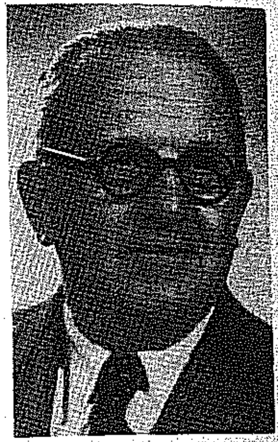
THE TEAPOT EFFECT

. . . a problem

By Markus Reiner



Markus Reiner teaches applied mechanics at the Israel Institute of Technology in Haifa, or the "Technion" as it is also known. By profession a civil engineer, he has worked as such for a whole lifetime—"doing science," he explains, "as a hobby." When Prof. Bingham of Lafayette College, Easton, Pa., learned about his work, he invited him to do research there, and Prof. Reiner spent two years (1931–1933) at Lafayette as research professor, cooperating with Bingham in the establishment of rheology as a new branch of physics. He is now head of Technion's rheological laboratory, where he treats concrete as a liquid and air as a solid. He has recently designed and built a centripetal airpump based on the fact that, as foreseen by Maxwell, air can be considered as a viscoelastic solid with a time of relaxation of about 10^{-10} seconds.

As probably everybody has experienced to his or her dismay, when tea is poured out of a teapot, the jet, more often than not, has a tendency not to flow in a nice ballistic curve, as intended, into the cup, but to follow the underside of the spout, and soil the table cloth. *Every* physicist from a large number whose opinion I asked on the possible reason for this phenomenon, replied it must be due to surface tension or, in other terminology, capillary action or adhesion. Now, surface tension is one of the most nebulous terms of physics; many textbooks on the subject will tell the student that there is no such thing, and that the proper term is surface energy. We need not go into this question here, suffice it to say that when the physicist is pressed to express himself more clearly, he will say that this teapot effect is obviously due to the adhesion between the liquid (tea) and the solid (spout), and that the "phenomenon" was no problem and not worth another minute's thought.

Now it can easily be shown that this explanation is incorrect. I do not wish to say that there is no adhesion between the liquid and the solid but when the spout is coated with some water-repellent material, e.g., paraffin wax, the phenomenon persists without any noticeable change. Therefore it cannot be *due* to adhesion, and the problem arises as to what physical property might be involved.

But perhaps I should first tell how I came to busy myself with this problem, because I also, of course, did not give it a minute's thought when pouring out my tea, being convinced, as every other physicist, that I well knew its reason, which was adhesion.

This is the story:

All those who know their Bible and others who know geography, know that the southeast coast of the Dead Sea is a vast salt desert, with huge masses of crystalline salt covering the ground. Now it is strange to note that there are great stretches of such ground where the upper surface is absolutely horizontal. This posed a problem to Dr. R. Bloch, Chief Chemist of the Dead Sea Works Ltd., Jerusalem. He guessed that this peculiarity might be due to the manner in which the dissolution of the salt of the upper layers takes place, and proceeded to investigate the question by experiment.

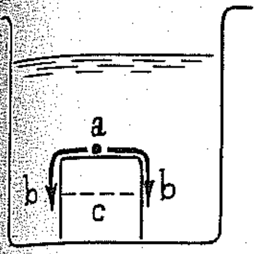


Fig. 1

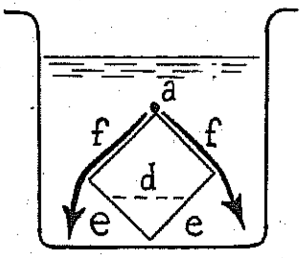


Fig. 2

When a NaCl crystal is put into a beaker with standing water the following can be observed:

Let the crystal be placed as shown in Fig. 1. Dissolution takes place in such a way that the horizontal top surface only is attacked while the vertical surfaces are protected by films of saturated salt solutions running down the sides. This can very well be seen when a permanganate fragment (a) is placed on the top of the crystal coloring the path (b) of the streaming salt solution. After several hours the crystal has been reduced to the height of the dotted line (c).

If the crystal is put into the water as shown in Fig. 2, it eventually takes on the form indicated by the dotted line (d). The faces (e) therefore also remain unattacked. Dr. Bloch thus discovered the surprising fact that the protecting film of concentrated salt solution sticks to the salt crystal against the kinetic energy of the stream (f) and against the action of gravitation. The explanation which suggested itself was "adhesion"; the salt solution film adheres to the solid crystal surface. To check this theory, an Erlenmeyer flask was immersed in a vessel filled with fresh water, upside down. A concentrated salt solution was slowly run into the upper surface (= the bottom) of the flask. A piece of permanganate served to show the stream of the NaCl solution (see Fig. 3). A film of less than one mm thickness of the heavier-than-water salt solution runs down the slope of the flask, and sticks to it on the surface, keeping on against gravitation. After a few centimeters of flow the film starts to wriggle, detaches itself from the surface, and sinks slowly down with turbulent eddies. This confirmed the phenomenon seen in the dissolution of the salt crystal in Fig. 2, with the generalization of solid glass taking the place of solid salt, so that one could assume the phenomenon to be present with any liquid stream in contact with any solid surface. But was it due to the adhesion between the liquid and the solid?

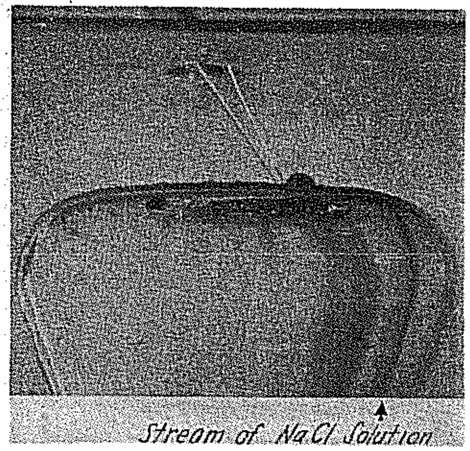
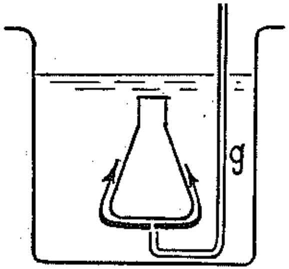


Fig. 3

In the experiment shown in Fig. 4, the Erlenmeyer was immersed in the upright position in a concentrated NaCl solution. Fresh water was now run through a U-tube (g) to the bottom of the flask; being lighter than the NaCl solution, it rose again along the slope of the flask sticking to the wall against gravitation. Again, after a few centimeters flow, detachment and turbulence could be observed.

Fig. 4



Since in the first experiment the NaCl solution seemed to adhere to the solid wall in preference of and displacing fresh water, while in the second experiment fresh water seemed to adhere to the solid wall in preference of and displacing salt water, adhesion as a surface-tension property has to be excluded as an explanation of the effect.

When he had progressed so far, my friend, Dr. Bloch, who is a chemist, turned to me, the rheologist.

THERE is no necessity of describing in detail further experiments which confirmed the result of excluding adhesion and supplied additional data. Suffice it to mention that instead of salty and fresh water, hot and cold water could be used. Also instead of glass I used metal surfaces making sharp angles between the horizontal and the sloped surface, avoiding the rounding off transition at the flask, and varied the degree of slope; the results were of the same kind. It could also be observed that the length of the stream along the sloped surface was smaller the smaller the slope, but never vanished. Even when the "sloped" surface was horizontal, there was a small length on which the stream followed this horizontal surface before detaching itself for the natural downward course.

But then I thought: why do all this in water, why not in air? And immediately it occurred to me: but

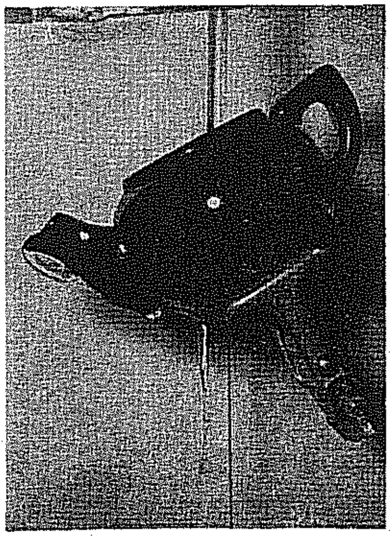


Fig. 5

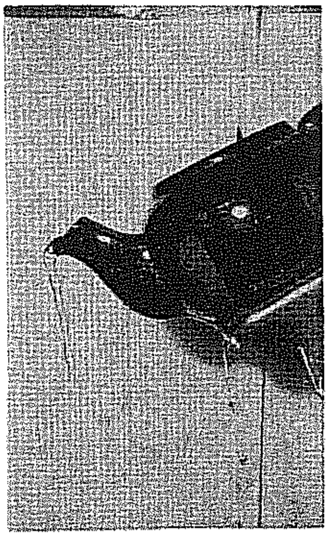


Fig. 6

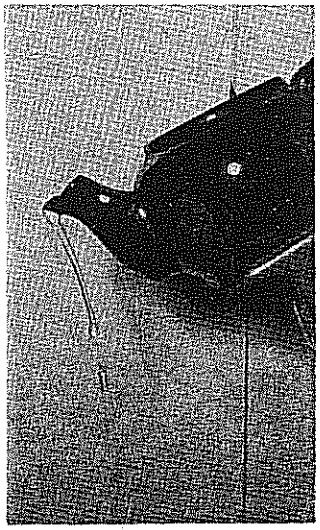


Fig. 7

Fig. 8

that is what the teapot does. Fig. 5 shows the teapot in action. It is fed from a tap above, and the water emerges from the spout sticking to the wall of spout, and going off when the bottom of the pot is reached. Sometimes it can be observed that water flows even along the bottom of the pot *uphill*. However, when the supply of water is increased, this effect is joined by another one. Part only of the issuing water sticks to the wall, but another part flows down more or less vertically (Fig. 6). But looking more closely we see that this downward jet shows a curious diversion from the vertical: curious in that it is directed opposite to what one would expect. Now increase the supply of water from the tap still more (Fig. 7); the "sticking" flow of water disappears but the jet persists in the wrong direction, only the more so. Increase the flow of the water still more, and you get the picture of Fig. 8, with the jet practically vertical. Still greater supply of water, and therefore increase of the velocity of the flow, results in the ballistic curve which we all expected and which is desired when pouring the tea into the cup; there is no necessity to take up space with an additional figure.

The teapot experiment accordingly did not supply a clue; on the contrary, we see that there are *two* phenomena present where we originally saw one only. There is (1) the phenomenon of a liquid layer "sticking" to a solid wall. There is (2) the phenomenon of an "antiballistic" jet.

LET us first treat the first. When a layer of viscous liquid flows along a solid surface, it is sheared. The layer can be imagined as consisting of laminae. The velocity of the lamina adjacent to the wall is zero*, and it increases linearily to V at the outermost lamina. Let h be the thickness of the layer, then a velocity gradient $\gamma = V/h$ is produced. By virtue of its viscosity the liquid resists its shearing deformation through internal shearing stresses $\tau = \eta\gamma$ where η is the coefficient of viscosity. However, as everyone who has had a course in elasticity or hydrodynamics knows, the shearing deformation just described does not exhaust the kinematics of the case. In addition to the shearing deformation which continuously reduces the right angles formed in the liquid by the lines of flow parallel to the solid surface and the normals to it, there also take place rotations of the elements of the liquid defined by vortices as shown in Fig. 9. Note that these rotations are of the nature of rigid bodies' rotations.

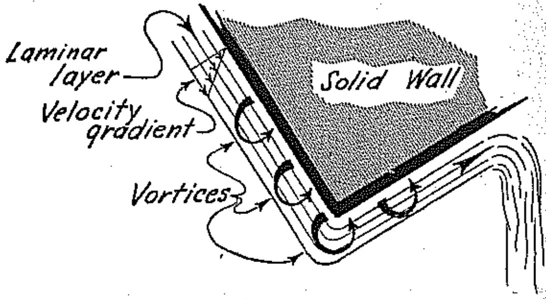


Fig. 9

Now let gravity cause or maintain the laminar flow of the liquid layer; it will produce work equal to the loss of potential energy resulting from the fall of the liquid mass from a higher to a lower level. This work is expanded in two different ways. Part of it is used up, dissipated, and converted into heat in the continuous shearing of the layer. Another part, however, is converted into the kinetic energy of the rotating elements. As the rotation is not accompanied by any deformation this part is not dissipated, but persists in a steady state, and can only decline with the velocity V.

It is suggested that this is the mechanism for the "sticking" of the liquid to the solid wall which actually is no sticking at all, but a kind of being pressed against the wall through the rotational kinetic energy of the vortices. The vortices also help the layer to turn corners.

If my explanation is correct, this disposes of the

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* This can be assumed even when the liquid does not "wet" the surface as shown by the fact that Poiseuille's formula can be applied in the case of mercury flowing through a capillary. Here a very thin layer of air separates the liquid mercury from the solid wall of the capillary, but this does not affect the result.

first effect. There are many other phenomena where it may be operative. For instance in order to safely pour a liquid from one receptacle into another, the experienced chemist uses a glass rod along which the liquid is made to flow. Or put your finger under a jet issuing from a tap, and watch the curious way in which the water is diverted from its course. Here, however, another hydrodynamical effect may be involved.* Another example is supplied by the drip groove which the architect provides in the windowframe to prevent rainwater from finding its way into the room (see Fig. 10).

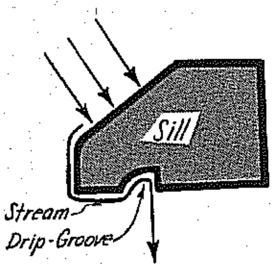

Fig. 10

He knows that oiling the underside will not help; he makes an incision (h) in order to break the kinetic energy.

Before leaving this subject, we may dispose of another explanation for the "sticking-on" effect in which it was suggested that air pressure active upon the outer surface of the layer, but absent where it is in contact with the solid wall, presses the layer on to the wall. However, this same air pressure does not prevent the layer from detaching itself from the wall when the velocity V has fallen so much that the kinetic vortex energy is insufficient for preventing it. Besides, as was described above, the effect is also present with a liquid (salt solution) flowing within a liquid (fresh water).

WE now come to the second teapot effect. I must confess that in this case I do not know of any convincing explanation, and for this reason I have given this little paper its subtitle. But I have a suggestion to make.

Before that, note that this second effect also can be performed with a liquid flowing within another liquid. In Fig. 11, a jet of salt water flows *downwards* in fresh water, in Fig. 12, a jet of fresh water flows *upwards* in salt water: both have exactly the same shape; as a matter of fact only the free surface of the liquid in the receptacle can show which is which.

Here we have no laminar layer to which we could apply our previous reasoning. True, at the opening of the spout there is a short distance over which the issuing liquid is sheared with a vortex in the right direction accompanying it. But is the kinetic energy of this vortex sufficient to revert the curvature of the jet? This may be doubted. When we look at Fig. 11, we see that the curvature of the issuing jet is first anticlockwise as it should be in a ballistic curve. In such a curve the curvature is gradually reduced but its sense is not changed. Here, however, it reverts to clockwise for no obvious reason. Could it be that the liquid can support *one-dimensional* stresses? I do not mean van der Waals forces which act isotropically in three dimensions, and are the cause of the well-known isotropic strength of liquids. I understand that the present view on the internal structure of water and similar liquids is that it is a kind of polycrystal with an intercrystalline amorphous phase, the whole difference with a solid polycrystal consisting in the temporary nature of the crystals which constantly lose and attach molecules. If this were so, there might be one-dimensional tension in the jet, and the jet would behave not differently from an elastic steel chain, as shown in an experiment described by Pohl. In order to produce in the issuing jet an *exaggerated* anticlockwise curvature, a *centripetal acceleration* must be present, in addition to the respec-

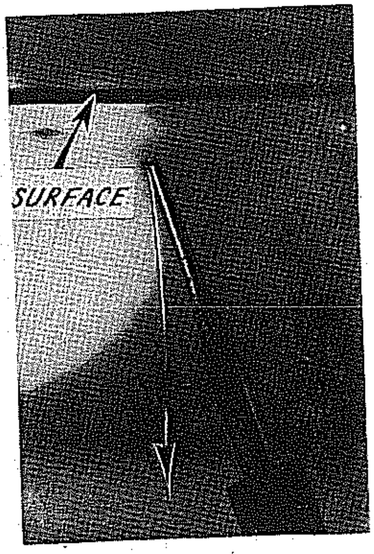

Fig. 11

Fig. 12

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* Compare Lighthill (1945).

tive component of the gravitational acceleration. However, no centripetal force exists to account for this. But if tangential tensions in the jet were present, they would have a resultant towards the center of curvature causing an acceleration in this direction (see Fig. 13).

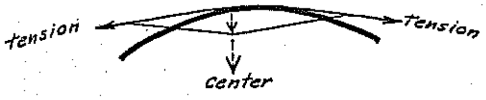

Fig. 13

When the anticlockwise curvature has gone far enough, gravitation prevails, and now produces a clockwise curvature in a reversed ballistic curve.

I have performed experiments under controlled conditions trying to find quantitative results, for instance by changing the temperature of a jet of water issuing from a horizontal tube made of a water-repellent plastic. However, it is very difficult to get rid of the first teapot effect. I had to give up, being occupied with other problems. But I thought it worth while to draw the attention of others to the complicated phenomena underlying such an every-day-observation. When I told an eminent physicist who has made the structure of water his special field, this story, he took a beaker, went to the sink in his room, and put the beaker under the tap.* When he opened the tap and let the water flow into the beaker and out of it, he could observe the second teapot effect and exclaimed: "I never saw this." Later I told the story to another colleague while riding in the London Underground. Suddenly he exclaimed: "Look here," and pointed to an advertisement above our heads. And here it was as a commercial artist had seen it (see Fig. 14).

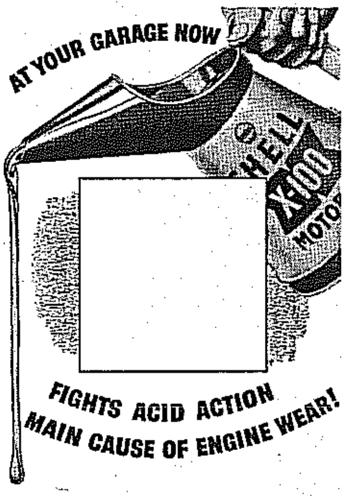

Fig. 14

I RETURNED home to Israel from England via France. One day I was standing before a nice fountain on the main square of Annecy. There were four lions at the four corners spouting water—and each one showed the teapot effect in a different stage. Here are two photographs (Figs. 15 and 16). When there is ample flow of water, the jet shows a ballistic curve.

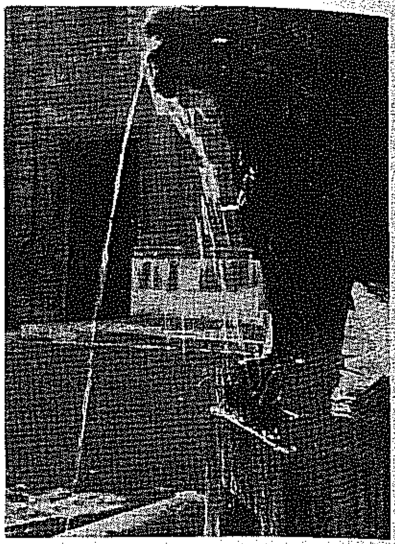

Fig. 15

Fig. 16

When the supply is less, a teapot effect accompanies it (Fig. 15). When the flow is still more reduced, the ballistic curve disappears, and the teapot effect remains (Fig. 16). It was winter, and the poor lion's forefeet were completely frozen in. . . .

REFERENCES

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2. R. Bloch and M. Reiner, Bull. Res. Counc. Israel, 2, 263 (1952).
3. M. Reiner, Bull. Res. Counc. Israel, 2, 265 (1952).

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* As a matter of fact the experiments which I have shown for historical reasons with a teapot can as well, or even better, be performed with any laboratory beaker.

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