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MATHEMATICAL MODELLING AND ANALYSIS OF THERMAL MANAGEMENT SYSTEM ARCHITECTURE FOR HIGH SPEED AIRCRAFT

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Abstract

Recent high speed aircraft design studies, like STRATOFLY MR3, were done to increase the TRL of aircraft and optimizing its performance within the supersonic range. Also these studies indicated the importance of aircraft systems interface analysis, in increasing the TRL of the aircraft. This paper presents a mathematical model for the TEMS taking STRATOFLY MR3 aircraft as the baseline, based on Conceptual Multi-Disciplinary Optimization (CMDO).

Keywords: TEMS, CMDO, Mathematical modelling, Interface analysis.

1. Introduction

Current rise in interest in space tourism and low orbital flights has refocused the attention on design and development of hypersonic commercial aircraft. Recent design studies, like STRATOFLY, were dedicated in increasing the TRL of aircraft and optimizing their performance within the supersonic range. The said design studies are building on the results of past theoretical aircraft designs, like ATLLAS II and LAPCAT II, which were designed for hypersonic flight. Increasing the TRL of these aircrafts is strongly dependent on an optimum design of the thermal systems and the interplay of the said system with the other systems in the aircraft.

To achieve this objective, different methods, for optimization of system design and systems interplay process during the conceptual design process, have been documented and cited in literature, with special focus on the computational performance of these methods. The main step for determining an optimum MDO method is the problem definition and formulation. Based on the formulation, various computational architectures are cited in literature; Multi-Disciplinary Feasible (MDF) method, Individual Discipline Feasible (IDF) Method, Collaborative Optimization (CO) method, Concurrent SubSpace Optimization (CSSO) method, to name a few.

Here, the author would like to spotlight the Multi-Disciplinary Optimization (MDO) study which was applied for design of aircraft/spacecraft and initially presented via the NASA document titled BLISS (Bi-Level Integrated System Synthesis). The document presents the method wherein identification of primary set of local system variables help in decomposing a complex system into simpler systems. Combination of the primary set of local variables helps in achieving the global system variables which are then optimized iteratively to achieve a balanced system design satisfying the mission requirements. The conclusions from this method helped in demonstrating the applications of BLISS to diverse, large scale systems design and diverse human organizations. BLISS has since been a benchmark study for comparison of different MDO methods.

Application of the MDO was done in ATLLAS II and LAPCAT II. ATLLAS II study helped in envisaging an aircraft capable of withstanding external thermal loads when cruising at Mach 5-6. This study provided a detailed methodology in designing a hypersonic commercial aircraft, by utilizing extensive computational thermal analysis and also providing optimum arrangement options for the propulsion unit of the aircraft. In this study Stochastic Multi-Disciplinary Improvement (SMDI) method was used before MDO technique which helped in achieving an integrated aircraft design capable of takeoff and transonic acceleration.

Continuing on this study, LAPCAT II, presented a detailed aircraft design capable of carrying 400 passengers, commercially, across antipodal routes at speeds of Mach 5. Building on the above two studies, another aircraft design was proposed called STRATOFLY MR3, which is capable of carrying 300 passengers on antipodal routes at speeds of Mach 8. STARTOFLY MR3 used the Multiple Matching Charts (MMC) method to achieve MDO in the study. The MMC method also considered environment sustainable goals as a variable during the analysis.

All these studies provided an insight into system interface requirements and how these requirements govern the TRL increase of the aircraft. Based on the analysis of these requirements and conclusion obtained, it is found that optimization of the Thermal Energy Management System (TEMS) is vital in achieving a high TRL for the aircraft. Moreover, this analysis also showed how the performance of TEMS is affected by the propulsion system of the aircraft. Hence, this paper presents the work done on TEMS design taking STRATOFLY MR3 aircraft as the baseline.

The thermal system design is modelled based on the Conceptual Multi-Disciplinary Optimization (CMDO) methodology. Detailed aircraft CAD model, preliminary mission requirements, system specifications and system functional requirements were used as baseline to update the low-level system functional requirements. The CAD model and the flight trajectory information was used to obtain the initial heat transfer parameters which are used as inputs for the computational analysis.

Results achieved from this analysis are used to build the preliminary mathematical model for the thermal system. This preliminary model is to be used to achieve the initial thermal analysis results done in STRATOFLY MR3, with higher accuracy, for comparative study. To complete building this mathematical model, a preliminary thermal database was developed to provide the material inputs during analysis.

Lastly, the mathematical model presented in this paper is the based on the Closed Loop Brayton Cycle (CLBC) used for the thermal system and the database being developed is for high speed aircraft having a combination cycle engines of Air Turbo Rockets (ATR) and Dual Mode Ramjet (DMR).

2. Background

Current research into the design of high speed vehicles has increased dramatically since space has become accessible post successful rocket launches from private space companies. This has lead to an increase in launch of private actors providing launch services from low earth orbits to Mid earth orbits. The goal of most aircraft companies is to promote the reduction in global aircraft emissions and to achieve high sustainability in design and propulsion. This sustainability objective is the core mission requirement in the current design studies for high speed aircrafts.

The work presented across the literature presents a bird eye view of the work carried out in the design of high speed aircrafts. As seen, the design of most of the initial high speed aircrafts is mainly a blended wing body design, but the later designs modified the design to wave-rider design. This design helped in achieving a controlled flight during the high speed cruise phase and a controlled distribution of heat fluxes across the surfaces. The wave-rider design allows for the incorporation of the a new propulsion tank design called the bubble tank design that allows for carrying more fuel and also provides more flexibility to the tanks.

The capability to carry more fuel during the flight will help in using the aircraft fuel as the working fluid for the thermal systems of the aircraft. However, it has been mentioned in literature that having a dedicated fuel source or a secondary fuel source for the thermal system will help in increasing it performance. [1] has presented the use of PAO as a working fluid for the thermal system. [2] have mentioned the use of helium as a working fluid for the thermal system. The efficiency of the systems using PAO was found to be considerably less than systems using a dedicated working fluid like helium.

Thermal systems design has undergone a standardization since Multi-Disciplinary Optimization (MDO) methods have been applied to study system integration and interaction with other systems. It has been observed how thermal systems govern the performance of high speed aircraft and multi-disciplinary solutions is the need of the hour for optimizing the design of next generation high speed aircraft. Various MDO methods like Multi-Disciplinary Feasible (MDF), Individual Discipline Feasible (IDF), Concurrent Subspace Optimization (CSSO), Bi-Level Integrated Synthesis System (BLISS) among others have been applied in the recent design studies of high speed aircrafts. The most recent study includes the STRATOFLY MR3 design study. This study was conducted to design an aircraft capable of carrying passengers over anti-podal route at a cruise altitude of 35-40km. The design methodology followed in this study is called the Multi-Matching Chart (MMC) method. This method provides a graphical representation of the aerodynamic and control variables against range and fuel consumption that allows to achieve an optimum design range for all flight speeds. This method also provides an insight as to how the system integration was achieved via graphical representation.

3. Thermal Systems

Different studies of the design of high speed aircrafts has been focused on increasing the propulsive and aerodynamic efficiency of the aircraft. Later designs have considered, in the design analysis, that the thermal systems play a pivotal role in increasing the said efficiencies of the different systems.

The thermal state for a hypersonic aircraft is governed by various parameter, which are highly dependent on the design of the other systems. For any hypersonic aircraft, the thermal system design can be divided broadly into 2 categories: Internal and external. The external thermal system design variables is highly dependent on the structure and aerodynamic properties of the aircraft, whereas the internal thermal system design parameters is highly dependent on the propulsion properties of the aircraft. An optimum solution range for these variables set is needed for the design of the thermal systems and the solution range varies based on the category of the aircraft, namely, Winged re-entry vehicles (RV-W), airbreathing cruise and acceleration vehicles (CAV), non-winged re-entry vehicles or space capsules (RV-NW) and ascent and re-entry vehicles (ARV).

The thermal system design for the ATLLAS II vehicle was done by applying a multidisciplinary approach. This approach included a simultaneous analysis of the aerodynamics and structural performance which were needed to understand the operative performance during the cruise range. The design analysis had working fluid as methane, which was also part of the onboard cooling systems.

The thermal system design for LAPCAT was done after achieving an optimal integration between the propulsion unit and an aerodynamically efficient wave rider structural design. The aerodynamic design efficiency that was achieved for LAPCAT was L/D>6. After designing the conical intakes, the overall drag estimation was done for the intake of the aircraft.

The analysis shown in [3] regarding the thermal system design for LAPCAT presents the design achieved based on methodology of parameter estimation relationships The analysis is done post determining the over drag estimation and the structural design of LAPCAT. The analysis presents the performance of each components of the propulsion system of LAPCAT and how the output variables based on propulsive efficiency are the input parameters for the thermal system design. These variables are the local variables whereas the thermal efficiency and performance variables are the global variables in the analysis presented. Identification of the governing equations was done and that helped in determining the thermal system design equations.

4. Energy management

As mentioned earlier, Thermal systems are mainly gas cycles systems. [4] presents thermal system that work on Rankine cycle with aircraft fuel as the working fluid and [2] presents thermal system that works on the Brayton cycle with Helium as the working fluid.

A normal Rankine cycle operates by continuously expanding and condensing the working fluid. The working fluid undergoes isobaric and isentropic process during the entire energy cycle. Rankine cycle engines have already been studied in detail within the automotive sector and are used to increase the working temperature of the fuel by decreasing the thermal loads.

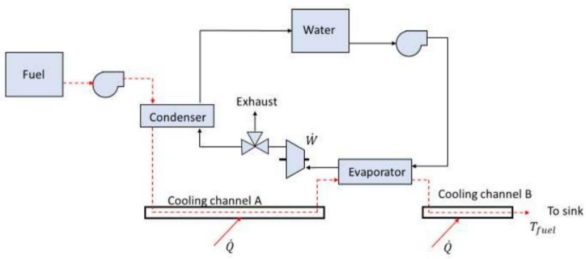

Figure.1. Rankine cycle TMS utilizing fuel as the working fluid [4]

As seen in the above figure, [4] presents a schematic of the Rankine cycle that uses aircraft fuel as the working fluid. The fuel passes through the heat pipes located in areas like the avionics bay and also the AC unit, following which the heat from the fuel is extracted by a condenser after which the fuel is passed to the Rankine cycle before being injected back into the combustion chamber or added at the exhaust section for thrust increment. The overall efficiency for a Rankine cycle is calculated as:

$$\eta = \frac{W_{net}}{Q_{in}}$$

A normal Brayton cycle operates by continuously expanding and compressing the working fluid. This cycle is mostly commonly used for aircraft jet engines and have proven their capability. In a normal jet engine, an open Brayton cycle is used. This basically means, that the excess heat generated at the end of the combustion process is lost. To increase the efficiency of the cycle, it will be possible to extract heat from the exhaust gases to reheat the fuel entering the combustion chamber, thereby achieving more thrust at the end of the process. This process is called a Closed Loop Brayton Cycle.

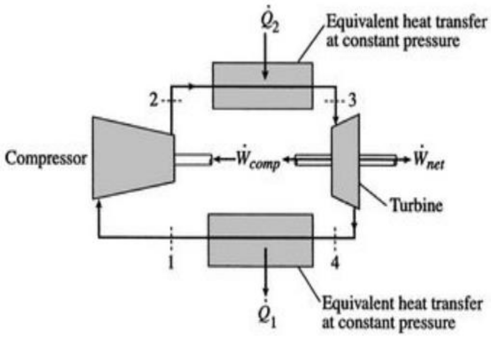

Figure.1. Basic Brayton cycle [2]

In a Closed Loop Brayton Cycle, the working fluid is passed to the heat pipes located near the combustion chamber and in the areas where heat generation is maximum. Normally, this working fluid will be the onboard fuel, which at the end of the thermal cycle, depending on the use, will be either liquid or vapour. If one of the design requirements is higher thrust, the fuel at the end of the thermal cycle, will be in vaporized state that can be directly injected in the exhaust allowing for a more higher thrust. If more efficient combustion is needed, the fuel can be injected in liquid state at the end of thermal cycle into the combustor chamber, which will allow for achieving higher combustion temperatures, which in turn will help in achieving low consumption of the fuel. The thermal efficiency of a Brayton Cycle is:

$$\eta_{thermal} = 1 - \frac{T_{atmosphere}}{T_{compressor\ exit}}$$

5. FUTURE WORK

The above discussion was presented to give the readers an insight to the process followed in obtaining a baseline thermal design. STRATOFLY MR3 aircraft design has been achieved by developing an appropriate aerodynamic database which was supplemented by a propulsive database. This aircraft is propelled by 6 Air-Turbo Rockets (ATR) and 1 Dual mode Ramjet (DMR) Engine. This combination of propulsion system requires an optimum and stable thermal system capable of providing the required cooling for passenger comfort and optimum fuel combustion, to achieve the sustainable propulsive requirements of the design. The input of these systems was used for designing the preliminary thermal system.

Current work is focused on refining the system design by applying the All-At-Once technique (AAO) for optimizing the performance of the system. Moreover, a common environment and thermal database is currently being developed to satisfy the set mission requirements. This method of obtaining the system design, by using pre-achieved results is called a bottom up approach and is normally used in Conceptual Multi-Disciplinary Optimization.

6. Copyright Statement

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