Experimental Evaluation of Throttling Characteristics in a Radial Injector Pump-Fed Rocket Engine

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Abstract. Throttleable liquid rocket engines are essential for missions requiring precise thrust modulation, including planetary descent and reusable launch applications. This paper presents an experimental evaluation of throttling performance in a pump-fed liquid rocket engine operating on a gas-generator cycle with earth-storable hypergolic propellants and a radial injector configuration. Throttling capability was achieved through modifications to the command pressure circuitry and gas-generator fuel regulator. Two hot tests were conducted to assess engine operability across a reduced chamber-pressure envelope. In the first test, chamber pressure was reduced stepwise to 66.7% of nominal conditions before shutdown, while in the second test throttling was demonstrated down to 48.6% and again ramping up to 100% chamber pressure, demonstrating repeatability and dynamic control. Stable combustion was maintained throughout the throttle range, with chamber pressure roughness remaining below 0.2% of the mean value. Characteristic velocity efficiency remained approximately 93% over most of the throttling range. No nozzle flow separation, cavitation, or dynamic instability was observed. Gas-generator regulation and turbopump operation remained satisfactory. The results demonstrate robust and repeatable throttling performance in a radial-injector pump-fed engine operating with earth-storable propellants.

Keywords: Chamber pressure, Combustion Stability, Gas Generator Cycle, Mixture Ratio, Throttling.

1 Introduction

Throttleable liquid rocket engines are essential for modern space missions that require precise thrust control. Thrust modulation, commonly referred to as throttling, has been studied since the early development of liquid propulsion systems [1] and is now indispensable for planetary descent, reusable launch vehicles and precision orbital maneuvers. Unlike fixed-thrust engines designed for a single operating point, throttleable engines must maintain performance, stability and structural integrity across a wide operating range.

In pump-fed liquid rocket engines, thrust is primarily determined by propellant mass flow rate, thus chamber pressure. Throttling is achieved by regulating propellant flow

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using thrust control valves, turbopump speed variation, injector geometry modification or a combination of these approaches [2][3][4]. However, throttling introduces strong dynamic coupling between the feed system, injector and combustion chamber. Injector mass flow depends on both upstream feed-line dynamics and downstream chamber pressure, making the system susceptible to combustion instabilities [5]. If not properly controlled, these oscillations can degrade performance and reduce structural margins.

Deep throttling was successfully demonstrated by the Apollo Lunar Module Descent Engine (LMDE), which required continuously variable thrust for controlled lunar landing [2]. More recently, reusable launch vehicles and planetary exploration missions have renewed the need for reliable wide-range throttling capability [1]. Upper-stage engines also benefit from thrust modulation to improve orbital insertion accuracy and mission flexibility [3].

Several methods have been developed to achieve throttling. Valve-based control is the most direct approach, where chamber pressure scales with propellant flow rate [4]. Variable-geometry injectors, such as pintle designs, improve throttling smoothness by varying effective flow area while maintaining injector pressure drop; this concept was successfully applied in the LMDE [2]. In pump-fed systems, turbopump speed modulation allows thrust variation according to classical turbomachinery affinity laws [3]. NASA's Common Extensible Cryogenic Engine (CECE) program further demonstrated deep throttling in an expander-cycle engine through coordinated turbopump and injector modifications [6]. Nevertheless, low-flow operation may approach cavitation and net positive suction head limits [4].

Earth-storable hypergolic propellants introduce additional considerations. Combinations such as N_2O_4 with hydrazine-based fuels offer long-term storability and reliable ignition, making them attractive for spacecraft propulsion and planetary descent systems [3]. However, reduced chamber pressure during throttling lowers injector pressure drop, potentially degrading atomization and mixing efficiency [4]. This can increase susceptibility to low-frequency combustion instability and reduce stability margins [5]. Throttling also affects cooling effectiveness, as reduced propellant flow lowers regenerative or film-cooling capacity, potentially increasing thermal stress during repeated throttle cycles [4].

Despite advances in modeling and experimental validation [1], deep throttling remains a multidisciplinary challenge involving combustion stability, turbomachinery operability, thermal management and control system response. In particular, limited experimental data exist for pump-fed engines employing radial injector configurations under throttled conditions.

The present study experimentally evaluates the throttling characteristics of a pump-fed liquid rocket engine equipped with a radial injector and operating on earth-storable hypergolic propellants. Emphasis is placed on combustion stability, injector performance and subsystem behavior across a defined throttle envelope relevant to planetary descent and reusable launch applications.

2 Methodology

In a typical liquid rocket engine, the fuel and oxidizer are stored in separate tanks and delivered to the combustion chamber through a feed system, where they are injected, mixed and combusted. The high-temperature combustion products are subsequently expanded through a convergent–divergent nozzle to produce thrust. The functional flow schematic of the engine considered in the present study is illustrated in Fig. 1. The engine is a bipropellant liquid rocket engine operating on a gas-generator (GG) cycle and utilizing hypergolic propellants. It employs a closed-loop control architecture in which engine thrust is regulated by maintaining chamber pressure at a commanded reference value.

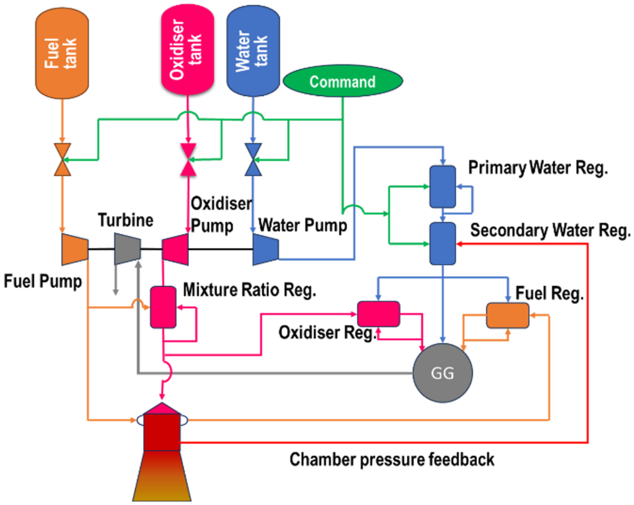

Fig. 1. Functional flow of engine in study

Thrust is regulated by controlling the flow rates of fuel, oxidizer and water supplied to the GG. In the GG, propellants combust and water injection limits turbine inlet temperature. The resulting hot gas drives the turbine, which is mounted on a common shaft with the propellant pumps. Mixture ratio in both the GG and main combustion chamber is maintained through mechanical pressure equalization. In the main chamber, oxidizer injection pressure is matched to fuel injection pressure using a mixture-ratio regulator. In the GG, injection pressures of fuel, oxidizer and water are equalized. A two-stage water regulator compares chamber pressure with the reference command pressure and modulates water flow to the GG; the propellant regulators adjust GG flow accordingly. During steady state operation, the secondary water regulator maintains chamber pressure at the reference value through negative feedback. Variations in chamber pressure adjust GG flow, turbine speed and pump delivery, thereby sustaining the required thrust level. The thrust chamber assembly comprises a radial injector, combustion chamber and convergent-divergent nozzle. The nozzle throat section is made of silica-phenolic material to withstand the high thermal and erosive loads encountered at peak heat flux conditions. Moreover, fuel-based film cooling is implemented, wherein a portion of the fuel is injected along the chamber wall to form a protective boundary layer, thereby reducing wall heat transfer and maintaining structural integrity during operation.

For the present test article, throttled operation introduces several performance and stability constraints associated with reduced chamber pressure. At reduced thrust levels, chamber pressure decreases, increasing the likelihood of internal flow separation within the nozzle due to overexpansion relative to ambient conditions. Such separation can generate unsteady side loads and fluctuating wall pressure distributions, particularly near the lower limit of the throttle envelope. However, computational fluid dynamics analysis of the present configuration indicates that flow separation is not expected below approximately 34% of nominal chamber pressure. During throttling, the decrease in injector pressure drop (ΔP) adversely affects spray breakup and mixing characteristics, leading to reduced combustion efficiency. This condition may result in elevated chamber pressure roughness and a narrowing of stability margins, especially when injector ΔP approaches the lower bound of the design specification. The propellant regulation system of the current engine also exhibits sensitivity during throttling. As chamber pressure decreases below approximately 60%, the propellant regulator approaches a near-closed condition, reducing controllability and introducing nonlinear response in the pressure-control loop. This behavior affects GG power balance and turbine speed regulation.

To enable throttling, modifications were implemented in both the engine command circuitry and the GG fuel regulator design. The chamber-pressure control loop was modified by incorporating a solenoid valve and a solenoid latch valve for controlled venting, as shown in Fig. 2. The GG fuel regulator piston geometry was revised by reducing the pintle angle from 10° to 6.5°, thereby improving flow metering sensitivity and control resolution under low-flow conditions. These modifications permit regulated adjustment of the reference chamber pressure, thereby enabling controlled thrust modulation across the desired throttle envelope.

The initial phase of throttling development for the present liquid rocket engine is undertaken to evaluate engine performance under reduced chamber pressure conditions. For this, two hot tests were conducted. In the first test, the chamber pressure is progressively reduced in predefined steps until engine shutdown. In the second test, the chamber pressure is throttled down to a reduced level, restored to nominal operating pressure and then throttled down again to assess repeatability and control stability.

The objectives of this phase include demonstrating the throttling capability of the engine using an external command-pressure-based throttling circuit; evaluating the performance of the modified propellant regulator under throttled conditions and demonstrating nozzle performance at reduced chamber pressures. Additional goals include studying combustion characteristics at lower chamber pressures through assessment of engine subsystem performance during throttling.

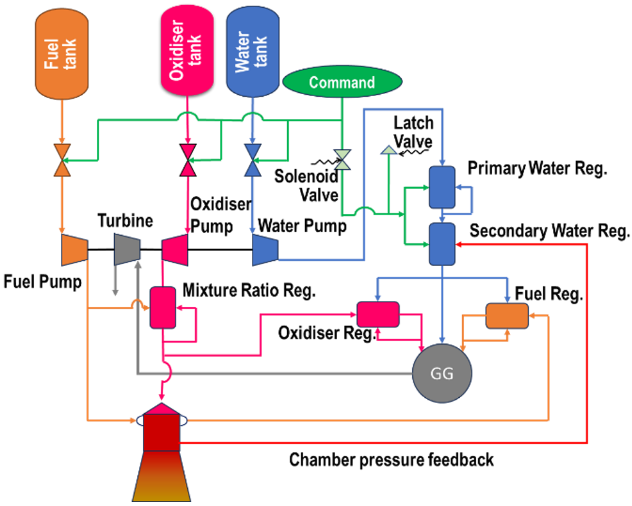

Fig. 2. Modified engine configuration for throttling tests

3 Results and Discussion

This section summarizes the hot-test results and examines engine performance, combustion stability and subsystem behavior under reduced chamber pressure conditions.

In the first hot test (T-1), the chamber pressure (P_C) was progressively reduced from the nominal operating condition to three discrete thrust levels, followed by a dwell at the GG closed flow condition and subsequently commanded shutdown at T_0+43s, as shown in Fig. 3. The venting sequence for command pressure was predefined prior to the test. After reaching the throttling level of 66.7%, command pressure venting was initiated at T_0+35s. Between T_0+40.2s and T_0+43s, a noticeable dwell in thrust level of 44.8% of nominal value was observed, attributed to the closing characteristics of the GG regulator. This regulator response temporarily limited further reduction in GG flow, resulting in a short stabilization period before shutdown. Overall, engine performance during throttled operation was found to be satisfactory. The achieved thrust levels are compared with predicted values in Table 1.

The anticipated performance and stability constraints associated with reduced chamber pressure, as discussed in Section 2, were evaluated during the hot test. No evidence of nozzle flow separation was observed, either from plume visualization using high speed imaging or from thrust measurements, indicating stable nozzle operation throughout the throttling range. Major performance parameters in the test T-1 are tabulated in Table 2.

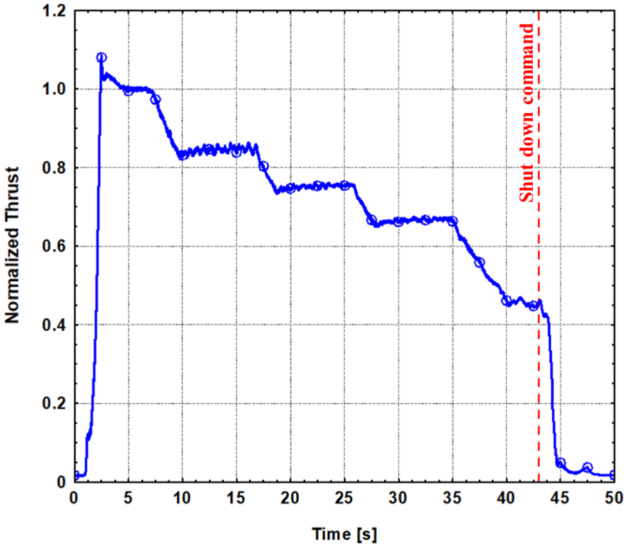

Fig. 3. Normalized Thrust profile in Throttling Test T-1

Table 1. Thrust levels in Throttling Test T-1

Time [s] (To+)	Thrust Level [%]	
	Predicted	Achieved
5 - 7	100.0	99.9
9.6 - 16.6	85.5	84.6
18.6 - 25.6	76.9	75.2
27.8 - 34.7	68.4	66.7
40.2 - 43	44.4	44.8

As expected, injector stiffness ($\Delta P_{injection}/P_C$) decreased with throttling due to the reduction in chamber pressure. Despite this reduction, chamber pressure remained stable across all throttle conditions. The measured chamber pressure roughness was limited to a maximum of 0.19% of the mean value at the throttle setting, indicating that adequate combustion stability margin was maintained. The low-frequency oscillations (~1 Hz) observed in chamber pressure correspond to the characteristic frequency of the thrust control loop. The characteristic velocity (C*) efficiency remained satisfactory across the targeted throttling range, maintaining a value of 93% for the targeted throttling. This indicates that combustion performance and propellant mixing efficiency were largely preserved during reduced chamber pressure operation. However, at the lowest throttle condition of 44.8% chamber pressure, the C* efficiency decreased to 89%. This reduction is attributed to the combined effects of lower injector pressure drop and diminished atomization quality at reduced chamber pressure, which can slightly affect combustion completeness.

Table 2. Major performance parameters in Throttling Test T-1

Normalized Main Injector & Combustion Performance					
Achieved Thrust Level [%]	$\frac{\Delta P_{injection}}{P_C}$ [%]		P_C roughness from mean value [%]	C* Efficiency	Achieved C_F
	Fuel	Oxidizer			
99.9	19.35	13.38	0.12	93%	1.55
84.6	16.89	11.73	0.19	93%	1.53
75.2	15.27	10.82	0.15	93%	1.51
66.7	13.66	10.11	0.17	93%	1.49
44.8	9.33	8.47	0.16	89%	1.42

GG Performance (Normalized with respect to nominal value)					
Achieved Thrust Level [%]	Injection pressures			GG Outlet Pressure	GG Outlet Temperature
	Water	Fuel	Oxidizer		
99.9	0.96	0.97	0.97	0.98	1.01
84.6	0.73	0.73	0.73	0.75	0.79
75.2	0.60	0.60	0.60	0.63	0.66
66.7	0.49	0.48	0.49	0.52	0.59
44.8	0.25	0.25	0.25	0.30	0.78

Turbopump Performance (Normalized with respect to nominal value)					
Achieved Thrust Level [%]	Pump outlet pressures			Turbine Speed	TP efficiency [%]
	Water	Fuel	Oxidizer		
99.9	1.00	1.01	0.99	1.01	36.3
84.6	0.80	0.83	0.84	0.89	35.0
75.2	0.69	0.73	0.74	0.82	33.7
66.7	0.59	0.64	0.65	0.75	32.1
44.8	0.37	0.42	0.42	0.55	22.1

The modified GG propellant regulator performed satisfactorily throughout the test. Even at reduced chamber pressures, the fuel and oxidizer injection pressures in the GG closely followed the regulated water injection pressure, indicating proper pressure equalization and mixture ratio control in GG. An increase in GG outlet temperature was observed. This rise was attributed to the reduction in command pressure, which consequently reduced the regulated water injection pressure supplied to the GG. The resulting decrease in water flow led to reduced cooling of the combustion gases within the GG, thereby increasing the turbine inlet gas temperature. This implies the reduced cooling margin availability at ~45% throttling level due to limited water flow.

Turbopump performance was also found to be satisfactory and consistent with chamber pressure trends, with no evidence of cavitation, instability or anomalous behavior during throttling. As expected, turbopump efficiency decreased at lower throttle settings due to operation away from the design-point flow.

In the second hot test (T-2), a more dynamic throttling sequence was executed where the chamber pressure was initially reduced from 100% to 48.6%, then restored back to the nominal 100% level, as shown in Fig. 4. Normalized Thrust profile in Throttling Test T-2. At T_o+33s, command pressure venting was initiated till shutdown of engine at T_o+47.4s. The achieved thrust levels are compared with predicted values in Table 3. Major performance parameters in the test T-2 are tabulated in Table 4. The observed trends were consistent with those recorded in Test T-1.

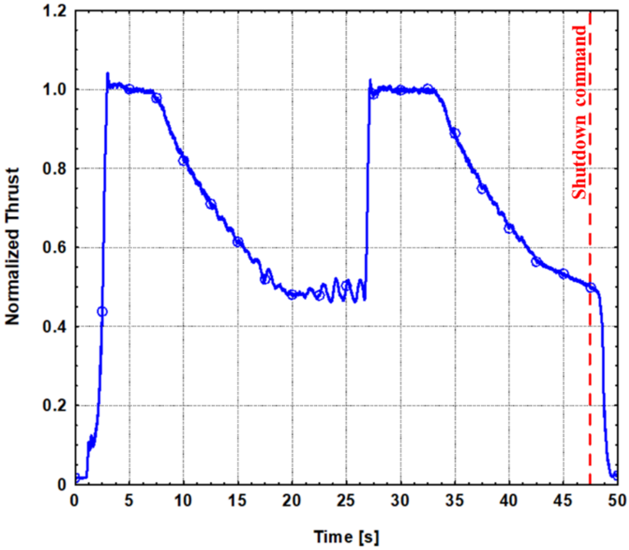

Fig. 4. Normalized Thrust profile in Throttling Test T-2

Table 3. Thrust levels in Throttling Test T-2

Time [s] (T_o+)	Thrust Level [%]	
	Predicted	Achieved
5 - 7	100.0	99.7
20 - 26	49.7	48.6
28 - 33	100.0	99.9

The second throttling test (T-2) demonstrated repeatable engine performance down to a throttle level of 48.6%. A low-frequency oscillation of approximately 1 Hz was observed in the chamber pressure under throttling condition. This behavior was attributed to thrust control loop dynamics associated with increased sensitivity of the water regulator as it approached the near-closed operating region. In this regime, small variations in regulator position produced amplified flow changes, resulting in low-frequency pressure oscillations about the commanded value. Despite the presence of these oscillations, overall engine performance during throttled operation remained satisfactory.

Table 4. Major performance parameters in Throttling Test T-2

Normalized Main Injector & Combustion Performance					
Achieved Thrust Level [%]	$\frac{\Delta P_{injection}}{P_C}$ [%]		P_C roughness from mean value [%]	C* Efficiency	Achieved C_F
	Fuel	Oxidizer			
99.7	19.69	13.45	0.11	93%	1.56
48.6	10.20	8.65	0.15	91%	1.42
99.9	19.66	13.47	0.13	93%	1.55

GG Performance (Normalized with respect to nominal value)					
Achieved Thrust Level [%]	Injection pressures			GG Outlet Pressure	GG Outlet Temperature
	Water	Fuel	Oxidizer		
99.7	1.02	1.01	1.01	1.01	0.91
48.6	0.29	0.29	0.29	0.33	0.68
99.9	0.99	1.00	1.00	1.00	0.96

Turbopump Performance (Normalized with respect to nominal value)					
Achieved Thrust Level [%]	Pump outlet pressures			Turbine Speed	TP efficiency [%]
	Water	Fuel	Oxidizer		
99.7	1.03	1.01	0.99	1.01	37.4
48.6	0.43	0.45	0.46	0.60	24.2
99.9	1.03	1.01	0.99	1.01	36.8

4 Conclusion

An experimental investigation of throttling performance in a radial-injector, pump-fed liquid rocket engine operating on a GG cycle with earth-storable hypergolic propellants was successfully completed. Controlled thrust modulation was achieved through modifications to the command pressure control circuit and the GG fuel regulator geometry, enabling stable operation across the desired throttle envelope.

The first throttling test demonstrated stable stepwise reduction of chamber pressure down to 66.7% of nominal conditions. Combustion stability was maintained throughout the test, with chamber pressure roughness remaining within acceptable limits and C* efficiency sustaining values near 93% over most of the throttle range. However, for

2.8s duration during venting of command pressure, throttling of 44.8% of nominal condition was achieved, with slightly lower performance. A marginal reduction in C* efficiency was observed at the lowest throttle setting, consistent with reduced injector pressure drop and atomization quality at deep-throttle conditions. No evidence of nozzle flow separation, thrust instability, or abnormal flow behavior was detected.

Gas-generator regulation remained effective across the throttle range, with proper pressure equalization among fuel, oxidizer and water injection circuits. At deep-throttle operation, reduced command pressure led to decreased water injection, resulting in an increase in GG outlet temperature and a reduced cooling margin. Turbopump performance followed chamber-pressure trends without signs of cavitation or dynamic instability. Although turbopump efficiency decreased at lower throttle settings due to off-design operation, overall engine operability was not compromised.

The second throttling test confirmed repeatability of engine performance down to 48.6% of nominal chamber pressure. A low-frequency oscillation (~1 Hz) associated with thrust control loop dynamics was observed at deep-throttle conditions; however, the amplitude remained limited and did not adversely affect combustion stability or subsystem coordination.

Overall, the results demonstrate that the implemented throttling strategy provides stable and repeatable throttling performance in a radial-injector GG cycle engine operating with earth-storable propellants. The findings contribute valuable experimental data for throttling applications and support the feasibility of employing such configurations in future descent and reusable launch missions.

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