Investigations on Micronozzle for Satellite Propulsion and Gas Mixture Separation

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by

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Abstract

Micronozzles operating with vacuum exit conditions find applications in satellite propulsion systems and aerodynamic separation processes. Research on flow characteristics of micronozzles is currently dominated by micro-thruster applications, followed by its use for gas mixture separation. Uniformity in the flow structure to obtain optimum thruster performance is the prime objective of the former, while the latter demands highly non-uniform species distribution of the flowing mixture. The literature review reveals that as the length scales are of the order of micrometres, carefully built apparatus and measurement systems are required to obtain data reasonably. Due to the scarcity of experimental data concerning flow parameters, a new experimental arrangement is developed using Interferometric Rayleigh scattering to measure the exit velocity of the nozzle. The generated experimental data is used along with literature data to validate the computational models developed in the current work. Flow regimes from the nozzle throat to the nozzle exit can change from near-continuum to rarefied, and therefore both continuum and kinetic approaches have been used for computational simulations. The classical N-S with linear slip model, DSMC method, and a hybrid N-S/DSMC based on the continuum breakdown concept are employed for the numerical simulations. The effect of divergence half angle, throat depth, and expansion ratio are analysed in detail to address the conflicting findings reported in the present literature. Results show an optimum divergence angle and length, maximizing the performance for a specific operating condition and nozzle size. It is noted that the inconsistencies in the literature are mainly due to exploratory efforts of small data sets. Re is very low as the nozzle size decreases to the nano-scale, and the subsonic layer fully occupies the divergent nozzle section even at very high-pressure differences. The results show that the performance is significantly influenced by the wall's thermal conditions. The study highlights the differences in flow behaviour between micro and nano-scale nozzles at various operating conditions. Based on numerical data obtained in this work, a new correlation is proposed to predict the thrust per unit width for micronozzles. A numerical investigation of the aerodynamic separation process associated with converging-diverging 2-D planar micronozzles shows that the enrichment of the heavier/lighter species near the axis/wall is significantly affected by the nozzle size. The aerodynamic separation effect is created mainly by (i) streamwise separation produced by the velocity slip between species

and (ii) lateral separation created by the curving of streamlines. The streamwise separation effect is higher in smaller nozzles creating heavier species concentration at the axis. The lateral separation effect increased with increased throat size. The result is a higher, lighter species concentration in the peripheral regions of the bigger nozzle. The lateral separation effect is found to be influenced by the nozzle divergent section shape. The divergent section with trumpet shape, truncated bell, and conical with high divergence are preferred for higher species separation performance. The results show that the presence of a heavier carrier gas deteriorates the separation performance. The backpressure conditions at the nozzle exit play a significant role in the curvature of streamlines at the nozzle lip. For curved micronozzles, streamwise separation, lateral separation, mass diffusion, and thermal diffusion can affect the separation performance. Further influencing the separation performance are factors such as the nozzle shape, wall temperature conditions, molecular mass ratio, and inlet mole fraction of the species. The results of this research will aid in the creation of improved designs for micronozzles utilized in satellite propulsion and aerodynamic separation processes.