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Feasibility Studies on the Cooling of Hybrid Rocket Nozzles using Supercritical Nitrous Oxide

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Abstract

The fundamental requirement in the development of Single-Stage-To-Orbit (SSTO) system is to implement a nozzle contour with altitude compensation characteristics which leads to increase in aerodynamic efficiencies. Also, the reusability of the SSTO is another challenge due to the thermal fatigue loads experienced by the launch vehicle. To overcome such challenges, cooling of the throat of the hybrid aerospike nozzle becomes essential as the nozzles experiencing greater heat fluxes at the outlet. In 2009, Patrick suggested the use of nitrous oxide (N_2O) in sub-critical regime as an active coolant for the nozzle component cooling. However, using sub-critical N_2O causes more complications by introducing multi phase flow and heat transfer characteristics. The science of supercritical fluids is the only possible solution which consists of homogeneous single phase chemistry. So, in the present study, Supercritical N_2O (T_C=309.58K, P_C=7.254MPa) is proposed as an active coolant for the cooling of aerospike nozzles. Thermophysical properties of N_2O are compared in both sub-critical and supercritical state and also an attempt has been made in order to correlate some of them as a continuous function of temperature and pressure. Statistical parameters are used to ensure the accuracy of developed correlations.

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Keywords: SSTO, Hybrid Rocket Nozzles, Nitrous Oxide, Regenerative Cooling, Aerospike Nozzles.

1. Introduction

Reusable single-stage-to-orbit (SSTO) missions are the future of rocket science and technology and lot many efforts have been made from past decades to make it possible in reality [1]–[7].

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To achieve SSTO, light weight and high performance propulsion systems required to be developed. The basic requirement in the development of SSTO is to have a nozzle contour with altitude compensation characteristics which would lead to increase the aerodynamic efficiencies of the launching vehicle. The development of hybrid rocket propulsion systems having aerospike nozzles are being in process of invention and widely tested by the researchers all over the globe [1]–[5]. It has been reported that hybrid rockets are safer to produce and economic in manufacturing as compared to the production of liquid fueled rockets. Different types of oxidizers have been employed in the development of hybrid rocket technologies. However, the critical challenges are related with the cooling, design complexity and manufacturing cost. Various studies on cooling of aerospike nozzles used in hybrid rockets have been done in the past and available in literature [1]–[11]. Regenerative cooling of hybrid rocket nozzles in which saturated nitrous oxide (oxidizer) has been used in order to reduce the heat loads on the nozzle throat [2], [3]. It was concluded that this cooling method can be suitable for the reusability of nozzle design. However, N2O at the saturated pressure may cause the complexity due to multi-phase flow and heat transfer phenomenon. To avoid such complexities, homogeneous fluids such as supercritical fluids can only be the solution to be used as coolants. Over the last decade, the community working in the field of refrigeration systems finds supercritical fluids useful due to existence in single phase for various applications [12]–[18].

Therefore, in this present work, an attempt has been made to introduce a novel concept of using supercritical nitrous oxide (SCN2O) as a coolant for hybrid rocket nozzles. While incorporating SCN2O as coolant, its properties (isobaric heat capacity, thermal conductivity) would expect to change with respect to temperature and pressure in the SC regime. Further, these properties would help in estimating the heat transfer rates while coolant is flowing through the channels. Therefore, it becomes crucial to know about these properties variation in the SC regime. Also, the thermophysical properties of the liquid nitrous oxide (LN2O) and SCN2O have been compared over a wide range of temperature and pressure. From 2-D and 3-D plots, dramatic variations in properties near the critical point have been observed and some interesting conclusions have been made from the study. In order to use the property data in future while generating fluid property codes at the time of computational studies, an attempt has been made to correlate thermal conductivity of SCN2O as a function of both temperature and pressure. Since a severe variation has been noticed in specific heat near the critical point therefore property has been correlated as a function of temperature only for different isobaric processes. Also to ensure the accuracy of developed correlations, statistical parameters have been computed which shows excellent accord with data extracted from NIST Database [19].

2. Methodology & estimation of thermo-physical properties of LN2O and SCN2O

To attain the thermophysical property data of LN2O and SCN2O (critical pressure and temperature 7.254MPa and 309.58K [20] respectively) NIST Database [19] has been used. Property data of SCN2O has been extracted from the NIST Database at and above the critical pressure (7.254-8.254MPa) for a wide range of temperature ranging from 309.58K to 470K. Property data for LN2O has been obtained at pressures ranges from (1.2 to 6.2MPa) and temperature ranges from (185-309K) in the subcritical regime. Estimation of thermodynamic property of LN2O and SCN2O is modeled with Helmholtz equations of state (EOS) explicit in energy, the modified Benedict-Webb-Rubin EOS, and an extended corresponding states (ECS) model and transport property with either an ECS method or the friction theory method [20].

3. Results and discussions

This section has been divided into two parts: in first part comparison between the thermophysical properties of LN2O and SCN2O has been done by plotting 2-D plots (Figure 1and Figure 2) and 3-D plots (Figure 3), in the other section correlation has been developed as a function of temperature and pressure for the SCN2O in order to estimate its thermophysical property (thermal conductivity) for the future use while generating computational codes for heat transfer/cooling analysis of hybrid rocket nozzles. Since drastic variations have been observed in isobaric specific heat near the critical region, it becomes complicated to correlate the property with a single correlation as a function of temperature and pressure because of the shifting of pseudocritical point to higher temperatures with respect to rise in pressure. Therefore, an attempt has been made to correlate specific heat as a function of temperature (309.58-