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GUEST EDITORIAL

Thermal science and engineering: Quo Vadis?

What could be the main reason for so many electric scooters catching fire lately in the country? Can we harvest potable water directly from the air without needing an energy source? Why is the earth's climate so favourable for life to sustain and propagate? What is the science behind the quick screening of thousands of passengers at airports for fever during the COVID pandemic?

Eclectic as they are, the one underlying principle behind finding answers to all such questions is 'thermal science or heat transfer'.

The science of heat transfer started as an empirical science in the 18th century, driven mainly by the field of energy conversion. The early focus, therefore, was on identifying the modes of heat transfer and their associated rate laws so that one could measure or calculate this quantity. The three fundamental modes of heat transfer, namely, conduction, convection and radiation and their corresponding rate laws, Fourier's law of heat conduction, Newton's law of cooling and Stefan–Boltzmann law of radiation, were empirically derived. A caveat, though, is in order here as the Stefan–Boltzmann law can also be derived from Planck's distribution of black body radiation intensity, though historically, the empirically derived rate law came first.

These laws allowed thermal science researchers and engineers to calculate heat transfer rates based on temperature or its gradient as the case may be. As a consequence, temperature and its measurement gained centre stage in the early development of the field. Fluid flow often accompanies heat transfer and a knowledge of the flow is a prerequisite to gaining a handle on the heat transfer. In view of this, measurements and theoretical developments in fluid mechanics started gaining traction.

What else did then remain? The problem of determining the temperature field (without the need for experiments) logically led to the development of the energy equation in conduction and later in convection. The latter required a seamless blending of principles from fluid mechanics, thermodynamics, constitutive relations for media and the application of rate laws to an elementary volume of a fluid known as the 'control volume'. The struggles, trials and tribulations in this journey constitute the history of the development of fluid mechanics and heat transfer. A watershed in this history is the development of boundary layer theory by Prandtl. It remains, till date, the crown jewel in fluid flow and convective heat transfer. This theory helped us gain an analytical handle on the problem of convection by providing estimates of the boundary layer thickness (usually of the order of only a few millimetres) from which one can obtain the convective heat transfer rate. Alongside, interest in problems such as stellar atmospheres and the melting of glass led to the development of the radiative transfer equation for calculating heat fluxes in an absorbing, emitting and scattering media.

The post-war period saw a tsunami of analytical and numerical methods, as heat transfer began to be applied to several engineering disciplines and outgrew its status as a junior partner in the science of energy conversion. The finite difference, finite volume and finite element methods for conduction and convection, analytical methods to solve the radiative transfer equation, the powerful enclosure method for both surface and gas radiation, techniques like the discrete ordinates method, contributed massively to enhancing the stature of the field, as one having a strong theoretical basis and a fertile ground for the analytical and numerical minded. The development of hardware and software hastened the conquest of several problems in heat transfer that have been troubling researchers for ages.

Alongside, superlative developments took place on the experimental side, starting from temperature measurements with thermocouples, infrared thermometres (they are ubiquitous now as thermal screening devices in airports, offices, malls and supermarkets), liquid crystal thermography, flow metering techniques including optical ones, hot wire anemometry, heat flux gages, wind tunnels and vacuum chambers for radiation experiments.

Once sufficient mastery was gained in the fundamentals, the community started focusing on methods to augment heat transfer by engineering surfaces and media (through now popular nanofluids) for the three basic modes as well as boiling and condensation. The last two nearly approach isothermal heat transfer, can give a very high thermal performance and, as expected, are massively popular and trending research topics now.

Heat transfer has now become truly interdisciplinary with applications in several fields like nuclear, aerospace, chemical, electrical, materials engineering and space technology, apart from increasing relevance to medicine, atmospheric science, additive manufacturing and so on.

At a more fundamental level, research continues to unravel the heat transfer mechanisms at micro and nano scales, establishing a theoretical framework for boiling and two-phase flow heat transfer where besides the medium, the surface-medium combination and factors like roughness and other surface properties play a crucial role in deciding the heat transfer enhancement.

A look at the highly cited research topics in thermal sciences and engineering in reputed international journals in the last five years gives us an idea of the direction and velocity of research. Highly cited fields include combustion, propulsion, computational fluid dynamics, multiphase flows, supercritical CO_2 cooling, gas turbine cooling, heat transfer in porous media, adsorption, experimental flow visualization and diagnostics. Advanced strategies to model turbulence, including stretching the capabilities of direct numerical simulation to higher Reynolds numbers, are gaining traction. Further, the paradigm shift towards sustainable technologies has led to an intensive focus on thermal energy storage, boiling and condensation. From the point of view of application, phase change material-based heat transfer, nanofluids, nanoengineering surfaces, mini- and micro-channel heat transfer have received much attention, especially in topics like electronic cooling and additive manufacturing. Intense research efforts continue in fluid flow and heat transfer issues in bioengineering and biomedical devices, hemodynamics and the use of microfluidics to design novel drug delivery solutions and targeted heating in the treatment of neoplasms.

India is on its path to becoming a net-zero carbon, net-zero water nation, in which thermal sciences will play a critical role, particularly in data centre cooling. Intense efforts are required to minimize energy and water consumption of compression chillers and cooling towers in data centres, as the nation scales up to becoming a truly digital India.

Equally important will be the role of thermal engineers/scientists to offer solutions for the thermal management of batteries, as the world, including our nation, moves towards cleaner and sustainable mobility solutions. More importantly, understanding the thermal transport within the battery cell due to electrochemical reactions will pave the way for accurately modelling thermal management solutions in electric vehicles (EV). A spate of recent electric scooter fire accidents in the country clearly points to inadequate understanding of battery thermal management system (BTMS) and a lack of adequate research in the country, both at the laboratory and field levels. Reliable BTMS is an absolute prerequisite for a secure EV ecosystem in India. Outside of employing new-age technologies like liquid cooling, phase change cooling and the development of advanced materials for thermal regulators, a lot of effort is required in dynamically assessing the thermal health of the battery system when the vehicle is in motion, with the help of a network of sensors, and applications of inverse heat transfer techniques, all of which point to the heavy use of machine learning algorithms and electronics.

Zero carbon and zero water targets for the country will necessitate the shift in research focus to heat transfer enhancement techniques in areas like boiling and condensation, passive cooling technologies for harnessing solar energy through photovoltaic (PV) cells, along with every possible improvement even in conventional energy conversion technologies. Even in solar PV cells, heating is a critical issue that hinders overall performance, as is the case with the hardware associated with new generation mobile communication technologies like 5G.

On the scientific side of thermal engineering, it is pertinent to mention here that even the problem of determining the earth's climate (and why it is so habitable) and its attendant changes are a pure radiative transfer problem, while weather itself is a convection problem with radiative and other forcings. In satellite meteorology, the remote estimation of rainfall on the ground is carried out from the top of the atmosphere radiation measurements atop satellites. The application of inverse methods has been a stellar contribution to radiative heat transfer. The role of radiation is critical for the nowcasting of severe storms and short-term heavy rainfall, where a combination of modelling and measurements from multiple instruments like radars, radiometers and so on are necessary. These radars and radiometers, which could be space-borne or ground-based, can dramatically improve forecast outcomes. Data sciences and machine learning are expected to play a huge role in these problems, as will be their contribution to engineering heat transfer.

Future trends in thermal science lie far beyond engineering and improvements in existing macroscale systems, where understanding thermal sciences helps sustain life better on the planet. Contributions from thermal engineering are also expected in clean air and water technologies in a world that is getting increasingly polluted. To ensure water security in the country, along with chemists, environmentalists and civil engineers, thermal science specialists will be required to scale up efforts in thermal desalination, passive evaporation, wastewater treatment and even in unexpected fields like medical sterilization. A recent example of a pioneering effort in clean water technology is that of researchers at ETH Zurich, Switzerland, who have now developed a technology that, for the first time, allows them to harvest water round the clock, with no energy input, even under the blazing sun. The goal was to develop a technology for countries with water scarcity, particularly for developing and emerging countries. More such innovative efforts that are India-specific are required so that a critical and holistic evaluation of competing technologies is done, with due diligence, for scaleup from the bench to the field to eventually achieve the zero-water target.

In almost all conceivable endeavours and enterprises of man, heat generation in one form or the other is inevitable. Heat transfer and thermal sciences will continue to have their pre-eminence and play a crucial role in the science and technology of transformation of energy and matter, as almost any technology eventually gets bound by the hard limitation imposed by the second law of thermodynamics, as a consequence of which, one has to necessarily deal with heat transfer!

Thermal science and engineering will continue to hold pride of place in several of the country's imperatives like AI for India, Digital India, Make in India and Atmanirbhar Bharat!

The thermal science juggernaut rolls on…

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