Regenerative cooling in Rotating Detonation Rocket Engine supplied with liquid propellants

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Abstract

The use of gaseous propellants to power Rotating Detonation Engines (RDEs) is widely tested in many research centers around the world. Nevertheless, the use of liquid propellants is more forward-looking for application in aerospace propulsion. The paper discusses the issues of detonation combustion of liquid propellants in a rocket engine. Tests were carried out to examine the influence of individual geometrical parameters of the engines, composition of the mixture and the mass flow rate on the process stability and on the performance of a rocket engine fed with liquid nitrous oxide and propane and walls temperature. A fully functional model of a rocket engine fed with liquid nitrous oxide and propane using a regenerative cooling system- is presented. An attempt to create and validate a numerical model of heat transfer in such an engine is also described.

Introduction

Liquid-propellant rocket RDE showed that such an engine can be small, lightweight and very efficient [1-6]. Previous research focused on design and testing of a rocket engine capable to lift the rocket and sustain its flight [7,8]. The biggest challenge up to now was extending its working time. Small size and detonation combustion process arise problems with heat transfer. In this article authors present research concerning optimization of heat transfer in liquid-propellant rocket RDE fed with liquid nitrous oxide (N2O) and liquid propane (C3H8). Liquid propane and liquid nitrous oxide were chosen because they are relatively convenient to handle and store in laboratory conditions [9]. Preliminary numerical model of heat transfer and experimental test stand used for validation of such a model were presented. Such a method of heat transfer could allow in the nearest future to design a full-scale rocket RDE with its own cooling system.

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Rocket liquid RDE – heat transfer problems

Developing CRD combustion chamber for applications in rocket propulsion presents various challenges concerning heat transfer. Detonation process by its nature is highly turbulent which boosts heat transfer between flow and combustion chamber walls. Hot, highly turbulent combustion products lead chamber to a very quick burnout. Moreover, combining high level of turbulence with a very small volume of the chamber makes it nearly impossible to introduce any kind of film cooling or separation of flame from the wall chamber.

Therefore it has been proposed to introduce regenerative cooling system in the engine and adjust it to the liquid-propellant rocket RDE requirements.

"Traditional" regenerative cooling system is favored by engines employing cryogenic liquid-propellants due to their very low temperature. They are passed through channels wrapped around combustion chamber wall leading to effective cooling of the engine's walls from flame and very high temperature exposure. Among other factors care is taken during flow around the engine's chamber and nozzle to prevent the coolant (usually fuel is preferred over oxidizer for a several reasons) from boiling and phase change. This would abruptly change heat transfer conditions and could lead to burnout and engine failure.

Other way round happens in the concept of regenerative cooling of rocket RDE. Previous research proved that in order to sustain stable detonation it is required that liquid propellants fed to the engine are sufficiently evaporated before the wave reaches incoming fresh mixture [10-12]. Since then laboratory test stands required some sort of heater to evaporate liquid propellants before they reached CRD combustion chamber. Additionally, phase change phenomenon rapidly increases heat flux. Those facts allowed to introduce the concept of regenerative cooling system that would evaporate liquid propellants during the flow along hot walls.

The preliminary calculation of heat transfer shows that vaporization energy covers about 9% of total heat energy of engine (for equivalence ratio = 1.5). If the transfer to the walls is not higher, it is possible to obtain stable detonation for a long time.

Initial assumptions and design requirements

As it was said in earlier papers [8], liquid propane (C_3H_8) and nitrous oxide (N_2O) were fed to the engine. Further, during the course of flow and heat transfer through the wall, the pressure dropped and temperature increased leading to phase change, until completely evaporated gas were injected to the combustion chamber.

The main goal was to extend time of work of the engine hence it has been proposed to develop numerical model and eventually validate it through experiment. For this purpose well-researched annular combustor geometry was chosen. Annular combustor in laboratory conditions has got advantage over small, lightweight conical-shaped RDE designed for rocket flight [8] that it is easier to place sensors for measurements in it. CRD combustors in every configuration (except so called "hollow" combustor) requires cooling two walls, whether it's geometry is either annular, disc, conical or of other type. Therefore both propellants, liquid propane and liquid nitrous oxide, were used for cooling rocket RDE with conical combustor however, in this case only N_2O (due to its higher than propane abundancy in the mixture) was used in the validation experiment to cool inner wall, while the second one will worked as a heat sink.

Engine's concept diagram is presented below:

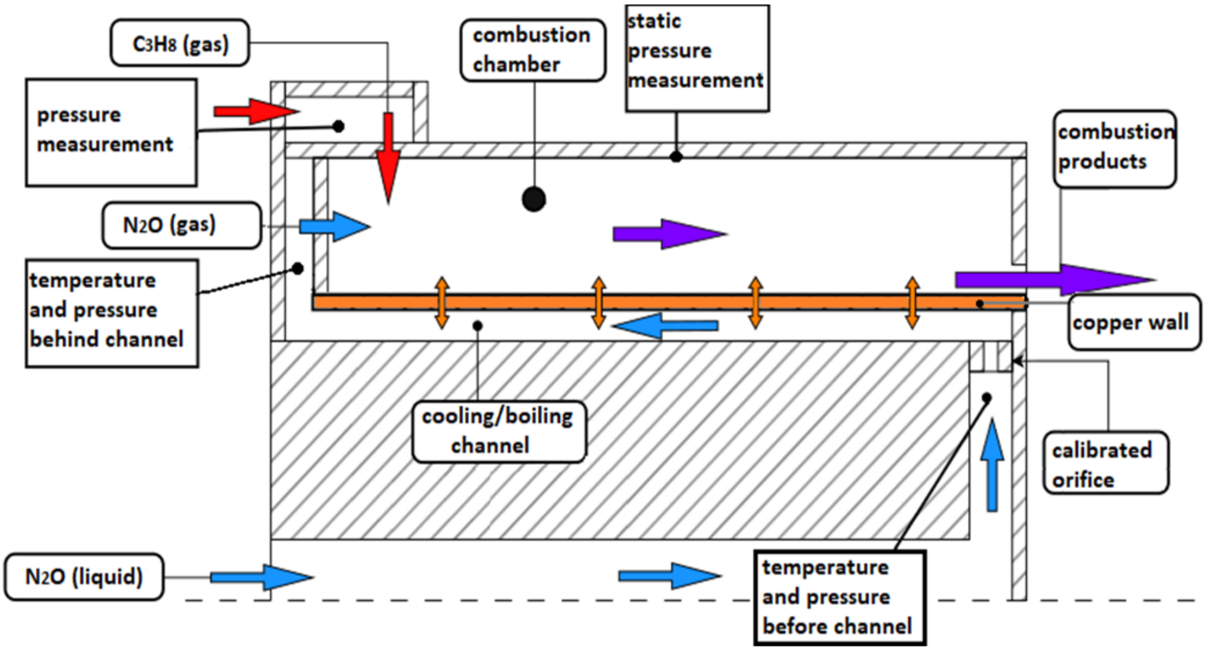

Figure 1: Rocket RDE with regenerative cooling system concept diagram.

Numerical setup

In developing numerical model the ANSYS Fluent software was used. Model of liquid nitrous oxide was simulated through User-Defined Functions (UDF) including its physical properties like: density, viscosity, thermal conductivity, specific heat capacity, their change with temperature and pressure-temperature saturation curve.

To simulate cooling and boiling process the Multiphase – Mixture model was used. Boundary layer allowed to keep y+ around or below value of 1 for sufficient conditions for simulation of heat transfer. Boundary conditions were equivalent to the already tested rocket RDE with conical combustor which are: mass flow rate of 0.15 [kg/s] at 2800 [K] through combustor and 0.13 [kg/s] of liquid nitrous oxide at 283 [K] through cooling channel. Copper wall of various thickness was placed between hot and cold flows. In initial approach hot flow through combustor was simulated solely by gaseous, hot nitrous oxide (while composition of components was 10:1), subsequently products of combustions were simulated. Both transient and steady cases were considered.

The most crucial factor in the simulation is purely empirical evaporation/condensation factor used in Multiphase-Mixture mathematical model. It determines the rate of phase change hence the inner wall temperature. Its determination was the aim of the validation experiment.

Experimental test stand

Propellants used in the experiments were nitrous oxide and propane. They were fed from main tanks to a separate, smaller pressure tanks in which they were pressurized with nitrogen to a specific pressure required to achieve desired mass flow rate and keep them in liquid state according to each pressure-temperature phase diagram. Those tanks were connected through supply lines with the engine and the solenoid valves were used to control duration of the experiment. Additionally, calibrated orifices were used in order to make sure that until definite place the propellants will remain liquid state. In case of nitrous oxide they were placed right before the cooling channel (at the end of supply channels) so that evaporation did not occur earlier. Ignition was conducted through barium nitrate pyrotechnic igniter placed in the combustion chamber before the test. Measurements were taken as follows:

The static pressure was measured in nitrous oxide feeding system, its plenum (right before injection to the combustion chamber) and in the middle of coolant flow path, in propane feeding system, its plenum (right before the injection to the combustion chamber) and in the combustion chamber.

Temperature was measured in the engine's nitrous oxide supply channels (right before calibrated orifice and injection to the cooling channel), in the middle of nitrous oxide flow path in cooling channel and at the end of cooling channel (before injection to the combustion chamber).

Mass flow rates were measured by two methods. The first one was using Coriolis flowmeter, the second one was weight-based measuring filled tanks weight before and after the experiment. Relative differences between those methods did not exceed more than 4%. All measurements were automated and filling and testing procedures were conducted with all security standards and requirements.

Below picture of the engine at the test stand during work was presented:

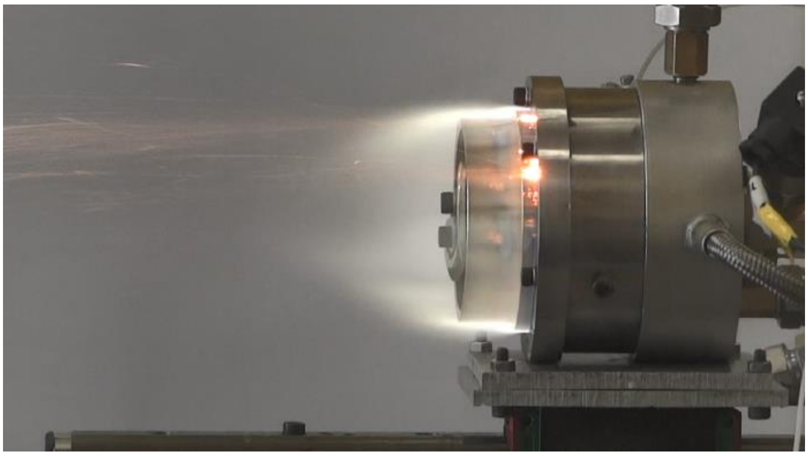

Figure 2: Experimental test stand of liquid-propellant rocket RDE with regenerative cooling during work

A sample of coolant (nitrous oxide) temperature measurements are presented below for 2.5 [s] of test:

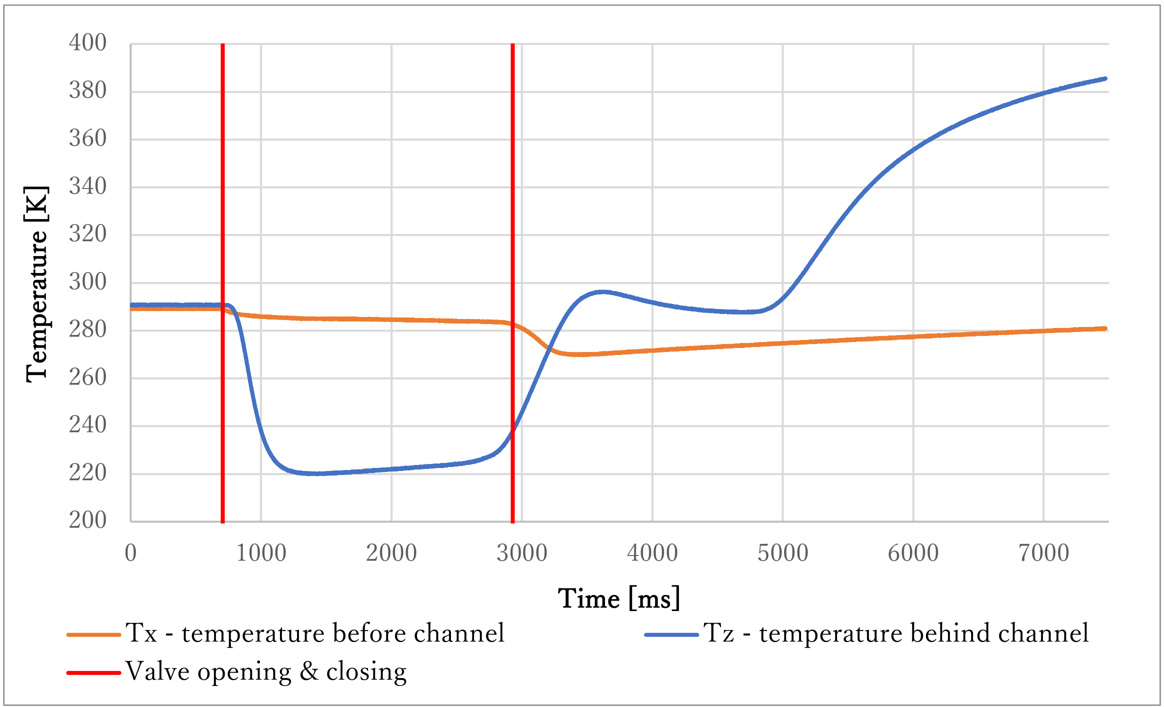

Figure 3: Coolant (nitrous oxide) temperature before and behind cooling channel. Test time t=2.5 [s]

Type K thermocouples used in this experiment has got certain delay what could be seen on "Tz" temperature measurement. Nevertheless taken pressure measurements into account it could be stated, that before cooling channel we could observed liquid nitrous oxide, while behind cooling channel it was completely evaporated, cold gas.

More results and their analysis will pe presented in the final paper.

Conclusions

According to the work done on this paper following conclusion were made:

- Cooling system is necessary to extend rocket RDE work time. In terms of liquid-propellant engine the regenerative cooling system is the most convenient one.
- Contrary to traditional regenerative cooling systems, it is necessary to evaporate cooling propellant in order to sustain stable detonation wave.
- Heat transfer is intensified due to controlled boiling process which is an advantage in terms of the aim of this research, which is the extension of rocket RDE work time above 20 [s].

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