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EVALUATION OF NOZZLE GEOMETRY IMPACT ON SOLID PROPELLANT MOTOR SHOCK CHARACTERISTICS

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ABSTRACT

Multiphase simulation models are crucial for running accurate fluid models of solid-propellant rocket motors. Using an Eulerian fluid simulation, which analyzes a control volume and determines the properties of a fluid inside a volume based on space and time, a UA1205 rocket motor using UTR3001 propellant will be simulated. Aluminum particles of 1 micron in diameter will be included within the engine exhaust, making it a particle laden gas flow. The rocket motor geometry will have ridges added in order to determine the effects of the new geometry on the velocity, shock characteristics, and noise levels. The Computational Fluid Dynamics (CFD) program STARCCM+ will be used to evaluate the nozzle behavior.

NOMENCLATURE

F = force ***[N]***
F_D = drag force ***[N]***
F_L = lift force ***[N]***
C_D = drag coefficient
g = gravity acceleration $[m \cdot s^{-2}]$
m = mass ***[kg]***
p = pressure ***[Pa]***
Re = Reynolds number
T = temperature ***[K]***
u = velocity $[m \cdot s^{-1}]$
h = enthalpy $[J \cdot kg^{-1}]$
d = particle diameter ***[m]***
r = jet radius ***[m]***
r_t = nozzle throat radius ***[m]***

Greek letters

α = volume fraction
ρ = density $[kg \cdot m^{-3}]$
λ = thermal conductivity $[W \cdot m^{-1} \cdot K^{-1}]$
σ_h = the turbulent thermal diffusion Prandtl number τ = shear stress tensor $[kg \cdot m^{-1} \cdot s^{-2}]$

Subscript

i = axis index p = particle
t = turbulent

1. INTRODUCTION

Solid propellants have long been used in the aerospace industry as an accompaniment to liquid propellants. These types of propellants can find use in many parts of the aerospace sector, such as the military and space fields, for their thrust capabilities, cost-effectiveness, shelf life, and simplicity of design. As opposed to liquid propellant motors, nearly all solid propellant motors can be stored without fear of degradation, making them useful for long-term stockpiling and storage. Even though liquid propellants can reach higher specific impulse ranges [1], solid propellant booster rockets continue to play a large role in the design of rocket craft for their higher thrust capabilities, making up the initial launch stage and ensuring heavy payloads are able to reach escape velocity. The UA1205 boosters used in several Titan rockets utilized UTR-3001 propellant, consisting of 16% aluminum (Al) as the fuel, ammonium perchlorate (NH4CLO4) as the oxidizer, and 84% polybutadiene acrylonitrile (PBAN) as the binding agent [2]. The byproducts of this combustion process, specifically aluminum particle agglomerations, can influence the velocity profile of the exhaust flow, making more complex multiphase simulation flows necessary.

2. BACKGROUND

In this simulation, a Eulerian multi-phase model was used to simulate the flow of gas and aluminum particulates exiting the nozzle geometry. The Eulerian multi-phase modeling approach is solved as a continuity and mass conservation (Eq. 1), momentum balance (Eq.2), and energy conservation equation (Eq. 3) for each separate phase. The Euler approach is usually less accurate than the Lagrangian method, as instead of tracking individual particles and their paths through a period of time it instead analyzes flow by determining the behavior of the fluid property functions of space and time.

$$\frac{\partial}{\partial t}\alpha_k\rho_k + \nabla \cdot \alpha_k\rho_k u_k = \sum_{j=1}^{N}\left(\dot{m}_{jk} - \dot{m}_{kj}\right) \dots (1)$$

$$\frac{\partial}{\partial t}\alpha_k\rho_k u_k + \nabla \cdot \alpha_k\rho_k u_k^2 = -\alpha_k \nabla p + \alpha_k\rho_k g + \nabla \cdot \alpha_k(\tau_k + \tau_k^t) + M_k \dots (2)$$
$$M = F_D + F_L + \sum_{j=1}^{N}(\dot{m}_{jk}u_j - \dot{m}_{kj}u_k) \dots (3)$$

$$\frac{\partial}{\partial t}(\alpha_k\rho_k h_k) + \nabla \cdot (\alpha_k\rho_k u_k h_k) - \nabla \cdot \left[\alpha_k\left(\lambda_k \nabla T_k + \frac{\mu_t}{\sigma_h}\nabla h_k\right)\right] = Q_k \dots (3)$$

3. MATERIALS AND METHODS

The converging-diverging nozzle geometry used in this simulation was based on the dimensions of the UA1205 rocket used by NASA [3]. The nozzle geometry can be found in Figure 1.

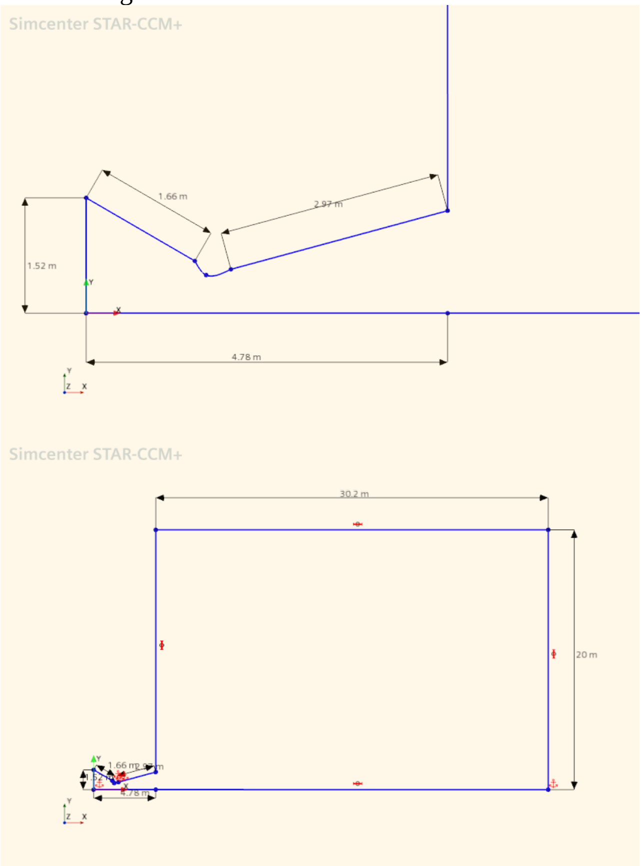

Fig. 1/2 Rocket Nozzle and Test Chamber Geometry

The test chamber geometry can be seen in Figure 2. For the nozzle, the left-most boundary was set as a stagnation inlet with a varying pressure based on a time chart created using BurnSim, inputting the fuel properties required from Martin and CALSPAN technical documents [2,4]. The upper geometry of the nozzle is set as walls. The three walls of test chamber were set as pressure outlets, with the bottom boundary being a symmetry plane. This 2D Eulerian simulation was run with the following models

- Adaptive Time Step
- Eulerian Multiphase (EMP)
- Gradients
- Implicit Unsteady
- Multiphase
    - Eulerian Phases
        - Constant Density
        - Flow
        - Ideal Gas
        - Laminar
- Multiphase Equation of State

- Multiphase Interaction
    - Phase Interactions
        - DMP-Physics Continuum
        - Drag Force
        - Heat Transfer
- Phase Coupled Fluid Energy
- Phasic Turbulence
- Solid Pressure
- Two Dimensional

The abrasive particles were set to be aluminum, with a diameter of .1 microns and the volume fraction of the aluminum particulates was set to 16% [5]. In the process of building and testing geometries and physics continua models, the base size of the mesh was set to .25 m in order to significantly reduce computation time. Once a simulation model was deemed to be working correctly, base sizes were pushed down to .01 m to get a more accurate representation of gas/particulate flow. These two meshes can be seen below in figures 3 and 4. The low-quality mesh has 2240 cells, 4354 faces, and 2405 vertices, while the high-quality mesh 71,398 cells, 139,794 faces, and 74,437 vertices. A time step of 1×10^{-4} seconds was used in both simulations.

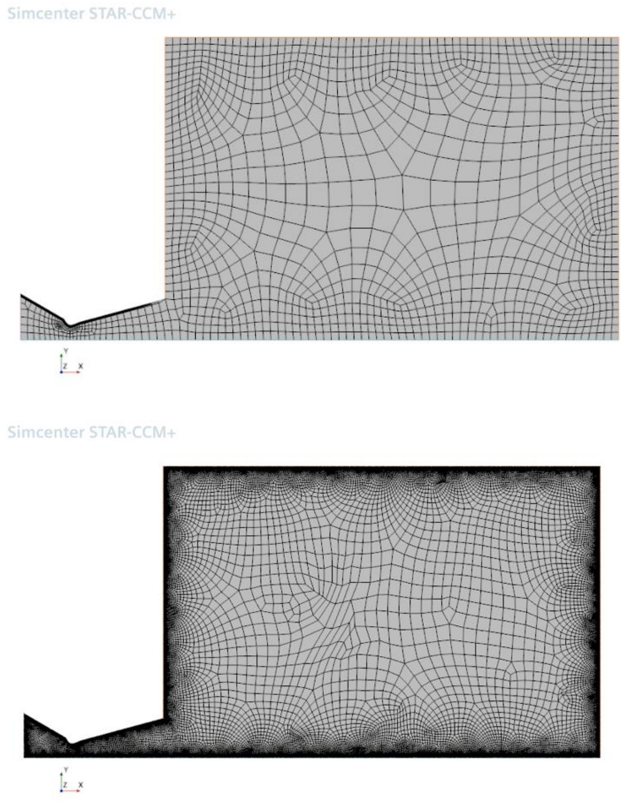

Fig. 3/4 Low- and High-Quality Meshes

In order to see the impacts of nozzle geometry on the supersonic shock, a ridged geometry was to be introduced into the upper slanted edge of the nozzle geometry, with a series of congruent semicircles lining the nozzle wall.

4. RESULTS AND DISCUSSION

The results of the fluid simulation for the ridgeless UA1205 solid motor can be seen below in figure 5 below.

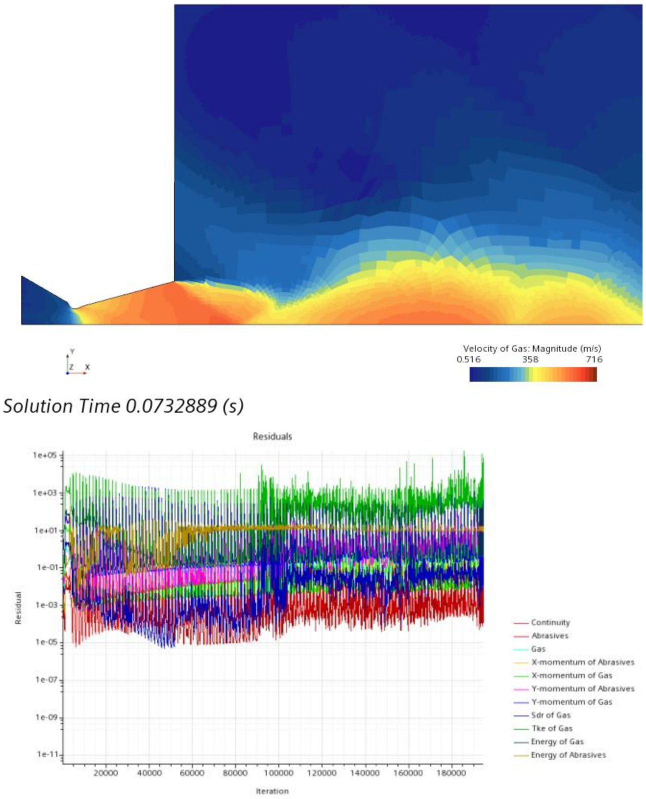

Fig. 5/6 Velocity Field of Nozzle Exhaust

The velocity field seems to be working well, but more run-time would be needed to see if the residuals begin a downward trend and correctly judge the simulations. Unfortunately, before a final comparison could be drawn between the ridged and ridgeless UA1205 nozzles, it was decided that the simulation files would be rebuilt in a steady state physics continuum as opposed to the current unsteady build. This would allow a faster convergence of a final fluid simulation result independent of the time and would make the research itself more streamlined. A working steady state simulation could not be successfully built in time to produce results.

5. CONCLUSION

This research project is far from completed and will have to continue as a steady state model is properly built. It is currently unknown why a steady state model does not work under the current physics continua settings, so testing and rebuilds will have to be done in order to ascertain why. Until this is done, analyzing the volume fraction of aluminum agglomerations will be extremely inefficient as the fluid simulations would have to run its full course to accurately model the aluminum concentration, which would take hundreds or thousands of hours.

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REFERENCES

[1] NASA. (n.d.). *PROPELLANTS*. NASA. https://history.nasa.gov/conghand/propelnt.htm

[2] Martin Company 1965, *TITAN III/MOL COMPATIBILITY STUDY (U)* , viewed 29 June 2021 https://www.nro.gov/Portals/65/documents/foia/declass/mol/138.pdf

[3] NASA 1971, *A STUDY OF PERFORMANCE AND COST IMPROVEMENT POTENTIAL OF THE 120-IN.-(3.05 M) DIAMETER SOLID ROCKET MOTOR*, viewed 29 June 2021 https://ntrs.nasa.gov/api/citations/19720007150/downloads/19720007150.pdf

[4] CALSPAN 1974, *DEVELOPMENT OF A MINIATURE SOLID PROPELLANT ROCKET MOTOR FOR USE IN PLUME SIMULATION STUDIES*, viewed 29 June 2021 https://ntrs.nasa.gov/api/citations/19740021096/downloads/19740021096.pdf

[5] Kovalev, O. B. (2002). Motor and Plume Particle Size Prediction in Solid-Propellant Rocket Motors. *Journal of Propulsion and Power*, *18*(6),1199–1210. https://doi.org/10.2514/2.6079