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Experimental and Numerical Investigation of Aluminum Particle Combustion in Solid Rocket Combustion Chambers

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Abstract

A numerical investigation of the combustion characteristics of Al particles in solid rocket motor is performed to obtain more accurate motor performance prediction. Combustion of solid propellant with Al particle emerges two-phase gas flow. The two-phase flow is analyzed by using FLUENT. The gas phase, the Navier-Stokes equations are solved numerically and for the particulate phase Lagrangian reference frame is used to model particles in discrete phase and their trajectories. Numerical model was validated with Ballistics Test (BATES) motor. The designed solid rocket motor was fired to test numerical model. Firings were conducted facilities of TUBITAK SAGE.

1. Introduction

Aluminum (Al) particles are usually added to solid propellants to increase the specific impulse of the solid rocket motor (SRM). However, incomplete combustion of aluminum may cause decrease in combustion efficiency. Aluminum particles may collect in aft end of the motor and some Al particle flow through the nozzle which causes decrease in specific impulse.[1] Therefore, Al particle combustion behavior should be accurately known to accurately predict motor performance.
In the present study, the aluminized solid propellant combustion and the SRM performance are investigated using both numerical and experimental techniques. In the numerical study, the two phase and reacting flow solution approach is developed by using Ansys FLUENT. In solid-fuel combustion modeling with aluminum particles, a Navier-Stokes solver Eulerian reference frame for modeling the continuous gas phase and a Lagrangian reference frame was used to model the particles in a discrete phase of the particles to simulate the combustion physics of aluminum burned gas oxidizing agent. The aluminum particles are sprayed into the combustion chamber so that the initial speed of the fuel surface is equal to the fuel combustion rate, and the aluminum particle combustion modeling is defined in the solver[2].[4] With this approach and analysis method, it is aimed to estimate the combustion chamber temperature accurately.
For accurate modeling of combustion reactions, estimation of particle distribution and size are important for analysis accuracy and for this purpose collecting aluminum particles in combusted gas and comparing the aluminum particles properties with numerical analysis is important requirement. In the experimental study, an aluminized propellant solid rocket motor is statically fired at the test stand of TUBITAK SAGE. Particles are collected in the plume by means of a steel probe. Sticky copper tape is wrapped around the probe.
The static firing tests of a rocket motor, which contains aluminized propellant, are conducted in the static rocket motor test stand. The thrust and the combustion pressure are measured to validate numerical study. Particles are collected to adjust particle behavior in combustion chamber. The collected particles are examined under electron microscope to measure Al particle diameters.

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2. Numerical Investigation

For many years, aluminum has been added as an extra energy source to solid propellant. Aluminum has high enthalpy of combustion and low burning rate. The combustion of aluminum-added solid propellant rocket motor results in the ”Two-Phase Flow”, which includes post-combustion gases, liquid aluminum and aluminum oxide components. The analysis was utilized to simulate the reacting flow in a solid rocket motor with an ammonium perchlorate (AP)/hydroxyl terminated polybutadiene(HTPB)/aluminum(Al) propellant.
Combustion of aluminized propellant has a number of complex properties of the combustion process. The first one does not decompose by evaporating from the aluminum combustion surface. It is approached that aluminum melts directly into the liquid state during the combustion process. In this study, the aluminum particles entering the combustion chamber from the propellant surface are liquid droplets and react with the combustion gases in the combustion chamber. The aluminum particles in the propellant melt and form liquid aluminum on the burning propellant surface at the time of the aluminized propellant combustion.
A large fraction of aluminum stands unreacted and in liquid state at the burning propellant surface due to the physical properties of aluminum and its oxide. Then, to describe the behavior of solid particles in the combustion chamber, droplet evaporation, droplet breakup, and condensation processes were modelled.
In this study, a Navier-Stokes solver Eulerian reference frame for modeling the continuous gas phase and a Lagrangian reference frame was used to model the particles in a discrete phase of the particles to simulate the combustion physics of aluminum burned gas oxidizing agent. The first step in taking into account the particle-gas interaction in rocket motors lies in the examining the particulate properties of uncombusted propellant and the successive combustion process.
Consequently, aluminum particles were sprayed into the combustion chamber so that the initial velocity from the fuel surface was equal to the fuel combustion rate, and aluminum particle combustion modeling was described into the solver. The calculated results show that the relatively slow combustion rate of the aluminum droplets may result in an expanded combustion zone within the chamber in place of a thin reaction zone.
There is temperature increase in the core and total pressure of the combustion chamber is also increased. The chemical composition and propellant gas density show spatially non-uniform distribution in the chamber as well.
The numerical approach to be followed was first tested in the literature that solutions on the BATES[2] motor and compared with these studies in the literature and validation of the solution method was tried. After similar results were obtained, a rocket motor designed in TUBITAK SAGE was examined by this numerical approach.

2.1 Numerical Model of Gas Phase

In the gas phase, the base flow conditions are based on equilibrium conditions of the propellant with formulation ammonium perchlorate (AP)/hydroxyl terminated polybutadiene(HTPB) without any aluminum particle. The base flow gases mass fraction is given in the table. These mass fraction is obtained by using NASA CEA tool that the formation of the propellant include 83.5294 % AP and 16.470% HTPB.

Table 1: Base Flow Species Mass Fraction

Species Mass Fraction (Without Al)	
Species	**Mass Fraction**
HCl	2.549471E-01
CO	2.524787E-01
H_2O	2.325186E-01
CO_2	1.455529E-01
N_2	9.952388E-02
H_2	1.090826E-02
Cl	3.544118E-03
OH	1.234553E-03
NO	1.244635E-04
H	1.120512E-04
Cl_2	3.529129E-05
O_2	2.654588E-05
O	1.327294E-05
NH_3	7.064219E-06

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The heats of formation were calculated using NIST data for each ingredient at the temperature that calculated. The properties of these ingredients are defined for input condition.

2.2 Numerical Model of Particle Combustion Modelling

The modeling solid particles fuel exhaust was added to the CFD model. The use of aluminum in propellants are injected in the gas flow as particle. Diameters of these particles are generally about 100 to 150 μm. with a majority of this particles in range of 10 to 30 μm.
Injected liquid aluminum droplets heated up to vaporization temperature via base flow temperature. The combustion between aluminum and the gas phase firstly start that the liquid aluminum particles turned to vaporized aluminum. The vaporized aluminum reacts with the gas stage of the oxidizing species to form aluminum oxide. The proper reaction mechanism is investigated for their application to solid rocket motor. The combustion within the solid rocket motor, oxidizer environment present in solid rocket motors. A simple model is used in this study.
Table 2 describes the aluminum reaction mechanism and advanced reaction rate parameters, where A, n and E are empirical parameters.

Table 2: Base Flow Species Mass Fraction[5]

No.	**Reaction**	**A**	**n**	**E**
1	Al+O_2=AlO+O	9.72E+13	0	159.95
2	Al+O+M=AlO+M	3.08E+17	-1	0
3	AlO+O_2=AlO_2+O	4.62E+14	0	19885.9
4	Al_2O_3=Al_2O_2+O	3.00E+15	0	97649.99
5	Al_2O_3=AlO_2+AlO	3.00E+15	0	126999.89
6	Al_2O_2=AlO+AlO	1.00E+15	0	117900
7	$Al_2O_2 <=>$ Al+AlO_2	1.00E+15	0	148900
8	Al_2O_2=Al_2O+O	1.00E+15	0	104249.94
9	AlO_2=AlO+O	1.00E+15	0	88549.86
10	Al_2O=AlO+Al	1.00E+15	0	133199.94
11	AlOH=AlO+H	1.00E+15	0	114700
12	AlOH=Al+OH	1.00E+15	0	132000
13	AL+H_2O=H+AlOH	1.14E+12	0	879.8
14	Al+H_2O=AlO+H_2	9.60E+13	0	5700
15	AlO+CO_2=AlO_2+CO	1.50E+10	0	-794.8
16	Al+CO_2=AlO+CO	1.74E+14	0	6400
17	AlH_3+H=AlH_2+H_2	4.75E+09	0	0
18	AlH_2(+M)=AlH+H(+M)	1.46E+15	0	46448
	LOW/	9.68E+14	0	39664.00/
	TROE/ 5.1 21.6 493 942			
19	AlH_3(+M)=AlH+$H_2(+M)$	1.48E+13	0	61112
	LOW/	1.01E+15	0	53826.00/
	TROE/ 0.06 885 552 3807			
20	Al+H+M=AlH+M	1.60E+17	-0.34	0
21	AlH+H=Al+H_2	1.00E+13	0	0
22	AlH_2+H=AlH+H_2	2.00E+13	0	0
23	Al=Al(l)	1.00E+14	0	0
24	Al_2O_3 = $Al_2O_3(l)$	1.00E+06	0	0

The analysis mentioned offers a more advanced tool for internal flow predictions of solid rockets than is currently accessible. The solver options are given in Table 3 for advance aluminized combustion processes.

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Table 3: Selected Options for Solver

Solver	**Pressure Based Coupled Solver**
Geometry	Axisymmetric
Turbulence Model	k - ω SST (Menter k- ω)
Species Model	Species Transfer
Reactions	Volumetric
Turbulence-Chemistry Interaction	Finite-Rate/No TCI
Chemistry Solver	Stiff Chemistry Solver
Mixture Properties	Chemkim Mechanism
Solver Time	Steady-State
Pressure Discretization	Third-Order MUSCL
Density Discretization	Third-Order MUSCL
Momentum Discretization	Third-Order MUSCL
Turbulent Kinetic Discretization	Third-Order MUSCL
Species Discretization	Third-Order MUSCL
Energy Discretization	Third-Order MUSCL

3. Application of Solid Rocket Motor Aluminum Combustion

3.1 Model Establishment and Validation

As a result of combustion reactions in the combustion chamber, temperature and particle distributions were found and the results are given in this section. First, the model is validated with BATES motor. The analyzes made in this part of the study were tried to be solved again under the boundary conditions given with Fluent CFD tool. Aluminum properties such as initial diameters and temperatures of the particles of the aluminum particle injected into the combustion chamber under boundary conditions are also included. The results were compared with the results in the literature. A solution methodology was developed for the solution of aluminum particulate propellant with similar results.
The numerical studies on distributed aluminum combustion in the solid rocket motor combustion chamber were performed by combining models for evaporation and condensation as well as reaction mechanisms and particle breakup was considered using a critical Weber number.
First, the model that implemented a BATES motor, particles are modeled Lagrangian particles and injected into base flow and combustion is modeled an empirical combustion rate model. The motor parameter are listed in Table 4.

Table 4: BATES Motor Parameters

Propellant Properties	**Value**
Composition	
AP	71%
HTPB	14%
Al	15%
Density	1794.6 kg/m^3
Burn Rate	9.0678 mm/s
Mass Flux (Solid)	16.27 kg/s/m^2

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The fuel wall temperature is set to 2674.15 K, which represents the flame temperature of the AP/HTPB mixture at 4.8 MPa chamber pressure. For the present study aluminum particles with uniform 30 micron starting diameter and 1000 K starting temperature are injected at the fuel wall boundary. Static temperature distribution can be seen in Figure 1.

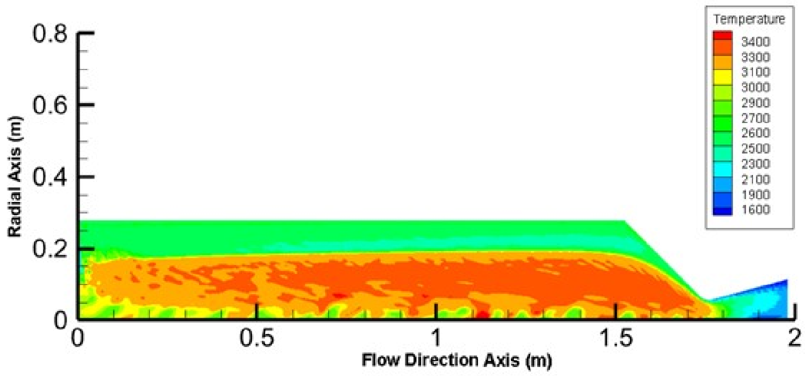

Figure 1: Static Temperature Distribution

Density distribution inside the rocket motor can be seen in Figure 2.

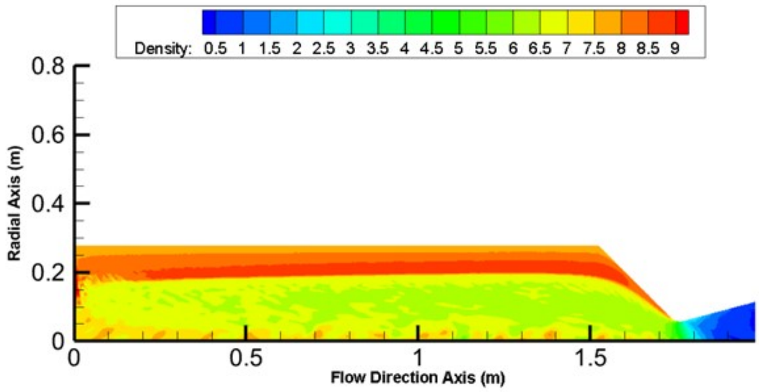

Figure 2: Density Distribution

Particle trajectory and their diameter distribution inside the rocket motor can be seen in Figure 3.

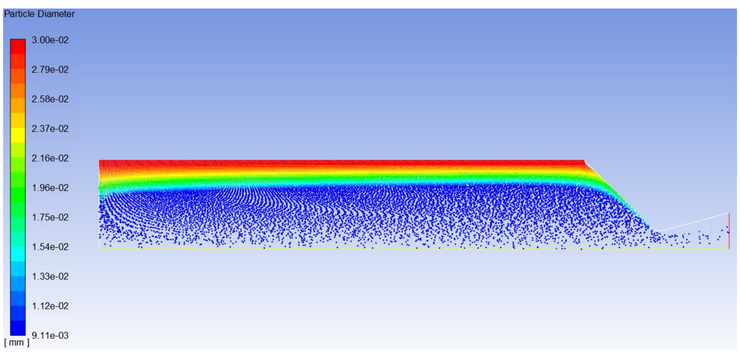

Figure 3: Particle Trajectory and Particle Diameter

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3.2 Application of the Model

The model is implemented on the SRM that was designed in TUBITAK SAGE, given in Figure 8. The solid propellant parameters are listed on Table 5.

Table 5: SRM Parameters

Propellant Properties	
Composition	Value
AP	71%
HTPB	14%
Al	15%

The fuel surface temperature is set to 2600 K, the flame temperature of the AP/HTPB mixture is also set to 4.4 MPa chamber pressure. Aluminum particles with uniform 10 micron starting diameter and 1000 K starting temperature are injected at the fuel wall boundary. Actually aluminum particle that mixed the fuel is not uniform, but the average number of added aluminum particle is close to 10 micron.
The analysis was performed and the contour plots can be seen in below figures. In Figure 4, calculated static temperature distribution is given. The model is also verified with comparing calculated combustion chamber pressure and measured chamber pressure form static firing of SRM.

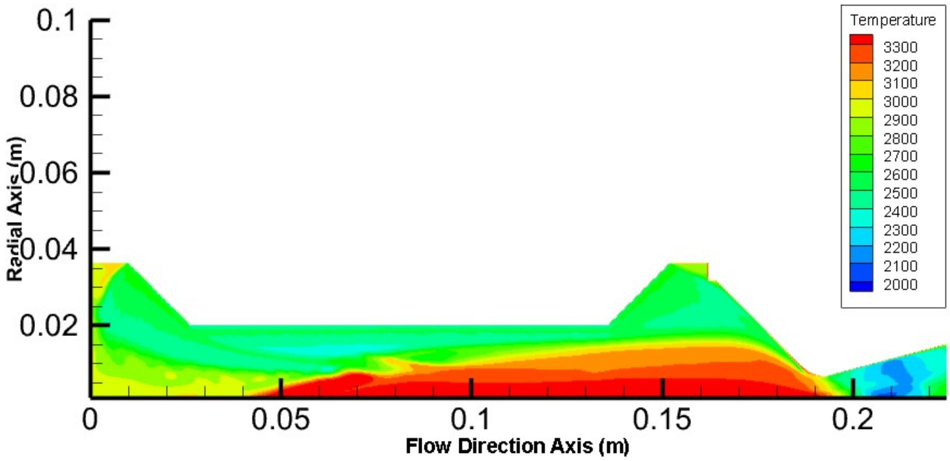

Figure 4: Static Temperature Distribution in SRM

In Figure 5 density contour can be seen.

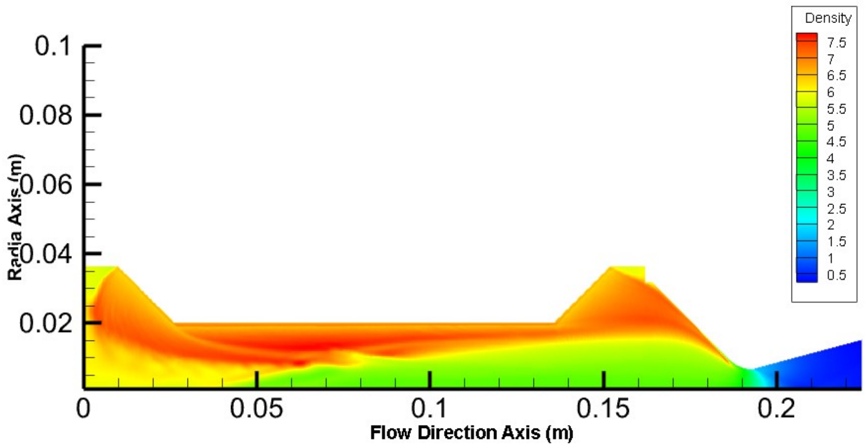

Figure 5: Density Distribution in SRM

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In Figure 6. particle trajectories out side the rocket motor is given. Particle diameter distribution can also be seen.

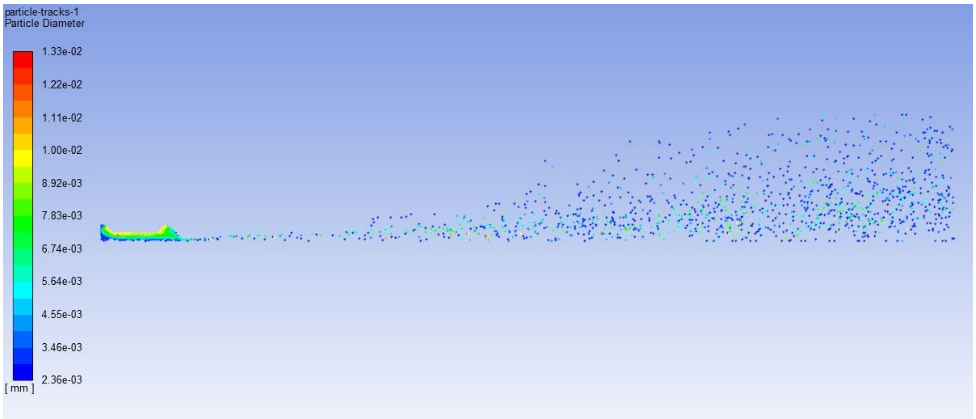

Figure 6: Particle trajectories inside plume

In Figure 7 particle trajectories and diameter change inside the SRM is given.

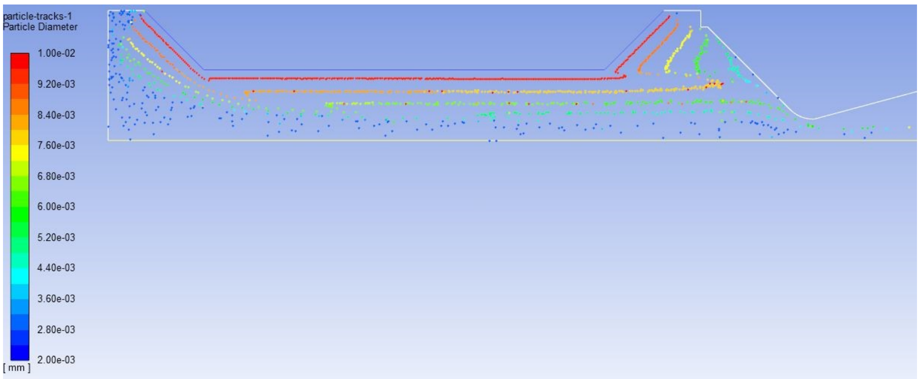

Figure 7: Particle trajectories inside SRM

4. Experimental Procedure

A small scale test motor was fired to investigate aluminum particles within nozzle exhaust. The test motor had graphite nozzle and the combustion chamber pressure was approximately 6 MPa. A Kulite pressure sensor was used with a 500kHz sampling frequency. Rocket motor produced about 1kN thrust which was measured with an HBM force transducer. The propellant used in the rocket motor contains Al, HTPB and AP. The sketch of the rocket motor is given in Figure 8.

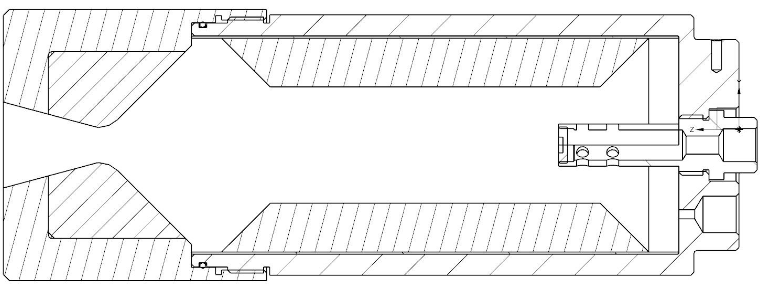

Figure 8: Small Scale Test Motor

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Test motor normalized thrust and pressure history is given in Figure 9.

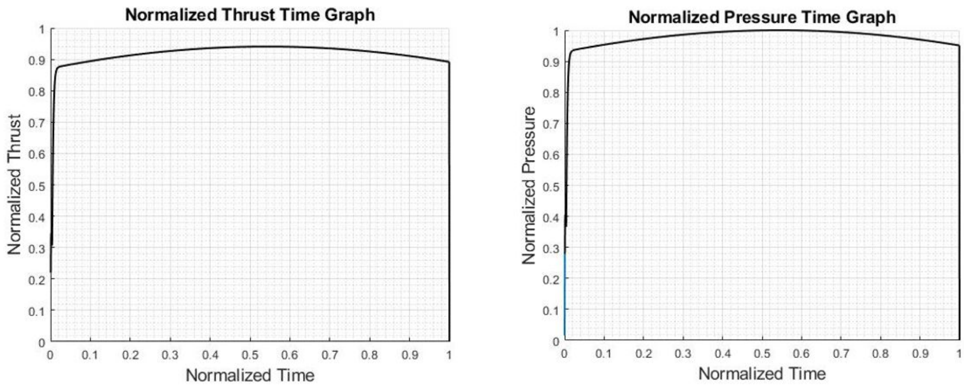

Figure 9: Small Scale Test Motor Normalized Thrust and Pressure History

Firing setup and Al particle collection setup is given in Figure 10. Front view of the solid rocket motor can be seen in the figure and particle collection apparatus were mounted to directly nozzle exit.

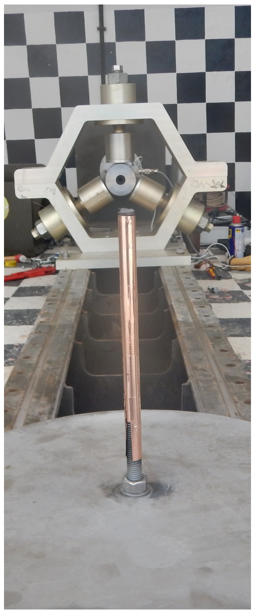

Figure 10: Small Scale Test Motor Firing Setup Front view

4.1 Experimental Apparatus

There were two main components in this setup. One was rocket motor which was mentioned above section. The second component was particle collection probe. The probe was a stainless steel rod which was 300 mm length and 15 mm in diameter. Copper tape was wrapped around the rod. The rod can be seen in Figure 11.

4.2 Aluminum Particle Collection

Particle collection from rocket exhaust plume described by Sambamurthi.[3] He developed copper tape method which was used in this study. Particle collection probe was located 1450mm away from the exit plane of the small scale rocket motor
During motor firing the probe was exposed approximately 1.5s to exhaust plume. Probe condition after motor firing can be seen in Figure 12.

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Figure 11: Al Particle Collection Rod

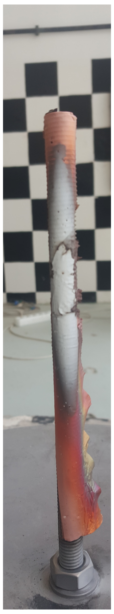

Figure 12: After Firing Particle Collection Rod

4.3 Analysis of Collected Particles

Scanning Electron Microscopy (SEM) was used to determine aluminum oxide particle size. Energy Dispersive Spectrometer (EDS), was used to differentiate particle type. The SEM and EDS samples were prepared from particles on the copper tape. The sample was also coated with palladium before the SEM/EDS analysis.
Collected Aluminum particles were analyzed under Scanning Electron Microscope (SEM). Al_2O_3 particle size distribution is given in Figure 13. Collected sample chemical composition is presented in Figure 14. Al_2O_3 particle SEM photography can be seen in Figure 15. Right hand side photograph is the close view of the left hand side photograph.

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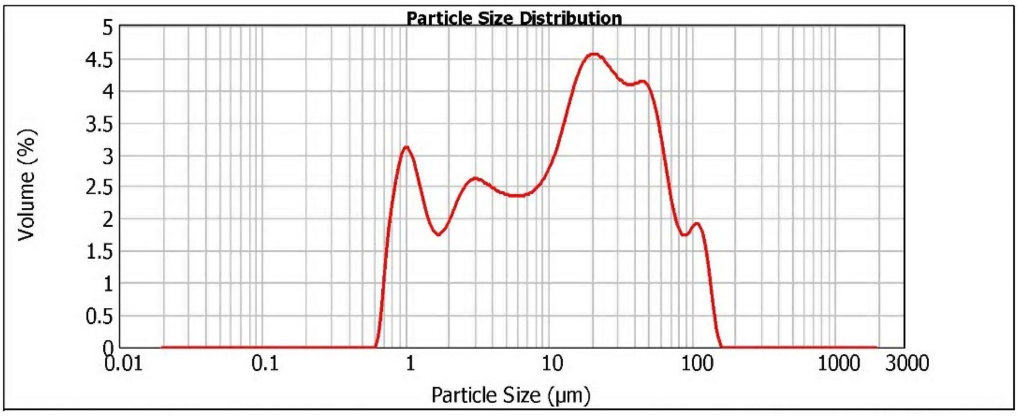

Figure 13: Al_2O_3 Particles Size Distribution

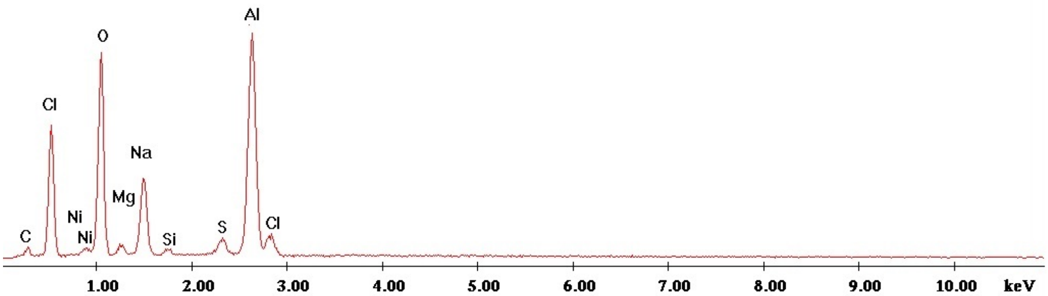

Figure 14: Particle Composition

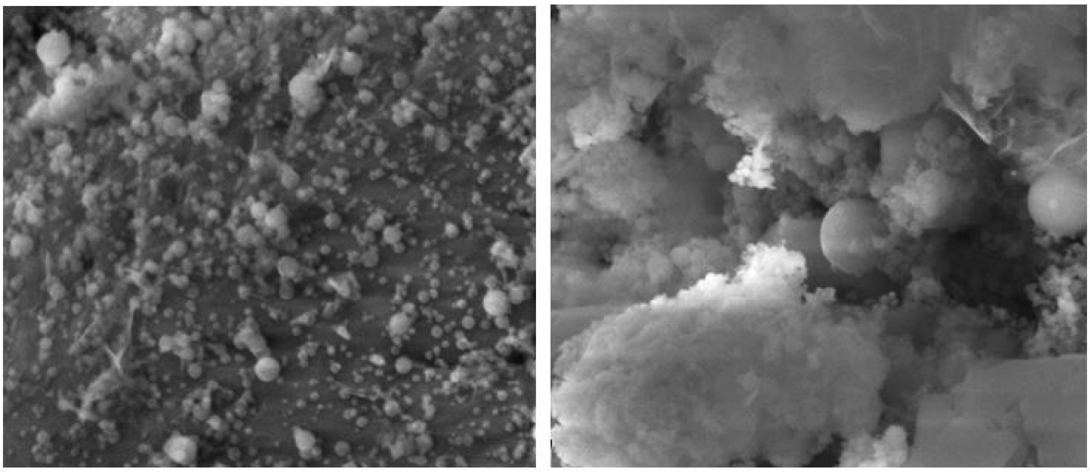

Figure 15: Al Particles under SEM

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5. Conclusion

In this study, a CFD modeling procedure is explained to predict thrust history of small scale solid rocket motor which has Al content. After model was constructed, rocket motor firing was performed to obtain related input parameters for the model like Al particle diameter. Al_2O_3 plume particles were collected according to method that developed by Sambamurthi.[3] A copper tape wrapped steel rod was used to collect plume particles. Collected particles were examined under Scanning Electron Microscope (SEM). The static firing results and CFD results were substantially agreed each other. The particle diameters were founded numerically at the place where particles were collected. Volume weighted mean diameters was around 3.4 microns. There are differences between numerical analysis and Particles Size Distribution measurements. It is understand that agglomeration was not modelled well and the differences can be explain that the aluminum particles in the propellant melt and form liquid aluminum take place at the burning propellant surface. A large fraction of aluminum remains unreacted and in liquid state at the burning propellant surface. Some liquid droplets coalesce into large agglomerates on the order of 100 to 200 microns.[2] These agglomerates leave the propellant surface and they traverse the motor chamber and some of them leave from motor chamber. Also aluminum collection with copper rod can cause agglomeration during the data collection. According to numerical analysis the chamber total temperature is calculated around 3500 K and the chamber pressure is calculated around 6.0 MPa. The analysis were performed for steady state conditions. Experimental and numerical results were compared with a point where there is no throat erosion. Measured pressure data from static firing was closely agreed with numerical model and the differences approximately 1.4%

6. Acknowledgments

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