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Film Cooling Method In Liquid Rocket Engine

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Cover Page Footnote

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Film Cooling Method In Liquid Rocket Engine

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***Abstract*— Design Criteria, Experimental Studies of Supersonic Shock Wave Interaction with Film Cooling, and High-Pressure Subscale Combustion Chamber of Film Cooling Liquid-Propellant Rocket Engines are all covered in this review study. Using earth-storable, space-storable, and cryogenic propellant combinations, the study establishes the applicability of film cooling to rocket engines in the high thrust range. The study's findings are given in this publication. Additionally, data from studies mixing different types of propellant were used to evaluate the analytical model's accuracy. Tests employing supersonic film cooling were done in the wind tunnel to investigate the impact of external shock waves on supersonic film cooling. The coolant injection was carried out at a supersonic speed. Furthermore, we discuss the important factors that impact film cooling, such as the efficacy of the injected film and the reduction in wall temperature. A high-pressure subscale combustion chamber was used in conjunction with a combination of cryogenic propellants to conduct the experimental investigation. It is critical to consider the increase in the coefficient of heat transfer.**

***Keywords*- Film cooling, Heat transfer coefficient, Influence parameters, Interaction of shock wave.**

Introduction

In terms of power, rocket engines are among the most impressive inventions ever made. For every action, there is an equal and opposite response, according to Newton's Third rule of motion. Exhaust gases from the engine go via the engine's nozzle. Force is generated in the opposite direction in response to an activity [1,4]. Because of hot-gas temperatures and combustion-chamber pressures the heat flux is developed which leads to damage to the casing of the combustion chamber, throttle area, and nozzle[2,3]. To prevent this damage, we require a cooling system in the rocket engine.

The cooling system plays three important roles as follows:

1. Removes excess heat from the engine.
2. Maintains the engine operating temperature where it works most efficiently.
3. Brings the engine up to the right operating temperature as quickly as possible.

Types of cooling systems:

- Ablative cooling
- Radiation-cooling
- Dump cooling
- Regenerative cooling
- Film cooling

I. FILM COOLING SYSTEM

A coolant fluid layer is put between the chilled surface and the hot gas flow to cool the film. Hydrazine fuels, such as monomethyl hydrazine, are used in combination with other cooling solutions in locations with higher thermal needs. The coolant film, which is injected into the wall, functions as a barrier between the hot gas and the structure of the building. Film cooling, which generates a chemically protective gas layer, can be used to slow down the rate of oxidation of the walls.

A. *Types of film cooling system*

1. Typical film-cooling rocket engine
2. Analytical methods

B. *Typical film cooling method*

The injector is responsible for producing a gas core that has a high efficiency of combustion by mixing the propellants and atomizing them. As indicated in figure 1, the lengths of the chambers L* range from ten to sixteen inches when the contraction ratios are low. At the wall of the combustion chamber, the injector also produces a fluid boundary layer that is homogenous and has a high velocity, allowing for maximal penetration all the way to the chamber throat.

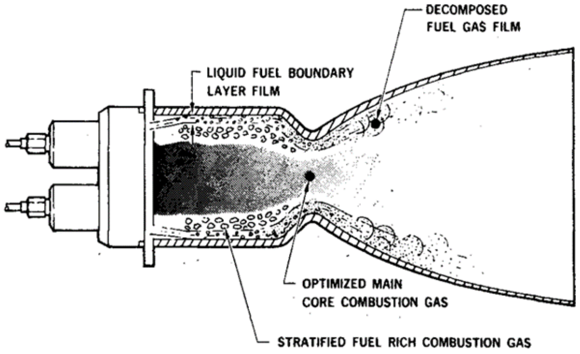


Figure 1. combustion chamber

Because of their high-temperature physical qualities, molybdenum, columbium, and pyrolytic or composite graphite are used as the materials for the combustion chamber. This allows for thinner walls and lighter designs to be created using these materials. In addition to this, the valves include thermal isolation, which helps to reduce the amount of temperature that is absorbed by the valve seat materials. In the reaction control rocket engines, film cooling has been utilised, and the fuels N204 and hydrazine have been employed.

Analytical methods

Part of the fuel is injected along the wall of the chamber so that it can act as a barrier between the gases made by the primary combustion process and the walls of the combustor. In almost all of the different types of rocket propulsion systems, the wall only loses a small amount of heat to the outside world through radiation and conduction. the equation used to figure out how much heat the combustion gases are sending to the wall through convection.

$$Q/A = h_g (T_{eff} - T_w)$$

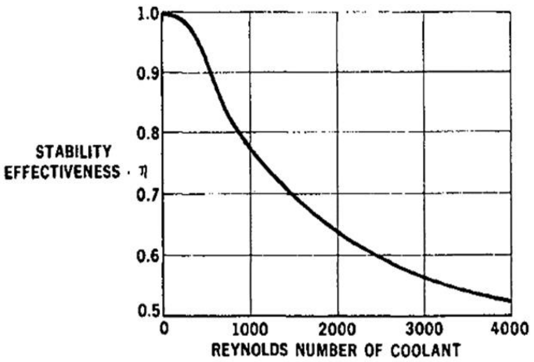
The length of the liquid-cooled region is

$L = [\eta\ W_L\ Cp_L\ (T_s - T_1)] / [Ph_g\ (T_r - T_s] + [\ \eta\ W_L\ \lambda\ ] / [P\ hg\ (Tr - T_s)]$

The first term on the right represents the distance from the injection point for which the effective gas temperature varies from its initial injection temperature to its saturated liquid temperature. The second term represents the distance over which the effective gas temperature is constant and equal to the coolant's saturation temperature.

The coolant flow was corrected by coolant Reynolds number which indicates a stability efficiency factor of the form where the Reynolds number of the coolant is

$Re_L = W_L / \pi\ D\ \mu_L$



C. *Performance Losses Due to Film Cooling*

Two models of the combustion process have been evaluated: first complete mixing of the flow and no mixing of the flow streams. The equation used is

$I_{sp} = (WI_{sp})g + (Wl_{sp})\ c / (W_g + W_c)$

The performance of the main core gas and the coolant is based on thermochemical equilibrium with injection conditions as the initial condition.

D. *Experimental Results*

Two engine design concepts were tested using N204/MMH at the 100-lb thrust level and F2/MMH at the 1000-lb thrust level. For the former R-4 series, experimental data from two series of tests.The R-4B engine consists of eight unlike main doublets and 8 or 16 cooling holes for chamber cooling. These injectors are shown in Fig. d. In both cases, approximately 25% of the total available fuel was used to cool the combustor.

II. FILM COOLING WITH SHOCK WAVE INTERACTION

The shock wave impingement on the film cooling method decreased the film cooling effectiveness. In film cooling, there are inherent shock waves due to the thickness of the separating lip or the inequality of the static pressure between the coolant and the primary flow at the exit of the coolant injector. Therefore, the shock wave decreases the effectiveness of the film cooling.

A. *Experimental methods and setup*

The coolant was injected using sonics in combination with a blowdown-type wind tunnel running at Mach 2.35. The temperature of the principal fluid, nitrogen, was approximately 280 degrees Kelvin, and the nitrogen's total pressure was around 1400 kilopascals. Throughout its entire length, the coolant had a temperature of around 230 degrees Celsius and a pressure of around 240 kilopascals. The coolant's static pressure, which was supposed to be present at the injector's exit, was slightly higher than the principal flow pressure of 100 kPa. The thickness of the boundary layer of the primary flow was roughly 5 mm at the location where the coolant injector outlet was positioned, according to pitot pressure measurements. The temperature of the recovery wall was measured with thermocouples measuring 0.65 millimeters in diameter. The mass flux ratio that the film coolant was expected to have in respect to the primary flow was set at 0.39.

Two kinds of shock generators were used to investigate the effect of the shock wave strength. Table 1 shows the features of the shock generators. The pressure ratios shown in the table were calculated with the shock wave relation.

Table 1. shock generator

Shock generator	**Deflection angle, degree**	**P2/P1**	**P3/P1**
1	3	1.21	1.44
2	6	1.44	2.02

Both the shock generators' and shock wave impingement's positions are shown in Tables 2 and 3. Tables labelled the shock generators' upstream, middle, and downstream locations as upstream, middle, and downstream, respectively. As seen in the schlieren picture, a sonic impediment occurred either at or near the impinging location of an event or separating shock wave.

Table 2 shock wave 1 position

	Middle	Downstream
Xsg/hinj	-2.5	85.0
Ximp/hinj	21.3	107.5

Table 3. shock wave 2 position

	Upstream	Middle	Downstream
Xsg/hinj	-15.0	-5.0	82.5
Ximp/hinj	3.5	14.3	102.0

B. Experimental Result

The shock wave generated during the experiment using the shock generator (SG)1 was only reflected by the wind tunnel wall. At the middle location, the shock wave reflected intricately, and the structure of the interacting zone was altered from when SG2 was employed upstream. Mass flow ratio and convective Mach number were lowered from their respective design values, and the cooling efficiency of the film was calculated as follows:

$$\eta_{FC} = (T_{aw} - TO_{\infty})/(TO_{c} - TO_{\infty})$$

The film cooling effectiveness scattered. There seem to be several reasons, e.g., the protrusion/hollow of the thermocouple from the wall surface. If there is the change of the wall temperature of 1 K, there is the change of the film cooling effectiveness of about 2% in this testing.

- When there was no shock generator, the film cooling effectiveness spread within about several percent.
- When there was a shock generator, there must be the fluctuating motion of the fluid in the separated region, and the spread of the film cooling effectiveness might be due to this unsteadiness.

There were no differences among the effectiveness when the shock generators (SGs) were located at the downstream position. SG1 did not affect the effectiveness.

The effect of the external shock wave on the film cooling was investigated in the Mach 2.35 wind tunnel, and the following conclusions were made clear.

1. There was little effect by the external weak shock wave of the pressure ratio of 1.21. The shock wave of the pressure ratio of 1.44 decreased the film cooling effectiveness.
2. The decrease of the film cooling effectiveness was mainly the result of the decrease of the local Mach number.
3. The increase of the heat transfer coefficient should be considered, as well as that of the adiabatic wall temperature in the interacting region.
4. Neither the mass nor the energy was transferred, whereas the momentum was transferred from the primary flow to the coolant layer in the interacting region

IV FILM COOLING IN A HIGH-PRESSURE SUBSCALE `

The area downstream from the point of film-coolant injection can be divided into three major sections:

- Due to a distinct division between secondary and main flow, the effect of the film is greatest in the core zone.
- As a consequence of the mixing of the film coolant into the hot-gas flow, the film-cooling efficiency decreases gradually with increasing distance downstream of the injection site in the mixing zone.
- The mixing of the film coolant into the core flow is completed in the boundary-layer area. In rocket engines, where the core flow is completely turbulent, the mixing occurs much faster than in other film-cooling applications.

Experimental setup

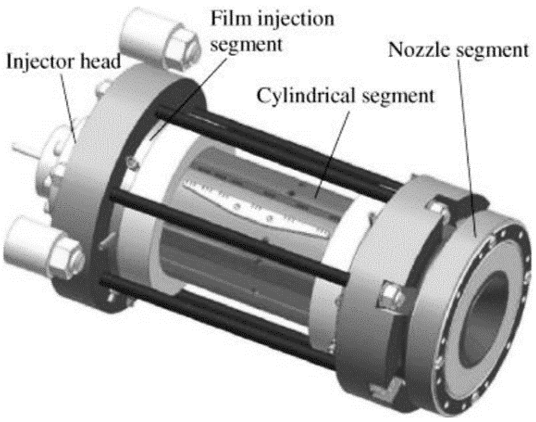


Figure 3. setup of nozzle segment

a. Combustion Chamber E

Stabile operation can be guaranteed for a chamber pressure up to 15 MPa in combination with a very high mixture ratio of oxidizer to fuel (ROF).

b. Film Injection Segment and Injector Head

The geometrical distribution is made in that way to get five identical injector triangles with one coaxial element

c. Instrumentation and Measurement Technique

Subscale combustion chamber E is equipped with a multiplicity of measurement sensors for pressure, temperature, and mass flow rates. Surface and wall thermocouples are integrated in the cylindrical segment and in the nozzle segment in the subsonic part as well as in the supersonic part.

d. Operating Conditions

Each pressure interval was divided into three sections with differing film-coolant mass flow rates, which gave nine different operating conditions for each hot run.

Experimental Result

In general, the efficiency of film-cooling is determined by a wide variety of geometrical (injection angle, slot height, slot width, and number of slots), fluid mechanical (blowing rate, ratios of momentum flux and boundary-layer thickness, turbulence levels, and Reynolds numbers), and thermodynamical (blowing rate, ratios of momentum flux and boundary-layer thickness, turbulence levels, and Reynolds numbers) and thermodynamical parameters (pressure, temperature, and ratios of pressure and temperature).

Parameter	**η**
Coolant mass flux	Increases
Slot height	Increases
Mach number coolant	Increases
Heat capacity coolant	Increases
Prandtl number coolant	Decreases
Molar mass coolant	Decreases
Injection pressure coolant	Increases
Distance from injection point	Decreases
Blowing ratio	Increases
Momentum flux ration	Increases
Convective Mach number	No influence

of the inner and two elements of the outer pitch circle.

III. CONCLUSION

Film cooling works well with propellant mixtures that employ hydrazine as a fuel source. They are more efficient because of their high vaporization temperatures, which allow them to remain in liquid state for a long time.

A mild external shock wave with a pressure ratio of 1.21 was tested in the Mach 2.35 wind tunnel to see how it affected film cooling. The results revealed that this external shock wave had a little influence. Due to the high-pressure ratio, the film cooling was greatly decreased. In the end, it was the decrease in the local Mach number that made the film cooling a success. It uses an open-loop mechanism to run.

The effect of the film blowing rate on the cooling efficiency of the film. Increasing the pace at which the film is blown enhances the local film-cooling efficacy, which is measured downstream of the point at which coolant is injected, in a linear manner. Film cooling efficiency may also be assessed by looking at the Reynolds number of the slot and the velocity ratio between the film and the hot gas.

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