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Maurício Sá GONTIJO

Aeronautics Institute of Technology, Aeronautical Engineering and Mechanics, Aerospace Propulsion and Energy, Brazil

INVESTIGATION OF THE EXISTING METHODS FOR DESIGNING PRE-COMBUSTION CHAMBERS IN HYBRID ROCKET ENGINES

Hybrid propellant rocket engines (HPRE) have been under development and advancement since the beginning of rocket propulsion research, alongside liquid and solid propellant rocket motors. However, its pace was much slower than that of the other propulsion types. Several companies have proposed hybrid launch vehicles in the last few years, and research and publications on such technology have increased significantly. One of the most crucial parts of HPREs is the pre-combustion chamber. This device is positioned upstream of the combustion chamber and downstream of the injection head, and it greatly affects the engine's performance, size, weight, and cost, and combustion stability. Therefore, propulsion engineers are intensely interested in understanding the processes occurring inside pre-combustion chambers. Unfortunately, there are few published works on the design of such systems. Additionally, many references only recommend empirical size relations, which may only serve as a design starting point. Observing this issue, this paper compiles all the methods for designing pre-combustion chambers and provides rich discussions on each. These methods are: 1) experiments, 2) empirical relations, 3) numerical simulations, 4) droplet vaporization models, 5) combustion instability models, 6) droplet collision outcome prediction, and 7) molecular dynamics. The positive and negative aspects of each method are also considered. Moreover, other components that affect the calculation are discussed, such as injectors and grain design. Finally, a development workflow recommendation was constructed by applying all the discussed methods to reduce related costs and obtain an optimized design.

Keywords: *pre-combustion chamber; hybrid propellant rocket engine; design workflow; droplet vaporization.*

Introduction

Hybrid Propellant Rocket Engines were, through several decades, aside from the main industry research and development. However, in the 90s, this trend changed with some initiatives, such as the AMROC [1]. In addition, only in the last few years has this technology received opportunities to integrate important space missions, such as HyImpulse, Innospace, SARA, Virgin Galactic, Nammo, and others [2-7]. This is the reason that a smaller number of publications exist on the detailed design of devices for this technology, even nowadays. One of the parts that lacks studies and is of substantial relevance is the pre-combustion chamber (i.e., pre-chamber or PC). The pre-chamber is responsible for providing enough volume for the liquid propellant to be injected, atomized, and vaporized (or partially vaporized), and for pre-heating the oxidizer gas. In case gaseous propellant is used, the pre-chamber may be shorter since no atomization and vaporization is required. In addition, [8] states that the PC must be long enough to permit the flow reattachment before the solid grain.

In general, a liquid oxidizer and a solid fuel is used [9]. One of the reasons for this is that, in majority of the cases, liquid oxidizers tend to vaporize faster than liquid fuels [10-12].

If the pre-combustion chamber is longer than required, a heavier and a more expensive engine is obtained. On the other hand, if it is shorter than required, the engine's performance is reduced and combustion instabilities may appear [13-15].

Common approaches

Three main techniques were approached in most of the projects. These are:

1) Experimentally;
2) Historic empirical relations;
3) Computational Fluid Dynamics (CFD).

Determining the PC size through experiments is the most expensive and time-consuming approach since it may take several hot and cold tests. Using empirical relations is a midterm in terms of costs since it may reduce the number of tests to develop a new HPRE by considering previous successful engines. Finally, CFD is being one of the most used approaches since computational capabilities are advancing rapidly, and it drastically reduces

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the number of experiments. However, a geometry is required to reach the CFD phase, and empirical relations may be used for initial estimations.

In addition to these three design procedures, new theoretical models are being developed, such as droplet vaporization models and feed system coupled instabilities models. These and other possibilities, alongside with some discussions on other engine's devices that affects the PC size is present in this work. In addition, a full methodology, combining the discussed techniques, is proposed for a full understanding of the behavior of the flow inside the PC and for a reliable design.

Experimentally-based design

As previously introduced in the last section, the experimental procedure is the most expensive. This approach consists of making several tests, dozens or even hundreds of tests. First, in order to reduce these costs, cold flows are performed. Cold flows may comprise individual injectors, a group of injectors (especially if impinging-based injectors are implemented), or the full injection head. These tests are useful for determining if coalescence or separation is obtained as an outcome of jets/droplets collision and a vaporization length. Indeed, this is just an approximation and are considered initial tests since the propellant isn't injected in an equivalent or similar atmosphere (i.e., ambient temperature and pressure). Additionally, propellant simulants are commonly employed in these tests, such as water or LN_2 [16-18].

After adjusting the pre-chamber size based on cold flow results, the hot tests may be performed. In such experiments, the characteristic velocity (C*) and, therefore, the combustion efficiency (ηC^*) are the main observed parameters since they evaluate the overall combustion chamber performance and efficiency, and the PC size directly impacts these parameters. Several PC sizes are tested, and a plot is built with C* and/or ηC^*. In addition, another important axis of this plot is the weight since a possible increase in performance may be unjustifiable due to a higher increase in weight.

Finally, through hot fire tests also provides valuable data on chamber pressure oscillations. It was found that the PC also impacts on combustion stability and this will be better discussed later. It is assumed that a stable combustion has a pressure oscillation lower than 5% [9].

Empirical relations

In general, pre-chamber Length over Diameter, or L_{pc}/D_{pc}, ratio ranges are used to design, at least, preliminarily the PC. The same dozens or hundreds of tests explained in the previous section are required to define a reliable ratio range. In addition, it is recommended that data from several different engines is compiled to enrich the empirical relation. Therefore, it is expensive and may take many years to reach a well-grounded L_{pc}/D_{pc}, which is why only a few relations are published in the literature. One of the most commonly used ratios, as a rule of thumb, is $L_{pc}/D_{pc} = 0.5$, as presented by [19]. [20] obtained a value of 0.53 with vaporization models. Besides experimental tests, CFD simulations and instability and vaporization models also aid in defining the ratio.

In most of the cases, the designer will calculate the diameter first since it is function of the grain final diameter. And the grain final diameter is determined based on some requirements, such burn time, initial port area, and limitations on initial oxidizer mass flux, which was found to be around of 650 kg/m²s for nitrous oxide/paraffin-based combinations [9, 21]. Above that value, blowoff or combustion instabilities may occur. It is important to mention that if other propellants are used, this value can vary, and in general, it is obtained through hot fire tests or with CFD. Then, finally, one may calculate the PC length with a selected value of L_{pc}/D_{pc}.

Computational Fluid Dynamics

CFD has been one of the most used tools during the development phases of rocket engines in the last few decades. It presents to be a reliable source of information of any part of the engine in which there is flow of any fluid. It is capable of simulating all involved processes, such as multiphase flow, mass transfer, ligament and droplet breakup, heat transfer, turbulence, and others. In addition, it can analyze 3D flows, which is, in general, a limitation of analytical models that are restricted to 0D, 1D, or Quasi-1D [10, 22, 23].

Even though it is a cheaper solution in comparison with the experimental approaches, it does not entirely substitute hot and cold tests. In addition, a relevant investment must be made in a simulation software, consumed electrical energy, powerful computers or a processor (CPU - Central Processor Unit or GPU - Graphics Processing Unit) cluster, and CFD-specialized engineers. Costs with Commercial-Off-The-Shelf (COTS) software may be avoided or reduced by using open-source codes (e.g., OpenFOAM). However, considerable time is required to develop and/or couple all needed models. Furthermore, a refined and reliable simulation may take days, weeks, or even months to converge, and many hours are required to draw the geometry, prepare it for the simulation, build the mesh, apply the correct models and boundary conditions, and post-process the results, so electrical energy consumption is not negligible [24].

CFD also helps to make adjustments other than the length and diameter. Some examples are the injector's geometry (it directly affects the PC sizes), the injector's disposition on the injection head, other possible devices inside the PC (e.g., diaphragms), modifications on the

solid grain inlet or combustion port, curving and smoothing sudden changes in diameter, and others. Additionally, recirculation, commonly obtained, may be observed and evaluated since it has a direct influence on the engine's performance and combustion instability [24-27].

Combustion instability

Some recent works related the dependency of the pre-chamber with acoustic instabilities. It was found that the combustion is stable if an injector, together with the PC geometry, generates a strong recirculation zone. This is due to the oxidizer pre-heating promoted by the recirculation before entering the grain combustion port. Also, it acts as a flame holding at the grain inlet since the propellants mixing is enhanced in that region [27]. A specific combustion instability type was deeply studied recently. This type is the feed system-coupled (FSC) instability, or L* instability. This instability happens only with liquid oxidizers and especially with cryogenic fluids. Additionally, it is characterized as a low-frequency instability with narrow peaks. Since it is coupled with the feed system, it is impacted by both the injectors and the tubing upstream the injector [28, 29]. The FSC instability can be avoided by employing cavitating venturis, choked injectors, or a cavitating venturi style injector. However, in some cases, these solutions are not possible to be used, whether because it does not apply to some oxidizers, such as using a cavitating venturi for two-phase flows (e.g., nitrous oxide – N_2O), or due to design restrictions on designing a choked injector, or because it is expensive to manufacture, such as the venturi injector [28, 30, 31].

In the cases where the FSC instability must be avoided by the pre-combustion chamber design, the Summerfield theory [32] was modified since it was originally proposed for Liquid Propellant Rocket Engines (LPRE), to be applicable for HPRE by [13, 15]. This theory relates the residence times in the pre-chamber (τ_{pc}), in the fuel grain (τ_f), and in the combustion chamber (τ_r) with a ratio of the average chamber pressure by two times the injector pressure drop. This parameter is mathematically defined as:

$$\beta = \frac{\bar{P}_c}{2\Delta P},$$

where $\bar{P}_c$ is the average chamber pressure, and ΔP is the injector upstream pressure minus the downstream one.

The critical line is defined when the growth in oscillation amplitude is equal to zero ($\alpha = 0$); if $\alpha > 0$ an unstable condition is obtained; and if $\alpha < 0$ a stable condition is obtained. Therefore, $\alpha = 0$ gives us a constant pressure oscillation amplitude. However, any perturbation may shift to the unstable combustion region, and the designer should place its design point in the stable region and relatively far from the critical line

Figure 1 shows the relation between β and the residence times dependent parameter presented below:

$$T = \frac{\tau_{pc} + 0.5\tau_f}{\tau_r},$$

where τ_{pc} is in function of the pre-chamber length, injection velocity, and the gas velocity at the combustion port. τ_f is in function of chamber pressure, port volume, combustion gas constant, average port temperature, oxidizer and fuel mass flow rates, the number of moles in the gas, and a boundary-layer delay time coefficient (obtained experimentally and may assume values from 0.55 to 2.05 in previous publications [13,33]). τ_r is in function of chamber volume, characteristic velocity, throat area, combustion gas constant, adiabatic flame temperature, and characteristic length. These and other important parameters of this model are better and more deeply described in [13, 15, 20].

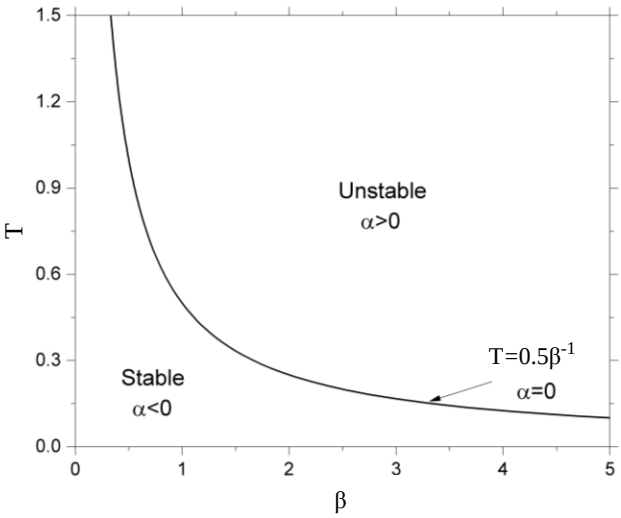

Fig. 1. Stability criterion for HPREs. Adapted with authorization from [20]

As shown above, the stable region is quite strict. The pre-chamber size directly impacts the τ_{pc} and the τ_r. Therefore, it is possible to change the region from stable to unstable only by varying the PC geometry and maintaining the grain and injectors design, which may be in a frozen development phase due to any restrictions in time or costs.

In addition to this analysis, some devices may be inserted in the PC to avoid instabilities and its size may be reduced, such as diaphragms [25]. Some types of injectors are also more prone to induce instabilities than others [28, 34].

Droplet vaporization

Droplet vaporization models are widely employed in LPRE design [10,12, 22, 35-40]. However, only a few

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published works have applied such a method to HPREs. The majority of the models solve a system of equations through numerical methods, such as 4th-order Runge-Kutta. Some of the governing equations are mass transfer, heat transfer, droplet heating rate, droplet acceleration, and gas velocity. An adaptation of Priem's model [37] was made in [20] by solving the governing equations on a liquid oxidizer droplet injected in an oxidizer-rich atmosphere. Figure 2 shows the scheme used to solve this problem. In this model, some assumptions are made, such as no combustion or chemical reactions in the PC, the oxidizer is injected as spherical droplets, and it remains spherical until the end of the simulation, constant thermophysical and transport properties of the gas, no turbulence effects, no droplet collisions, one-dimensional flow, only convective heat transfer exists, and all droplets are equal and injected with same temperature, size, and size.

In [20] the whole Priem adapted droplet vaporization model is well described with the complete system of equations and the used flowchart of the algorithm. Also, constructive discussions were made based on results and comparisons with real hot fire tests from two different HPREs.

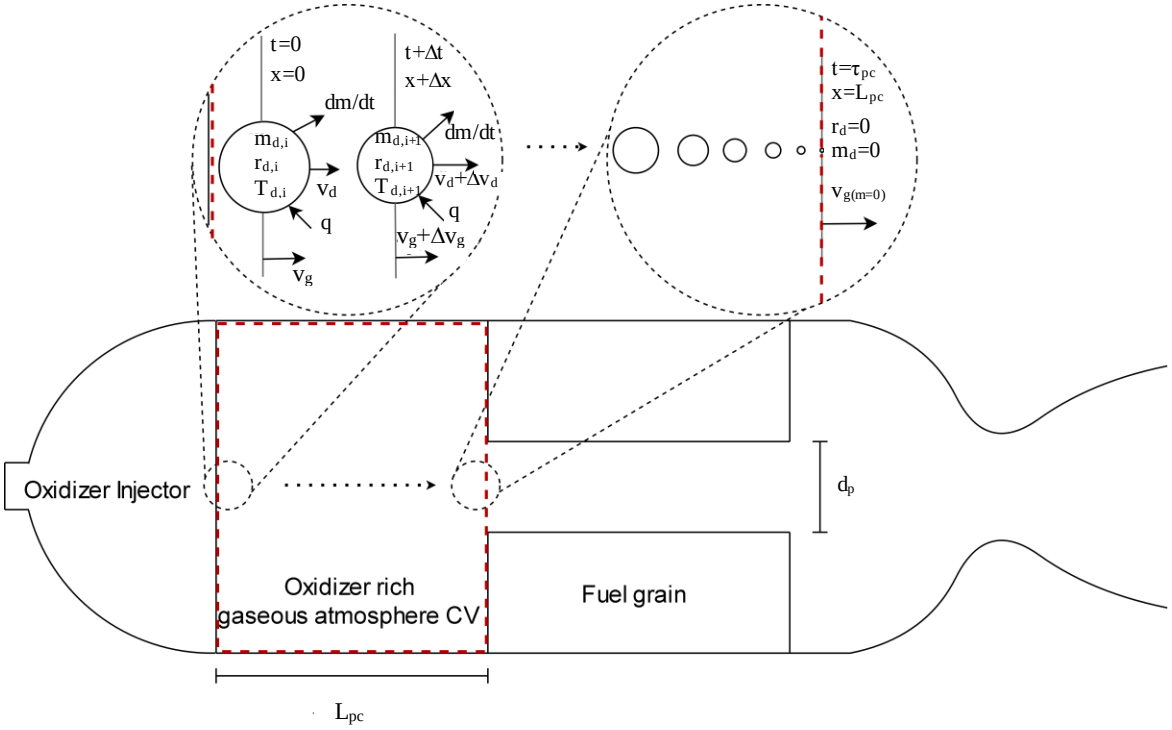

Fig. 2. Scheme of a 1D vaporization model applied to a PC design. Adapted with authorization from [19]

In the above figure, t is for time, m for mass, q for heat, x for position, r for radius, d_p is the port diameter, T_d is the droplet temperature, L_{pc} is the PC length, and the subscripts d, g, and i are related to the droplet, the gas, and each iteration, respectively. By solving the equations for two different HPREs that were tested with various conditions, such as pre-chamber length, chamber pressure, injector pressure drop, and oxidizer mass flow rate, the minimum required length for complete vaporization could be calculated for each condition. In addition, the minimum required length for stable combustion was calculated for each condition based on the theory discussed in the previous section. Considering the maximum value between these two lengths, a new range values for the L_{pc}/D_{pc} ratio was proposed to be $0.26 \leq L_{pc}/D_{pc} \leq 0.66$, which is where the majority of the values were. Also, the mean value between all data was found to be 0.53, a very close value to the ratio proposed by [19] of 0.5, as previously mentioned.

Thus, the correct approach would be to design the PC with a sufficient size to ensures stable combustion and complete vaporization of the droplet.

Molecular dynamics

Another technique that may be used to analyze droplet vaporization is the Molecular Dynamics (MD) or, if chemical reactions are considered, the Reactive Molecular Dynamics (RMD) [41-43]. MD and RMD are proving to be another useful tool to better study all aspects related to the process involved in the interaction between liquid droplets and the PC gas environment. Due to its versatility in creating customized systems and its ability to analyze molecule per molecule one is able to simulate

a vaporizing droplet accurately. Several works were published in this line of study [45-47]. However, there is lack of publications on hybrid rocket propulsion.

Unfortunately, analyzing real-size droplets alongside the gas around them requires a high computational capacity. It may take several days/weeks to finish such a simulation. Thus, some scaling law should be used in order to make these analyses possible or worth it to be performed. In general, droplet sizes in rocket engine applications are in the order of micrometers, and simulations were conducted with scaled-down droplets with nanometers [48]. The scale factor used is defined below:

$$\text{Scale Factor} = \frac{N_{d,s1}{}^{2/3}}{N_{d,s2}{}^{2/3}},$$

where subscripts s1 and s2 refer to two scaled simulations. By using the above scale factor, the results were validated with the D^2 law [49]. In addition to the scale factor, the use of parallel computing led to a simulation time of around 24 to 72 hours on a nanometer scale [50]. With modern computational advancements, this time can be even smaller. An example of MD on droplet vaporization inside a PC with a Liquid Oxygen (LOx) droplet in a Gaseous Oxygen (GOx) medium is shown in Figs. 3, 4, and 5. It is important to mention that this is just an example created for illustration, and a too-small number of molecules was placed. Each figure shows a time step in the initial stage, intermediary, and final stages. The right images are the molecules (dispersed = gas; concentrated = liquid, due to density), the middle ones have a liquid iso-surface, both shows the simulation box, and the left ones shows a histogram of the number of molecules with the position in X coordinate, in which 0 is the center of the droplet.

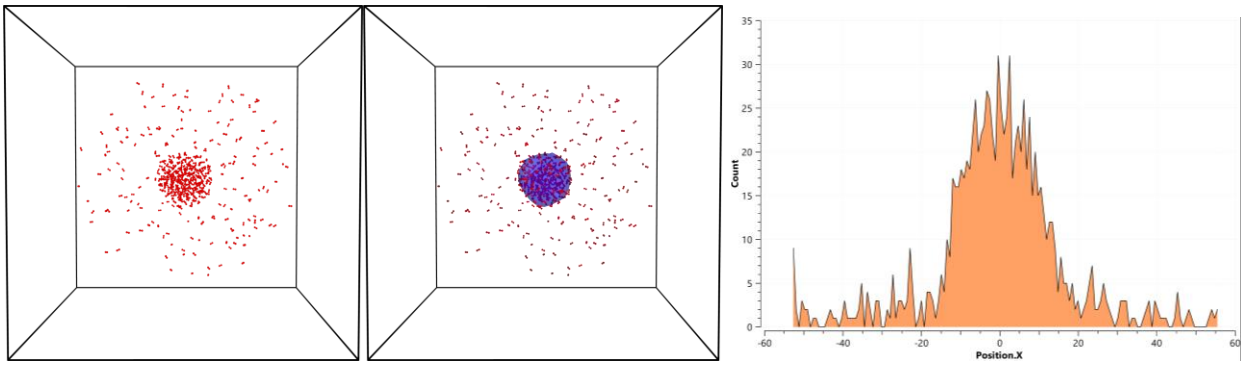

Fig. 3. MD (initial stage) – Left: Simulation / Middle: Simulation with liquid iso-surface / Right: Histogram

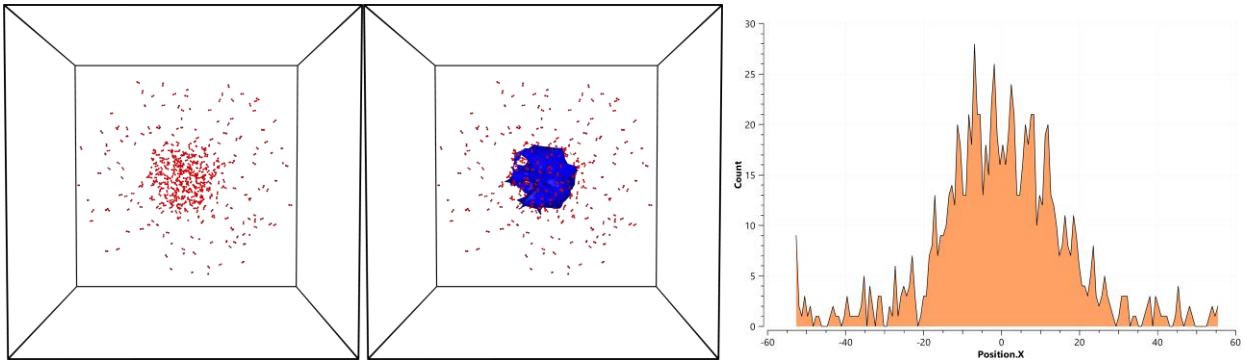

Fig. 4. MD (intermediate stage) – Left: Simulation / Middle: Simulation with liquid iso-surface / Right: Histogram

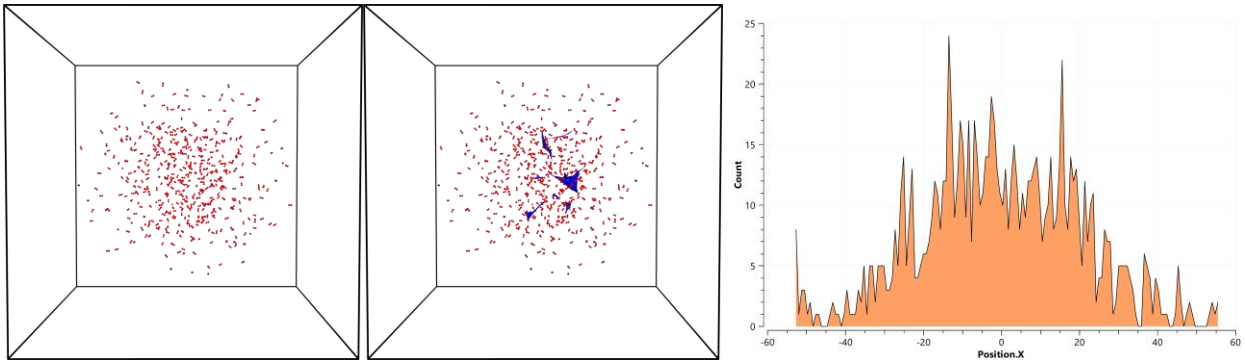

Fig. 5. MD (final stage) – Left: Simulation / Middle: Simulation with liquid iso-surface / Right: Histogram

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Discussion on the impact of injector and grain design, and collision outcomes

The injector has a direct impact on PC geometry, as already mentioned. It affects, in terms of the L* instability, the three residence times (τ_{pc}, τ_f, and τ_r) and the β. Also, the recirculation may be reinforced or attenuated inside the PC by the injector design.

In terms of droplet vaporization, the injector has direct impact on the mass transfer rate, or vaporization rate, on the heat transfer, on the droplet heating rate and on the droplet acceleration. In general, smaller droplets with low injection velocity is desired. In this way, the droplets tend to vaporize in a shorter volume.

Droplets injected inside the PC will eventually collide with each other. These collisions may be beneficial or harmful to the engine's performance. If a high amount of coalescence is present as a result of the collisions, the required PC size is increased since the resultant droplet size is larger, and, therefore, the residence time for complete vaporization is increased. On the other hand, if separation is obtained, the required PC size is decreased since smaller droplets are generated. To obtain separation, higher relative droplet Weber numbers are recommended [17, 49, 51], which is mathematically defined below:

$$We_{dr} = \frac{d_d \rho_L v_{rel}^{\ 2}}{\sigma},$$

where d_d is the droplet diameter, ρ_L is the liquid density, σ is the surface tension, and v_{rel} is the relative velocity between the two droplets. The relative velocity depends only on droplet velocities and on injection angles. The droplet velocity is obtained after the droplet breakup and is a fraction of the injection velocity, which is defined as $U_0 = C_d(2\Delta P/\rho_L)^{1/2}$, where C_d is the discharge coefficient, and ΔP is the injector pressure drop. Therefore, the injector pressure drop is the main parameter used to control the droplet Weber number [52]. [16] proposed another form of the equation by summing the two droplets' radii instead of one diameter. Although an increase in pressure drop leads to a decrease in droplet diameter, leading to a decrease in Weber number, it also increases the droplet velocity, which makes the Weber number increase since it is squared. So, increasing the pressure drop is beneficial to obtain smaller droplets and a higher Weber number, which is vital to decrease required residence time and decrease coalescence probability, respectively, but it increases the droplet velocity, increasing the required residence time. Of course, one cannot increase indefinitely the ΔP since some limitations, such as weight, make it impractical. Unfortunately, there is a lack of references in the literature investigating collision outcomes of oxidizer droplets. It is much more common to find references on hydrocarbons and water.

To understand the behaviors of the injection velocity, droplet Weber number and droplet size, determined by the Sauter Mean Diameter (SMD) calculated in the next equation [54], the graphs in Figs. 6, 7, and 8 were plotted for N_2O and LOx.

$$SMD = \frac{500 d_0^{\ 1.2} \mu_L^{\ 0.2}}{\rho_L \sigma},$$

where d_0 is the discharge orifice diameter and μ_L is the dynamic viscosity. U_0 is used instead of v_{rel} to calculate a single droplet Weber number. The following graphs were obtained for LOx under 90 K and 1 bar and for N_2O under 298 K and saturation condition since it is stored as a two-phase fluid and commonly used as a self-pressurizing oxidizer [55, 56].

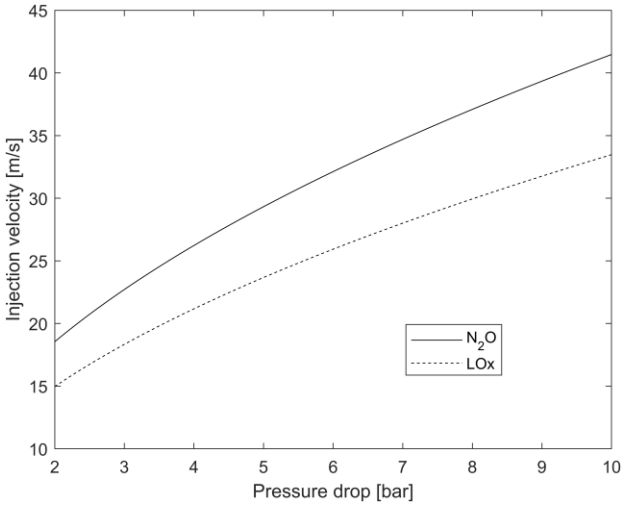

Fig. 6. U_0 in function of ΔP for N_2O and LOx

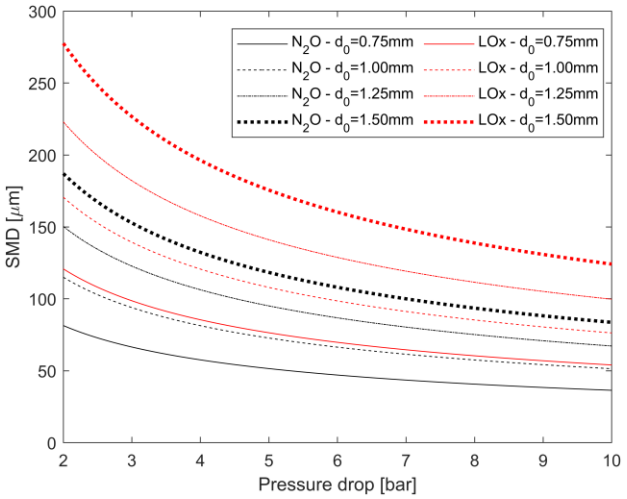

Fig. 7. SMD in function of ΔP and d_0 for N_2O and LOx

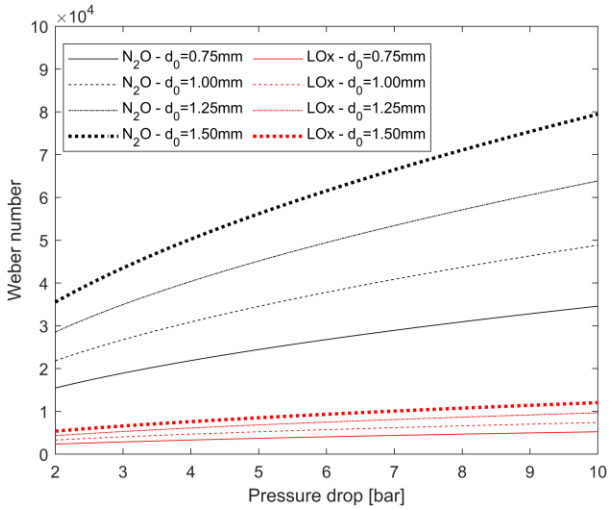

Fig. 8. We in function of ΔP and d_0 for N_2O and LOx

As the above equations and graphs show, the We increases with pressure drop. To calculate those results, the injector Weber number was calculated. Therefore, instead of using d_d and v_{rel}, d_0 and U_0 were used.

One crucial factor to consider is that only the SMD is shown in the graphs. Nevertheless, the injector produces a distribution of droplet sizes, and some values along the distribution may be considered to evaluate if all droplets will vaporize.

Lastly, the grain design also directly impacts the combustion instability and droplet vaporization models. It affects directly the three terms of the residence times dependent parameter T. In addition, the gas acceleration is calculated in function of the port diameter.

Development workflow

All the exposed methodologies in this work are relevant and may be used to design pre-combustion chambers. Moreover, combining them is also possible and can be part of complete a development workflow. The proposed steps are as follows: 1) The first step would be predicting the droplet collision outcomes, 2) followed by a preliminary design based on empirical relations. 3) Then, the pre-chamber size is calculated through droplet vaporization and 4) instabilities models. 5) The next step would be validating the models through CFD and 6) finally validating with experimental tests. In each step, a verification should be made for any required modification based on the discussions made in this work, such as weight and size restrictions, performance, and other parameters.

The next figure presents this workflow on a block diagram, which provides a visualization of the methodology. It is important to mention that this approach is focused on the pre-combustion chamber design. However, as previously discussed, other components may impact on it and other steps may inserted if these components can be modified.

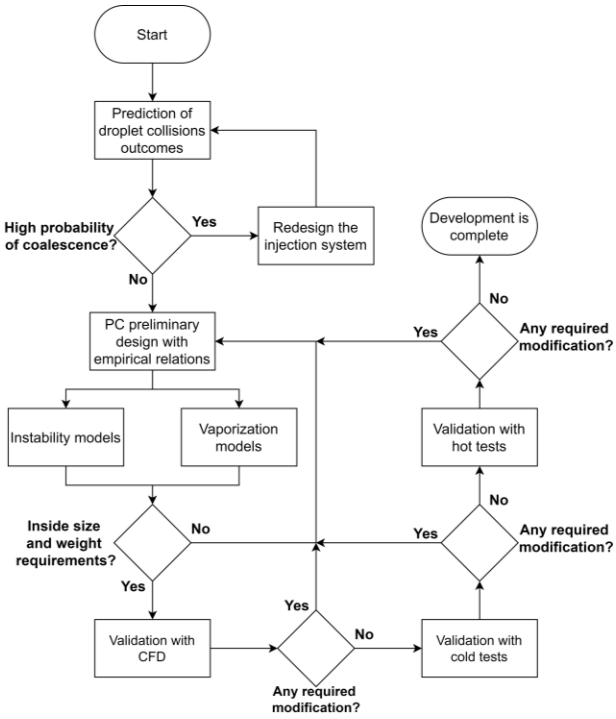

Fig. 9. Pre-combustion chamber development workflow

Following the above-proposed methodology, the most expensive phases, such as CFD simulations and experimental testing, are reduced since, nowadays, analytical models for droplet vaporization and combustion instability prediction present to be reliable. Even though numerical simulations are considerably cheaper than hot testing, they are much more expensive than running the analytical models. However, although these models are reliable, CFD investigations and, most significantly, cold and hot tests cannot be substituted by them. This is mainly due to the fact that these models do not capture all involved processes, and some assumptions are made.

Conclusions

A pre-combustion chamber has a vital role in enhancing the engine's combustion stability and performance. However, a full comprehensive methodology to design such a component was a necessity in the academic community. This paper presented all aspects related to the PC development in already published methodologies. Combining these approaches, a complete development workflow was proposed with (1) Prediction of droplet collision outcomes; (2) PC preliminary design with known empirical relations; (3) Combustion instability prediction and droplet vaporization models; (4) CFD validation; (5) Cold flow tests, and; (6) Hot fire tests.

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The proposed workflow may not be followed in every project, due to some time or financial restrictions. However, following it will provide a reliable design. In addition, it is important to remember that verifications must be made in every step, and re-designs should be made if required. Finally, this work is helpful for any engineer to properly design a pre-chamber with stable combustion and high efficiency.

Conflict of Interest

The author declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The work has no associated data.

Use of Artificial Intelligence

The author confirm that he did not use artificial intelligence methods while creating the presented work.

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ДОСЛІДЖЕННЯ ІСНУЮЧИХ МЕТОДІВ ПРОЕКТУВАННЯ КАМЕР ПОПЕРЕДНЬОГО ЗГОРЯННЯ В ГІБРИДНИХ РАКЕТНИХ ДВИГУНАХ

Маурісіо Са Гонтіхо

Гібридні ракетні двигуни (ГРД) розробляються та вдосконалюються з самого початку досліджень ракетного руху, поряд з рідинними ракетними двигунами та твердопаливними ракетними двигунами. Однак їхній розвиток відбувався значно повільніше, ніж інших типів двигунів. За останні кілька років кілька компаній запропонували гібридні ракети-носії, а дослідження та публікації на цю тему значно зросли. Однією з найважливіших частин ГРД є попередня камера згоряння. Цей пристрій розташований перед камерою згоряння та після інжекційної головки і має великий вплив на продуктивність двигуна, розміри, вагу, вартість та стабільність згоряння. Тому інженери-двигунобудівники дуже зацікавлені в розумінні процесів, що відбуваються в попередній камері згоряння. На жаль, існує невелика кількість доступних публікацій щодо проектування такої системи. Крім того, багато джерел лише рекомендують деякі емпіричні співвідношення розмірів, які можуть бути лише початковою точкою проектування. Враховуючи цю проблему, ця стаття збирає всі методи проектування попередніх камер згоряння та детально обговорює кожен з них. Ці методи включають: 1) експерименти, 2) емпіричні співвідношення, 3) числове моделювання, 4) моделі випаровування крапель, 5) моделі нестабільності згоряння, 6) прогнозування результатів зіткнення крапель, і 7) молекулярну динаміку. Також розглядаються позитивні та негативні аспекти кожного методу. Крім того, обговорюються інші компоненти, що впливають на розрахунки, такі як дизайн інжекторів і зерна. Нарешті, рекомендації щодо робочого процесу розробки були складені шляхом застосування всіх обговорених методів для зниження витрат і отримання оптимізованого дизайну.

Ключові слова: камера попереднього згоряння; гібридний ракетний двигун; робочий процес проектування; випаровування.

Маурісіо Са Гонтіхо – Аеронавтичний технологічний інститут, аеронавігаційна інженерія та механіка, аерокосмічна тяга та енергетика, Бразилія.

Maurício Sá Gontijo – Aerospace Engineer, Master's Student of the Aeronautical Institute of Technology - ITA, Aeronautical and Mechanical Engineering, Aerospace Propulsion and Energy, São José dos Campos, São Paulo, e-mail: mauricio.sa.gontijo@gmail.com, ORCID: 0000-0002-7648-0093.