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Combustion characteristics and turbulence modeling of swirling reacting flow in solid fuel ramjet

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ABSTRACT

This paper reviews the historical studies have been done on the solid-fuel ramjet engine and difficulties associated with numerical modeling of swirling flow with combustible gases. A literature survey about works related to numerical and experimental investigations on solid-fuel ramjet as well as using swirling flow and different numerical approaches has been provided. An overview of turbulence modeling of swirling flow and the behavior of turbulence at streamline curvature and system rotation are presented. A new and simple curvature/correction factor is proposed in order to reduce the programming complexity of SST-CC turbulence model. Finally, numerical and experimental investigations on the impact of swirling flow on SFRJ have been carried out. For that regard, a multi-physics coupling code is developed to solve the problems of multi-physics coupling of fluid mechanics, solid pyrolysis, heat transfer, thermodynamics, and chemical kinetics. The connected-pipe test facility is used to carry out the experiments. The results showed a positive impact of swirling flow on SFRJ along with, three correlations are proposed.

1. Introduction

1.1. Ramjet motor

Ramjet or flying stovepipe is an air-breathing propulsion engine that contains no moving parts in which the flight is based on ram air compression thereby fixed components are used to compress and accelerate intake air using ram effect. Then, the thermal energy is imparted to the gas from burning fuel (solid, liquid, or gas) after that the exhaust gas expands through the nozzle produces forward thrust. However, ramjet needs another propulsion system (e. g., booster rocket) to accelerate it to a high speed and then starts the operation cycle. There are three main types of ramjets in terms of fuel type, gaseous-fuel ramjet (GFRJ), liquid-fuel ramjet (LFRJ), and solid-fuel ramjet (SFRJ); and two types in terms of combustion, subsonic combustion (ramjet) and supersonic combustion (scramjet) which are provide supersonic and hypersonic flights, respectively. Generally, ramjet can serve in both civilian and military applications as in space launch vehicle, gun projectile, missiles, and aircraft with range from boost-to main propulsion system (see Figs. 1 and 2).

Solid-fuel ramjet (SFRJ) is the simplest and most reliable subsonic combustion propulsion system using hydrocarbon solid fuels, because the fuel is stored and burned in the combustor, the combustion is self-controlled according to the flight conditions and the internal design of the engine. SFRJ basically consists of air intake system, combustion chamber, and nozzle in which the combustor contains flame-holder and cylindrical solid fuel grain (see Fig. 3).

When an SFRJ flies at a lower altitude as the air there is dense it ingests large mass flow rate of air with high values of air mass flux, pressure, and temperature in the combustion chamber. The requirement of correspondingly high fuel flow rate for this large mass flow rate of air can be met since the regression rate of fuel is proportional to air mass flux, pressure, and temperature. At higher altitudes as the air there is thin, the SFRJ ingests low mass flow rate of air with reduced values of air mass flux, pressure, and temperature in the combustion chamber. The requirement of reduced fuel flow rate at this condition can again be met because of the above regression rate dependency [2].

In military applications, SFRJ can serve in both missile systems and gun-launched projectiles. Figs. 4 and 5 show the profiles of four types of SFRJ powered missiles/projectiles reported from USA [3,4]. Fig. 4b depicts the 229 mm SFRJ-powered missile (air-to-air, air-to-surface, and surface-to-surface) with rocket motor booster. Meanwhile, Fig. 5 represents SFRJ-assisted gun-launched projectiles; type 75 mm with spin-stabilized and fin-stabilized SFRJ propelled gun-launched projectile.

A typical construction of an SFRJ-assisted gun-launched projectile is

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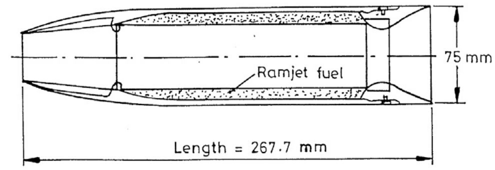
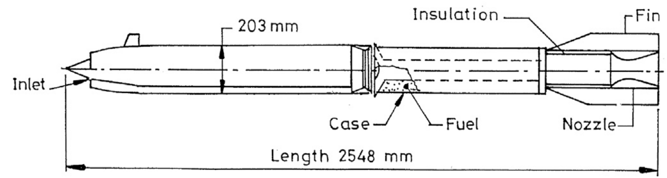
Fig. 1. U.S. Talos/Vandal operational missile (1950 today) [1].



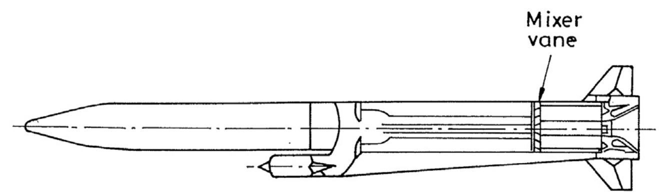
(a) Non-bypass with vane mixing device.



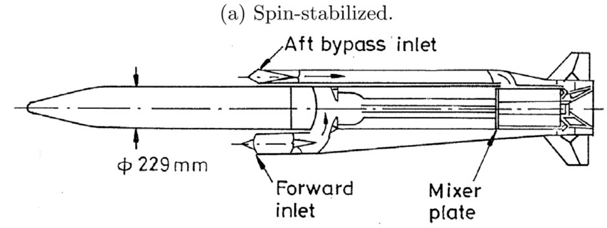
(b) Bypass with simple orifice mixing device.

Fig. 4. SFRJ-powered missiles [3].

Fig. 2. U.S. D-21 operational reconnaissance vehicle carried by SR-71 Blackbird [1].



(a) Spin-stabilized.



(b) Fin-stabilized.

Fig. 5. SFRJ-assisted gun-launched projectiles [4].

provided in Fig. 6 which comprises of two parts; the front part and rear part. The first one has a diameter less than the gun barrel diameter while the rear part contains the actual engine in which the fuel grain is stored. The outer diameter of the rear part is less than that of the front part to provide an annular passage between the gun barrel and the engine-exterior.

The operation of this projectile is as follows; on firing the gun, high pressure and high-temperature gasses are evolved by the gun propellant. These gasses fill the annular passage between the gun barrel and the engine-exterior, and the space within the engine; and, forcing the piston, push the projectile. The fuel grain in SFRJ is thus exposed to high temperature (> 3000 K) and very high-pressure combustion gasses during the projectiles travel within the gun barrel. This travel time is very short, a few milliseconds. The projectile is then ejected into the atmosphere at a supersonic Mach number around or greater than 2. From this instant, the sudden depressurization within the SFRJ, the opening of intake by the release of the frangible diaphragm and the one-way valve, and the gushing of air into the SFRJ take place in very quick successions in a matter of a few milliseconds.

Air flows into the SFRJ with a stagnation temperature of 540 K or more, and through external and internal deceleration processes its Mach number is decreased to a value around 0.3– 0.4 at the air inlet of the rearward step. Having been exposed to high temperature and very high-pressure gasses within the gun barrel and now on being exposed to high-temperature air, the fuel grain may get automatically ignited. The hot combustion products thus formed are accelerated through the nozzle with exit momentum greater than the inlet value, thereby producing thrust. The range of projectile, therefore, can be considerably enhanced with the assistance of an SFRJ [2]. Since SFRJ combines high propulsion performance with a very low degree of system complexity, it seems to be an attractive method to increase the flight range and/or the flight velocity of gun launched projectiles. For instance, co-operative study program on SFRJ propulsion for gun-launched projectiles (Fig. 7) was conducted by Sweden and Netherlands by means of designing, manufacturing and flight testing a generic SFRJ propelled projectile [5].

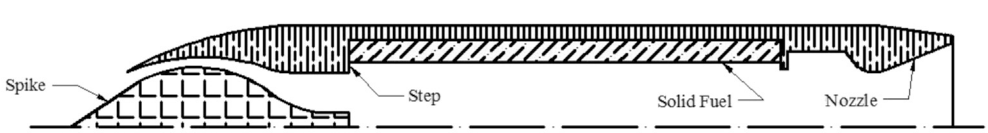


Fig. 3. Solid-fuel ramjet components.