Institute of Physical Chemistry
Polish Academy of Sciences

address: Kasprzaka 44/52
01-224 Warsaw, Poland
tel.: +48 22 3432000
fax/tel.: +48 22 3433333, 6325276
email: ichf@ichf.edu.pl
WWW: http://www.ichf.edu.pl/

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Milikelvins drive droplet evaporation

Evaporation is so common that everybody thinks it's a well understood phenomenon. Appearances can be, however, deceptive. Recently, a new, earlier not predicted mechanism of evaporation was discovered. Experiments and simulations performed at the Institute of Physical Chemistry of the Polish Academy of Sciences and the Institute of Physics of the PAS not only confirm its existence, but also indicate that it plays the crucial role in evaporation process in the nanoscale.

Too hot? It’s not only because of summer. It's also likely that the sweat on your skin stopped to evaporate efficiently enough. Evaporation affects the “climate” inside our body, but is equally important for the climate of the entire planet – and for how fast laundry dries or how efficient car engines are, as well. In spite of its omnipresence in the human environment, the physicists still do not fully understand its course after 130 years of research efforts. Now, thanks to experiments and simulations performed by research teams at the Institute of Physical Chemistry of the Polish Academy of Sciences (IPC PAS) and the Institute of Physics of the PAS (IP PAS), the secrets of evaporation finally came to light.

“Usually you can easily predict what will be the beginning or the end of a given physical process. Answering the question, which path is selected by nature to complete the process, is much more difficult. For evaporating droplets, it had since long been known that temperatures – before the evaporation started and after it was completed – were the same. But what occurs between these two moments in time, so when all this is happening? That was the question we didn't know a good answer for”, says Prof. Robert Hołyst (IPC PAS).

Existing theoretical models of the evaporation process assumed that the rate of evaporation depends on how fast the molecules attach to or detach from the surface of a liquid. The measurements indicated, however, that during evaporation a barrier should be formed on the droplet surface, hindering the molecules to cross the liquid-vapour (or vapour-liquid) interface. Recent experiments carried out by various research groups worldwide have proven, however, that such a barrier does not exist, and virtually every molecule falling on the liquid surface does not detach from it. The researchers noticed also a clear temperature jump at the interface between the droplet and its surrounding, and found that pressure remains constant during evaporation. These effects were not predicted by the existing theoretical models.

With this in mind, Prof. Hołyst's research team decided to use computer simulations to analyse evaporation of nano-sized droplets. Simultaneously, the team at the Institute of Physics of the PAS carried out – technically very demanding - measurements on real systems, using microdroplets evaporating inside an electrodynamic trap. The study included examination of evaporation of water into its own vapour in air, glycol and glycerol into nitrogen, and argon into its own vapour. The outcome of the study indicates that temperature of the evaporating liquid is the prime factor responsible for the evaporation of droplets.

“Evaporation turns out to be a process driven by very small temperature differences. Often, only ten-thousandth parts of kelvin are enough to make it happen!”, says Dr Eng. Daniel Jakubczyk (IP PAS).

The key role in evaporation plays the heat flux between the droplet and its surrounding. And this is hindered in the case of small-sized objects, because each droplet is surrounded by a thin layer of its own vapour.

“The thermal insulation mechanism operating here reminds the Leidenfrost effect. Everyone knows it, as we all have seen water droplets sliding on a hot pan or a bottom of an iron. If the heat flux between the pan and the droplet would be really efficient, the droplets would boil and evaporate instantly. This is, however, not the case, because droplets slide on water vapour, forming an insulating layer between the droplet and the hot surface”, explains Prof. Hołyst.

The thermal insulating layer, forming around the evaporating droplet, is thick enough to efficiently restrain the heat flux. The thickness of the layer depends, however, primarily on the conditions in the environment and is not related to the droplet size. That’s why a nanometer-sized droplet “senses” thicker insulating layer (compared with its size) and evaporates more slowly than it would follow from the evaporation rates characteristic for micrometer or milimeter droplets. Moreover, because of the sizes of nanodroplets, the insulating layer at their surface generally contains not many molecules. This is an additional insulating mechanism, confining the energy flux to low-efficient modes of transfer related to IR absorption and emission.

The new formula proposed by the researchers from the IPC PAS describes correctly the course of the process both for typical, large drops, and for tiny droplets with sizes approaching single nanometers.

“Small droplets can evaporate within nanoseconds, whereas large drops need up to a few tens of minutes. The experiments confirmed that in spite of such a large time span, extending over a dozen of orders of magnitude, our formula correctly describes the kinetics of all these processes”, stresses Dr Marek Litniewski (IPC PAS), a co-author of the research.

The findings of researchers from the IPC PAS and IP PAS, published in the “Soft Matter” journal, will be used in many areas, e.g. in nanotechnologies and material engineering, studies on the climate and the greenhouse effect (water vapour is the main greenhouse gas in the atmosphere of Earth), and in meteorology, to mention a few only. Interesting opportunities appear in the technology and can lead to, i.a., new more efficient combustion engines.

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The Institute of Physical Chemistry of the Polish Academy of Sciences (http://www.ichf.edu.pl/) was established in 1955 as one of the first chemical institutes of the PAS. The Institute's scientific profile is strongly related to the newest global trends in the development of physical chemistry and chemical physics. Scientific research is conducted in nine scientific departments. CHEMIPAN R&D Laboratories, operating as part of the Institute, implement, produce and commercialise specialist chemicals to be used, in particular, in agriculture and pharmaceutical industry. The Institute publishes approximately 200 original research papers annually.

CONTACTS:

Prof. **Robert Hołyst**
Institute of Physical Chemistry of the Polish Academy of Sciences
tel. +48 22 3433123
email: rholyst@ichf.edu.pl

Dr Eng. **Daniel Jakubczyk**
Institute of Physics of the Polish Academy of Sciences
tel. +48 22 1162991
email: jakub@ifpan.edu.pl

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Research conducted at the Institute of Physical Chemistry of the Polish Academy of Sciences and the Institute of Physics of the PAS revealed that tiny temperature differences – even as small as ten-thousandths parts of kelvin – are the primary driving force in droplet evaporation. (Source: IPC PAN, Grzegorz Krzyżewski)