COOLING SYSTEM OF ROCKET NOZZLES

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Annotation: The purpose of studying this topic is to study in detail the cooling system of launcher nozzles. A comparison of the cooling systems of today's launch vehicles and the launch vehicles of the last century and an evaluation of the revolutionary process.

Key words: regenerative cooling, Bartz equation, circulating propellant.

Introduction: Regenerative cooling is a crucial technique in rocket engine design, as it enhances engine performance and reliability by utilizing the cryogenic properties of the propellants to regulate temperatures within the combustion chamber and nozzle. By circulating the fuel around these high-temperature areas, the engine not only protects structural integrity but also preheats the fuel before it enters combustion, improving efficiency and thrust. This dual use of the propellant serves to both cool the engine and optimize the combustion process, making regenerative cooling a favored approach in modern rocket technology.

Regenerative cooling, first conceptualized by Carl Wilhelm Siemens in 1857, was practically implemented in liquid hydrogen liquefaction by James Dewar in 1898. Although Robert Goddard initially built a regeneratively cooled engine in 1923, he later deemed it overly complex. This technology saw more substantial development with Gaetano Arturo Crocco in 1930 and was adopted in Soviet rocket engines in the early 1930s by Fridrikh Tsander and Valentin Glushko, as well as in German engines by Klaus Riedel. Austrian scientist Eugen Sänger also conducted notable experiments with engine cooling during this period, primarily utilizing water or alternative cooling circuits rather than regenerative cooling. The V-2 rocket engine, notable for its powerful thrust of 25 tons (245 kN), featured a regenerative cooling system designed by Walter Thiel, which involved circulating fuel around the combustion chamber. However, the original design using steel for the chamber proved inadequate for cooling, leading to the implementation of a film cooling system that injected fuel directly onto the chamber's inner surface to mitigate overheating. This adjustment, along with the burning of diluted alcohol at low pressure, aimed to prevent engine melting, a design philosophy that was carried over into the American Redstone engine. The Soviet U-1250 engine, designed by Aleksei Mihailovich Isaev in 1945, pioneered regenerative cooling by using a thin copper lining within the combustion chamber, with fuel circulating through the corrugated steel walls to efficiently absorb heat. This innovative design allowed for the use of more energetic fuels and higher chamber pressures, establishing a standard for Russian engines. In contrast, American engines employed a "spaghetti construction" method, utilizing brazed copper or nickel alloy tubes for cooling, a concept attributed to Edward A. Neu in 1947; however, more recent designs like the RS-68 have started adopting the cost-effective Russian approach.

Regenerative cooling is a crucial technique in rocket engine design, utilizing the rocket fuel itself as a coolant to manage thermal loads in thrust chambers. Fuel circulates through intricately designed passages either cooled by brazed tubes or milled channels allowing it to absorb heat as it travels from the nozzle exit to the injector face. By employing smaller cross-sectional areas for these passages, engineers increase the coolant's velocity, thereby enhancing cooling efficiency in the critical high-heat regions of the engine. This method remains integral to optimizing engine performance and safety under extreme conditions.

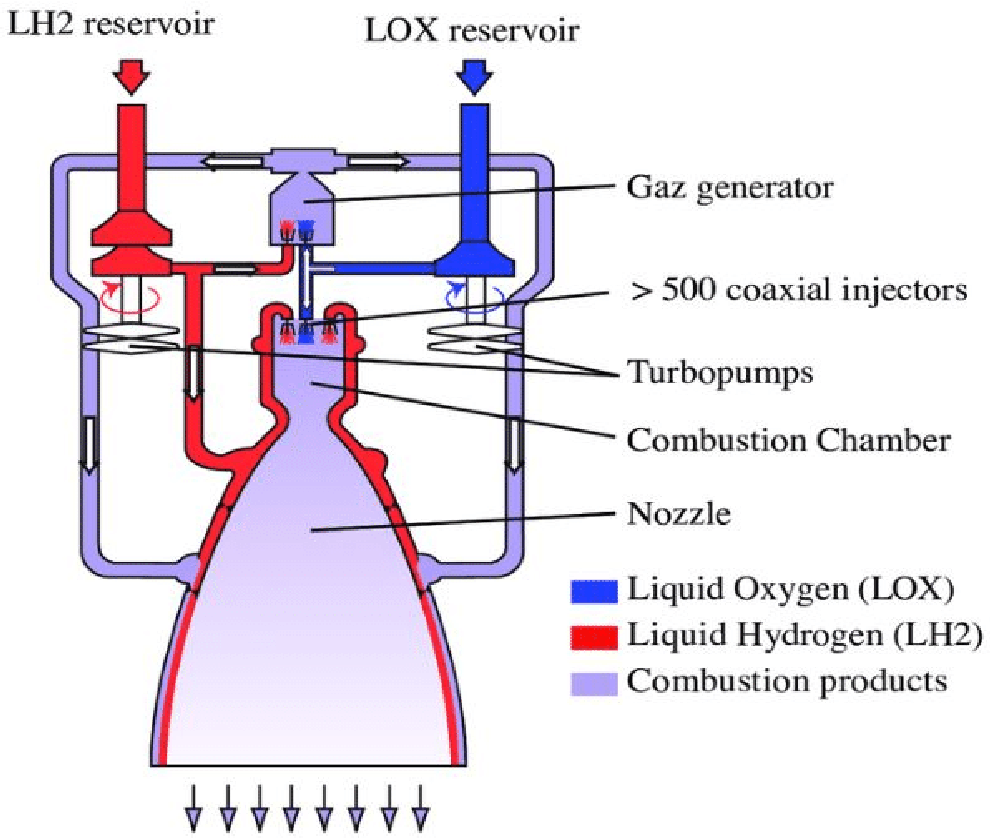
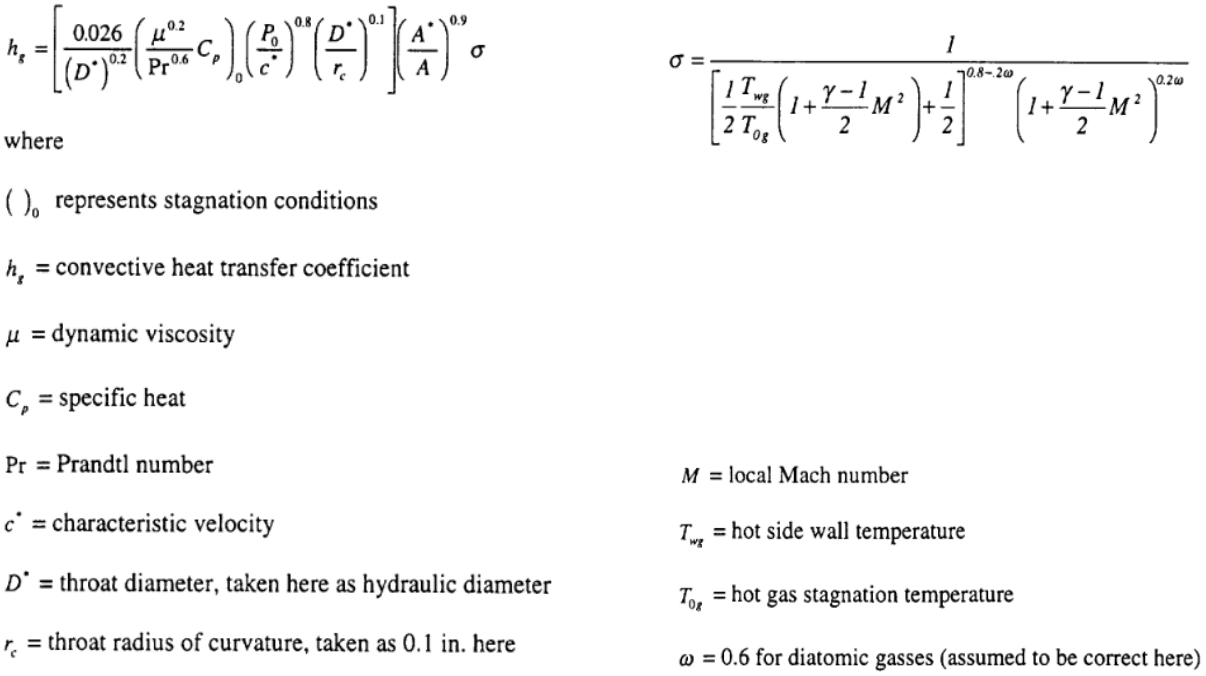


Fig1: *principle of regenerative system.*

The Bartz equation is a widely used empirical formula in heat transfer applications to estimate the heat flux from hot combustion gases, relying on parameters such as temperature, gas properties, and flow characteristics. It is particularly helpful for calculating heat transfer in combustion systems, allowing engineers to predict thermal performance and ensure efficient energy utilization while maintaining structural integrity in high-temperature environments.



$$h_g = \left[\frac{0.026}{(D^*)^{0.2}} \left(\frac{\mu^{0.2}}{\Pr^{0.6}} C_p \right)_0 \left(\frac{P_0}{c^*} \right)^{0.8} \left(\frac{D^*}{r_c} \right)^{0.1} \right] \left(\frac{A^*}{A} \right)^{0.9} \sigma$$

$$\sigma = \frac{1}{\left[\frac{1}{2} \frac{T_{wg}}{T_{0g}} \left(1 + \frac{\gamma - 1}{2} M^2 \right) + \frac{1}{2} \right]^{0.8-.2\omega} \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{0.2\omega}}$$

where

$(\ )_0$ represents stagnation conditions

h_g = convective heat transfer coefficient

μ = dynamic viscosity

C_p = specific heat

Pr = Prandtl number

c^* = characteristic velocity

D^* = throat diameter, taken here as hydraulic diameter

r_c = throat radius of curvature, taken as 0.1 in. here

M = local Mach number

T_{wg} = hot side wall temperature

T_{0g} = hot gas stagnation temperature

ω = 0.6 for diatomic gasses (assumed to be correct here)

Fig2: *Bartz equation.*

Indeed, the heat transfer process into the coolant is influenced by a complex interplay of factors such as the temperature gradient between the heat source and the coolant, the heat transfer coefficient, the thermal conductivity of the chamber wall, and the flow dynamics of both the coolant and gas. Additionally, the specific heat capacity and the initial temperature of the coolant fluid play critical roles in determining the overall efficiency of heat transfer, ultimately affecting the system's thermal performance and stability. In systems utilizing subcritical pressure coolants, film boiling can create insulating gas layers, leading to rapid wall temperature increases and potential failure. In contrast, nucleate boiling, which prevents film formation, enhances heat transfer by allowing gas bubbles to collapse quickly, potentially tripling heat flow rates. However, with many contemporary engines employing supercritical coolants, these boiling techniques are less applicable. Additionally, regenerative cooling is typically not used alone; it is often combined with methods like film, transpiration, and radiation cooling for improved thermal management.

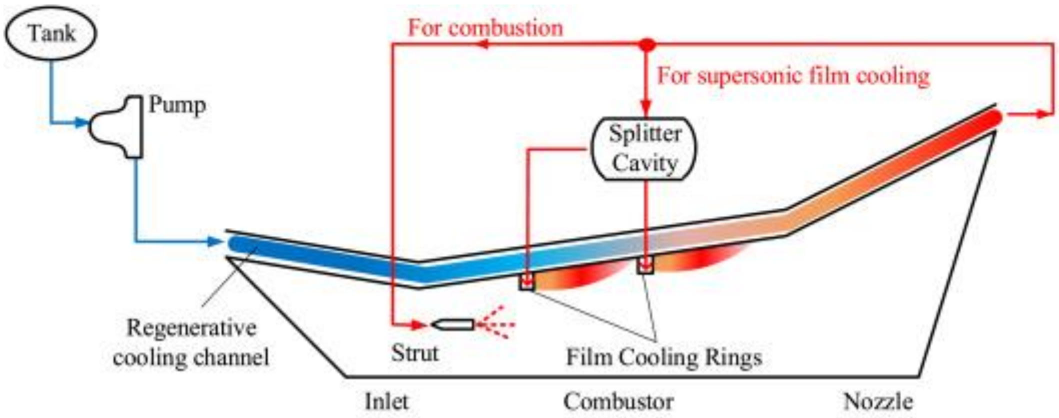


Fig3: *evaluation of regenerative cooling.*

Conclusion: Regenerative cooling in rocket engines involves circulating propellant through cooling channels where the pressure is higher than the combustion chamber, resulting in compressive stresses on the inner liner and hoop stresses on the outer wall. High temperatures weaken the inner liner material, often copper or nickel alloys, leading to thermal stresses that can cause cracking, especially at the throat after multiple firings. To counteract the compressive loads, the inner liner requires mechanical support from the channel walls and backing plate, and various manufacturing methods including brazing and 3D printing are employed to achieve the intricate geometries needed for effective cooling. Even now, the regenerative cooling system is actively used in rocket nozzles, for example, we can cite all types of carrier rockets.

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