EDUZONE: International Peer Reviewed/Refereed Multidisciplinary Journal (EIPRMJ), ISSN: 2319-5045
Volume 11, Issue 2, July-December, 2022, Available online at: www.eduzonejournal.com

Theoretical Study on Film Cooling Process for Rocket Combustor

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ABSTRACT

The definition of film cooling is combined with regenerative cooling which is an efficient way to ensure the long term, safe and secure functioning of liquid rocket engines with higher heat flux densities. The liquid rocket engines need an effective wall cooling systems to reduce high heat fluxes from the hot combustion gases to the engine wall in the thrust chamber. Using liquid fuel propellant to sheet cool the interior chamber liners is one method of achieving this goal. For use in a combined convective and film-cooled combustion chamber with an accelerated hot gas, an existing film cooling model has been adapted.

Keywords: Combustion, Film Cooling, Nozzle, Regenerative, Rocket Engine.

INTRODUCTION

One of the most difficult problems is the thermal protection of rocket engines in space transportation systems. Combustion chambers and rocket nozzles experience heat loads and temperatures that are substantially higher than the point at which recently developed materials break. Effective cooling techniques are required to lower thermal loads and ensure the dependability of rocket engines. Improvements in nozzles thermal protection have been made thanks to cooling techniques such regenerative cooling, radiation cooling, film cooling, transpiration cooling, and ablation [1]. The maximum flux occurs in the close proximity to nozzle throat, and an effective cooling of the throat area is crucial for enhanced reliability and reusability. The regenerative cooling system is a standard cooling system for almost all modern main stage, booster, and upper stage engines [2]. There are various cooling system techniques film cooling, heat sink cooling, transpiration cooling, ablative cooling, radiation cooling and dump cooling which are developed in the previous years to reduce regenerative cooling load and propellant requirements.

In order to shield the combustion chamber walls from the impact of hot combustion gases, film cooling is a widely utilized cooling technique in rocket engines. Through slots or orifices, a liquid or gaseous film is introduced into the combustion chamber. One of the effective cooling techniques is film cooling technology. In this method, holes are drilled into the surface to be cooled and a secondary fluid is introduced. To prevent the wall from being overheated by the hot flow, coolant is injected through holes in the surface to create a thin thermal insulation layer. Many factors affect the film cooling process. A coolant-to-hot mainline velocity ratio, blowing ratio, momentum ratio, pressure ratio, temperature ratio, density ratio, and turbulence intensity are the key physical factors that affect film cooling [3-5].

Guelailia et al. examined how mass flow rate affected the efficiency of film cooling and heat transmission over a gas turbine rotor blade. The leading-edge region's cylindrical holes are swapped out for converging slot holes to increase the efficiency of film cooling (console). They claimed that converging slot holes offer better protection against film cooling than straightforward cylindrical ones [6].

Khorsiet. al. shows the impact of a downstream crescent-shaped block on the flow field and film cooling efficiency across a flat plate was numerically investigated. It was discovered that, in contrast to the straightforward case without the block, using a short, crescent-shaped block as a coolant flow deflector body significantly increases the effectiveness of film cooling [7].Ankit et.alpresented a study on nozzle flow partition that is carried out by simulation of rocket nozzle designed Fusion 360and ANSYS to inspect the laminar as well as turbulent regime for deviating section of nozzle [25]. Ankit et.alreviewed about pintle injector used in rocket nozzle along with motor combination for generating higher amount ofthrust. It show the influence of spray angles and characteristics such as flow as well as combustion on spray images,droplet size, momentum ratio, opening distance and SMD distributions which affect the injector geometry [26].Ankitet.al paper discussed a theoretical and conceptual design for compact size 2 stage sounding rocket by focusing onstructural optimizations at various levels. The aim of the paper is to develop a two-stage sounding rocket withoverall length constrained to 1 meter [27]. The aim of paper is to design a two stage sounding rocket and its nozzles using fusion 360 and analysis of differentproperties using simulation on ANSYS software. The rocket is designed to reach maximum apogee to performscientific experiments and can be recovered safely after use [28].

METHODOLOGY

Cooling Techniques

Ablative Cooling

Particularly for short-duration systems like booster engines, which have an operational window of only a few minutes, ablative cooling is used. Ablative cooling is used, particularly in the nozzles of solid rocket boosters.

Radiation Cooling

This technique allows for the cooling of locations with relatively low heat flux, such as the nozzles of tiny, low-performance engines or the nozzle components of larger engines.

Dump Cooling

According to this theory, the coolant is injected into the nozzle at a specified expansion ratio and employed as a film for the downstream component after pouring through cooling channels inside the liner material and being discharged by sonic outlets (like Vulcain) at the end of the nozzle skirt the nozzle portion [8].

Film Cooling

For tiny nozzles with a low heat flux, this approach can be utilised alone; however, for engines with higher heat loads, it can also be employed in conjunction with dump cooling at the lower nozzle portion [9].

Film cooling is a popular cooling technique used in rocket engines to shield the combustion-chamber walls from hot combustion gases. Through slots or orifices, a liquid or gaseous cooling film is delivered into the combustion chamber, protecting the chamber walls not only immediately downstream of the injection but also a few hundred film-coolant-slot heights away. For very high heat fluxes, film cooling can be used either alone (for example, in small engines for satellite propulsion) or in conjunction with regenerative cooling, as it is used, for example, in the SSME of the space shuttle, the Vulcain 2 of the European launcher Ariane 5, and the RD-170 based family. By using film cooling, it is possible to reduce the thermal and structural stresses on the chamber walls as well as the mechanical strains placed on the turbo pumps by the pressure drop in the cooling channels. There is still a lack of knowledge on the factors affecting the effectiveness of film cooling as well as the influences on the combustion process itself under conditions characteristic of rocket combustors.

A secondary fluid is injected during film cooling onto the exposed surface of the component. The additional fluid can be supplied in a number of methods when cooling a film. Most frequently, holes or slots are employed, and several combinations have been researched. In more recent thermal design concepts, one of the effective cooling approaches is film cooling. High cooling efficiency, easy thrust chamber design, and a relatively small pressure drop are all advantages of film cooling. When a new generation propulsion system is created, these advantages make the use of film cooling quite appealing. Over the years, research on film cooling has mostly focused on gaseous film cooling applied to gas turbine air foils, followed by work on film cooling of rocket combustion chambers.

Nearly all of the air foil’s exterior surfaces that are in contact with the hot combustion gases—including the leading edges, main bodies, blade tips, and end walls—are subjected to film cooling. By placing a layer of coolant fluid between the surface that has to be protected and the hot gas stream, film cooling can be done. Through slots or perforations, the fluid is delivered directly into the combustion chamber and directed along the walls we can see in fig. 1.

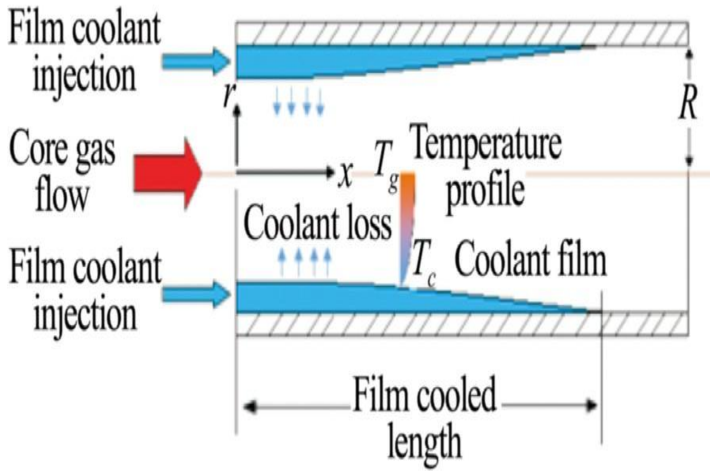

Figure 1. Schematic of the physical system

A typical temperature distribution in a combustion chamber that uses film cooling, extending from the hot combustion gases to the outside of the chamber wall we can see in fig. 2 below.

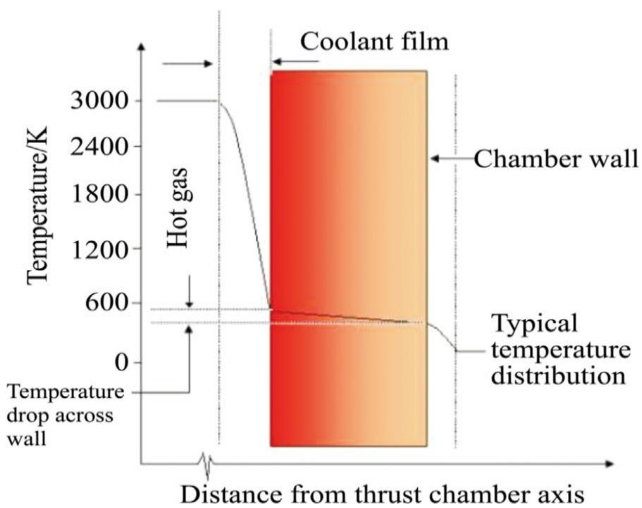

Figure 2. Typical temperature distribution of combustion chamber across wall.

It can be seen that the coolant coating has a cooling effect and lowers the temperature of the chamber walls. By injecting liquid fuel or oxidizer through combustion chamber wall slots or holes or through the propellant injector, coolant film can be produced. The cooling effect will persist up to the throat region in the case of a shorter combustion chamber. In a fully film-cooled design, injection on points is located at incremental distances along the wall length. In order to extend chamber life by lowering thermal stresses, film cooling of rocket engines will be a key component in the development of reusable and booster rocket engines. The related specific impulse reduction makes effective use of the coolant films essential [10].

Liquid Film Cooling

Since the early 1950s, liquid film cooling (LFC) has been researched in an effort to first understand the impact of various injection configurations and coolants on the film cooling performances, and then to determine its suitability for use in rocket applications. Very few of them deal with compound angle injection of gaseous coolant inside a cylindrical geometry, despite substantial research in the field of film cooling and a range of experimental and computational databases that are available. Even fewer studies compare gaseous and liquid film cooling for the same injector designs, and even fewer study liquid film injector orientations [11-19].

Gaseous Film Cooling

Nuclear and very energetic liquid chemical rockets may both benefit from gaseous film cooling. There aren't many studies on film cooling that directly relate to rocket engines and deal with gaseous-film cooling. One of the most promising methods for reducing the heat load on the nozzle wall is gaseous film cooling. The turbine exhaust gas (TEG) is easily accessible as film coolant for gas-generator cycle engines. The properties during steady operation can be predicted, but it is unclear how film cooling behaves under transient situations. Since side loads are one of the deciding criteria for the usage of film cooling during the transient operation of rocket nozzles, it is important to thoroughly investigate the side loads produced during the transient operation. An investigation of this cooling is prior to the initial feasibility tests carried out in rocket combustion chambers and nozzles; it was necessary to comprehend the effects of various coolant injection processes on the main stream boundary layer [20-24].

CONCLUSION

In order to prevent the wall surfaces from unexpected heating, the majority of high-pressure rocket engines also have film cooling in addition to regenerative cooling. The goal of the current study is to comprehend how the film coolant affects the wall heat flux and chamber temperature in the thrust chamber of the PLR D6.1 subscale rocket operating at supercritical pressure. Film cooling has recently emerged as a key solution for coping with high heat flow and high combustion temperatures. The history of liquid and gaseous film cooling of rocket combustion chambers was studied in this article, which also included a summary of earlier work using experimental, analytical, and numerical techniques. In the combustion chamber walls, liquid film cooling is typically used using gasoline as the coolant. Although more work still has to be done to fully understand the liquid film cooling process from the ground up, significant progress has been made. For engines operating at subcritical conditions, models are available to reasonably accurately predict the liquid film length. The results of the film cooling research demonstrated how well the hydrogen film that was injected protected the nozzle extension's lower portion.

ACKNOWLEDGMENT

I would like to express my gratitude towards Mr. Ankit Kumar Mishra, Executive Director and Research Advisor at **ASTROEX RESEARCH ASSOCIATION, DEORIA** for helping me throughout the research work and providing hissincere guidance and support for successful completion of the project.

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