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A NOVEL OSCILLATION PHENOMENON OF THE WATER RIVULET ON A SMOOTH HYDROPHOBIC SURFACE

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ABSTRACT

An experimental investigation on a novel oscillation phenomenon of the water rivulet on a smooth hydrophobic surface has been conducted. It is concluded that the oscillatory motion of the water rivulet on the smooth surface, which is normally observed after the unstable meandering rivulet is restabilized due to increase of the discharge, is maintained by the capillary force. The oscillatory motion is steady in the hydrodynamical sense, for phase of the oscillation is always the same at each point in the space. The wave length of the rivulet oscillation increases wiyh increasing the discharge linearly. During the expansion and contraction processes, the oscillation energy given at the pipe mouth is dissipated at the interface between the rivulet and smooth plate through the interaction. Owing to this energy dissipation, the wave length of the rivulet oscillation increases with increasing the distance from the pipe mouth along the rivulet locus. It is suggested that the restable water rivulet on the smooth plate is turned alternatively by 90° around the central axis essentially by the same mechanism as that of the water jet falling in the air vertically downwards.

INTRODUCTION

When the rain runs down the windowpane in a stream, it normally meanders instead of going straight. Such a stream will be, hereafter, called as a *rivulet*. The perimeter of the contact area between the rivulet and solid surface is the *triple-phase*(or *contact*)*line* because of the conjunction of the water, air and solid surface. The angle at which the water touches the solid surface at the *contact line* is the *contact angle*. It is measured between the solid surface and tangent to the water surface.

The common observation that water droplets cling to a contact line indicates that a contact line is in equlibrium over a range of contact angles rather than at a single value. The water spreads over the surface of a solid body only when the contact angle exceeds some upper limit, while it contracts only when contact angle becomes below some lower limit. After either event the contact angle is again within the range of values that makes for stability. The upper limit is called the *advancing contact angle*, the lower one the *receding contact angle*. The stability of the contact line of a rivulet to be in equilibrium at different values of the contact angle is referred to as the *contact-angle hysteresis*. It is the hysteresis that enables a liquid droplet to cling to a solid surface.

Since the water molecules in the rivulet on a smooth surface are pulled downward along the line of maximum slope of the surface by gravity it may be natural to expect the locus becomes straight. Yet, in many experiments(e.g. Tanner 1960, Kern 1969, 1971, Gorycki 1973, Nakagawa 1982, Nakagawa and Scott 1984, Gulkin and Davis 1984, Davis and Tinker 1984), the vivulet *meanders*, thus developing bends that connect relatively straight stretches slanting to one side or the other. Furthermore, rivulets display a large variety of intriguing instability phenomena. Kern(1969, 1971), for example sees the break-up of a rivulet into droplets, rivulet meandering, and turbulent rivulet. Nakagawa and Scott(k984) have proposed a plausible mechanism of the stable rivulet meandering on a smooth hydrophobic surface on the basis of their detailed observation. Very recently, Nakagawa(1992) has reported that any rivulet exhibits four different patterns, viz., droplet, stable-meandering stream unstable-meandering stream, and restable stream.

In the present study, the formation mechanism of beads of a rosary, and origin of the periodicity in the water rivulet on a smooth hydrophobic surface will be examined and discussed.

EXPERIMENT

In this study, three experimental arrangements 1, 2, and 3 have been used. Fig. 1 shows a schematic diagram of the present experimental arrangement 1. The glassy smooth Plexiglas plate showing no waves or any other unsteady behavior is 100 cm long and 60 cm wide, and the head water tank allows a constant discharge through a vinyl pipe. The three different pipes having inner diameters of 3 mm, 5 mm, and 8 mm are used for the arrangement 1. The pipe mouth is set on the centreline of the plate at a point 20 cm down the slope from the upper edge:The experimental variables are the discharge Q, measured by weighting the water discharged in a given time, and the surface slope α, measured with a protractor. The maximum discharge for each surface slope is chosen as an amount above which the rivulet is restabilized, while the surface slope is set at 2° at first, and then is varied from 5° to 80° at 5° intervals.

The cross-section of the rivulet is measured pointwise, using a slender needle of 0.1 mm diameter, held perpendicular to the plate surface. The height measurement is made at 5 mm intervals along the direction of maximum slope, and at 1 mm intervals along a line normal to the central axis of rivulet. Sinuosity of the rivulet is determined in the following way: The total length of stable meandering rivulet is measured by tracing the plan locus of central axis, using ink on to the transparent plate, while the length projection of rivulet on the line of maximum slope length is measured directly.

Motion of the rivulet is very sensitive to the condition of the plate surface. Therefore, a dry surface is carefully prepared for each the experimental run, wiping the surface with soft hygroscopic tissues, and then leaving the surface for about 30 minutes prior to the next run.

The present experimental arrangement 2 is in principle same as the arrangement 1. However, the arrangement 2 is different from the arrangement 1 in several points. That is, scale of the Plexiglas is 50 cm long and 30 cm wide. In addition to the water, the glycerin and silicone-oil are used in order to investigate into effects of the viscosity and surface tension on the rivulet characteristics. A rotary pump is used for feeding the drained liquid to a constant head tank, so that it becomes possible to provide a known discharge on the plate surface through a vinyl pipe of 6 mm inner diameter. The pipe mouth is arranged on the central line of the plate and at a point 10 cm down the slope from the upper edge. The experimental variables are the discharge Q, and surface slope α, which is varied from 5° to 80° at 10° intervals.

The experimental arrangement 3 is rather different from the arrangements 1 and 2. In terms of the arrangement 3, the water jet being emanated from a narrow rectangular slit(15 mm long, 1 mm wide) has been examined with a clear intention of finding the plausible similarity between the novel oscillation phenomenon on the water rivulet on a smooth hydrophobic surface and the water jet falling in the air vertically downward or Rayleigh oscillation(Rayleigh 1879). The constant head tank allows a given amount of the water discharge through the slit: The water from the head tank is fed to a hollow circular cylinder (300 mm long, 50 mm inner diameter) through a vinyl pipe of 10 mm inner diameter. The cylinder is held in vertical, and then a circular Celluloid sheet of 0.5 mm thick on which the rectangular slit is engraved is attached to the underneath. The water head is varied from 60 cm to 100 cm at 10 cm intervals. The front- and side-views of the water jet are measured along the loci pointwise at 1 mm intervals, using a slender needle of 0.1 mm diameter held perpendicular to the front- and side projection planes, respectively.

RESULT AND DISCUSSION

Fig.2 shows boundaries dividing a total of four patterns appeared in the water rivulet on the smooth hydrophobic surface. The ordinate is the normalized discharge defined as $\hat{Q}=Q/(d\nu)$, while the abscissa is the surface slope α, where Q is the discharge, d the pipe inner diameter, and ν the kinematic viscosity of the fluid. Note that the normalized discharge may be considered to have same physical meaning as the Reynolds number. It is evident in this figure that for each surface slope with increasing $\hat{Q}$ the rivulet normally exhibits four patterns consecutively, viz., droplet, stable meandering rivulet, unstable meandering rivulet, and restable straight rivulet. For example, at α=10° the rivulet experiences the first transition from droplet to stable meandering rivulet at $\hat{Q}\simeq10$. The second transition from the stable meandering rivulet to unstable meandering rivulet occurs at $\hat{Q}\simeq440$. The third transition from the unstable meandering rivulet to restable straight rivulet occurs at $\hat{Q}\simeq2140$. It may be, however, worth noting that before the rivulet becomes a restable straight one, at

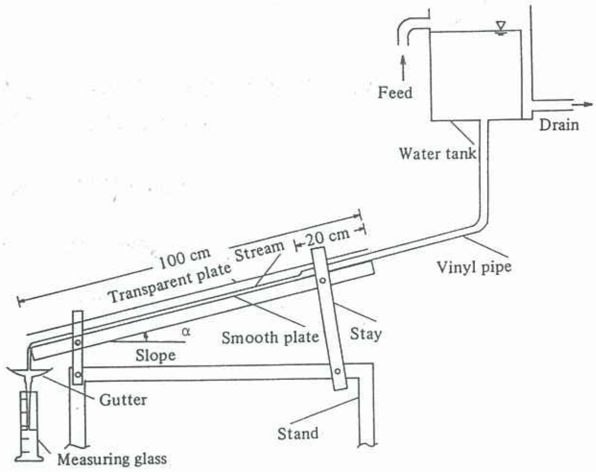

Fig. 1 Schematic diagram of the arrangement 1.

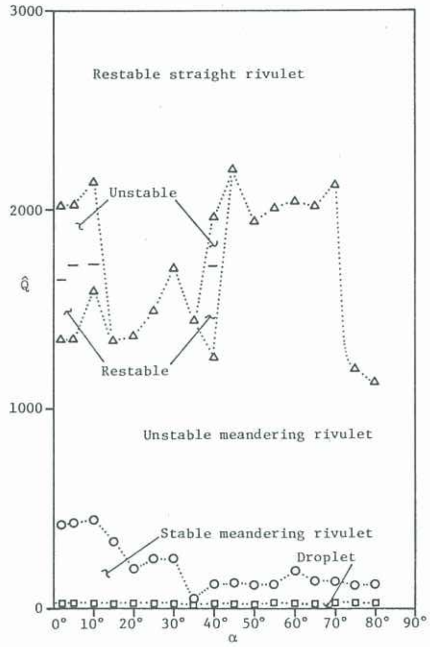

Fig. 2 Boundaries among water rivulet patterns on a smooth Plexiglas plate delineated on the normalized discharge $\hat{Q}$ - surface slope α plane.
Pipe diameter d=0.8 cm

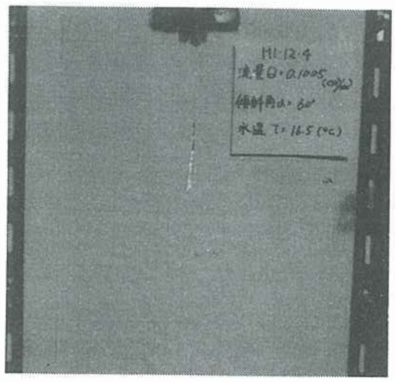
Fig.3 Water droplets on a smooth Plexiglas plate.
$Q=0.101\ cm^3/s, \alpha=60°, d=0.6\ cm$,
$\hat{Q}=Q/(d\nu)=15$, $We=\rho Q^2/(\sigma d^3)=6.3\times10^{-4}$.

$\hat{Q}$≈1580 the unstable meandering rivulet is restabilized once, and then at $\hat{Q}$≈1720 the restabilized meandering rivulet becomes unstable again. It is realized that these provisional transitions happen to appear when the surface slope is at 2°, 5°, 10°, and 40°, respectively.

Fig.3 shows the water droplets on the smooth Plexiglas plate, where $We=\rho Q^2/(\sigma d^3)$ is the normalized surface tension, ρ the density of fluid, and σ the surface tension. It is realized that droplet formation of the liquid is governed by We, but not by $\hat{Q}$. That is, the water on the smooth Plexiglas plate forms droplets only when We becomes smaller than a critical value.

Fig.4 shows an unstable meandering rivulet on the smooth Plexiglas at $\hat{Q}$=951 and α=30°. The rivulet becomes more unstable with increasing the distance from the pipe mouth along the central axis. This suggests that turbulent fluctuations in the rivulet are generated by the interaction of flow in the rivulet and plate surface. This causes an imbalance in forces acting on the rivulet, and thus an instability of the straight-line motion. The principal factor in the appearance of an asymmetrical stress on the rivulet is likely to come from the asymmetrical cross-sectional form itself. The surface-tension forces acting on the rivulet always direct tangentially to the water surface, so that the horizontal component of the surface-tension force acting on the rivulet is the product of the surface-tension and cosine of the contact angle. There must be a net across the rivulet surface tension force, acting in the direction of the thinner part of the rivulet towards the side with the smaller contact angle. Thus, effect of the asymmetry may be to swing the rivulet in the direction of its thinner side. At the downstream end of the rivulet, the contact angle on the lower side(*thicker* part)exceeds the advancing limit mainly due to the gravitational force and centrifugal force acting on the water molecules in the flow, and thus it moves to the right direction facing to the picture leaving a several child-rivulets on the left. It may be worth pointing out here that those child-rivulets also meander. It is, therefore, natural to consider that *origin of the meanders exists in the flow itself*.

It is evident that during the motion of rivulet to the right direction a surface-tension force must come into play, and thus pull the rivulet toward the upper side(*thinner* part). That is, the surface-tension force always acts so as to resist the motion of rivulet.

Fig. 5 illustrates the plan form, longitudinal cross-section, and transverse cross-sections of a restable straight water rivulet on the smooth Plexiglas plate at $\hat{Q}$≈1972 and α=30°. The width of the rivulet increases with increasing the distance from the pipe mouth along the central axis, and takes the local maximum value at x≈5 cm, whereas the height decreases with increasing the distance from the pipe mouth along the central axis and takes the local minimum value at x≈5 cm. Then, the width decreases with increasing the distance from x≈5 cm and takes the local minimum value at x≈10 cm, whereas the height increases with increasing the distance from x≈5 cm and takes the local maximum value at x≈10 cm. In the further downstream, increase/decrease cycle of the rivulet width(or decrease/increase cycle of the rivulet height) is repeated in several times along the central axis, and finally the rivulet is transformed into a smooth straight stream having an almost constant transverse cross-sections. The transverse cross-sections around each node of the rivulet plan form possess a single peak near the

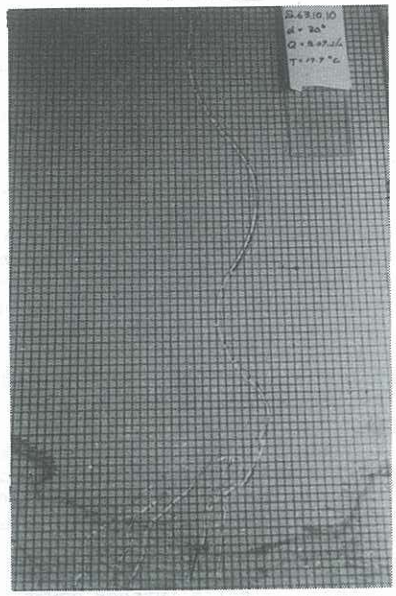

Fig. 4 Unstable meandering water rivulet on a smooth Plexiglas plate.
Q=8.07 cm^3/s, $\hat{Q}$=951, α=30°, d=0.8 cm.

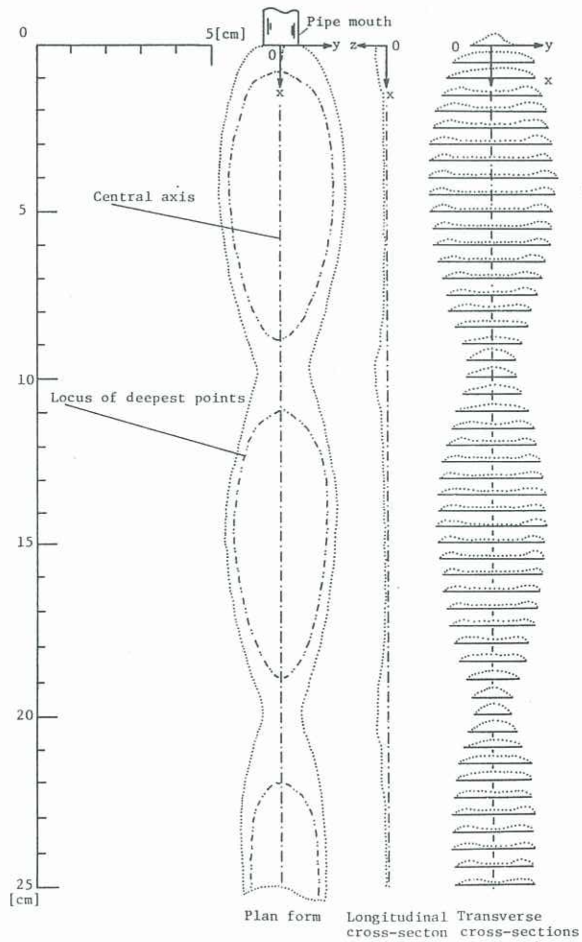

Fig. 5 Plan form, longitudinal cross-section, and transverse cross-sections of restable straight water rivulet on a smooth Plexiglas plate.
Q=11.7 cm^3/s,$\hat{Q}$=1972,α= 80°,d=0.8 cm.

central axis, while the rest cross-sections possess double peaks where one peak is near the left edge and the other peak near the right edge. The decrement rate of the rivulet width from $x\simeq5$ cm to 10 cm is smaller than the increment rate from the pipe mouth to $x\simeq5$ cm, but it is greater than the increment rate from $x\simeq10$ cm to 15 cm. Thus, it is considered that with increasing the distance from the pipe mouth along the central axis, the local maximum width of each bead in the rivulet decreases, but its length increases.

Fig.6 shows front- and side-views of the water jet being emanated from a rectangular orifice in the air vertically downwards at the normalized discharge $\tilde{Q}=Q/(l\nu)=891$, l is the longer side-length of the orifice. Origin of the right hand coordinate system is chosen at the geometrical centre of the orifice. The width of the water jet sheet in the x-y plane decreases with increasing the distance x and takes a local minimum value at $x\simeq2.3$ cm. However, from $x\simeq1.2$ cm the water jet sheet starts being expanded into the positive and negative z directions, respectively, within the x-z plane, which is normal to the x-y plane. In the further downstream, width of the water jet sheet within the x-z plane increases gradually with increasing the distance x and takes a local maximum at $x\simeq2.9$ cm, and then it decreases with increasing the distance x and takes at $x\simeq4.5$ cm.

Moreover, from $x\simeq3.5$ cm the water jet sheet within x-z plane starts being expanded into the positive and negative y directions, respectively, within the x-y plane. Width of the water jet sheet within the x-y plane increases gradually with increasing the distance x and takes a local maximum at $x\simeq4.9$ cm, and then it decreases with increasing the distance x. However, in the downstream of $x\simeq6.0$ cm, the water jet sheet breakes into numeral droplets by entraining the surrounding air.

CONCLUSION

It is found that phase of the rivulet width on the smooth plate is opposite to that of the rivulet height. That is, the rivulet width takes a local maximum at the point where the height takes a local minimum, and *vice versa*. The transverse cross-sections around each node of the rivulet plan form possess a single peak near the central axis, while the rest cross-sections possess double peaks, where one peak is near the left edge and the other peak near the right edge. With increasing the distance from the pipe mouth along the central axis the local maximum width of each bead in the rivulet decreases, but its length increases.

It has been demonstrated clearly that direction of the water jet sheet is turned, alternatively, 90° around the longitudinal axis when the water jet falls in the air vertically downwards. The physical reasoning of this curious 90° turn of the jet sheet has been attributed to the turning mechanism of two parallel water jet sheets colliding each other with same velocity but opposite direction. On the basis of these considerations it is concluded that the water rivulet on the smooth plate is turned alternatively by 90° around the central axis by the same mechanism as that of parallel jet sheets.

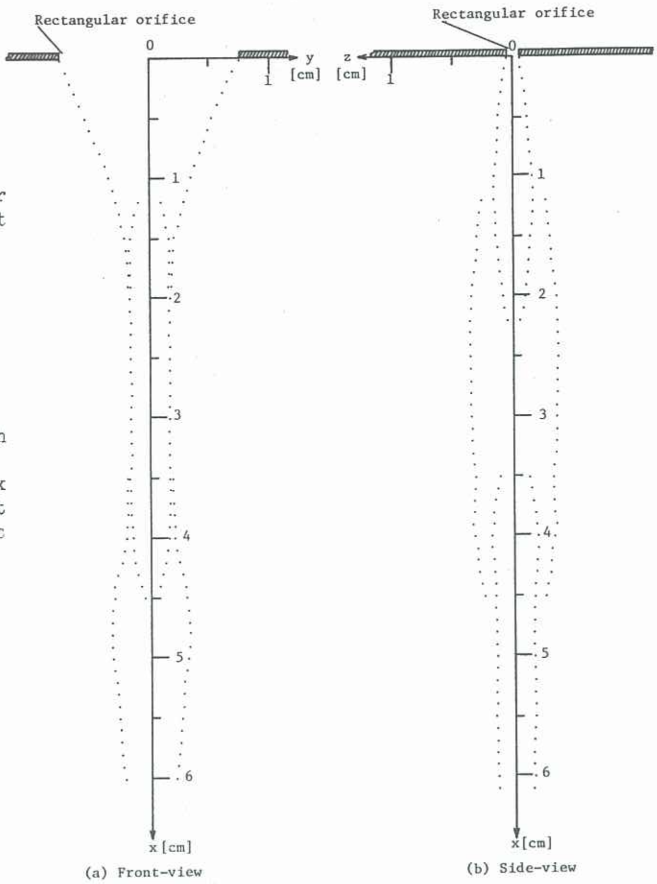

Fig.6 Water jet being emanated from a rectangular orifice(15 mm × 1 mm) in the air vertically downwards. $Q=14.3\ cm^3/s$,

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