論 文 の 内 容 の 要 旨

論文題目 Flow Field and Performance Analysis of Common Channel Added to Coaxial Nozzles for Future Hypersonic Vehicles

（将来の極超音速機用の同軸ノズルに付加された共通ダクトの流れ場と性能解析）

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For the development of future hypersonic passenger transportation, it is required to develop air-breathing propulsion system that can operate in flight stages at various Mach numbers ranging from subsonic, supersonic through hypersonic speeds. It can be achieved by combining two or more propulsion systems. A simple configuration for combining multiple propulsion systems can be co-axial engine configurations. Such configuration had been applied historically in the SR71 black bird engines, which integrates the Pratt and Whitney J58 engine with a ramjet engine. Co-axial configuration was also proposed for the hypersonic air breathing flight as the Synergistic Air-Breathing Rocket Engine (SABRE). In the SABRE engine configuration, an air-breathing rocket engine is combined with ramjet as an axisymmetric co-axial configuration. However, there is limited fundamental understanding of single or dual mode operations of combined co-axial nozzles in hypersonic environment and its impact on thrust performance and what will be the effect of adding a common channel that have the potential of augmenting the thrust of the coaxial jets sharing a common total external area. The current study focuses on experimental and numerical investigation of co-axial supersonic air jets discharging into hypersonic flow environment from the base of axisymmetric slender body in single (either central or surrounding jet) or dual (both jets) operation modes through a proposed common channel. in order to study the augmentation of total thrust from both the nozzles, the wall of outer nozzle have been extended so that central and surrounding jets interact in a confined passage before exhausted into the low-pressure hypersonic external flow. In this research, this confined passage is termed as common channel. Single and dual operation modes for co-axial nozzles with common channel can be descried as; when a single supersonic jet exits at the base of hypersonic vehicle, low environmental pressure at high altitude would cause the supersonic jet to be under-expanded most of the time during its flight and subsequently leads to loss of partial thrust due to the need of further expansion. The extended straight passage can reduce the expansion level, which may lead to the improvement in the thrust performance. However, extending length of straight passage can also add the weight and can increase the length of vehicles. The longer extended common channel can also lead to reflection of waves on the wall, including expansion front, depending on expansion level and Mach disk. Mach disk may also form before the end of common channel, which may lower the performance of the system. Hence, it is important to understand the effect of common channel length on thrust for single (either central or surrounding only) and dual operational modes to optimize the length. It is expected that the optimum length of common channel can improve thrust performance by reducing the expansion level in each single operational mode and provide some common region to augment thrust in dual operation mode.

The main objective of current study is to evaluate the performance of co-axial nozzle in hypersonic environment and to study the effect of the common channel to enable thrust augmentation for various operation modes. The study is conducted by qualitative experimental flow visualization of shock structure for single and dual operation modes with common channel. Further, numerical simulations are performed for cases to evaluate the performance of system by thrust calculations. Further parametric study has been performed for resized model by isentropic as well as CFD simulations for various central and surrounding jet Mach numbers without common channel. Further, CFD simulations have been performed to study the effect of common channel on flow field and thrust performance.

Coaxial engines exhaust jets flow has an impeded complexity in regards how to model the exhaust jet flows as well as the flow structure within and outside the body, not to mention the effect of using a cold airflow in the experiment to simulate the actual hot exhaust engines jet flow; In the current research the experimental model is an axisymmetric slender body having a jet generator in it, is consider to simulate a combined cycle engine for the hypersonic flight. The jet generator is composed of two coaxial axisymmetric nozzles and a short common channel, in which two jets meet before being exhausted at the base of the body. The experiments have been performed for small slender body kept in hypersonic Mach 7 flow, which consists of two high-pressure chambers and two co-axial nozzles at the base: central nozzle (Mach 4) and surrounding nozzle (Mach 2.8) along with extended common region, called common channel. Schlieren images have been captured for single and dual operation modes. Axisymmetric numerical simulations have been performed for further understanding of the flow interactions and were validated with experimental images. Later, the parametric study has been performed for resized model with various exit Mach numbers for central and surrounding jets along with effect of no common channel and with common channel for various operation modes, that is Single central jet operating only, surrounding jet operation only, and dual operational mode in which both jets are in operation.

The main motivation of current study was to evaluate performance and flow-field of two coaxial jet system operating in hypersonic environment with the addition of a common channel to the coaxial exhaust flow nozzle. Initially the experimental study have been conducted for small slender body having two high-pressure chamber and having central and surrounding nozzle with common channel, which exhausted the supersonic flow in hypersonic environment. Although the experiments model can only provide qualitative Schlieren images, the numerical simulations are also conducted to evaluate performance and compare flow field with experiments in order to validate CFD results qualitatively. Single point pressure measurement on the wall of common channel was also performed to compare with numerically computed pressure in various single and dual operation modes. Further, parametric study based on 1-D isentropic calculations and CFD simulations have been performed for slightly enlarged slender body with two co-axial supersonic jets without common channel to understand the effect of varying Mach numbers of central and surrounding jets. The main findings in case of no common channel by 1-D and CFD studies is that the central and surrounding should have same total allowable exhaust area at dual jets operating mode in order to achieve higher total thrust than sum of thrust from individual jets operating in single operation mode.

The introduction of short and long common channel in single and dual operation modes have significantly modified the jet flow-field but the main advantage in performance is only observed in single mode surrounding jet operation. At Mach 2 surrounding jet single mode operation, the thrust have increased 12-14 % with short and long common channel than no common channel case. However, in central jet single mode operation, the thrust have decreased by 12-14 % in presence of short and long common channel. These differences in performances of single operation modes are because of difference in flow structures in presence of common channel for conical jet (in central jet only operation) and annular jet (in surrounding jet operation). The presence of common channel have a negligible effect on thrust performance when operating dual jets together. However, it can also be noted that the best distribution of exit area is when both jets central and surrounding have the same or similar injection Mach numbers exhausted into the common channel.

Suddenly expanded nozzle is well studied for the case of single jet expanding in higher area channel. However, the effect of surrounding jet on a suddenly expanded central jet in hypersonic environment has not been studied in the literature according to the knowledge of authors. The current study will evaluate the performance of common channel in following cases: single operation mode with central jet expanding in the common channel, surrounding jet expanding in the common channel, and the effect of the common channel when both jets injected in the common channel. The main objective of current study is to evaluate the performance of co-axial nozzle in hypersonic environment and study the effect of the common channel to enable thrust augmentation for various operation modes. The study is conducted by qualitative experimental flow visualization of shock structure for single and dual operation modes with common channel. Further, numerical simulations are performed for cases to evaluate the performance of system by thrust calculations. Further parametric study has been performed for resized model by isentropic as well as CFD simulations for various central and surrounding jet Mach numbers without common channel. Further, CFD simulations have been performed to study the effect of common channel on flow field and thrust performance.

As per the current research the use of the common channel is recommended for a coaxial jet with a surrounding jet that have a relatively low exit Mach number with under-expanded jet condition, on the other hand; when having such system of coaxial jets sharing the same exhaust exit area; most of the common area should be utilized by the central jet nozzle; in such descried configuration the common channel will be effective during which the surrounding jet only is in operation. A possible scenario of an effective use of the common channel is when having a coaxial configured RBCC (Rocket Based Combined Cycle) in which the common exit area will mainly used by a central rocket engine that will be active during the subsonic and in space flight regime, and during the hypersonic regime the surrounding jet (can be set as a scram jet) only will be in operation; in which by using the common channel the expansion of the exhaust flow will be improved resulting in an increase in thrust.