Combustion science workshop*

The fourth P. J. Paul memorial combustion science workshop was held recently in Pune, following the three previous successful meetings. A summary of the last two meetings is available in *Current Science*[1,2]. The tradition of inviting faculty and scientists in R&D institutions to discuss work-in-progress of combustion science practised in the academic environment and problems of development in defence and aerospace industry was continued this year with the focus of problems related to propellants, propulsion and combustion in engines. Participation of a number of young researchers from some laboratories of DRDO and students from academic institutions provided a vibrant environment. They had 20 presentations accompanied by discussions. There were two additions compared to the earlier workshops: a document containing the summaries of the presentations was available to all participants and there was a formal inauguration of the workshop by dignitaries.

Selected highlights of the scientific presentations are provided below:

The first talk was by Lazar Chitilapilly (VSSC, Thiruvananthapuram) on the recent successful flight of an experimental supersonic air breathing engine. The long-waited flight test of the vehicle that used hydrogen as the fuel was highly successful and provided valuable technical data on the engine performance in a specifically designed flight path more difficult to achieve compared to earlier successful flights by other countries. Interesting details of ignition and steady combustion of hydrogen fuel in the scramjet were presented.

M. Dharavath, P. B. Manna and Debasis Chakraborty (DRDL, Hyderabad) presented the tip-to-tail CFD simulation of a hypersonic vehicle under development as an essential part of the vehicle design. The validity of the model was indicated to be due to good comparison of the sub-models of aerodynamics and combustion in the scramjet. An associated presentation on reduction in the chemical kinetics of hydrocarbon-air for use in examining ignition performance of kerosene like hydrocarbons in supersonic combustion systems was made by S. Basu, P. B. Manna and Debasis Chakraborty.

On the unsteady combustion of solid propellants, Jayesh Upadhyay *et al.* (High Energy Materials Research Laboratory (HEMRL), Pune) presented an experimental study on the evaluation of the response function obtained by initiating pulse-generated instability in rocket motors using nitramine-based composite solid propellants. The associated T-burner study to evaluate the response function was presented by Sunil Jain (HEMRL). Modelling these instabilities with a refined mechanistically based steady-state model of composite solid propellants was presented by Varunkumar and Vishal Arun (Indian Institute of Technology Madras) and H. S. Mukunda (Jain University, Bengaluru). The strength of the model was indicated to be excellent in comparison with a large number of experimental data. V. Chaitanya, M. Gaurav and P. A. Ramakrishna of IIT Madras presented the simulation of burn-rate properties of composite solid propellant using a modified sandwich model. Some differences in expectations of burn-rate performance between an earlier work and the present one were highlighted. There were discussions on these topics that could trigger further research by different groups in this area.

Avtar Singh and Arvind Kumar (HEMRL) presented a new collapsible mandrel technology for generating intricate port geometries in small, solid rocket motors. The advantage of the new technology is that complex designs can be produced accurately with greater ease compared to what can be accomplished with segmented mandrels.

Abhishek Richhariya (DRDL, Hyderabad) presented several interesting issues in connection with fuel-rich motors for solid fuel ramjet applications. He discussed the performance estimation using classical ideas of equilibrium break down and the new ideas of partial equilibrium with select species reacting slowly compared to other fast reacting species to explain the observed performance (characteristic velocity, c^*) of these systems. This subject evoked much discussion. Thekkekara presented one-dimensional modelling of air-breathing propulsion system.

Two presentations were made by Arindrajit Chowdhuri and Irishi Namboothiri (IIT Bombay) on new choices for hypergolic liquid propellants and functionalized polycyclic cage compounds as high energy materials. The need for these materials and the possible relevant properties for applications were debated.

Joseph Mathew (IISc, Bengaluru) spoke of the application of the large eddy simulation (LES) model that he has been developing over a time on compressor cascade aerodynamic performance. He showed that even a coarse LES calculation is far superior to transition-sensitive Reynolds averaged Navier–Stokes calculation in capturing the essential features of the transition process in a practical tandem cascade problem.

Saptarshi Basu (IISc, Bengaluru) discussed the near-field break-up atomization of liquid sheets in co-annular swirling gas flow field using high-speed shadowgraphy. He also presented the results of break-up length scales and provided insights into the controlling spatio-temporal scales.

Sundar Krishnaswami (GE, Aviation, Bengaluru) described the key challenges faced in the development of the state-of-the-art combustion technology with low emissions for propulsion combustors in GE Aviation, and the approaches they are making in advancing the new technologies.

H. S. Mukunda and B. S. Dixit (Jain University, Bengaluru) spoke of a new feature resulting from the thermal data of pan fires, namely, the $1/f$ behaviour in the spectral content of temperature fluctuations inside the fire. They indicated that this feature known in many physical systems as a pink noise may have implications in modelling pool fire phenomenon that is worth pursuing.

S. G. Markandeya and Anil Kumar (Fluidyn, Bengaluru) presented studies

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on fire or detonation-related aspects of hydrogen-air during possible accident scenarios of nuclear power plants. While several aspects of combustion have been or can be understood within the known knowledge base, deflagration–detonation transition in such instances needs further research.

Two presentations discussed laminar premixed flame speed determination and related aspects. C. Pratap (Indian Institute of Space Technology, Thiruvananthapuram) presented measurements on flame speed in spherically expanding flame technique and calculations using PREMIX code with GRIMech3.0 chemical kinetics. Sudarshan Kumar (IIT Bombay) presented a review of various techniques for measuring laminar burning velocities, bringing out inconsistencies in the results and ways of rationalizing the temperature dependence of the burning velocity.

Nagendra Babu (Vehicle Research and Development Establishment, Ahmednagar) presented the use of commercial diesel engines for UAV applications.

The major takeaways from the workshop were intensive interactions on both the fundamental and applied aspects of combustion science. A few collaborations and joint projects of relevance to solid propellant combustion, etc. may also emerge from this workshop.

1. Shivakumar, V., Ramakrishna, P. A. and Mukunda, H. S., *Curr. Sci.*, 2015, **108**(8), 1412–1413.
2. Mukunda, H. S., Bijukumar and Ramakrishna, P. A., *Curr. Sci.*, 2016, **111**(9), 1440–1442.

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MEETING REPORT

High entropy materials*

High entropy materials (HEMs) as a research field in materials science and engineering has matured over the last few years. In 2004, Yeh *et al.*[1] and Cantor *et al.*[2] coined the term 'high entropy alloys' (HEAs) for the newly discovered multicomponent and multiprincipal (CoCrFeNiMn) metallic cocktails[3]; research activities were mainly centred on the metallic alloys. This has led to the discovery of many FCC and BCC HEAs[4], including refractory HEAs[5]. In 2012, a novel entropy stabilized multicomponent ceramic alloy was reported[6] and thus, the materials or phases predominantly stabilized by configurational entropy of mixing are now known to be HEMs. It has expanded the field, opening up new vistas of exciting research on these materials. This field has recently emerged as one of the most fascinating and challenging areas of materials research.

In order to take stock of the advancement, the second international workshop on HEMs was held. The first workshop was held in 2015 at IIT Madras[7]. The second workshop attracted scientists from academia, national laboratories as well as industries to understand the latest development in the area of HEMs. The workshop was attended by 150 participants, including several delegates from Austria, Australia, Germany, Taiwan and USA. There were 22 oral and 30 poster presentations. The first International Conference on High Entropy Materials (ICHEM) was held in Taiwan[8].

The workshop began with a brief address by B. S. Murty (IIT-Madras) and a welcome speech by M. Ghanashyam Krishna (School of Engineering Sciences and Technology, University of Hyderabad (UoH)). The technical session began with a plenary lecture by J. W. Yeh (National Tsing Hua University, Taiwan) on the issue of breakthrough applications of HEAs. He pointed out the possibilities of several potential applications, such as turbine blades, moulds/dies, and radiation damage-tolerant materials for atomic energy applications. The most important among them is the development of new bond coat for turbine blades in gas turbines, steam turbines, etc. He has extensively studied $Ni_{30}Co_{33.5}Cr_{21}Al_5Y_{0.5}$ HEA composition for such applications. In addition, HEAs could find applications in cutting tools, hard facing for wear-resistant parts; helium-cooled fast-breeder reactor, etc. Murty discussed challenges in HEA research, especially in the interpretation of experimental data on diffusion in these multicomponent alloys obtained by his research group using tracer diffusion at Germany. It is evident that the diffusion coefficient in these alloys must be scaled with melting temperature of the alloys for any relative comparison. D. Miracle (USA) described the strategies to accelerate development of novel HEMs. According to him, combinatorial approach can dramatically accelerate the development of HEMs by rapid scanning of compositional landscape. R. Banerjee (USA) discussed the aspect of thermodynamic equilibrium in HEMs. Obtaining a single-phase HEA in a large temperature range is constrained by the precipitation of second-phase during cooling to lower temperature. Using $Al_{0.3}$CoCrFeNi HEA-forming system, he demonstrated the formation of second-phase precipitates by heat treatment at different temperatures, which is controlled by competition between thermodynamic driving force, activation barrier of nucleation and kinetics of the process. K. Kulkarni (IIT-Kanpur) described the role of cross effects in multicomponent diffusion prevalent in HEMs. These effects are due to relative thermodynamic interactions and differences in individual interdiffusion coefficient. In case of Co–Cr–Fe–Ni equiatomic alloy, he advocated methods of calculation of the

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