Tiny heat engine may be world's smallest

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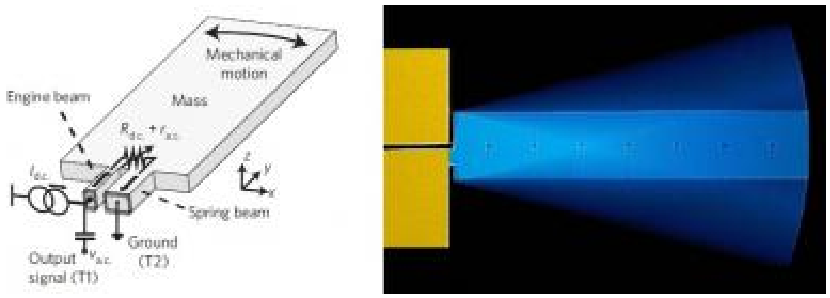

(Left) This illustration shows the entire heat engine and its electrical connections. (Right) A modified electron-microscope image shows the heat engine in motion. The amplitude of the motion in the figure is exaggerated. Image credit: P. G. Steeneken, et al. ©2011 Macmillan Publishers Limited.

(PhysOrg.com) -- Steam engines, combustion engines, and diesel engines are all different types of heat engines, which operate by converting heat energy into mechanical work. Although heat engines have existed for a long time, reducing their size down to the microscale is very difficult since both their efficiency and power density greatly decrease when their size decreases. In a new study, scientists have designed and built a miniature heat engine with a displacement volume of just 0.34 cubic micrometers, possibly making it the smallest heat engine ever built.

In their study, Peter Steeneken and coauthors from [NXP Semiconductors] in Eindhoven, The Netherlands, explain that, instead of using a fuel to generate heat, this heat engine uses [electricity] to generate heat, which it then converts into mechanical power.

The basis of the heat engine is a solid piece of micrometer-sized silicon crystal that has two short beams jutting out from one end. When 1.2 milliamps of DC current is applied to one of the beams, the beam heats up as a consequence of its electrical resistance, and expands due to thermal expansion. As a result of the piezoresistive effect, the resistance of the beam decreases when it expands so that it cools again, forcing it to contract. The mechanical power from the beam's expanding and contracting is used to drive the entire silicon crystal into sustained up-and-down oscillation. As a result of its small dimensions, the crystal oscillates at a high frequency of 1.3 MHz, moving back and forth more than a million times per second.

"The key [to making such a small working engine] is that we use a new operation mechanism that enables silicon to be used as a working substance," Steeneken told *PhysOrg.com*. "Silicon can be structured using lithographic techniques which are optimized in the semiconductor industry. This allows much smaller device dimensions. At the same time, the heat capacity of silicon is much higher than that of gases or liquids, which also helps in reducing the device size. The way we transport energy to the engine using electrical interconnects also helps, because electrical wires can be made much thinner than pipes to transport gases or fluids (the viscous friction of a pipe or tube becomes very high when its diameter is reduced).

"From a scientific view, the main significance of the work is that the feedback mechanism that converts the electric current into sustained oscillating mechanical motion is new. We have demonstrated it in silicon, but it is expected to play a role in many other materials. The motion is generated by a heat engine mechanism. Similar to an internal combustion engine in a car, fuel is converted into heat and the heat is converted into motion. In the silicon heat engine we have made, the fuel is electricity, and the heat is generated in a silicon beam."

While this heat engine is extremely tiny, it's difficult to determine whether it is the absolute smallest, since that depends on which parts of the engine are measured. The space occupied by the working mechanism (in this case, the beam) is defined as the engine displacement volume, which is 0.34 cubic micrometers and would be the smallest heat engine to date. But the entire silicon resonator is a little over 1,000 cubic micrometers, which would not make the heat engine the smallest in the world.

"The power to drive the motion is generated in a tiny, 280-nm-thick silicon beam," the researchers wrote in a summary. "The beam has about the same volume as an average-size bacterium like E. coli. Because in this case the power (1 mW) is concentrated in a silicon resistor beam of very small volume, it generates an enormous heating power per volume in the beam (2 petaWatts/m^3, or $2x10^{15}$ W/m^3). If the same power per volume would be applied to a larger sized crystal it would melt before the oscillation phenomenon could be observed, which is probably one of the reasons why this type of heat engine has not been reported before in larger structures."

The researchers found that the new heat engine has a very good power density if calculated using the engine displacement volume. The power density is almost 1,000 times higher than that of a modern car engine, meaning that, if a car engine and its power were scaled down to the same volume as the silicon beam, the silicon heat engine would generate 1,000 times more power. The new heat engine's power density is also significantly higher than that of other microengines. On the other hand, calculating the power density using the volume of the total structure yields a less favorable power density than other engines. The researchers expect that modifying the new heat engine's design could further improve the power density, as well as the efficiency, which is currently low compared to other heat engines.

As the researchers explained, the tiny heat engine could have applications as a small clock or mechanical oscillator. Currently, most accurate clocks are made of a quartz crystal that determines the frequency in combination with a circuit of transistors in a silicon crystal that generate the oscillation power from a battery. The advantage of using the silicon heat engine as a clock is that both the quartz crystal and the transistors are not needed, thus making the device much smaller, simpler and cheaper to produce. In addition to watches, the small clocks could be used to generate high-frequency RF signals for wireless communication devices or to generate the clock-frequency of a microprocessor in a computer chip.

In their experiments, the researchers also showed that the heat engine could act as a refrigerator when the thermodynamic cycle is inverted. In order to do this, the engine beam is connected to a voltage rather than a current, which decreases any oscillations in the device, cooling its surroundings. The researchers demonstrated that the refrigerator could decrease its temperature to 70 K (-200°C). However, the cooling power is very small and probably won't be useful for cooling large quantities of matter. But the refrigerator could have applications in sensitive detectors where Brownian motion needs to be eliminated as much as possible because it is a source of noise that reduces sensitivity.

More information: P. G. Steeneken, et al. "Piezoresistive heat engine and refrigerator." *Nature Physics*. Advance Online Publication. DOI: 10.1038/NPHYS1871