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Keep Cool to Reduce Friction," Suggests a New Study of Nanoscale Water Condensation

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"Keep cool to reduce friction" might be the advice given to designers of nanoscale machinery by researchers who have just completed a study of factors influencing the formation of "water bridges" – capillary connections that can glue surfaces together, giving rise to friction forces.

When surfaces touch in a humid environment, moisture forms water bridges, or capillaries, between them. On familiar size scales, this process – known as nucleation – helps hold sand castles and wet concrete together, and is critical to the formation of clouds. But sometimes these structures can be less helpful, causing friction sufficient to slow or even stop nanoscale machinery – or in food processing, creating large clusters of sugar, salt, baby cereals or coffee.

By studying the frictional forces acting on an atomic force microscope (AFM) tip drawn across a glass surface, researchers at the Georgia Institute of Technology have demonstrated for the first time that the formation of these capillaries is thermally activated. Their study suggests that it may be possible to reduce the adhesion between surfaces by reducing temperatures and putting nanoscale surfaces into motion before the water bridges have time to form.

"When you move very slowly, there is time for a capillary to form at each tiny bump or asperity in the surface," explained Elisa Riedo, an assistant professor in Georgia Tech's School of Physics. "But when you move faster, you have fewer capillaries. If you go fast enough, the capillaries do not have time to form."

Understanding the relationship between nucleation time and temperature could be crucial to the designers of very small devices that must operate in the presence of moisture, as well as to the food processing industry. “Since formation of the capillaries affects friction and adhesion between particles, if we understand this relationship, we can understand how small particles and nano-surfaces glue together,” she noted.

A report on the research, which has been sponsored by the National Science Foundation and the Petroleum Foundation, was published in the journal Physical Review Letters on September 23rd.

Experimentally, Riedo and her postdoctoral collaborator Robert Szoszkiewicz used an AFM with specially-crafted ball-shaped tips that had diameters ranging from 40 to 100 nanometers. That provided a multi-contact area of approximately 30 square nanometers.

While maintaining a constant humidity of about 40 percent, they moved the tip across a slightly rough glass surface that had irregularities approximately one nanometer high. While the tip was moving, they recorded the resistance to motion – measured in piconewtons or nanonewtons – while varying the temperature and velocity.

By charting their data, they saw evidence that the friction measured was directly related to temperature, suggesting the growth of capillary structures increases as temperature increases.

“The more energetic the water molecules are, the more likely it is that they will form capillaries,” said Szoszkiewicz. “We found that nucleation times grow exponentially with the inverse of temperature.”

The researchers found that the nucleation times of nanoscopic capillaries increased from 0.7 milliseconds to 4.2 milliseconds when the temperature decreased from 332 to 299 degrees Kelvin – which is approximately room temperature.

“To form water bridges, molecules need to overcome an energy barrier. The thermal energy can provide the energy they need, however, it takes time for these bridges to form,” Riedo noted. “The longer the surfaces are together, the stronger the contact will be because more bridges can form.”

When surfaces come close together, several processes can occur, Szoszkiewicz said. After contact, moisture naturally adsorbed on the surfaces – along with water molecules from the air – will concentrate close to the true contact point because of diffusion. Some initial water bridges will then form between contacting asperities.

When objects move close together but don’t touch, a different process occurs. Moisture adsorbed on each surface may coalesce, and because of attractive forces, jump together, forming a water bridge. At a given temperature, this nucleation process will differ for each surface depending on its ability to adsorb moisture. Newly formed capillaries then act as water sinks, attracting more water molecules because pressure inside the capillary bridge is lower than the pressure outside it. The process continues to a point at which an equilibrium capillary bridge is formed.

“The question we considered was what would be the dominant phenomenon and what would be the time scale for both phenomena,” Szoszkiewicz said. “We have experimentally demonstrated that with nano-rough surfaces, nucleation will be dominant.”

Beyond applications to atmospheric science, the food industry and nanoscale sliding machinery, the findings suggest another way to control ink flow in dip-pen nanolithography. In that process, ink flowing from an AFM tip is used to write nanoscale patterns that could be useful in such processes as semiconductor lithography.

“In this case, you might use the temperature dependence to increase the velocity of the ink flow, decrease it, or make the flow improbable,” said Riedo. “There are a lot of implications for the technology. Each of the materials involved will have its own properties regarding velocity and how rapidly it forms capillary bridges.”

The researchers also measured the size of energy barrier required for water molecules to nucleate. “This energy was predicted by theoretical models using classical thermodynamics, and it matched really well with our experiments,” said Riedo.

The researchers hope the information they provide will help engineers deal with capillary forces in a more efficient way. Because water is ubiquitous, more information is needed about how it behaves at the nanoscale.

“Water is of crucial importance everywhere in our world – in biology, earth sciences, atmospheric sciences and industrial processes,” Riedo noted. “From a fundamental point of view, it is difficult to do theoretical models of water. But there is a huge interest in this from both theoretical and technological standpoints.”

Source: Georgia Institute of Technology

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