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THERMODYNAMIC ANALYSIS OF A MODIFIED NACELLE ON A CRUISE FLIGHT TO INCREASE FUEL ECONOMY AND PERFORMANCE OF THE BOEING 737-900 WITH EXTENDED RANGE

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Abstract. *The present study concerns a redesign of the nacelle's aerodynamic profile for the Boeing 737-900ER to reduce fuel consumption and increase the range factor during cruise flight. For this, an explanation of the technical characteristics of both the approached aircraft and the engine that compose it was made, besides the standardization that regulates the creation of this modified aerodynamic profile Through a Computational Fluid Dynamics simulation it was possible to analyze the performance of the nacelle in each section of the project modified in terms of temperature, flow velocity, pressure and enthalpy of stagnation. In addition, a software was developed in the Python programming language capable of simulating, under the established conditions, the trends in the behavior of the turbofan engine performance parameters and the parameters of the ideal air-standard Brayton cycle analysis. In this sense, one of the characteristics of these trend curves was relevant when describing the thrust specific fuel consumption and the specific thrust, for all bypass values in the used range, as parameters with a practically constant rate of change for the operating range the Mach number on the cruise flight. After all these procedures, through a 21.8% increase in fan output speed when comparing the modified nacelle model with the original one, it was possible to determine other percentage relationships between the results obtained in the two simulations, as an increase of 24.57% in the range factor (equivalent to 7381.7 km) and a 25.26% decrease in thrust specific fuel consumption. These relationships give qualitative relevance to the results, not only because they are testified through similar literature and works, but mainly by creating an opportunity to study, forecast and develop aircraft projects without the need for a prototype, thus generating savings for companies and accessibility to academics and researchers.*

Keywords: *Turbofan, Nacelle, Brayton Cycle, Thermodynamic, Boeing*

1. INTRODUCTION

Gas turbines are thermal machines designed with the aim of providing advantages for the various flight modes. These machines are coupled to the fuselage of the aircraft through a structure called nacelle, which aims to provide a solution necessary for the multiple flight circumstances and also to protect the turbofan from foreign objects (Tomita et al., 2005). The large aircraft currently manufactured are equipped with the so-called "turbofan" technology, which have the same operating principle as conventional gas turbines and are made by a set of blades (fans), axial compressors, combustion chamber and turbine (Tomita et al.,2006), which is important for the control of turbine airflow, the design of control of its component and importance for the performance of the aircraft (Tomita et al., 2006; Palharini, 1999).

In this sense, it can be stated that submitting the real model of an excellence engine like this one is not very economically viable for all spheres of technology developers, since it can generate high costs for companies in the aeronautics industry and even decrease accessibility of academics to improve the operation of this gas turbine. As a result, there is a need for an efficient and affordable methodology to improve engineering projects like this. A noteworthy fact is that the use of computer support in this opportunity for innovation in projects is essential and clearly capable of optimizing the time of calculation and analysis, which are two extremely important aspects with respect to aircraft. Assuming an analysis of the theme for reducing fuel consumption and increasing travel range, the present work aims at the aerodynamic design of a NACA 6409 modified profile measurement, as well as the effect of the same on nacelle core parameters during cruise flights.

2. MATERIAL AND METHODS

This study started from the deepening of knowledge about the thermodynamic cycle of aircraft engines, extending to the aerodynamic aspects. This was made possible by the works Elements of Gas Turbine Propulsion (Mattingly,

1996) and the Principles of Engineering Thermodynamics (Moran et al., 2013), which progressively and didactically contemplated the subjects in question. In addition, it was also necessary to seek technical information about the Boeing 737-900 (ER) and the CFM56-7B engine in order to have the input data for the equations that model the parametric cycle analysis of an ideal turbofan.

Therefore, calculations were performed manually for this examination of the ideal behavior of turbofan with the equations provided by the cited bibliography and the technical input data. In this sense, it was possible to adapt the calculation model to the Python programming language (represented schematically in the figure 1) in order to generate trend analysis graphs for the engine parametric performance and compare both with the results obtained by the authors of this research and those presented by Mattingly (1996). The fact that most graphics are functions of Mach number in station zero allows to analyze in each flight condition the behavior of the turbofan engine during the cruise. This clarifies what will be presented in the results and discussions section.
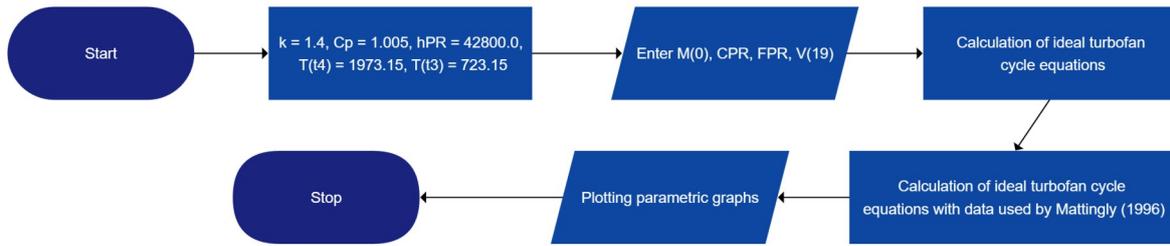

Figure 1. Flowchart of simulation software.

The software schematically represented in the flowchart of the figure above starts with the definition of the constant values for the purpose of calculating the parametric cycles, in order to generate a table for the user with the parameters and variables of the station according to SAE ARP 755A. Next, data from flight conditions (such as ambient temperature and Mach number values) are requested from the user to generate performance analysis curves.

Therefore, the equations of the parametric performance cycle and the aerodynamic variables to measure the range factor are calculated as functions of the Mach number (M), both with the simulation data of the modified nacelle and with those from the literature by Mattingly (1996). The results of these calculations are stored in data structures to be used to feed the part of the algorithm responsible for plotting the graphs that represent: thrust-specific fuel consumption, specific thrust, thrust ratio, and thermal, propulsive, and overall efficiencies, all of which as M functions.

3. THEORY

3.1 Aircraft performance

The total thrust an aircraft needs is the first performance parameter and provided by two sources: the nacelle and the engine. Usually, the engine contribution is referred to as "uninstalled engine thrust (F)", while the term "installed engine thrust (T)" expression refers to the total thrust generated by both contributions. The first portion, F, is obtained by the sum of the internal forces exerted on the nacelle control surface along the propulsion system stations (Mattingly, 1996). For a propulsion system such as turbofan, the equation (1) for the uninstalled engine thrust is

$$F'_{ini}+F_{ini}+\left(P_0-P\right)A_0-\left(P_9-P_0\right)A_9=\left(\frac{\dot{m}_9 V_9-\dot{m}_0 V_0}{g_c}\right)+\left(P_9-P_0\right)A_9, \tag{1}$$

From the equation of thrust, which is the first performance parameter, it is possible to determine the second parameter, since it is given by the ratio between the specific fuel consumption and the generated thrust (Mattingly, 1996). This is the equation (2)

$$S=\frac{\dot{m}_f}{F}, \tag{2}$$

3.2 Range Factor

The flight time of an aircraft is generally limited by the amount of fuel available, which also generates a maximum distance (range) that can be achieved with the flight. According to Mattingly (1996), this distance can be obtained by the range factor (RF) equation (3) and its variables (4), (5) and (6)

$$RF = \left(\frac{C_L}{C_D} \right) \left(\frac{V}{TSFC} \right) \left(\frac{g_c}{g_0} \right),$$

(3)

$$C_L = \frac{nW}{qS_W},$$

(4)

$$q = \left(\frac{k}{2} \right) PM_0^2,$$

(5)

$$C_D = K_1 C_L^2 + K_2 C_L + C_{D0},$$

(6)

3.3 Parametric cycle analysis of ideal engines

The analysis of a thermodynamic cycle basically consists of examining the performance of a fluid during the processes to which it has been subjected. Specifically, a parametric approach to this analysis takes into account a set of key elements such as design options (an example is the bypass ratio) and the flight conditions (Mach Number) to model the performance of a generic-air-breathing engine (also known as the "rubber engine"). From this, is possible evaluate trends in the graphical behavior of engine performance parameters (such as specific fuel consumption) that will help you select the elements used in this modeling that best meet project expectations (Mattingly, 1996).

For this analysis, we will consider only the stations contained in the motor core, second the SAE ARP 755A. From this, we define the first step as a rearrangement (7) of the equation that determines the thrust of the uninstalled mechanism so that the same equality can be expressed by flight conditions such as Mach number and ambient pressure (Mattingly, 1996).

$$F = \left(\frac{a_0}{g_c} \right) \left(\frac{\dot{m}_9}{\dot{m}_0} \frac{V_9}{a_0} - M_0 \right) + \frac{A_9 \cdot P_9}{\dot{m}_0} \left(1 - \frac{P_0}{P_9} \right),$$

(7)

Similarly, in the second step the rate of speed is rewritten (8) in terms of gas properties and also flight conditions. The third step is defined by developing an expression (9) for the Mach number. In the fourth step, we adopted the same process as above to find out the temperature ratio (10). The expression for fuel / air ratio (f) based on the components thermal performance can be determined from the first law of thermodynamics (11). This completes the fifth step.

$$\left(\frac{V_9}{a_0} \right)^2 = \left(\frac{a_9^2 \cdot M_9^2}{a_0^2} \right) = \left(\frac{k_9 \cdot R_9 \cdot g_c \cdot T_9}{(k_0 \cdot R_0 \cdot g_c \cdot T_0)} \right) M_9^2,$$

(8)

$$M_9^2 = \frac{2}{k-1} \left[\left(\frac{P_{t9}}{P_9} \right)^{\frac{k-1}{k}} - 1 \right],$$

(9)

$$\frac{T_9}{T_0} = \frac{\frac{T_{t9}}{T_0}}{\frac{T_{t9}}{T_0}} = \frac{\frac{T_{t9}}{T_0}}{P_{t9}^{\frac{k-1}{k}}},$$

(10)

$$\dot{m}_0 c_p T_{t3} + \dot{m}_f h_{PR} = \dot{m}_0 c_p T_{t4},$$

(11)

The sixth step, under favorable conditions, develops an equation for the thermal performance of the turbine (t) related to its respective power output, so that it can be expressed in flight condition parameters. The next step is to analyze the specific thrust based on the previous steps. The eighth step develops an expression for thrust specific thrust

consumption (S) from the results obtained in steps 5 and 7.Finally, the ninth step is devoted to writing equations that model both thermal and propulsive efficiency.

4. RESULTS AND DISCUSSION

From the data collected on the operation of the Turbofan and the geometry of the nacelle, the calculations were developed for the aerothermodynamics analysis of the NACA 6409 modified nacelle and compared to the Nacelle NACA 6409 without modifications as proposed by Sharanabasappa et al. (2012). In this case, to analyze the flow, the author disregarded the geometric shape of the Turbofan for analysis, according to figure 2.
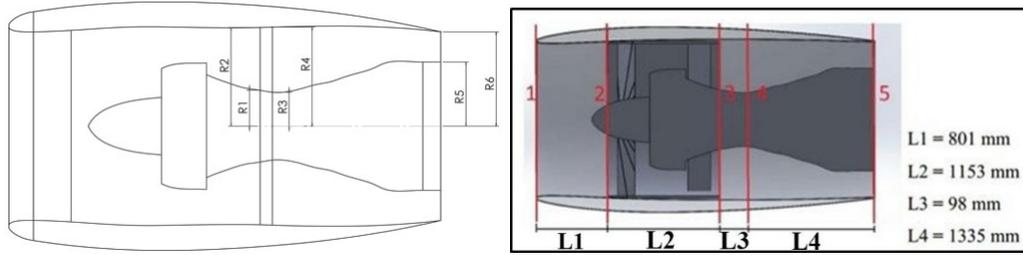

Figure 2. Inner rays (in millimeter) of NACA 6409 modified nacelle: R1=295; R2=750; R3=268; R4=788; R5=505; R6=789.

Sharanabasappa et al. (2012), however, did not take into account the geometry of Turbofan, unlike the one proposed in this study, where the geometry of the Turbofan CFM56-7B was taken into account, having these influences in the internal areas to the nacelle, which exerts influence in the flow of air. The aero-thermodynamic calculations were carried out, taking into account 7 variables: velocity, enthalpy of stagnation, static enthalpy, stagnation pressure, static pressure, stagnation temperature and static temperature. For this, 5 points of analysis were determined along nacelle NACA 6409 as shown in Figure 2. Thus, taking account of cruise flight conditions at an altitude of 12500 m, a temperature of 223.15 K and a pressure of 17.74 kPa, calculations were performed region by region in order to compare the results obtained by the modified nacelle and unmodified. To determine the mass flow rate that exceeds the set, a comparative method was used, taking into account the cruise flight speed of a Boeing 737 - 900 / 900ER (0,79 Mach number) and the suction capacity of turbofan CFM56-7B to the altitude of 0m.

Thus, the nacelles were analyzed under the following conditions: height (12500 m, for a temperature of 223,15K and pressure of 17,74 kPa), velocity (268.83 m/s, with Mach 0,79), mass flow (182.72 kg/s) and maximum thrust (86740.30 N). With the starting values, we used the equations to calculate the analysis parameters at each point. According to the literature, 80% of the thrust produced and 80% of the total flow goes through the bypass. For calculation purposes, therefore, one has to multiply the values presented in the table above by the factor of 0.8. The formulations used to calculate each factor are represented by the equations (12), (13), (14), (15) and (16):

$$h_{0n} = h_n + \frac{V_n^2}{2}, \tag{12}$$

$$T_{0n} = T_n + \frac{V_n^2}{2C_p}, \tag{13}$$

$$F_{fan} = \dot{m}_{bypass}\left(V_b - V_a\right), \tag{14}$$

$$\dot{w}_{fan} = \dot{m}\left(h_b - h_a\right) + \dot{m}\left(\frac{1}{2}\right)\left(V_b^2 - V_a^2\right), \tag{15}$$

$$\frac{V_b^2}{2}\rho + P_{0b} = \frac{V_a^2}{2}\rho + P_{0a}, \tag{16}$$

With the known rays, it is possible to calculate the areas in regions 3 and 4, where Area 3 = 0.84m² and Area 4 = 0.85m². Thus, regardless of the density variation along the by-pass and treating the flow as compressible, we have the values at point 4. Also disregarding the variation of the Potential Energy and the variation of the specific mass, the

Bernoulli equation is applied and having Area 5 = 0.48m², we have the values for point 5. Applying the above equations for each point and performing the proposed calculations, the result table for the NACA 6409 modified nacelle below is reached.

Table 1. Results for NACA 6409 modified nacelle.

Point of analysis	1 and 2	3	4	5
Speed, m/s	268.00	744.60	739.33	1300.92
Stagnation enthalpy, KJ/Kg	465.33	521.24	521.24	521.24
Static enthalpy, KJ/Kg	429.42	244.02	247.93	-324.96
Stagnation pressure, KPa	29.85	94.96	94.96	-55.23
Static pressure, KPa	17.74	61.20	8.57	58.06
Stagnation temperature, K	258.73	314.36	314.36	314.36
Static temperature, K	223.00	38.53	42.42	72.38

By varying the areas of analysis and considering A4 = 0.96 m2 and A5 = 0.52 m2, we have the results table for the nacelle NACA 6409 without modifications proposed by Sharanabasappa et al. (2012) above. The values remained constant in points 1, 2 and 3 because at these points there is no change in the area. For the purpose of confirming the calculations, we used the CFD simulation results. However, it was only possible to use these simulations as a base, due to the fact that both works disregard the work performed by the turbofan at the moment of the simulation. Thus, as the main objective is to analyze the effects of nacelle geometry of NACA 6409 modified profile in relation to the original NACA 6409 profile and not to alter other parameters, it is possible to see in the simulations the behavior of the flow in each region and through this behavior perform a comparative analysis between the two nacelles.

As the realized thrust was disregarded in the analyzes, no significant temperature and total pressure variations were observed along nacelle NACA 6409, the main parameter of analysis being then the flow velocity of the flow along the profile and output, which directly influences the thrust delivered to the aircraft. Again, the results of these simulations are explained due to the fact of disregarding, for the simulations, the work done by the fan, diverging then by the literature. By inserting, therefore, the input and output parameters in the software used for the simulation, it shows the behavior of the flow following such parameters. Divergent of the analytically calculated points, there was an input velocity of 268 m/s and an output of 1067.83 m/s and an input static pressure of 17.74 kPa and a calculated output of 44.33m/s. However, it is possible to observe some variations within the analyzed profile, such as the variation of the static temperature along the nacelle.

It is possible to explain the temperature distribution along the profile, so that when the area increases, the temperature is also increased and the speed is reduced. At reduced area points, a lower temperature is observed, with the temperature at the 223 K entry point and the exit point, calculated at 47 K. For the NACA 6409 modified nacelle, with a reduced thickness of 39% , the air flow inside the profile was simulated to obtain the velocity behavior along the points studied.From the calculations performed, comparing to the NACA 6409 profile without modifications, higher through put velocities were perceived, which is highly desirable since higher output velocities provide greater thrust transmitted to the aircraft. Not farther than expected, larger speeds were found in smaller sections. The output speed of the NACA 6409 modified profile was 1300.92 m/s against the speed of 1067.83 m/s nacelle profile NACA 6409 without modifications.

In static temperature, however, it is possible to see variations with the modifications of the areas of analysis. At calculated analytical values, the static temperature ranges from 223K at the entrance to 72.38K at the exit. This is explained by the velocity and enthalpy variation along the analyzed points.

Up to this point, the results obtained have been validated from simulations that disregard the engine effect and consequently the effects that this nacelle modification provided to the intrinsic core performance. To expand the perspective of the results obtained when considering the thrust dependent aerothermodynamics processes, calculations were performed from the characteristics of the CFM56-7B engine (composes the Boeing 737-900ER structure) and from the literature review in Mattingly (1996). Under the conditions of this cruise flight, the compressor pressure ratio (CPR) of value 24 and a fan pressure ratio (FPR) of 3 were adopted for the turbofan. In this sense, another consideration was that the velocity at station 9 during the modified nacelle simulation was the same as that measured in the NACA 6409 results. In these conditions, the turbofan under analysis presented a behavior of performance parameters similar to those theorized by Mattingly (1996) in "Elements of Gas Turbine Propulsion", thus testifying the results obtained. This fact can be verified through the graphs below.
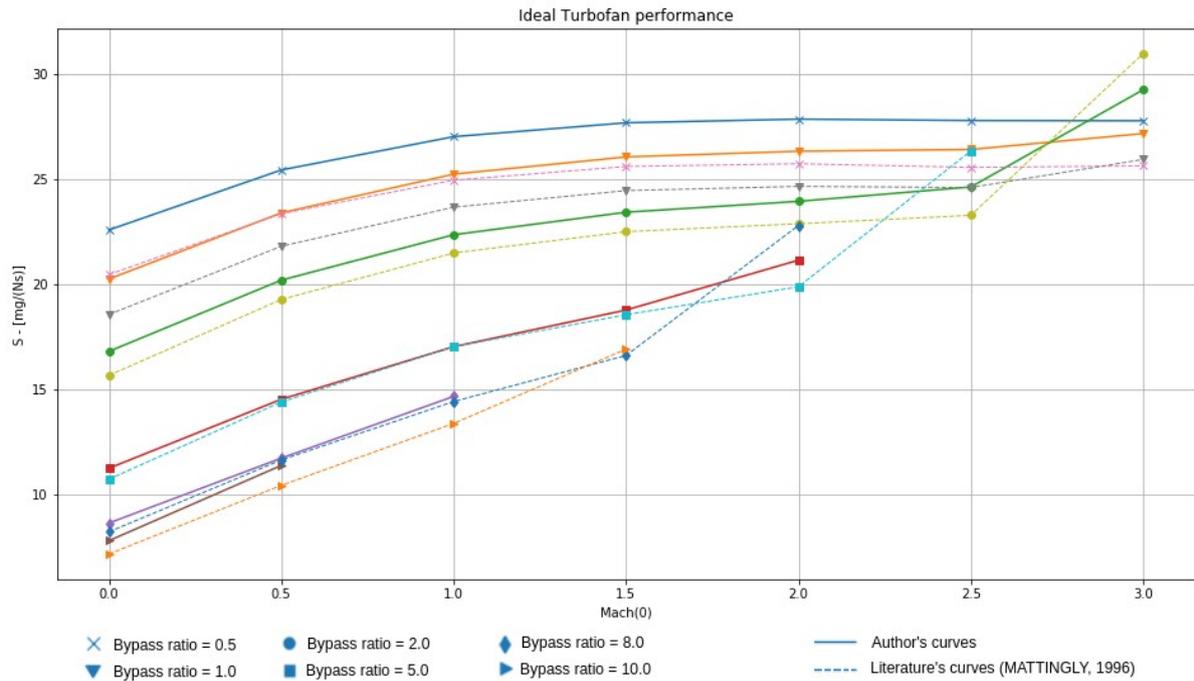
Figure 3. Thrust specific fuel consumption versus M_0.

In figure 3 it is possible to observe that besides the fuel consumption (S) values being directly proportional to the Mach number (M), for high bypass ratio (BP) values the consumption increase tends to be faster and linear. However, for the range of M at which the engine operates ($0.5 \leq M \leq 1.0$), the rate at which the S curve increases (ie its slope) is virtually invariable between different bypass values. The behavior of the specific thrust curve provides important information: only for low-bypass ratios, specifically for values 0.5, 1.0, 2.0 and 5.0 can flight achieve a supersonic condition with low thrust values. Moreover, the rate at which the specific thrust decreases in the operating range (ie, bypass equal to 5.0 and M equal to 0.79) is virtually invariable among the other curves of this graph. Another significant trend is that for high-bypass ratios the engine achieves a gradually lower value for cruise mach.

In analyzing the results it is inferred about the ratio of the thrust generated by the core over the same generated by the fan that the decrease of this represented curve is indirectly proportional to the bypass values, so that for the curve where the BP is equal to 10.0 its behavior is considerably linear.
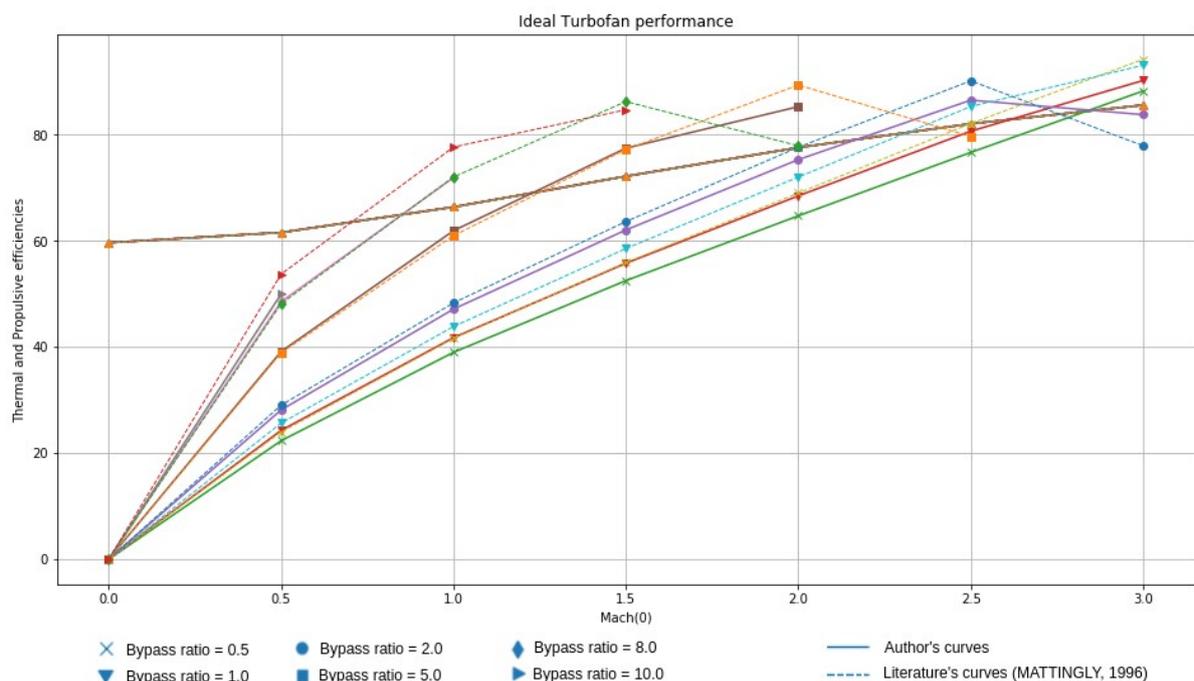
Figure 4. Thermal and Propulsive efficiencies versus M_0.

The multi-informative graph of figure 4 shows a thermal efficiency common to all BP values that has a growth proportional to the cruise mach values, with an apex at the moment turbofan operation becomes supersonic. Not only that, but this graph also provides an illustration of a propulsive efficiency trend where increasing behavior has an indirectly equivalence with increasing bypass values, a characteristic that is also observed in the overall efficiency. Moreover, the highest values for the high BP curves are reached in the lows M, while the low Bypass-ratio curves reach the apex of the propulsive efficiency at high Mach values.

The above figure illustrate the trends in CFM56-7B engine behavior, however it is not clear with the aid of these graphs the effects that the nacelle modification generated on the turbofan core. Therefore, after some calculations of the velocity proportion in station 19 (equivalent to station 5 in the nacelle simulation) as a function of the parameters plotted above, under the conditions of the cruise flight and the assumptions mentioned above, the following percentage decrease was obtained: S (25,26%), FR (21,04%), (8,21%) and (8,21%). Among these analyzes, one of the most important is the range factor (RF). The percentage increase of this parameter is shown following along with the main result measured against the core (the thrust): F (41,04% ; 122.4 [kN]) and RF (24,57% ; 7381.7 [km]).

5. CONCLUSION

After carrying out a detailed bibliographic review about the subject the authors studied the principles of the operation of the reaction engines, a principle used in a large part of the commercial aviation being studied in specific the operation of turbofans. This previous theoretical study made it possible to generate a new model for the nacelle profile from NACA standardization: the modified NACA 6409. Sequentially, both the aforementioned profile and the original NACA 6409 profile were subjected to Computational Fluid Dynamics (CFD) simulations that provided significant operating data for an analytical comparison between the models used. This is confirmed by noting in the proposed profile (modified NACA 6409) an output speed 21.8% higher than in the original profile, a positive result since this speed is responsible for the thrust of the aircraft.

It was observed in the CFD simulation performed that the regions of lower static temperature coincide with regions of higher velocity and lower enthalpy. This fact confirms the thermodynamic principles and the calculations previously made to the simulation. Despite the satisfactory results obtained in the work, it is important to emphasize that the power of the turbofan was disregarded during the CFD simulations since the objective was to analyze only the behavior of the fluid (air) in the two nacelle profiles studied.

Considering the effects generated by the thrust, it was noted that despite the percentage decrease in fuel consumption (25,28%) of the Boeing 737-900ER, which is a significant parameter in commercial aviation and one of the turbofan's differentials, the range of non-refueling flight increased to approximately 7380 km (24,57%). In addition, from the parametric graphs it was possible to notice an almost constant rate of change of the S and Specific thrust curves along the bypass values, with respect to the engine operating range in terms of the Mach number (M), that is, $0.5 \leq M \leq 1.0$. However, the increase in thrust to 122 kN during the cruise flight cost a considerable reduction in propulsive and overall efficiencies, which provides an opportunity to improve this study.

6. ACKNOWLEDGEMENTS

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