Scientific Report

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Thermodynamics: Can macro learn from nano? (TD 2011)

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Summary

Recently, significant progress has been made in developing theoretical frameworks and experimental systems for exploring the thermodynamics and energetics of small systems. At the same time, challenges such as climate change and scarcity of resources require novel approaches at a very macroscopic scale. Some of these challenges, such as energy distribution, involve highly complex systems with possibly nonlinear behaviour. This workshop brought together scientists in these different areas, with the goal to achieve cross-fertilization between the nano- and macro-thermodynamics communities.

During two and a half days, 38 participants heard 24 oral presentations and actively participated in three discussion sessions on the topics:

- Thermodynamics of small systems
- Macroscopic and finite-time thermodynamics
- Thermodynamics of biological systems
- Solid-state cooling and thermoelectric power generation

SCIENTIFIC CONTENT AND DISCUSSION AT THE EVENT

Nanoscale thermodynamic systems are of significant current interest because they offer unique opportunities to understand how biological energy conversion works at the molecular scale, as well as offering opportunities to increase conversion efficiency in thermal-to-electric and solar-to-electric energy conversion, to name a few. At the same time, the presence of significant fluctuations due to the small size of the systems, as well as the fact that it is the fluctuations themselves that lend nanoscale systems their unique properties, means that macroscopic thermodynamics (which relies on averages) cannot be applied. Presentations at the workshop summarized the development of stochastic thermodynamics, that is, a new thermodynamic theory that accounts for nanoscale phenomena. A second focus was on emerging experimental systems, such as “Maxwell Demon” devices that allow the test of these novel fundamental theories, such as fluctuation-dissipation relationships. A second example is the use of quantum dots and nanowires as model systems for efficient thermoelectric power conversion.

Another focus was the development of finite-time (maximum power) theories and experiments for nanoscale energy conversion.

At the more macroscopic scale, it is apparent that the incorporation of advanced thermodynamics is lacking in the analysis and optimization of macro systems. New approaches to the implementation, with an understanding of the benefits of a rigorous application, of the 2^{nd}-Law in the analysis and optimization of macro systems is lacking. The rigorous application of the 2^{nd}-Law in macro thermodynamic systems has been slow in coming with respect to its application in the nano and micro world of thermodynamics. Thermodynamic research as applied to nano to micro thermodynamic systems routinely and rigorously apply the 2^{nd}-Law, however, there is greater interest to better apply the concept of exergy for these small scale thermodynamic systems. There does need to be a clear understanding of the methodology for applying a “proper” reference temperature in order to define exergy for nano to micro scale thermodynamic systems.

There may be additional opportunities to define research in nano to micro scale thermodynamic systems that would lead to improvements in macro thermodynamic system operation. This may lead to new approaches that would better account for localized equilibrium assumptions and define the physics governing macro thermodynamic systems operating far from equilibrium.

Macro thermodynamic systems are becoming increasingly dynamical in nature with thermodynamic analyses based upon classical thermodynamic to define their operation and performance potential. Typically these dynamical thermodynamic systems are operating far from equilibrium with an assumption of local equilibrium for property evaluation. However, it is not entirely clear if this will continue to hold true with the development of rapid-responding macro thermodynamic systems. Firstly, if a local equilibrium assumption is appropriate, the approach may be as simple as defining a variable localized control volume that gets smaller or larger depending upon the property gradients within the macro thermodynamic system. This would hold true to local equilibrium assumptions. Secondly, rapid-responding macro thermodynamic systems typically operate far from equilibrium but may offer increased efficiency and decreased energy dissipation.

ASSESSMENT OF THE RESULTS AND IMPACT

A central goal of this workshop was to kick off the development of a roadmap for the crossfertilization of new and established theories and applications across the nano-to-macro scale divide. It is clear that modern thermodynamics has made significant progress in the developing frameworks and experimental model systems for nanoscale energy conversion. It is also clear that these novel systems offer some significant advantages over existing, macroscale power converters, but the upscaling of such systems to macroscopically useful scales is a central challenge for the future. An unexpected result of the workshop was also a surprising lack of use of some well-known thermodynamics concepts and optimization tools in macroscopic systems, and it appears that much can be gained by simply putting existing knowledge into practice in the car and airplane industry.

Bringing together such diverse thermodynamic technical expertise reinforced the fact that thermodynamics is indeed a unifying theory. It was clear that there are abundant research opportunities in the study of thermodynamic systems spanning length and time scales of nano to micro to macro. Furthermore thermodynamics is far from being a mature theory as reflected in the numerous technical presentations and discussions during this workshop. This appears to be especially true when thermodynamic research spans length and time scales of nano to micro to macro as applied to diverse technical fields such as biology, chemistry, physics, and engineering.

In terms of impact, there was significant value in the representatives from the nano- and macro community to meet and to learn about the status of research and applications in their respective fields. Important personal contacts were created, and future collaborations are likely; if successful, this could lead to significant scientific and applied impact if the two communities can truly inspire each other.