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Comparative Analysis of Analytical and Computational Thermal Models for the Free Double Piston Engine

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Effective thermal management is essential to ensure the performance, reliability, and longevity of advanced propulsion systems. The Free Double Piston Composite Cycle Engine (FDP-CCE) introduces a novel propulsion architecture that combines the efficiency of conventional piston engines with the structural configuration of turbofans. However, the elimination of crankshafts and the adoption of air lubrication systems introduce significant thermal challenges, particularly due to high temperatures in the combustion chamber and cylinder walls. This study presents the development of a computational thermal management tool aimed at evaluating and optimizing cooling strategies for the FDP-CCE. The tool couples an analytical heat transfer model with bypass air cooling to improve heat dissipation and maintain controlled temperature distribution across critical engine components. A parametric analysis is performed to investigate the effects of various material properties and bypass air heat transfer coefficients on overall thermal efficiency. The analytical and computational models produced similar results, validating the simplified 0D-1D model and enabling its use in further development due to its reduced computational cost. The findings contribute to the advancement of next-generation propulsion systems by providing a foundation for the integration of effective thermal control in composite cycle engines.

1. Introduction

The Free Double Piston Composite Cycle Engine (FDP-CCE) represents a novel propulsion concept that integrates the operational principles of traditional piston engines with the advanced architecture of turbofans. Kaiser et al. (2018) introduced the composite cycle engine concept, focusing on design optimization for future propulsion systems. Klingels (2013) proposed a free-piston compressor design tailored for high efficiency. This innovative configuration offers significant potential for enhanced thermal efficiency, reduced emissions, and a simplified mechanical design, making it a strong candidate for next-generation propulsion systems (Kaiser et al., 2021). The free-piston configuration of the FDP- CCE eliminates the need for conventional crankshafts and lubrication systems, leading to the reduction of engine weight and complexity (Mikalsen and Roskilly, 2007). This design also enables higher piston velocities and allows for more compact engine structures, resulting in significant performance improvements (Kaiser, 2020). The effective management of growing thermal waste energy on board modern aircraft has become an increasingly critical challenge (Coutinho et al., 2023). Historically, the issue of thermal management was predominantly associated with aircraft experiencing excessive aerodynamic heating at high Mach numbers (Smith, 2021). However, the increasing magnitude of heat loads has made thermal management a significant consideration even for subsonic aircraft (van Heerden et al., 2022). Over the decades, advances in materials science, such as heat-resistant alloys and composites, alongside innovations in cooling technologies (e.g., air cooling and liquid cooling), have greatly improved the thermal efficiency and reliability of aviation engines (Yang, 2024). Computational tools for heat transfer

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modelling have further enhanced the ability to predict and address thermal stresses, laying the groundwork for modern thermal management strategies.

Emerging propulsion technologies, such as ultra-high bypass ratio (UHBR) geared turbofan engines and electrified propulsion systems, are expected to exacerbate thermal management challenges (Jafari et al., 2020). Future aircraft are projected to require cooling systems capable of managing megawatt-scale heat loads, far exceeding the kilowatt-level requirements of current designs. Chapman et al. (2020) discussed the development of thermal management systems for electrified aircraft, addressing the challenges posed by increased thermal loads. Matuschek et al. (2024) further assessed the performance of engine-integrated cooling systems in advanced fighter configurations, highlighting the escalating demands on thermal control technologies. This trend is further driven by the increased integration of electrically powered subsystems in civil transport aircraft. These developments underscore the need for innovative and integrated thermal management solutions to ensure safety, operational efficiency, and sustainability in next-generation aircraft.

The FDP-CCE seeks to address these challenges by combining the simplicity and thermal efficiency of piston engines with advanced thermal management principles. However, this innovative configuration presents significant thermal management challenges, particularly during the combustion phase, where high piston speeds and air lubrication systems contribute to elevated temperatures within the piston engine. Without effective heat dissipation, these thermal loads can lead to overheating and reduced operational longevity. In order to face these challenges, this study develops a computational model that incorporates the bypass effects, as investigated in Fotis et al. (2025), providing a comprehensive analysis of how bypass air contributes to enhance the thermal performance and overall heat management strategies. Specifically, this study integrates the results of the heat transfer model (Fotis et al., 2024), focusing on the peak thermal loads at the boundaries to evaluate the effectiveness of bypass air in the cooling of the two- stroke Free Double Piston (FDP) engine in order to improve its thermal efficiency.

2. Key thermal management requirements

Effective thermal management is critical requirement for the operation of the two-stroke Free Double Piston (FDP) engine. As shown in Figure 1, the cross-sectional view of the FDP assembly highlights the compact and integrated design of the engine. Figure 2 illustrates the two pistons and their division into distinct zones, for a more detailed analysis of heat transfer processes across different regions of the engine. Specifically, the arrows are utilized to explain how the heat transfers between the zones from the two pistons.

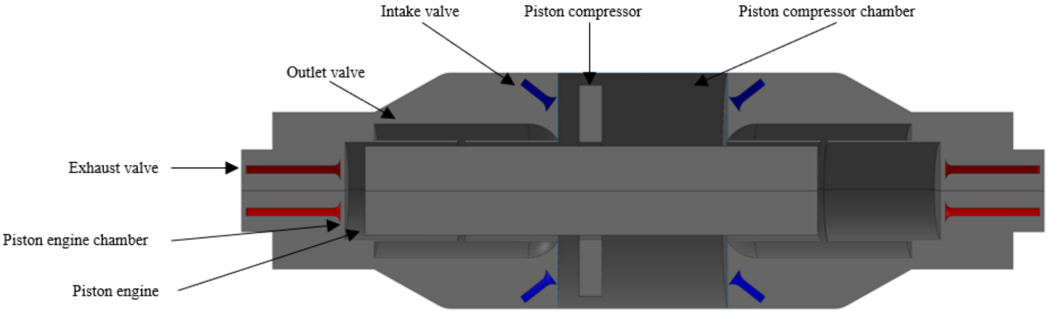


Figure 1: Cross sectional view of the FDP assembly (Fotis et al., 2024)

The thermal management of the FDP engine leverages a novel heat transfer model (Fotis et al., 2024), using its heat flux results, which are integrated into the analytical model. Table 1 lists the peak thermal loads observed in the walls and heads of the FDP engine cylinders. These values highlight the areas requiring the most attention in terms of thermal management.

Table 1: Peak thermal loads on the walls and heads of the FDP engine

Component	Peak Thermal Loads [MW/m^2]
Cylinder Head Engine	1.339
Cylinder Wall Engine	1.344
Cylinder Head Compressor	0.525
Cylinder Wall Compressor	0.610

The data indicates that the cylinder walls and heads of the piston engine experience the highest thermal loads, with values reaching approximately 1.34 MW/m². In comparison, the piston compressor regions experience lower thermal loads, with values of approximately 0.6 MW/m². This highlights the necessity for advanced cooling mechanisms in the piston engine zones to prevent overheating.

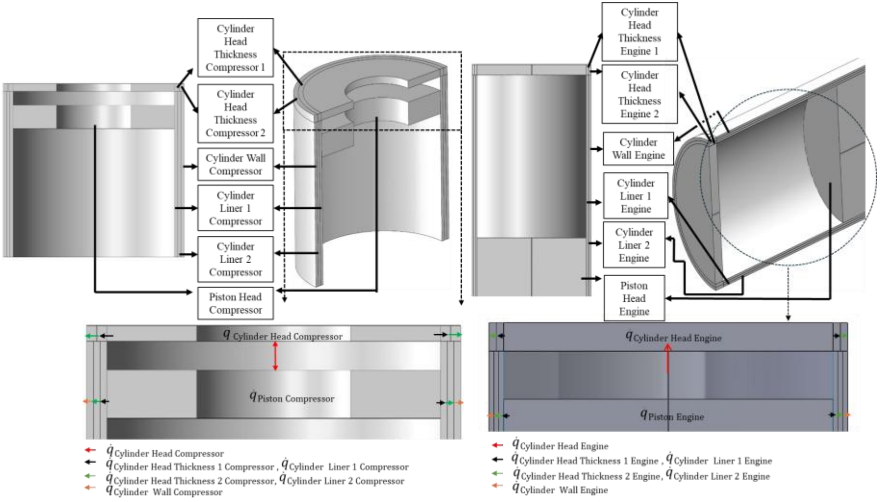


Figure 2: Detail representation of the heat transfer analysis of the piston compressor and piston engine

3. Free double piston thermal management approach

This section outlines the key cooling concepts and methodologies considered during the evaluation and provides a comprehensive description of the strategies employed to enhance the thermal performance of the Free Double Piston (FDP) engine. The methodology is focused on the exportation of the heat flux data from the 2-stroke 0D-1D FDP model (Fotis et al., 2024). These wall flux results are integrated as input for the external heat transfer analysis. Next step, an analytical model was developed, using bypass air for cooling. This analytical model is then compared against a computational model to validate its accuracy. The objective of this approach is to maintain the temperature distribution of the FDP engine layers within acceptable material limits, thereby ensuring reliable engine operation.

Analytical and computational investigations for bypass air cooling

As an initial approach, the cooling of the free double-piston engine for aviation applications was assessed using bypass air with varying heat transfer coefficients to quantify the thermal management requirements of the structure. Both computational model simulations and one-dimensional (1D) analytical calculations were conducted within the same range of bypass air mass flow rates as indicated in Table 3. Material selection for the piston cylinder was also investigated. Finally, the results of both methods were compared to validate the analytical model against the computational model.

3.1.1 Computational model setup

The computational model of the two-stroke Free Double Piston (FDP) cylinder engine, as illustrated in Figure 3a, consists of two pistons: the piston compressor and the piston engine. The yellow arrows in the figure indicate the key geometric components of the FDP. The black arrows highlight the surrounding regions of the cylinder which play a significant role for bypass air flow. The two thin red regions represent the materials of the cylinders and the surrounding areas. A uniform grid was used to discretize the computational domain, as shown in Figure 3b. The total number of cells of the computational domain is approximately 1.34 M. The main computational setup parameters are summarized in Table 2. These parameters include key aspects such as the grid size and the boundary conditions applied to both pistons.

Table 2: Computational Setup and Mesh Grid Size

Parameter	Value	Units
Piston wall flux	Peak thermal loads as detailed in Table 1	MW/m^2
Elements size	2×10^{-3}	m
Number of elements	1.34 M	-

3.1.2 Analytical model setup

As illustrated by the red thick dashed line in Figure 3a, the developed thermal model evaluates the temperature distribution by discretizing the piston-cylinder assembly into distinct layers:

- Inner piston wall: Acts as the primary heat source, receiving heat flux derived from the FDP operation. The heat input is based on the results from Fotis et al. (2024).
- Outer wall: Represents conductive heat transfer through the surrounding material, facilitating heat dissipation to the external environment.
- Surrounding bypass air: Heat is dissipated from the outer wall to the bypass air through convection. Radiation can also be accounted, its effect is small in relation to convection when a cooling method is added.

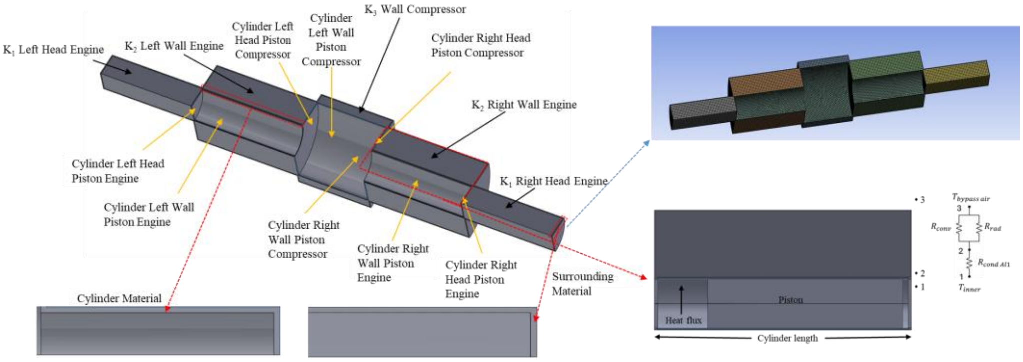


Figure 3: Domain of analytical and computational model for using bypass air for cooling and computational grid of the thermal management area around the piston.

3.1.3 Strategy of both models for using bypass air for cooling

Both models follow an approach for the evaluation of the cooling efficiency using bypass air, considering two critical parameters:

- Bypass Heat Transfer Coefficient: A range of 50 to 350 W/m²K is employed to optimize convective cooling performance. This range is derived from theoretical calculations for air flowing over cylindrical geometries at high velocities.
- Material Selection: The thermal properties of the cylinder and surrounding materials were evaluated to determine their influence on heat transfer efficiency. Material selection significantly affects the heat transfer rate, thermal conductivity and the overall cooling performance.

3.1.4 Enhancement of convective cooling via bypass transfer coefficient

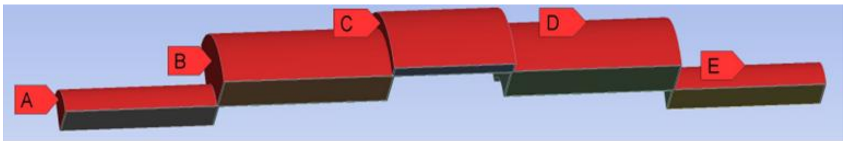
The first factor focuses on optimizing convective cooling by varying the bypass heat transfer coefficient. This coefficient, which ranges from 50 to 350 W/m²K, represents the efficiency of heat transfer from the outer wall flows to the bypass air. The areas where the bypass heat coefficients are applied are shown in Figure 4 with the red colour.

Table 3: Analytical and computational model main criteria

Variable-criteria	Value	Units
Aluminum temperature limit	573	K
Nickel alloy temperature limit	1273	K
R1	0.05	m
R2	0.06	m
R3	0.11	m
Bypass heat transfer coefficient	50 to 350	W/m^{2}K

3.1.5 Evaluation of piston and surrounding materials

The second factor examined in this study focuses on evaluating the thermal properties and performance of materials used in the inner piston wall and the surrounding regions of the Free Double Piston (FDP) engine. The primary goal is to identify an optimal material combination that enhances heat dissipation while ensuring reliable performance under the high thermal loads of FDP engine operations. The surrounding regions of the cylinder are constructed from aluminium alloy, chosen for its lightweight properties and high thermal conductivity. These characteristics enable the material to facilitate the heat dissipation, as it helps remove heat from the system quickly. Two materials were evaluated for the inner piston wall: aluminium alloy and nickel-based alloy. The nickel-based alloy was chosen due to its low thermal conductivity, which reduces heat dissipation, and its ability to withstand higher temperatures than aluminium alloy.



A: k_1 left head engine face
B: k_2 left wall engine face
C: k_3 wall compressor face
D: k_2 right wall engine face
E: k_1 right head engine face

Figure 4: Key faces of the FDP engine where the bypass heat transfer coefficient varies (Fotis et al., 2025)

4. Discussion and Results

As illustrated in Figures 5 and 6 there can be seen a close agreement between the two modelling approaches, showing a similar trend in the temperature distribution in the thermal layers, with a maximum deviation of approximately 4.5 % which can be attributed to property calculations. The resulting temperatures of both methodologies even with the best-case scenario, that being 350 W/m²K at the bypass side, significantly exceeded both materials' critical temperature limits, highlighting the necessity for enhanced cooling strategies. The calculation error for both surrounding wall and piston wall temperature is calculated according to Eq(1).

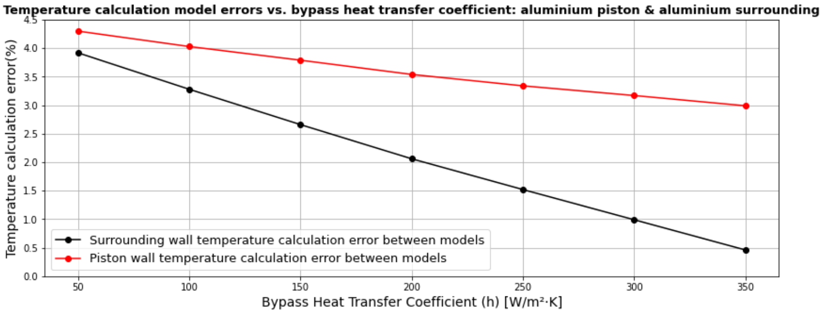


Figure 5: Calculation error in resulting temperatures between analytical and computational models for an aluminium-based alloy used in both piston cylinder and surrounding regions material

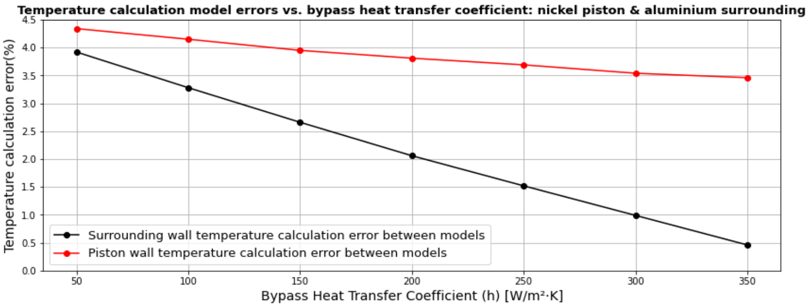


Figure 6: Calculation error in resulting temperatures between analytical and computational models for a nickel-based alloy used as the piston cylinder material and an aluminium-based alloy used in the surrounding region

$$Temperature\ calculcation\ error\ (\%) = \frac{T_{computational} - T_{analytical}}{T_{computational}} \cdot 100\ \% \tag{1}$$

5. Conclusions

This study presented a comprehensive methodology for the thermal management of the Free Double Piston (FDP) engine by integrating bypass air cooling. A computational model was developed to validate the analytical model. The validation results indicated that bypass air cooling alone, with heat transfer coefficients ranging from 50 to 350 W/m²K, was insufficient to meet the thermal management requirements of the engine. The findings underscore the necessity of using additional cooling mechanisms to ensure effective heat dissipation. The 1D analytical method was favoured over computational modelling due to its lower computational complexity and reduced processing time, making it a more efficient tool for further design optimization. The developed computational framework provides a robust platform for analysing and optimizing cooling strategies, offering valuable insights for further advancements in composite cycle engines.

Nomenclature

FDP – Free Double Piston, -
CCE – composite Cycle Engine, -
R1 – inner piston wall radius dimension, m1
R2 – outer wall radius dimension, m
R3 – surrounding wall radius dimension, m

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