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Analysis of the Nozzle Design for Rocket-Candy Using a Systemic Model

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Abstract. This paper presents a systemic model for the simulation of the design of a nozzle for R-Candy. This research is focused on a complex system using the methodology of 5 phases based on the tools of systemic modeling and general systems theory. The rocket motor was designed using Solidworks, which consists of the igniter system, the combustion chamber, and the nozzle. Usually, a Laval-type nozzle (convergent-divergent) is used for rocket motors, taking advantage of the exothermic properties of the potassium nitrate and sorbitol fuel mixture in a solid state. The simulation was carried out using the computational fluid dynamics software FEATool, evaluating temperature, velocity, and pressure. The results obtained by the R-Candy software give guidelines for a broad preliminary panorama for the manufacture of rocket motors in experimental rocketry.

Keywords. Rocket engine, Solid Fuel, CFD, Nozzle

1. Introduction

Experimental rocketry has become a fundamental tool for researching parts of space with low orbits. These investigations do not require expensive rocket motors since their missions or objectives are substantially smaller than those for orbit missions where satellites cannot have good sampling [1]. However, the aerospace sector in Mexico is very limited in developing these activities due to a lack of vision or political issues [2].

The object of the research focuses on one of the most critical systems of a rocket, the propulsion system, carrying out a systemic model to encompass all the subsystems

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found within the R-Candy. In this way, it simulates the design of an R-Candy using computational fluid dynamics using the FEATool software [3] and the Solidworks design. Likewise, additive manufacturing was carried out to visualize the assembly of the components that make up the R-Candy: the lighter cap, combustion chamber, and Laval Type nozzle [4].

One of the main goals to consider in this research is the characteristics of the proposed candy-type propellant (Potassium Nitrate-Sorbitol 65:35) since these serve as boundary conditions when running the simulation and having the values of temperature, pressure, and the velocity field generated in the R-Candy. The limitations that arise are the little information on the characteristics of the fuel; FEATool considers the simulation as a closed system, so it must be calibrated more than once to have the desired results, to be able to work and interact with more software tools that are needed. FEATool gives an approximation that helps in a preliminary analysis of an R-Candyph's design.

2. Rocket engine classification

Rocket engines are classified depending on the type of fuel they use or the strength of their impulse. A combustion engine-powered system known as a space rocket generates enough kinetic energy to expand some of the gas that escapes through the nozzle. Typically, vehicles designed for space with an engine of this type are called missiles or rockets [5]. One of the main objectives of rockets or missiles is to fulfill a function responsible for delivering objects into space, such as space vehicles, space probes, space satellites, and men into space. As mentioned, it is a system with an internal combustion engine that generates kinetic energy to expand the gas to obtain jet propulsion. Generally, space rockets consist of a structural system, a propulsion system, and a payload system. The structure protects the fuel tanks and the payload.

Newton's Second Law states that the engine has applied a force on the gas molecules to accelerate them and that the size of this force is given by mass times acceleration $F = m \times a$. The principle is similar to that of the first gunpowder rockets from 1232. On the other hand, a missile obeys Newton's third law, also called the principle of action and reaction: For every action, there is always a reaction, and the reciprocal actions between two bodies are always equal and in opposite directions [6]. The third law introduces the main primordial characteristics of the concept of force: interaction between two bodies. These forces are always referred to as two bodies, A and B, each exerting a force on the other of equal magnitude and opposite direction. A combustion engine is a closed chamber where combustion occurs. The ignition inside the engine generates pressure in all directions. The combustion chamber does not move in any direction since the forces interacting on the opposite walls of the chamber cancel each other out.

The pressure produced on the interior lateral walls in the opposite direction will continue without exerting force. Then, the pressure at the top of the chamber will begin the thrust since there is no pressure on the bottom side. Chemical combustion generates much power, pulling the air downward with great force. In other words, the air generates the rocket's propulsion by reacting with the same force as the combustion gases in the engine chamber. For this reason, it is called a jet-propulsion rocket. Since you do not obtain oxygen in outer space like Earth, fuel and oxidizer must be carried in tanks to burn fuel. Depending on the mass, the magnitude of the thrust tends to vary, as does the speed of the gases expelled through the opening. If the temperature of the gases is higher, the thrust will increase. Therefore, the combustion chamber and the opening from the high temperatures produced by combustion must be protected. One of the solutions that have been given to this problem is to make a coating on the engine walls using a soft jet of the fuel used in the rocket, thus generating a thermal insulator and, in turn, using it as engine coolant.

Unlike the engines that propel airplanes, which are jet engines, the primary function of rockets is to operate in space; they do not have air inlets and must use their oxidants. It plays the role of oxygen in fuel ignition. The fuel and oxidizer of a rocket or propellant are available in a solid or liquid state. The side boosters on a space shuttle previously used solid fuel, while many rockets today use liquid propellants.

The push for liquid-fuel rocket engines began in the 1920s. One of the first liquid-fuel rockets is known to have been manufactured by Goddard and was launched in 1926 near Auburn, Massachusetts. Half a decade later, the first German liquid-fuel rocket was built privately. In 1932, the Soviet Union launched its missiles for the first time. A liquid fuel booster is a rocket engine that uses liquid propellants. Liquids have the advantage of having a considerable density, which makes the volume of the tanks smaller and thus stores the propellants in that state. On certain occasions, small and straightforward engines are used with an inert fluid found in a high-pressure tank instead of pumps to force the passage of the propellants into the combustion chamber.

2.1. Composition of candy rocket propulsion - sorbitol

Candy rockets, or R-Candy, are a type of rocket propellant manufactured with sugar as fuel and contain an oxidizer. This fuel is divided into three groups of materials: the oxidant, the fuel, and the additives. This fuel type is mainly concerned with the ease of finding the chemicals used to manufacture it. There are different formulations for preparing this mixture, where the fuel is found in composite components, and the most occupied oxidant is potassium nitrate (KNO_3). To date, there are three mixtures mainly used in Candy-type engines [7]:

- Potassium nitrate – Sorbitol (KNSO).
- Potassium nitrate – Sucrose (KNSU).
- Potassium nitrate – Dextrose (KNDX).

The ideal composition for this type of propellant is 65% oxidizer and 35% fuel. Meanwhile, additives are found in different substances and act as catalysts or improve the aesthetics of flight takeoff. There are different methods for preparing a Candy-type rocket propellant. One is dry compression, which does not require heating; it only requires grinding the components and the engine gasket. However, this method is not recommended for high-importance experiments. Another one to mention is that dry heating does not melt the KNO_3, but it melts the sugar, and then the KNO_3 grains are suspended in the sugar [8]. It is possible to find the specific impulse, the total impulse, and the thrust relatively lower than those of other rocket fuels of composite models occupying the same amount of grain. Still, the candy-type fuel is significantly cheaper. Fuel is the substance that carries the ignition. It causes the rapid release of gases by expansion and provides thrust when leaving the nozzle. As explained previously, the oxidant supplies the oxygen necessary for combustion. Finally, and optionally, some additives speed up or improve combustion. However, some add sparks, flames at takeoff, or smoke to facilitate tracking the rocket during flight [9]. As previously mentioned, many sugars are used for candy-type fuel. Sorbitol, a sugar-containing alcohol often used as a sweetener in certain foods, produces a less unstable propellant with a slower burning rate, which reduces the risk of cracking the propellant grains. Sugars with double-bonded oxygen, such as fructose and glucose, are not thermally stable and tend to generate caramelization when overheated. Still, an advantage is that they have a lower melting point and make preparation easier. Sugar alcohol groups such as sorbitol are less prone to this breakdown. Other commonly used sugars include erythritol, xylitol, lactitol, maltitol, or mannitol.

3. Materials and Methods

This article uses Churchman and Ackoff's methodology and describes one of the first relevant systematic efforts on systems methodology [10]. This methodology consists of five phases: problem formulation, model construction, model testing, model solution, and finally, model implementation. Figure 3 depicts the phases of the operations research methodology established by Churchman and Ackoff (see Figure 3).

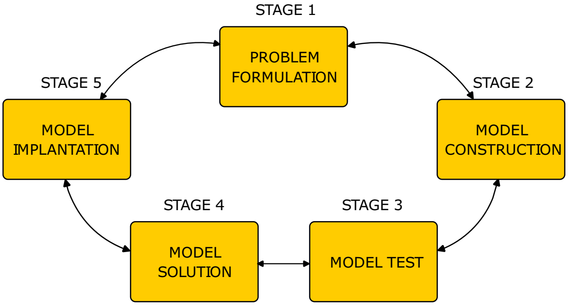


Figure 1. Phases of research methodology for complex systems by Churchman and Ackoff.

For the characterization, a literature review was carried out through articles, universities, and different types of rockets implemented throughout the history of the aerospace sector, concluding that the nozzle mainly used for this type of rocket is that of Laval. One of the factors in the Candy type fuel is the elaboration of this propellant, which helps us with the ignition of the combustion chamber and the nozzle. In the various methods for this chemical preparation, dry compression is found, which does not require heating; the components are crushed and later added to the combustion chamber. Another one is that dry heating does not melt the KNO_3 but melts the sugar, and then the KNO_3 grains are suspended in the sugar. Figure 2 shows the representation of the systems and subsystems found in the case study.

Next, some subsystems will be applied to study the entire system to design and simulate a nozzle for R-Candy. The nozzle is the first level, which will be the main object of study. It is the only one that will have a relationship and interaction with all the other subsystems, focusing on it as the priority element of the research because if that element fails or does not meet the objective, the case study would have to be analyzed and reviewed again in the literature and consulted with experts. The subsystems at the

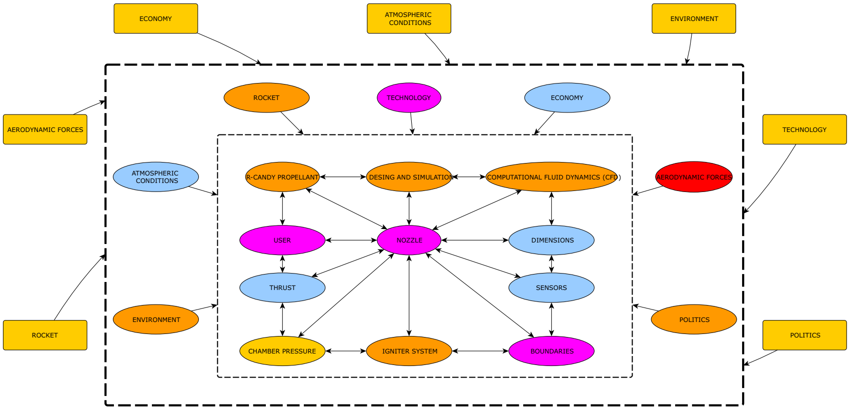
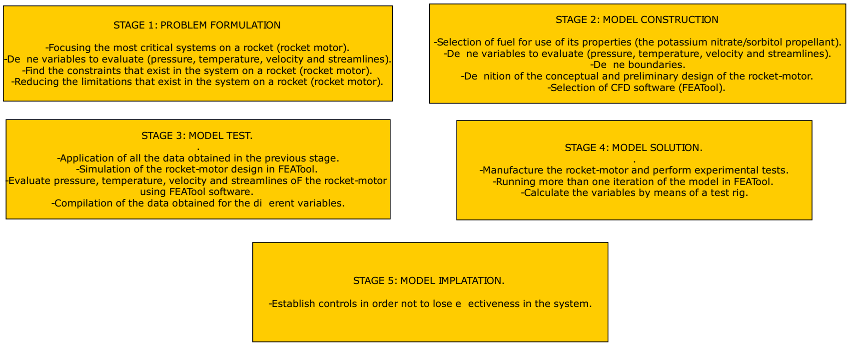


Figure 2. Phases of research methodology for complex systems [11].

second level interact with different objectives, such as the user, dimensions, R-Candy fuel, thrust, combustion chamber, flame, thermal camera, sensors, computational fluid dynamics, design, and simulation. Understanding that these components can be interfered with, modified, removed, or changed if there is a failure or it generally affects the system. In the third and fourth levels, we have subsystems that interact and relate to different objectives, such as the rocket, aerodynamic forces, economy, politics, technology, environment, and atmospheric conditions. Assimilating that they will always exist and that although they will remain and affect the system, they cannot be modified, interfered with, removed, or changed. If it affects the general system, a change must be sought at the previous levels to satisfy the primary objectives.

The methodology developed in this research is summarized in five phases: The first presents the current situation of the problem, which consists of the behavior of R-Candy; the second synthesizes and defines the model and variables to be measured; the third executes the model test; the fourth presents the model solution; and finally, the fifth implements the model (see Figure 3).


STAGE 1: PROBLEM FORMULATION

-Focusing the most critical systems on a rocket (rocket motor).
-Define variables to evaluate (pressure, temperature, velocity and streamlines).
-Find the constraints that exist in the system on a rocket (rocket motor).
-Reducing the limitations that exist in the system on a rocket (rocket motor).

STAGE 2: MODEL CONSTRUCTION

-Selection of fuel for use of its properties (the potassium nitrate/sorbitol propellant).
-Define variables to evaluate (pressure, temperature, velocity and streamlines).
-Define boundaries.
-Definition of the conceptual and preliminary design of the rocket-motor.
-Selection of CFD software (FEATool).

STAGE 3: MODEL TEST.
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-Application of all the data obtained in the previous stage.
-Simulation of the rocket-motor design in FEATool.
-Evaluate pressure, temperature, velocity and streamlines oF the rocket-motor using FEATool software.
-Compilation of the data obtained for the different variables.

STAGE 4: MODEL SOLUTION.
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-Manufacture the rocket-motor and perform experimental tests.
-Running more than one iteration of the model in FEATool.
-Calculate the variables by means of a test rig.

STAGE 5: MODEL IMPLATATION.

-Establish controls in order not to lose effectiveness in the system.

Figure 3. Phases of the methodology.

4. Results

4.1. Simulations

The FEA Tool, a software application for finite element analysis (FEA), was used to carry out CFD simulations. FEA is a computational method for predicting how structures and materials behave under various physical conditions

Once the initial parameters and boundary conditions were determined, different values of the primitive variables—velocity in x, velocity in y, pressure, and temperature—were obtained to interpret the results. Numerical viewers were located in the domain at the rocket's center to capture the behavior (see Figure 4). The initial parameters used are shown in Table 1.

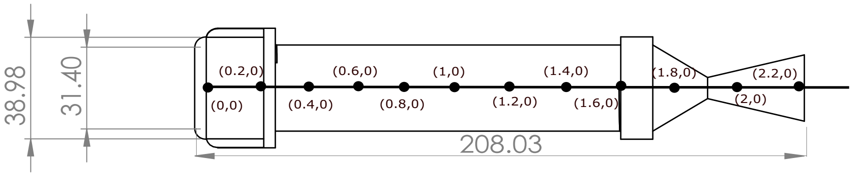


Figure 4. Rocket geometry and viewers location.

Table 1. Initial Parameters

Parameters	Values
Ideal Specific Impulse	164 s
Theoretical characteristic escape velocity	938 m/s
Combustion temperature	1327C
Ideal density	1841 kg/m^3
Autoignition temperature	300 ^{o}C
Burning rate	11.3 mm/s

According to Richard Nakka [12], the stoichiometric coefficients and the properties obtained from this potassium nitrate-sorbitol fuel at a pressure of 1000 psi in the combustion chamber.

Figure 5 shows the total velocity when the flow behavior is steady. As expected, the velocity increases in the second stage of the nozzle. Total velocity values are depicted in Figure 6. Analogously, Figure 7 shows the pressure. Figure 8 depicts the behavior. Finally, 9 shows the Temperature. Figure 10 depicts the behavior. The flow accelerates to supersonic speeds in the diverging section of a converging-diverging nozzle. According to the principles of compressible flow and the isentropic relations, as the cross-sectional area grows, the speed grows while the pressure and temperature drop [13]. The additional rectangular domain is introduced to prevent backflow.

4.2. Physics Experiments

Richard Nakka [12] presents the theoretical bases for operating a solid-state fuel composite rocket motor. It mainly emphasizes the procedure that must be carried out in ex-

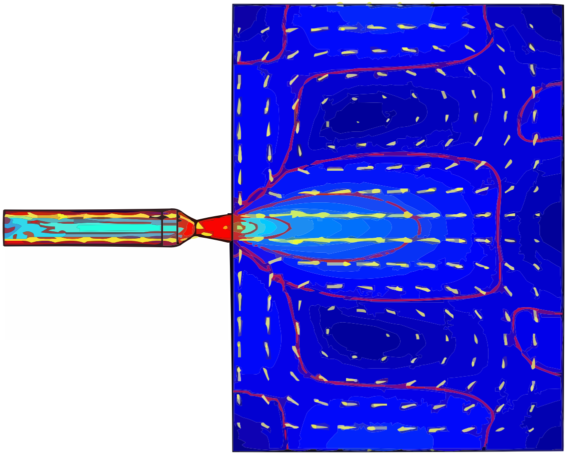


Figure 5. Total velocity field, with directional components.

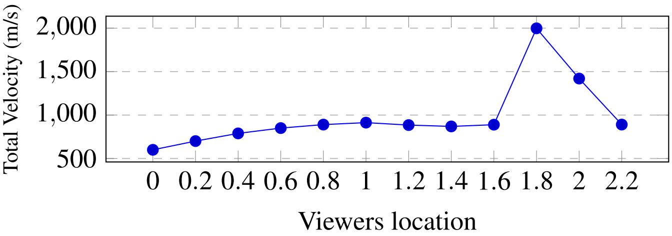


Figure 6. Behavior of velocity at the center, as expected, the velocity increases in the nozzle.

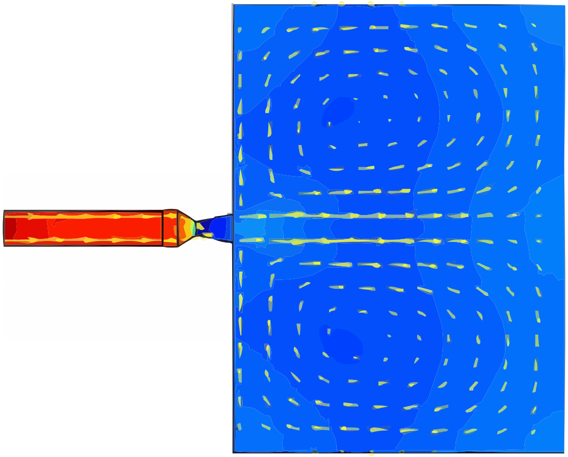


Figure 7. Pressure, with directional components.

perimental engines that are typically efficient and of lower performance: selecting the main variables involved in the design of the combustion chamber, igniter plug, nozzle, and fuel, finally having their dimensions for the desired performance, and analyzing the

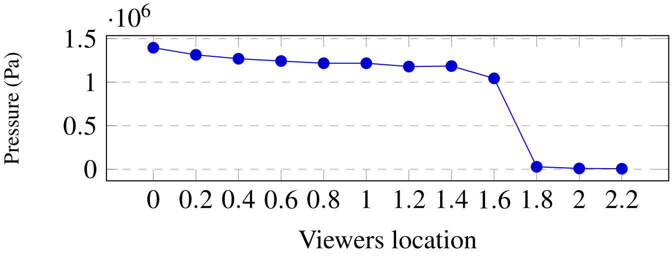


Figure 8. Behavior of pressure at the center, as expected, the pressure decreases in the nozzle.

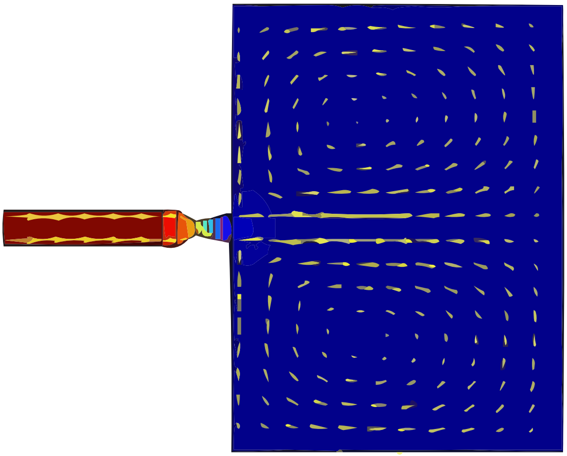


Figure 9. Temperature, with directional components.

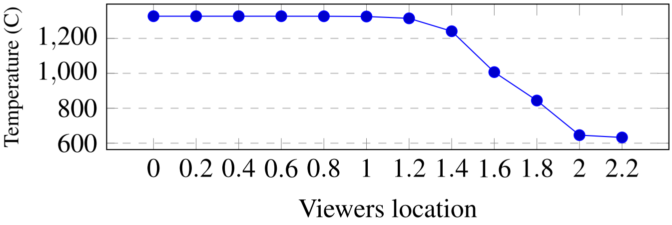
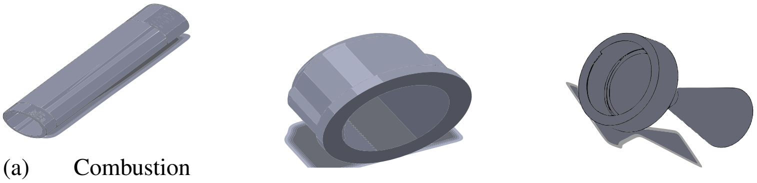


Figure 10. Behavior of pressure at the center, as expected, the pressure decreases in the nozzle.

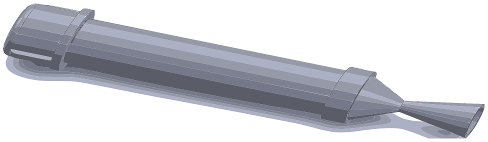
variables that you want to study. The rocket motor's preliminary design was obtained through CAD software, specifically in Solidworks, where a 3D model was obtained by designing each of its components and having the plans for its subsequent manufacturing. Possible materials for machining the combustion chamber and the Laval-type nozzle are analyzed, concluding that under their characteristics and easy obtaining of each of the materials, galvanized steel and 1020 steel can be used (see Figure 11). The candy-type fuel comprises the oxidant potassium nitrate KNO_3, and, as fuel, sorbitol alcohol with sugar (polyol). The first step in the preparation is to grind the potassium nitrate until it obtains a fine texture. Subsequently, the sorbitol must be dried to eliminate all traces of residual water. A dry, homogenized mixture is finally achieved when the two components are mixed in a single container. The ideal temperature for obtaining the propellant grain must be within the range of 115 °C-125 °C, which must be controlled. The rocket engine's performance is evaluated through a static combustion test using a test bench coupling a single-point load cell of 100 kg capacity, an ignition system connected to the engine cover, and an electronic control system for data acquisition. This test allows the rocket motor to be measured in force, pressure, and temperature. The electronic electrical system is programmed using Arduino.



(a) Combustion chamber

(b) Ignitor

(c) Nozzle



(d) Assembly of the three components.

Figure 11. 3D printing of the igniter components for validation.

5. Final remarks

This article demonstrated the purpose of creating a systemic model by applying General Systems Theory. This method laid the groundwork for running a simulation interacting with boundary conditions to determine how the R-Candy's temperature, pressure, and field speeds change. A rough design of the R-Candy was necessary before simulating its behavior. The simulation had to be run several times before it got closer to the collected data.

It is concluded that this article's most important contributions include creating the systemic model for simulating the design of a nozzle for the R-Candy, thereby providing excellent reliability to the study system. Additionally, the results obtained are gratifying, as the FEATool software allowed analyzing variables with minimal data on the fuel's characteristics, facilitating the definition of boundary conditions.

It is essential to highlight that this work has contributed to understanding the behavior of R-Candy under various conditions and laid the groundwork for future research and developments in the propulsion field. General Systems Theory and advanced simulation tools like FEATool have proven effective and efficient approaches to addressing complex problems in systems engineering.

Looking to the future, it is suggested that more detailed studies be conducted with more experimental data to validate the model further and improve its accuracy. It would also be beneficial to explore the integration of other simulation software and compare their results to ensure the model's robustness. Additionally, optimizing algorithms could lead to a more efficient and reliable nozzle design.

Finally, this study underscores the importance of interdisciplinary collaboration, combining knowledge of systems theory, thermal engineering, and fluid dynamics to advance the development of safer and more effective propulsion technologies. As such, the research presented here is a step forward in the design and analysis of R-Candy and a model of how to address complex problems in modern engineering.

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