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Pressure surges caused by the operation of a cryogenic shut-off valve

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Abstract

Minimizing weight is a fundamental objective in the design of liquid rocket engines, which serve as the primary means of transportation beyond Earth's atmosphere. However, this objective must be carefully balanced against the need for sufficient structural redundancy and robustness to withstand extreme operating conditions. One critical factor influencing structural integrity is the water hammer phenomenon, a transient pressure surge that can impose unexpected mechanical loads on engine components during propellant operation. In this study, we investigate the water hammer phenomenon associated with the cryogenic shut-off valve in a liquid rocket engine, with a particular focus on pressure surges observed during ground tests and flight operations. These surges are hypothesized to result from the condensation of the cryogenic oxidizer during valve actuation. A comprehensive understanding of this phenomenon is essential for accurately predicting mechanical loads and optimizing structural design.

1. Introduction

High-pressure shockwaves, also know as water (or fluid) hammer, can occur within a piping system when a fluid in motion is abruptly forced to change direction or stop. This rapid change in momentum generates a pressure wave that travel through the fluid, potentially causing damage to the piping system. Water hammer can cause significant damage to the overall piping system due to both singular events and cumulative damage occurring over time. This transient pressure surge is also a critical phenomenon to consider for the reliable operation of liquid rocket engines.

Water hammer most frequently results from rapid valve closure, which generates a sudden pressure surge in piping systems. As the valve closes, the flow rate decreases continuously, causing a positive pressure buildup upstream of the valve. The closure decelerates the liquid column in the pipe. However, due to the incompressibility of the fluid, the entire column cannot slow down instantaneously. Instead, a pressure wave travels upstream at near acoustic velocity a, opposing the flow direction. When the wave encounters still-moving liquid, it brings it to rest. The stationary liquid between the wavefront and the valve becomes compressed and pressurized. If the valve closes faster than the pressure wave's round-trip time, $t_r = \frac{2 \times L}{a}$, the compression effect intensifies significantly. The velocity change Δv during closure governs the resulting pressure head H, defined by

$$H = \frac{\Delta v \times a}{g} \tag{1}$$

Thus, when closure time is less than t_r, the propellant feed pipe can experience the full Joukowsky head.

Water hammer can also occur downstream of a valve, particularly when the valve is not located near the pipe end. Rapid flow interruption causes a downstream pressure drop to the liquid's vapor pressure, triggering cavitation (the formation of vapor cavities). The downstream liquid column reverses direction, accelerating to nearly its original velocity before cavitation begins. When this returning liquid collides with the residual liquid or the valve, it mimics an instantaneous valve closure on a sub-scale timescale, generating an extreme pressure surge. The resulting water hammer can be severely destructive due to the high-energy collision.

Condensation-induced water hammer (CIWH) occurs when vapor cavities of a cryogenic fluid downstream of a valve are rapidly cooled by the cryogenic liquid, triggering a sudden phase change. The subcooled vapor condenses explosively into liquid within the piping system, generating destructive pressure waves. A similar phenomenon, steam-induced water hammer, caused by the condensation of water vapor, has been widely researched in nuclear industry applications due to its significant operational risks.[1,2] In rocket propulsion systems, cryogenic CIWH has recently gained research attention.

Gouriet et al.[3] carried out cryogenic tests to characterize the multiphase fluid hammer phenomenon generated by the

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discharge of pressurized cryogenic liquid (LN2) into a closed end pipeline. Their results demonstrated that cryogenic fluid hammer is primarily driven by the high vaporization rate of the liquid phase, leading to rapid pressure attenuation between successive pressure surges compared to non-cryogenic liquids. Klein et al.[9] conducted a series of fluid hammer experiments using both H_2O and LN2, comparing their respective behaviors to establish a foundational basis for selecting substitute fluids in ground testing scenarios for launch vehicles.

In this paper, we briefly present the Joukowsky pressure theory and the design of a cryogenic shut-off valve, followed by a discussion of the pressure surges observed during the valve's operation in a liquid rocket engine.

1.1 Pressure surge downstream of the valve

In order to gain a brief insight into the pressure surge downstream of the valve due to rapid closure, the simplified equation for transient flow, neglecting friction and minor effects, has been derived. Figure 1 illustrates a control volume for the conservation equations. When the valve closes, the adjacent fluid downstream of the valve is abruptly decelerated from velocity v_0 to rest by the rarefaction wave generated at the valve face. This rarefaction wave propagates to the next fluid layer, bringing it to rest. Consequently, a low-pressure wave travels downstream at sonic speed a, successively decelerating each subsequent fluid element. By equating the net mass influx to the temporal rate of mass accumulation within the control volume, the mass conservation equation becomes:

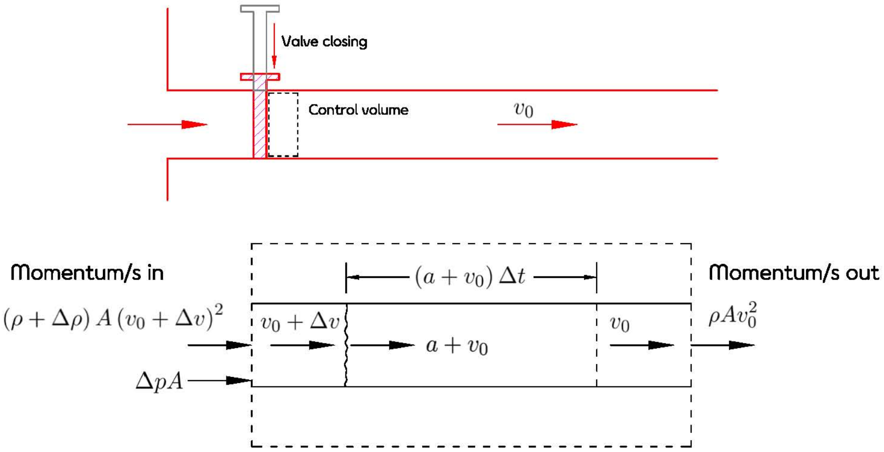

Figure 1: Instantaneous stoppage of liquid flow in the control volume for conservation equations.

$$
\begin{aligned}
(\rho + \Delta\rho)\,A\,(v_0 + \Delta v) - \rho A v_0 &= \frac{A\,(a + v_0)\,\Delta t\,[(\rho + \Delta\rho) - \rho]}{\Delta t} \\
&= A\,(a + v_0)\,\Delta\rho \qquad (2)
\end{aligned}
$$

By the Newton's second law for fluid motion, the rate of change of momentum within the control volume is equal to the sum of forces acting on it. This momentum conservation equation is derived through following steps:

$$\Delta p A = A\,(a + v_0)\,[(\rho + \Delta\rho)\,(v_0 + \Delta v) - \rho v_0] + \rho A v_0^2 - (\rho + \Delta\rho)\,A\,(v_0 + \Delta v)^2 \qquad (3)$$

Substituting the mass conservation relation Eq. (2) and eliminating cancelling terms, the expression simplifies to:

$$\Delta p A = A\,(a + v_0)\,(\rho\Delta v) - \rho A v_0 \Delta v = \rho A a \Delta v \qquad (4)$$

Consequently, the valve closure generates a pressure drop downstream of the valve, characterized by the fundamental relation:

$$\Delta p = \rho a \Delta v \qquad (5)$$

When the pressure transient reaches vapor pressure, cavitation occurs with liquid column separation. Subsequent cavity collapse produces destructive pressure waves.

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1.2 Cryogenic shut-off valve

The reliable supply and shut-off of oxidizer and fuel are critical for the proper operation of liquid rocket engines in launch vehicles. Various on-off valves are responsible for propellant control within the system. Among these, the main oxidizer shut-off valve, which regulates oxidizer flow to the combustion chamber, holds particular significance. This component operates under extreme condition involving cryogenic temperature and high-flow rates in high-pressure environments.

While most on-off valves only control propellant flow through basic open/close operations, the main oxidizer shut-off valve must requires both a recirculation pre-cooling line and a primary outlet directing oxidizer to the combustion chamber.[4] This dual-path design enables pre-cooling of the oxidizer delivery system prior to engine startup. During this phase, liquid oxygen circulates through the recirculation line back to the propellant tank. This configuration effectively makes the valve a specialized three-way device with a main outlet to the combustion chamber and a secondary recirculation path as illustrated in Figure 2.

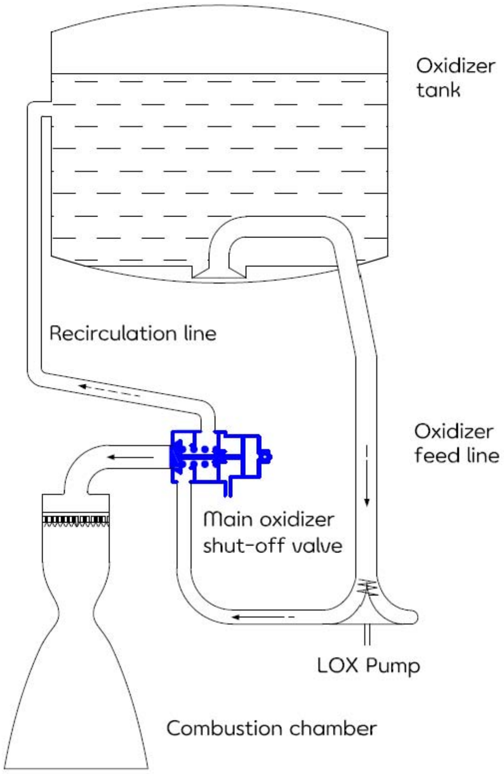

Figure 2: Simplified schematic representation of a liquid rocket engine with a main oxidizer shut-off valve, indication flow direction based on valve position (dashed line: close, solid line: open).[6]

The oxidizer shut-off is a self-sustaining poppet valve that remains open solely through the operating pressure of the working fluid (liquid oxygen), eliminating the need for an external pilot pressure supply. This design enhances operational reliability by leveraging the inherent pressure of the working fluid, thereby reducing the risk of unintended valve closure caused by actuator leakage. However, the valve's performance characteristics are influenced not only by variations in working fluid pressure but also by the internal flow dynamics within the recirculation pathway.

An opposing force against valve opening is generated by the pressure differential between the valve's inlet and outlet. Consequently, the pilot pressure required for valve actuation increases in directly proportional to the inlet pressure. However, once the valve begins to open, the pressure-induced force abruptly diminishes, resulting in rapid valve actuation. During engine startup, when the valve's inlet pressure reaches its design level, the opening travel time is typically $\sim$ 10 ms.[5,7] Similar to the valve opening, the valve closes very quickly due to the recirculation pre-cooling function. During valve closure, the operating fluid flows into the recirculation path of the valve. This increases the pressure inside the recirculation cavity, augmenting the force in the direction of valve closure and resulting in a faster closing speed of the self-sustaining valve.[6] Ultimately, the high opening and closing speeds of the valve pose a risk of surge pressures related to the condensation of cryogenic flow.

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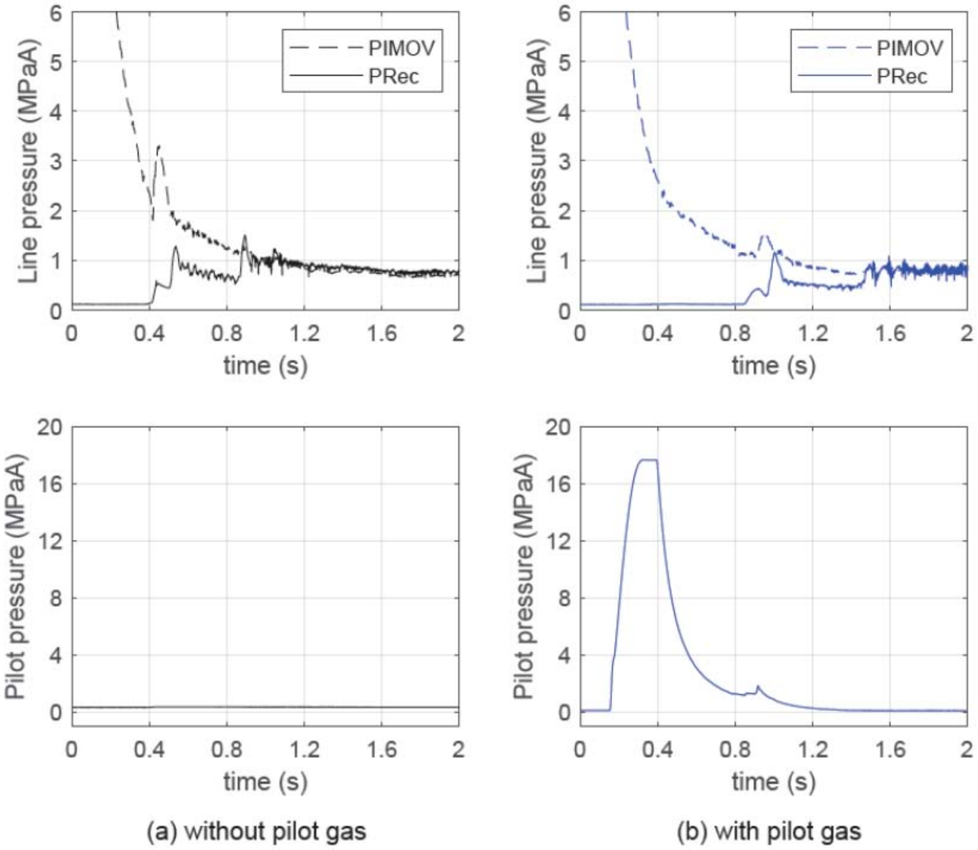
2. Water hammer phenomena and discussion

Water hammer phenomena induced by the rapid actuation of the valve are observed during both ground engine combustion tests and in-flight operations. Notably, configuration differences of propellant feeding systems downstream of the valve's recirculation port between ground test and in-flight environments may affect the propagation and severity of pressure transients. During ground testing, the recirculation line is vented to the atmosphere for operational simplicity. In contrast, flight configurations connect the recirculation line to the LOX (Liquid Oxygen) tank to chill the liquid oxygen supply lines.

2.1 Ground combustion tests

During ground-based combustion tests, relatively weak pressure surges were detected in both the main flow line and the recirculation line during valve closure. The rapid valve closure causes an abrupt stoppage of the incompressible flow, resulting in a pressure rise upstream of the valve. Additionally, pressure surges develop in the recirculation line, which is activated upon valve closure, due to vapor condensation within the system.

The pressure surges can be mitigated by extending the valve closing time using the pilot gas. Specifically, the pilot gas is supplied just before the valve closes, and the closing speed is controlled by the pressure of the discharged pilot gas. With this method, the pressure surge upstream of the valve is reduced by lowering the inlet pressure at the moment of valve closure, as well as by increasing the valve closing time. However, there is no significant change in pressure transients in the recirculation line. This is because the pressure surge is primarily influenced by the two-phase condition in the recirculation line, which is relatively insensitive to the valve closing speed.



(a) without pilot gas

(b) with pilot gas

Figure 3: Pressure evolutions during valve closing in ground combustion tests (PIMOV: pressure at valve inlet, PRec: pressure inside the recirculation line).

The pressure surges during valve closure are shown in Fig. 3. It is clearly shown that the pressure surge amplitude decreases with increasing closing time. This effect is more pronounced because the LOX feeding length between the valve and the pump is sufficiently short to significantly reduce the pressure wave's round-trip time. The pressure transient shows two peaks in the recirculation line: the first is due to the abrupt mass influx at the valve closing moment,

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and the second results from the collapse of vapor cavities during LOX priming. Pressure wave characteristics depend on initial fluid conditions inside the line. The pressure surge is maximized when the shock is condensation-oriented at the flow area contraction, such as at an orifice.[8]

2.2 In-Flight

Under in-flight conditions-when the recirculation line is connected to the propellant tank-significant pressure surges occur in the line during valve opening. At valve opening actuation, the recirculation line's internal pressure drops to the vapor pressure, triggering LOX column separation. This saturation state then induces condensation driven by the elevated pressure due the LOX tank head, resulting in a rapid high-pressure rise. Figure 4 shows transient evolution of pressure (PRec) and temperature (TRec) in the recirculation line.

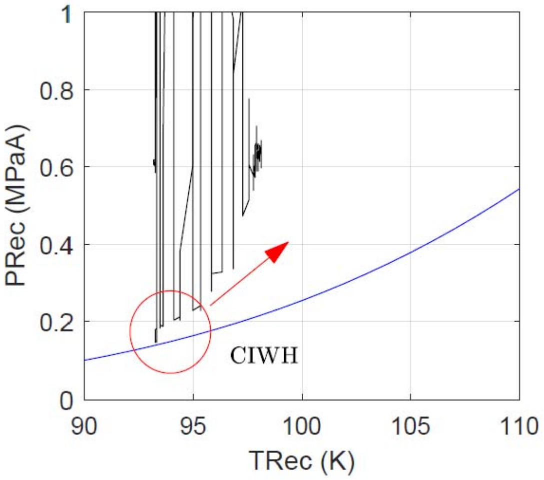

Figure 4: Evolution of the pressure and the temperature at the recirculation line just after valve opening (blue line: LOX saturation line).

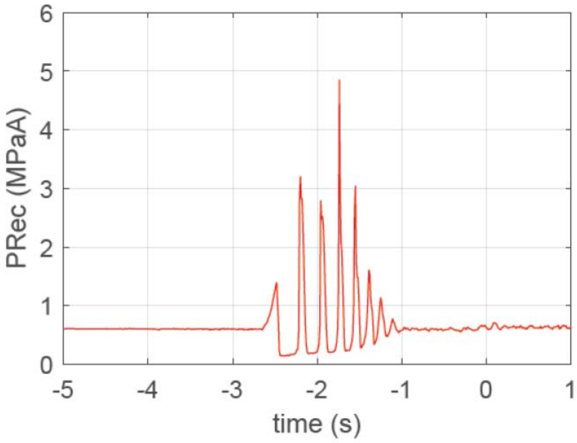

Figure 5: Evolution of pressure inside the recirculation line at valve opening.

Figure 5 shows the typical water hammer induced by condensation in the recirculation line immediately after the valve opening during engine start. This phenomenon is similar to the fluid hammer with cavitation described by Klein et al. (2023).[9] Following the final cavitation-induced pressure valley, a harmonically damped oscillation becomes visible, comparable to a water hammer without cavitation. The time between each peak, in other words, the duration of wave troughs, decreases with an increase in fluid temperature as pressure oscillations progress. The valve's internal operating conditions play a positive role in withstanding the structural loads induced by peak pressure surges at the recirculation port connection. Both the recirculation line and the valve meet structural safety requirements for pressure surge conditions.

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3. Conclusions

In this study, we investigate the water hammer phenomenon associated with the cryogenic shut-off valve in liquid rocket engines. Pressure surges induced by cryogenic oxidizer condensation are observed during both ground tests and flight operations. It is demonstrated that these pressure surges are primarily influenced by the piping system connected to the valve. During ground tests, the recirculation line is flooded with cryogenic oxidizer, and pressure surges result from a sudden collapse caused by local condensation in the line. In contrast, during flight conditions, pressure surges occur when a stationary flow is abruptly stopped by valve closure, driven by cryogenic oxidizer condensation near the valve. While the current design meets structural load requirements, there remains potential for further improvement through the adoption of additional devices, such as gas chambers.

4. Acknowledgments

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