6th Prof. P. J. Paul Memorial Combustion Researchers' Meet

& Workshop on Combustion Science in Biomass Fire & Instability- Science in the Aid of Practice

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Book of Abstracts

FIRE & COMBUSTION RESEARCH CENTER

JAIN DEEMED-TO-BE UNIVERSITY

Prof. P.J. Paul Memorial Combustion Researchers' Meet

The principal aim of these workshops is get on an invited basis, the faculty (and their students) and scientists of R & D laboratories to come together and discuss in-progress parts of combustion science practiced in the academic environment and problems of development in defence and aerospace industry. The significant difference between this workshop and regular conferences is the in-depth discussion that occurs after each presentation. It is aimed at learning from each other and allowing the students to relate the research practiced in their environment with developments. It was (and is) held in a retreat mode to enable long walks and discussions to resolve differences in viewpoints beyond the conference room and learn some successes and failures in a direct conversational mode.

6th Prof. P. J. Paul Memorial Researchers' Meet

The researchers meet on combustion and fire is being conducted every year in memory of Prof P J Paul, an eminent scientist in the field of combustion, rocket propulsion and renewable energy. This meet will address the recent issues and developments in these areas.

The event provides a platform to talk about various scientific challenges and recent developments through series of presentations followed by intensive discussions. Faculty /senior researchers as well as students/ younger researchers present their findings in the presentations.

The discussion space in the workshop is aimed at much higher levels than in standard conferences and includes research students from advanced institutions. This helps them progress in their field and provide inputs to mature as research scientists of significance.

The series has successfully completed five workshops hosted by prestigious institutions across the country. The first meet was hosted by Jain University. IIT-Madras, VSSC-Trivandrum, HEMRL-Pune and DRDL- Hyderabad have hosted the event subsequently wit participation about 30 from outside the institutions and much larger active researchers from within the institution.

One of the reasons for holding these at different institutions is to integrate the flavour of the subjects dealt with in these institutions.

The current meet, 6th in the series, is once again hosted by Jain deemed-to-be University under its exclusive Fire & Combustion Research Center with a theme:

‘Combustion Science in Biomass, Fire and Instability: Science in the Aid of Practice.’ The key speakers of the event are the eminent scientist/ researchers addressing their challenges in the said theme and it are hoped that it will continue to benefit the combustion community. Participation will be from several DRDO laboratories including HEMRL Pune, DRDL – HYD & GTRE.

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Content

(In Alphabetical Order of Speakers)

Progress on Advanced Clean Biomass Combustion Systems for Domestic and Industrial Applications

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Much progress has happened in forced draft clean combustion systems beyond the batch mode operating reverse downdraft stove (Oorja, the commercial name). Over last four years, at Fire and Combustion Research Center, JGI, several varieties of biomass clean combustion devices have been conceptualised, realised and commercialised. These constitute continuous combustion systems that depend centrally on ejector induced draft demanding higher power for air supply arrangement. Amongst the varieties developed and commercialized are (a) those with inclined grate and air supply arrangements suitable for self-feeding with pellets and similar fuels of varying densities, (b) arrangements including travelling grate for fuels like rice husk, (c) horizontally configured ejector based air supply and (d) vertically arranged ejector configurations with either single pan or multi-pan arrangements. Applications include power levels of one to several hundred kg/h with user-defined demands of variable thermal power, short or long combustion zone, limited height of the system, widely varying density, fuel shape and size such as with fire wood, waste-wood, cashew shell waste, corncobs and other agricultural residues all on clean combustion mode. While expecting to meet these demands against clean burning gaseous fuels like natural gas or LPG is sufficiently challenging in terms of science of combustion, the *truly most challenging problem* has been to design a domestic cooking solution (at 1 kg/h level) with the biomass range noted above because the solution should be aesthetically appealing and affordable as well. The search for the solution considered perlite a light weight ceramic material that could be used with cement to produce cast configurations. A two-pan configuration using these ideas that can be used for cooking, bath water heating and wet cloth drier has been developed; the system uses a special 2 W blower and is supplied with 12 V rechargeable battery based power. It has been field tested in a limited way. More recently, single pan light weight system has been developed using a combination of metal and HFI bricks with the aim of meeting the requirements of domestic stove described above. Most of the systems have been standardized around air supply via jets through holes in struts introduced into the combustion chamber. The design of domestic systems is around jet velocities of 10 m/s to limit the particle carry over. The measured emissions of CO and particulates (PM2.5) meet WHO norms interpreted for Indian conditions of use. Larger systems use jet velocities up to 25 m/s to make the systems more compact.

At the time of writing, about twenty large biomass based combustion systems (3, 15, 50 and 100 kg/h) in horizontal and vertical combustion modes have seen commercialization and a few hundred clean burning forced draft 1 kg/h systems have been field tested. While the pathway to building these novel and new combustion larger power systems (3.5 to 100 kg/h) seems clear, wider dissemination of domestic stoves in a commercial mode calls for more effort and perhaps better times in view of challenging non-level playing ground created by Government initiated *subsidized* LPG system infusion, even though meaningful and desired use in rural communities is a need.

Ajey Nagarkatti, Research Associate, FCRC,
Jain (Deemed-to-be University), Bengaluru

Development of a CFD Model for Calcination in Cement Kilns

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Decomposition of calcium carbonate (calcination) is a major energy consuming process in cement production. Currently the thermal energy required for calcination is mainly obtained by burning coal. Replacing at least a part of this with other fuels such as industrial and agricultural wastes is expected to reduce the cost of production. In this work, a 3D CFD based model of a full size cement kiln for calcination is being developed to analyse the performance of cement kilns with such alternate fuels. The processes modelled involve calcination of limestone particles and simultaneous burning of coal or other fuel particles. First, studies on experimental setups are done with coal as fuel and the results are compared with the published measurements. Further, some exploratory studies are done for the full scale model with coal and other fuels.

KR Anil Kumar, General Manager, Fluidyn Consultancy (P) Ltd, Bengaluru

Energetic Materials: Ageing and its Effects

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Pyrotechnics and other energetic materials such as explosives and propellants are often stored for extended durations. The exposure to elevated temperature and humidity is known to contribute towards the degradation of energetic materials over time. This degradation, known as chemical ageing, can lead to a significantly decreased or increased burning rate. Techniques to predict the future state of a given energetic material composition are very important for ensuring the safe and effective use of these materials. The attempt to understand the phenomena involved in this process and elucidate them using thermal analysis techniques is reported here.

Anirudha Ambekar, Asst. Professor, School of Mechanical Sciences, Indian Institute of Technology, Goa

Testing Methods for Fire Fighting Foams - Experience at UL-JFL

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This paper is related to an analysis of the foam qualification tests with the state-of-art fire testing lab (UL-JFL) at Jain (deemed-to-be University) in 2016 to test active fire suppression agents using the UL 162 standard and observations on a comparative assessment of foam tests with different standards. Most of the fire tests carried out here is to satisfy certification requirements arising out of sales of new foams to end users. Of the 100+ foams are tested till date, 90% have conformed to UL specifications.

Analysis of test data generated at UL-JFL for 3% AFFF foam concentrates (67 tests) indoors is presented. Recording foam expansion ratio (foam volume/liquid volume) and quarter drain time (time taken to drain 25% of liquid) is a necessary prerequisite for all foam tests. Fire tests are performed in a 50 square feet MS pan (this corresponds to 2.15 m x 2.15 m size) with about 2 inch (~51 mm) deep n-heptane fuel floating on a 2 inch water layer and 8 inch free board (space of the region above the heptane layer to the edge of the pan) with a 1-minute burn. Fire-fighting by a qualified fire fighter begins with turning on the foam after the one-minute burn. Achieving 90% fire control within 3 minutes after pre-burn as judged by a qualified UL engineer and blanket burn back containment over 20% area in 5 minutes after re-ignition of a 300 mm diameter hole created in the foam blanket are two major pass criteria. Statistical analysis of the data show that faster draining foams have achieved 90% control earlier compared to higher drain time foams. However, higher drain-time foams have recorded greater pass margins (fire containment to smaller areas). Further, average drain times for certified foams (about 56 in number) is about 150 s with σ of 28 s, and for failed foams (7 in number) it is 100 s with σ of 25 s.

A comparative study of US based UL-162, and Indian BIS 4989 in practice in India shows that all standards have test methods for sealability, stability and flowability of foams. UL tests are performed in a square pan while other standards prescribe circular pans, the argument of UL approach being that flowing into the corners of square is a critical criterion to assess foam flowability. In UL tests burn back resistance is determined with a hole in the blanket while BIS involves insertion of metal pot containing burning fuel into the blanket. Exposing foam directly to fire increases test severity. Overall, it appears UL test criteria is severe compared to other standards.

HN Basavaraj, Research Associate, FCRC, Jain (Deemed-to-be University), Bengaluru

Studies on Nano-Boron Powder Combustion in a Gas Turbine like Liquid Fuel Combustor at Ambient Pressure

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Boron with its thirty percent higher energy content and more than two-fifty percent higher density compared to conventional hydrocarbon fuels is expected to increase energy density of air-breathing propulsion systems significantly. Issues that need resolution are: indigenous production of nano-boron at optimized costs, combustion when integrated in a slurry form with high density liquid fuels like JP-10 or either directly or in the form of the powder. Taking note of the literature information that boron requires high ignition temperatures (> 1600 °C), the current approach aims to introduce an air-jet induced boron nano-powder directly into the high temperature zone of the combustor.

At FCRC, a work was initiated in 2013-14 to evaluate the feasibility of powdery boron combustion. Boron powder (costing ~ Rs 600/g if procured directly) was synthesized from boric acid through magnesio-thermal reduction and was combusted in a standard LPG T-20 burner (30 kW) successfully. Results were presented in 2016 GATET workshop at GTRE. Subsequently, CARS project was given by GTRE in 2018 to FCRC for Boron synthesis and combustion in a liquid fuel combustor at ambient pressure. In an accompanying presentation, the production of high purity nano-boron is described.

An ambient pressure combustor is developed and run on kerosene using a conventional (0.75 g/s) kerosene atomizer. A boron powder dispensation mechanism is also developed that utilizes air from compressor as a part of fluidization-ejection system. The stainless steel cylindrical combustion chamber is 70 mm internal diameter with tangential air supply at the head end and through two rows of 2 mm dia holes, ten in each row on the periphery of the inner shell. Preliminary combustion trials have shown that a steady and stable flame is obtained between an air-to-fuel ratio (A/F) of 25 to 50. Thermocouple measurements of flame temperature with R-type thermocouple of 200 µm bead diameter show values of 1350 to 1650 K for the range of A/F indicated. The temperature variations across the combustion chamber correspond to a pattern factor {(max temp – min temp)/mean temp} of 0.15. Fine boron powder injected into the combustion chamber with the peak temperature of ~1400 K at 5% of kerosene flow rate showed an increase of 200 K indicating that boron has enhanced the heat release inside the combustion chamber.

Further experimental studies are in progress to establish exit temperature contours at the spectrum of A/F needed for combustor operations. The plan of experiments includes measurement of temperature contours at specific air-to-fuel ratios with kerosene and JP-10 fuels as well as comparing the combustion process by direct injection as well as boron injected as slurry with both liquid fuels.

CS Bhaskar Dixit, Director, FCRC, Jain (Deemed-to-be University), Bengaluru

Modern Clean Biomass Combustion Devices for the North East

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North Eastern region with seven states has had many issues related fossil fuel supply and other goods as well over a long period of time. While cooking in the main land can occur with LPG serving most urban and peri-urban communities, biomass is the main source as a backstop arrangement for most people in the Northeast. Therefore, there is an important necessity to look for clean combustion technologies for domestic and semi-commercial as well commercial hospitality industry. A search for such devices from China took a favorable turn with providential connect with FEAST. This journey that has begun only a few months back is supported by M/s Zigma industries for product design and manufacture has led to fast development strategy. The aim is to cover a large number hostels and other eating establishments as well vegetable drying applications with clean biomass based combustion devices. Also the current practice of usage of a large number of charcoal stoves for room heating and cooking is intended to modified to those with much reduced emissions of carbon monoxide and higher thermal efficiency. This presentation describes the progress made in this direction and what is intended to be achieved.

Bidhan Chandra Loitongbam, Managing Director,
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LOX-Methane Engine: Promising Candidate for Future Space Propulsion

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LOX-Methane engine is expected to bring many advantages to reality for future propulsion system, such as high performance, reusability and so on. Methane is one of the most interesting solutions as propellant for liquid rocket engines, in combination with Oxygen, due to good performances achievable in terms of specific impulse (Isp ~ 370 s) combined with operation advantages, such as storability, low toxicity, availability and production cost, as compared to hydrogen. Out of common hydrocarbons, methane has the highest vacuum specific impulse; in comparison, kerosene, the closest chemical hydrocarbon has a vacuum specific impulse of about 355 seconds. Methane is a soft cryogenic that is not corrosive and has very low toxicity; thus it is easier to store, requires less insulation and fewer handling concerns than comparable hydrogen fuel systems. Additional features of methane regard its good cooling capability and well known material compatibility, that make it ideal for regenerative cooling thrust chambers. From a propulsion point of view methane leads to low soot combustion and a good capability to cool the combustion chamber without the risk of cracking and deposit.

Liquid methane is about six times denser than liquid hydrogen; thus, methane tanks weigh much less and/or require less storage volume than comparable hydrogen tanks. Several studies show that methane coking and soot decomposition are of minimal concern as compared to kerosene and other complex hydrocarbon fuels; this allows for reusability, multiple-restarts and longer burn times. Additionally, methane is a natural gas that is relatively easy to extract on Earth and is about 5 to10 times cheaper to acquire and store than liquid hydrogen. This paper highlights about the merits of LOX Methane engine and its suitability for the future launch vehicles of ISRO.

KS Biju Kumar, Division Head, Engine Fluid Systems & Analysis Division, VSSC, Thiruvananthapuram

Numerical Investigation of Dual Mode ScramJet

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Air breathing propulsion beyond certain Mach numbers (M~>6) necessitates scramjet engine. During acceleration phase (M~1.5-3) Ramjet is a viable option. To combine best of these two technologies with a single fixed geometry engine, the concept of Dual mode ramjet engine (DMRJ) is in limelight in the recent published literature. In ramjet mode, careful modulation of fuel injection and heat release causes thermal throat which helps in subsonic combustion. In scramjet mode, the engine operation is performed with supersonic combustion. Detailed numerical studies are carried out for Hydrogen fuelled HyShot-2 dual mode scramjet combustor for varying equivalence ratios and investigated the thermal choking phenomenon. Reynolds averaged Navier-Stokes equations are solved along with Mentor's SST turbulence model. For chemically reacting flow 7 species 7 reactions are considered for H2-Air combustion, eddy dissipation concept model is used for combustion modelling (TCI). Predicted wall pressures are in good agreement with experimental data as well as reference computations, while predicted wall heat fluxes are in moderate agreement. Thermal choking has occurred for φ=0.38 which is confirming with experiments. It is also observed that the normal shock stands at particular location for each equivalence ratio above 0.38 and found to be quasi-stable. Present numerical studies for high speed turbulent reacting flows have helped in getting more insight into flow physics involving shock enhanced mixing, shock boundary-layer interaction, and wall heat transfer effects, also it addresses the predictive capabilities of present RANS based methods for scramjet like flow fields. Turbulence-chemistry interaction by EDC model accompanied by 7-step, 7-Species H2-Air chemistry model resulted reasonably good predictions when compared with benchmark experiments. Further studies are planned for predicting unsteady normal shock upstream movement with increasing equivalence ratio

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Combustion Instability in Gas Turbine Afterburner: GTRE Experience

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An afterburner of an aero gas turbine engine provides significant thrust augmentation which is critical to the performance and mission of a modern aircraft. A serious problem associated with the development of afterburners is the occurrence of high amplitude pressure oscillations during their operation. These high amplitude oscillations are driven by the interaction between the combustion process and the acoustic field in the afterburner, and are usually referred to as combustion instability. In the gas turbine afterburner, low frequency oscillations (tens to hundreds of Hz) of such nature are called buzz while high pressure oscillations (in thousands of Hz) are called screech. Combustion instabilities can be suppressed/mitigated by controlling the excitation mechanism and/or increasing the acoustic damping in the system.

GTRE afterburner has undergone extensive testing at various testing campaigns. During these tests, combustion instability (screech) has been observed in the afterburner. The analysis of dynamic pressure measurement data shows that the screech frequencies corresponds radial and tangential acoustic modes of the afterburner duct. The radial mode gets trigged at lower afterburner pressures and at higher equivalence ratio as compared to the tangential mode. GTRE has followed the different approaches like damper design, fuel distribution and flame-holder modifications to suppress screech in afterburner. GTRE experiences in handling afterburner screech will be presented during the meet.

S Ganesan, Scientist, 'F', Gas Turbine Research Establishment, DRDO, Bengaluru

Biomass Gasification with O_2/CO_2 and O_2/Steam Mixtures – Propagation Regimes, Carbon-Monoxide and Hydrogen Yield

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Biomass thermo-chemical conversion under O_2/CO_2 and O2/steam conditions is experimentally investigated to establish steady propagation regimes and the corresponding CO_2 and steam conversion potentials. Packed bed configuration with counter-current flame propagation is chosen for this purpose and three different fuels are used (agro-residue pellets, coconut shells and wood pellets). Steady flame propagation is established at different superficial velocities and the following quantities are measured – temperature along the reactor, mass consumption rate and exit gas composition. The propagation regimes, similar to earlier studies with air, fall under the following two categories – (1) gasification – volatile oxidation accompanied by char reduction and (2) char oxidation dominated – simultaneous char and volatile combustion. Invoking equilibration of volatile oxidation under gasification conditions, a new procedure is established to estimate CO and H2 yield.

For experiments with O_2/CO_2 mixtures, oxidizer streams containing 20, 25, 30, 40 and 50% O_2 (v/v) (rest CO_2) were investigated. Corresponding reference experiments with O_2/N_2 mixtures are performed for comparing the net CO_2 conversion. In general, net CO_2 conversion (NCC) is significant around the volatile stoichiometric point and falls off on either side as the oxygen mass flux is decreased or increased. NCC is zero in very rich regime i.e. when $\phi_v >> 1$ due to low bed temperatures and also when $\phi_v < 1$ due to char oxidation. Maximum NCC of 627 g/kg of biomass is observed with 30% O_2/70% CO_2 (v/v) case at ϕ_v = 0.96 for agro residue pellets. Cold gas efficiency (ηg) is as high as 85% for the maximum NCC case. Enhanced gasification efficiencies of O_2/CO_2 cases as compared to corresponding air cases is due to the additional conversion of CO_2 to CO (predominantly $C + CO_2 \rightarrow 2CO$). The difference in the fraction of char left over with CO_2 and N_2 cases is consistent with this observation.

For oxy-steam experiments, O_2 fractions of 23, 30 and 40% by mass (rest steam) were used. Novelty of the current work is in the use of upstream bed temperature in the range of 120-150 °C; the lower limit to avoid condensation of steam, while the upper limit is to avoid bulk de-volatilization of the bed. This has enabled evaluation of the intrinsic hydrogen generation potential of biomass, unlike earlier works where very high steam temperatures (>700 °C) were used. Estimated H_2 yield is in the range of 35 - 40 g/kg of biomass. Role of the reaction, $C + H_2O \rightarrow CO + H_2$, volatile stoichiometry and connected parameters like bed temperatures, regime of operation (combustion vs gasification), char conversion etc., on the yield of hydrogen and CO is brought out. Maximum cold gas efficiency of 71% is obtained for the case with 30% oxygen and superficial velocity of 18 cm/s; the corresponding hydrogen yield is 38 g/kg of biomass.

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Application of Compressible Multi-fluid Formulation for the Numerical Simulation of Granular Propellant Combustion

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Reactive solid energetic materials in granular form are common in pyrotechnique igniters, guns and other fluidized bed combustion systems. Numerical prediction of the ignition transient in solid motors with pyrotechnique igniters is a complex task wherein the explosive chain is to be accurately modelled. Here the ignition chain is initiated by electrically heating a resistance wire covered with an initiator propellant. The high temperature gases from the initiator enter the granular bed at one end and the propellant granules there are heated to ignition by these gases. They in turn produce more hot gases and ignite more granules. The gases generated from the ignited granules penetrate through the pores of the granules and heat up the remaining granules to ignition. Thus the flame spreads. Combustion waves igniting these granules propagate through the bed carrying pressure, density and velocity disturbances. This may lead to a detonation wave causing the Deflagration to Detonation transition (DDT) also. The combustion products from the igniter come out as sonic jets and expand to the ambient conditions before impinging and igniting the main propellant grain. Hyperbolic models are mandatory for the numerical simulation of these wave propagation phenomena.

Two-phase flow models for gas-particle systems are generally classified as Dilute and Dense depending on the volume fraction occupied by the particle phase. In the case of dilute gas-particle flows, the particle phase pressure and stresses are neglected. Granular propellant combustion comes under the category of dense gas-particle flows due to the high volume fraction of the particle phase. The governing equations account for the exchange of mass, momentum and energy exchange between the phases through source terms which forms the basis for the loss of hyperbolicity of the governing equations. The compressible multifluid formulation wherein both the phases are considered as compressible with appropriate equations of state is currently being extensively used for the numerical simulation of DDT. The seven equation model (Baer and Nunziato & Saurel and Abgrall) is the most popular model for granular propellant combustion. But the main difficulty is that the governing equation for volume fraction evolution alone is in non-conservation form which creates difficulties in implementing standard upwind schemes. The six equation model, wherein the gas and particle pressures are assumed equal, has been extensively used for complex two-phase flow problems using all the popular upwind schemes but not much for the granular combustion. Of late for granular propellant combustion, seven-equation models in full conservation form are being derived and are being increasingly used. Our experience with these models will be shared.

T Jayachandran, Professor, Indian Institute of Technology –Madras, Chennai

Internal Flow Path Analysis of a Hypersonic Cruise Vehicle with Hydrocarbon Fuel

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Numerous studies have been carried out by NASA and Boeing Company to evaluate various hypersonic vehicle concepts for a number of missions. These studies focused on hydrogen fuelled vehicles whose mission requirements could be satisfied by lifting bodies. Recent studies involving hydrocarbon fuelled vehicles have required significant changes in vehicle aerodynamic design to accommodate the higher platform loadings associated with conventional fuels. This paper discusses about the reacting flow analysis of the internal flow path a hypersonic vehicle with hydrocarbon fuel (i.e., liquid kerosene fuel). Design of the fuel injection system for isolated scramjet combustor has been carried out initially, and same has been implemented for the vehicle. Liquid kerosene fuel with a constant equivalence ratio (ϕ) of 1.0 is used to simulate the reacting flow simulations. Three-dimensional Navier-Stokes equations are solved along with SST-kω turbulence model using the commercial CFD software CFX-17.2. Single step chemical reaction with Lagrangian Particle Tracking Method is used for the combustion of kerosene fuel. Swept back type of fuel injection struts were chosen based on the previous experience gained from the kerosene fuelled scramjet combustor design of DRDL. Detailed flow field is analysed for the flight condition of 30 km altitude, 6.5 Mach no and 4o angle of attack both for nonreacting and reacting flow conditions. Simulations

captured complex flow features like the shocks generated from the nose and ramps of the vehicle, cowl-shock impingement on vehicle under surface and its reflection in the intake and combustor walls, reacting flow behaviour inside the combustor etc. Flow is largely non-uniform at the inlet of the combustor. Detailed flow filed data at various axial stations and wall pressure distribution along the internal flow path of the vehicle are presented.

Malsur Dharavath, Scientist, Defence Research and Development Laboratory, Hyderabad

High Fidelity Eddy-Resolving Simulations to Capture Surface Roughness Effects in Gas Turbines

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Components of the gas turbine engines are aerodynamically smooth on deployment. In-service degradation due to various damage mechanisms progressively roughens the surfaces of these components. During the design phase, the aerodynamic analysis is carried out under the assumption that the surfaces are smooth; largely ignoring the performance penalties (or in some cases benefits) and the safety issues encountered due to surface roughness. There is an increasing awareness in the gas-turbine community to include roughness effects during the design phase to account for the following detrimental symptoms: drop in the performance, increase in the specific fuel consumption, excessive temperatures in localised zones and the loss of stall margin under extreme cases. This talk will focus on the role of high fidelity eddy-resolving simulations to capture the surface roughness effects on the transitional and turbulent boundary layers. Case studies on the distributed roughness on a flat plate under zero pressure gradients and real roughness on a flat plate subjected to adverse pressure gradients, typical of a highly loaded turbine blade, will be discussed.

Nagabhushana Rao Vadlamani, Assistant Professor, Indian Institute of Technology Madras, Chennai

Challenges in the Development of Combustion System for Small Gas Turbine Engines

RD Navindagi
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This presentation overviews the requirements, design drivers, challenges and trends in the development of combustion systems mainly for small turbo fan engines. This presentation gives the Operational/Performance/Durability requirements of combustion systems. Relevant issues of atomisation, heat transfer, modelling and testing of combustion systems for achieving the targeted aero-thermal performance are discussed.

GTRE’s experience in design, modelling and testing of two architectures of small combustors will be presented. Test facility details and the experimental results of these combustion systems will be briefly presented.

The necessity and challenges of high density and high energy fuels and their effects on such combustion systems will be discussed. GTRE’s efforts in the development of the high density and high energy fuels in collaboration with various national institutes, present status and challenges will be described.

RD Navindagi, Scientist - ’G’, Gas Turbine Research Establishment, DRDO, Bengaluru

Recent Progress on Tipu Rockets from Excavations in Nagara, Karnataka

G Nidhin Olikara
Olikara Tractors
Shimoga

The Mysore metal cased rockets predate their European counterparts. A recent discovery of over 2000 of these rockets from Nagara in Shimoga district of Karnataka has given us an opportunity of investigating the physical and metallurgical characteristics of these rockets. The investigation has thrown up some fascinating results which provide us with several clues into their design, content and method of manufacture. They are also reflective of the technological and manufacturing strength that Mysore wielded at the close of the 18th Century. This presentation while introducing the findings to the audience also puts forward several questions relating to them that need answering after further research.

G Nidhin Olikara, Owner, Olikara Tractors, Shimoga

Recent Advancements in the Technologies for Production of Precipitated Silica from Rice Husk Ash and in the Chemical Scrubbing of Hydrogen & Sulphur in Combustible Gases

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A. Technology for Generation of Precipitated Silica from Rice Husk Ash (RHA):

The technology developed at CGPL, IISc about a decade back had a novel approach of using CO2 for the precipitation as against conventional usage of H2SO4 with a break-through in regenrating NaOH. However, this patented technology required more R&D to make it viable. Three major developments that were added recently are - (i) Pressurized digestion that took that took the silica extraction to go up to 85% as against the earlier 55%. (ii) Introduction of high performance ejectors that made a break-through in getting of silica of uni-modal pore distribution in desired range. (iii) Introduction of a retrofit to preheat the silica slurry during drying that brought down that enhanced the dryer capacity. These steps along with recycling of waste water and enriching regenerated chemicals have made the technology more viable and acceptable to the industries.

An industrial plant at 5 TPD capacities is built and the quality of the product qualified for the industry standards. The high quality of the silica known to fall in the category of highly dispersible silica (HDS) and finds its use in industries like tyre, detergents, toothpaste, food and many others that render the technology as a good means to convert waste to wealth.

B. Technology for Scrubbing of H_2S from combustible gases from industrial effluent plants:

This technology basically adopts chemical scrubbing using iron chalets that selectively absorb H_2S from a gaseous stream and the chemical is regenerated by oxidation using ambient air. The technology, being more than a decade old, faced adequate challenges in the field, dominantly due to the complex behaviour of precipitated sulphur. Recent advancements in the newly developed sub-systems, in combinations are found to provide solutions to most of the observed problems. They include (i) Introduction of spray column with strongly impinging jets using an annular injector that improved the operability and maintenance with an uptime of 95%. However, they required clean-up in about two weeks, moderately acceptable. (ii) An ejector introduced with liquid recirculation was high performance, with reduced hardware and power consumptions and showed high quality of absorption of H_2S. However, the sulphur deposits at the throat required cleaning in about 3-4 days with plants of higher concentrations of H_2S. (iii) The next configuration evolved included a sparging system that has overcome all these problems and have been doing well in a maintenance free mode. Constraint of this system is in its demand higher inlet gas pressure. (iv) Concerning the regenerators, in the recent development ejectors are added that is found to have brought down the excess air drastically and reduce the power consumption significantly. This configuration has eliminated evaporation losses as well and has provided a maintenance-free run of the plant.

Based on the field conditions, with combination of the recently developed modules as described above the technology is found to meet the industrial challenges and has been successful in operation in the past 3-4 years and has contributed for power generation of 5 to 6 MWe from biogas gernated at industrial effluent treatment plants.

NKS Rajan, Principal Research Scientist, Indian Institute of Science, Bangalore

Solid Oxide Fuel Cells Fuelled by Alternate Fuels

N Rakesh and S Dasappa
Centre for Sustainable Technologies,
Indian Institute of Science, Bengaluru

The work focuses on the use of syngas derived from biomass through gasification in Solid Oxide Fuel Cell (SOFC) button cells to generate electricity. As tar has been reported to be detrimental to SOFC operation, a detailed gas characterization was carried out. A reliable, cost-effective method was developed, which uses Cold Solvent Trapping alongside Gas Chromatography-Mass Spectroscopy/ Flame Ionization Detector (GC-MS/FID) system, for this study. A novel electrolyte supported SOFC button cell was tested using an SOFC test rig established at Indian Institute of Science, Bangalore. Parametric studies were carried out with hydrogen to establish the base line scenario. Tests were carried out with syngas to study the effect of CO on the cell performance. Characterization of the cell was carried out to understand the possible mechanisms of failure. The study establishes the gas quality and points to the need for further cleaning of gas. The preliminary studies show that higher hydrogen content in the gas enhances the cell performance and CO can be detrimental to the cell, when supplied along with Hydrogen.

N Rakesh, PhD Scholar, Indian Institute of Science, Bangalore

Specific Power Enhancement of Small Two-Stroke Engines using Nitromethane Blends

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With the applications of the Unmanned Aerial Vehicles (UAVs) expanding from just short surveillance to some of the modern civil and defence needs which include weapon/cargo delivery, long-range surveillance and combat, there is a need to develop propulsion systems which have high specific power, high efficiency and good reliability. Small two-stroke engines have found popularity for medium endurance missions. However, there is a need to further enhance the specific power of these engines. The main goal of the present work is to enhance the specific power of small two-stroke spark ignition engines through the use of fuel additives during conditions like take off and climb.

Comparing the properties of various fuels, nitromethane which is popular in drag racing was found to be an attractive option as a fuel additive due to the presence of two oxygen atoms in each of its molecule. However, only limited work has been carried out on the use of nitromethane as a fuel additive in IC engines. Hence, detailed experimental analysis was carried out to study the effect of nitromethane addition on the performance of the small two-stroke IC engines.

Preliminary tests were carried out to evaluate some important properties of nitromethane blends. Results showed that the heating value of nitromethane is much lesser than gasoline. But the adiabatic flame temperature was found to be higher than gasoline. Also, the laminar flame speed measurements indicated that the flame speeds increase with increasing fraction of nitromethane in the fuel blends.

A small fraction of methanol was used as a medium to mix nitromethane and gasoline, which are normally immiscible. When tested on an unmodified engine, a large rise in engine torque (31%) and BTE (14%) was obtained. However, the BSFC (33%) increased for the nitromethane blends. Next, various engine parameters like spark timing, equivalence ratio and compression ratio were optimised to further increase the engine torque and reduce BSFC. The results obtained with engine optimisation showed a net torque improvement of 42%, BTE improvement of 35% and BSFC rise of to only 9% in comparison to gasoline at stock engine conditions. To further bring down the BSFC, methanol was replaced with ethanol and butanol. This change resulted in BSFC rise of only 5% over the stock gasoline fuelled engine.

Hence, it is possible to obtain high engine power output with the use of nitromethane as a fuel additive in small two – stroke IC engines. This could potentially increase the payload carrying capacity of the UAVs and make them suitable to carry out some of the modern UAV applications.

PA Ramakrishna, Professor, Department of Aerospace Engineering, IIT Madras, Chennai

Biomass stove technology for semi-industrial applications in Karnataka and other regions

N Ravi Kumar
Harith Avani Technologies
Bengaluru

Traditionally having worked on thermal biomass gasification systems and processed biomass supply for over two decades, I also acquired the know-how for clean biomass combustion technology with HC3D (Horizontal Continuous Clean Combustion Device and VEBCOD (VErtical Biomass COmbustion Device) from FEAST and have rapidly been exploring a number of food related applications for replacing LPG based systems in view of the economy it offers. This presentation describes the range of applications tackled or in the process of being completing. These include, roasting industry, deep frying industry, metal blackening industry, cooking in hostels and establishments with wide range of requirements – cooking for 50 to 5000 people. All these are based on combustion devices with power levels ranging from 6 kg/h to 100 kg/h. A range of fuels is contemplated – sawmill and furniture wastes that are either directly used or pre-processed for size reduction, firewood in as-received dry condition, coconut wastes including sized fronds and husk, cashew shell waste. The supply of fuel is organized only when required. It is felt that this approach that depends currently on the spread by word-of-mouth information transfer as it is in early stages of commercial deployment will expand rapidly. Large scope for this exists in urban market when the fuel supply is ensured along service when needed.

N Ravi Kumar, Proprietor, Haritha Avani Technologies, Bengaluru

Ammonium Dinitramide (ADN) Based 'Green' Monopropellants: Aspects of Heterogeneous Catalysis and Combustion

S Reshmi

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The spacecraft propulsion system enables orientation (altitude control) and positioning (orbit control including de-orbiting) of spacecraft after injection into the required orbit by the launch vehicle. The most common spacecraft propulsion involves monopropellant thrusters, wherein a propellant is catalytically or thermally decomposed into hot gases which are then expanded through a nozzle. Hydrazine is commonly used as a monopropellant for spacecraft applications in satellite thrusters. However, personal safety and environmental issues have caused a concern on the use of hydrazine due its toxicity, high vapour pressure and carcinogenity. Hence, in recent years several 'green' monopropellants are emerging. Amongst these, ammonium di nitramide (ADN) based monopropellants has emerged as 'green propellant' candidate for spacecraft propulsion. Monopropellants based on ADN are very attractive due to their relatively low toxicity and vapor pressure. It also offers flexibility to formulate propellants blends with different fuels and solvents with non-toxic ignitable fumes. Based on numerous theoretical studies, a baseline propellant using ADN–water-alcohol was evolved. The specific impulse (Isp) achieved for the system in ~257s, which is higher than hydrazine based monopropellants whose Isp is about 238 s at identical thruster operating conditions. Thus the system provides an enhancement of 6% in terms of specific impulse and 30% in terms of density impulse. The important aspect in the development of a new monopropellant is its ignition. The thrusters based on hydrazine use catalytic ignition, which is simple and reliable. ADN monopropellant also undergoes combustion by decomposing on the surface of a catalyst. The flame temperature of ADN based propellant is nearly twice that of hydrazine based propellants. The high combustion chamber temperature of ADN based monopropellant is a real concern since it might deteriorate the catalyst bed. This is one of the challenging aspects related to the evaluation of ADN monopropellant in thrusters. The choice of catalyst support material and active element in the catalyst that can trigger the decomposition determines the performance of the thrusters. In this context, various types of catalysts support with active materials with iridium and platinum with monometallic oxide systems such of copper, iron, nickel, cobalt, lanthanum and cerium have been developed and evaluated in-house. The combustion proceeds through thermodynamic phase transition consist of both evaporation and condensation of ADN. The species evolved from the burning propellant surface into the gas phase include vapor ADN and its decomposition products. The temperature regime for solid to foam layer formation is 333 to 663 K. Above 663 K, the sublimed ADN undergoes decomposition to various gaseous products like ammonia, nitrous oxide and dinitramidic acid. In the temperature regime of 663 to 1600 K visible flame appears with liberation of nitrogen, water, oxygen and oxides of nitrogen.

S Reshmi, Scientist/Engineer SG, Vikram Sarabhai Space Centre, Thiruvananathapuram

Certification through Virtual Testing

Sachin Kumar Rai
UL India Private Limited
Bengaluru

The presentation will cover an overview of product certification process and how virtual testing is helping to reduce actual physical tests in UL. Basic aspects of fire safety and the ways to model it will be presented through specific case studies such as (i) use of modeling for testing and predicting performance of fire sprinklers (ii) modeling fire spread over attic (iii) building façade fire modeling (iv) smoke and egress modeling in basement car park (v) use of machine learning for modeling a material property test. These examples will demonstrate the extensive role of simulation in the process of certification to eliminate the submission of physical parts for future design, support client's preliminary review documents and carry independent V&V for testing. At the end, existing challenges and future for certification by virtual testing will be discussed.

Sachin Kumar Rai, Tech Lead, Fire Modeling*, UL India Private Limited, Bengaluru*

Some Intriguing Aspects of Pan Fires and an Approach to Modelling the Behaviour

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This work is aimed at understanding the pool fire combustion behaviour on small diameter pans to examine the role of wall material that awaits exploration as also the fuel depth that was already uncovered as an important parameter even in large pans. n-Heptane fuel was burnt in 200 mm diameter, 40 mm deep pans made of aluminium, mild steel, stainless steel and glass (material thermal conductivity range of over a hundred and thermal diffusivity range of seventy) were studied with fuel depths of 10, 13 and 20 mm. Measurements included fuel mass, wall temperatures at select locations and fuel depth temperature with time of burn. Also gas phase temperatures inside the fire were measured using thermocouples. Several interesting results have been uncovered in these studies.

1. Measurement of gas phase temperatures showed values around 1100 K with literature values varying between 1100 to 1450 K at different pan sizes. This apparent connection of flame temperature with pan size was resolved when "heated" thermocouples were used to measure the temperature inside the fire. The measured values went up to 1450 K even in small pans and was also found to be independent of pan size. The conclusion was that sooting on cold thermocouple was responsible for spurious results.

2. The mass loss with time shows distinct behaviour. All the pans show two flux durations depending on the wall thermal conductivity. Glass pan shows a fuel flux of 10 g/m^{2}s over substantial burn duration and increased flux of 12 -13 g/m^{2}s occurs later. Higher thermal conductivity (SS – 0.016 kW/m K, MS – 0.032 kW/m K and Al- 0.15 kW/m K) pans show higher durations of higher burn flux; Burn flues of up to 60 g/m^2 s are observed over 40% burn duration.

3. A special experiment conducted with MS pan with water cooling around the sides showed behaviour similar to glass pan. This clearly showed that wall conduction plays a significant role in the burn profiles of all materials with the lowest flux contributed by convection. And convective heat transfer is expected to be similar at all pan sizes and for all wall materials. Radiation (at these pan sizes) is expected to play a small part in the heat flux to the fuel (~ 5 to 7%) consistent with the understanding in the literature.

4. Wall temperature behaviour is also interesting. Glass, SS. MS and Al show tip temperatures of ~ 550, 450, 420, 380 K (± 20 K for larger values) and the wall bottom edge temperature indicates that it is much higher for MS and Al than for SS. While the first part is related to higher heat flux drawn from the tip towards the bottom along the wall, the latter behaviour is more complex expression of the relative change of thermal conductivity. The temperature rise rates also contribute to the burn behaviour since conductive heat transfer through the wall is so influenced.

5. A plot of wall temperatures with time can be set out in terms of fuel regression as well. Such a plot is expected to express the intrinsic behaviour of thermodynamic variables

with the progress in the fuel consumption. Such plots show the intrinsic unsteady and near steady burn segments clearly.

6. Modeling of the unsteady burn behaviour has been attempted. The question of the description of wall temperature behaviour – as to the time dependence is better expressed through relationships of wall temperatures in terms of regression that invokes wall thermal conductivity (k_w) and associated non-dimensional quantities or through unsteady behaviour expressed through unsteady scaling ($\sqrt{\propto_w t}$) comes under question. Tracing the burn behaviour better happens only for a consistent unsteady description with time as a variable is adopted. The reason has been traced to the very sensitive dependence while the comparisons are impressive allowing for experimental differences, the general validity of the model needs to be established over a larger range of pan sizes and more importantly fuels – diesel and iso-propyl alcohol being the important contenders.

A Shivakumar, Research Engineer, FCRC, Jain (Deemed-to-be University), Bengaluru

Synthesis of Nano-Boron and Related Studies at FCRC

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This paper reports the efforts to produce elemental amorphous Boron at a purity level of more than 90% and at fine particle sizes less than a micron in a project sponsored by GTRE, Bangalore. One of more well known processes, namely, Magnesio-thermic reduction of boric anhydride (B2O3) to Boron is chosen as the process here. Several developmental hurdles towards the production of high purity nano-Boron have been overcome. The final process consists of starting with boron anhydride and magnesium along with sodium chloride, all of high purity, reducing their size and mixing them in proportions close to 1:1.05:0.71 (w) and performing in an inert environment of nitrogen, a controlled combustion process with the material being arranged in the form of a pressed heap in a container surrounded by insulation. The resulting black product is subjected to sequential leaching using HCl/NaoH/HF towards removal of primarily magnesium oxide and also associated impurities like silica. The product quality is assessed using SEM, EDX & particle size analysis. These indicate that Boron purity of >90% with particle size ranging from 250 nm to 500 nm. Zeta Pals, % particle size distribution results confirm that >98% particles are in this range and the effective diameter is 251.1 nm. Some developmental issues related to production and analysis of purity is highlighted.

AVe Sowriraajan, Associate Professor, FCRC, Jain (Deemed-to-be University), Bengaluru

Simulation Studies of Non-Reacting and Reacting Flows over a Triangular Bluff-body

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Stabilization of flame behind a bluff-body is one such technique used in high speed combustor. The recirculation zone created behind the bluff-body reduces the flow velocity. It helps to meet the turbulent flame speed and hence it avoids blow-out. This technique is applied in practical combustors. Afterburner of high-speed aircrafts uses this technique with the help of v-gutters. The flow field behind v-gutter is of fundamental and practical interest. Volvo conducted experiments on afterburner with v-gutter to provide velocity, turbulence and temperature data. This data set serves as bench mark data to validate CFD methodology. In this present study, CFD simulations are performed with ANSYS Fluent software to capture various flow features.

Both URANS and LES simulations are carried out in this study. In the case of URANS, the criterion of near wall grid requirement is full filed with 0.65 M grids. The predicted value had shown some difference in recirculation length and the velocity profile at various cross flow planes. In order to resolve the large scale flow structure and about 70 % turbulent kinetic energy in LES, fine mesh are generated near the v-gutter with 3 M grids in the entire computational domain. The prediction with LES had shown better agreement with the experiments. The vortex shedding is clearly noticed with velocity filed with both the simulations.

In the case of reacting flows, the local velocity and density fields are different. It suppresses the large scale vortex formation. The URANS simulations with 0.65 M grids did not show any significant changes in flow structure. In the case of LES, vortex formation and convection are noticed. Hence, LES studies are important to understand unsteady flow features. In the present study, the equivalence ratio is also varied to explore the flow oscillation. The combustion instabilities are considered in the near future.

AT Sriram, Associate Professor, Ramaiah University of Applied Sciences, Bengaluru

Empirical Correlation for Predicting Laminar Burning Velocities of Syngas -air Mixtures at Elevated Temperatures

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Mumbai

Laminar burning velocity of nine different syngas compositions has been measured at elevated temperatures (350-650 K) for various equivalence ratios using an externally heated diverging channel method. The measured values are compared with the predictions of two detailed kinetic models (GRI 3.0 and FFCM-1). The predictions of FFCM-1 for various syngas (H2/CO/CH_4/CO_2/N_2) mixtures accurately capture the fundamental combustion characteristics, and GRI 3.0 mechanism over predicts the laminar burning velocity for fuel rich syngas mixtures. Temperature exponents mildly decrease with an increase in equivalence ratio for mixtures investigated in the present work. Two correlations, one using linear regression, and another, a linear equation model is proposed to predict the laminar burning velocity accurately for various syngas compositional modifications. The developed linear model can be used for direct calculation of laminar burning velocities of different syngas compositions. Similarly, a temperature exponent correlation and its comparison with present measurements and simulations are also presented. The efficacy of the proposed models is evaluated through a detailed comparison with the literature. The model provides an excellent matching for following syngas compositions; 0.05 < $X_{H_2} < 0.50$, 0.08 < XCO < 0.50, 0 < X_{CH_4}< 0.13, 0 < X_{CO_2}< 0.50, 0 < X_{N_2}< 0.65, for an

equivalence ratio range of 0.7 – 1.25, and mixture temperature from 300 - 650 K.

Sudarshan Kumar, Professor, Indian Institute of Technology Bombay, Mumbai

Predicting the Thermal Response of Bodies Engulfed in an Open Pool Fire Accident

Sudheer Siddapureddy
Indian Institute of Technology- Dharwad
Dharwad

The thermal response of bodies engulfed in fire is essential to understand the fire accident scenarios. The body responds differently to different fire environment. The temperature rise of these bodies, due to a fire accident, not only depends on the heat release rate of the fire but also on the thermal properties of the body. A simplified methodology, using adiabatic surface temperature (AST), is investigated to predict the incident heat flux to different cylinders engulfed in different pool fires. Several open pool fire experiments are performed with diesel as the fuel and with pool diameters. Numerical fire simulations are validated and extended for larger pool fires and for different fuels. This methodology provides an effective way for thermal test simulations.

Sudheer Siddapureddy, Assistant Professor, Indian Institute of Technology, Dharwad

Composite Propellant Engineering with The Heterogeneous Quasi 1-D Model - Practitioners' Perspective

S Varunkumar (IIT Madras, Chennai),
Mujeeb Shaik & VM Lakshmi (VSSC, Tiruvanantapuram),
Avtar Singh & Rohit (HEMRL-Pune)

The traditional 'trial and error' based approach to AP/HTPB based composite propellant has worked so far. It has led to successful demonstration of space boosters and ballistic missile systems, not generally prone to 'acoustic instabilities'. But 'tactical missiles', which have much lower stability margins, have needed enhanced time and resources in development with associated uncertainties in the relationship between propellant ingredients and instability. This problem is further compounded by the complex interface effects created by use of the ever increasing list of exotic candidate materials as burn rate modifiers. Since the instabilities are connected to steady burn behavior, it is considered important and relevant to address the this. It was therefore thought that modeling the steady propellant combustion at the level of detail in which the propellant composition is taken into account, would help the development of solid propellant compositions for launch vehicles and ballistic missiles and benefits especially in 'tuning' burn behaviour using catalysts would accrue. The earlier BDP based simple models did not evolve to be predictive design tools and the recent CFD based approach, though elegant and has predictive capability, lacks the ability to include many physical effects. Also, the CFD approach is far too time-consuming for becoming an aid in development. The HeQu1-D framework based model fills this gap as a predictive tool for steady burn behaviour, that (1) matches the earlier models in simplicity and in addition, accounts for '3-D gas phase behavior' as good as CFD, (2) more importantly, can account for various effects of energy release and melt layer due to additives like aluminum, $SrCO_3$, oxamide, as well as nitramines and (3) can be used by propellant designers for a-priori determination of the composition required for a given application. A few practitioners from development agencies have begun using the MATLAB® implementation of the model. Their perspectives on the model, specifically, what are seen as promising avenues for application of the model and associated challenges will be discussed. Issues in precise determination of AP particle size distribution, a prerequisite for using the model and some insights from use of various techniques for the same will be presented. Predicted burn rates for a few compositions from these agencies along with experimental results will be brought out. While the road ahead for possible adoption seems clear, there is still much ground to be covered in shared understanding of the complex burn behaviour due to particle size distribution and ingredient specific influences in terms of stoichiometry and melt.

S Varunkumar, Assistant Professor, Indian Institute of Technology – Madras, Chennai

Professor PJ Paul - A Brief Profile

With BSc in Engineering from Kerala, Prof. P J Paul obtained his Master degree from the Chemical Engineering Department at the Indian Institute of Science, Bangalore in 1973 and the Doctoral degree from the Engineering Faculty (Aerospace Engineering Department), in 1982. Prof. Paul joined as an Assistant Professor at the Aerospace Engineering Department in 1984 and later became a full Professor. During this period he guided 20 PhD Thesis and 4 MSc Thesis in different areas of Combustion. He has guided over 20 ME thesis. Prof. Paul had over 130 publications including patents, conference, books, etc. Some of the specific investigations are described briefly below. Flammability limits, Stretched flames, Development of 2-D code for low speed flows, Solid fuel combustion, Modeling of composite solid propellant combustion, mixing and combustion in shear layers, ignition of solid propellants, char gasification, distillery waste incineration, flow in ejector ramjet combustors, studies on cyclone combustors, ejector ramjet combustors, burning area evolution of solid propellant grains, computational study of flow in a vortex tube, He has taught several courses during these years including AE 248: Rocket Engines. From 1987 onwards, every year, AE 246: Combustion. From 1995 onwards, AE 244: Liquid Propellant Rockets. From 1985–86 onwards, AE 245: Mechanics and Thermodynamics of Propulsion.

He was Chief Executive, Advanced Bioresidue Energy Technology Society since Dec 2003 and Convener, Joint Advanced Technology Program since May 2004.

Moments with Prof. P. J. Paul

HS Mukunda

I have known Professor Palakat Joseph Paul called by me many a time Paule due to my closeness towards him for over thirty five years, very intimately. His academic life like of mine and several others began and continued all along at the Institute. A singular quality that distinguished him is the ability to think deeply over several aspects of reacting flows including flow control and response aspects. Thinking about valve designs or fluid related hardware elements seemed also native to him a feature that received appreciation from many.

The fundamental quality of providing sharp clean responses to technical questions that I saw in him when I was an examiner for his M E thesis (under Prof. V G Kubair in chemical engineering department) whether he knew the responses fully or partially never changed over these years, in particular when he became a research student studying regression in hybrid rocket engines (with me and Prof. V. K. Jain).

His academic life has been intertwined with mine and the students in a rich way. The biannual international combustion symposia offered a much looked-forward-to challenge to write scientific papers of significance to qualify for presentation. There were eight symposia over twenty years (we missed two in between) that we attended together with other colleagues and students. These provided opportunities to showcase the scientific prowess and brush shoulders with the best in the field. At the 1998 symposium there was an accepted paper presented as a poster alongside Prof Forman William's poster. After we showed him what we had done he remarked “somebody should take interest in my work as well” somewhat jocularly and of course we sought to understand what he had done. At these moments of interaction, I found Paule to be at his best, extremely sharp, absorbing the crucial points and responding at amazing speed somewhat unlike what one saw him in normal interactions. I also believe that he was very comfortable with small group discussions, when and where he would react softly and sharply rather than in formal large gatherings.

He has always been soft-spoken in a self-effacing manner and would offer the leadership role to his colleagues without a murmur; this would not mean that he would not react at technical points improperly made – in fact he would do this with unusual precision on occasions. He was also somewhat a reluctant writer requiring much persuasion to publish his scientific work.

There is much benefit that I have derived personally – whenever I was faced with a tough scientific question, perhaps one of the few persons I looked forward to talking to was Prof. Paul for the expected range or limit to the depth of discussion could be very wide. While his plans to do scientific work that he had charted for his students was curtailed by his untimely passing away, I for one and many colleagues would feel his absence whenever critical technical questions about science or technology are debated.

We all hope his family will derive comfort from the knowledge of how fine a human being he was and what all he did during his professional life.

1st Prof. P. J. Paul Memorial Combustion Researchers' Meet

22 - 23 February 2014
Jain (Deemed to be University)
Bengaluru

2nd Prof. P. J. Paul Memorial Combustion Researchers' Meet

24 - 25 February 2015
Beach Resort
Chennai

The Second Combustion Science Workshop was held recently following the first successful meeting that took place at Jain University (JU) Campus, Bengaluru on 24 and 25 February 2014. The principal aim of these workshops was to get the faculty (and their students) and scientists of R&D laboratories to come together and discuss combustion science practiced in the academic environment and problems of development in defence and aerospace industry. The significant difference between this workshop and regular conferences is the in-depth discussion that occurs after each presentation. It is aimed at learning from each other and allowing the students to relate the research practiced in their environment with developments. It was (and is) held in a retreat mode to enable long walks and discussions to resolve differences in viewpoints beyond the conference room and learn some successes and failures in a direct conversational mode. The current meet had 25 presentations, including 6 student presentations. Selected highlights are listed below.

The first talk was presented by H. S Mukunda (IISc, Bengaluru) on what is termed ‘quantitative minimalism’ in combustion science in the current context, but with wider applicability. Specifically, he addressed the role of diffusion limitedness versus kinetic role in combustion science. He brought out from his own work, factors that were included in earlier work but later excluded after re-examination of ideas and accounting for more experimental data. He stated that taking large chemistry as important in complex problems must be weighed against its true role, since such an effort could be time-consuming and not so-relevant subsequently. He also mentioned that in problems of combustion with complex chemistry and condensed phase physics as in solid propellants (reactive c-phase) or biomass, it is prudent to take simple chemistry where needed and seek with care if the phenomenon is dominated by diffusion limitedness. Modelling phenomena without complex chemistry, if not relevant, would be far more straightforward and a reality check will anyway be the final word. Taking what is most essential rather than all factors into account was the prime emphasis.

V. Raghavan (IIT Madras) spoke on the flame spread process in a long pan fire with methanol as the fuel. The full conservation equations were solved both in the gas and condensed phase and the results were displayed; the broad features of the propagation process were captured. Bhaskar Dixit (JU) spoke on the role of free board in small pan fires. Both experimental and modelling studies were discussed.

The heat flux along the wall was traced to the conductive heat transfer through the quench zone above the lip. The model was shown to capture the effects of free board and other aspects.

In the session on solid rocket motors, Kalyan Chakravarty (DRDL, Hyderabad) focused on analytical and computational tools for solid motor instability. He described the development of a quasi-1D code that can predict damping coefficients accurately as that of CFD in most cases, and almost the exact frequencies; it could be a good substitute for CFD, which is far more time-consuming. He spoke about an important possibility of a segment with much larger burning area as a middle segment of a long motor to ensure meeting the total burn area need, but ensuring stability as the unstable burn related contribution to mass flow rate is correspondingly reduced due to large fraction of mass addition close to the pressure node. Varun Shivakumar (IIT Madras) described the steady-state modelling of composite propellants, arguing that this is essential to make realistic predictions of unsteady behaviour of motor operation using composite solid propellants. He argued for the minimum model elements with the burning of the largest particle surrounded by a uniformly coated binder with fine particles. He and his student M. Zaved presented the results for a large number of propellants of Miller for which the burn rate data were available. Excellent comparisons were shown for a large number of propellants and for some propellants, the need for computation of propellant burn process was indicated to quantify one factor in the propellant model. Arvind Kumar (HEMRL, Pune) agreed to collect data on propellants produced at HEMRL and examine the model presented for further improvement in predictive capability. He indicated that aluminium combustion would be superior when it is coated with nickel.

P. A. Ramakrishna and Nikunj Rathi (IIT Madras) explained systematically the approach for ramjets for flight Mach numbers in the range 6–8, usually reserved for scramjets. The argument for the suggestion on ramjets arose from the consideration that a new propellant combination had the promise of much higher flame temperatures, thus enabling energy addition even at higher stagnation temperatures experienced at Mach numbers of 6–8. R. Abhishek (DRDL, Hyderabad) explained the principles for the choice of a propellant for a solid fuel ramjet based on the tactical mission scenarios. He indicated that meeting mission objectives needed boron-based fuel-rich propellants that are easy to ignite; the central issue of boron combustion in the secondary combustion chamber was also brought out. He indicated that the availability of boron of the right specification was also in question. A. N. Gupta (Premier Explosives Ltd, Hyderabad) described the role of the source of ammonium perchlorate in controlling the burn rate behaviour of composite propellants being produced for defence applications.

There were two presentations on thermoelectric generators (TEG) for power generation by Sudarshan Kumar (IIT, Mumbai) and Ganesh Pavan (JU) who described the attempts to establish the operating efficiency of a TEG system. The JU system was designed for 10 W output at an efficiency of 2.5%. Sudarshan Kumar presented his work on TEG with emphasis on micro combustion process in fine tubes with similar performance. J. Jayaprakash (VSSC) discussed the recent flight of GSLV-Mk3 (also termed LVM3-CARE mission) carrying a re-entry payload with several flight details not usually available otherwise. He mentioned a problem related to burn rate of the solid propellant that appeared to be lower than expected despite all standard practices for propellant production and testing established over a long time. This was an invitation for academia to put their minds to the issue. Biju Kumar (LPSC) presented the issues surrounding the cryogenic (liquid oxygen–liquid hydrogen) testing. He indicated that in a major static test conducted, the engine experienced high frequency instability of the first tangential mode (about 3.3 kHz), which was unexpected because of earlier tests. On a careful study, the issue was traced to cavitating venturies that had been placed in the high-pressure fluid supply circuit. The conditions in the cavitating venturi caused pressure fluctuations due to local flow velocity being larger than the acoustic speed of the twophase flow. Resolution of the problem was sought in increased area of the venture such that the local speed was brought down below the two-phase acoustic speed. This change showed that all normal test behaviour was recovered. Of course, such a situation was not expected to occur in flight mode since the system does not have cavitating venturies. T. Sundararajan (IIT Madras) spoke about computational efforts on the simulation of the high-altitude test facility being built at Mahendragiri (ISRO). Exhaustive simulations displayed known physical insights into the problem.

S. R. Chakravarty (IIT Madras) and his student provided impressive timeresolved flow pictures of combusting flow stabilized behind a step. Many interesting details of the flow dynamics were brought out; to whether these phenomena are still coupled to the incoming flow remains to be resolved. R. I. Sujith (IIT Madras) spoke about intermittency in flows as precursor to fully turbulent flow and associated chaos with particular reference to flows in gas turbine engines. The usefulness of the knowledge of a precursor to instability is yet to be explored. His student, E. Gopalakrishnan spoke engagingly about the role of noise in causing flow transitions (the bifurcations), some smooth and some abrupt with experiments on Rijke tube. Dalton Maurya and Gurusharan Singh (GTRE, Bengaluru) outlined the issues facing combustion processes in gas turbines today.

Gurusharan Singh clearly brought out where they stand with regard to after-burner instability issues. Achintya Mukhopadhaya (Jadavpur University) discussed the extensive tools like colour sensing, crossed wavelet transform technique and symbolic time-series techniques to provide an early detection of lean blow-off situations in gas turbines using premixed and partially premixed flames.

A. Ramesh (IIT Madras) spoke on the use of biogas in homogenous charge compression ignition engine with diesel for auxiliary injection. This effort aimed at small engines compete with standard low-capacity direct injection diesel engines working on dual-fuel mode and small capacity gas engines working on biogas directly. Sri Vallabha (IISc) spoke on the large eddy simulation of jet flows with water spray using several strategies for sub-grid scale modelling. The computations were carefully performed and comparison with experiments showed some parts to be reasonable and some others as not so good. As to why there were differences between predictions and experiments and how to reconcile them were also discussed. Many experiments on droplet dynamics were reported by Anand and colleagues (IIT Madras). P. Mahesh (IIT Madras) described measurement of drop distributions with advanced laser technology in situations of interest to gas turbines. He indicated that while the use of drop size distribution with d^2 law was standard in gas turbine combustor design, the drop groups that he has measured might influence emissions and need to be accounted for. Swetaprovo Chaudhuri (IISc) spoke of the need for taking turbulence– combustion interaction in premixed flames to a greater level of detail than considered now and presented an approach to track the flame movements in a turbulent flow field and its consequences.

There were three independent student presentations. S Snehesh (IISc) presented his work on Fischer–Tropsch process, particularly on catalyst development, since this was an item commercially denied for supply for development in India; very encouraging reactor performance was reported. S. Krishna (IISc) spoke of the experiments on trapped vortex combustor with methane and syngas as fuel with reasonable comparison with calculations.

Anirudha Ambekar (IIT, Mumbai) spoke on the combustion behaviour of liquid monopropellant – isopropyl nitrate. The results of the elegant experiments at high pressure were explained on the basis of wall heat transfer coupled combustion process.

The meeting had several takeaways further collaborations between various institutions which participated in the workshop in respect of understanding propellant combustion and progressing steady and unsteady solid propellant modelling efforts to continue. Highlighting the issues on gas turbine combustion will lead to greater GTRE–academia interactions aimed at resolving problems of significance in gas turbines. Other along the beach conversations in the evenings and mornings has created prospects for greater interactions among all concerned.

3rd Prof. P. J. Paul Memorial Combustion Researchers' Meet

24 - 25 February 2016
Vikram Sarabhai Space Centre
Thiruvananthapuram

The third combustion researchers meet was held in Vikram Sarabhai Space Centre (VSSC) at Thiruvananthapuram during 27 and 28 February 2016, following the second successful meeting that took place at a beach resort in Chennai1. The tradition of getting faculty and scientists in R&D institutions on an invited basis, to discuss in-progress parts of combustion science practiced in the academic environment and problems of development in defense and aerospace industry was continued this year as well with much wider and deeper interest by the participants. The aim of creating a conducive environment for learning from each other and allowing the students to relate the research practiced in their environment with developments seemed a well worth the idea because many students participated in this workshop. The current meet had 29 presentations from faculty and scientists with 6 student presentations. Selected highlights are set out below.

The first talk was presented by Sujith (IITM) on using theory of complex networks in thermo-acoustics; the basic idea being that acoustic signals from flowing fluids contain the nature of the local flow field and such signals when subject to select analysis may reveal the flow behaviour. Much discussion followed. Establishing the value of such analysis on the basis of conservation equations was suggested as being important. Sundararajan (IITM) spoke of the use of genetic algorithms in optimizing the performance parameters of liquid rocket engines. He described how the best operating conditions within the constraints given could be arrived at using this algorithm. Varun Shivakumar (IITM) spoke of a model of heterogeneous quasi-1D model for composite solid propellants that were shown to predict the burn rate behaviour of a large number of propellants. The principal features of the new qualsi-1D model were elucidated and the features that give confidence in making good predictions were brought out. Joseph Mathew (IISc) presented the progress on LES by explicit filtering for problems of flows with shocks that are relevant to propulsion. The simulations of free supersonic jets, and jets impinging on wedge deflectors relevant to space launch vehicles were shown to be consistent with experimental results. Swethaprovo Choudhuri (IISc) presented the work on mitigating instability by subjecting the swirler in a combustor to a rotary motion such that the higher intensity turbulence and higher swirl number generated in the flame stabilization region might alter the flame position, structure and thereby mitigate thermo-acoustic instabilities. Several techniques, such as particle image velocimetry, high speed, intensified, chemi-luminescence imaging was utilized to observe the impact of swirler rotation rate on the dynamics of the unstable flame. The disruption of the flame– corner vortex interaction in outer recirculation zone due to an enhanced turbulent flame speed and increased swirl number are found to be responsible for the observed mitigation by the proposed strategy.

A. Mukhopadhyay (Jadavpur University) described the fundamental experimental and analytical studies on jet breakup phenomena pursued in his laboratory. The conclusion that these studies corroborate with linear stability is consistent with the literature. Srikrishna Sahu (IITM) spoke on the laser-based measurements related to droplet clustering in sprays with regard to their cause and consequence using a twin-fluid air-assist atomizer. The present work has obtained a comprehensive data set for droplet clustering statistics for different liquid mass loading (by varying the air and the liquid volume flow rates) on water spray. Krithika Narayanaswamy (IITM) spoke about chemical kinetic modelling of jet fuel surrogates using computational tools. The use of surrogates is to more accurately assess the role of specific components in jet fuels.

Bhaskar Dixit (Jain University) discussed the work he was doing on some puzzling situations encountered in diesel -on- water pool fire combustion along with his colleagues.

Experiments with the combustion of a diesel layer over water for a long burn time of 30 to 45 minutes showed that after the main fire there was a long pause and an unexpected substantive flare-up. Studies on small pool fires showed that the relatively small density difference between diesel and water allowed some diesel to sink and this would surface later when the density of water came down due to heating and caused the flare up. A. T. Sriram (M.S. Ramaiah School of Advanced Studies, Bengaluru) presented the computational results on a model can-type combustor's flow field that consists of combinations of interesting elementary configurations like jet-in-cross-flow, opposed jets and swirl. He described the results of computations based on k-ε model for turbulence and eddy dissipation model for combustion. Many details of can combustion process were described. K. R. Anilkumar (Fluidyn, Bengaluru) discussed the issues around the formation and explosion of a non uniform hydrogen-air mixture arising out of high pressure cryo-storage of hydrogen. Accidental leak of hydrogen from such storage systems, it's mixing with the ambient air resulting in the formation of a non-uniform hydrogen-air mixture, and ignition of this mixture was the subject of computational study. It was thought desirable to have a method which is relatively inexpensive and at the same time reasonably accurate, to evaluate the consequences of this potential risk, mainly in terms of the explosion overpressures. The method consisted of a combination of a 1D pseudo-source model for the expansion of the high speed hydrogen jet from the leak, 3D finite volume model for the dispersion of hydrogen in the ambient air and a modified flame-let turbulent combustion model for the burning of the resultant non-uniform hydrogen-air mixture. The modelling approach for this problem was the subject of much discussion, because it was not clear how a diffusive combustion process was being modelled like a turbulent premixed flame.

C. Prathap (Indian Institute of Space Science and Technology (IIST), Thiruvananthapuram), described experiments on combustion of natural gas to limit the emissions of nitric oxides that he had performed in a laboratory overseas. Rajesh Sadanandan (IIST) provided a broad brush overview of role of optical and laser diagnostic techniques in cryogenic propulsion research. The presentation was more in the form of a tutorial on the subject. Kowsik Bodi (IIT Bombay) described the studies he was performing on the computation of high enthalpy flows – magneto hydrodynamic flows at extreme conditions of temperature and pressure including fusion reactors with issues of arc stability. While foundations for computations are being laid, he indicated that more work needs to be done on this subject. Saurabh Sharma (IIT Bombay) spoke of the work with Sudarshankumar on flameless combustor for liquid fuels using direct injection. Characterization of droplet size distribution and exploration of the flameless combustion process were described.

On the second day, H. S. Mukunda (IISc) spoke about possible aspects of interest to future based on things remaining undone in the past as well as those other ‘good’ ideas from overseas. Specifically, he brought out that new hybrids with the promise of high performance should be coupled to single-stage-to-orbit vehicles for ensuring reliable safe option for cheap access to space (CATS). He further emphasized that the science missions of ISRO could be a part of technology mission for greater impact on the nation. Subhash chandran (DRDL) spoke on hypersonic propulsion for defense applications. He described their current efforts on a vehicle under development and some variants for meeting future demands. Sundar Krishnaswami (GE Aviation, Bengaluru) described development of the low emissions technology for propulsion combustors in GE Aviation. A brief history of the development of the twin annular premixing swirler (TAPS) approach to combustor design was provided, and comparison with the prevailing technology was highlighted along with the approach to the product certification. Lastly, forward-looking technology focus areas were described.

V. Narayanan (Liquid Propulsion System Centre, Thiruvananthapuram) described the issues and problems in the development of liquid rocket engines and the role played by P. J. Paul at several stages. Amongst others, he spoke of issues with ignition in the gas generator section at low mixture ratio, and combustion instability problems of the new design of semi-cryo engine under development now. He emphasized that more theoretical studies were needed in respect of vacuum ignition of steering engine, ignition of gas generator at low mixture ratio, saw tooth pattern observed in the main thrust chamber after hot test and combustion instability modelling of semi-cryogenic engines for providing strength in making critical decisions in short duration high risk development of these engines. Jayaprakash and Kiran Pinumall (VSSC) presented an analysis of pressure spikes in large segmented solid rocket booster motors used in PSLV vehicle. In the pressure history of these motors, small pressure spikes less than 1.5 atm with a sharp rise in pressure with rise duration less than 100 ms are observed occasionally between 50 and 100 sec of the motor burning time, these being consistent with momentary increase in vehicle acceleration. After consideration of various possibilities, these were traced largely to partial blockage of nozzle throat due to the passage of partially burned debris from the polyurethane slabs between segments of propellants. P. A. Ramakrishna (IITM) and Manu (VSSC) spoke of the idea of a new generation hybrid propellant combination not explored anywhere else – concentrated hydrogen peroxide and aluminium (70) – wax (30) combination as a high performance green propellant option for ISRO. While Ramakrishna brought out the results of performance improvements on the launch vehicle of PSLV class indicating a substantive improvement in payload capability varying from 15% and far more depending on the choices of elements, Manu described encouraging results of the very recently (previous day) conducted experiments on the system at VSSC.

S. M. Pande (High Energy Materials Research Laboratory (HEMRL), Pune) spoke extensively on the development of high energy propellants based on nitrate esters and RDX/HMX combinations needed in defense applications. He indicated that many aspects of development have been mastered at this time and these propellants will enter into propulsion systems soon. Aspects of safety of this class of propellants are being pursued presently. Akansha spoke of her preliminary studies with HEMRL on development testing of pulse induced instability in solid rockets of 40 kg class; these tests are being continued. H. S.

N. Murthy (IITM) and R. Perumal (Shri Harikota range) spoke on the experimental studies on ageing-related issues in composite solid propellants. Studies on the role of the additive-copper chromite on the burn rate of propellant were made by determining the role of the additive on ammonium perchlorate burn rate itself. Apparently, accelerated ageing showed decrease in burn rate. This was related to the decomposition of copper chromite due to thermal cycling over long periods of time. Jeenu (VSSC) spoke about the work he has done with his colleagues on the alumina particle size distribution in the combustion products of composite propellants with 18% aluminum loading, details that would be of value in modelling the combustion process and performance estimation. Using a large quench bomb the burnt particulate was collected in a solvent and the particle size distribution was measured using laser diffraction particle size analyser and the surface structure is examined by scanning electron microscope. The study showed that the particles are spherical and their sizes vary from 0.1 to 300 microns. The particles have tri-modal distribution with modes at 1, 4 and 70 microns.

Thomas (VSSC) described the safety issues in large scale solid propellant processing for PSLV and GSLV class vehicles. One aspect that came up was safety in the use of fluid energy mill for fine ammonium perchlorate grinding on which practices in ISRO and HEMRL seemed different. It was suggested that this aspect needs to be discussed further. B. Chellathura (ISRO Propulsion System Complex, Mahendragiri) described the production, storage and handling of storable and cryo-liquid propellants, namely, UH-25, di-nitrogen tetroxide, mono methyl hydrazine, MON-3 and hydrazine, liquid oxygen and liquid hydrogen. The major hazards associated with earth storable propellants were identified as toxicity, corrosivity, fire, explosion, air and water pollution. The major hazards with cryogenic propellants and the various safety precautions taken during storage and handling of these hazardous propellants were discussed in detail. Safety lessons learnt from incidents during testing of liquid propulsion systems at IPRC were also discussed for understanding the extreme hazardous nature of liquid propellants.

Holding the workshop at the VSSC, Thiruvananthapuram brought a large number of practitioners of rocket science and technology and allowed intensive discussions on current problems and ways of overcoming them. It is possible that a few collaborations and joint projects of relevance to aerospace combustion science will emerge from this workshop.

4rd Prof. P. J. Paul Memorial Combustion Researchers' Meet

24 - 25 February 2017
High Energy Materials Research Laboratory
Pune

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-awaited 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 Bhaskar 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 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.

5rd Prof. P. J. Paul Memorial Combustion Researchers' Meet

23 - 24 February 2018
DRDL
Hyderabad

Following the four successful workshops on combustion science held at Jain University, Bangalore in 2014, Beach Resort, Chennai in 2015, VSSC, Thiruvananthapuram in 2016 and HEMRL, Pune in 2017 (see refs 1 -3) the theme for the fifth workshop held on 23rd and 24th February 2018 at DRDL, Hyderabad was centered around missile development related problems. Even so, the variety in the nature of problems in combustion science was preserved in this workshop The workshop inaugurated by Director, DRDL had 21 presentations on novel aspects related to solid propulsion, high-speed air breathing propulsion, liquid jet breakup, combustion instability in gas turbine afterburner, fire research, premixed flame dynamics, biomass gasification, micro-combustion, high enthalpy flows and other combustion processes. The specialty of the workshop was that the participants numbering around a hundred including about twenty students were shown the integration activities of HyperSonic Technology Demonstrator Vehicle (HSTDV) to be flight tested soon and the test firing of Liquid Fuel RamJet (LFRJ) engine. The demonstration of a full scale liquid ramjet engine added a strong reality content to the workshop.

The first talk was presented by Prof. H.S. Mukunda on quantitative minimalism and scaling laws. Emphasizing the role of scaling laws in combustion science, an example of the behavior of pan fires and their prediction explored in recent times at Fire and Combustion Research Centre at the Jain University was presented. The simpler scaling approaches as well as more formal methodologies were presented to model the complexities of thermal conduction, Marangoni effects and the formation of convective flows leading to the hot zone inside the liquid fuel.

Prof. Bhaskar Dixit of Jain University presented the study of wind effect reduction for indoor pool fire tests through porous wall configuration. The role of ambient wind disturbances beyond 0.3 m/s was extracted by specifically designed experiments. The new design of a large indoor fire test facility (12 x 18 x 12 m) using porous wall was studied to understand the air entrainment behavior of the pool fire inside the fire test bay using large eddy simulation based NIST package of fire dynamics simulator software and favorable comparisons with experiments was demonstrated.

Much discussion on the choice of the porous wall design followed.

There were seven talks were on solid propellant combustion. Sri PVG Brahmanandan, Advanced Systems Laboratory (ASL), Hyderabad gave presentation on present issues and future requirements of the design and development of solid rocket motors for various strategic and tactical applications with burn times from a fraction of a second to 110 seconds, thrust levels from 250 kgs to 90 tons, diameters from a few tens of mm to a few thousands of mm and propellant mass from a fraction of a kg to a few tens of ton. The new technologies required to improve volumetric loading, rocket motor mass fraction and aging characteristics were highlighted.

Dr. R. Srinivasan of ASL presented the applications and challenges of pyrotechnics, pyro mechanisms and explosive ordnance and brought out the advantages of its uses in space craft, underwater vehicle systems, launch vehicles and missiles where weight is at a premium. Typical examples of rocket motor ignition, stage separation, fairing release, location aids, time delay trains and command destruct systems were presented. High reliability, life and functionality in extreme operational environments were considered a major challenge in the development of these systems.

Mr. Pandu Karanth of DRDL, Hyderabad presented the development of pulsing technique to demonstrate the combustion stability of solid rocket motor. He explained the experience of mild to severe oscillations sometimes, with significant shift of the mean pressure and higher harmonics of rocket motor chamber pressure in tactical systems in longitudinal modes. Pulser technique that was specifically developed for this project to suit the motor configuration was used extensively to demonstrate the solid rocket motor stability.

Mr. Arvind Kumar, HEMRL, Pune presented the necessity of nano-diamond synthesis and 3D printing to develop efficient solid propellants for defense and space applications. Also presented was the advantage of using 3D printing process in the casting of composite propellant. In a answer to a query, Prof. B.N. Raghunandan clarified that samples of composite propellant has already been made at IISc using 3D printing technique at the Indian Institute of Science.

Ms. Souraseni Basu of DRDL presented the numerical simulation using large eddy simulation for a motor port configuration with deep circumferential slots since it was found that there were significant unsteady pressure oscillations. It was also observed that due to significant blockage near the exit of the nozzle, new aerodynamic throat is produced upstream of the geometrical throat leading to oscillations. Change of geometry to remove the aerodynamic throat allowed reduced rocket motor pressure oscillations significantly.

Mr. K. Gnanaprakash and Prof. S. R. Chakravarthy of IIT, Madras discussed the unusual burning rate trends of certain nano-aluminized composite propellant formulations through sandwich combustion. Using high-speed, highmagnification imaging of combustion of sandwiches (made of alternating laminae of ammonium perchlorate (AP) and a matrix of hydrocarbon binder mixed with fine AP and nano-aluminium particles) in the 1–12 MPa pressure range. The lamina leading edge flames (L-LEFs) are seen to control the burning rates of the sandwiches even in the case of the fast burning matrix that contains nano-Al.

Mr. Nagendra Kumar and Prof. P.A. Ramakrishna of IIT, Madras presented the experimental and computational studies on the effect of ignition on LPDL of AP and AP with additives. It was shown that adding a small fraction of additives / impurities shifts the LPDL of AP drastically from 20 bar. Various intriguing aspects of the experimental observations were sought to be explained through computational studies focused on the effect of incident heat flux on the surface during ignition of AP along with the variation in thermal properties.

Dr. K. Ashirvadam, GTRE, Bangalore described the screech instability (high and audible frequency) problems caused due to unsteady coupling between the pressure oscillations and the combustion heat release in gas turbine afterburner. Various instability-driving mechanisms like vortex shedding coupled with fuel atomization, vaporisation and mixing of large-scale vortical structures from bluff body flame-holders were described. Screech mitigation studies like modification of a perforated liner, ventilation in the V-Gutter, and flame-holder modifications were presented. The high point of the presentation was very high speed videos of the mixing layer from the v-gutter edges.

Dr. S. Varunkumar, IIT, Madras discussed computational approaches to afterburner screech. His study showed that the growth of perturbations follows the classical instability pattern – exponential growth (linear instability) of pressure amplitude of standing wave (s) followed by a limit cycle. The role of bias flow on the pressure oscillations influenced by acoustics-heat release coupling was analysed using CFD framework. The work that is now at its early stage showed promise along directions aimed at understanding and resolving the problem in practice.

Dr. A.T. Sriram, M. S. Ramaiah University of Applied Sciences, Bangalore, presented a numerical flow simulation of compressor combustor combined configuration. The computational tool was validated for transonic flow in NASA rotor 37 compressor and can-type model combustor of Tay engine. Three blade passages of compressor rotor, four blade passages of compressor outlet guide vanes and about 30o sector of a propane fuelled combustor with one fuel injector was simulated with k-ω turbulence model and eddy dissipation combustion model. Apart from improvements on individual components through the simulations, they helped generation of performance map of the rotary system.

Prof. Avijit Kushari, IIT, Kanpur described an experimental program to study the dynamics of a liquid jet in a swirling flow of air and presented the results. The effect of liquid jet Reynolds number and momentum ratio on jet breakup and primary atomization with swirling air flow was studied under ambient pressure conditions. Further, a range of Weber numbers were considered to simulate the cross flow in annular passage at elevated pressures. The location of jet breakup, jet penetration, droplet size and velocity at different locations were estimated through detailed visualization with high-speed imaging and tomographic re-construction and PDPA (Phase Doppler Particle Analyser) system.

Dr. Santosh Hemchandra, IISc, Bangalore, presented the studies on coherent unsteady nature of flows with swirl stabilized premixed flames from the stand point of hydrodynamic stability analysis. Various shear layer modes - sinuous, varicose, ring, inviscid centre, viscous center mode - were detected. The influence of flame attachment on the stability of these modes was presented. Dr. Swetaprovo Chaudhuri, IISc, Bangalore, presented the genesis and evolution of premixed flames in turbulence. The mean local flame displacement speed of the leading points was shown to be related to the global turbulent flame speed, with a finite time-lag and the dispersing flame particles were shown to follow Bachelor's pair dispersion law related to the ratio of generation to annihilation time-scales.

The experimental investigation on dynamics and performance of a thermal pulse combustor was presented by Prof. Swarnendu Sen, Jadavpur University. The influence of inlet geometry and fuel composition on the variation of frequency of operation was investigated. The pulsating behaviour is inferred to be due to complex interaction of hydrodynamic (vortex shedding) and acoustic effects. Hysteresis behaviour was observed in both amplitude and frequency for specific cases.

Sri Rajnikanth, DRDL, explained the concept of hypersonic glide and fixed point scramjet operation for long range hypersonic mission. The status of various critical technologies; namely, high lift aerodynamic configuration design, high temperature materials for airframe and scramjet combustor, descent phase trajectory and endgame are presented. Sri Rolex Ranjith explained the Dual Combustion Ramjet (DCR) engine which is composed of a subsonic dump combustor, a tandem supersonic combustor, and two separate inlets. DCR engine can operate at wide operating Mach numbers (3.5 to 6.5) and thus enhances the HCM's air-breathing mode operation and thereby reducing the overall system weight and makes the vehicle capable of air launch is considered for air launched option. Sri G. Vijay Kumar, DRDL presented the thermal analysis for both airframe and hydrocarbon fuelled scramjet combustor. Preliminary analysis shows that the hydrocarbon fuel can be used for cooling the combustor with Niobium alloy material and silicide coatings. Candidate materials for remaining portion of the configuration were expected to be C-SiC composites, Inconel, Nimonic alloys and titanium.

Dr. Afroz Javed, DOTE presented the DNS studies of confined mixing layers of dissimilar gases with large temperature difference pertinent high speed propulsion system. Two and three dimensional simulations were carried out using higher order numerical scheme to understand the structure and evolution of supersonic confined mixing layer of similar and dissimilar gases. The major outcome of this study are that the growth rates of dissimilar gases are affected far more by large temperature difference than by compressibility, and that the growth rates of compressible shear layers formed between dissimilar gases are better predicted using k-ε turbulence model.

Dr. Kowsik Bodi, IIT Bombay, presented the two-dimensional finite volume computations of high enthalpy hypersonic flow over a cylinder and flat plate. The predicted temperature variation along the stagnation line for hypersonic flow ($T\infty$ = 196 K) over a cylinder and computed velocity profile for a laminar hypersonic flow over a flat plate compare well with available literature data. Although, curve-fit method for the thermodynamic and transport properties was computationally inexpensive, composition-based method has the advantage that it can be applied to any mixture of gases.

Dr. NKS Rajan, IISc, Bangalore, presented the recent activities at CGPL, IISc in the areas of bio-waste treatment processes. The injection of superheated steam mixed with secondary air enhances the hydrogen fraction in the producer gas from 18% to 26%, an option for cleaner combustion. The biogas generated from bio-methanation based treatment plants from sewage and industrial effluent need removal of H_2S for power generation. Industrial plants were designed to handle H_2S concentrations ranging from 0.5 to 10% to provide clean energy generation of about 4 MW electrical power.

Prof. Sudarshan Kumar, IIT, Bombay presented the development of single and dual micro-combustor based thermoelectric generator with high power density (~0.14 mW/mm^3) and conversion efficiency of 4.7 % with liquefied petoleum gas as the fuel. The compactness and high output power with significantly improved conversion efficiency appears to have potential for portable micro-scale power generators for remote stand-alone applications.

One of the important conclusions of the final discussion was that future meetings could be on a theme basis and should involve far more vigorous discussions on the current problems in research and development to bring in students to understand the on-going research areas.

Snaps from the Past

A compilation: CGPL, IISc

With current students

Professor Paul receiving the "FICCI Annual Award for Outstanding Achievement in Research in Science and Technology" from the Prime Minister, during the Annual General Meeting of FICCI held in Delhi on 28 December 2005.

1998 - Addressing Conference on Waste Management

2002 -With Karnataka Minister Mrs. Nafeesa Fazal

2002 - Falicitatiting Prof. Dattaguru, JATP

2004 - With Central Minsiter Mr Muthannavar

2005 - In a Meeting of Experts with UNIDO