Numerical Simulation of Combustion Enhanced Mixing Gaseous Oxidizer Hybrid Rocket Engine

By

Mohammad Bahaa Eldin Shaker

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE
In
Aerospace Engineering

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Prof. Aly Abd El-Fattah Hashem

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Title of Thesis: Numerical Simulation of Combustion Enhanced Mixing Gaseous Oxidizer Hybrid Rocket Engine

Key Words: combustion, mixing, numerical simulation, cfd, hybrid rocket

Summary:
Hybrid rocket engines incorporate propellants in two different phases. The main shortcomings of hybrid rocket motors is their poor propellants mixing and limited fuel regression rate.

This work has two main objectives, the first is to establish and validate numerical simulation models capable of predicting the performance of hybrid rocket motors. The second is to propose approaches to enhance propellants mixing and regression rate. Finally, the overall motor performance, and the effectiveness of these approaches is evaluated.

The diaphragm mixing enhancement approach proved to yield better performance relative to basic default configuration without enhancements, but the performance of the swirling oxidizer configuration is found to be superior to both cases.

Ansys Fluent finite volume CFD solver was used for simulation, multiple RANS based turbulence models were tested, k-epsilon standard was eventually selected. Multi-species analysis involving propellants was made. Eddy dissipation models was used for combustion modeling.

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I would to like to acknowledge the endless support and guidance of Prof. Ali A. Hashemin his efforts to make the body of this work possible. I am also grateful for Dr. Ahmad Tawfikfor his valuable assistance and guidance.

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Nomenclature

a: regression rate coefficient
A_e: nozzle exit area
A_t: nozzle throat area
C^*: characteristic velocity
D_a: Damköhler number
E: total energy
$\vec{F}$: External or gravitations body forces
g: gravity acceleration
h: enthalpy
h_j^0: Enthalpy of formation of species j
I: Unit tensor
I_{sp}: Specific Impulse
$\vec{J}_j$: Diffusion flux of species j
k: turbulence kinetic energy
K_{eff}: effective thermal conductivity, $k+k_t$
n: regression rate exponent
P_{c1}: pressure at sensor near the injector
P_{c3}: pressure at sensor near the nozzle
r: regression rate
R: reaction rate
R_j: Volumetric rate of creation of species j
S_m: mass source term
S_{ct}: turbulent Schmidt number
T: thrust
$\vec{v}$: velocity vector
Y_i: species mass fraction
$\bar{\bar{\tau}}$: Stress tensor
μ: Molecular viscosity
ρ_l, ρ_g: liquid and gas density
ϵ: turbulence dissipation rate
μ_t: turbulent viscosity
$\nu'_{i,r}$: stoichiometric coefficient for reactant $i$in reaction r
$\nu''_{i,r}$: stoichiometric coefficient for product i in reaction r
$k_{f,r}$: forward reaction rate constant for reaction r

Subscripts

c: combustion
e: nozzle exit
f: fuel
g: gas
ox: oxidizer
p: propellants
t: nozzle throat
l: liquid

Abstract

Hybrid rocket engines incorporate propellants in two different phases, in contrast to pure liquid or pure solid rocket engine. Hybrid rockets usually involve liquid or gaseous oxidizer, and solid fuel.

Hybrid rockets offer many advantages over solid propellant rockets, such as safer propellants handling, less sensitivity to grain mechanical failures, the possibility of throttling or shutting down the engine and higher specific impulse.

In addition, it offers a simpler feed system design compared to liquid propellant rockets. However, their specific impulse performance is generally lower than liquid rockets.

This work proposes a Computational Fluid Dynamics approach to predict the performance of hybrid rocket engines using Ansys Fluent finite volume solver. Combustion with emphasis on turbulent mixing between liquid oxidizer (nitrous oxide) and solid fuel (paraffin wax) is investigated.

Turbulence models K-epsilon standard, K-epsilon RNG (Re-Normalisation Group), k-omega standard and k-omega SST (Shear Stress Transport) were investigated, it was found that K-epsilon standard turbulence model results were in good agreement with experimental data.

Both Finite-rate combustion model and Eddy-Dissipation combustion model were investigated, it was found that Eddy-Dissipation model is more appropriate for modeling the combustion phenomena, this was justified by the fact that combustion in flows with large Damköhler number was governed by the turbulent eddy frequency in the presence of a much smaller chemical timescale.

A major shortcoming of hybrid-propellant rocket motors is their low regression rate due to diffusion controlled mixing. A turbulence inducing device has been introduced in order to enhance turbulent mixing and yield higher regression rate.

Regression rate data were employed using experimental data available in literature. The emerging flow field change has been studied and was found to yield better turbulent mixing between propellants. The results were found to be in good agreement with the experimental data available in literature.

Chapter 1: Introduction

1.1. Overview

Hybrid rocket engines incorporate the oxidizer and fuel in two different phases, where oxidizers are usually liquid or gaseous, while fuels are solid.

Figure 1-1shows a conventional hybrid rocket engine consists of a liquid oxidizer tank. Sometimes a pressurizing tank, using gas such as nitrogen; is added upstream a liquid oxidizer tank.

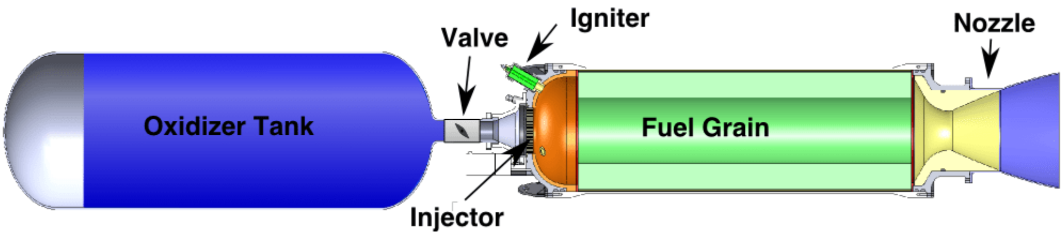

Figure 1-1 Schematic design of hybrid rocket engines

The liquid oxidizer then passes through the injector responsible for the atomization process of the oxidizer. The ignition system induced heat evaporates fraction of the oxidizer as it passes through the solid fuel grain. Successful ignition initiates the combustion process and the turbulent flame spreads along the grain. Subsequently, the whole mixture is expanded through a convergent-divergent nozzle generating thrust.

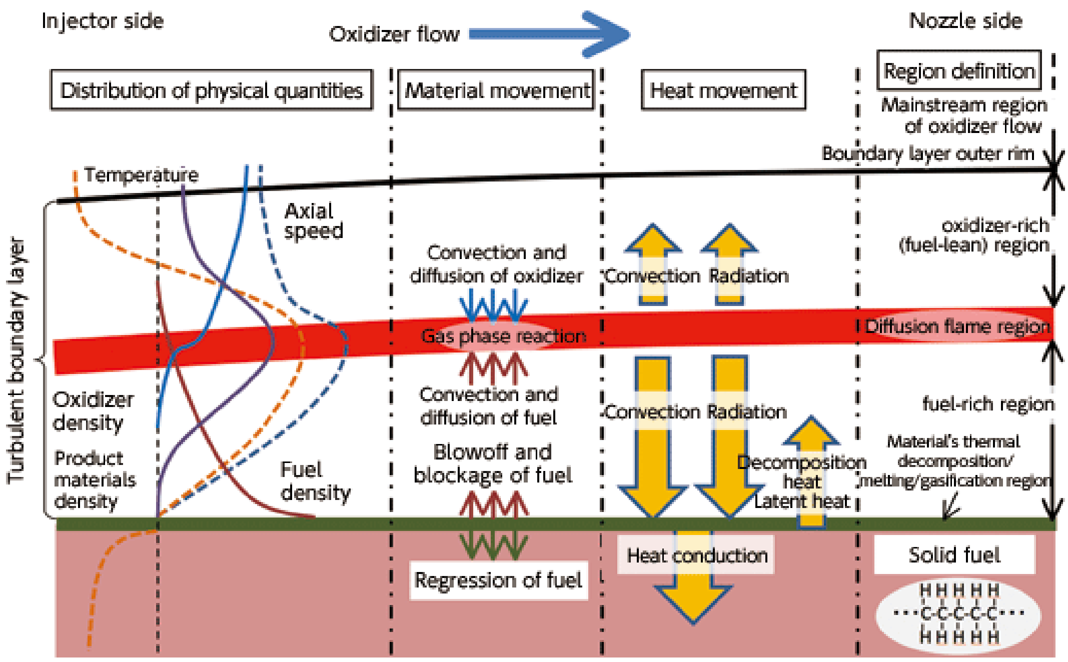

Figure 1-2Turbulent diffusion flame combustion near solid fuel grain

Hybrid rocket engines offer the following advantages over purely liquid propellants rocket engines:

- Safer handling due to less intimate contact between fuel and oxidizer.
- Denser fuel reduces the system's overall volume.
- Less complex feed system is required.
- Failures in hybrid engines tend to be more benign.

There are also many advantages over purely solid propellants rocket engines:

- Less explosion hazard and safer handling.
- Less sensitivity to grain fractures and mechanical failures.
- Hybrid engines offer more controllability through throttling and shut off capabilities.
- Higher specific impulse.

A major shortcoming of hybrid rocket engines is their low regression rate, which is the rate by which solid fuel evaporates (pyrolysis). Recent research efforts have attempted to address this issue using different approaches such as:

- Fuel Additives:
  Incorporation of reactive high energy fuels such as aluminum further increases regression rate, specific impulse and fuel density.

- Multi-port and non-conventional port fuel grains:
  It is possible to design a fuel grain with multiple ports, and each one of these ports may have its cross section profile designedin a manner that increases the side area of the port as much as possible, however, such designs introduce issues regarding grain and web integrity during the burn.

- Using fuels that form a liquid layer during combustion:
  Some fuels form a low viscosity liquid layer adjacent to solid fuel grain during burning, the liquid layer introduces a new component to the regression rate, called the "entrainment" component. This leads to the entrainment of liquid fuel droplets from the liquid layer to the grain gaseous core.

- Mixing enhancement:
  It is possible to use oxidizer swirling injection for, or turbulence inducing devices, such as the diaphragms investigated in this work.

1.2. History

- First work on hybrid rocket engines started on 1930s in Germany and USA. A 10 KN motor using gaseous nitrous oxide and coal was tested. In 1940s, researchers started using LOX (Liquid Oxygen) along with many different fuels.

- ❖ AMROC (American Rocket Company) developed the largest hybrid rocket engines ever built during 1980s and early 1990s. A 1.1 MN engine was tested, it consisted of LOX (Liquid Oxygen) as oxidizer and HTPB (hydroxyl-terminated polybutadiene) as fuel.
  SpaceDevcompanylater acquired all the assets of AMROC, they built SpaceShip One and Spaceship Two, experimental air-launched rocket-powered aircrafts with suborbital flight capability.

Figure 1-3 SpaceShipTwo during ascent

1.3. Objectives

The objective of this work is to investigate via numerical modeling approach using commercial CFD codes to predict and analyze the performance of hybrid rocket engines. Furthermore, mixing enhancement approaches are introduced and the changes in flow field and overall performance are investigated.

This work starts with proposing numerical models suitable for hybrid rocket engines simulation, including turbulence and combustion models. An experimental campaign conducted by Grosse[1] is used to validate the numerical simulations.

Afterwards, mixing enhancement approachesand their effects on the flow field are investigated and validated using Grosse's experimental data[1].

1.4. Thesis Outlines

- ❖ Chapter one contains a brief introduction of engine characteristics, thesis objective and outline.
- ❖ Chapter twodiscusses literature review and recent research of hybrid rocket engines numerical simulation.
- ❖ Chapter three contains the relevant governing equations, simulation definition, selection of simulation models and mesh convergence study.