Seminar

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Institute for Plasma Research

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Title: Design and Development of Cryogenic Turboexpander, Indigenous Helium Liquefier and its Major Components

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Abstract

Cryogenic turboexpander is a device that is used for refrigeration and liquefaction cycles of various gases. The nozzle and radial inflow turbine are the critical components of such systems, and its performance has a significant effect on the overall efficiency of the system. Therefore, an optimum design procedure of such components is necessary to provide the maximum thermal efficiency and better cooling capacity.

In this work, the design methodology of a non-axisymmetric convergent nozzle using a curve-fitting approach is proposed. The curves used for designing the nozzle are based on a combination of fifth and third-order polynomial at upper and lower surfaces respectively. Numerical simulations are conducted to visualize the fluid flow and thermal characteristics for two cryogenic fluids, nitrogen and helium at three different inlet pressure and temperature using computational fluid dynamics (CFD) tool ANSYS CFX®. Numerical results are further validated for medium and low-pressure helium by comparing it with the available experimental data.

After design of a convergent nozzle, an effective one-dimensional design methodology of a radial inflow turbine by considering different loss correlations is presented using nitrogen as a working fluid. A Sobol sensitivity analysis is carried out to determine the sensitivity index of major non-dimensional design variables, which have a significant effect on efficiency and total loss of the turbine. The optimal range of important non-dimensional variables such as blade speed ratio, pressure ratio, ratio of hub and shroud radius to turbine inlet radius are predicted using artificial intelligence techniques. This approach improves the turbine efficiency and power output by 4.00% and 18.90% respectively as compared to the existing model developed at NIT Rourkela. The three-dimensional numerical simulations are carried out to investigate the fluid flow, thermal characteristics, and critical properties that are extremely difficult to determine experimentally at different cryogenic temperatures. The obtained numerical results are validated with the experimental results.

The design procedure of nitrogen turboexpander is extended for high and low-pressure (16 and 4.5 bar) inlet fluids at different operating temperatures. The various losses obtained during the design process are discussed in detail. After that, a comparative numerical analysis is performed to visualize the effect of fluid flow and thermal performance at different spans and streamwise location of a nitrogen turboexpander.

The one-dimensional design is further extended for a helium turbine, where the optimal range of the most significant non-dimensional variables is identified through sensitivity analysis and artificial intelligence methods. Based on this approach, three turbines and nozzle (turboexpander) systems are designed for three operating conditions (high, medium, and low pressure). After that, a comparative numerical analysis is carried out to visualize the flow field and thermal performance of helium turboexpander at three different operating pressure and temperature. Furthermore, the numerical results are validated with the available experimental and numerical data from the literature. The variation of Mach number, Reynolds number, Prandtl number, static entropy, static enthalpy, temperature, and pressure inside the turboexpander are characterized at different spans and streamwise locations. The study also demonstrates the flow separation region, vortex formation, tip leakage flow, secondary losses, and its reasons along with the spanwise location.

Finally, the experimental test-rig is developed to understand the thermal performance of a nitrogen turboexpander at different operating pressure (6 −8 bar), rotational speed (60,914−120,529 rpm), inlet temperature (150−120 K), and mass flow rate (0.01−0.09 kg/s). The experimental results are presented to examine the isentropic efficiency, temperature drop, enthalpy drop, and power output of the turboexpander at different mass flow rate, rotational speed, and pressure ratio. The maximum temperature and enthalpy drops are 29.46 K and 34.5 kJ/kg respectively which is obtained for case 1 at a rotational speed of 119,614 rpm (75% of the designed rotational speed) and the mass flow rate of 0.08 kg/s and pressure ratio of 3.85. Based on the experimental data, an artificial intelligence model is developed to predict the optimal range in which the turboexpander has maximum isentropic efficiency and temperature drop. Also, the error analysis is carried out to measure the effectiveness of experimental parameters.

VECC is involved in the development of indigenous helium liquefier. The work aims to develop the helium liquefier and its important components at VECC Kolkata. The work starts with the process simulation of the designed modified Claude cycle-based helium liquefaction system. The energy and exergy analysis of the cycle at different operating modes has been completed. In the proposed helium liquefaction cycle, four plate-fin type heat exchangers were used which play a very crucial role in determining the thermodynamic performance of the liquefaction system. Therefore, the design, simulation, fabrication, and testing of these heat exchangers are very important. The design and numerical simulation have been incorporated to analyze their thermodynamic performance using Aspen EDR®. The heat exchangers are fabricated at Apollo Heat Exchangers Pvt. Ltd., Mumbai. The inspection (dimensional and physical configuration) and testing (external and inter-stream) of the fabricated plate-fin heat exchanger have been completed using a mass spectrometer leak detector (MSLD) at room temperature. The procedure is repeated after the thermal cycling of heat exchangers up to liquid nitrogen temperature at VECC.

The three-dimensional model of piping and instrumentation (P&I) diagram of the helium test setup is also completed and based on which the pipe connection and welding have been started. The adsorber vessel (80 K & 20 K) is also designed and fabricated. It is used in the assembly of helium test set-up. In addition, the fabrication of external piping connection of the cold box with the helium compressor and Oil Removal System is also developed. Component assembly work of the cold box for the test setup is completed. After the testing, the performance of the warm and cold turboexpander will be determined at different operating conditions.

The P&I diagram of final helium liquefier is also completed. Based on P&I diagram, a three-dimensional model of the piping of cold box comprising four heat exchangers and two turbo-expanders has been completed.

Keywords: Turboexpander; Numerical and experimental analysis; Sobol sensitivity analysis; Artificial intelligence techniques; Cryogenic fluids