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Experimental study of water transport on a generic mirror

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Abstract

An experimental study of water transport on a generic mirror was carried out. The experimental set-up was a generic mirror that had a total height of 30 cm and a width of 20 cm with 52 holes with a diameter of 1 mm, see figure 1. As the water was introduced, the ambient air formed a rivulet that traveled towards the trailing edge of the mirror. The rivulet breaks up at the trailing edge or just continuously drains on the flat side of the mirror. This rivulet will also break up at the end and form droplets whose size depends on the flow rate and the velocity of the ambient flow.
The experiment was done at Volvo Car Corporation using three different water flow rates (0.8, 0.5 and 0.2 l/h) and four ambient velocities (11, 14, 19 and 25 m/s). A high-speed camera was used to visualize the water, which contained a fluorescent liquid for easier post processing. Every case was repeated five times in order to obtain reasonably good statistics for the rivulet path and second-order droplets. In this paper we distinguished between moving and non-moving separation of rivulets/films. A moving rivulet is a rivulet that has a velocity when it breaks up, and a non-moving rivulet is one that does not have any velocity when it breaks up. In the latter case it accumulates water at the edge before it breaks up and sheds from the edge. The experiment shows good agreement with previous separation criteria for moving film. The correlation for the non-moving films resulted in a different correlation as compared to Tivert & Davidson (2010). This discrepancy can be an effect of errors in the local air velocity estimation or have to do with geometry.

Introduction

Liquid films and rivulets play a major role in many processes in industry. For instance, liquid films are of interest in various kinds of cooling devices in terms of facilitating separation of liquid and gas in oil industry and in fuel mixing in engines. Different models available for simulating a liquid film or a rivulet flow, such as the classical fourth-order model of Bernis & Friedman (1990) and the boundary layer model. The choice of model depends on the types of features required.

However, the thin liquid film approach has some drawbacks that are of great importance, especially the break-up issue. It does not allow the thin film to break-up by itself because the models do not include the physics for break-up. This is a problem because almost all important flows contain some sort of break-up into smaller films or droplets. The solution is to use experimental correlations and one can use the correlations in Friedrich et al. (2008) or Maroteaux et al. (2002) when the film is moving. If the film is non-moving, the correlation in Tivert & Davidson (2010) can be used, but it seems that break-up is dependent on geometry thus requiring further validation work. In the experiment presented in this paper, both moving film and non-moving film separation criteria will be validated.

Experimental set-up and method

The generic side mirror with its dimensions is shown in figures 2 and 3. The mirror is mounted on a vertical plate 2.9 m long and 1.6 m wide. The mirror is placed 0.9 m from the leading edge of the plate, as can be seen in figure 4.

The cameras used in the experiment were a high-speed camera and two video cameras. The two video cameras were used when the rivulet was traveling on the mirror where there was no need of high accuracy. The resolution and frequency of the video cameras were much lower than of the high-speed camera. The high-speed camera was placed so it could captured the separation of the rivulet. The resolution of the high-speed cam-

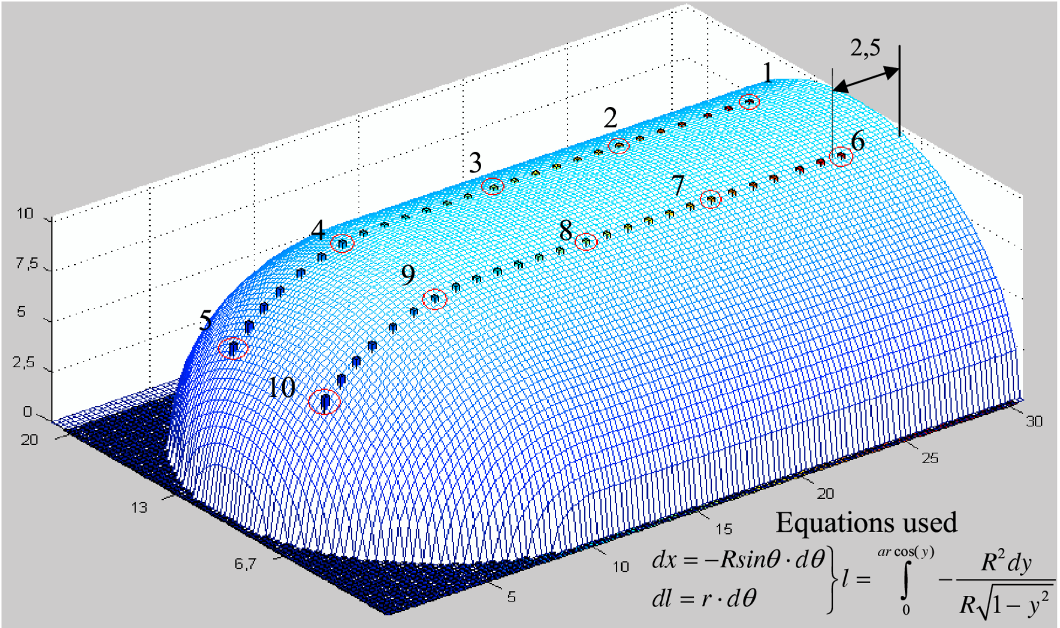

Figure 1: Generic mirror

era was 256×256 and the operating frequency was 1000 Hz. The camera set-up during the experiment is shown in figure 5, where A is the location of the video cameras and B is the position of both the video cameras and high-speed camera, but at different horizontal positions. The velocity and the size of the released droplets were obtained by high-speed filming, and UV liquid was used to acquire sharper pictures. The measurements were repeated at least eight times for each water flow rate and ambient air flow to obtain good statistics.

Correction has been made for the experiments error such as blurriness and converting between different formats. Greater detail on the experimental work is given in Lafuente (2006).

The pictures were analyzed in Matlab where the movement of each droplet was detected. The velocities of the droplets were obtained from the camera frequency. The “seek” algorithm and the approach for finding droplets and calculating the velocities are described below.

Step 1: Define a very coarse two-dimensional grid with a cell size of approximately $0.5cm$ x $0.5cm$ (see figure 6) where each cell is checked to see whether it contains any water.

Step2: If there is any water in a large cell, then an algorithm finds the pixels that cover the droplet.

Step 3: If a droplet is in two or more cells, then a new large cell is defined. It is not a problem if there is more than one droplet in a cell.

Step 4: Compute a corresponding radius of the closed area.

Step 5: Compute the distance between a droplet at two consecutive photos and divide it by the time elapsed between the two photos, which gives the speed of the droplet.

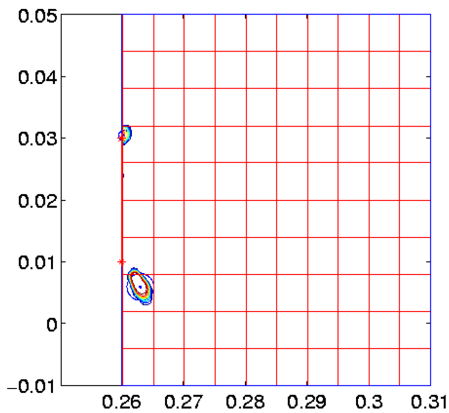

Figure 6: The seek algorithm, the search mesh and a droplet with its corresponding radius

The following steps were used to get the location and width of the rivulet:

Step 1: The rivulet was filmed by the video camera. It was sufficient to use one frame of the entire film be-

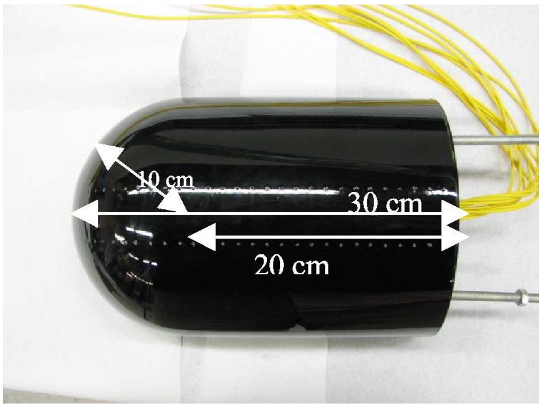

Figure 2: The generic mirror with dimensions (front view)

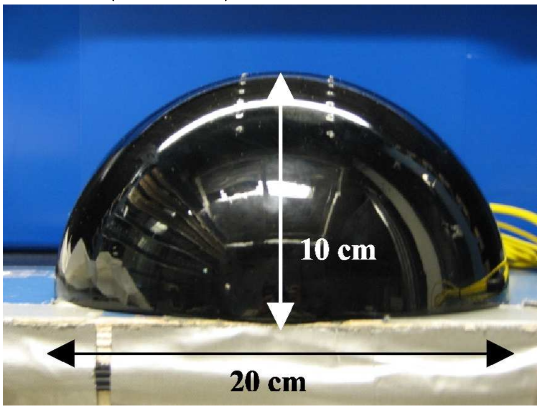

Figure 3: The generic mirror with dimensions (side view)

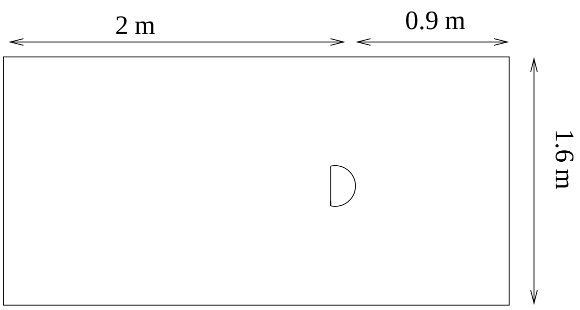

Figure 4: Dimensions of the experimental set-up

cause the rivulet was stationary in each experiment, although the rivulet was not in the same place in different experiments.

Step 2: The use of UV liquid in the water made it easy to obtain an accurate location of the rivulet.

Step 3: Repeat step 2 for the five experiments.

Step 4: The mean path of the rivulet was calculated.

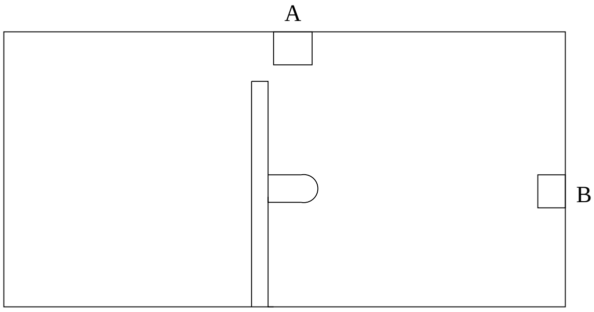

Figure 5: A and B are the camera positions. The ambient air velocity is directed into the paper.

The width was also measured at four different places along the path and was then averaged for the five experiments.

Step 5: The center line of the rivulet was then mapped into the millimeter paper.

Exactly the same procedure was used to find the separation points.

Results

The main object was to gain a good understanding of the water transport on a mirror-like object. The experiment was also an opportunity to investigate whether the formulas and correlations in the literature for separation were fulfilled in this test case. The generic mirror had 52 holes that were drilled, but only ten of them are used in this experiment. Figure 1 shows which holes are used and their location. In the first part of the experiment, the rivulet path was of interest. The path of the rivulet is shown in figures 7 and 8. The path is strongly dependent on ambient velocity as can be seen in the figure. As the experimental results showed only a weak dependency on the water flow rate, only one flow rate is presented here. The path of the rivulet is a mean path of five experiments. The widths of the rivulets are not shown in figures 7 and 8 but are listed in table 1.

Figures 9 and 10 show where the rivulets separate from the generic mirror. A comparison of the separation points with the rivulet path in figures 7 and 8 shows that, in many cases, the end of the rivulet is not at the separation point. The explanation is that the rivulet travels along the lower edge of the mirror and, in most cases, the separation would take place close to the lower outer edge of the half sphere of the mirror, as can be seen in figures 9 and 10. The reason why there are many separation points located in this refion is not yet clear.

Figure 11 shows the present correlation for non-

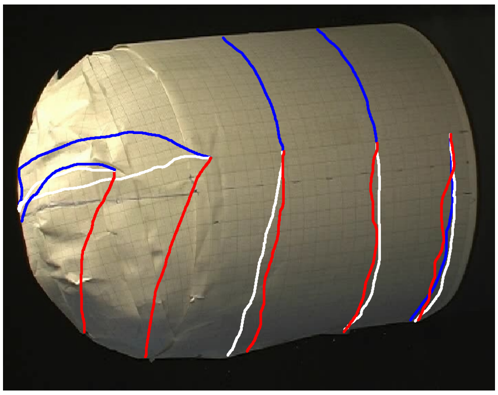

Figure 7: Rivulet path for holes 1-5 with three different velocities. Red: $V_c = 11\,m/s$; white: $V_c = 19\,m/s$; blue: $V_c = 25\,m/s$

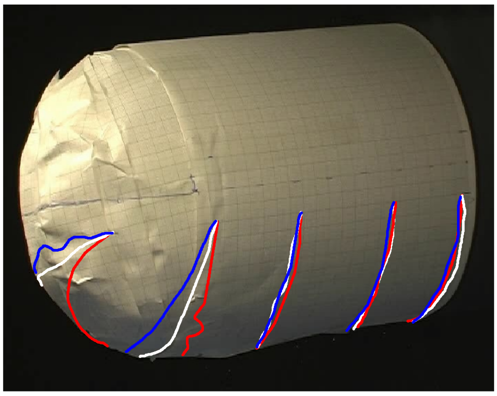

Figure 8: Rivulet path for holes 6-10 with three different velocities. Red: $V_c = 11\,m/s$; white: $V_c = 19\,m/s$; blue: $V_c = 25\,m/s$

moving separation, and the equation for separation is:

$$We = -96 + 174 V_c$$

The formula is only valid inside the interval $11 < V_c < 25$.

If the rivulet or a film is non-moving at an edge, it will separate from the surface if the Weber number is above the curve shown in figure 11. The Weber number is calculated as follows

$$We = \frac{\rho_f h_f V_c^2}{\sigma}$$

where ρ_f is the density for the liquid in the rivulet or the film, h_f is the height of the rivulet at the edge just before it separates, σ is the surface tension and V_c is the ambient air velocity. The height as a function of the Weber number is shown in figure 12 and, as expected, the critical height gets smaller when the air velocity increases.

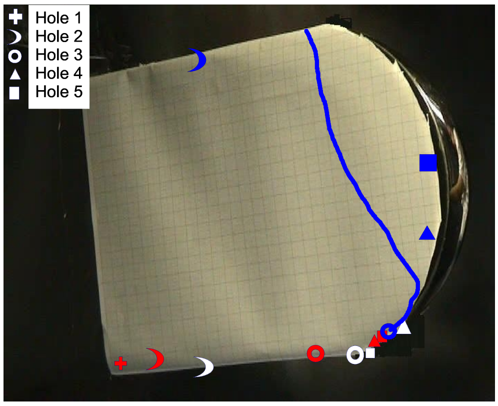

Figure 9: Separation points for holes 1-5 with three different velocities. View from downstream. Red: $V_c = 11\,m/s$; white: $V_c = 19\,m/s$; blue: $V_c = 25\,m/s$

Hole	Velocity, V_c (m/s)	flow rate (l/h)	Width (mm)
1	11	0.2	2.1
3	11	0.2	1.7
5	11	0.2	2.1
1	14	0.2	2.1
3	14	0.2	2.2
5	14	0.2	2.4
1	19	0.2	2.3
3	19	0.2	1.2
5	19	0.2	1.9
1	25	0.2	2.1
3	25	0.2	1.2
5	25	0.2	1.8

Table 1: The width of the rivulet at different conditions

Comparing the correlation and critical height in this study with Tivert & Davidson (2010), it is seen that the critical height is lower in the present experiment. The reason for this is probably that the ambient air velocity is used in the calculation of the Weber number. The local air velocity is higher in the present experiment than in the previous investigation because of the acceleration caused by the curvature of the front side of the mirror. Unfortunately there were no measurements of the local velocity. The use of the ambient velocity in the Weber number is probably not the best choice; it would have been much better to use the shear stress.

Friedrich et al. (2008) proposed a criterion for break-up when the film is moving over an edge: if the fraction is larger than one, the film/rivulet will separate.

$$F_{ratio} = \frac{\rho_f u_f^2 h_f}{2\sigma}$$

Here u_f is the velocity of the film. When the air ve-

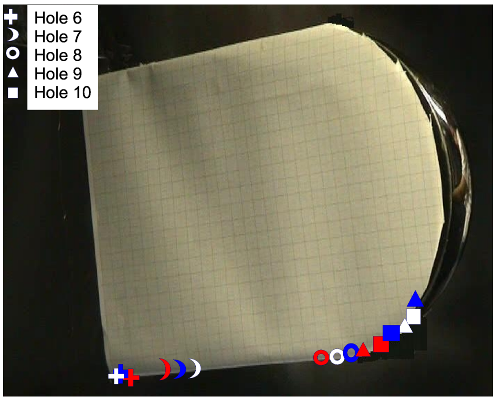

Figure 10: Separation points for holes 1-5 with three different velocities. View from downstream. Red: $V_c = 11\,m/s$; white: $V_c = 19\,m/s$; blue: $V_c = 25\,m/s$

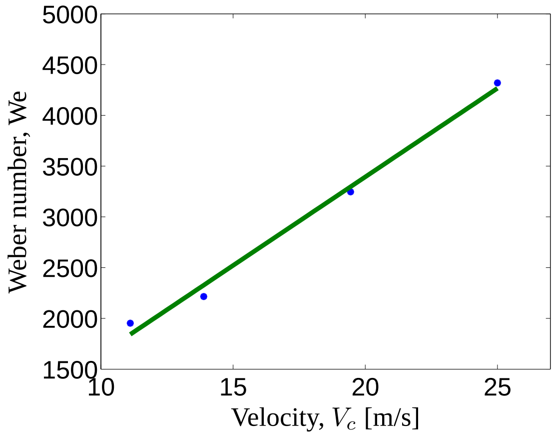

Figure 11: Dots: experimental Weber number; green line: the correlation in least square sense

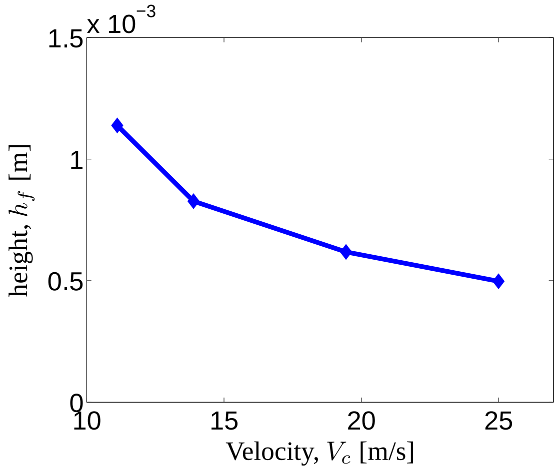

Figure 12: Critical hight for different air velocities

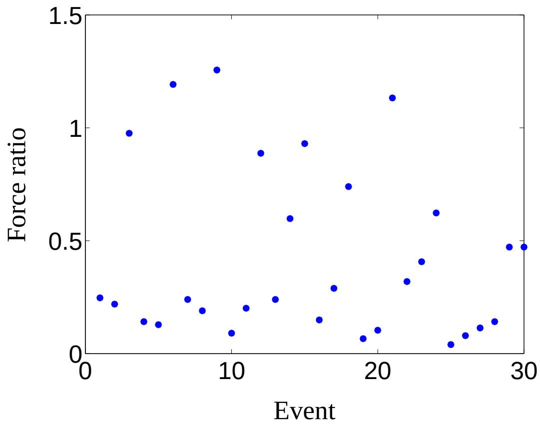

Figure 13: Friedrich Force balance. Beginning from the left with hole 1 with $V_c = 11$, then hole 1 $V_c = 19$ and so on, at right hole 10 with $V_c = 25$

locity was 25 m/s the rivulet did not stop at the edge and accumulate water (i.e non-moving separation), but it separated directly (i.e moving separation) or continued over the upper edge and drained down along the flat side of the mirror to the lower edge of the mirror, as sees in figure 7. Therefore another criterion is needed to judge whether it would separate or accumulate. If the criterion in Friedrich et al. (2008) were used, there would be three separations, as can be seen in figure 13, but only one separation was obtained, namely in the case of 25 m/s and when the water comes from hole two. The reason why the criterion overestimated the number of moving rivulet separations can be an overprediction of the rivulet velocity. There was no opportunity to measure the rivulet velocity during the experiment, so the velocity is an estimation from mass conservation.

Each experiment in which the separation was of interest was run for two seconds and was filmed by the high-speed camera. The radius and velocity for every droplet in each picture during the separation experiment are shown in figures 14 and 15 and the averaged quantity is shown in figures 16 and 17. One can clearly see that the radius decreases the further away the droplets come from the mirror. This is due to the break-up of the droplet. The droplet breaks up into smaller droplets if the diameter is larger than a critical diameter corresponding to the Weber number for the droplet. The velocity of the droplets increases the further downstream they get. This is caused by the drag increase because of acceleration of the droplets. It is also due to the break-up of the droplets, however; when the droplets are smaller they get a shorter relaxation time and will accelerate to

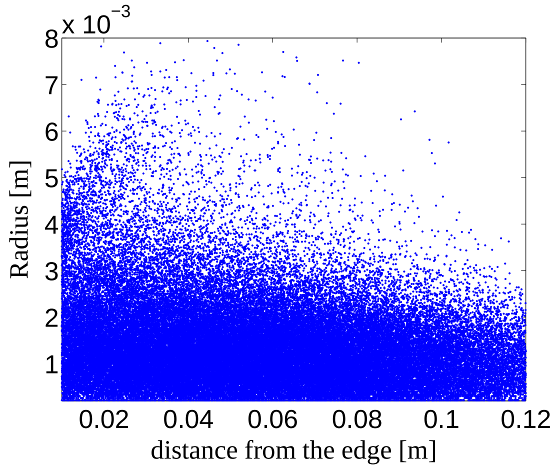

Figure 14: The dots are the diameters of the droplets at different positions from the mirror

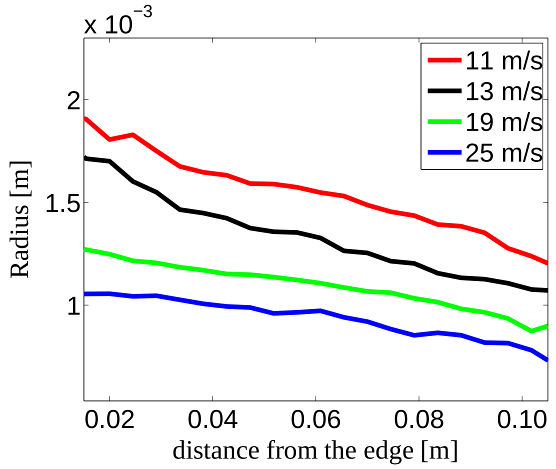

Figure 16: Mean radius for various ambient velocities at different positions from the mirror

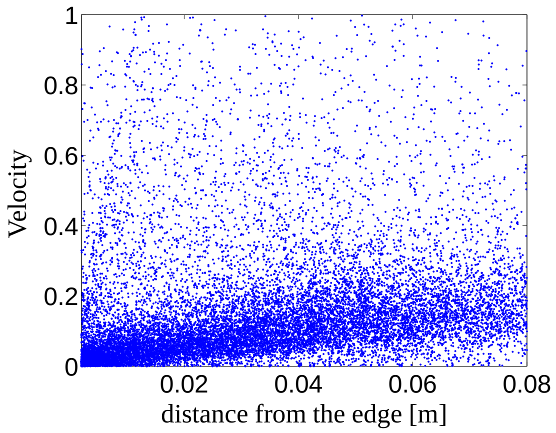

Figure 15: The dots are the velocities (normalized with V_c) of the droplets at different positions from the mirror

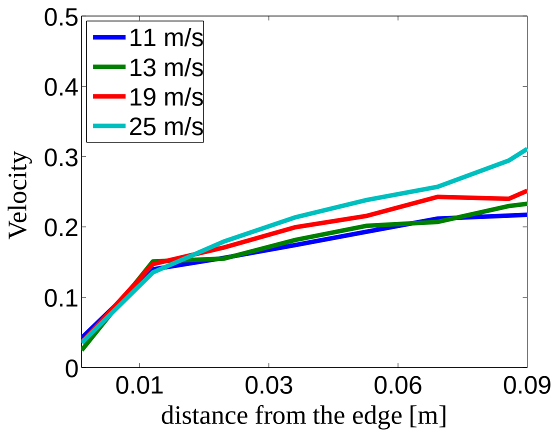

Figure 17: Mean velocities (normalized with V_c) of the droplet for various ambient velocities

the ambient velocity more rapidly. In figures 17 and 15 the particle velocity was divided by the ambient velocity.

Conclusions

An experimental study of water transport on a generic mirror was carried out. The generic mirror had 52 drilled one-mm holes, and ten of them were used to introduce water in the present study. Four ambient air velocities and three water flow rates were used in the experiment. The rivulet path was strongly dependent on the ambient air velocity but showed almost no dependency on water flow rate. A correlation for non-moving rivulet/film separation is presented, and the experiment also showed some moving rivulet separations. Friedrich et al. (2008) criterion was used for moving rivulet/film separations, and the correlation slightly overpredicts the number of separations. However it can be caused by an overestimation of the rivulet velocity in this study. The correlation in this study has at least one serious drawback: the use of the ambient air velocity in the correlation for the critical Weber number. To get a better separation model for non-moving rivulets/films, it is probably necessary to use the shear stress instead of the ambient velocity. One way to obtain the shear stress is to simulate the air flow with large eddy simulations. The results will be much more general if the local quantity is used; different geometries can then more easily be compared and a general model for non-moving rivulets may finally be achieved.

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