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ORIGINAL ARTICLE

Review on film cooling of liquid rocket engines

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Abstract Film cooling in combination with regenerative cooling is presently considered as an efficient method to guarantee safe operation of liquid rocket engines having higher heat flux densities for long duration. This paper aims to bring all the research carried out in the field of liquid rocket engine film cooling since 1950. The analytical and numerical procedure followed, experimental facilities and measurements made and major inferences drawn are reviewed in detail, and compared where ever possible. Review has been made through a discussion of the analyses methodologies and the factors that influence film cooling performance. An effort has also been made to determine the status of the research, pointing out critical gaps, which are still to be explained and addressed by future generations.

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1. Introduction

Liquid rocket engines developed for space missions encompass a wide spectrum of performance and structural requirements. Thrust levels may vary from a few Newtons to many thousands of Newtons, with burning time from fraction of a second to hours. In all these engines, the energy released by the propellants must be contained inside the thrust chamber and accelerated through the nozzle to extract the thrust. Extremely high heat flux levels and temperature gradients are present not only in the immediate vicinity of the injector head, but also in the nozzle throat region. It is seen that the maximum heat flux occurs in the close proximity to nozzle throat, and an effective cooling of the throat area is crucial for enhanced reliability and reusability. Regenerative cooling is the standard cooling system for almost all modern main stage, booster, and upper stage engines [1]. Different cooling techniques such as film cooling, transpiration cooling, ablative cooling, radiation cooling, heat sink cooling and dump cooling have been developed in the past to reduce regenerative cooling load and propellant requirements. Film cooling can be employed either at the combustion chamber or at the nozzle of a

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Nomenclature

c	specific heat (unit: J/(kg·K))
CM	turbulent mixing coefficient
D	film cooling test section inside diameter (unit: m)
Da	Damkohler number
h	convective heat transfer coefficient (unit: W/(m^2·K))
H^*	heat release potential, $(T_{ad}\text{-}T_{g,t})/T_{g,t}$
I	engine thrust (unit: N)
I_{sp}	specific impulse (unit: 1/s)
L	width of adiabatic wall (unit:m)
M	blowing ratio, $\rho_c v_c/\rho_g v_g$
$\dot{m}$	mass flow rate (unit: kg/s)
P	pressure (unit: bar)
Pr	Prandtl number
q	heat flux (unit: W/m^2)
Q_s	scaled heat flux ratio, $(q_{hot}\text{-}q_{cold})/(q_{max}\text{-}q_{cold})$
R	chamber radius (unit: m)
S	coolant slot height (unit: m)
T	local temperature (unit: K)
Tu	turbulence intensity (unit: %)
N	average velocity (unit: m/s)
v	velocity (unit: m·s^{-1})
V	vaporization rate of the liquid surface (unit: lbm·in^{-1}·s^{-1})
VR	velocity ratio, v_c/v_g
We	Weber number
x	axial distance measured from the coolant injection point (unit: m)
X	non dimensional distance from the coolant injection point, x/D
α	thermal diffusivity (unit: kg/(m·s))
β	tangential angle
δ	factor distinguishing the initial mixing and developed region of the jet
χ	entrainment factor for plane, unaccelerated flow with continuous slot injection
θ	shape factor for the mixing layer profile
γ	azimuthal angle
ρ	density (unit: kg/m^3)
ε	adiabatic film cooling effectiveness, $(T_{ad}-T_g)/(T_c-T_g)$
η	film cooling effectiveness, $(T-T_g)/(T_c-T_g)$
ω	injection parameter

Subscripts

ad	adiabatic
c	coolant
cc	combustion chamber
$cold$	non reactive heat flux
g	main stream flow
hot	reactive heat flux
max	maximum heat flux
e	entrainment
t	total

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rocket engine. Liquid film cooling with fuel or oxidizer as the coolant can be employed in the combustion chambers of gas generator/expander/staged combustion cycle engines. In case of gas generator cycle, the turbine exhaust gas can be used as a gaseous film coolant in the combustion chamber or nozzle sections. It is found that all these methods lead to reduced wall temperatures.

The mechanism by which film cooling maintains a lower combustor wall temperature is considerably different from that of convective cooling. Film cooling is accomplished by interposing a layer of coolant fluid between the surface to be protected and the hot gas stream. The fluid is introduced directly into the combustion chamber through slots or holes and is directed along the walls (Figure 1). A typical temperature distribution from the hot combustion gases to the exterior of the chamber wall in a film cooled

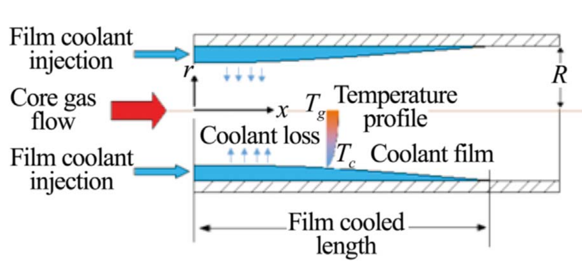

Figure 1 Schematic of the physical system.

combustion chamber is shown in Figure 2. It can be observed that the coolant film produces a thermal insulation effect and reduces the chamber wall temperature. Coolant film may be generated by injecting liquid fuel or oxidizer through wall slots or holes in the combustion chamber, or through the propellant injector. 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 points are located at incremental distances along the wall length. In liquid film cooling, the vaporized film coolant does not diffuse rapidly into the main gas stream but persists as a protective layer of vapor adjacent to the wall for an appreciable distance downstream from the terminus of the liquid film. The film coolant also forms a protective film which restricts the transport of the combustion products to the wall, thus reducing the rate of oxidation of the walls.

Engines like SSME, F-1, J-2, RS-27, Vulcain 2, RD-171 and RD-180 use film cooling technique for combustion chamber cooling. Several open-cycle rocket engines have turbine exhaust gas (TEG) delivered to the nozzle for film cooling, including the F1 engine [2] and J2 engine [3] of the United States, the upgraded LE5 engine [4] of Japan and Vulcain 2 of the EADS Astrium. In Vulcain-2 engine, the combustion chamber wall film cooling has been employed from the injector face plate down to the nozzle throat Section [5]. Engines like Vulcain 2 uses this cooling

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