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Thermodynamic model for a rocket engine cycle

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Abstract. In an era marked by the burgeoning popularity of space stations among both developing and developed nations, the demand for rockets has surged at an unprecedented pace. This meteoric rise in rocket usage has brought to the forefront a critical challenge: the efficient cooling of rocket engines. To address this issue, engineers have explored innovative solutions. One highly promising approach involves the incorporation of fuel-conducting pipes within the walls of the engine, utilizing the cooling properties of the circulating fuel to counteract the intense heat generated during combustion. Additionally, engineers have successfully employed a protective layer of aluminum oxide on the engine's inner walls to enhance thermal insulation. These solutions, however, are not one-size-fits-all; they must be tailored to account for engine reusability and mass. Nevertheless, the combined use of internal fuel pipes and aluminum oxide coating has emerged as an exceptionally cost-effective and efficient method to mitigate the damage caused by heat during fuel combustion. This ground-breaking cooling strategy holds the potential to revolutionize all liquid rocket engines, offering a sustainable and reliable solution as the world's interest in space exploration continues to soar.

Keywords: cooling, layer, reused, effective.

1. Introduction

The history of rocket engines can be traced back to about 1880. In the period of 1880 to 1930, "Russian scientist Konstantin E. Tsiolkovsky worked on theoretical problems of propulsion-system design and rocket motion and on the concept of multistage rockets" [1]. Later on, "Robert H. Goddard independently developed ideas similar to those of Tsiolkovsky about spaceflight and propulsion and implemented them, building liquid- and solid-propellant rockets" [1]. This rocket was invented in 1926 and is the world's first liquid-propellant rocket. After 1926 before 1930, Hermann Oberth developed much of the modern theory for rockets independent of previous discoveries. His improvements in the practicality of the propulsion theory contributed to the development of military use of rockets, especially in Germany. Figure 1 shows the most common liquid-propellant rocket engine in the world.

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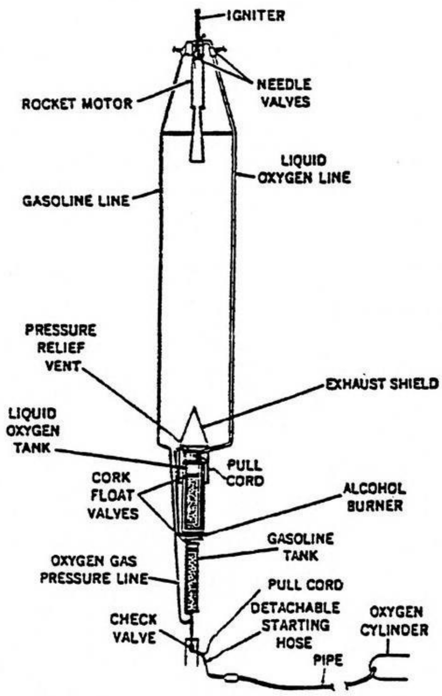

Figure 1. The world's liquid-propellant rocket [2].

The development of rockets accelerated during World War II, from the year of 1931 to 1945. The most remarkable achievement during that era was the creation of the German liquid-propellant V-2 rocket and the Me-163 rocket-powered airplane. Until the 1950s, three generations of Rocketdyne engines were designed, which were called Redstone, Thor, and Jupiter. Thor and Jupiter changed the fuel used for burning from ethanol to a mixture of kerosene and liquid oxygen and were able to provide a 668 thousand newton thrust to the rocket. Then in the 1960s, the MA-3 rocket engine series came out. MA-3 engine series contains a pair of LR89, which is shown in Figure 2, supercharged engines, which will be discarded when they are no longer needed, in order to provide extra thrust when the rocket is launched. Then, the LR105, which is shown in Figure 3, supporting engine would help to propel the rocket until the rocket got into its track. This is the basic model for modern rocket engines. After the 1960s, Atlas, Delta, and Titan only changed little from previous rocket engines, for example, the number of supercharged engines or the fuel.

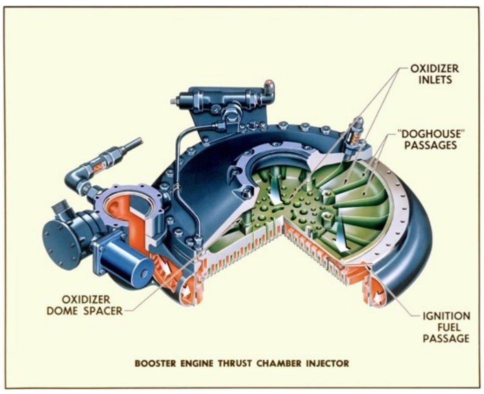

Figure 2. LR89[3].

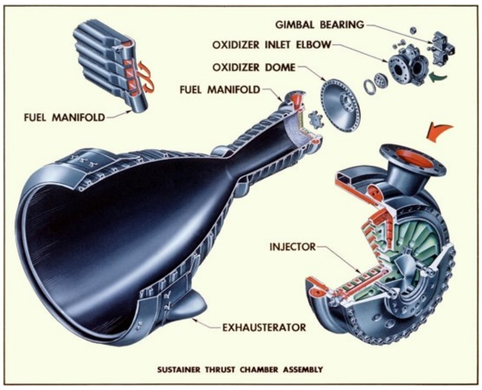

Figure 3. LR105[4].

The engines used currently didn't change much as well. Current engine series used usually contains 2 side booster and one main engine and uses the mixture of liquid oxygen and liquid hydrogen to be fuel. However, this kind of rocket engine usually can only be used once due to the extremely high temperature cause damage to the engine. Modern engines after suffering from heating by the combustion of the fuel, metal wall of the engine will become thinner which is not able to be used for another rocket. [5] If we construct a layer of pipes, which are used to conducting pipes in the wall of the engine, it can effectively reduce the damage to the engine due to the liquid fuel inside the pipes can absorb a great proportion of heat. In addition, applying a layer of aluminum oxide on the inner side of the engine can reduce corrosion to the metal wall. Therefore, each engine's condition after its first launch will be much better than current engines, and it is able to be reused.

2. Methodology

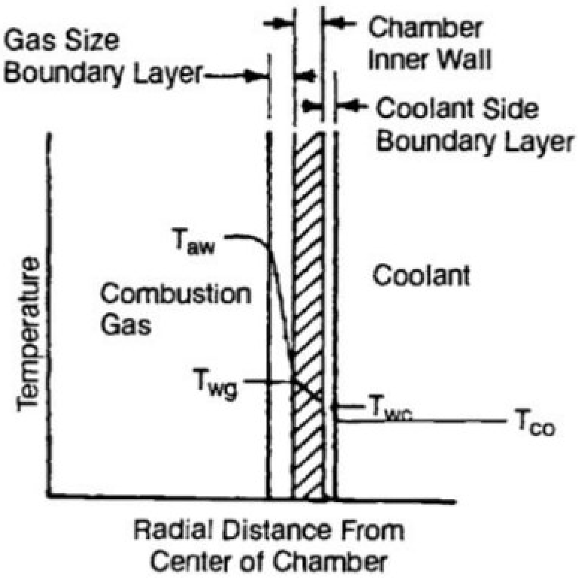

Figure 4. Thermodynamic model[6].

Figure 4 shows the engine model for later calculations. Based on Figure 4, in the steady-state scenario of a one-dimensional setup, the transfer of heat from the combustion gas to the coolant involves a combination of convective heat transfer across multiple layers and conductive heat transfer through the engine's chamber wall. Additionally, radiative heat transfer, which is primarily significant within the

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combustion chamber, can contribute anywhere from 5% to 35% of the total heat transferred from the combustion gas to the chamber wall. This heat transfer can be determined using the equation provided below as Eq.1, where q represents the rate of heat flux, h_g denotes the heat transfer coefficient on the gas side, T_{aw} represents the adiabatic wall temperature, and T_{wg} represents the temperature on the gas-side of the wall. The adiabatic wall temperature, T_{aw}, can be obtained by multiplying $(T_c)_{ns}$ by a stagnation recovery factor.

$$q = h_g(T_{aw} - T_{wg}) \tag{1}$$

The temperature on the gas side of the wall, T_{wg}, is dependent on the material used to construct the chamber. By examining the physical properties of pure copper, it has been determined that the yield stress of copper becomes unstable within the temperature range of "940°F to 1160°F" [7]. Assuming that the chamber is made of C11000 copper, a maximum working temperature of 840°F has been set. Once the adiabatic wall temperature Ta w, the gas-side wall temperature T_{wg}, and the heat flux at the throat of the chamber have been calculated, the equation Eq.1 can be utilized to determine the value of q. It is important to note that q remains constant across the entire chamber wall, providing the necessary data for calculating the temperature of the coolant-side wall T_{wc} using Eq.2. In this calculation, the assumed wall thickness is t_w, and k_{wall} represents the thermal conductivity of the wall.

$$q = \frac{k_{wall}}{t_w}(T_{wg} - T_{wc}) \tag{2}$$

The following are additional assumptions that have been taken into account for the purpose of calculating the outcome. The regenerative cooling system was configured to utilize 45 square channels with a constant square cross-section, each having side lengths of $\frac{1}{16}$ -inch. An extra amount of coolant was introduced into the regenerative circuit to facilitate film cooling and increase the overall mass flow rate to 1.26 lbm/s. To mitigate machining difficulties, the thickness of the chamber wall was established at $\frac{1}{8}$ -inch. Within the regenerative cooling circuit, the pressure of kerosene reduces by 10.8 psi, while its temperature increases by 68.3°F. By employing a flow rate of 0.60 lbm/s of kerosene for film cooling, it is predicted that the maximum temperature reached by the wall would be around 626.3°F. It is worth noting that this temperature remains significantly below the previously mentioned maximum permissible service temperature.

3. Discussion

Exploring space and launch satellites are becoming a topic being concerned by a great number of countries. Therefore, cooling of rocket engine is a problem must be solved in order to successfully launch a rocket. If a better solution is found, countries around the world can apply this solution to the development of their rocket engine. In addition, a better solution may be able to achieve engine reusing which will reduce the budget for all countries. If the engine, whose wall contains pipes conducting fuel and with a layer of aluminum oxide, is constructed, the pipes and the fuel inside the pipes will be able to absorb a great amount of heat. That means the damage to the engine for each launch can be reduced. Therefore, the engine can be reused for at least one time.

Many assumptions are made during the exploring process. The material used to construct chamber, number of channels, cross-section is of each channel, thickness of the chamber wall, flow of additional coolant through the regenerative circuit. The result is the proposal can reduce the maximum wall temperature to be far below the previously stated maximum allowable service temperature, which means the damage to the structure will be reduced to a very low level.

However, this method has some disadvantages. The most significant disadvantage is the calculations are based on ideal conditions, more research need to be done before the method put into use.

Future explorations for cooling of rocket engine can continue to refine or make changes on the model built in this paper.

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4. Conclusion

This paper is aimed to explore a way that can effectively cool the engine. By calculating the maximum temperature of the wall, it indicates that tube wall is an effective way to cool the thrust chamber wall. Thus, the result for the study is build a tube wall inside the wall of thrust chamber for cooling. This will promote rocket engine to be reusable for several launches due to continuous exploration for cooling method will one day be able to reduce the damage to the wall [5] to a small percent which means the engine is in relatively good condition and able to thrust another rocket. However, the calculation did in the paper is a bit ideal, actual data will probably not be exactly the same with the results. Therefore, more detailed experiments and explorations are necessary before the method to be put into practice.

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