
LO_x/ETHANOL GAS GENERATOR: INVESTIGATION AND DEVELOPMENT

R. H. S. Hahn, L. B. Nascimento, and D. S. Almeida

Instituto de Aeronáutica e Espaço (IAE)
50 Praça Marechal-do-Ar Eduardo Gomes, São José dos Campos/SP, Brazil

This paper presents preliminary experimental results of a gas generator (GG) developed for research to determine the burning characteristics in mixture ratios below the stoichiometric and the validation of the chemical equilibrium software, as well as performance calculations, with own developed software used specifically in the design of this model of GG. For this work, tests were carried out at pressures below nominal operation point for an initial investigation of combustion behavior in low mixture ratio. The results show the possibility to a new analysis method which leads to development of numerical tools to investigate its behavior.

ABBREVIATIONS AND ACRONYMS

A50	Aerozine 50 (50/50 UDMH/N ₂ H ₄)
C^*	Characteristic velocity
CEA	Chemical equilibrium with applications
GG	Gas generator
HCO	Hydrocarbon omission
LO _x	Liquid oxygen
LPRE	Liquid propellant rocket engine
N ₂ H ₄	Hydrazine
NTO	Nitrogen tetroxide
PNAE	National Program for Space Activities
RP1	Refined petroleum 1 (kerosene)
UDMH	Unsymmetrical dimethylhydrazine
ZRH	Zero reaction hypothesis

1 INTRODUCTION

During first liquid propellant rocket engine (LPRE) development, around 1930s, the use of pumps to increase propellant pressure at combustion chamber inlet

faced the need of a new way to drive the turbine. The solution found was to use a small combustion chamber with a diluent in gas path to reduce its temperature in a range acceptable to the turbopump work safely [1]. The first evolution of GG for LPRE began in Germany by Hellmuth Walter Company, with use of catalytic decomposition of hydrogen peroxide to provide gas at elevated temperature for the system with no possibility of burnout. It led to a simple solution which is used until now in RD-107 and RD-108. However, GG using concent hydrogen peroxide has a limitation of energy due to maximum temperature of decomposition. To increase exhaust gas temperature aiming to create a more efficient engine, XLR71 program starts to use fuel injected into GG, resulting in combustion of ethanol at 92,5% with decomposed hydrogen peroxide [2]. At this time, the ethanol was replaced by kerosene due its higher specific impulse and new GG developed starts to use the same propellant as combustion chamber instead of hydrogen peroxide [3]. As a result, investigation regarding liquid oxygen (LOx) / ethanol GG was abandoned for studies on the new more energetic propellant combination resulting in a lack of information about LOx/ethanol fuel-rich combustion at mixture ratio far from stoichiometric.

For L75 LPRE, in development at Institute of Aeronautics and Space (IAE) and as a part of National Program for Space Activities (PNAE) [4, 5], the LOx/ethanol combination was chosen due to its advantages of its ready availability in Brazil, nontoxicity, and more stable chemical fuel composition. Also, its behavior on cooling capability and very low soot formation during combustion were considered as the positive points during its choice [6]. In this context, a deep investigation on combustion of LOx/ethanol in a mixture ratio distant from stoichiometric for GG development was proceeding. This investigation results in an analysis methodology capable of better estimating combustion parameters as well as numerical tools to help its design during development status. The first row of hot tests also was proceeded and compared to theoretical studies to improve its precision.

2 DEVELOPMENT OF L75 GAS GENERATOR

During its first design, the L75 Engine GG was projected to achieve combustion gas temperature of 900 K with fuel excess in order to avoid turbine damage and with thermal margin which also allows to extend its operational envelope, providing power to engine specified range of mixture ratio and chamber pressure. However, initial theoretical models show that a very low mixture ratio is needed to generate this temperature, being far from available literature information. The flammability boundary was also unknown for LOx/ethanol mixture as well as global combustion parameters at mixture ratio below 1.0.

Using proposed two-zone GG [7, 8] to achieve final gas temperature, this GG was divided in a combustion zone, responsible to maintain a stable combustion

at moderate temperature without chamber damage followed by a dilution zone that will reduce overall temperature to the specified one. The first preliminary design was carried out considering GG as a simple combustion chamber divided into two separated configurations.

The initial configuration was to attain a global combustion mixture ratio to achieve desired pressure and temperature, followed by a configuration taking into account just the combustion zone to define its desired mixture ratio, temperature, and injection configuration.

For the global configuration, a preliminary combustion temperature approach considers the worst case scenario which results in a mixture ratio far below stoichiometric. Despite general information regarding GG with LOx/refined petroleum I (RP1) and nitrogen tetroxide (NTO)/aerozine 50 (A50) [9, 10] shows temperature disagreement from equilibrium model as a result of low residence time inside combustion chamber, partial combustion with evaporation, and molecular breakdown of fuel, the mixture ratio boundary of these events was uncertain. In this approach, the capability to increase mixture ratio can improve knowledge of LOx/ethanol combustion behavior in the further tests.

For combustion zone, however, initial studies of its efficiency and flammability boundary were conducted with simpler platform using GOx/ethanol rocket engine. The initial test was carried at already known mixture ratio behavior to be a combustion base and, thereafter, the mixture ratio was decreasing up to the known operational limit of test stand. Main injection parameter was kept constant in order to avoid different mixture behavior inside combustion chamber. The preliminary thermal approach for combustion zone also considers the worst case scenario to avoid damage of the test device led to a stable combustion at mixture ratio below to 0.6 with good combustion efficiency. With these, a set of test was possible to estimate initial parameters for desired combustion zone and its GG dilution zone. All considerations took into account a perfect combustion at this stage of development which makes possible to evaluate combustion performance in the future tests.

2.1 Two-Zone Gas Generator

When one moves away from stoichiometric, the combustion starts to become more susceptible to spontaneous instability [11] and may flame out due to proximity of flammability boundary. In some cases, the required exhaust temperature cannot be achieved, resulting into combustion extinction of GG. However, this issue can be solved with two-zone GG.

The main idea of two-zone GG originated on the first GG development [1] with use of even more than two propellant combinations. While keeping a more stable and efficient zone to provide heat, the second injection system sprays liquid to absorb the excess heat, until all system achieves thermal equilibrium at

specified temperature. This design leads to a wider range of mixture ratio pro device and allows to operate in a more stable combustion zone. Recent study also shows the improvements into use of a stoichiometric combustion zone with hydrocarbon fuel in order to reduce the soot formation, increasing stability and efficiency [8]. The third component also can be added to improve gas adiabatic specific work when decreasing exhausts molecular mass of mixture.

However, for L75 GG, the first zone was defined just to keep combustion stable at low mixture ratio while the second zone will absorb heat up to thermal equilibrium. The dilution zone function is spraying ethanol inside combustion flow, which allows quick evaporation and creates a “bubble” region with pure fuel. The spray also induces turbulence in combustion, allowing combustion gas mixture with pure fuel, making possible to react with free radical from combustion, resulting in increase of global energy.

2.2 Chemical Equilibrium Model

When one takes into account a combustion chamber with large residence time and near to stoichiometric, the chemical equilibrium model agrees with experimental results due to enough time to simplified combustion products react and the rate of reaction between combustion products became constant. In GG, however, its small internal volume resulting in low residence time and temperature compatible with mixture ratio far from stoichiometric causes combustion products increase in variety due to molecular breakdown at no oxygen environment [12]. At these conditions, the chemical equilibrium models start to deviate from real conditions, resulting in an inaccurate prediction of combustion parameters [13].

Considering a two-zone GG, it is possible to estimate combustion parameters with more precision when equilibrium model is induced to avoid the formation of more stable chemical compound. However, this approach usually provides confident combustion parameters in a mixture ratio slight wider than pure chemical equilibrium.

According to [12, 14], heating ethanol to temperature below 1500 K in an oxygen free environment, the molecular breakdown usually takes several seconds to start to produce some simple hydrocarbons while some more complex compounds start to appear faster. In GG, this condition led to a temperature decrease which also increases time needed to breakdown complex molecules.

An initial evaluation of combustion of GOx/ethanol at mixture ratio below as 0.6 shows a good approach of this technique with experimental results, showing combustion efficiency near to unity on static tests at low chamber pressure.

2.3 Thermal Dilution

Using a second injection system was possible to generate turbulence in combustion while thermal diluent was injected in a specified angle to increase cham-

ber residence time and velocity to penetrate in hot gas flow. The injector was also designed to provide a good spray in order to improve evaporation rate of ethanol. A preliminary approach considers that all fuel was evaporated and mixed with combustion product at the end of GG cylindrical section without chemical reaction and achieving thermal equilibrium. The combustion enthalpy also reduces during combustion cooldown, which results in an interactive calculation using different molecular omission while combustion gas temperature is decreasing.

While a global molar mass cannot be directly measured and global combustion temperature cannot be measured with accuracy, in this phase, the characteristic velocity C^* can provide a good approach of phenomena inside combustion chamber.

3 FIRST RESULTS

Due to unknown behavior of combustion of LOx/ethanol at this mixture ratio region, the first row of hot test was carried out at low chamber pressure while keeping mass flow rate at design values by using equivalent nozzles with different critical section areas. Thus, the chamber pressure can be gradually increased as the behavior of combustion parameters are checked at different pressures (Fig. 1).

The ignition system also has an important role for combustion at the very first moments of this procedure, with use of resonance igniter [15] operating

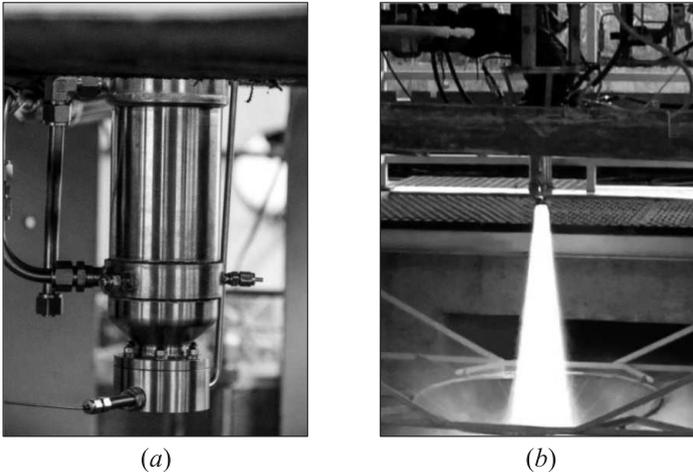


Figure 1 Gas generator mounted in the test stand (a) and during a hot test (b)

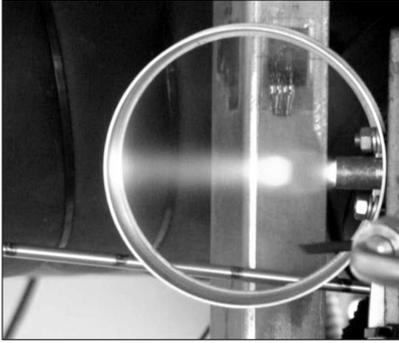


Figure 2 Igniter during nominal operation to verify hot gas interaction with metallic chamber material

with GOx and the same fuel as GG and mixture ratio adjusted to 15, which operates as an oxidizer supply, keeping combustion zone mixture ratio high during ignition procedure in order to facilitate the start of combustion. Several tests of igniter were carried out to verify any possible interaction of oxidizer rich gas with metallic wall of GG combustion chamber. During the igniter tests, it was used a 110-millimeter diameter stainless steel ring as shown in Fig. 2.

A specific ignition sequence was adjusted to provide enough energy to ignition, keeping mixture ratio in

combustion zone at a known level for a small period of time at expected transient and during a possible steady-state regime.

3.1 Hot Test 1

The first test of GG was limited in 5 s to verify ignition transient and cutoff behavior with enough time on steady-state to analyze collected data and evaluate the presence of stable combustion. This test showed an oscillation around 0.5 Hz in combustion pressure, presented in Fig. 3, which later was identified as LOx

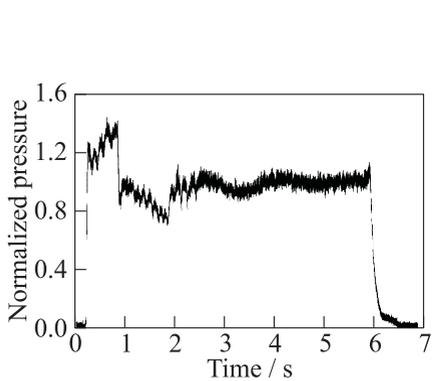


Figure 3 Combustion chamber pressure curve of the first hot test

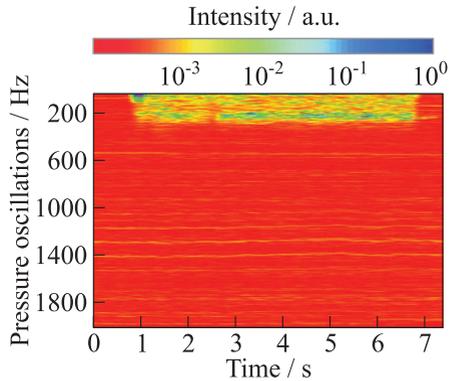


Figure 4 Spectral behavior of pressure oscillations of the first test

injector cavitation due to elevated temperature of oxidizer. This test also shows a 6-hertz oscillation in the combustion chamber pressure, between ignition and near to the 2.5-second operation, as result of LOx pressure regulator system behavior. Another phenomena identified was the higher combustion chamber pressure during the first 0.5 s which was occasioned by the ignition source.

Also was verified a minor pressure oscillation up to 200 Hz with very low energy as shown in Fig. 4, likely caused by dynamic of hydraulic lines.

The first verification also shows a low combustion efficiency characterized by a chamber pressure lower than expected, which also led to a mixture ratio shift due to injector dynamics. The mass flow rate also increases and induces a higher amount of fuel injected into dilution zone.

Due to uncertainties, the amount of sensors was kept as minimum to avoid any damage. With confirmation of combustion, next test was performed at the same conditions, with except for an increase of chilldown time in order to reduce the oxidizer lines temperature, improving the ignition transient.

3.2 Hot Test 2

The second test was performed at the same inlet parameters as the first test. However, to avoid two-phase LOx, a chilldown time was increased and burn time limited to 20 s to better investigate the steady-state regime. The ignition was evident and an initial analysis presented a more stable combustion without LOx injector cavitation. As shown in Fig. 5, the combustion chamber pressure during the first 0.5 s of operation was higher due to the ignition source.

As the previous test, a pressure oscillation with smaller peak-to-peak value and low energy was registered. However, its likely hydraulic oscillation shows

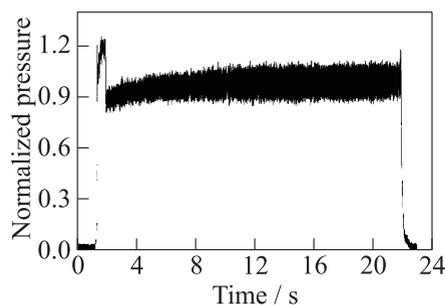


Figure 5 Combustion chamber pressure curve of the second hot test

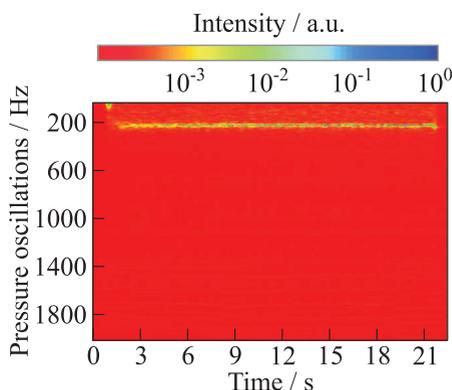


Figure 6 Spectral behavior of pressure oscillations of the second test

a more concentrated energy at a narrow spectrum with frequency peak around 200 Hz as presented in Fig. 6.

Also was verified a combustion efficiency slightly higher than the previous test confirmed by increase of combustion pressure which led to a mixture ratio and total mass flow rate closer to the specified due to injector dynamics.

3.3 Hot Test 3

For this test, an equivalent nozzle with reduced area of critical section was used to increase combustion chamber pressure. At the same time, total burn time was decreased to 15 s as previous test showed that it is enough time to achieve steady-state and acquire transient information for the present study. The ignition sequence adopted was performed with no modification and the chilldown time increased. The higher combustion chamber pressure during the first 0.5 s, shown in Fig. 7, was due to ignition source providing extra energy for the GG transient, as described in the previous tests.

A stable combustion was also achieved with improved efficiency validated by increase of chamber pressure as expected. The mixture ratio was kept constant and diverged from the previous test less than 0.26% showing a good repeatability of inlet parameters while the characteristic velocity C^* increased by 6.7%.

The higher pressure also damped almost all pressure oscillation in hydraulic system as shown in Fig. 8. Also, it is possible to verify a sparse energy at the same region up to 200 Hz as in the previous test. Since injector dynamics were the same, it is possible to disconsider its participation in this phenomenon. Once this dynamics is not the primary aim of this study, no further details of this oscillation were investigated in the present work.

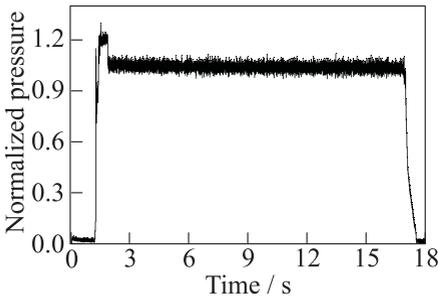


Figure 7 Combustion chamber pressure curve of third hot test

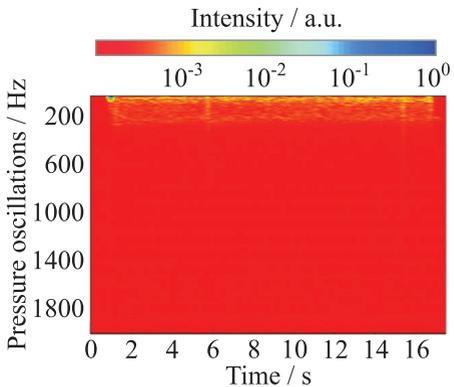


Figure 8 Spectral behavior of pressure oscillations of the third test

This test was also the last of these series due to need of deep analysis of all information collected and verification of the necessity of modifications in order to improve design tools and to adjust the design parameters for the project's needs.

4 ZERO REACTION HYPOTHESIS

The first analysis performed with three test data collected shows combustion efficiency lower than the expected and a need for design improvements to achieve design requirements for GG. A chemical equilibrium method for C^* determination also induces a higher than achieved efficiency. At this mixture ratio, also a hydrocarbon omission results in a temperature incompatible with achieved performance, leading the threshold of combustion and molecular breaking of combustion zone still unknown. Due to large amount of fuel injected into dilution zone, good approach for this case at the first analysis disregarded significant amounts of reaction of fuel from thermal dilution zone with high temperature gas from the combustion zone.

This hypothesis permits the inference that the molar amount of combustion gases will be added to the molar amount of injected ethanol inside a constant volume and pressure, resulting in a global molar mass adjusted according to the amount of species inside combustion chamber. Moreover, the specific heat of products will change according the ethanol heat while combustion gas cools down, leading to total specific heat ratio proportional to the gas amount and its temperature at equilibrium.

According to Chemical Equilibrium with Applications (CEA) [16], at mixture ratio and chamber pressure of three tests, it is possible to verify the presence of 4 most important combustion products with considerable contribution to parameter verification. At its, respectively, temperature and, according combustion zone, mass flow rate, it is possible to obtain the mass flow rate of substances inside combustion chamber as show in Table 1.

Table 1 Mass flow rate (in g/s) of main combustion products for this analysis

Substance	Test 1	Test 2	Test 3
CO ₂	174.04	171.37	181.36
CO	43.99	41.20	43.69
H ₂	12.21	12.75	13.45
H ₂ O	84.85	75.78	80.64
C ₂ H ₅ OH	1052.67	1029.55	1089.95

Table 2 Main combustion parameters for this analysis

Test	Molar weight, g/mol	Specific heat ratio	Temperature, K	ΔH_{EtOH} , kJ/(kg·K)
1	33.46	1.245	353.7	142.27
2	33.28	1.247	457.6	1158.63
3	33.29	1.205	509.0	1247.47

The results also show a small production of atomic hydrogen and OH, with a total mass flow rate of both components less than 10 mg/s (Table 2).

According to final temperature achieved by this method, it is possible to verify that in the first test, a large amount of ethanol from dilution zone was still in liquid form as well as water coming from the combustion zone. This phenomenon was evident due to low value of C^* in this particular test (Fig. 9).

The amount of heat from combustion zone was not enough to evaporate all ethanol, resulting in a possible two-phase flow at nozzle critical section. Using the zero reaction hypothesis (ZRH) with CEA [16], it is possible to estimate temperature in function of mixture ratio with only compounds of reaction as shown in Table 1. It led to curve presented in Fig. 10 which also compares with hydrocarbon omission (HCO) and normal mode on CEA (described as classic).

Despite the threshold of zero react is not full known, it is possible to establish lower and upper boundary for expected combustion temperature with this two-zone GG.

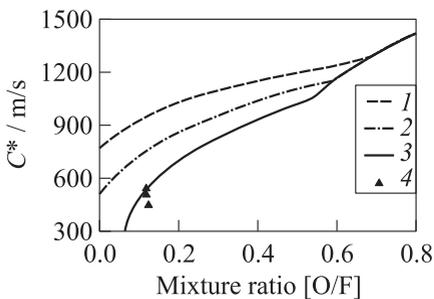


Figure 9 Theoretical C^* as a function of mixture ratio (1 — classic; 2 — model HCO; and 3 — model ZRH) and experimental results from three tests (4)

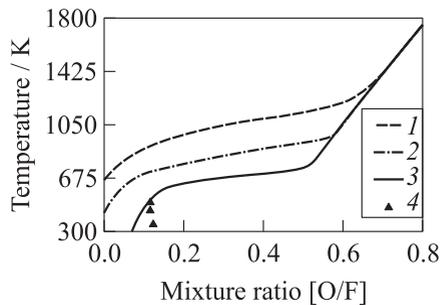


Figure 10 Combustion temperature as a function of mixture ratio (1 — classic; 2 — model HCO; and 3 — model ZRH) and theoretical temperature from three hot tests (4)

5 GAS GENERATOR DESIGN TOOL

For GG analysis, a code in C++ was developed to help improve performance, changing inlet parameters in order to verify global behavior of this device. Initially, a group of primary models to evaluate injector dynamics and performance was added to a general combustion chamber design model. This part of code led to an initial estimative of overall performance and enables to specify inlet conditions for the next step.

The second part of code was implemented with a simplified model for turbulent mixture wall layer in LPRE, described by Vasiliev *et al.* [17] which takes into account a combustion zone mixture ratio decrease due to secondary injection of mass flow rate. The relation of secondary injection and combustion gas mass flow led to preliminary estimate of combustion temperature along cylindrical longitudinal section of chamber, considering a stirring coefficient assumed to an elevated turbulence due to fuel injection nonparallel to combustion gas flow. For this initial calculation, a chemical equilibrium model is used with different approaches while combustion temperature changes. Lastly, a model of GG geometry, based on combustion chamber global parameters was implemented in order to provide its internal geometry. This addition also allows to introduce a regenerative cooling if necessary.

A preliminary approach assumes a full equilibrium in a high-temperature fuel-rich combustion and during mixture ratio decrease followed by residence time reduction, a group of hydrocarbons is omitted according estimates from molecular breaking from fuel pyrolysis [12, 14]. Just after secondary injection, which in this case is ethanol, the model of ZRH is used to deliver general combustion parameters at steady-state conditions as shown in Fig. 11 from the third test.

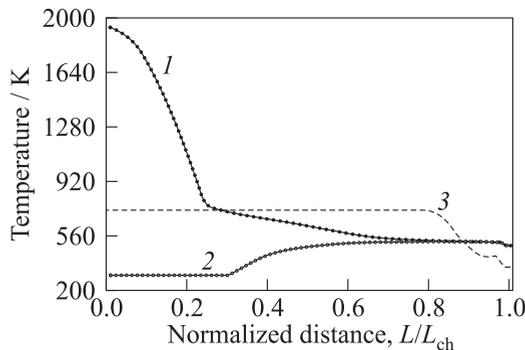


Figure 11 Theoretical temperature evolution of combustion products and ethanol from dilution zone (near to the chamber wall) along GG chamber for the third test: 1 — core; and 2 — wall. Dashed curve indicates the shape

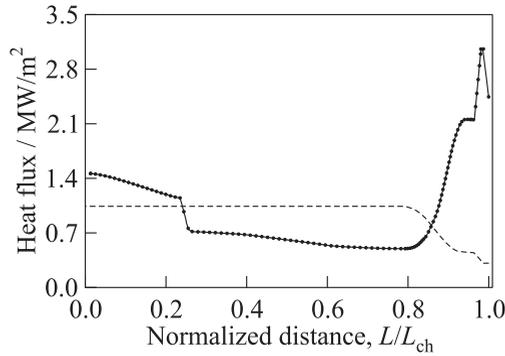


Figure 12 Heat flux prediction along GG chamber for the second test. Dashed curve indicates the shape

To estimate an initial heat flux, the code uses the Bartz model [18]. In the case of regenerative cooling analysis, fuel inlet parameters as temperature, viscosity, and boiling margin are updated iteratively with information from heat transfer, providing additional information for expected combustion performance. On the other hand, an option, which considers only the capacitive and radiative cooling, provides enough information to initial investigation, leading to faster results at the initial stage of design (Fig. 12).

Thus, it is possible to estimate an initial behavior for gas conditions as well the ethanol inside combustion chamber of GG and will allow the calibration of theoretical models employed as well as the correction parameters for this specific case under development.

6 CONCLUDING REMARKS

For the GG configuration under study, where mass flow of combustion gas is a small percentage of total flow and assuming no reaction between dilution zone with combustion products, it is possible to estimate with confidence the global parameters of LOx/ethanol GG. Despite small quantity of experimental results, initial models improve knowledge of this device behavior and also show a satisfactory stability of combustion at very low mixture ratio and low chamber pressure.

New tests will be held to verify the mixture ratio threshold for ZRH and HCO as well as new temperature measurements will be implemented in order to establish an experimental comparison with theoretical models presented in this paper. For future studies, a mixture ratio by combustion chamber pressure

matrix will allow the creation of a database for this combustion parameters and behavior to compare with possible methods for analysis.

New improvements on GG design were also performed with information acquired during these first tests and led to a more dynamic system design with possibility to increase accuracy of inlet parameters adjustment resulting in a reliable design.

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