Unusual fluid behavior observed in microgravity

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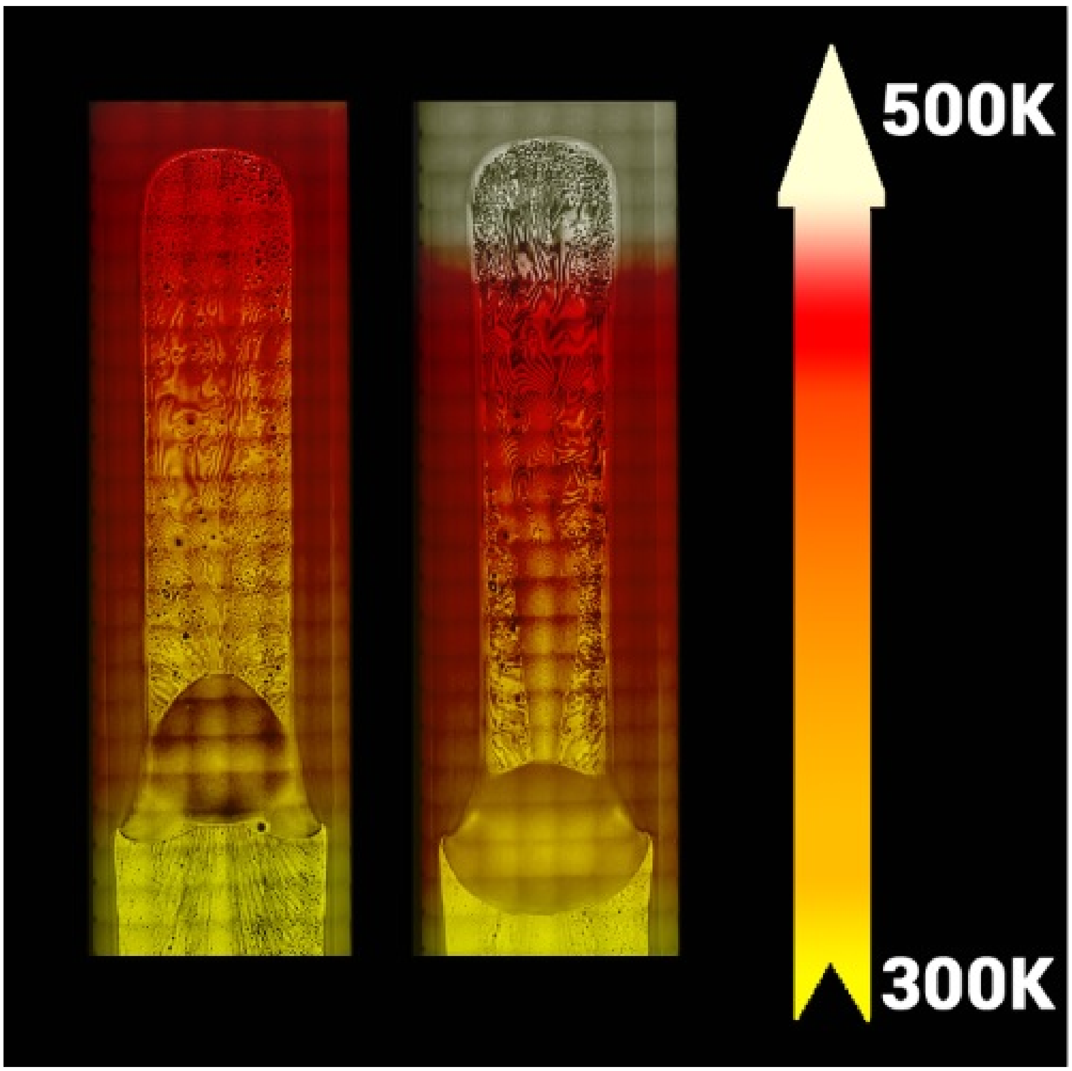

Condensation on a heat pipe on the ISS. Credit: Kundan et al. ©2017 American Physical Society

(Phys.org)—Normally when a liquid is heated above its boiling point, it evaporates, turning into a vapor. But when scientists recently performed an experiment on the International Space Station (ISS), they observed that the vapor near a heat pipe condensed into a liquid even when the temperature was 160 K above the substance's normal boiling point. The results show that microgravity significantly alters the processes of evaporation and condensation, but the scientists do not yet have a complete explanation for the phenomenon.

The research team, consisting of scientists from Rensselaer Polytechnic Institute and the NASA Glenn Research Center, have published a paper on the surprising observations in a recent issue of *Physical Review Letters*.

This is not the first time that unexpected behavior in heat pipes, which are devices used to cool components of a spacecraft, has been observed in microgravity. In 2015, many of the same researchers made a related, counterintuitive observation during experiments conducted on the ISS.

At that time, the researchers observed that increasing the heat input to a heat pipe did not cause the device to dry out near the heated end as it does on Earth, but instead it caused liquid accumulation there. At the time, the processes responsible for this phenomenon were not completely understood.

In the new study, the researchers performed a similar heat pipe experiment with pentane and found that, as the heat input to the surface increased, the amount of condensation increased. They observed the effect at temperatures of up to 160 K above the normal boiling point of pentane, the point at which the experiment reached its safety limits. In general, liquid above its boiling point is said to be in a "superheated" state. Here, the researchers describe the hot end of the heat pipe as being flooded with superheated liquid.

Although the researchers do not have a complete theoretical explanation for what causes this condensation phenomenon, they know based on previous research that it arises in part due to the Marangoni effect. This effect stems from the physical characteristics of the heat pipe. A heat pipe has a heated end and a cooled end, which creates a primary temperature gradient along the hot-cold axis of the pipe. But since the liquid film on the heat pipe's surface is not uniform, the temperature gradient is three-dimensional and varies over the entire pipe surface.

These temperature gradients, in turn, create surface tension gradients. This then leads to the Marangoni effect, which occurs when cooler liquid, which has a higher surface tension than hotter liquid, pulls the hotter liquid toward it. In the end, the effect produces Marangoni-driven flows—one from the heated end to the cooled end, and another from the center of the pipe to its edges. These flows occur even in the hot "evaporation zone" of the pipe, and they generate an instability in the liquid layer that reinforces the condensation. The scientists also suspect that micro- or nanoparticles on the pipe surface amplify natural perturbations and so help initiate condensation in those regions.

As the scientists explain, the reason that this condensation is readily observable in a microgravity environment but not on Earth is that the stronger gravity on Earth restricts the return flow of liquid from the cooled end to the heated end of the heat pipe, which greatly reduces the Marangoni forces. Nevertheless, the scientists note that the condensation phenomenon does occur under Earth's gravity, though on a smaller scale, and is easily confused with surface contamination.

Overall, the scientists explain that the unusual fluid behavior is scientifically interesting for a few reasons.

"There are two fundamentally interesting aspects to the study," coauthor Joel Plawsky at Rensselaer Polytechnic Institute told *Phys.org*. "The first is the emergent behavior that comes from having a closed system. Neither the flooding phenomenon we witnessed in 2015 nor the condensation phenomenon we witnessed here were observed in more open systems where there was only evaporation or only condensation occurring. In this system, since the condensed liquid and the evaporating liquid are in constant communication with one another, more unusual fluid behaviors arise.

"The second interesting aspect is how important interfacial and especially intermolecular forces can be, even though they operate at length scales many orders of magnitude smaller than the scale of the heat pipe. In this case, the restoring intermolecular forces help fuel the condensation locally, and that translates into large changes in film thickness that can be observed globally. Again, this only occurs if all length scales can exchange information with each other as they can in a closed, heat pipe system."

Besides being of fundamental interest, the results could help scientists understand the limitations of heat pipes as cooling devices for spacecraft, and guide the design of improved versions. In the meantime, the researchers plan to further investigate the behavior of fluids in microgravity through modified experiments.

"We, and a number of others, have shown that adding a second chemical component to the system can negate some of the detrimental features observed during operation with a pure fluid," Plawsky said. "We will be trying experiments, similar to the ones we have already run, with fluid mixtures. In such cases, Marangoni stresses, driven by temperature gradients, can be offset by opposing stresses driven by composition gradients. However, since one now has added another degree of freedom by adding the second component, additional, unexpected phenomena may appear."

He added that, if the ISS were to be equipped with a high-speed image capture capability, it would allow the researchers to investigate the exact nature of the instability and how the instability changes in frequency and amplitude as the heat input into the device is changed.

"There is talk of developing a heat pipe facility on the International Space Station," he said. "If that could be built it would be very interesting to be able to investigate alternative geometries like capillary pumped loops, triangular cross section pipes, or multi-legged oscillating heat pipes and see if there are any large-scale unexpected phenomena that develop. All these experiments would be done with transparent systems. Even though a transparent system will not operate as efficiently as a metallic system, it offers the advantage of being able to see where the liquid and vapor are and better understand the fluid dynamics occurring inside."

More information: Akshay Kundan et al. "Condensation on Highly Superheated Surfaces: Unstable Thin Films in a Wickless Heat Pipe." *Physical Review Letters*. DOI: 10.1103/PhysRevLett.118.094501