Conceptual Design and PerformanceNumerical Modeling of Hybrid Propulsion Motor

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Abstract— **Conceptual design algorithm of hybrid rocket motor with solid fuel and liquid oxidizer is investigated in this study. Hybrid chemical rocket propulsion is presently of interest due to reduced system complexity compared to classical chemical propulsion systems. A computational code for conceptual design and performance modeling of hybrid propulsion motor developed. Results are validating with experimental test results.**

Keywords-hybrid propulsion; solid fuel; liquid oxidizer; conceptual design; numerical modeling; experimental test

Hybrid motors are a group of chemical propulsion motors in which fuel and oxidizer are in deferent physical phases. In a typical hybrid, the fuel is a solid and oxidizer is a liquid. However, it is possible to use solid oxidizers with liquid fuels [1]. This motor contain a fuel grain as like as solid fuel motors, but this grain contains fuel only and oxidizer is injected from oxidizer feeding system across oxidizer injectors on the fuel surface. Propulsion thrust is based on combustion of these two propellants in combustion chamber. Thus hybrid motors are a combination of solid and liquid motors. Fig 1 shows schematic of a hybrid motor.

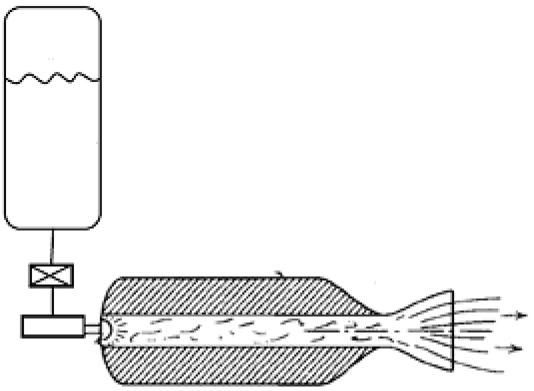

Figure 1. hybrid motor with self-pressurizing feeding system schematic

Advantages of hybrid propulsion are 1) safety and simplicity of handling and storage because of inert propellants and non explosive mixtures, 2) higher specific impulse than common solid motors, 3) lower cost, because of reduced failure modes which permit the use of commercial grade materials and processes. These advantages and others caused to widespread researches on replace of ordinary solid and liquid motors with these motors [2]. For training on this technology, using them in sounding rockets is selected in this research. Sounding rockets as a step of achieve to launch vehicles technology are developed in many countries before [3].

I. HYBRID MOTOR COMPONENTS

Main components of hybrid motors are oxidizer, fuel, combustion chamber, grain, nozzle, oxidizer tank and feeding system, oxidizer injection system and ignition system. All the liquid motor oxidizers are usable in hybrid motors. Effective parameters in select of a proper hybrid oxidizer are specific impulse, high density, high boiling point, easy pumping, stability, storability, cost, handling, safety and no change in attribute with temperature changes [1]. Usual oxidizers of hybrid motors are nitrogen monoxide (N2O), liquid oxygen (LOX) and hydrogen peroxide (H2O2). Different methods for oxidizers feeding are used in hybrid motors, as like as pressurized feeding and pump feeding.

Another method for oxidizer feeding is self-pressurizing system which is used in hybrid motors. Spaceship one is a successful example of using this system [4].

One of disadvantages of hybrid motors is oxidizer to fuel ration shift during burning. Opening the port during burning causes an oxidizer to fuel shift with burning time, this can lower theoretical performance. But proper design minimizes this loss. Combination of hydroxyl-terminated polybutadiene (HTPB) and nitrogen monoxide (N2O) as fuel and oxidizer have less specific impulse (Isp) reduction during O/F shift (figure 2). This combination is used in spaceship one, the successful commercial hybrid propulsion spacecraft (2001). Safety, environmental cleanliness, accessibility, low cost and unique capability of N2O for use in self-pressurizing oxidizer feeding system in room temperature which causes excellent simplicity to this system are advantages of this combination. Figure 1 show schematic of a self-pressurizing oxidizer feeding system. This combination and this feeding method are selected in this research. N2O in room temperature and oxidizer tank pressure is in liquid-gas physical phase equilibrium. When some liquid exit from oxidizer tank, remain liquid-gas mixture

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with a little evaporating of liquid oxidizer became in new liquid-gas physical phase equilibrium. This event recovers most of pressure reduction in oxidizer tank. Disadvantages of HTPB/ N2O combination and self-pressurizing feeding system are limitation of combustion chamber pressure because of limitation of tank pressure and reduction of tank pressure during burning time. Usually this feeding system is appropriate for small motors with small thrust.

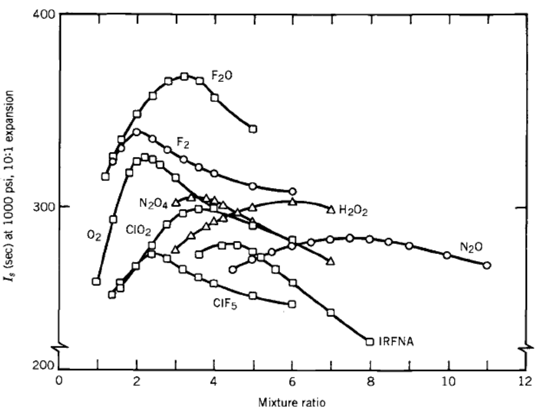

Figure 2. specific impulse of varius oxidizer in combination of HTPB in diference O/F ratio

II. CONCEPTUAL DESIGN PROCESS

Conceptual design is an important part of life cycle of a product. Motor conceptual design usually based on previous experiments. Iteration, try and error and modifying Basic configuration, final configuration develops. Also final configuration is different from basic configuration but their nature is the same. Importance of conceptual design is in two points. At first, basic configuration is a simplified model of final product which allows to modeling the performance of product with simplifications. Second, conceptual design results determine general information about product, as like as mass, thrust and sizes.

In general, the goal of hybrid motor conceptual design are determining combustion chamber pressure, oxidizer tank pressure, burning time, fuel and oxidizer mass, nozzle expansion ratio, size, mass and geometry of combustion chamber and fuel grain. Deferent methods for motor conceptual design are developed. Usually inputs and outputs of these methods are deferent. Input parameters and output results must satisfy desired requirements.

Now we describe hybrid motor conceptual design procedure: first with mission requirements, develop basic design of motor in a nominal working point and determine geometry, dimension and mass of each subsystem. Next, for performance modeling, develop a semi-dynamic model due to theoretical relations of hybrid motors.

A. Hybrid motor variables

Each hybrid motor has six main subsystems: oxidizer tank, oxidizer feeding, fuel grain, nozzle, igniter and motor structure. Due to these subsystems, hybrid motors has many variable parameters. In motor design, motor parameters consists three groups: constrains, outputs and variable parameters.

B. Design constrains

Constrains of our problem are 1-ambient pressure (P_0) 2-gravity constant (g) 3- Motor external diameter (D_{out}) 4-Fuel density (ρ_{fuel}) 5- oxidizer density (ρ_{oxid}) 6-combustion efficiency (η_{comb}) 7- constant coefficient (a) and power (n) of hybrid fuel regression rate equation 8-maximum ratio of length to diameter $(L/D)_{Max}$.

C. Design outputs

Design outputs are nozzle exit velocity, nozzle exit Mach number, throat area, burning area, fuel grain's port cross section area, flow Mach number in fuel grain's port and others.

D. Design variables

Design variables are 1- motor mean thrust (T) 2- approximate burning time (t_{burn}) 3-combustion chamber pressure (P_{cc}) 4-initial mass ratio of oxidizer to fuel $(O/F)_i$ 5-geometry of fuel grain 6- number of fuel grain's ports (N) 7-maximum flow mach number in fuel grain's port (M_{Max}). Cylindrical grain with multiple cylindrical ports is chose for grain geometry because of Simplicity of analysis of this type of grain. Figure 3 shows schematic of fuel grain.

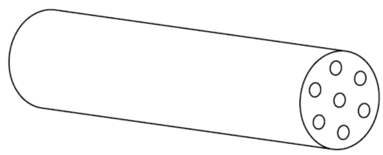

Figure 3. fuel grain schematic

III. BASIC DESIGN FOR A NOMINAL WORKING POINT

Governor equations in hybrid motor flow are three dimensional Navier- Stokes with applying turbulent models. Solving these equations need complicated and time consuming calculations. References show that in motor design there is no need to solve these complicated equations and engineering relations and experimental correlations can attain the desirable results [1, 2].

Thermodynamic properties of combustion products, as like as isentropic parameter (γ), theoretical specific impulse, flame temperature and molecular mass can drive from using commercial combustion codes as like as CEA [4]. Thrust of motor derived from

$$T = \dot{m}V_e + A_e(P_e - P_{out}) \tag{1}$$

In which $\dot{m}$ = nozzle mass flow, V_e = exhaust gas mean velocity, A_e = nozzle exit cross area, P_e =nozzle exit pressure and P_{out} = ambient pressure.

Specific impulse is derived from

$$I_{sp} = \frac{T}{\dot{m}g} \tag{2}$$

If we assume that $P_e = P_{out}$, we have a current proportion between I_{sp} and V_e due to equation 1 and 2. Vacuum specific impulse could calculate with combustion properties and combustion chamber pressure. Combustion chamber pressure, exit pressure and Mach number in nozzle exit (M_e) can relevant in follow equation

$$P_0 = P_e\left(1+\frac{\gamma-1}{2}M_e{}^2\right)^{\frac{\gamma}{\gamma-1}} \tag{3}$$

Nozzle exit velocity can drive from equation 4:

$$V_e = M_e\sqrt{\frac{\gamma R T_c}{1+\frac{\gamma-1}{2}M_e{}^2}} \tag{4}$$

Throat section area (A_t), total pressure of combustion chamber (P_0) and propellant mass flow are related by

$$P_0 = \frac{\dot{m}}{A_t}\sqrt{\frac{RT_c}{\gamma}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{5}$$

In a convergence –divergence nozzle, exit section area to throat area ratio can calculate from

$$\frac{A_e}{A_t} = \frac{1}{M_e}\left[\left(\frac{2}{\gamma+1}\right)\left(1+\frac{\gamma-1}{2}M_e^2\right)\right]^{\frac{\gamma+1}{2(\gamma-1)}} \tag{6}$$

Oxidizer to fuel mass ratio definition is

$$\frac{O}{F} = \frac{\dot{m}_o}{\dot{m}_f} \tag{7}$$

Total mass flow is

$$\dot{m} = \dot{m}_o + \dot{m}_f \tag{8}$$

For calculation of fuel regression rate in hybrid motors, various experimental and analytical equations developed [1]. In this research we use equation 9 for determine fuel regression rate [2].

$$\dot{r} = aG_0^n \tag{9}$$

In which $\dot{r}$ is fuel regression rate and G_o is oxidizer flux. Due to equation 9, fuel regression rate in hybrid motors is not direct function of combustion chamber and depends on flow of oxidizer or total propellant flow. In equation 9, a and n are experimental multiple factor and power of fuel regression rate equation. Many researches are developed to determine these factors for various hybrid propellants [1]. In this study we use results of an experiment research [5].

Fuel grain's port cross section area and oxidizer flow can relate with bellow equations:

$$\dot{m}_o = N(\rho_o V A_p) \tag{10}$$

$$G_o = \frac{\dot{m}_o}{NA_p} \tag{11}$$

In above equations V is flow velocity in grain's ports and A_P is each port cross section area.

Next equation is about geometrical relation between fuel mass flow, fuel grain length and fuel regression rate.

$$\dot{m}_f = N\rho_f \dot{r} P_p L \tag{12}$$

In this equation, P_p is port cross section perimeter and L is length of fuel grain. Combining equation 1 to 12 make a linear non static model for hybrid motor. After calculating gas dynamics and propulsion parameters, we estimate mass and size of subsystems.

A. Motor structure conceptual design

Structure of hybrid motor consists of nozzle, combustion chamber, oxidizer tank and oxidizer injection system. A key problem in design of hybrid motor nozzle is substance of insulator. Unlike solid motors which use graphite based nozzles, in hybrid motors because of oxidizer rich nature of combustion products, usually use phenol based composites for nozzle insulation. This material has a good resistance about chemical reaction with oxidizer. Experimental equation 13 is used for estimate nozzle mass [6].

$$m_{noz} = 125\left(\frac{m_{prop}}{5400}\right)^{\frac{2}{3}}\left(\frac{\varepsilon}{10}\right)^{\frac{1}{4}} \tag{13}$$

In which m_{noz} is nozzle mass, m_{prop} is propellant mass and ε is nozzle expansion ratio.

Combustion chamber includes chamber case, head cap, tail cap, injectors and insulation. For calculating mass of combustion chamber, we use equation 14:

$$m_c = \rho_c \left[2\pi R_{out} L_c t_c + 4\pi R_{out}^2 t_{clo} \right] \tag{14}$$

In which m_c is mass of combustion chamber, ρ_c is density of chamber case material, R_{out} is outer radius of chamber, t_c is thickness of cylindrical part of case and t_{clo} is thickness of head and tail caps.

For estimating oxidizer tank mass, we use pressure vessels design relations. Mass of injectors, igniter, regulator and other components estimated from our last experiences. Figure 4 shows Schematic of combustion chamber and nozzle.

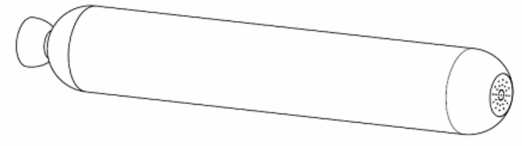

Figure 4. combustion chamber and nozzle schematics

IV. PERFORMANCE MODELING

For hybrid motor performance modeling, we use previous equations and drive a semi-dynamic model for hybrid motor performance estimating. This model used for modeling hybrid motor during burning time. Other equations which used in this modeling are described below.

Oxidizer injector's mass flow in conceptual design estimate from simple orifice relation:

$$\dot{m}_{oxid} = kA_t \sqrt{2\rho \Delta P} \tag{15}$$

In this equation, k is orifice discharge factor, A_t is orifice throat cross area, ρ is density of fluid and ΔP is pressure deference in both sides of orifice. Assume hydraulic losses in piping are negligible, ΔP equals deference of pressure of oxidizer tank exit and combustion chamber pressure. For determine fuel grain's port radius, we use Tailor extension and thus:

$$r_p^{n+1} = r_p^n + \dot{r}\Delta t \tag{16}$$

In above equation, r_p^{n+1} = fuel grain's port radius in time $n+1$, r_p^n = fuel grain's port radius in time n, $\dot{r}$ = regression rate between this two time and Δt = deference of this two time. Equation 16 is valid only for cylindrical ports. For other geometries, must drive this equation for their geometry and conditions.

V. RESULTS

Figure 5 shows thrust and specific impulse of the study during burning time. Figure 6 shows combustion chamber and oxidizer tank pressure during burning time. For validating the results, we use results of experimental test in an Iranian research center on hybrid motors. Figure 7 shows setup of this test stand. Figure 8 compares numerical model results and experimental results for motor thrust vs. time. The figure shows acceptable accordance between numerical modeling and experimental results. Figure 9 shows results of total mass flow, oxidizer mass flow, fuel mass flow and oxidizer to fuel ratio during burning time. As we predict before, due to fuel mass flow change during burning time, oxidizer to fuel ratio have a severe change.

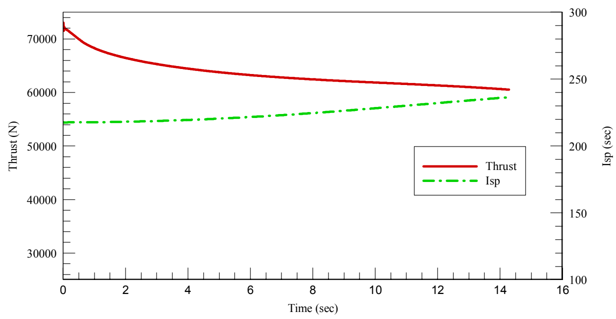

Figure 5. thrust and specific impulse vs. time

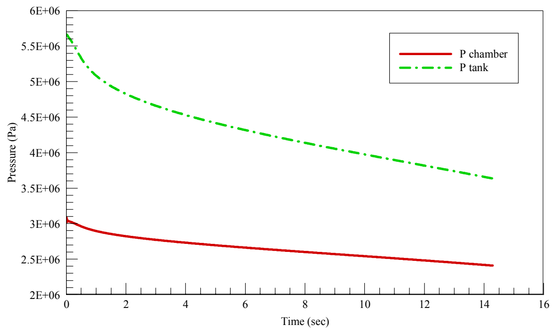

Figure 6. pressure of combustion chamber and fuel tank vs. burning time

Figure 7. test stand setup

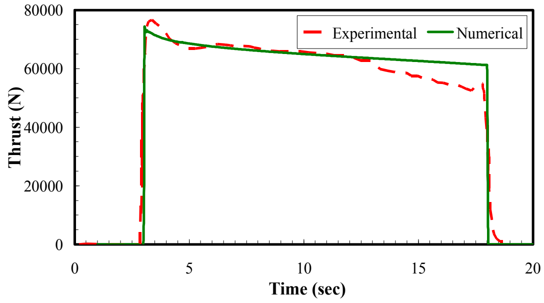

Figure 8. thrust vs. time for numerical and experimental results

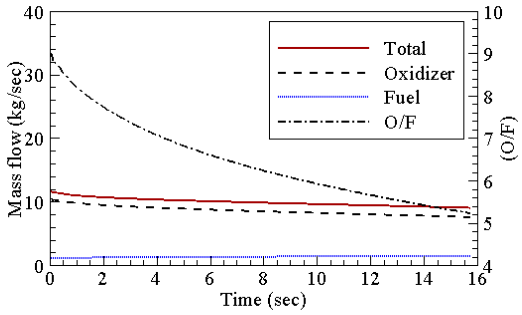

Figure 9. mass flow vs. time

VI. CONCLUSION

A conceptual design algorithm for hybrid motors is developed. Performance Numerical modeling is discussed and results of this modeling compared with experimental results. Conceptual design and performance modeling of hybrid motor shows that we can estimate the performance of these motors with usual physical and gas dynamic assumptions. Severe assumptions will result better results which can use for preliminary and detail design. Hybrid motor advantages cause to very good research interest on them in universities and academic research centers. Hybrid chemical propulsion is presently of interest due to reduced system complexity compared to classical chemical propulsion systems.

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