Design and Analysis of Liquid Rocket Engine Regenerative Cooling Jackets: *Emphasis on Computational Modeling*

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Abstract

An analytical computational procedure was developed in MATLAB to efficiently design the coolant channel height profile of a regeneratively cooled liquid rocket engine using the chamber wall temperature as the primary design point. The procedure employs a linear control volume marching scheme proceeding from the coolant channel inlet up through the chamber wall to the main injector face, successively iterating on the primary fluid variables. A conjugate analysis is used to accurately capture the heat transfer interaction between the hot combustion gases in the chamber and the cryogenic liquid fuel in the coolant passages. Verification of the procedure was achieved by comparing analytical results with exact solutions and another existing fluid analysis procedure in addition to published experimental data from the RL10 engine. A design trade study focusing on the main descent engine for the Altair Lunar Lander was carried out to explore the coolant channel design capabilities of the procedure at varying chamber pressures and mixture ratios as well using different chamber materials. The results of this trade study pointed to lower pressures and moderate mixture ratios as providing the best results. A copper chamber, as opposed to a stainless steel chamber, also resulted in beneficial lower pressure losses and slightly higher levels of heat pickup in the coolant channels in several cases. Overall, the procedure was successful in both designing coolant channel height profiles and in analyzing existing channels in an accurate and timely fashion while maintaining a sufficient level of flexibility and expansion capabilities.

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Nomenclature

A	=	coolant channel cross-sectional area
A_{fin}	=	fin convective surface area
A_p	=	coolant channel perimeter
AR	=	aspect ratio
a	=	speed of sound
C_p	=	specific heat at constant pressure
D	=	diameter
dx	=	control volume length
E	=	modulus of elasticity
f	=	friction coefficient
g_c	=	gravitational correction factor
H	=	static enthalpy
h	=	heat transfer coefficient
hgt	=	height
I_{sp}	=	specific impulse
i	=	position index
k	=	thermal conductivity
L	=	total coolant channel path length
M	=	Mach number
MW	=	molar weight
$\dot{m}$	=	mass flow rate
m	=	intermediate calculation parameter
N	=	number of X
P	=	static pressure
Pc	=	chamber pressure
Pr	=	Prandtl number
$\dot{Q}$	=	heat transfer rate
q''	=	heat flux
Re	=	Reynolds number
R_u	=	universal gas constant
S	=	source term
T	=	static temperature
t	=	wall thickness
u	=	velocity
V	=	velocity
w	=	width
α	=	thermal expansion coefficient
α_c	=	fuel film cooling flow angle
ε	=	roughness
γ	=	specific heat ratio
η	=	efficiency
ρ	=	density
μ	=	dynamic viscosity

Subscripts:

avg	=	average
c	=	fuel film cooling
cool	=	bulk coolant or coolant channel(s)
cv	=	control volume(s)
cw	=	cold wall
f	=	film
fin	=	coolant channel fin/land
g	=	free stream combustion gas or chamber
hw	=	hot wall
hyd	=	hydraulic
i	=	inlet
m	=	metal
r	=	reference property
sm	=	surface
t	=	total
throat	=	combustion chamber throat

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1. Introduction

One of the most important aspects that must be considered when designing a new liquid-fueled rocket engine is how to effectively cool the chamber and nozzle. Some manner of cooling is imperative to prevent their deterioration or complete destruction due to the intense heat to which both are subjected. The typical methods of cooling often include one or even a combination of the following methods: regenerative, dump, film, transpiration, ablative and radiation cooling.[12] The method that is the primary focus of this current effort is regenerative cooling, which is by far one of the most commonly used methods to cool moderate thrust range engines. Regenerative cooling works by passing the cryogenic fuel through channels or tubes built into the wall of the thrust chamber and/or nozzle. This effectively cools the wall by exchanging the heat generated by the combustion gases with the colder fuel before it enters the combustion chamber through the main injector. Experiments performed in the past have attempted to use the cryogenic liquid oxidizer instead of the fuel as the coolant but this was not examined in this study. A cross-section of a sample regeneratively cooled wall that uses longitudinal channels is shown below in Figure 1.1:

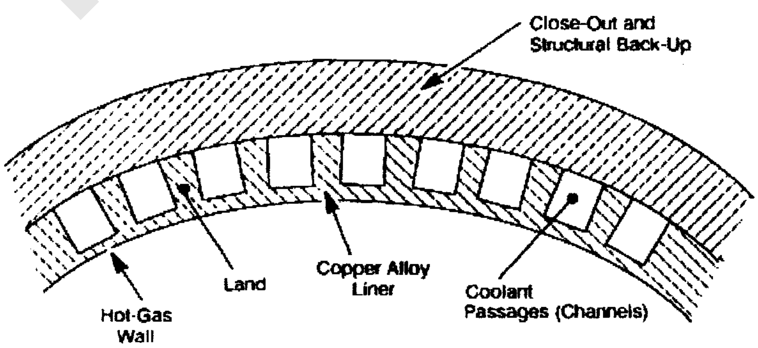

Figure 1.1. Regeneratively cooled chamber wall cross-section[12]

There are many different types and configurations of regenerative cooling including channels or tubes that spiral around the nozzle or loop up and down its length. However, longitudinal channels, running in a single pass axially along the outer wall as shown in Figure 1.1, is the primary type considered for this study. In addition to regenerative cooling, fuel film cooling is also sometimes used to supplement regenerative cooling when specific fuels are used, such as RP-1 and methane. Fuel film cooling works by injecting a small percentage of the cryogenic fuel coolant through tiny orifices in the chamber wall at various axial locations along the thrust chamber; this provides a cool film boundary layer between the wall and the hotter free-stream combustion gases. This boundary layer helps keep the wall cooler and reduces the amount of heat absorbed by the bulk coolant flow. Fuel film cooling was initially researched in this study but was not included in the final procedure due to the added level of complexity it requires.

1.1. Development Motivations and Goals

The primary motivation behind this thesis is to develop a design and analysis procedure for rocket engine combustion chamber cooling channels. A previously developed design tool, written in Simulink and Matlab, simulates the engine, allows trade studies to be performed, and serves as a primary source of technical data. In order to run an engine simulation with this procedure, data from thermal analysts must be obtained to provide the sections of the procedure related to heat transfer with the necessary inputs. This adds a significant amount of time to the process of running the simulation since the analysts must separately rerun analytical tools each time a new case needs to be run. The reason for developing this procedure is to eliminate the need for consulting the thermal analysts by providing a stand alone procedure that correctly sizes the longitudinal coolant channels of a regenerative-cooled liquid rocket engine, given basic inlet conditions and geometry, in order to maintain a constant prescribed chamber wall temperature. Its secondary function is to analyze a pre-existing coolant channel geometry profile, and based on prescribed inlet conditions, calculate and output all of the important fluid properties and temperature profiles along the length of the channel. A primary factor in the procedure's practicality is its ability to save time and thus it must quickly provide results that are accurate enough to support trade studies as well as preliminary design and analysis work.

An important first step that must be taken when discussing this procedure is to layout the primary attributes that define its usefulness and how the combination of these features lead to a unique solution to this problem. One of the prime benefits of this procedure is its development in MATLAB, one of the most widely used engineering-oriented computer languages, both in the workplace and at educational institutions. The fact that it was written in MATLAB also means that it can be seamlessly integrated with Simulink, an extremely powerful block diagram style modeling and simulation program, which is currently being used to simulate various rocket engines.

Another critical aspect of the new procedure is that it employs a conjugate design and analysis technique, combining both fluid dynamics and heat transfer in order to accurately model the thermal interaction between the combustion chamber gases and the liquid fuel coolant. In addition, in order to increase the accuracy of these calculations, viscous friction in the channels is taken into account through the use of the Churchill correlation[6] which allows the usage of different values for the channels surface roughness to capture the different manufacturing tolerances used in channel fabrication if desired. Similarly, real fluid properties were used throughout the procedure instead of making isentropic or ideal fluid assumptions, again to enhance accuracy. Especially when dealing with the high temperatures and pressures and unusual fluids used in liquid rocket engines, it is imperative that real fluids properties are used as extensively as possible since most of the ideal assumptions are not valid in the flow regimes under consideration. Currently the program RefProp[18], developed by NIST, is used to lookup the coolants various fluid properties and at this time, it supports oxygen, parahydrogen, hydrogen, methane, nitrogen, helium, RP-1 and water. Thus, the procedure can theoretically support any number of these propellants. The only limitation at this point is that RefProp cannot be used to obtain real fluid data for the combustion gases in the chamber which require a separate set of look-up tables. As long as these tables are available or can be generated to support the user's choice of fuel and oxidizer, all of the RefProp fuels may be used and the procedure can support all of the common propellant choices.

One of the most important attributes of the procedure is its ability to optimize the coolant channel geometry when running in design mode. When designing a coolant channel profile, the inlet conditions, including the height of the inlet to the channel and the desired hot wall temperature that needs to be maintained along the length of the chamber, are initially specified. With this information, the procedure will attempt to design a coolant channel profile by varying the height of the channel along the length of the chamber until it achieves a profile that maintains the constant desired hot wall temperature.

The final two assets that the procedure employs that increase its usefulness are its ability to support multiple metal layers or thermal coatings in the chamber wall and the built in structural analysis and fabrication limits. The chamber wall of a rocket engine is sometimes very complex from a materials standpoint, with multiple layers of different metals bonded together and/or thin thermal coatings that prevent the high temperature and corrosive combustion gases from melting or eating away at the surface of the wall. At this current stage of development, the procedure allows the user to input up to three different layers of metals or coatings with varying degrees of thickness. The procedure currently supports four different materials including stainless steel, copper, zirconium oxide, and NARloy-Z, but is setup to allow more materials to be added if data correlating thermal conductivity as a function of material temperature is available. It would be advantageous to expand this section of the procedure to a theoretically infinite number of layers but this requires significant effort beyond the scope of this investigation given that its focus is on the conjugate heat transfer and not the wall structure. By allowing multiple layers and types of materials in the chamber wall, more realistic chambers can be designed and chambers already in existence that use a wide array of materials can still be analyzed successfully.

Finally, in regards to structural analysis, as part of the normal analysis or design process, the procedure has a section that performs a simple flat surface in bending calculation to verify that the pressure forces within the coolant channel are not high enough to deform or lead to the failure of the coolant channel wall. A simple thermal stress analysis is also performed as well. Since these types of calculations are approximate, a more detailed structural analysis would need to be conducted if the pressure forces or thermal stresses turn out to be too high. In addition, there are built in checks at the beginning of the procedure that limit various geometric parameters in the engine to remain within today's known fabrication limits or the fabrication limits of the facilities that would be used to manufacture the engine's thrust chamber.

1.2. Background

The topic of coolant channel design has been the focus of research for some time now although the development of rectangular longitudinal coolant channels has become more common recently since the manufacturing techniques required to construct them with exceptional accuracy are relatively newer. The original form of longitudinal cooling, which is not directly addressed by this investigation, was typically achieved using a series of tubes brazed together along the inside wall of the chamber to form coolant passageways. Modern coolant channels are usually integrated into the wall material and fabricated with advanced machining and etching processes.

One of the early studies undertaken to look at issues surrounding coolant channels in regeneratively cooled engines was performed by NASA in the mid-1960s at the Lewis Research Center[16]. In conjunction with hot-fire tests and studies performed with real hardware, a computer program was also developed that incorporated finite-difference numerical techniques in order to obtain and characterize wall temperature and heat flux distributions in chambers with rectangular coolant channels. Their analyses were carried out at steady-state and focused primarily on the various heat transfer coefficients, their variation across a given coolant channel, and the effects they had on the wall temperatures. Although their heat transfer analysis of the coolant channels was very detailed to obtain these results, their work focused primarily on the analysis of given channel geometry and experimental data. This allowed the researchers to concentrate on the trends of the heat transfer coefficients and their effects. Thus, although they have provided a solid foundation for coolant channel analysis in their specific case, which used hydrogen and fluorine, their technical note did not document any attempt to use or develop their procedure for coolant channel design purposes.

One of the definitive books on the design of liquid-propellant rocket engines, first written by Huzel and Huang[12] in the mid-1960s, before being updated several times since then through the early 1990s, discusses regenerative cooling in some detail. The first edition from 1967 outlines regenerative cooling, focusing primarily on tubular wall construction and the associated brazing techniques involved in its construction. Rectangular coolant channels, however, were not mentioned although a section has since been added and appears in the newest edition written in 1992. The research they present highlights the importance and benefits of channel-wall design in high pressure applications as well as in high heat-flux situations. In the newest edition, several computer programs are mentioned including a boundary-layer program that is used to compute heat transfer coefficients as well as several programs that are used to analyze a given configuration and solve for the important temperature distributions in the chamber wall. One such program, called REGEN, performs a two-dimensional analysis while coupled with one-dimensional equations for compressible flow. Again, no specific mention is made about using any of the procedures in a design specific fashion and instead, focus primarily on analyzing the performance of given geometry rather than attempting to output a new computer-generated geometry.

Another important paper from which many of the equations and methodology used in the development of the current procedure come is the NASA Technical Memorandum on the RL10A rocket engine written in 1997[2]. An extensive overview is given that outlines the primary equations used to develop a heat transfer model that accurately simulates the interaction between the hot combustion gases and the cryogenic fuel flowing through the coolant tubes. Several existing procedures were used in the analysis performed including the Rocket Thermal Evaluation (RTE) procedure, the RL10 ROCETS system model, and another thermal analysis procedure developed at the NASA Lewis Research Center. Given that the RL10A engine was developed in the 1960s, their research was performed and procedure was developed to enhance the understanding of the existing RL10 engine. This also provided validation of these analysis tools for use on future engines for which there is no existing data. Once again, the primary use of these various system models and analysis procedure was to develop a further understanding of the intricacies of the RL10A engine in the hopes of improving its performance and thus, it was not used to specifically design new coolant channels for the engine. The RL10 engine uses coolant tubes rather than rectangular channels to perform its regenerative cooling; therefore, although a perfect comparison of results from their research can not be compared to this project, general validation is possible because the equations and methodology overlap between the two studies.

In a similar NASA Technical Memorandum[23] written a year later, the use of high aspect ratio coolant channels was considered in several different design configurations including several continuously variable designs, a bifurcated design, and finally, two stepped channel wall designs. In order to analyze these designs, two programs, the rocket