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editorial

Heat Transfer in Miniature Heat Engines

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Many science fiction stories depict portable devices, such as "phasers" and "light sabers," that produce enormous power from a very compact power source. Ignoring other questions regarding the feasibility of such devices, let's consider the energy density needed to accomplish such feats. For example, imagine that our futuristic ray gun should heat and vaporize a modest 1 kg of water given at room temperature; this requires about 2,400 kJ. If the power pack weighs no more than 100 g, then its energy density should be at least 24,000 kJ/kg. Current battery technologies, and even advanced concepts under development today, provide a disappointing energy density of around 500 kJ/kg. However, the energy density of hydrocarbon fuels is more than 40,000 kJ/kg, and hydrogen provides 120,000 kJ/kg. So these futuristic devices could be within reach, if we discover how to convert these fuels into electricity or another high-quality form of energy using very small, light, and reasonably efficient thermal converters.

The practical applications for miniature thermal converters are of course more diverse and useful than futuristic toys and weapons. Small heat engines can provide an on-board power source for remote sensors, robots, and other devices that operate autonomously and cannot be connected to a power grid. A miniature high-energy-density power source can replace batteries in portable entertainment and communication devices, reducing considerably the load to be carried around. This could be especially important in military, camping, or other field uses that do not permit frequent recharging. Miniature power sources could even connect to the electrical system of fixed structures as an extreme case of distributed generation, to supplement or replace the electricity drawn from the main power grid; this could make sense especially if the heat source for the miniature devices is renewable rather than conventional fuel [1].

The recent surge in Micro-Electro-Mechanical Systems (MEMS) technology permits consideration of very small heat engines. MEMS enables the manufacture of devices with a feature size measured in microns, using mass production techniques developed for the microelectronics industry. Distinct mechanical, flow, and electronic components can be integrated into a single chip-type system and manufactured within the same workflow environment. These features offer the potential for low cost, high-precision miniature devices. Much of the MEMS effort is directed into applications such as electro-mechanical sensors and actuators, electro-optic switches, or chemical sensors. However,

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there is also an emerging interest in MEMS-scale thermal energy conversion (i.e., heat engines [2, 3]).

Heat transfer plays a crucial role in the miniaturization of heat engines. Conduction heat transfer, which is usually secondary to convection and radiation in large-scale devices, becomes more significant in the smaller scale. The conduction heat flux is inversely proportional to the distance that heat needs to traverse; as devices shrink in size, this distance is diminished, and the heat flux can be higher for the same temperature difference. This is true for conduction through solid elements (e.g., heat exchanger fin or tube wall) and fluid (e.g., from a channel wall to the "bulk" fluid at the center of the channel). This effect is especially important in closed cycle engines, where the heat input and rejection are done via heat exchangers rather than internal combustion and exhaust. A prominent example is the Stirling cycle: one of the major sources of irreversibility and reduction of efficiency in Stirling engines is imperfect heat transfer in the external heat exchangers and in the regenerator [4]. A significant improvement in heat transfer may therefore increase the efficiency of some engines as they shrink in size, contrary to the common wisdom that smaller engines tend to be less efficient.

The previous discussion referred to increasing heat flux for a given amount of active heat transfer area. However, when the scale of heat exchangers shrinks, the relative amount of heat transfer area can increase as well. Consider scaling a heat exchanger such that all linear dimensions (flow duct width, wall thickness, etc.) vary linearly with the overall size L. The total heat transfer area scales with L^2, while the device total volume scales with L^3. The specific heat transfer area (active area per unit device volume) scales then with L^{-1} and therefore increases with miniaturization. This is well known for heat exchangers and micro-reactors based on micro-channels, which show much higher energy density relative to conventional size heat exchangers.

Designing miniature engines and heat exchangers requires a working knowledge of the flow and heat transfer processes that occur in micro-scale geometries. Some available data show a departure from the well-known correlations that are commonly used in macro-scale heat transfer problems. These results suggest that for micro-scale geometry, the friction coefficient is lower and the Nusselt number is higher than in corresponding macro-scale cases with dynamically similar conditions [5]. Another interesting effect is the reduction of the effective thermal conductivity of materials relative to the bulk macro-scale conductivity when geometric features such as fin thickness become comparable to the mean free path and material boundary effects on the bulk properties become significant [6]. Therefore, the thermal design of micro-scale devices requires a careful examination of the available engineering tools to determine if they are still valid and adapt them as needed to the micro-scale world.

The significant role of conduction heat transfer can also have a detrimental effect on the miniaturization of heat engines. Every heat engine has a hot region (hot heat sink in standard thermodynamic models) and a cold region (cold heat sink, or heat rejection part). Some of the heat going through the engine passes from the hot engine part to the colder part by conduction through the engine body. This portion of the energy, sometimes called "thermal shunt," is a loss since it does not participate in the thermodynamic cycle. When the engine linear size L is scaled down, the produced power usually scales with the engines volume ($\sim L^3$). The heat conduction power is proportional to the cross-section area ($\sim L^2$) divided by the conduction path length ($\sim L$), scaling then linearly with the engine size. The fraction of the energy lost by conduction relative to the engine's total power scales therefore as L^{-2}, increasing rapidly when the length of the device becomes small [7, 8]. Estimates using a range of temperatures and material properties show that practical miniaturization can go down to the scale of about one centimeter, but smaller engines are subject to excessive shunt loss and a significant reduction in efficiency [1, 7]. A similar thermal shunt mechanism occurs in miniature heat exchangers, where loss by thermal conduction along the heat exchanger walls becomes significant when the heat exchanger size shrinks [9].

It is interesting to consider whether the thermal shunt loss is truly a limiting mechanism preventing any further miniaturization of thermal converters beyond the centimeter scale. At the micron scale and below, the conventional treatment of heat transfer based on continuum mechanics does not apply. Molecular transport in rarified fluids and phonon transport in solid matrices become the relevant models. The conventional thermodynamic analyses based on continuum flow through standard cycles also cease to be the appropriate tool for the analysis of energy conversion processes. Therefore, the results presented above are irrelevant, and a completely new methodology is needed. The range of submicron thermal energy transport and conversion cannot then be dismissed but rather could hold surprises and potentially useful methods for thermal energy conversion. If nano-scale engines turn out to be feasible and can be manufactured by yet-undiscovered technology, then they might be deposited on large sheets of cloth or thin boards. These sheets will generate electricity "magically" just by touching a hot surface. This brings us back to the realm of fantastic devices worthy of science fiction stories. However, the rapid rate of progress in micro-scale and nano-scale technologies could lead to such capabilities in the near future, and innovative thermal engineering is a crucial element in this progress.

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