Using openMotor to Compare Port Shapes and Custom Propellent

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OpenMotor is a free software for designing motors. It provides theoretical visualizations for the performance of customizable solid rocket motors, nozzles, and propellant. I used openMotor to compare two custom propellants I made myself: Happy Times and Sad Times, as well as a custom port design in the shape of a propeller (Figure 2).

Propellant and Port Simulations

In order to create two sufficiently different propellants to compare, I made a chart comparing some of the default propellants that openMotor had to offer and analyzed correlations and trends in their parameters (Table I).

For instance, I noticed that Cherry Limeade, a default propellant, had a density of 0.06 lb/in^3 with a maximum pressure of 1000 psi. A different default propellant, KNSU, had a density of 0.065 lb/in^3 and a max pressure of 1500 psi. With my default propellants, Happy Times and Sad Times, I tried to capture the range of parameters (upper and lower limits) as well as implied correlations: like Cherry Limeade, Happy Times has a lower density and a lower max pressure, and like KNSU, Sad Times has a higher density and a higher max pressure. In this way, I attempted to create propellants that were within the realm of possibility but were on opposite ends of the spectrum for typical solid rocket propellants.

Figure 1 shows the Thrust and Pressure profiles for a burn of Happy Times and Sad Times using BATES design in a 10-in long motor with a 2-in diameter and 1-in diameter portal.

Figures 3 shows the performance of Happy Times and Sad Times with my custom-designed propeller-shaped port (Figure 2).

Parameter Simulations

The next step of my analysis on basic performance of these custom propellants was to choose three parameters to change and see what effect they had on the motor performance. The first of these parameters was divergence half-angle. Figures 5 and 6 show screenshots of openMotor's simulation when I changed the divergence half angle to 60 degrees and 10 degrees. The effects are that the impulse, delivered ISP, and thrust coefficient change with a change in divergence half angle. All three parameters lower with an increase in divergence half-angle.

I also experimented with changing the exit diameter of the nozzle. During all previous simulations, the exit diameter had been 2 in. Figures 7 and 8 show what happens when I increase the diameter to 3 inches and decrease the diameter to 1.5 inches (less than the diameter of the motor) respectively. With a larger diameter, the Impulse, Delivered ISP, and Delivered Thrust Coefficient are reduced. However, with a decrease in nozzle exit diameter to even less than the diameter of the propellant, Impulse, Delivered ISP, and Delivered Thrust Coefficient are increased. This makes sense seeing as with the same mass flow rate, a decrease in area would necessitate an increase in thrust.

The final parameter I experimented with was the length of the propellant. Figure 9 shows the graph for a 20-in long Happy Times in BATES configuration to be compared to the left side of Figure 1, which was only half as long. The thrust is massively increased, reaching a maximum of more than twice that of the 10-in-long Happy Times, at around 2500 N. This makes sense to me due to the fact that a longer propellant would equal a longer burn period, which would produce more thrust.

Erosion and Build-Up Parameters

In the previous simulations, I had left the slag build-up coefficient and throat erosion coefficient at 0.

In increasing the Slag build-up coefficient to 1 in-psi/sec, I saw an increase in the Impulse to 910 Ns, delivered thrust coefficient to 1.03 and ISP to 169.76 seconds. (Figure 10) Previously, the numbers were 882 Ns, 164.53 seconds and 1.01 respectively. (Figure 6)

In increasing the thrust erosion coefficient to 1 thou/sec-psi, thrust and impulse and overall performance decreased dramatically (Figure 11), the burn time increased, and the thrust coefficient delivered decreased to only 0.06 (Figure 12).

Summary and Analysis

Happy Times is a lighter, less dense propellant, with a lower specific heat ratio, a higher burn rate exponent, a lower burn rate coefficient, and a higher combustion temperature than Sad Times. The burn rate exponent may have had the biggest effect on the thrust, due to the rate of burning equation:

(Eq 1) $$r = aP_c^n$$

Where r is the burn rate, Pc is the chamber pressure, a is the burn rate coefficient, and n is the burn rate exponent. Perhaps Happy Times could have produced even more Thrust had the burn rate coefficient been higher. The biggest difference between Happy Times and Sad Times is the molar mass of the exhaust, but I'm not sure how that parameter contributes to motor performance.

BATES port shape burned steadily and its thrust and pressure increased linearly with time (Figure 1). This makes sense, given that the inner diameter surface area increased at the same rate (the derivative of the area of a circle, to be exact). My custom design had a thrust profile that started out very high, then decreased greatly and burned rather steadily at the end (Figure 3). This makes sense because much more surface area was exposed initially, but then the "arms" of the propeller shape slowly burned through the rest of the propellant until at the end, there was only a circular shape remaining.

As for the effect of the thrust erosion coefficient, Lenior and Robillard's equation may apply (Eq2)

(Eq2) $$r_b = aP_c^n + \frac{AG^{0.8}}{L_{0.2}} e^{\frac{-\beta \rho_b r_b}{G}}$$

The burn rate would be increased by the effect of thrust erosion. Looking at the graph in figure 11, perhaps this is the case initially, where thrust increases dramatically in the first few milliseconds in comparison to the BATES graphs with no thrust erosion (Figure 1), but over time, the thrust decreases. I think this may be due to erosion complicating the geometry and instead of burning steadily as in an ideal solution, burning would happen unsteadily. I'm unsure of the cause of this phenomenon but to surmise that thrust erosion in solid motors will decrease thrust efficiency but may be desired if one wants a longer burn time and higher initial thrust from a BATES design solid motor.

Tables and Figures

Table I: Parameters of openMotor's default propellants, Happy Times and Sad Times

Parameter	Unit	Cherry Limeade	Ocean Water	KNSU	Happy Times	Sad Times
density	lb/in^3	0.060333	0.05961	0.065029	0.06	0.065
max pressure	psi	1000	1000	1500	1200	1500
burn rate coeff	s*psi^n	0.024986	0.016901	0.0665	0.025	0.06
burn rate exponent	n	0.3273	0.382	0.319	0.4	0.3
specific heat ratio		1.21	1.25	1.133	1.2	1.3
combustion temp	K	2800	2600	1720	3000	1500
exhaust molar mass	g/mol	23.67	23.67	41.98	24	42
Characteristic velocity	ft/s				**5156**	**2678**

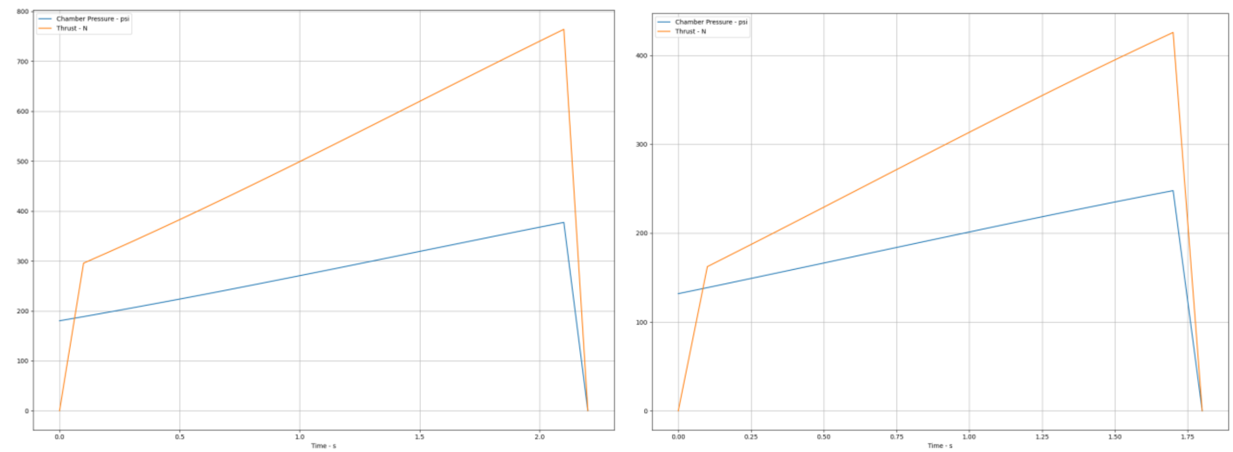

Figure 1: Chamber Pressure and Thrust vs. Time for a 10-in long BATES Happy Times (left) and Sad Times (right)

Figure 2: The Face and regression patter of my custom propeller port in the openMotor UI

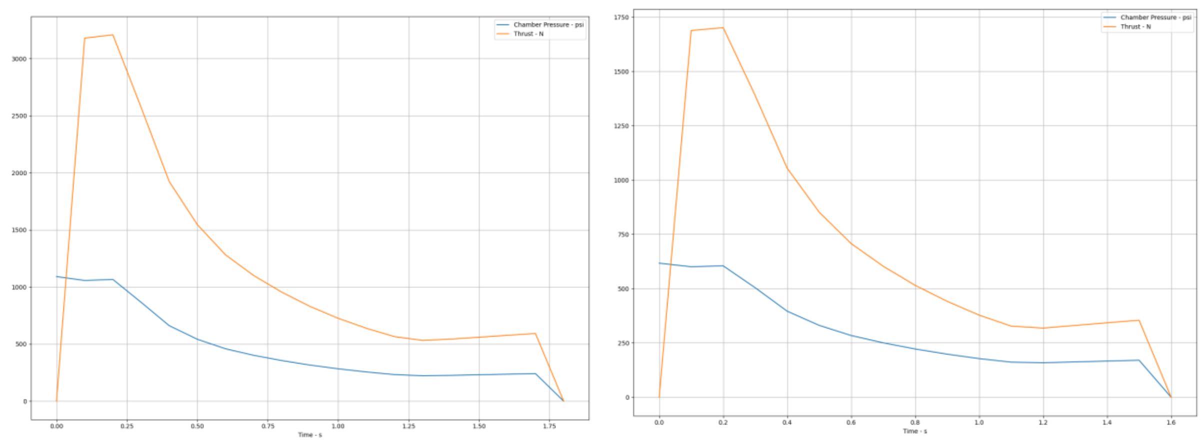

Figure 3: Happy Times (left) and Sad Times (right) using the custom propeller port

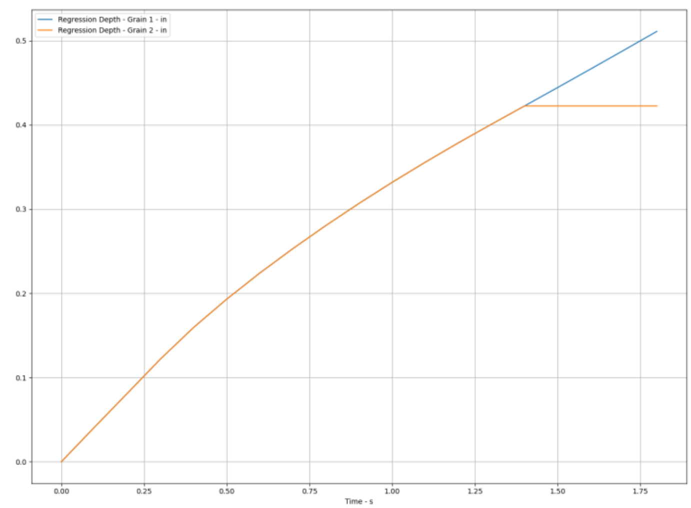

Figure 4: Regression depth vs. Time for both BATES grain (Grain1) and propeller grain (Grain2) using Happy Times propellant

Motor Statistics

Motor Designation:	J317	Average Pressure:	188.76 psi	Propellant Mass:	1.21 lb
Impulse:	667.25 Ns	Peak Pressure:	250.61 psi	Propellant Length:	10.00 in
Delivered ISP:	124.34 s	Initial Kn:	83.00	Port/Throat Ratio:	2.25
Burn Time:	2.00 s	Peak Kn:	114.39	Peak Mass Flux:	0.37 lb/(in^2*s) (G: 1)
Volume Loading:	64.00%	Ideal Thrust Coefficient:	1.19	Delivered Thrust Coefficient:	0.76

Figure 5: BATES Happy Times with a divergence half-angle of 60 degrees

Motor Statistics

Motor Designation:	J420	Average Pressure:	188.76 psi	Propellant Mass:	1.21 lb
Impulse:	882.91 Ns	Peak Pressure:	250.61 psi	Propellant Length:	10.00 in
Delivered ISP:	164.53 s	Initial Kn:	83.00	Port/Throat Ratio:	2.25
Burn Time:	2.00 s	Peak Kn:	114.39	Peak Mass Flux:	0.37 lb/(in^2*s) (G: 1)
Volume Loading:	64.00%	Ideal Thrust Coefficient:	1.19	Delivered Thrust Coefficient:	1.01

Figure 6: BATES Happy Times with a divergence half-angle of 10 degrees

Motor Statistics

Motor Designation:	I260	Average Pressure:	188.76 psi	Propellant Mass:	1.21 lb
Impulse:	547.97 Ns	Peak Pressure:	250.61 psi	Propellant Length:	10.00 in
Delivered ISP:	102.11 s	Initial Kn:	83.00	Port/Throat Ratio:	2.25
Burn Time:	2.00 s	Peak Kn:	114.39	Peak Mass Flux:	0.37 lb/(in^2*s) (G: 1)
Volume Loading:	64.00%	Ideal Thrust Coefficient:	0.69	Delivered Thrust Coefficient:	0.59

Figure 7: BATES Happy Times with an exit diameter of 3 in

Motor Statistics

Motor Designation:	J456	Average Pressure:	188.76 psi	Propellant Mass:	1.21 lb
Impulse:	958.62 Ns	Peak Pressure:	250.61 psi	Propellant Length:	10.00 in
Delivered ISP:	178.64 s	Initial Kn:	83.00	Port/Throat Ratio:	2.25
Burn Time:	2.00 s	Peak Kn:	114.39	Peak Mass Flux:	0.37 lb/(in^2*s) (G: 1)
Volume Loading:	64.00%	Ideal Thrust Coefficient:	1.31	Delivered Thrust Coefficient:	1.11

Figure 8: BATES Happy Times with an exit diameter of 1.5 in

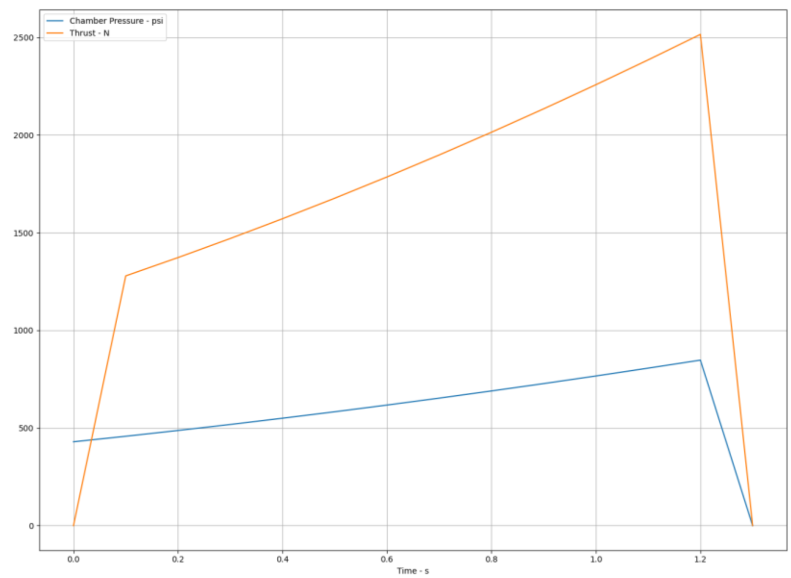

Figure 9: BATES Happy Times with a propellant length of 20 inches

Motor Statistics

Motor Designation:	J433	Average Pressure:	197.59 psi	Propellant Mass:	1.21 lb
Impulse:	910.95 Ns	Peak Pressure:	271.87 psi	Propellant Length:	10.00 in
Delivered ISP:	169.76 s	Initial Kn:	83.00	Port/Throat Ratio:	2.25
Burn Time:	2.00 s	Peak Kn:	120.12	Peak Mass Flux:	0.37 lb/(in^2*s) (G: 1)
Volume Loading:	64.00%	Ideal Thrust Coefficient:	1.21	Delivered Thrust Coefficient:	1.03

Figure 10: BATES Happy Times with Slag Build-up of 1 in-psi/sec

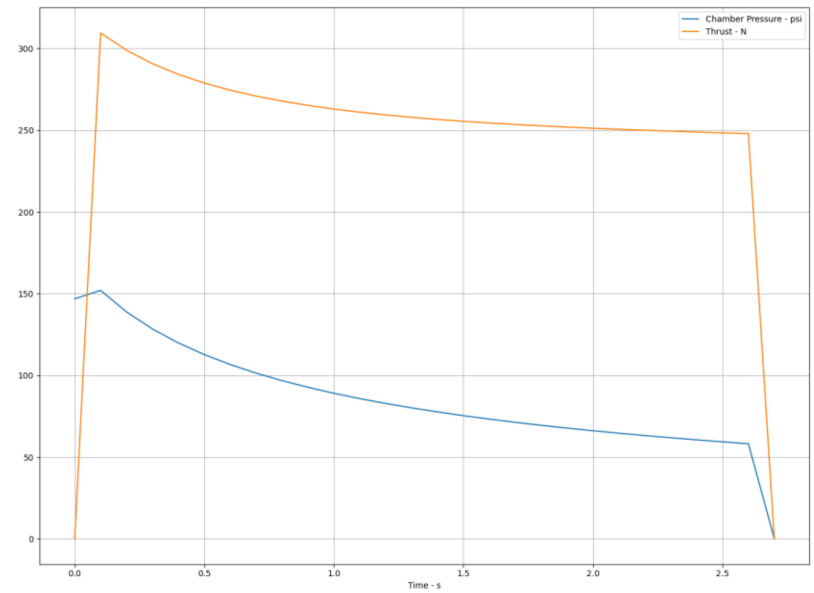

Figure 11: BATES Happy Times with Thrust Erosion Coefficient of 1 thou/s-psi graph

Motor Statistics

Motor Designation:	J244	Average Pressure:	85.79 psi	Propellant Mass:	1.21 lb
Impulse:	685.19 Ns	Peak Pressure:	151.97 psi	Propellant Length:	10.00 in
Delivered ISP:	127.69 s	Initial Kn:	83.00	Port/Throat Ratio:	2.25
Burn Time:	2.70 s	Peak Kn:	84.73	Peak Mass Flux:	0.37 lb/(in^2*s) (G: 1)
Volume Loading:	64.00%	Ideal Thrust Coefficient:	0.61	Delivered Thrust Coefficient:	0.52

Figure 12: BATES Happy Times with Thrust Erosion Coefficient of 1 thou/s-psi numbers