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Micro heat engine research cracks an age-old thermodynamic puzzle

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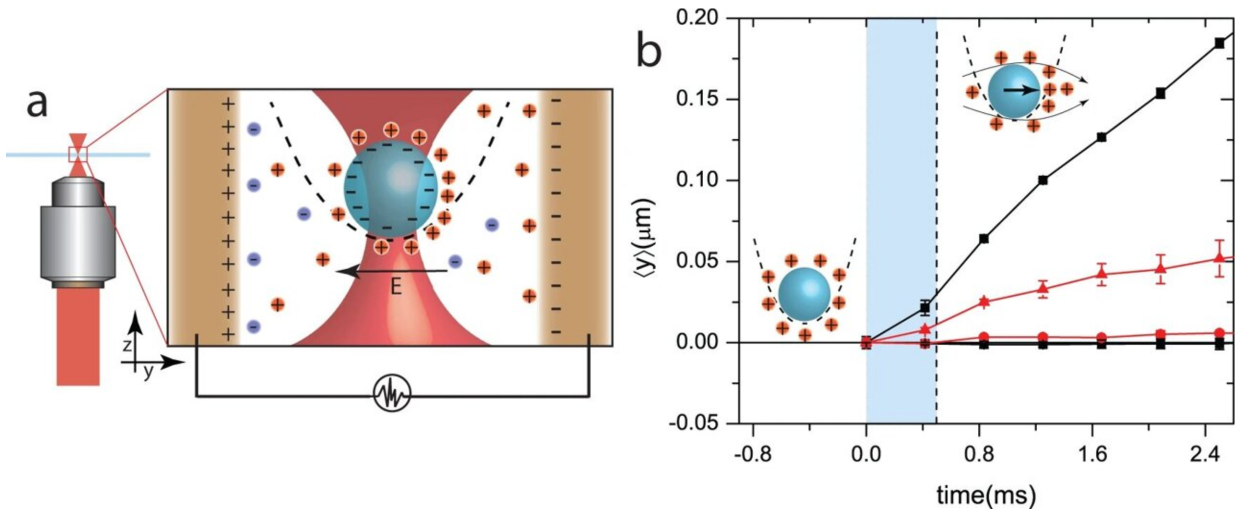

Trapped colloid in an electric field. **a** is a schematic diagram of our experimental setup, where a colloidal particle (blue sphere) suspended in an ionic solvent is trapped at the focus of a converging laser (red) that creates a harmonic potential (dotted line). Electric field, **E**, generated by applying a potential difference (DC bias) to the copper electrodes (brown), polarizes the counterion cloud around the colloid and results in electroosmotic flows depicted in inset of (**b**). Such flows drag the particle from the trap center, and the mean displacement, $\langle y \rangle$ on applying a potential difference, $V_{in} = 0.5V$ (red triangles) and $1.2V$ (black squares) from the time of switching the field is plotted in (**b**). Also since the flows occur along **E**, displacements in the perpendicular direction $\langle x \rangle$ (red and black circles corresponding to $V_{in} = 0.5V$ and $1.2V$) are within the limits of experimental error. The error bars correspond to standard error of mean over ≈7000 experiments. In our experiments, electrophoretic noise is generated by replacing V_{in} by a freshly sampled random voltage every 0.5 ms marked by the dotted line. Within this time range (shaded blue), the particle is dragged in the direction set by the electric field and is the source of the non-Markovian behavior of electrophoretic noise. Credit: *Nature Communications* (2023). DOI: 10.1038/s41467-023-42350-y

Designing a heat engine that can produce maximum power at maximum efficiency is a major challenge. Practical heat engines are limited to a theoretical efficiency called the Carnot limit, which sets a cap on how much heat can be converted to useful work.

In a breakthrough, researchers at the Indian Institute of Science (IISc) and Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR) have devised a novel "micro heat engine" that has overcome this limitation at the lab scale. The study was published in *Nature Communications*.

"What was considered impossible until today, we have demonstrated that it is possible: achieving both high efficiency and high power simultaneously," says corresponding author Ajay K Sood, National Science Chair Professor at the Department of Physics, IISc, and Principal Scientific Adviser to the Government of India.

Heat engines convert heat into work—for example, moving a piston in a certain direction. For an engine to be 100% efficient, when the process is reversed—the piston returns to its original state—there should be no heat wasted, which is what was proposed by French physicist Sadi Carnot in 1824. This is only theoretically possible if the process happens extremely slowly, but that also means that the power output will be zero, making the engine practically useless. This is known as the power-efficiency tradeoff.

"Since the 1970s, people have been attempting to address the power-efficiency trade-off. In the early 2000s, researchers explored microscopic systems to overcome this challenge. Interestingly, in 2017, a paper claimed that it was impossible to solve this thermodynamic puzzle," says Sudeesh Krishnamurthy, former Ph.D. student at the Department of Physics, IISc, and first author of the study.

In the current study, the team mimicked the functioning of a conventional heat engine at the micron scale. Instead of using a mix of gas and fuel, they took a tiny gel-like colloidal bead and used a laser beam to direct its motion, similar to how the piston works in a macroscopic engine.

"Our unique micro-scale engine operates with just one particle," says Rajesh Ganapathy, Professor at JNCASR and another author. The size of the engine is very small, about 1/100th the width of a single human hair, he adds.

The team also used a rapidly changing electric field to cycle the engine between two states. Under these conditions, they found that the waste heat dissipated drastically reduced, bringing the efficiency close to 95% of the limit specified by Carnot.

"What we have achieved is a reduction in heat distribution time through the introduction of the electric field. This reduction in heat distribution time allows the engine to operate at high efficiency and simultaneously yield a large power output even while operating at high speeds," says Krishnamurthy.

Previously, the team designed a high-power engine that used a live bacterium to push the particle and power the system. This time, the researchers replaced the bacterium with an electric field to move the particle more efficiently in the colloidal medium and to increase the system's durability.

The results from the experiments show that, under certain conditions, high power can be achieved with high efficiency. Such an advancement could pave the way for more energy efficient devices in the future.

"If one can draw a message from here and try to see how to make a practical interpretation of this micro engine, that is the next part of the story," says Sood. "We have opened doors that scientists almost gave up opening due to the thermodynamic constraints set by Carnot in previous studies."

More information: Sudeesh Krishnamurthy et al, Overcoming power-efficiency tradeoff in a micro heat engine by engineered system-bath interactions, *Nature Communications* (2023). DOI: 10.1038/s41467-023-42350-y

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