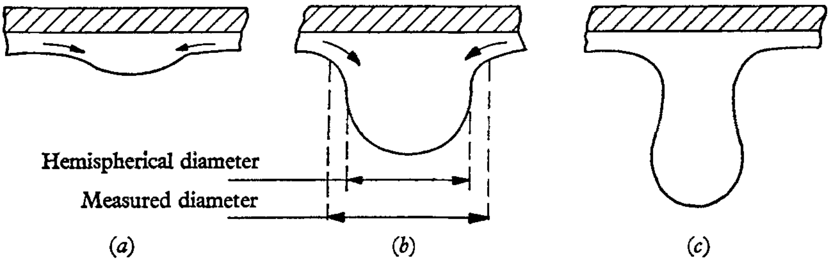

FIGURE 1. Drop formation on a flat horizontal plate. (a) Protrusion, (b) transition, (c) drop.

The condition considered here is similar to this and occurs in the case of heat transfer by condensation to a rotating surface described by Hoyle & Matthews (1964). A protrusion in the condensate layer will develop at a point of disturbance, and, when the centrifugal force acting on the protrusion just overcomes the surface-tension force retaining it on the surface, the protrusion will be thrown off the cylinder tangentially with a velocity of about $\frac{1}{2}D\omega$ and a radial acceleration of $\frac{1}{2}D\omega^2$. The formation, growth, and throwing off of such protrusions is the subject of study reported here.

3. Apparatus

The apparatus used is shown in figure 2 with an 8 in. diameter rotor in position. The steam passes axially across the rotor, condensing on the curved surface which is cooled internally by water.

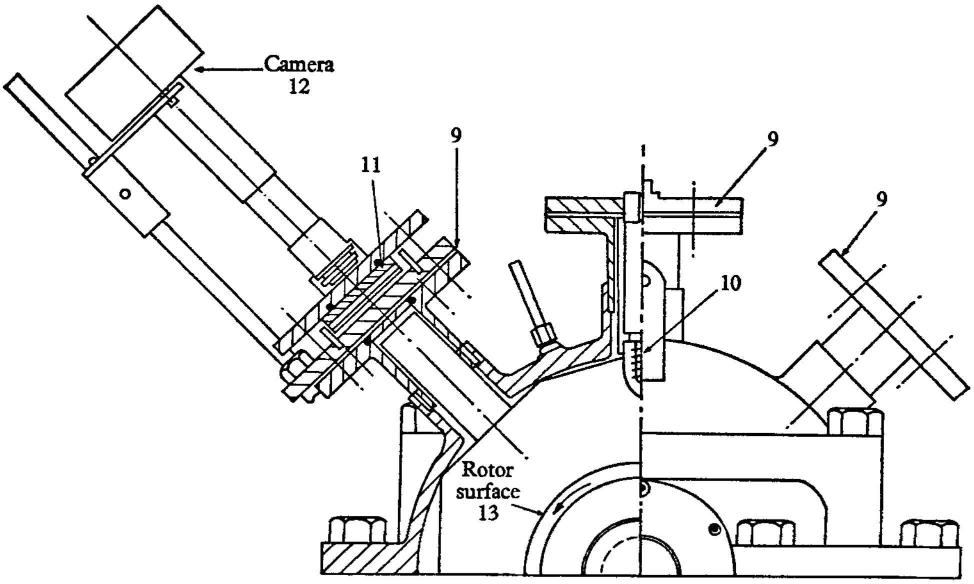

FIGURE 2. Top half of steam enclosure showing position of camera relative to the rotor surface.

The photographic flash illumination tube, 10 in figure 2, is directly above the rotor centre line, and illuminates parts of the rotor surface on the upward- and downward-moving sides.

The rotor surface was viewed by eye through the side branches and photographs of the condensate were taken by a camera, 12, with telephoto lens directed towards an area, 13, on the rotor surface. The window, 11, through which the photographs were taken is heated by an electric heater coil to evaporate any condensate striking the inner surface of the window.

Although the surface of the rotor was plated with 0·001 in. of nickel, the machining marks can be seen in the photographs. These are 0·012 in. apart with radial depths of 0·001 in. or less. Before a test, the surface was washed with carbon tetrachloride, alcohol, and water, polished lightly with fine emery, and rubbed with fine abrasive powder on a moistened cloth.

4. A study of the condensate layer

4.1. *Observations by unaided eye*

Observations by unaided eye were made with no steam in the casing. Water was allowed to run on the rotor surface from a pipe at rates comparable with the condensation rate of steam in tests described later.

At very low speeds the water ran down both sides of the rotor, but protrusions appeared as the speed increased, until, when the radial acceleration was about $12g$, radial drainage by centrifugal force became of dominant importance and drainage under gravity was negligible. Protrusions were then distributed evenly over the cylindrical surface but were widely spaced and made slow, apparently random, movements on the rotor surface. In addition there was a general but slow drift in a direction opposite to the motion of the rotor, implying that air friction was appreciable. Each protrusion persisted for a minute or so, moving in the manner described above, and after several hundred revolutions suddenly disappeared.

For all well-developed protrusions a reflexion of the illuminating source can be seen (figure 3, plate 1) on the curved surface of the protrusion, and also a second concentration of light can be seen on the rotor surface at the edge remote from the source of light. Outside the protrusions, below them in the photographs, are their shadows on the rotor surface. From the nature of the edges of protrusions it was inferred that the area of surface between protrusions was covered by a thin layer of condensate. The drop breakaway was sudden and therefore it is thought that the flow in the thin layer between protrusions occurs at varying rates with short-duration interruptions.

4.2. *Observations by photography*

Photographs were taken of the condensate layer. Except in the case of two photographs, the radial acceleration was always greater than $12g$, and in one case as high as $160g$. Therefore in these tests it was assumed that drainage due to gravity was not significant, that protrusions were uniformly distributed over the surface, and that area 13 was typical of the whole surface.

Many photographs were taken, both for control purposes under various defined conditions and for experimental purposes, of which those shown in figures 3 (*a*) to (*c*) are typical. They were taken while steam at 27 lb./in.^{2} was condensing at rates between 28 and 42 lb./h for the whole apparatus, giving mean heat fluxes of 26,000 and 39,000 B.Th.U./ft.^{2} h.

5. Discussion of results

For a cooled shaft of fixed diameter and constant surface condition rotating in a steam atmosphere the following independent variables affect the condition of the water layer,

(i) the speed of rotation ω,
(ii) the condensation temperature T_s,
(iii) the temperature of the surface of the shaft.

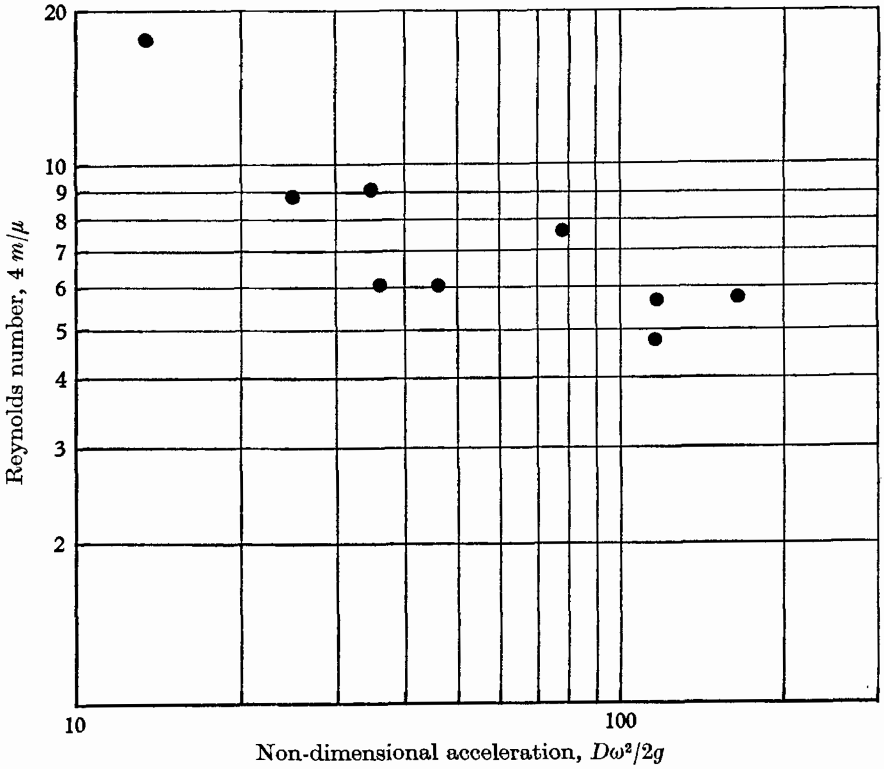

FIGURE 4. Relationship between Reynolds number of condensate approaching periphery of a protrusion and centrifugal acceleration. ●, Experimental results derived from figure 3.

In the caption beside each photograph in figure 3 these have been expressed in terms of non-dimensional radial acceleration $D\omega^2/2g$, the condensation temperature T_s, and the heat flux q''.

For the thin layer of water flowing into a protrusion the critical velocity is such that Reynolds number

$$R_e = 4m/\mu = 2100,$$

where m is the mass flow rate into one protrusion per unit length of periphery, and μ is the dynamic viscosity of the condensate. Taking the conditions of one case as an example, the number of protrusions was 10, giving an average catchment area of 0·113 in.^{2} for each protrusion. From this and the area of the curved surface the total number at any one time was calculated. The total heat flux of 27,000 B.Th.U./ft.^{2}h gave the flux for each protrusion, from which, with the latent heat of 940 B.Th.U./lb. and the observed diameter of protrusion d, m could be found. Thus it was calculated that the Reynolds number was 7·6. Values of Reynolds number for each condition are plotted in figure 4, where it will be seen that the maximum value was only about 17, indicating that conditions in the film were laminar throughout the range of tests.

5.1. *The growth of protrusions and the effect of speed on their size and number*

At constant speed, while a protrusion grows, the centrifugal force acting on it

$$\left(\rho\frac{2}{3}\frac{\pi d^3}{8}\frac{D\omega^2}{4}\right)$$

in the case of a hemispherical protrusion, where d is the diameter of a protrusion or drop, and ρ is the density of condensate. The centrifugal force increases with the cube of the protrusion's diameter and applies an increasing force during growth tending to cause the protrusion to fly off. The surface-tension force $\pi d\sigma$ is increasing only directly with diameter, where σ is the surface tension of the condensate. When the protrusion is ready to fly off it has a size that is particular for that speed. This is confirmed in the photographs where all well-developed protrusions are seen to be the same size at any one speed (see figure 3).

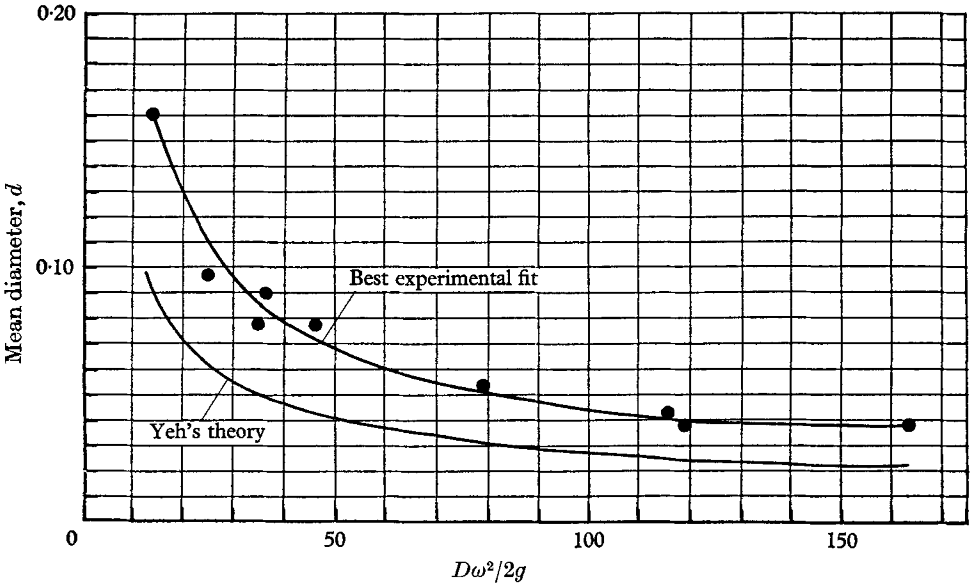

FIGURE 5. Relationship between mean diameters of protrusions per unit area and centrifugal acceleration. ●, Experimental results taken from figure 4.

The centrifugal force increases with the square of the speed but the surface-tension force is not directly dependent on speed. Therefore a protrusion will, at higher speeds, fly off earlier in its growth, and the critical diameter d at the instant of flying off will be smaller at higher speeds. The diameters of protrusions were measured from the photographs and are plotted in figure 5 against acceleration $D\omega^2/2g$. It can be seen from the best line for these measurements that the critical diameters decrease with increasing speed.

The hemispherical-drop diameters, calculated from Yen's formula (1954),

$$d = \sqrt{\frac{12\sigma}{\rho\left[\left(\tfrac{1}{2}D\omega^2\right)^2 - g^2\right]^{\frac{1}{2}}}}$$

are plotted in figure 5 against acceleration $D\omega^2/2g$. It can be seen that the measured diameters are in some cases as much as 1·5 times greater than those calculated from Yeh's formula, probably because, as seen in figure 1 (*b*), the measured diameter is likely to be greater than the true diameter due to a tendency to include part of the meniscus in the measurement.

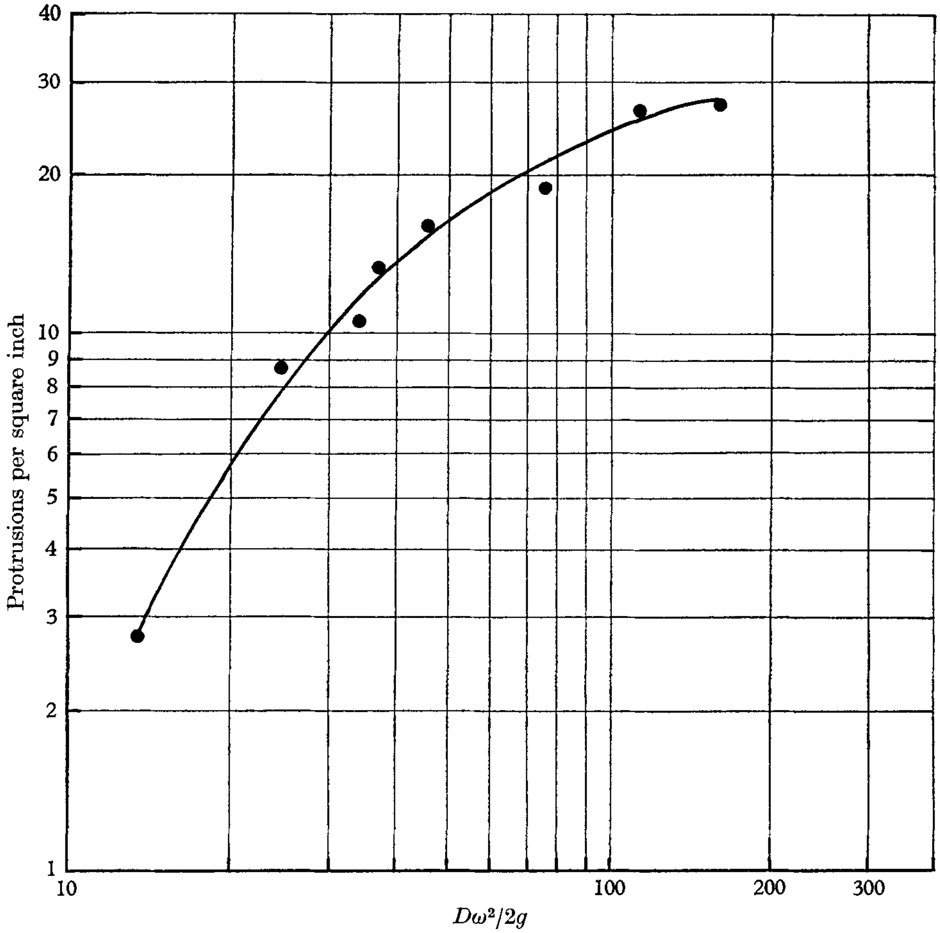

FIGURE 6. Relationship between number of protrusions per unit area and centrifugal acceleration.

In the field of view of the photographs the number of protrusions in each case was divided by the area to find the number per unit area, and the results in number of protrusions per square inch are shown plotted in figure 6 against the non-dimensional acceleration. The best curve shows an increase in the density with increase of speed.

For a study of heat transfer, for instance, it is important to know the area covered by protrusions in distinction to the area covered by film, as less heat will flow through a protrusion than through the film. From the best curves in figures 5 and 6 a curve of percentage area covered by protrusions has been plotted in figure 7 against centrifugal acceleration. For accelerations over 20*g* the area covered by protrusions decreased with speed probably because their duration is less at higher speeds. For accelerations below 20*g* there is a drop in area.

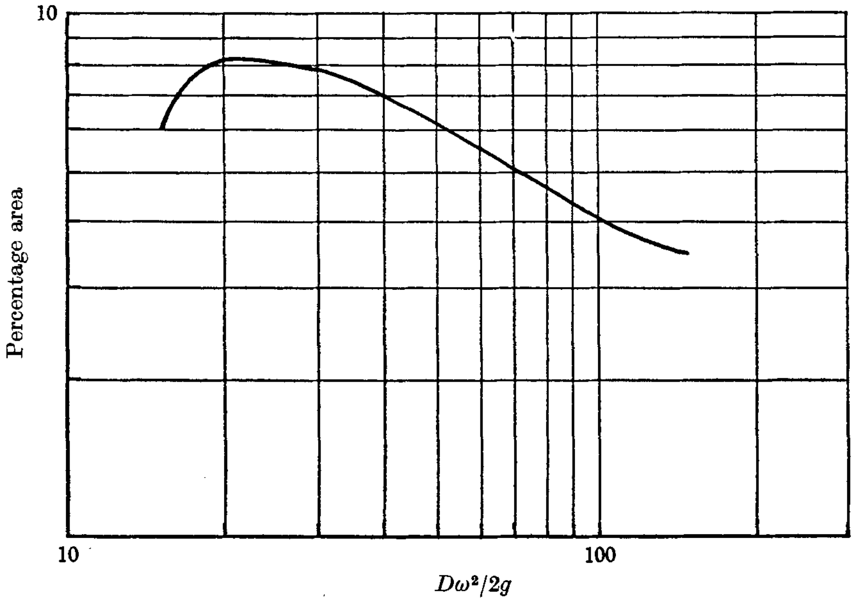

FIGURE 7. Relationship between percentage area of shaft covered by protrusions and centrifugal acceleration.

6. Conclusions

The following conclusions have been reached so far:

(i) the water layer consisted of protrusions rising from a film,

(ii) drainage of the film occurred by growth and throwing off of protrusions,

(iii) the protrusions decreased in size with increase of speed,

(iv) the number of protrusions per unit area increased with speed,

(v) the flow in the film between protrusions was laminar in all the conditions tested,

(vi) the area covered by protrusions reached a maximum at about 20*g*.

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