

Regenerative Cooling Based Gasification of Liquid Reactants for Rotating Detonation Engine Operation

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1 Introduction

Rotating detonation engines (RDEs) are a class of air-breathing and rocket engines that have gained traction in the last 20 years. This new type of pressure-gain combustion engine is designed to harness detonations instead of deflagrations as a combustion process. In an RDE, one or more detonation waves propagate around an annular combustion chamber to produce continuous thrust, thus solving the non-constant thrust problem of pulse detonation engines (PDEs). The RDE design leads to a more compact and possibly more efficient type of rocket engine. They have higher performance in smaller volumes than traditional rocket engines [1]. This allows the engines to be packed in a tighter formation or smaller spaces on a rocket. It can also be used to increase the payload or fuel of a rocket. Many organizations have been designing, building, and testing RDEs, including research institutions such as Concordia University [2]–[5]. Some larger practical contributions towards usable flight engines have come from NASA firing an RDE for over 250 seconds [6], [7] and the Japan Aerospace Exploration Agency (JAXA) launching their S-520-31 sounding rocket and testing an RDE [8], [9].

The use of detonations generates a tremendous amount of heat flux, due to the reaction zone compactness. During some experiments at Concordia, the test engine melted itself due to a combination of the low material melting point, use of (near-)stoichiometric mixtures, and longer burn times. Practical engines however require long burn times. Additionally, the pressure gain advantage of RDEs requires fast propagating detonation waves, as close to the Chapman-Jouguet speeds as possible. Combined with the relatively narrow detonability limits of propellants of interest, the use of near-stoichiometric propellants is required and the combustion temperature cannot be lowered through chemistry. These factors, combined with the fact that realistically attainable melting points, for metals, cannot exceed $\approx 1300\text{--}1500\text{K}$ ($1027\text{--}1227^\circ\text{C}$), mean that an RDE cooling system for the engine becomes a requirement. Compounding on the previous requirements, the detonability, detonation wave structure, and propagation dynamics for multi-phase mixtures have been an active area of research for several decades. The use, in the RDE combustion chamber, of gaseous reactants is thus desirable.

A variety of cooling strategies exist for rocket engines involving solids, gases, or liquids. Non-liquid cooling options include: ablative cooling, which ejects material and thus energy transferred to the wall, as a form of heat removal; film cooling, which utilizes a layer of cooler propellant along the outer walls to dilute the generated heat to a non-reactive co-propellant; and heat sink cooling, which uses engines with large masses to absorb and contain the heat. Those methods, however, lead to potentially lower

efficiencies through the inherent heat loss process originating in the combustion chamber. Another class of cooling utilizes liquids. Liquid cooling cycles include transpiration cooling, which sweats coolant through the chamber and nozzle walls; water cooling, which flows water through the walls similar to a heat exchanger; and regenerative cooling. Regenerative cooling utilizes the waste heat produced by the engine to increase the temperature of the incoming propellants before injection into the combustion chamber. To absorb the maximum amount of heat possible during the regenerative heat transfer, incoming propellants must be liquid. The ability of a fluid to absorb heat is increased in the liquid phase as opposed to that in the gaseous phase. Therefore, it is important for the cooling fluid to be completely in the liquid phase of the material. However, from a detonation standpoint, it is imperative that the liquid propellants of the liquid regenerative cooling cycle be expanded to the gaseous phase prior to injection into the combustion chamber of the engine.

In this paper, we explore the ability and feasibility of regenerative cooling by simulation, followed by the methods to build and test the mechanisms of the cooling system. This paper is organized to first examine the need for cooling in an RDE. It then discusses the various methods of cooling systems implemented.

2 Liquid Cooling Cycles

Liquid cooling cycles for a rocket engine involve small cooling channels along the sides of the combustion chamber and nozzle, wherein cooling fluid flows, carrying heat away. These small channels can be made using small tubes or machined slots into the chamber and nozzle walls. Both options are typically difficult to manufacture. With advancements in additive manufacturing, 3D printing has become a new option for manufacturing regeneratively-cooled chambers and nozzles [10].

Some liquid cooling cycles that have been modeled or are currently used on RDEs are transpiration cooling [11] and water cooling [12]. These systems require additional equipment along with water storage to be used on the engine. While these solutions may work well on a land-based research engine, they are not feasible on a rocket where limited space and low weight are driving design constraints. Regenerative cooling has the benefits of lower weight and space requirements than other liquid cooling systems. While there have been some attempts to design and model a regenerative cooling system for rocket engines and RDEs [13]–[16], there are no working regenerative cooling systems for an RDE.

The expander cycle is a regenerative cooling cycle that uses the fuel to cool the combustion chamber in a rocket engine. The fuel absorbs heat from the chamber and gets vaporized. The gaseous fuel is burned in a turbine that powers pumps for the engine's fuel and oxidizer. This cycle can be modified for use on an initial RDE design by performing two changes. The system can be changed to a pressure-fed system, thereby removing the complexity of the turbine and pumps for the feed system. Secondly, the system can be modified to cool the chamber with both propellants as opposed to just the fuel. Finally, the propellants can be throttled to a lower pressure, bringing them to a gaseous phase prior to injection.

3 Numerical modeling

The regenerative cooling system will be modeled using 1D thermodynamic modeling and CFD simulations. First, simulations must be performed to determine the heat loading on the internal wall of the combustion chamber and a potential cooling system. The heat flux through the chamber walls will be estimated from published experimental RDE results and used to determine the requirements for a regenerative cooling system.

From the CoolProp [17] thermodynamic library, a phase diagram of ethylene and nitrous oxide was created. Figure 1 shows the phase diagram with points of interest highlighted. The points are also

highlighted in figure 5. Point 1 represents the low-temperature and high-pressure conditions at which the propellants are stored before use in the RDE. Maintaining the propellants at point 1 ensures they remain in the liquid phase. The propellants can then flow through the cooling channels towards point 2. As shown, point 2 remains within the liquid region of both propellants. By passing the propellants through a valve, the pressure is reduced, shifting to point 3, where they both cross their respective vapor curves and transition into the gas phase. In this case, a constant temperature expansion is represented, but the influence of constant enthalpy processes will be evaluated. This method helps determine the range of appropriate temperatures and pressures for propellant storage as well as the amount of heat required to bring them to the desired states within the cooling system. For this work, ethylene and nitrous oxide were selected as propellants for their ease of liquefaction, relatively high cryogenic temperatures, and, in the gas phase, ease of detonability.

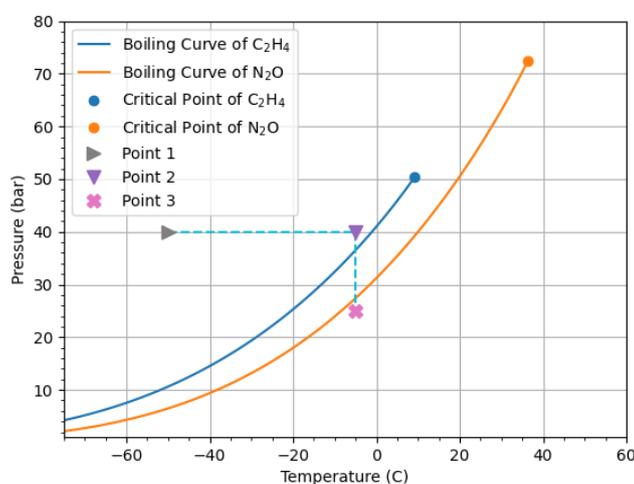


Figure 1: Phase Diagram of Ethylene and Nitrous Oxide.

Following initial calculations of state for propellant storage, cooling system dynamics (using 1D models and CFD), and detonation properties, the regenerative cooling cycle will be optimized using the entire suite of tools. Once valid results are obtained, a physical apparatus will be built and tested.

4 Experimental apparatus

The Concordia research RDE testing platform, shown in fig 2, is designed for modularity and robustness, allowing iterations on the injection system. It comprises a flow system, injection ports, and an annular combustion chamber. Notably, the engine does not have a nozzle of any sort. This is to decrease the thrust and allow for easier mounting, testing options, and detonation visualization.

The RDE is placed inside a test chamber, and combustion tests are performed. One wall of the test chamber, as shown on the right in fig 3, consists of an acrylic and polycarbonate layered panel. These sheets act as a viewing port to maintain visual access to the test article during testing, allowing for visual confirmation of ignition and burn. Finally, the exhaust system includes an extension with a similar viewing port to visualize the combustion chamber dynamics during tests, as shown on the left in fig 3. Using a high-speed camera, the detonation waves can be visualized using self-emitted light.

As shown in fig 4, the test article is mounted to a thrust stand and fired directly into the exhaust vent system. CO₂ flows following a test run to extinguish any remaining flames and push unused propellant and combustion products into the exhaust system.



Figure 2: Research RDE testing platform. Left: Engine as viewed from the annular combustion chamber. Right: Engine as viewed from inside the oxidizer plenum. (Rear plate removed.)



Figure 3: Right: Test chamber as seen from test article viewing port. Left: The exhaust system and combustion chamber viewport.

The test chamber enables the RDE to be tested safely in an indoor laboratory. It was designed with the intent of catching any shrapnel in the event of catastrophic failure of the test article. The test chamber is vented to the building's exterior and includes various safety measures, including a high-flow ventilation system, to ensure that propellants and combustion products are pushed through the exhaust system and out to the atmosphere. In addition, burst disks and vent holes are included to decrease the risk of an overpressure event inside the test chamber.

The target propellants are C_2H_4 and N_2O . The propellants are pressurized and chilled to low temperatures to ensure they are in the liquid state. The flow diagram can be seen in fig 5.

For initial tests, the engine will utilize ethylene and gaseous oxygen as propellants, and CO_2 will be used as a simulant inside a single pipe cooling channel. The critical and liquid/gas saturation properties of CO_2 mimic well those of both ethylene and nitrous oxide, with only the triple point pressure being significantly higher than that of the real propellants. Expanded pressure can be adjusted to test the modeling without creating solid CO_2 . Temperature and pressure measurements along the model cooling channel will be used to compare to the modeling results.



Figure 4: The RDE mounted inside the test chamber.

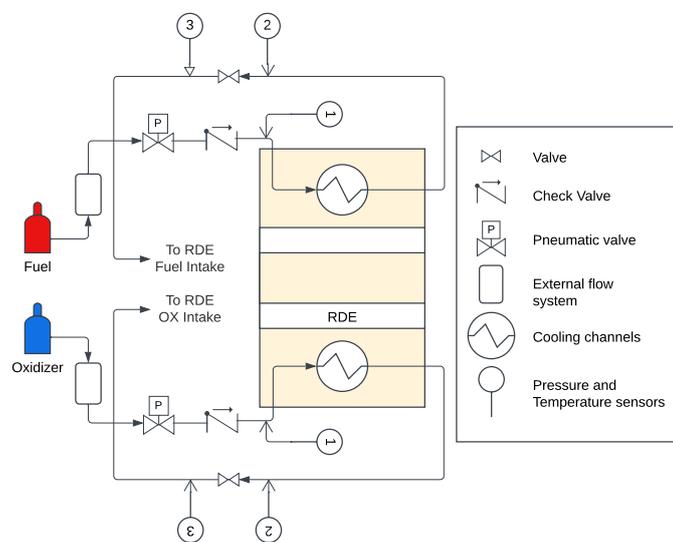


Figure 5: Plumbing & instrumentation diagram (P&ID) of a regenerative cooling system on an RDE. The numbered locations refer to the thermodynamic states of fig. 1.

5 Conclusion

This paper explores the necessity and feasibility of creating a regenerative cooling system on an RDE. Various cooling methods are discussed and examined while regenerative cooling is chosen. The cycle is analyzed and modeled. Test methods are evaluated and performed to validate the design. Future work will include building a final regenerative cooling cycle, implementing, and testing it on a fully functioning $C_2H_4-N_2O$ fueled RDE.

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