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C2Or2B-01: [Invited] Design and Development of a State-of-the-Art Cryogenic Testing Platform for Liquid Hydrogen Applications

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Liquid hydrogen (LH_2) is emerging as a promising alternative to fossil-based fuels to reach net-zero targets by 2050 due to its purity, high volumetric density compared to compressed gas, and versatility. However, designing infrastructure to handle LH_2 presents significant challenges, necessitating rigorous testing at cryogenic temperatures (20 K) to evaluate the materials and systems involved. This study introduces a novel, state-of-the-art cryogenic testing platform comprising five newly designed equipment to evaluate cryogenic properties.

Cryogen-Free Mechanical Testing Cryostat (MTC): The MTC is precisely engineered to comply with industry standards, including ASTM E8/E8M, ASTM D638, and ASTM D3039/D3039M, to meet the specific requirements of tensile testing for a range of materials including metals, plastics and composites. The system features a tensile loading capacity of 50 kN and integrates a two-stage Gifford-McMahon (GM) cryocooler within a customized self-reacting tensile testing jig. In addition to the cryostat design, this study presents the novel gripper design adopted for this cryostat system and its performance in both room and cryogenic temperatures.

Composite Leak Testing Cryostat (CLTC): The CLT setup enables the quantification of cryogenic gas leakage under thermal stress and uniaxial loads applied to cylindrical composite specimens. Given the critical importance of cryogenic composite tanks in LH_2 and space applications, real-time measurement of gas leakage caused by failures such as microcrack generation and delamination is essential. The CLTC system measures the gas leakage due to 1 atm pressure difference while incrementally increasing loads. This equipment not only assures the serviceability of the composite but also allows the determination of the maximum stresses that can be tolerated by the material with specified leak rates.

Magnetic Refrigeration Testing Setup (MRTS): Magnetic refrigeration is a promising technology for reliquefying LH_2 boil-off from tanks to reach zero boil-off conditions. This lab-scale MRTS facilitates the testing and optimization of magnetocaloric materials, refrigerants, and magnetic systems enabling industrial-level upscaling. The equipment can accommodate both permanent and superconducting magnet systems up to 8T and uses supercritical helium as the working fluid, circulating at a flow rate of 0.2 g/s, extendable to 7 g/s. The design incorporates two GM cryocoolers, an actuator system, and four heat exchangers to replicate real-world conditions. The novel transient numerical modelling approach adopted in this design evaluates the regenerator bed's performance integrated with heat exchangers and an external magnetic field, quantifying the hydrogen liquefaction rate.

Cryogen-Free Thermal Conductivity Testing Cryostat (TCTC): Thermal conductivity is one of the critical properties in cryogenic infrastructure design for both structural and insulation materials. Comparative to traditional boil-off measuring techniques of thermal conductivity measurement, utilization of GM cryocoolers embedded cryostat allows more flexibility in measurements. However, designing the equipment with minimal thermal noise interfering with the readings is challenging. TCTC is designed based on the concept of C1774 and it can accommodate both cylindrical and flat samples. Finite element modelling used in TCTC design facilitates the precise analysis of thermal interferences during measurements and enables the development of effective strategies to mitigate potential failures.

Hydrogen Liquefier: The lab-scale hydrogen liquefier integrates a GM cryocooler with an ortho-para hydrogen catalytic bed, enabling efficient hydrogen liquefaction. Gaseous hydrogen will be taken in at a mass flow rate of 10 mg/s within a range of pressures of 35 −50 bar in the equipment. A 100 L LH2 dewar is incorporated into the cryocooler system for the storage of liquid hydrogen with minimum boil-off.

Overall, this study presents the innovative designs and design methodologies adopted in developing this advanced cryogenic testing platform. Additionally, it delves into the insights gained and the challenges encountered throughout the equipment design and development process.

Author: KRISTOMBU BADUGE, Shanaka (The University of Melbourne)

Co-authors: COSTA, Susiri (The University of Melbourne); Mr PREMAKUMARA, Amila (The University of Melbourne); GUNARATHNE, Upeka (The University of Melbourne); Mr SAKVITHI, Hasala (The University of Melbourne); Mr NAZEEM, Is Haaq Ahamed Mohamed (The University of Melbourne); Mr THEJAN, Sachintha (The University of Melbourne); Mr LOCHANA, Harindu (The University of Melbourne)

Presenter: KRISTOMBU BADUGE, Shanaka (The University of Melbourne)

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