Advanced Rocket Engine Thermal Analysis

1.1 Motivation: Previous design procedure relied on commercial software, reference books and simple equations to engineer the thermal cooling system for Ignus 1. While the engine operated safely, the cooling efficiency, with 20% film cooling, has much room for improvement; as confirmed with visual accounts of 'fuel dripping out the nozzle' during the hot-fire. Upon examination of the archived documents and memo on the Drive, it was discovered that the thermal system design procedure lacked the rigor and accuracy to design an optimized system.

1.2 Purpose: This document shall serve to explain the new design procedure for designing the thermal cooling system of a rocket engine. Emphasis will be placed on Cooleo, which predicts the cooling performance of the engine cooling system.

1.3 Introduction:

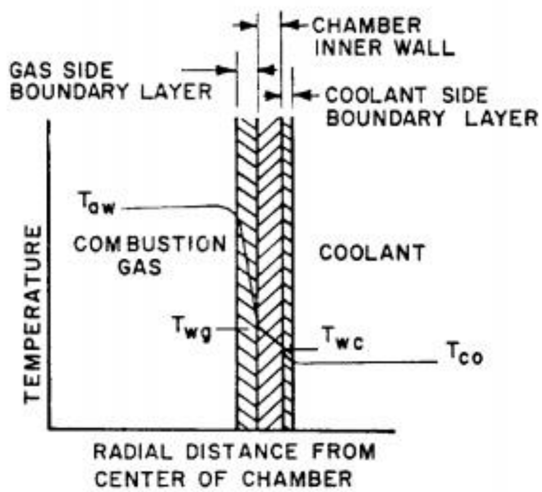


Figure 4-26.—Heat transfer schematic for regenerative cooling.

In general, no known material to man can withstand the extreme pressures and temperatures involved in an operating rocket engine for long, and a thermal protection system must be designed to protect the engine. As shown in *Figure 4.26*, the typical thermal problem involves ensuring temperature at the wall is well below 40% of its melting point, or critical creep temperature (CCT). Repeated firing of the engine induces thermal and pressure cyclic load, which causes permanent deformation beyond the CCT. Material thermal properties such as Young's modulus also changes with temperature, hence it is desirable to keep the operating temperature of the wall below its reference CCT. For Inconel 718, the CCT is 700K, or 400 degrees Celsius.

Due to boundary layer formation on the wall, a thin layer of slow moving gas forms the gas-side boundary layer. This acts as an insulating blanket that helps lowering the temperature. The effect can be enhanced by admitting a thin layer of liquid propellant along the gas-side wall, known as film cooling. Alternatively, coolant may be passed on the other side of the wall to remove the heat convectively, which is known as regenerative cooling. A typical engine utilizes the combination of both film and regenerative cooling to help maintain the CCT.

2.1 Theory:

In general, the steady state heat transfer is defined as the following,

$$q = h_g (T_{aw} - T_{wg}) \qquad (4\text{-}10)$$

where

- q = Heat flux or heat transferred across the stagnant gas film per unit surface area per unit time, Btu/in^2-sec
- h_g = Gas-side heat transfer coefficient, Btu/in^2-sec-deg F
- T_{aw} = Adiabatic wall temperature of the gas, deg R = $(T_c)_{ns}$ × turbulent boundary layer recovery factor (ranging from 0.90 to 0.98)
- T_{wg} = Hot-gas-side local chamber-wall temperature, deg R

The gas side wall temperature, T_{wg} can be defined as the CCT of 700K as discussed above. The term, h_g captures the complex nature of convective heat and mass transfer at the boundary layer, and can be estimated by empirical relations such as Bartz as given by (4-11) through (4-16). This information is obtained through RPA output.

$$h_{gc} (T_{aw} - T_{wg}) = q = \left(\frac{k}{t}\right)(T_{wg} - T_{wc}) \qquad (4\text{-}19)$$

$$= h_c (T_{wc} - T_{co}) \qquad (4\text{-}20)$$

$$= H (T_{aw} - T_{co}) \qquad (4\text{-}21)$$

$$H = \frac{1}{\frac{1}{h_{gc}} + \frac{t}{k} + \frac{1}{h_c}} \qquad (4\text{-}22)$$

where

- q = Heat flux, Btu/in^2-sec
- h_{gc} = Overall gas-side thermal conductance, Btu/in^2-sec-deg F (see eq. 4-18; without deposits, $h_{gc} = h_g$)
- h_c = Coolant side heat-transfer coefficient, Btu/in^2-sec-deg F
- k = Thermal conductivity of chamber wall, Btu/in^2-sec-deg F/in
- t = Chamber wall thickness, in
- T_{aw} = Adiabatic wall temperature of the gas, deg R
- T_{wg} = Gas-side wall temperature, deg R
- T_{wc} = Coolant side wall temperature, deg R
- T_{co} = Coolant bulk temperature, deg R
- H = Overall heat-transfer coefficient, Btu/in^2-sec-deg F

Equations (4-19) thru (4-22) extend the heat transfer to include the wall, and regenerative cooling. In steady state heat transfer, all heat transfer flux must be equal.

2.2 Regenerative Cooling Theory

Regenerative (Regen) cooling works by removing heat via forced convection of a coolant on the cool-side of the chamber walls. The coolant is usually a liquid propellant which has a high thermal capacity to absorb the heat. This method is highly efficient as the absorbed heat becomes added enthalpy for the combustion, but comes at the cost of a pressure drop required to push the coolant against viscous friction. In general, the regen channels' geometry may take on 1) co-axial 2) tubular or 3) rectangular cross sections, in order of increasing pressure drop.

When designing regen channels, it is important to keep in mind the operating pressure and temperature within the coolant. Refer to *Figure 4-27*, Line A1-A2-A3 represents coolant below critical point, and line B1-B2-B3 represents coolant above critical point. Substances are distinguished clearly between liquid and gas by a vapor dome. Beyond the apex of the dome (the critical point), the distinction becomes ambiguous and substance can exhibit extreme thermophysical properties. This is crucial as cooling predictions depend on the thermophysical properties such as thermal capacity, conductivity, etc.
For the Ignus engine, coolant in the regen channels runs above the chamber pressure of 500 psi, which is well above the critical pressure of 315 psi (2.2 MPa) for RP1. Under supercritical condition, no boiling can occur and wall temperature increases continuously with increase in heat flux. It is then crucial to maintain the coolant temperature below the critical temperature of 660K, beyond which "a gradual transition to a stable supercritical vapor-film boundary layer begins". This has the effect of lowering the heat transfer coefficient and coolant heat absorption, and wall quickly heats to failure.

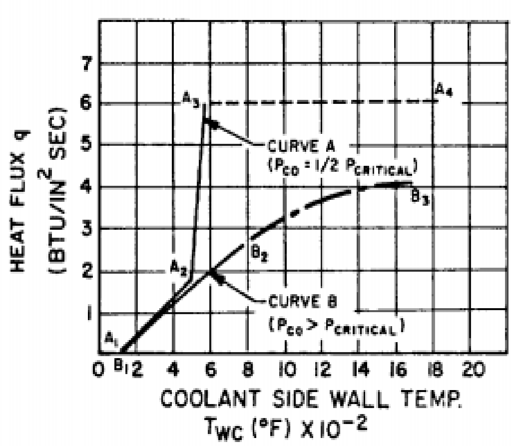


Figure 4-27.–Heat flux versus coolant side wall temperature of typical propellant in various heat transfer regions.

Some basic thermodynamical properties of the two propellant options are summarized in the following table.

		RP-1	T(S)-1	Methane
Boiling point (1 bar)	K	450-547	466-547	112
Freezing Point	K	224	226	91
Density @ 16 °C	kg/m³	809	836	0.72
Density (liquid) @ boiling point	kg/m³			422.5
Kinematic Viscosity (liquid)	mm²/s	3.02 @ 274 K	4.01 @ 274 K	0.28 @ 111 K
Critical Temp.	K	662	658	190
Critical Pressure	Pa	2 171 848	1 820 000	4 599 200
Specific Heat Capacity	J/(kg K)	2093	1980	3480
Specific Energy	MJ/kg	43.34	43.13	50
Volume specific energy (liquid)	MJ/m³	34 934.14	35 887.02	21 125.00
Coking limit	K	560	?	950
Handling properties		Storable	Storable	Cryogenic
		$CH_{1,952}$	$CH_{1,946}$	CH_4
Molecular mass	kg/kmol	172	167	16.043

Table 1 Thermodynamical Properties [4],[8]-[10]

2.2.1 Regenerative Cooling Analysis

As mentioned previously, the regen cooling efficiency (h) is limited by the pressure drop across the cooling channels (ΔP). In order to understand the order of variation between h and ΔP, a dimensional analysis is needed. The Nusselt number, Nu, which describes the cooling efficiency, is given by equation (4-23) as follows:

$$Nu = C_1 Re^{0.8} P_r^{0.4} \left(\frac{\mu}{\mu_w}\right)^{0.14} \qquad (4\text{-}23)$$

where

- C_1 = a constant (different values for various coolants)
- Nu = Nusselt number = $h_c d/k$
- Re = Reynolds number = $\rho V_{co} d/\mu$
- P_r = Prandtl number = $\mu C_p/k$
- μ = coolant viscosity at bulk temperature
- μ_w = coolant viscosity at coolant sidewall temperature
- d = coolant passage hydraulic diameter, in
- k = coolant thermal conductivity, Btu/sec-in^2-deg F/in
- ρ = coolant density, lb/in^3
- V_{co} = coolant velocity, in/sec
- C_p = coolant specific heat at constant pressure, Btu/lb-deg F

$$Nu = \frac{h_r \cdot d}{k} = C \cdot Re^{0.8} \cdot Pr^{0.4} \cdot \frac{\mu}{\mu w}^{0.14}$$

$$h_r = \frac{k}{d} \cdot \ C \cdot Re^{0.8} \cdot Pr^{0.4} \cdot \frac{\mu}{\mu w}^{0.14}$$

But $Re = \frac{\rho V d}{\mu}$ and V is a function of the diameter given constant mass flow, hence:

$$h_r = \frac{k}{d} \cdot \ C \cdot \left(\frac{\rho}{\mu}\right)^{0.8} \cdot d^{0.8} \cdot \left(\frac{\dot{m}/\rho}{N \cdot \frac{\pi}{4} \cdot d^2}\right)^{0.8} \cdot \left(\frac{\mu Cp}{k}\right)^{0.4} \cdot \frac{\mu}{\mu w}^{0.14} = K \cdot d^{-1.8}$$

The analysis yields that, $h_r \sim \frac{K}{d^2}$; $K\ is\ constant$

A similar analysis yields: $\Delta \mathrm{P} \sim \frac{K'}{d^5}$

The simple dimensional comparison shows that ΔP increases much faster than *h*, so the cooling efficiency is fundamentally limited by the pressure drop budget. Even then, as *h* depends on *d*, one may tailor the regen geometry such that cooling is highest for critical region of heating and lower elsewhere to optimize cooling for the given available ΔP budget.

2.3 Film Cooling Theory

Film cooling involves admitting a thin layer of liquid coolant, usually the fuel, to the hot-gas side of the chamber wall. The layer, in addition to the hot gas boundary layer, forms an isothermal blanket that is highly effective in lowering the wall temperature. A rough estimate of the film cooling mass flow can be found using the equations:

(1) Estimate flow and liquid length from

$$\int_{\text{inj. pt.}}^{L_\ell} h_g\,(T_r - T_{sat})\;dA = \left(\frac{\eta_m}{\eta_g}\right) w_{FC}\;(C_p\,\Delta T_{sub} + \Delta H_v)$$

For cylindrical chambers, the result of integration is

$$h_g\;(T_r - T_{sat})\;\pi D_c L$$

(2) Calculate h_g and T_r from table X.

(3) Find (η_m/η_g) in ref. 60 or use 0.4 as a conservative approximation.

(4) Set T_{wg} equal to T_{sat} in liquid region.

The equation assumes all heat is transferred into the sum of the energy to both heat and boil the film coolant. Some properties of RP-1 at atmospheric and room temperature is given by:

Substance	Formula	Melting temp. T_f K	Boiling temp. T_b K	Melting enthalpy h_{sl} kJ/kg	Boiling enthalpy h_{lv} kJ/kg	Density (mass) ρ kg/m³	Thermal expansion $\alpha\cdot 10^6$ K^{-1}	Compres-sibility[a] $\kappa\cdot 10^9$ Pa^{-1}	Surface tension[b] σ N/m	Thermal capacity c_p J/(kg·K)	Thermal conductivity k W/(m·K)	Dynamic viscosity $\mu\cdot 10^6$ Pa·s
Kerosene, Jet A-1, RP1	($C_{12}H_{24}$)	230[g]	450[g]		250	820	830	0.70	0.028	2000	0.13	2400

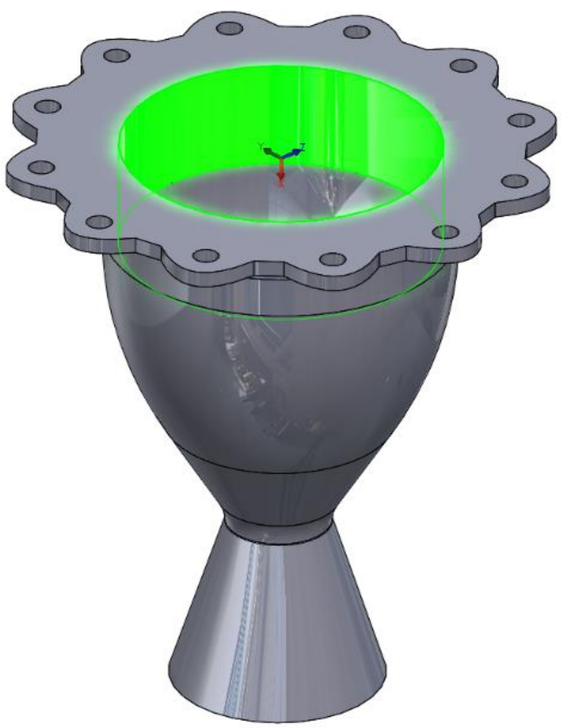
Compared to regen cooling, film cooling is a much more complex phenomena and a rigorous analysis is extremely complicated. Its interaction with the hot-gas boundary layer, viscosity, supersonic interactions at the throat and other phenomena presents a highly coupled, non-linear set of equations that can only be solved with an advanced software package such as ANSYS Fluent. The following analysis will be developed in increasing order of rigorness.

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19730022965.pdf
http://webserver.dmt.upm.es/~isidoro/dat1/eLIQ.pdf

2.3.1 Film Cooling Phenomena

When fuel is injected onto the chamber walls, it undergoes heating from the hot combustion gases but also lose heat to the walls and regen coolant, resulting in film coolant evaporation and boiling. At the operating chamber pressure of 500 psi, the coolant experiences supercritical, non-boiling heating. But the static pressure decreases along the CD nozzle and falls below the critical pressure of RP-1 before the throat. At which point, the surface of the film coolant exposed to the hot combustion gas will be well above its saturation temperature, and nucleate boiling will take place. Let's define Phase 1 to be the supercritical heating and Phase 2 to be the non-supercritical phase. The goal of the analysis then, is to find out the optimal film coolant mass flow rate for efficiency and adequate cooling.

2.3.1 Film Cooling Analysis



A cylindrical shell control volume (CV) is defined on the inner perimeter of the combustion chamber, as shown in green. The CV has radius Rc and spans from x to x+Δx. The shell has infinitesimal thickness, and represents the volume containing the layer of film coolant injected. The coolant element injected into the CV carries an enthalpy at time t, and leaves the CV carrying an enthalpy at time t+Δt. In this process, heat is transferred into the coolant element via hot combustion gases by $q_c = h_c \cdot (T_{aw} - T_{co})$ but heat is also transferred into the wall and regen coolant by $q_w = h_w \cdot (T_{co} - T_w)$. The CV then, captures the coupled heat transfer between the hot combustion gas with film coolant and film coolant with regen coolant. What goes in, must come out. The analysis essentially accounts for all energy transaction within the CV.

2.3.1.1 Assumptions:

- Neglect nucleate boiling / evaporation effects: $\dot{Q}_v = \dot{m}_v = 0$
- Neglect viscous interaction of film with the wall: $\tau_y = 0$
- Fluid fills up the CV
- Steady state
- Cylindrical CV

2.3.1.2 Fundamental Equations:

$$e_{in} = \rho u C_p T(2\pi r)\Delta \mathrm{r}|_x$$

$$e_{out} = \rho u C_p T(2\pi r)\Delta \mathrm{r}|_{x+\Delta \mathrm{x}}$$

$$Q_{in} = q_c(2\pi r)\Delta \mathrm{x} = h_g A \cdot (T_{aw} - T_{co})$$

$$Q_{out} = q_w(2\pi r)\Delta \mathrm{x} = h_r A \cdot (T_{co} - T_w)$$

2.3.1.3 Analysis:

$$e_{out} + Q_{out} = e_{in} + Q_{in}$$

$$e_{out} - e_{in} = Q_{in} - Q_{out}$$

$$\rho u C_p T(2\pi r)\Delta \mathrm{r}|_{x+\Delta \mathrm{x}} - \rho u C_p T(2\pi r)\Delta \mathrm{r}|_x = q_c(2\pi r)\Delta \mathrm{x} - q_w(2\pi r)\Delta \mathrm{x}$$

But, $\rho u(2\pi r)\Delta \mathrm{r} = \dot{m}$ and dividing by Δx and taking limit of Δx to 0, yields:

$$\frac{d\dot{m}C_p T}{dx} = (q_c - q_w) \cdot 2\pi r$$

Where, $q_c = h_c A \cdot (T_{aw} - T_{co})$ and $q_w = h_w A \cdot (T_{co} - T_w)$

$$\frac{\dot{m}C_p}{2\pi r}\frac{d\dot{m}C_p T}{dx} = -\alpha T_b + \beta$$

Where, $\alpha = h_g + h_r$ and $\beta = h_g T_{aw} + h_r T_w$

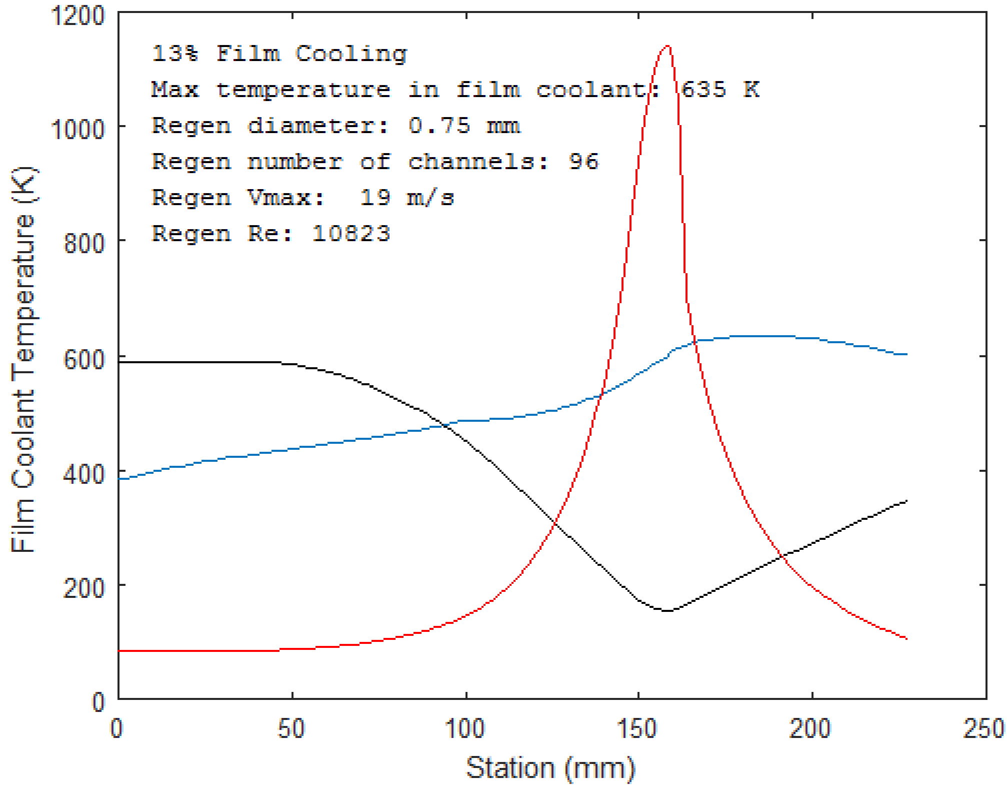
Integrating with x=0 to L with T=Tin to Tout to obtain:

$$T_{out} = \frac{\beta}{\alpha} + \left(T_{in} - \frac{\beta}{\alpha}\right) \cdot e^{-\frac{2\pi R L \alpha}{\dot{m}C_p}}$$

The above relation relating the geometry, mass flow, and inlet/outlet temperatures. It is a powerful equation that may be used to either estimate mass flow required, critical boil-off length, or the temperature at each station as desired.

3. CooleO

With the governing equations for cooling derived previously, it is now possible to create a program that simulates the temperature along the entire rocket chamber given design constraints. CooleO utilizes the governing equation derived in the previous page to predict film coolant temperature at each station of the engine. The temperature is numerically integrated along the chamber stations taking into the changing thermophysical properties of RP-1.



An output of the simulation shows the engine contour (black), heat flux coefficient (red) and film coolant temperature (blue). With the film coolant acting as an isothermal sink, the chamber walls are kept cool and the predicted max of 635K is within the CCT. The result is similar compared to that of RPA's output. With an additional margin, *it was determined that a film cooling of 15% of total mass flow is satisfactory for cooling.*

The program also yields the fluid dynamics information in the regen channel: Reynolds number, maximum velocity and pressure drop. This information can be used to check variables values are within constraint. Furthermore, the program also calculates the regen channel diameter (tubular), which information can readily be incorporated into the CAD.