Characterization of design parameters for Pintle injector using liquid propellant

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Abstract

Pintle injectors were invented in the mid-1950s and, since then, have proven to be efficient and capable of maintaining stable combustion. They allow for throttling and complete shut-off of the propellant flow (face shut-off), making them attractive for various unique applications that require easily adjustable thrust.

A pintle injector introduces propellants through two intersecting jets—one annular and the other radial—forming a characteristic umbrella-shaped spray. Depending on the flow configuration (fuel-centered or oxidizer-centered), this setup ensures efficient atomization and mixing. There are two main types of pintle injectors: fixed and movable. Both configurations have their advantages and can be applied in different scenarios.

One of the unique features of the pintle injector is its reliable operation and combustion stability during throttling. Throttling is achieved by adjusting either the flow area or the pressure drop, both of which influence the mass flow rate and chamber pressure. It has been found that, to allow safe throttling, the injection velocity of the propellants should remain between 10–50 m/s, and the pressure drop across the injector should stay within 5–25% of the combustion chamber pressure.

Flow from pintle injectors creates recirculation zones that promote efficient combustion and protect the chamber walls, contributing to combustion stability. In addition, pintle injectors are generally highly stable, though at low thrust levels, instabilities such as chugging, buzzing, screaming, and LOX boiling can arise if not properly managed.

Atomization and mixing are among the most critical design considerations for pintle injectors, as these directly affect spray angle, droplet size, and overall combustion performance. Spray angles and droplet sizes can be characterized using dimensionless parameters such as the Blockage Factor (BF), Skip Distance Ratio, Total Momentum Ratio (TMR), and Sauter Mean Diameter (SMD).

Empirical and theoretical models demonstrate how these parameters influence spray angle, droplet size, and injector performance across various throttle settings.

An alternative design for the injector involves having the main flow pass through multiple holes rather than a single uniform opening. The shape and number of holes are important design parameters that affect injector performance. The Blockage Factor, which represents the ratio between the total area of the holes and the area of a single uniform opening, should ideally range between 0.3 and 0.7 for optimal performance.

The Skip Distance Ratio represents the distance that the radial flow must travel before colliding with the opposing fluid, divided by the pintle diameter. A recommended value for this ratio is 1.

The Total Momentum Ratio (TMR) represents the momentum ratio between the two injected fluids. It has been observed that a lower TMR results in a smaller spray angle, while a higher TMR leads to an increase in the spray angle.