# Hybrid Rocket Engine Design with Multi-Objective Vibrational Genetic Algorithm

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***Abstract*—In this study, the conceptual design of a single-stage hybrid rocket engine of a low-altitude sounding rocket is developed using the Multi-Objective Vibrational Genetic Algorithm (MOVGA). A hybrid rocket engine design having single circular port fuel grain with constant cross-section doped with oxidizer is done. Hybrid rocket engine is fueled by Hydroxyl-Terminated Polybutadiene (HTPB) with oxygen as the oxidizer. This is probably the first study in which the MOVGA is used for a hybrid rocket engine design problem. Vibrational genetic algorithm used in the hybrid rocket engine design problem as a comprehensive mutation technique provides diversity in the population in order to explore and find the global optimum quickly. For a high efficient hybrid rocket, the design problem is formulated as maximization of the flight altitude with minimum total mass with engine size (length to diameter ratio) constraint. The algorithm estimates the optimum hybrid rocket engine design including thrust, sizing and flight altitude calculations. Consequently, a mechanical design of a manufacturable and testable hybrid rocket engine is accomplished by means of the MOVGA in reasonable CPU times.**

***Keywords*—rocket engine design; hybrid engines; hybrid rocket engine design problem; multi-objective vibrational genetic algorithm.***

## I. Introduction

Human development has always been closely interested in transportation. At the beginning of the twenty-first century the development of rockets may be seen as a breaking through revolution in transport. So far, only a few humans have travelled in rocket-propelled vehicles, but a significant amount of commercial and domestic communication is now reliant on satellites. The proposed return to the Moon, and new programs to send humans to Mars present a resurgence of interest in space exploration for the new era [1].

Rocket propulsion system produces the thrust to move the vehicle through the air. These systems can be classified according to the type of their energy source (chemical, nuclear, or solar), the basic function (booster stage, sustainer, attitude control, orbit station keeping, etc.), the type of vehicle (aircraft, missile, assisted take-off, space vehicle, etc.), size, type of propellant, type of construction, or number of rocket propulsion units used in a vehicle [2]. Rocket engines may work with two types of propellant chemicals; solid (Solid Rocket Engine, SRE) or liquid (Liquid Rocket Engine, LRE). Hybrid propulsion systems (Hybrid Rocket Engine, HRE) involve the combination of both solid and liquid propellants [3]. Hybrids have been investigated for a long time by researchers. The first research was using Gaseoline–collophonium mixture and liquid oxygen on a 500 N thrust motor and done by Soviet researchers S.P. Korolev and M.K. Tikhonravov. This engine was tested on 13 August 1933 and propelled a rocket at 1500 m altitude [4].

Several studies are also done on HREs in literature [5-8]. These studies are intended to combine the propellants to minimize the costs and environmental influences and to maximize the simplicity, performance and safety [9]. One of the practical usages of HRE in a vehicle is "Space Ship One" and it is a three-place, high-altitude research rocket, designed for sub-orbital flights to 100 km altitude. It features a non-toxic, liquid nitrous-oxide/rubber-fuel hybrid propulsion system [10].

A sample HRE is presented in Fig.1 [4]. In Fig.1 combustion chamber (#1), nozzle (#2), oxidizer tank (#3), fuel grain (#4), injector valve (#5), head of the injector valve (#6) and burning port (#7) are showed. The storage of the oxidizer as a liquid and the fuel as a solid is the main concept on HRE. This design is less predisposed to chemical explosion than the other designs. The fuel is filled within the rocket combustion chamber in the form of a cylinder. And this chamber is contained with a circular channel called a port hollowed out along its axis. After ignition, a diffusion flame forms over the fuel surface thorough the port. The combustion is proceeded by heat pass from the flame to the solid fuel causing continuous fuel vaporization until the oxidizer flow is finished [11].

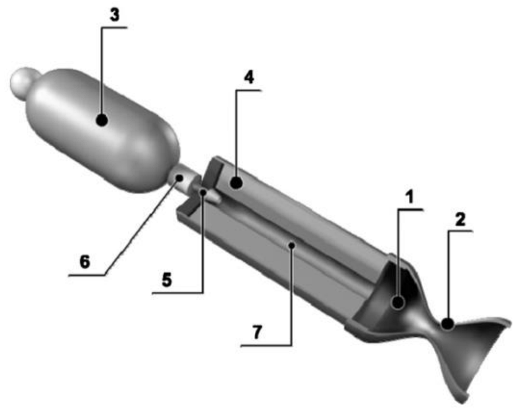


Fig. 1. HRE structure [4].

HRE design problem is studied especially after 1960s. The development of hybrid rockets from 1930s to 1990s is studied by Altman [12]. A ballistics model has been developed for investigating the influence of fuel-grain design on the overall performance of hybrid rocket boosters by Vonderwell *et. al.* [13]. Casalino and Pastrone [14] are studied the parameters that affect the design of a HRE for small satellite and they analyzed the benefit of the oxidizer flow rate control. Multiobjective optimization of two-stage rockets for Earth-to-orbit launch is studied by Bairstow *et.al.* [15]. The problem aims to deliver a payload to orbit at some cost and they proposed a Multi-Objective Genetic Algorithm (MOGA) to solve the problem. Kosugi *et.al.* [16] also proposed MOGA for multidisciplinary design optimization of a hybrid rocket. Chiba *et.al.* [17] studied a single-stage launch vehicle with HRE has been conceptually designed by using design informatics, with problem definition, optimization, and data mining point of view. In the study, the multidisciplinary design optimization and data mining were performed by using evolutionary hybrid computation. Kanazaki *et.al.* [18] studied to improve on parameterization for conceptual design method of three stage hybrid rocket. As a metaheuristic approach, MOGA is again employed to solve multi-disciplinary design exploration of a three-stage launch vehicle concept using a HRE. A MOGA is also used by Kanamori *et.al.* [19] for the conceptual design methodology of three-stage hybrid rocket including the thrust evaluation, the vehicle sizing and the trajectory analysis. A swirling-oxidizer-type HRE with a single cylindrical grain port is designed with using a MOGA by Kanazaki *et.al.* [9]. Kanazaki *et.al.* [20] also studied the multidisciplinary design optimization of a launch vehicle with a HRE and they proposed a Non-dominated Sorting Genetic Algorithm-II (NSGA-II) to solve two design problems.

In this paper, a Multi-Objective Vibrational Genetic Algorithm (MOVGA) is proposed to solve the HRE design problem. As far as we know, this is the first study for the usage of MOVGA for a HRE design problem. Vibrational Genetic Algorithm (VGA) is first proposed by Hacioglu and Ozkol [21-22] and this method is used for transonic airfoil design and optimization. VGA is also used for inverse airfoil designs [23], continuous covering location problems [24], optimization of 3D wing geometries [25] and enhanced with a Voronoi diagram for path planning of autonomous unmanned aerial vehicles [26] in literature.

Using the MOVGA, optimum design of a HRE that can be manufactured and tested for a low-altitude sounding rocket is developed. The design problem considers the maximization of the flight altitude and minimization of the total mass with engine size (length (L) to diameter (D) ratio) constraint. It also includes the thrust evaluation, sizing and altitude estimation for a vertical launched rocket with HRE. This study employs the Hydroxyl-Terminated Polybutadiene (HTPB) as fuel, and the oxygen as oxidizer.

This paper is organized as follows. Second title covers problem definition with mathematical model and HRE performance evaluation calculations. Third section includes the proposed MOVGA and the following section explains the computational study. The paper ends with conclusion section.

## II. PROBLEM DEFINITION

### A. The Mathematical Model

The mathematical model of the HRE design problem is explained in this section. The model has a main objective function ($f_{total}$) with combination (i.e. weighted sum) of two objective functions. The combined first objective is maximization of altitude ($f_{altitude}$) and the second objective is minimization of initial total mass (i.e. $m_0$) ($f_{totalmass}$). Since $f_{total}$ is a minimization function (Equation 1), the first objective function is also turned to a minimization function in the formula. Besides, the combined objective functions have different scales, they are normalized (Equation 2 and 3). In the normalization maximum and minimum values of the objective functions are used in the formula and they are assigned in the computational study section. $w_1$ and $w_2$ are the weights of the functions. The model is constructed to design an engine under the assumption that aspect ratio of the test rocket *L*/*D* is limited to 20.0 as a constraint (Equation 4). Higher aspect ratios may cause higher vehicle dimensions.

The model is presented as below:

$$min.f_{total} = w_1 \cdot f_{altitude}^{norm} + w_2 \cdot f_{totalmass}^{norm} ;$$

$$w_1 + w_2 = 1 \quad (1)$$

$$f_{altitude}^{norm} = \frac{(\max(f_{altitude}) - f_{altitude})}{(\max(f_{altitude}) - \min(f_{altitude}))} \quad (2)$$

$$f_{totalmass}^{norm} = 1 - \frac{(\max(f_{totalmass}) - f_{totalmass})}{(\max(f_{totalmass}) - \min(f_{totalmass}))} \quad (3)$$

$$L/D \geq 20 \rightarrow f_{total} = 1000000 + (L/D) \quad (4)$$

### B. HRE Performance Evaluation

In the present study, a single-stage HRE is conceptually designed. A typical hybrid rocket consists of the nozzle, the combustion chamber, the oxidizer tank, and the payload, as shown in Fig.1. Due to its simplicity of grain design/processing and efficiency for fuel utilization, combustion chamber has single port fuel grain geometry with constant circular cross-section to supply the oxidizer. In Fig.2, evaluation procedure for the HRE design is given.

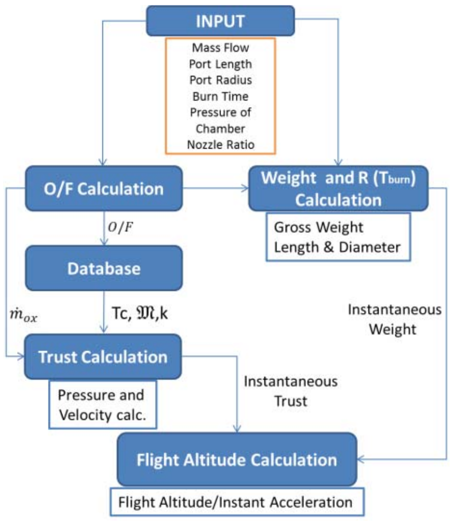


Fig. 2. Overview of the HRE performance evaluation.

The thrust $T(t)$ of a hybrid rocket can be calculated from applying the principle of the conservation of momentum by using pressure and net momentum outflow per unit time at the nozzle exit, as stated below.

$$T(t) = \eta_t(\gamma \dot{m}_{prop} u_e + (P_e - P_\infty)A_e) \quad (5)$$

Here, $\eta_t$ is total thrust loss coefficient, $\gamma$ is momentum loss coefficient due to friction at nozzle exit, $P_\infty$ is pressure of atmosphere, $u_e$, $P_e$ and $A_e$ are exit nozzle velocity, pressure and area, respectively, and they can be obtained from chamber pressure $P_{ch}$ and nozzle area ratio $\in$, which are design variables. Last, $\dot{m}_{prop}(t)$ is mass flow of the propellant which is the sum of oxidizer mass flow $\dot{m}_{oxi}$ and fuel mass flow $\dot{m}_{fuel}$.

$$\dot{m}_{prop} = \dot{m}_{oxi} + \dot{m}_{fuel} \quad (6)$$

Thrust of the HRE depends on the oxidizer flow rate, which also governs the regression rate of the fuel in the radial direction. While the propellant regression rate of a solid rocket is proportional to the chamber pressure, regression rate for a hybrid rocket is assumed to only depend on the oxidizer mass flux, which is constant along the port [2].

$$\dot{r(t)} = \frac{dr}{dt} = a_o G_{oxi}^n(t) \quad (7)$$

The coefficient $a_o$ and exponent $n$ are empirically determined by the choice of fuel and oxidizer. For this study, a typical conventional hybrid fuel, HTPB-$O_2$ with $a_o = 0.104$ and $n = 0.681$, is used in the calculations [2]. $G_{oxi}$ is the local mass flux rate of the oxidizer in the combustion port. For circular port geometries with radius $R$, $G_{oxi}$ can be expressed as:

$$G_{ox}(t) = \frac{\dot{m}_{oxi}}{\pi R^2} \quad (8)$$

Instantaneous combustion port radius $R_{port}$ is calculated as a function of time by subtracting the integrated value of fuel reduction for combustion time $T_{burn}$ from initial port radius $R_{port}(0)$, which are other design variables of the evaluated optimization problem.

$$R_{port}(t_i) = R_{port}(0) - \int_0^{T_{burn}} \dot{r}(t)dt \quad (9)$$

Combustion chamber is designed according to the fuel grain size, and its diameter is decided by the given initial port radius and the final port radius found at the end of the combustion duration time $T_{burn}$. The mass production rate of fuel is estimated from regression rate according to a relation of the form:

$$\dot{m}_{fuel} = 2\pi\rho_{fuel} R(t) L \dot{r}(t) \quad (10)$$

Port length $L$ is the design parameter. Considering the oxidizer mass flow as another design parameter, mass mixture ratio $O/F(t)$ can be determined as follows.

$$O/F(t) = \frac{\dot{m}_{ox}}{\dot{m}_{fuel}} \quad (11)$$

With the instantaneous O/F ratio known, theoretical characteristic velocity $c^*$, ratio of specific heats $k$, molecular mass $\mathfrak{M}$ and chamber temperature $T_c$ are obtained from the experimental data given for certain mixtures of the selected fuel and oxidizer [27].

For a vertical launched rocket, which is supposed to be a point mass for the altitude calculations, the equation of motion is defined as:

$$a(t) = \frac{T(t) - D(t)}{M_{tot}(t)} - g \quad (12)$$

Drag $D(t)$ is evaluated by using the following equation, which ignores frictional drag and only considers pressure drag.

$$D(t) = \frac{1}{2}\rho V^2 S_{ref} C_D \quad (13)$$

$S_{ref}$ is reference/frontal area of the vehicle, and drag coefficient $C_D$ is taken as similar to drag coefficient of a bullet.

For the structural analyses, it is assumed that length of the rocket is equal to twice the length of the nozzle and combustion chamber. Radius of the rocket is also assumed to be equal to the radius of the fuel port. Initial weight of the rocket is defined as the summation of fuel, oxidizer and payload, plus 10% of all for the structure. Mass of the payload is 1 kg.

## III. PROPOSED MULTI-OBJECTIVE VIBRATIONAL GENETIC ALGORITHM

The GA is an effective metaheuristic algorithm for optimization problems [28]. It has population based evolutionary search strategy that the solutions are evolving to better solutions with crossover, mutation and selection operators. The pseudo-code and the operators of proposed MOVGA are presented below.

| **Algorithm:** Pseudo-code of MOVGA |
|---|
| **Begin**<br>Set initial parameters<br>Generate initial population<br>Evaluate initial population<br>$g \rightarrow 0$ /* $g$: generation number */<br>**repeat**<br>Apply ranking based selection to the current population<br>Generate new children with crossover<br>Apply mutation<br>Vibrate population /* in every $I_p^{th}$ generation */<br>Evaluate new children<br>Apply elitism<br>Apply environmental selection (update population)<br>$g \rightarrow g + 1$<br>**until** $g \geq g_{max}$<br>Show best solution<br>**End** |

### A. Representation and Fitness Function

The MOVGA has a real valued representation. The representation has oxidizer mass ($m_{oxi}$), engine length ($L$), initial port radius ($R_{port(0)}$), combustion duration time ($T_{burn}$), chamber pressure ($P_{ch}$) and nozzle area ratio ($\in$) values of HRE design. The fitness function is minimization of $f_{total}$. Since this function is normalized, it has values between 0 and 1. Design variables and their upper and lower bounds are listed in

Table I. The ranges are determined according to the needs of the engine for a small sound rocket.

TABLE I: DESIGN VARIABLES AND GENE REPRESENTATION

| | Design Variables | Lower Bound | Upper Bound |
|---|---|---|---|
| **Gene 1** | $M_{oxi}$ [kg] | 0.005 | 10 |
| **Gene 2** | $L_{Port}$ [m] | 0.01 | 0.6 |
| **Gene 3** | $R_{port}(0)$ [m] | 0.005 | 0.1 |
| **Gene 4** | $T_{burn}$ [s] | 5 | 10 |
| **Gene 5** | $P_{ch}$ [bar] | 10 | 40 |
| **Gene 6** | $\epsilon$ | 1 | 10 |

## *B. Initial Population and Parental Selection*

Random initial population is preferred. An initial solution (i.e. chromosome, individual) is generated by assigning random real numbers to the genes between their ranges presented in Table I. $\mu$ number of individuals are generated and $\mu$ parameter is tuned in the computational study. Rank weighting selection strategy is used for parental selection.

## *C. Crossover and Mutation Operators*

Blend crossover operator (BLX-$\alpha$) is used for generating new children from parents. An example is presented as follows. $\lambda$ number of children are generated in every generation.

$$\left.\begin{array}{l} G_1 = (x_1^1, x_2^1, \dots\dots, x_N^1) \\ G_2 = (x_1^2, x_2^2, \dots\dots, x_N^2) \end{array}\right\} Parents \quad \beta_1 = (\beta_1, \beta_2, \dots\dots, \beta_N) \;\; \} Random \tag{14}$$

$$\gamma_i = (1 + 2\alpha)\beta_i - \alpha \tag{15}$$

$$Children \begin{cases} G_1' = (x_1', \dots, x_N') & x_i' = \gamma_i x_i^1 + (1-\gamma_i)x_i^2 \\ G_2' = (x_1'', \dots, x_N'') & x_i'' = \gamma_i x_i^2 + (1-\gamma_i)x_i^1 \end{cases} \tag{16}$$

A simple random resetting mutation is selected for mutation operator. Randomly selected gene of a child is changed with a random real value $\beta$ between the ranges of the gene $[a_i, b_i]$.

$$x_i' = x_i + \beta(b_i - a_i) \tag{17}$$

Crossover probability ($P_{cp}$), BLX parameter ($\alpha$) and mutation probability ($P_m$) are set in the computational study.

## *D. Vibration*

Vibration is a comprehensive mutation application strategy which is used on the population to have effective diversity inside. By exerting a vibrational mutation to the population during genetic process, the individuals expand over the design space periodically in order to explore the GA efficiently and find the global optimum quickly [21]. The technique can be used in design optimization problems [21-23, 25]. When these studies are examined, the most important advantage of VGA is that it enables the usage of large mutation rate and small population size in the genetic optimization process.

From the initial steps of the genetic process, vibrational mutation is used and applied on each individual just after the reproduction phase. Every individual in the population mutate at every $I_p^{th}$ generation, and the $P_m$ has to be equal to $1/I_P$. Vibrational mutation is defined as:

$$x_i^m = x_i^m \cdot [1 + w_M \cdot MA \cdot (0.5 - u)] \qquad m = 1, \dots, \mathrm{n} \qquad i = 1, \dots, \mathrm{kn} \tag{18}$$

Here, $x_i^m$ are the genes, kn is the chromosome length, n is the total number of individuals in the population, $MA$ is the main amplitude which affects the change of genes between borders, $u$ is a random real number between [0,1] and $w_M$ is a real number between [0,1] that is assigned by the user. $u$ and $w_M$ both control $MA$, which is arranged for minimization problem as follows.

$$MA = \left[\frac{\log(1+AF_K)}{\log(1+AF_0)}\right]^r \tag{19}$$

$AF_k$ and $AF_0$ are mean fitness values at the current and inceptive generations of the genetic procedure, respectively. $r$ is a real number.

## *E. Environmental Selection and Stopping Criteria*

The generated $\lambda$ number children and selected "$\mu$ x $e$" number ($\mu$ - $\lambda$ number) of elitist children of previous generation are transferred to the next generation. Elitism parameter ($e$) is tuned in computational study. The algorithm stops when the generation number reaches to $g_{max}$ or the difference between the fitness function values of the last two generations are smaller than a $z$ value. The $g_{max}$ and $z$ parameters are also set in computational study.

# IV. COMPUTATIONAL STUDY

A selected problem instance from literature is used to show the performance of MOVGA. The MOVGA is coded in Java and the calculations are performed on a Intel Core i7-4700MQ computer which has 2.4 GHz CPU and 16 GB RAM.

## *A. Parameter Tuning*

The selected key parameters of MOVGA are tuned and the others are set in computations. The key parameters are $\mu$, $P_m$, and $e$. 10 runs are made for tuning the key parameters and the best values are determined. The tuned and selected other parameters of MOVGA are presented in Table II.

TABLE II: ASSIGNED PARAMETERS OF MOVGA

| Parameter | Value(s) |
|---|---|
| $\mu$ | Among: 30, 50, 100; Set: 50 |
| $P_m$ | Among: 0.1, 0.2, 0.3; Set: 0.1 |
| $e$ | Among: 0.1, 0.2, 0.3; Set: 0.2 |
| $P_{cp}$ | 1 |
| $\alpha$ | 0.5 |
| $\lambda$ | 40 |
| $w_M$ | 0.4 |
| $r$ | 1 |
| $g_{max}$ | 1000 |
| $z$ | $10^{-7}$ |
| max ($f_{totalmass}$), min ($f_{totalmass}$) | 10, 0 |
| max ($f_{totalaltitude}$), min ($f_{totalaltitude}$) | 10000, 0 |

## B. Results

30 runs are made for a problem with 9 different objective function weight combinations. The weights are ranging between 0.1 to 0.9. The results of 9 set combinations for MOVGA are showed in Table III and the pareto front results of the weights are presented in Fig. 3. The CPU times of MOVGA are ranging from 9.58 to 25.901 seconds.

TABLE III: RESULTS

| Set | *Altitude* $w_1$ | *Mass* $w_2$ | **Best** $f_{total}$ | **Mean** $f_{total}$ | **Worst** $f_{total}$ | **Ave. CPU Time (sec.)** |
|---|---|---|---|---|---|---|
| 1 | 0.1 | 0.9 | 0.11078 | 0.11104 | 0.11177 | 9.580 |
| 2 | 0.2 | 0.8 | 0.20634 | 0.20681 | 0.20973 | 21.900 |
| 3 | 0.3 | 0.7 | 0.27391 | 0.27399 | 0.27417 | 25.173 |
| 4 | 0.4 | 0.6 | 0.32640 | 0.32658 | 0.32790 | 25.753 |
| 5 | 0.5 | 0.5 | 0.36954 | 0.36985 | 0.37054 | 25.901 |
| 6 | 0.6 | 0.4 | 0.40335 | 0.40375 | 0.40416 | 25.737 |
| 7 | 0.7 | 0.3 | 0.42581 | 0.42627 | 0.42724 | 25.005 |
| 8 | 0.8 | 0.2 | 0.43646 | 0.43705 | 0.43754 | 24.576 |
| 9 | 0.9 | 0.1 | 0.43034 | 0.43110 | 0.43204 | 24.069 |

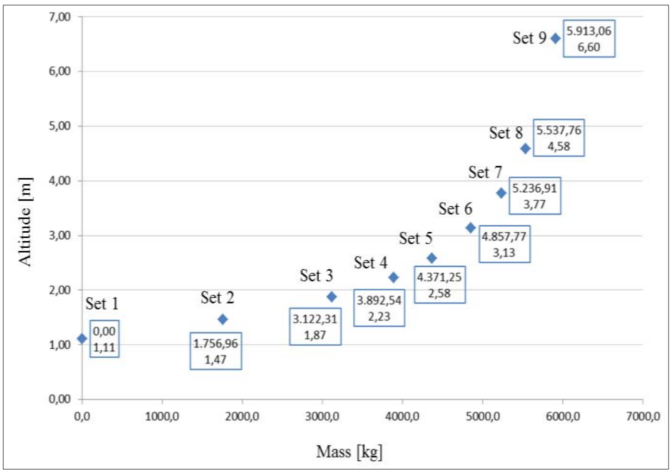


Fig. 3. Pareto front results of 9 set combinations.

Results show that, although the set 1 has the best fitness function ($f_{total}$), the calculated altitude is zero "0". Correspondingly, set 9 has the worst $f_{total}$, and the mass is the heaviest. Therefore, both designs are not efficient for the HRE. For instance, the altitude of set 9 is reachable with other efficient HRE designs changing upper and lower bounds of the genes. Under these circumstances, the most efficient HRE design and the weight combinations can be found by comparing mass and altitude values. The best rate of gaining altitude against used mass can be calculated in set 4 with 1744.09 m. is reached per 1 kg. mass. In set 4, the HRE can reach to 3892.54 m. with 2.23 kg. mass. The values of the HRE design of set 4 is presented in Table IV.

TABLE IV: DESIGN VARIABLES OF SET 4

| | **Design Variables** | **Found Value** |
|---|---|---|
| **Gene 1** | $M_{oxi}$ [kg] | 0.727 |
| **Gene 2** | $L_{Port}$ [m] | 0.599 |
| **Gene 3** | $R_{port}(0)$ [m] | 0.00505 |
| **Gene 4** | $T_{burn}$ [s] | 9.901 |
| **Gene 5** | $P_{ch}$ [bar] | 39.98 |
| **Gene 6** | $\epsilon$ | 4.72 |

In Table IV, the results are found as oxidizer mass ($m_{oxi}$) is 0.727, engine length ($L$) is 0.599, initial port radius ($R_{port}(0)$) is 0.00505, combustion duration time ($T_{burn}$) is 9.901, chamber pressure ($P_{ch}$) is 39.98 and nozzle area ratio ($\in$) is 4.72. For another selection strategy, if the mass limit is 3 kg., than set 5 can also be used to design HRE to reach to the maximum altitude.

## V. CONCLUSION

In this study, a single-stage HRE of a low-altitude sounding rocket is conceptual designed by using the MOVGA. Design problem has an objective function with the combination of the maximization of the altitude and the minimization of the total mass. With little changes in the genes, vibrational mutation allows the algorithm to have diversity in the population. Among 9 set combinations for MOVGA, results show that total mass of the rocket increases dramatically as the maximum flight altitude is set higher. Set 4 weight combination is suggested for a HRE design. The design parameters are going to be used for an experimental study. The optimum HRE design will be manufactured for ground and flight tests.

Other (meta)heuristics, matheuristics or hyperheuristics can also be tried for the HRE design problem. Design parameters can be changed for bigger sized and efficient HREs for future studies. Rocket aerodynamic design parameters (i.e. fin dimensions) may be considered for other type of desgn problems. Besides, the proposed algorithm can also be used for other type of rocket engine design problems. Other types of objective functions such as maximum "g" force can be added to the mathematical model.

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