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EFFECT OF HYDROGEN BLENDING ON OPTIMUM MACH NUMBER OF RAMJET ENGINE

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ABSTRACT

The presented study aimed to determine the performance parameters especially the optimum flying Mach number during different operating conditions of ramjet engine. The thermodynamic model is written based on dimensionless groups of pressure and temperature throughout the cycle of Ramjet engine. The study represents an investigation of the characteristics of the Ramjet engine fired with hydrogen blended fuel. The selected percentages of blended fuel areranged from (0-100%) hydrogen. Five selected blending ratio (20%, 40%, 60%, 80%, 100%) hydrogen was tested to predict the performance parameters of Ramjet engine. The optimum value was at Mach no. of 2.4 at higher blended fuel.

Keywords: *air-breathing engines, ramjet, hydrogen, blended fuel, specific thrust.*

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Nomenclature

c_p	Constant pressure specific heat, $kJ/(kgK)$
F	Thrust force, N
F_s	Specific thrust force, $N/(kgs)$
h	Enthalpy, kJ/kg
h_{PR}	Lower heating value, kJ/kg
$\dot{m}_0$	Mass flowrate of air, kg/s
$\dot{m}_f$	Mass flowrate of fuel, kg/s
M	Mach number
p	Static pressure, Pa
T	Static temperature, K
T_{max}	Material temperature limit, K
f	Fuel-to-air ratio
v	Air velocity, m/s

1. INTRODUCTION

The aerospace systems and high-speed transport aircraft require flying in wide speed and high altitudes ranges. Such requirements need not only traditional engines on the whole flight trajectory but an engine with flexible work regime as well. Ramjet is the most promising engine among the air-breathing engines considering the design, the structure of the engine as well as the mode of operation. Unlike the other air-breathing engine ssuch as turbojet or even that gas turbine or its different cycle arrangements, ramjet contains no moving parts the matter which makes it lighter, simpler and wider spreading[1, 2].

Ramjet can be operated either by solid or liquid fuel. The liquid hydrogen is commonly used as a fuel in ramjet engine. The characteristics of fuel definitely play an important role in determining the performance of ramjet engine especially that in concern with flight Mach number and thrust force. The demand on jet fuels still increases day by bay and in the aviation sector unlike the power generation plants, the renewable energies do not contribute in the energy production. Therefore it is worth to test the compatibility of alternative fuels for the air-breathing engines and in particular the ramjet engine. The aviation biofuel can reduce greenhouse gas emissions.

Since a ramjet engine can be considered as a chemical propulsion engine, which converts the heating value of combustion of fuel with air into exhaust flow kinetic energy, it can be seen as a thermodynamic device. To predict the ramjet engine's performance, a model based on thermodynamic analysis is usually used. The model of ramjet and turbojet is commonly assumed to be based on Brayton cycle which contains two adiabatic and tow isobaric processes [2-4].

Roux J.A. study theoretically the optimum free stream Mach number for maximum thrust flux, minimum specific fuel consumption and optimum Mach number for fuel and material limit for ideal ramjet/scramjet without assigning a specific operating fuel and derive an explicit formulas to determine these parameters. Till Roux works these values were determined numerically or graphically as he claimed [5-8].

Min Ou et al performed thermodynamic analysis of ramjet engine at wide working conditions. They discussed the effect of the pressure ratio and temperature ratio on the performance of a ramjet, and the entropy production in the isobaric combustion process of the combustor is the main part of the total entropy in the whole process. In their study, they showed that the specific cross sectional area and the air to fuel ratio play an important role on the whole engine and they calculated the optimal value of them [9].

2. EFFECT OF TYPE OF FUEL ON THE PERFORMANCE OF RAMJET ENGINE

The efficient combustion process is controlled by some major factors; one of them; the fuel heating value since it determines the heat released by combustion. Therefore the lower heating value of the fuel that will be burned plays an important role in the design and numerical simulation of combustion processes within air-breathing engines or in particular ram/scram jet engines. Till nowadays there are two options to operate these engine either hydrocarbon fuels or hydrogen fuels. The performance parameters change dramatically with type of fuel used as shown in **Figure 1.** In general ramjet engine is more suitable to operate within the range of Mach number of (3-6), after this the scramjet is more suitable in the flight Mach number more than 6[9].

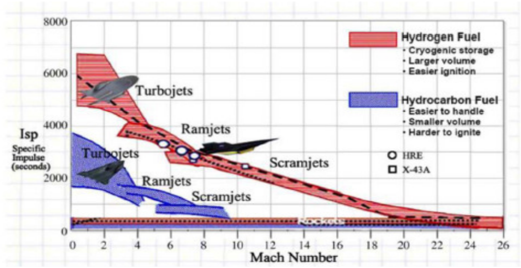

Figure 1 Hypersonic engine specific fuel impulse vs. free stream Mach number [10]

Recently, there has been a significant attention in the use of dual fuel and blended fuels to operate air-breathing engines due to its environmentally-friendly properties especially that include biodiesel as one of its constituents because it is renewable and more environmentally friendly than other types [11].This, in its turn, gives the motivation to study the characteristics operation performance parameters of the ramjet engine when fired by such fuels and figure out feasibility in using it as a working fuel from different performance curves.

3. MATHEMATICAL MODEL

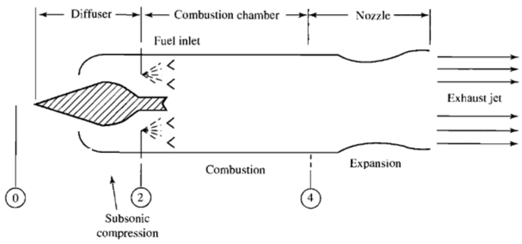

Figure 2 shows the physical model of a ramjet engine which includes an inlet, a combustor and a nozzle.

In thermodynamics analyses of ramjet, the engine is usually considered as Brayton cycle, in which the combustion is supposed to be a constant pressure heating process. This consideration is quite valuable if we take a look on the results of the comparison between experimental and theoretical data of the experiments which were conducted in the university of Queensland as shown in **Figure 3** which is summarized by ref. [12, 13].

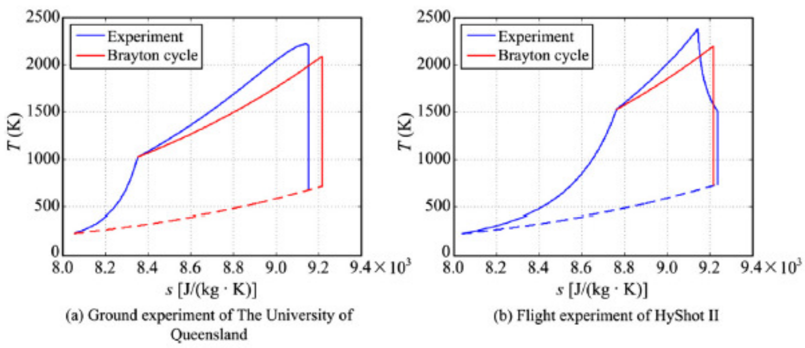

Figure 3 Comparison of T-s diagram between the experiments and results of Brayton cycles [13].

The total to static temperature and pressure ratios of the free stream can be defined as:

$$\tau_r = \frac{T_{t0}}{T_0} = 1 + \frac{\gamma-1}{2} M_0^2 \quad (1)$$

$$\pi_r = \frac{p_{t0}}{p_0} = \left(1 + \frac{\gamma-1}{2} M_0^2\right)^{\gamma/(\gamma-1)} \quad (2)$$

$$\tau_b = \frac{T_{max}}{T_0} \quad (3)$$

The specific thrust force can be defined as

$$F_s = \frac{F}{\dot{m}} = a_o M_o \left(\sqrt{\frac{\tau_\lambda}{\tau_r}} - 1\right) \quad (4)$$

Where $\tau_\lambda = \tau_r \tau_b$

And the specific fuel consumption

$$SFC = \frac{C_p T_o (\tau_\lambda - \tau_r)}{a_o M_o h_{PR} (\sqrt{\tau_\lambda / \tau_r - 1})} \quad (5)$$

Where the fuel/air ratio

$$f = \frac{C_p T_o}{h_{PR}} (\tau_\lambda - \tau_r) \quad (6)$$

The thermal efficiency

$$\eta_T = 1 - \frac{1}{\tau_r} \quad (7)$$

And the propulsive efficiency

$$\eta_p = \frac{2}{\sqrt{\tau_\lambda / \tau_r} + 1} \quad (8)$$

Where the overall efficiency can be found as

$$\eta_o = \eta_T \eta_p = \frac{2(\tau_r - 1)}{\sqrt{\tau_\lambda \tau_r} + \tau_r} \quad (9)$$

Combustion model

The combustion chamber is designed to burn a mixture of fuel and air to deliver the resulting gases to the turbine at a uniform temperature. The combustor wall is assumed to be adiabatic and frictionless. The gas temperature of the turbine must not exceed the allowable structure temperature of the turbine. A schematic of combustion chamber is shown in **Figure 4**. Since the process is adiabatic with no work transfer, the combustion process is assumed to be isobaric heat addition process, so the energy equation, is simply[14];

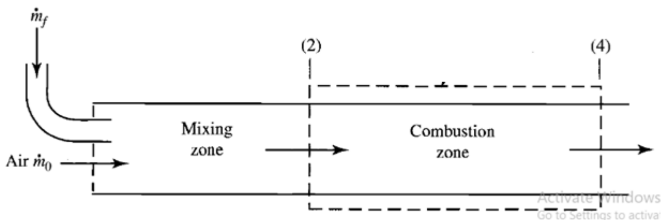

Figure 4 Model of the combustor

$$\sum(m_i h_{i,3}) - (h_2 - f.h_{f,t}) = 0 \quad (10)$$

Now making the enthalpy of reaction at a reference temperature of 25 C, so equation can be expanded in the usual way to get[15];

$$(1 + f_t) c_{p_g} (T_3 - 298) + f_t \Delta H_{25} + c_{p_a} (298 - T_2) + f_t c_{p_f} (298 - T_f) = 0 \quad (11)$$

By simplifying equation () the theoretical fuel to air ratio will be:

$$f_t = \frac{c_{p_g}(T_1 - T_3) + c_{p_a}(T_2 - T_1)}{c_{p_g}(T_3 - T_1) + \Lambda H_{25}} \quad (12)$$

The actual (fuel / air) ratio for given temperature difference is given by;

$$f_a = f_t / \eta_b \quad (13)$$

The following Correlation was obtained to get maximum thermal efficiency[15]:

$$\eta_{max} = \left((25.47 + 29.2J) + (2.2 + 3.3J)\ln(C_1 + C_2)\right)\% \quad (14)$$

Where

$$J = ln\left(\frac{T_{max}}{1000}\right) \quad (15)$$

The above equation examined the variation of maximum thermal efficiency with both hydrocarbon and alcohol fuels with fuel parameter $(C_1 + C_2)$ taken from the equation of reaction:

$$C(fuel) + O_2 \rightarrow C_1(CO_2) + C_2(H_2O) \quad (16)$$

The resulted values of lower heating value in different blended mixture of kerosene and hydrogen are listed in Table 1. These values were calculated from above mentioned equations.

Table 1 Blended fuel heating values with different blending ratio

% H_2	% Kerosine	Hpr	nCO2	nH2O	nO2	C1	C2	C1+C2
0	1	42500	12	11.5	17.75	0.676056	0.647887	1.323944
0.1	0.9	50250	10.8	10.45	16.025	0.673947	0.652106	1.326053
0.2	0.8	58000	9.6	9.4	14.3	0.671329	0.657343	1.328671
0.3	0.7	65750	8.4	8.35	12.575	0.667992	0.664016	1.332008
0.4	0.6	73500	7.2	7.3	10.85	0.663594	0.672811	1.336406
0.5	0.5	81250	6	6.25	9.125	0.657534	0.684932	1.342466
0.6	0.4	89000	4.8	5.2	7.4	0.648649	0.702703	1.351351
0.7	0.3	96750	3.6	4.15	5.675	0.634361	0.731278	1.365639
0.8	0.2	104500	2.4	3.1	3.95	0.607595	0.78481	1.392405
0.9	0.1	112250	1.2	2.05	2.225	0.539326	0.921348	1.460674
1	0	120000	0	1	0.5	0	2	2

Expansion Process

The nozzle expands the gas to or near the ambient pressure, and the temperature decreases from T_4 to ambient temperature with a corresponding increase in the kinetic energy per unit mass. The following equations dominant the flow according to the following equation and law of conservation of energy in which all chemical energy burned in combustion process will convert into kinetic energy:

$$h_4 + \frac{v_4^2}{2} = h_0 + \frac{v_0^2}{2} \quad (17)$$

From this equation, the exit velocity can be easily determined and thus the other parameters like specific thrust, specific fuel consumption and thermal efficiency will be calculated.

Optimum Mach number

The relationship between specific thrust and Mach number and the resulting graph shows that the maximum value of specific thrust is exhibited at a certain Mach number for some value of T_{max}. An analytical expression for this optimum Mach number can be derived by taking the partial derivative of this relationship with respect to flight Mach number, setting this partial derivative to zero, and solving as follows, the whole procedure is explained in [2, 4].

Referring to equation (4) and differentiate gives

$$\frac{\partial}{\partial M_0}\left(\frac{F}{\dot{m}_0}\right) = a_0 \frac{\partial}{\partial M_0}\left[M_0\left(\sqrt{\frac{\tau_\lambda}{\tau_r}} - 1\right)\right] = 0 \qquad (18)$$

$$\sqrt{\frac{\tau_\lambda}{\tau_r}} - 1 + M_0\sqrt{\tau_\lambda}\frac{\partial}{\partial M_0}\left(\frac{1}{\sqrt{\tau_r}}\right) = 0 \qquad (19)$$

Now

$$\frac{\partial}{\partial M_0}\left(\frac{1}{\sqrt{\tau_r}}\right) = -\frac{1}{2}\frac{1}{\tau_r^{\frac{3}{2}}}\frac{\partial \tau_r}{\partial M_0} = -\frac{1}{2\tau_r^{3/2}}\frac{\partial}{\partial M_0}\left(1 + \frac{\gamma-1}{2}M_0^2\right) = -\frac{(\gamma-1)}{2\tau_r^{3/2}}M_0 \qquad (20)$$

Re-arranging, substituting and solving for the value of Mach no. and thus the maximum specific thrust occurs when

$$\tau_{r\ for\ max\ F_s} = \sqrt[3]{\tau_\lambda} \qquad (21)$$

and

$$M_{0\ for\ max\ F_s} = \sqrt{\frac{2}{\gamma-1}\left(\sqrt[3]{\tau_\lambda} - 1\right)} \qquad (22)$$

4. RESULTS AND DISCUSSION

Applying the physical properties of air and considering constant specific heats, the mathematical model was run for different percentages of hydrogen starts from 0% to 100%. Only five of them (20%, 40%, 60%, 80%, 100%) were selected to plot the multiple performance curves of ramjet. Also, four different maximum temperature in the combustor section (1600 K, 1800 K, 2000 K, 2200 K) were selected.

Figure 1 shows the specific thrust against Mach no. with different values of blend ratios. Obviously as much as higher hydrogen in fuel constituents the higher is resulted specific thrust. Beyond the optimum value of Mach no. which was 3.2, the specific thrust tends to decrease because of higher mass flow rate than that of optimum value.

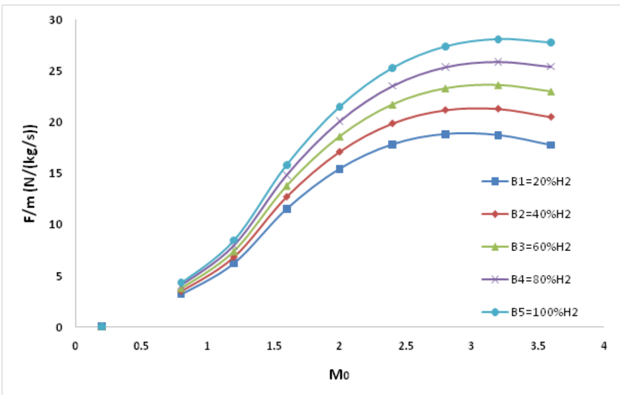

Figure 1 The relationship between specific thrust and Mach no. at different blended ratios

The behavior of the specific fuel consumption can be interpreted as a combination of three major influences; flight Mach number, temperature ratio τ_{λ} and the heating value of the fuel. The heating value of the fuel in this study is a function of blending ratio and how much hydrogen does it contain. Thus, as the flight Mach number increases, the required increase in energy requirement appears. At beginning of operation the engine is expected to consume more fuel till it reaches a steady and stable flight condition. This explain the higher consumption of fuel at low Mach no. and decreasing of it with increasing of Mach no. as shown in **Figures 2 & 3** respectively.

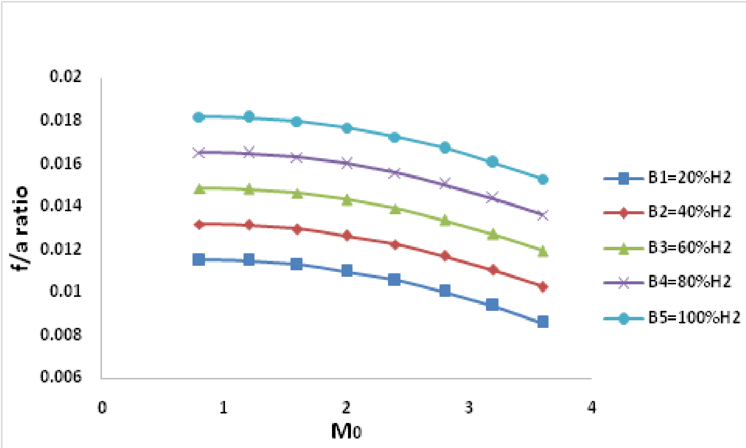

Figure 2 The relationship between fuel to air ratio and Mach no.

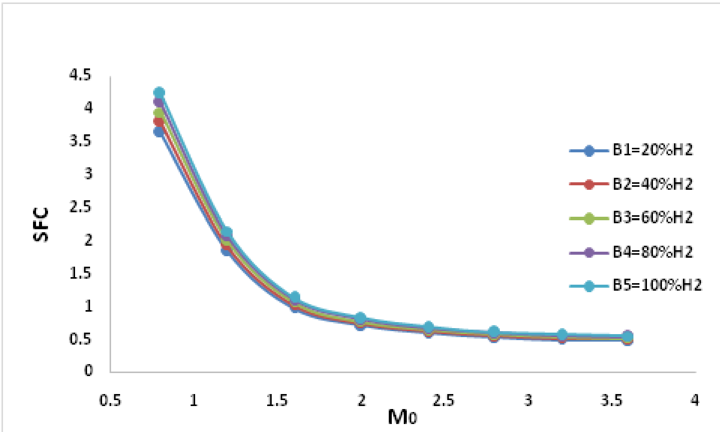

Figure 3 The relationship between specific fuel consumption and Mach no.

The effect of blended ratio on the performance parameters is studied. As the ratio of hydrogen is increased, the Mach no. also increases due to increasing of heating value of fuel and more power produced which is well reflected in **Figure 4.**

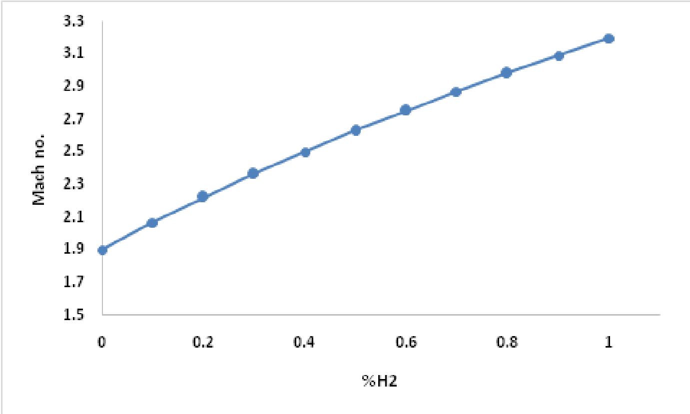

Figure 4 The relationship between Mach no. and the blend ratio

Thermal efficiency is plotted versus the Mach no. which increases with increasing of the value of Mach no. regardless the heating value of fuel, i.e., the fuel type and blend ratio as shown in **Figure 5**. Maximum the thermal efficiency is also plotted versus blend ratio and once again versus the maximum temperature. The thermal efficiency increases marginally with low blend ratio and low temperature but tend to increase rapidly at higher values (80% blend ratio and 2500 K) which is shown in **Figure 6& 8**.

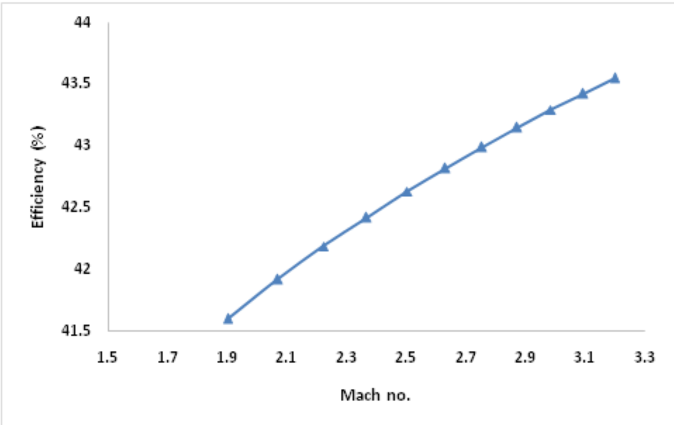

Figure 5 Thermal efficiency versus Mach no

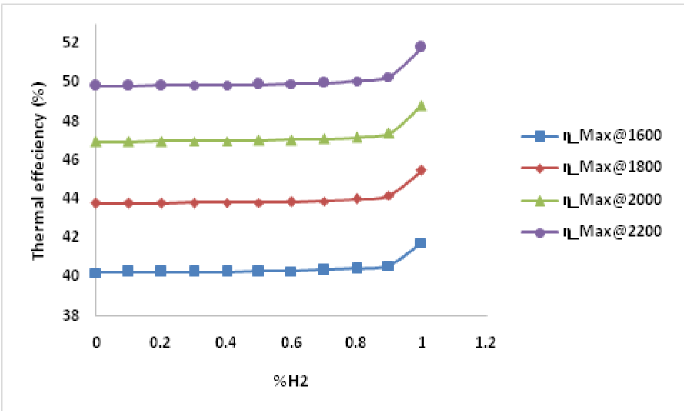

Figure 6 The relationship between maximum thermal efficiency and blend ratio at different vlaues of maximum temperature

The propulsive efficiency in air-breathing engines especially in ram and scram jet plays an important role in prediction the performance of such engines. In order to increase the propulsive efficiency the exit velocity should be reduced. This, of course, will come with a penalty in thrust if the mass flow is not reduced. An obvious way to obtain good propulsive efficiency is to move a very large mass throughout the engine. Propulsive efficiency is calculated at different conditions and showed a rapid increase at first period of flight time to reach a stable state beyond that as shown in **Figure 7**.

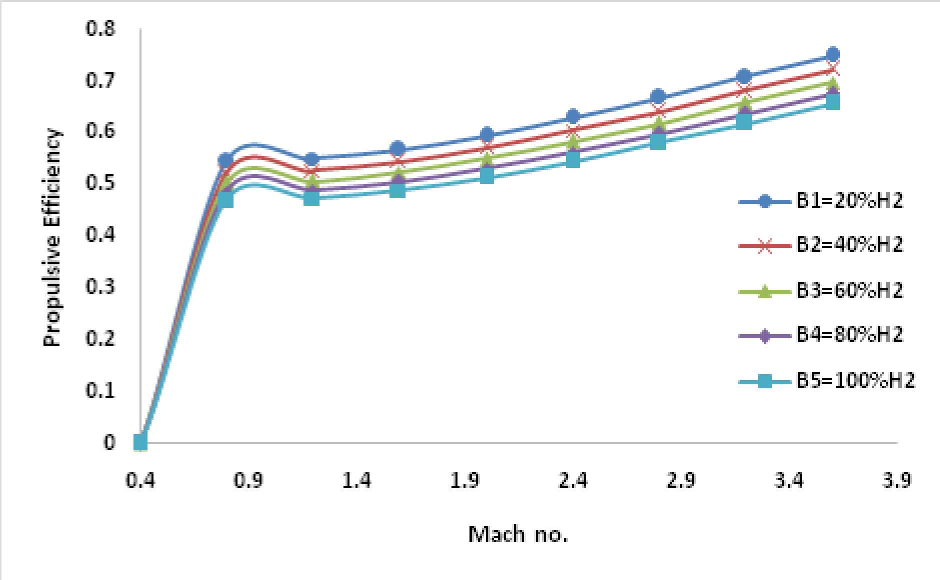

Figure 7 The Propulsive Efficiency versus Mach no

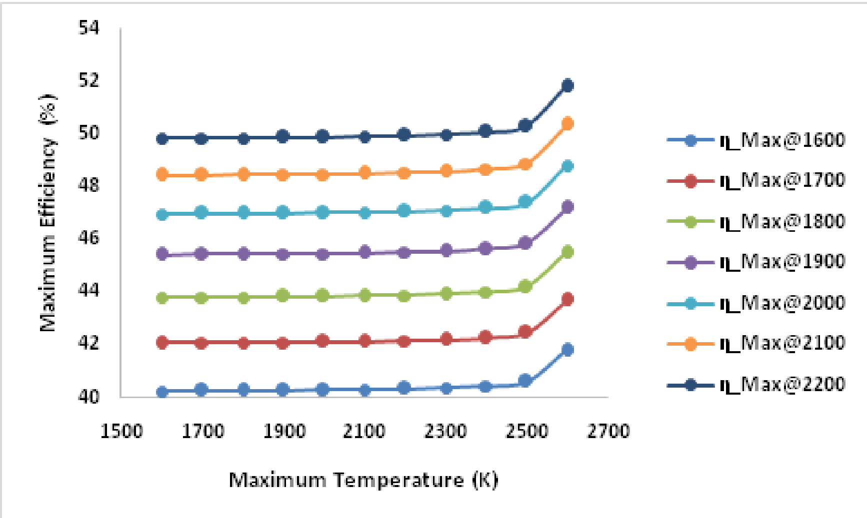

Figure 8 The relationship between Maximum Efficiency and Maximum Temperature

Validation of the model

Although less attention in previous studies was directed on testing ramjet which operates with blended fuel, comparison of this model was tested with different review studies[16-20]. By running the model with pure kerosene or pure hydrogen and comparing the results with that of the previous references. The trends, values and major performance curves were approximately coincided since the model shows a good and reliable agreement.

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