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Tip-to-tail numerical simulation of a hypersonic air-breathing engine with ethylene fuel

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End to end CFD simulations of external and internal flow paths of an ethylene fueled hypersonic air-breathing vehicle with including forebody, horizontal fins, vertical fins, intake, combustor, single expansion ramp nozzle are carried out. The performance of the scramjet combustor and vehicle net thrust-drag is calculated for hypersonic cruise condition. Three-dimensional Navier–Stokes equations are solved along with *SST-k–ω* turbulence model using the commercial CFD software *CFX-14*. Single step chemical reaction based on fast chemistry assumption is used for combustion of gaseous ethylene fuel. Simulations captured complex shock structures including the shocks generated from the vehicle nose and compression ramps, impingement of cowl-shock on vehicle undersurface and its reflection in the intake and combustor etc. Various thermochemical parameters are analyzed and performance parameters are evaluated for nonreacting and reacting cases. Very good mixing (∼98%) of fuel with incoming air stream is observed. Positive thrust–drag margins are obtained for fuel equivalence ratio of 0.6 and computed combustion efficiency is observed to be 94 %. Effect of equivalence ratio on the vehicle performance is studied parametrically. Though the combustion efficiency has come down by 8% for fuel equivalence ratio of 0.8, net vehicle thrust is increased by 44%. Heat flux distribution on the various walls of the whole vehicle including combustor is estimated for the isothermal wall condition of 1000 K in reacting flow. Higher local heat flux values are observed at all the leading edges of the vehicle (i.e., nose, wing, fin and cowl leading edges) and strut regions of the combustor.

1. Introduction

Hypersonic propulsion can be used very effectively for high-speed transport, national defense, space access etc. and scramjet engine is the preferred choice for such applications. Curran [1] reviewed the scramjet engine development in various countries including United States, Russia, France, Germany, Japan and Australia during 1960–2000. Although, research on scramjet engines started way back in the 1960, flight testing of scramjet-powered airbreathing mission is attempted only in the last decade. Many technical issues need to be addressed before scramjet engines are used in any practical vehicle. Different fuel injection systems namely struts, pylons or cavities [2] are used for scramjet engine. Injection, mixing and burning of fuel within the combustor length are some of the major challenges in the realization of a flight worthy scramjet combustor. For volume limited applications and for $M_\infty < 8$, hydrocarbon fuel has many advantages. Vaporization, mixing and combustion of a kerosene fueled scramjet combustor using struts are studied in detail [3] to deliver the required thrust for a hypersonic flight vehicle. The successful Mach-7 flight test of hydrogen fuelled scramjet powered hypersonic flight vehicle (X-43A) [4,5] and Mach-10 flight of hydrocarbon fuelled scramjet vehicle (X- 51A) [6] in the last decade demonstrated the capability of airframe-integrated scramjet engine and hypersonic air-breathing vehicle design tools. A Hypersonic Flight Experimental Vehicle, (Hyflex) was flight tested [7] in 1996 as the precursor engineering demonstrator of HOPE (H-II Orbiting Plane) program of Japan. The development of a small-scale, 4.2 m long dual-mode scramjet-powered, experimental hypersonic vehicle [8] to demonstrate the capability of prediction of aero-propulsive thrust–drag balance is also reported by MBDA, France and ONERA.

Paneerselvam et al. [9] explained the development of an autonomous operation of a scramjet combustor at hypersonic flight speed (∼6.0–6.5) for a flight duration of about 20 s. Although, air launch is an attractive option for hypersonic air-breathing mission by carrying the scramjet integrated vehicle along with the booster to certain altitude using a high powered aircraft followed by acceleration to the desired Mach number by the booster and scramjet engine testing as was done in X-43, ground launch option is considered for the proposed mission. A solid rocket motor

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booster is being used to carry the scramjet integrated cruise vehicle from ground to the desired altitude and scramjet integrated vehicle would be separated and tested. Liquid kerosene is considered as fuel of the scramjet engine considering the volume limited applications of the mission. The fuel is injected in the incoming air stream through series of struts placed in the combustor flow path to have proper fuel distribution in the whole combustor width. Scramjet combustor configuration was changed in several iterations to meet the requirement of the hypersonic vehicle. Number of ground test in connected pipe mode tests [10,11] and numerical simulations [12,13] were carried out to finalize the number of struts, their positions and fuel injection locations to have benign thermal environment and optimum performance of the flight sized engine.

Ethylene fuel also provides an attractive option for scramjet engine as the injection is performed in gaseous phase and its simpler chemical structure enables easy ignition. Tam et al. [14] proposed optimum strut design from their numerical studies of gaseous ethylene fuel/air mixing characteristics with several strut fuel-injection schemes in Mach 2 inflow condition in a rectangular flow path. Malsur et al. [15] performed three-dimensional reacting simulations for fight worthy scramjet combustor with ethylene fuel injected from a row of struts placed in the flow path for the ground test condition to guide the experimental work. Engine performance in terms of mixing (nonreacting flow with fuel), combustion efficiencies, and thrust is evaluated from simulation results for different fuel equivalence ratio.

Although, CFD tools were used very extensively for the design and analysis of various subsystems of hypersonic airbreathing engine and to understand many complex reacting/non-reacting flow issues like laminar/turbulent transition on forebody, aerothermodymamics, surface heating, high speed combustion etc in hypersonic flight regime; complete vehicle analysis integrating both external and internal flow together is very limited in open literature. For high speed airbreathing system, the vehicle's undersurfaces act as a propulsion device and the aerodynamics and propulsion are so strongly coupled that any demarcation of the subsystem is difficult. The coupled external–internal flow simulations would enable the designer to look at the problem in an integrated way in which thrust minus drag and other performance parameters could be obtained directly from the simulation. Voland et al. [5] reported a tip-to-tail post-test CFD analysis for X-43; but, much detail is not available in the open literature. Malsur et al. [16] carried out an end-to end simulation of a liquid kerosene fueled hypersonic air breathing vehicle with strut based fuel injection system. The simulation demonstrated the positive thrust–drag margin and the computed performance parameters are being used by vehicle designers for mission planning.

In the present work, an integrated reacting-nonreating flow simulation for a hypersonic airbreathing vehicle with gaseous ethylene fuel is performed. Three-dimensional Navier–Stokes equations are solved along with SST-k–ω turbulence model using the commercial CFD software *CFX-14* [17]. Computations are carried out on block structured grid generated by *ICEM-CFD* [18] grid generator package. Infinitely fast rate chemistry is used for combustion modeling. Combustor performance and vehicle aerodynamic parameters are evaluated from the simulation results. Heat flux distribution at various vehicle surface and combustor is also estimated from the integrated simulation considering aerodynamic heating as well as the fuel burning in the combustor.

2. Geometrical details of hypersonic vehicle

The schematic of the hypersonic cruise vehicle is shown in Fig. 1. The total length of the vehicle is 7*W*, where *W* is width of cruise vehicle. There are two ramps placed ahead of the intake entry. The length of the intake is about 1.3*W* including intake cowl with the cross-sections of 0.7*W* × 0.3*W* and 0.7*W* × 0.1*W* at the entry and exit respectively. The total length of the combustor is 2.4*W*. The combustor is having varying cross sections. Initially, it has an isolator of 0.1*W* to reduce the non-uniformity of the intake flow which is followed by divergent sections with three different angles. A solid wall is placed at 0.3*W* downstream from combustor entry in the middle of the combustor, which makes combustor into two modules. Four struts are provided in each module in such a manner that one module is the mirror image of the other with respect to the middle wall. The struts are straight and cross section remains constant along the height of the combustor are also shown in the same figure. Nine injection holes with 1 mm diameter are provided on either side of the strut to inject the gaseous ethylene fuel inside the combustor. First strut is placed near to the middle wall while 4th strut near to the side wall. The single expansion ramp (*SER*) nozzle with upward divergence angle is attached at the exit of the combustor A bottom nozzle cowl with downward deflection is attached with the bottom wall at exit of the combustor to provide stability and control force for the vehicle.

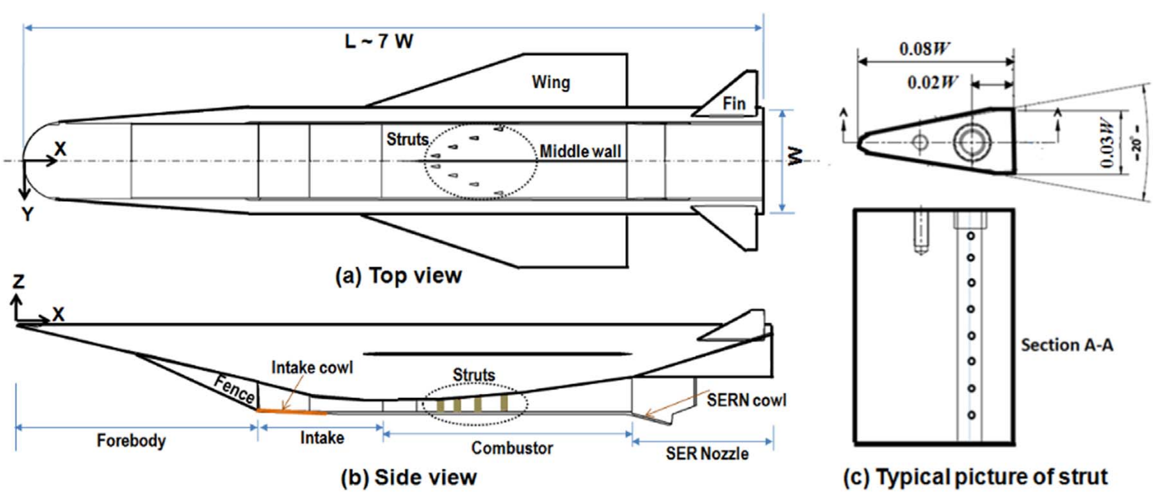

Fig. 1. Schematic of hypersonic cruise vehicle with integrated scramjet propulsion system.