Coupled Design of a Supersonic Engine and Thermal System

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Abstract

Supersonic aircraft are inherently challenging to design because they are highly coupled multidisciplinary systems that operate in a diverse range of flight regimes. As modern supersonic aircraft become lighter and require greater electrical capabilities, the propulsion and thermal management systems become performance critical. In this work, we develop a coupled propulsion-thermal model and perform gradient-based optimization to simultaneously design the engine and thermal system. After constructing the full multidisciplinary system, we solve a series of optimization problems using the coupled model with both "lifting" (refrigerating) and non-lifting thermal management systems. We sweep through a range of heat transfer requirements to evaluate how the performance of the optimal engine varies. Depending on the heat transfer requirement, optimization reduces fuel consumption up to 2.6% when using a thermal lifting system, showing the relative importance of considering the engine and thermal systems simultaneously.

Keywords: Multidisciplinary design optimization; engine design; thermal systems; gradient-based optimization.

1. Introduction

The next generation of aircraft, in both the commercial and military sectors, must meet increasingly stringent requirements, including constraints on fuel consumption, noise, emissions, heat, and cost. To meet these performance metrics, aircraft designers must innovate, from the system level to individual parts. The propulsion system has a particularly large effect on overall aircraft performance, since it both propels the aircraft and provides auxiliary power.

As aircraft become lighter and more electrified, thermal constraints become more limiting and critical for the system level design. Military aircraft are especially constrained thermally due to radar, communications, and weapons systems. Many operational constraints, such as radar observability and weight limits, reduce the available ways to dissipate heat. Heat can be rejected via airstreams within the engine without drastically increasing radar signature. Because of this, interactions between the propulsion and thermal systems have been studied extensively for military aircraft [1, 19, 2, 3, 11]. The effect of heat exchangers within engine bypass ducts is a specific area of interest. Bypass heat exchangers are useful in both transonic and supersonic aircraft. Prior work has studied bypass heat exchangers using wind-tunnel experiments [5, 14] and computational methods [1, 19, 5, 14]. Bypass airflow heat exchangers are also useful in transonic commercial airlines, including the Boeing 787, which has a surface cooler to reject engine oil heat and generator heat [6], showing the wide applicability of this research.

Instead of conducting experiments to evaluate new aircraft system designs, we use computational modeling, which allows designers to rapidly evaluate systems at a relatively low cost. To capture the effects of bypass heat exchangers, we need to model both the engine and thermal systems simultaneously and in a fully coupled manner. This has been done previously by Allison et al. [1] and by Puterbaugh et al. [19], who found interesting trade-offs between engine performance and thermal dissipation capacity. However, few of these studies looked at changing the design of the engine or thermal system, and no previous study has performed optimization on the coupled system.

By using multidisciplinary design optimization (MDO) [18], we can vary the design of a complex system to minimize an objective function subject to constraints. However, to explore a large design space efficiently, we need to use gradient-based design optimization [16]. Gradient-based optimization methods require the total derivatives of the system for all functions of interest. Generally, this means that the multidisciplinary computational models must be developed with efficient derivative computation in mind. In the case of coupled engine-thermal systems, we need the derivatives of any quantity of interest (fuel burn, thrust produced, heat dissipated) with respect to all engine and thermal design variables.

In this paper, we first discuss the relevant theory behind engine and thermal system modeling. We then use NASA's OpenMDAO framework [7] to construct a model that couples the engine and thermal system and efficiently computes the relevant gradients. We construct a 3-stream, split-flow supersonic turbofan engine and examine different thermal system architectures, including a simple heat-lifting system. We then perform a series of optimizations to show how the engine and thermal systems interact together and find optimal designs for a variety of thermal loads and flight conditions. We find that the addition of the thermal lifting system decreases the fuel consumption for a thermally-constrained supersonic flight condition by amounts ranging from 1.5% for 2.5 kW of heat rejection, to 2.6% for 15 kW of heat rejection.

2. Model Description

2.1 Propulsion Model

The propulsion system is modeled using a 1D thermodynamic cycle implemented in pyCycle [8], which is developed using OpenMDAO [7]. pyCycle is designed to model propulsion systems within the context of larger systems, especially for MDO applications. The tool provides a library of elements, such as inlets, compressors, combustors, and turbines, that can be combined to create an engine cycle. pyCycle has similar modeling capabilities as the industry standard, NPSS [12]. pyCycle also provides efficient analytic derivatives, which are necessary for gradient-based optimization.

In this work, we use pyCycle to construct our three-stream split-flow supersonic engine model, which is shown in Fig. 1. We also show the engine model with the addition of the thermal lifting system in Fig. 2, which is explained in detail in Sec. 2.2.2. Throughout the paper, we perform single-point design optimization, though pyCycle has the ability to run multipoint optimization problems in parallel. We use a supersonic top-of-climb flight condition throughout this work, since a previous multipoint design study found it was the most limiting condition [10].

We include installation effects using a series of surrogate models based on data from a fixed-shape supersonic inlet. Based on the free stream Mach number, projected capture area, and inlet area, we compute bleed, bypass, and spillage drag terms to account for installation losses. These drag contributions are subtracted from the net thrust of the rest of the engine cycle to obtain an installed net thrust, which is used to measure engine performance. Split-flow turbofans are realistically not used in the supersonic regime, though we use a split-flow architecture here to study engine-thermal interactions with a relatively simple engine model. For the same reason, the engine architecture used here does not have an afterburner.

Figure 1: The 3-stream engine schematic with bypass duct heat exchanger.

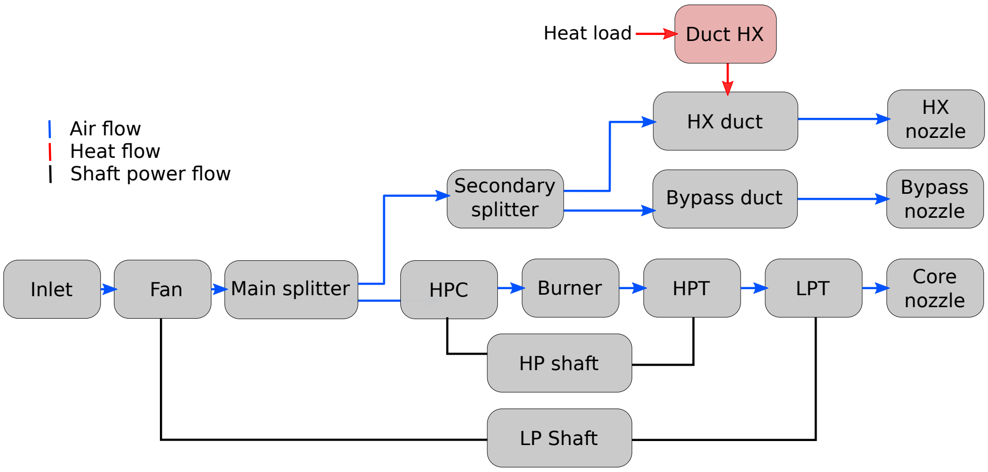
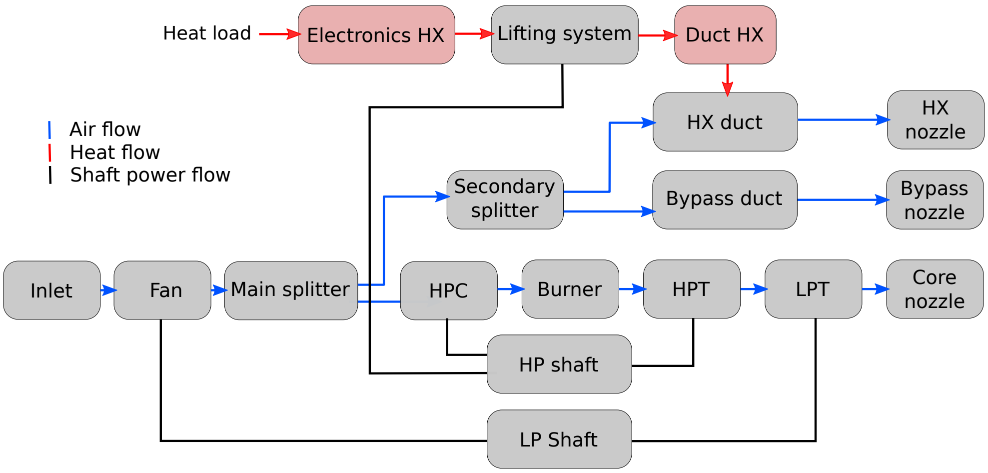


Figure 2: The same 3-stream engine architecture, but with the thermal lifting system added.



2.2 Thermal System Model

2.2.1 Heat Exchanger Description

Heat exchangers provide an interface with favorable heat transfer properties between hot and cold fluids. The steady-state heat transfer of a heat exchanger can be computed via the N_{TU}-effectiveness method as

$$
\begin{aligned}
q &= \varepsilon \frac{UA_{\text{overall}}}{N_{\text{TU}}} \left(T_{\text{in,h}} - T_{\text{in,c}} \right), \\
N_{\text{TU}} &= \frac{UA_{\text{overall}}}{C_{\text{min}}}, \\
\varepsilon &= \Phi \left(N_{\text{TU}}, \frac{C_{\text{min}}}{C_{\text{max}}} \right),
\end{aligned}
$$

where q is the heat transfer rate, ε is the heat transfer effectiveness, $T_{\text{in,h/c}}$ are the fluid inlet temperatures, N_{TU} is the number of thermal units, UA_{overall} is the overall heat transfer coefficient times the corresponding heat transfer area, $C_{\text{min}}, C_{\text{max}}$ are the maximum and minimum values of the fluid heat transfer capacity $\dot{m}c_p$ for the hot and cold sides, and Φ is an analytical or empirical function that depends on the flow arrangement of the heat exchanger (for example, crossflow) [13].

For this study, we modeled crossflow, plate-fin heat exchangers with offset strip fin geometry. This configuration is considered a "compact" heat exchanger because it has a large surface area to volume ratio, suitable for gas-liquid or gas-gas exchange in weight-sensitive aerospace applications [13]. The offset strip fin geometry improves convective heat transfer coefficients compared to straight fins. The heat exchanger design problem involves choosing appropriate geometry and material thickness to satisfy heat transfer, pressure loss, weight, and volume requirements. Figure 3 illustrates a cross section of plate-fin flow channels, including the parameters width, height, fin thickness, and plate thickness.

We used a heat exchanger model from the OpenConcept library. OpenConcept* is an aircraft "conceptual design and optimization toolkit" built on the OpenMDAO framework, including simple, conceptual-level models of systems components [4]. The OpenConcept [4] heat exchanger model implements the N_{TU}-ε equations to compute heat transfer, and uses an empirical correlation from Manglik and Bergles [17] for convective heat transfer and friction coefficients specific to the offset strip fin geometry.

For this study, we used values representative of a air-liquid heat exchanger, with cold-side channel width and height 1 mm, and hot-side channel width 14 mm by 1.35 mm. We did not vary the heat exchanger geometry design variables during optimization but optimizing these parameters would most likely improve system performance slightly. The heat exchanger in the bypass stream of the engine occupies the entire duct. We achieve this by setting the frontal area of the heat exchanger to be same as the bypass duct area computed by the engine design case.

2.2.2 Lifting System Description

The ability for the heat exchanger to transfer thermal energy into the bypass stream is dependent on its surface area, the fluid properties at both the hot and cold sides of the heat exchanger, as well as the temperature difference between the two fluids. One way to increase the temperature difference is to use an air cycle machine (ACM), a type of heat pump which uses mechanical work to transfer heat from a cooler fluid to a warmer fluid. Although more total heat is produced due to thermodynamic cycle inefficiency, the heat exchanger transfers heat faster due to the larger temperature differential. To power this thermal lifting system, energy can be used from bleed air or shaft power offtakes from the engine.

In this work, we use shaft power from the high-pressure shaft to lift the thermal energy. This directly introduces a weak coupling between engine performance and thermal system efficiency as some energy must come off of the shaft to power the lifting system. However, the magnitude of the shaft power used in the lifting system is dwarfed by the total power in the engine, so this coupling is inconsequential. For a design later presented in this paper, the lifting work taken off the shaft is about 33 hp, while the shaft is producing more than 19 000 hp, which means that the lifting system is using about 0.17% of the shaft power. The more important trade-off is between the amount of lifting work done and the heat generated during the process. Although the heat load is at a higher temperature as it is lifted, the greater total heat amount that needs to be dissipated has an effect on the optimal engine design.

Nominally, this ACM operates as a closed Brayton cycle, where the working fluid that transmits heat is recirculated through a series of elements. In a closed Brayton cycle, the working fluid flows through a low-temperature heat exchanger and accepts heat. The fluid then enters a compressor and contracts, leading to a higher temperature working fluid. This heated fluid then flows through a high-temperature heat exchanger, where energy is dissipated. The fluid then goes through a turbine and expands before interacting with the low-temperature heat exchanger as the cycle continues. In our model, the low-temperature heat exchanger interfaces with the electronics load on the hot side and the Brayton cycle on the cold side. The high-temperature heat exchanger takes heat from the Brayton cycle on the hot side and transfers it to the bypass duct airstream. This realistically accounts for the losses in heat transfer between the fluids, since we do not assume instantaneous and lossless heat transfer in the lifting system.

Instead of explicitly modeling the Brayton cycle using pyCycle, we model it using a system of equations based on assumed friction losses and performance efficiencies to capture the relevant physics without adding unnecessary complexity to the model. These equations are formulated to take in the amount of lifting work provided by the engine shaft, and compute the heat loads that must be transferred at both the electronics and duct heat exchangers. We solve for the heat load from the lifting system that must be dissipated using the duct heat exchanger, and get

$$Q_h = \frac{W'}{1 - T_c/T_h} = \frac{\eta_p \eta_f W}{1 - T_c/T_h},$$

where Q_h is the lifted heat load, W' is the efficiency-adjusted work, T_c and T_h are the temperatures of the cooling fluid at the electronics and duct heat exchangers respectively, W is the work coming off the shaft, η_p is the shaft power transfer efficiency, and η_f is the friction loss efficiency. We can then solve for the cold-side heat load and get

$$Q_c = Q_h - (2 - \eta_f)\eta_p W.$$

Q_c is the amount of heat transferred from the actual heat load, e.g., our electronics heat output. The losses due to friction are lost to the cold reservoir, leading to a higher Q_c value than in an ideal case. Throughout this work, we use $\eta_f = 0.95$ and $\eta_p = 0.95$ as nominal representative values. A schematic of the work and heat flow for this simplified cycle is shown in Fig. 4. The full engine-thermal model with the lifting system included was previously presented in Fig. 2, which shows the shaft power offtake that is used to power the lifting system.

2.3 Fully Coupled Model

By directly coupling the propulsion and thermal system models, we can evaluate the performance of the full system while correctly accounting for the systems' interactions. An extended design structure matrix (XDSM) diagram [15] showing the data passing between the models and optimizer is shown in Fig. 5. The optimizer provides design variable values to the engine and thermal systems. pyCycle

*https://github.com/mdolab/openconcept/

Figure 4: The lifting system

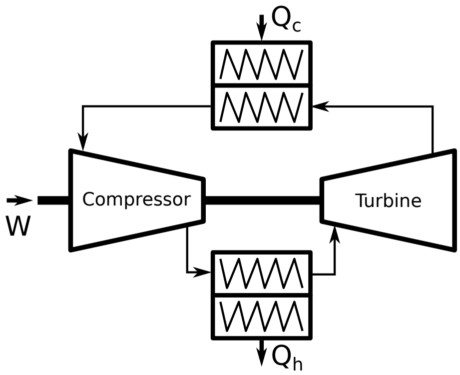
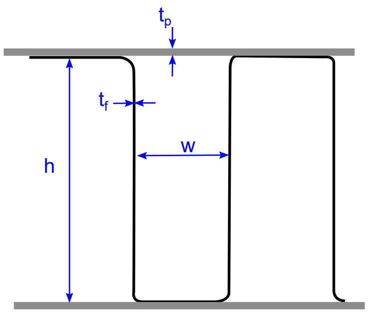
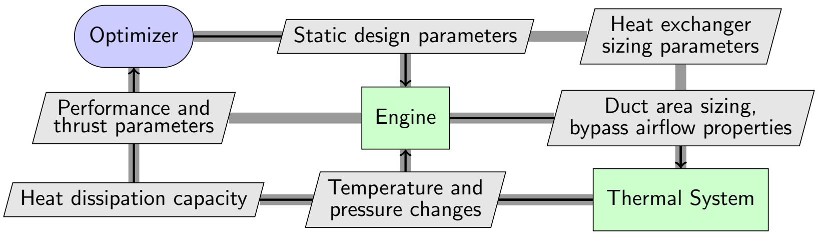


Figure 3: Plate-fin heat exchanger geometry



computes the bypass duct airflow properties, including air temperature, heat capacity, density, thermal conductivity. These properties are then passed to the heat exchanger model, which then computes the heat transfer and pressure drop across the heat exchanger to pass back to the engine model. These coupled systems are converged simultaneously using a Newton solver with an Armijo–Goldstein linesearch. Because we constructed the models in OpenMDAO with MDO in mind, we can modularly change the system grouping and solver settings based on knowledge of how best to converge the complex system.

Figure 5: The XDSM diagram for the engine-thermal system.



One major advantage of using OpenMDAO [7] is that the framework automatically computes the coupled adjoint for a multidisciplinary system, which efficiently computes the total derivatives needed for gradient-based optimization. The creator of the multidisciplinary model only needs to provide the analytic partial derivatives of each component within subsystems, and OpenMDAO uses chain rule and the modular analysis and unified derivatives theory [9] to compute the total derivatives of the system. This greatly decreases the implementation cost of developing novel multidisciplinary systems that provide analytic derivatives. For this work, we compute the analytic partial derivatives of the computational blocks in the propulsion and thermal systems individually, provide these to OpenMDAO, which then computes the total derivatives for all functions of interest with respect to the design variables while accounting for the direct coupling between the disciplines. This modular flexibility allows models developed in OpenMDAO to be easily coupled and used in gradient-based MDO.

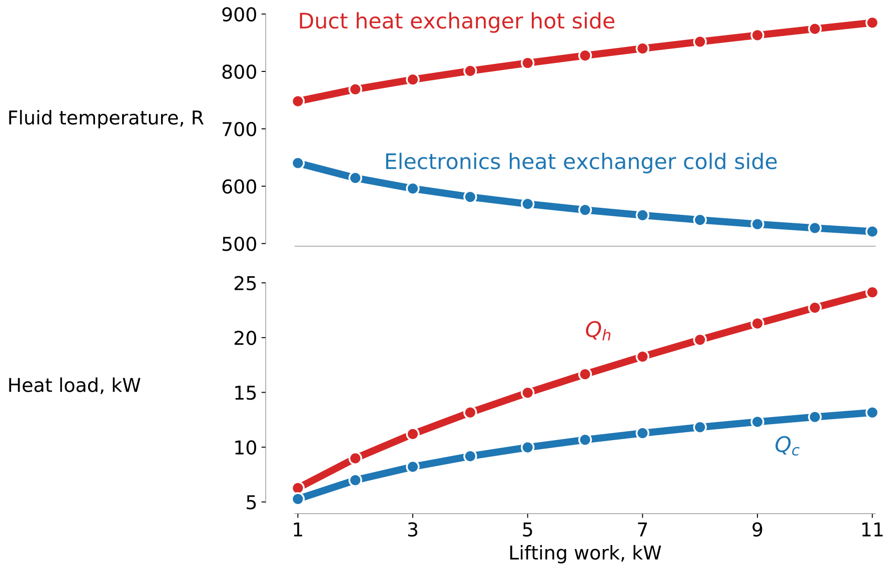
Throughout this work, we are interested in examining the trends and coupling between the engine and thermal systems instead of the absolute numbers from the analyses and optimizations. We assume a constant temperature and single-source heat load, when in reality this thermal system would have multiple heat loads at different qualities. The interactions between the disciplines are captured here without using exact efficiencies, element maps, and sizing parameters from engine manufacturers. This allows us to more publicly examine the coupled system and report on our findings.

3. Parameter Studies

We can use the fully coupled model to explore multidisciplinary trade-offs of interest to both engine and thermal system designers. We can vary engine design parameters, such as bypass ratios, design Mach numbers, pressure ratios, element maps, and efficiencies. On the thermal system side, we can control the heat exchanger geometric variables, such as fin length, width, spacing, and offset distance. For the thermal lifting system, we can vary the mass flow through the ACM and the heat exchanger variables that interface with the ACM. In this work, we examine a small subset of these design parameters while holding the others constant to highlight how these variations affect overall system performance.

To gain an intuitive understanding for how the thermal lifting process affects optimal engine performance, we analyzed the coupled model across a sweep of lifting work values. We used the same fixed engine design used in the BPR study and did not perform any design optimization here. Figure 6 shows the temperatures and heat loads for the hot and cold sides of the lifting system for 11 different nominal lifting work values. As the amount of lifting work done increases, the temperature difference in the ACM increases, which means the heat exchangers can dissipate more thermal energy due to the larger temperature difference between the hot and cold sides. However, the work used to lift the thermal energy must also be dissipated by the heat exchangers, which means more thermal energy is put into the bypass airstream. The optimal amount of lifting work, accounting for the increased temperature difference and larger thermal loads, depends on the bypass airflow properties and heat exchanger designs. Depending on the vehicle flight conditions, different lifting work amounts will be optimal based on the amount of heat dissipation required.

Figure 6: As more lifting work is added to the thermal lifting system, the amount of heat that must be dissipated increases, as does the temperature of the air within the ACM. Q_h is greater than Q_c due to the added heat from the lifting work.



4. Optimization Results

As discussed previously, there are a large number of potential optimization problems that could be solved to study the design space of this model. We first compare optimal engine performance for the non-lifting and lifting thermal systems across a range of heat transfer requirements at a single flight condition. Table 1 shows the optimization problem formulations for both thermal system types. The lifting work design variable is only present in the engine-thermal model that includes the lifting system.

We are minimizing the fuel flow to the combustor while meeting a heat transfer requirement at a supersonic flight condition. The optimizer has control over fan pressure ratio (FPR), overall pressure ratio (OPR), the main BPR, and the design sea level static thrust for all cases, as well as the lifting work for the lifting system cases. The Ac_{des} variable controls the capture area of the inlet, which we constrain to be equal to the capture area of the supersonic case to accurately compute installation drag. We sweep through heat transfer requirements from 2.5 kW to 15 kW for both thermal system architectures and perform optimizations at each point, prescribing the heat transfer amount using an equality constraint. For these optimizations, we hold the secondary BPR fixed to 1.0 to simplify the optimization problem.

Table 1: The optimization problems for both coupled system types. The lifting work variable is only in the lifting system problems.

Category	Name	Lower	Upper	Units
Objective	Fuel flow	–	–	lbm/s
Variables	FPR	1.5	5.0	–
	OPR	15.	35.	–
	$F_{net,SLS}$	22 000	35 000	lbf
	Ac_{des}	600	1200	in^2
	Main BPR	0.05	–	–
	Lifting work	0.5	–	kW
Constraints	Capture area ratio	1.	1.	–
	$F_{net,TOC}$	7600	–	lbf
	Heat transfer	2.5	15	kW

Figure 7 shows the optimized results for the two types of coupled systems. We see that by using a lifting system, the optimal fuel flow at the supersonic flight condition is improved between 1.5% to 2.6%. The only ways for the non-lifting system to meet the heat transfer requirement are by changing the bypass airflow or duct size, whereas the lifting system can also change the quality and quantity of the thermal load.

Tables 2 and 3 show the optimal design variable values. Examining the optimal designs, as the heat transfer requirement increases for the non-lifting system, the optimizer chooses to decrease FPR, which lowers the temperature of the air in the bypass duct, allowing for more heat transfer with the heat exchanger. On the other hand, the lifting system can have a higher FPR while still meeting the designated heat transfer, leading to a more efficient engine. The addition of the lifting system allows the optimizer to find the thermodynamically optimal engine design for each heat transfer requirement. This is partially possible because we are only considering engine performance at a single flight condition.

Figure 7: The lifting system allows the optimizer to find a lower fuel burn across all heat transfer requirements.

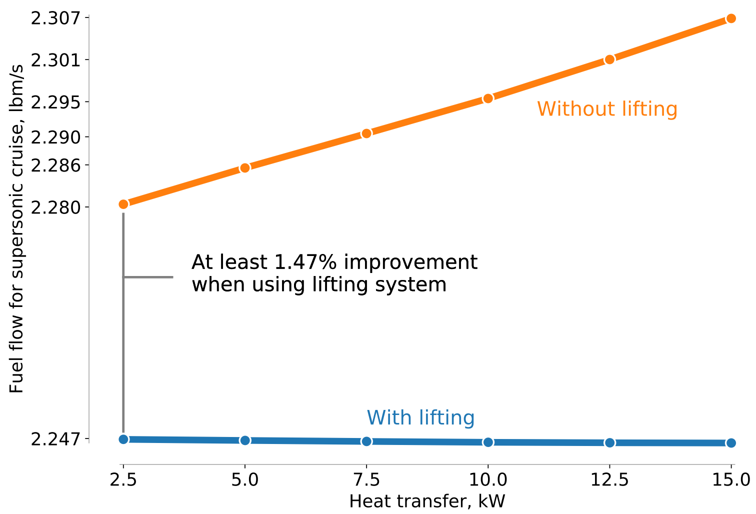


Table 2: Optimal design variable values for the non-lifting system.

Heat transfer, kW	Design thrust, lbf	OPR	FPR	Main BPR	Fuel flow, lbm/s
2.5	31584	35.0	3.050	0.598	2.280
5.0	31548	35.0	2.787	0.589	2.286
7.5	31504	35.0	2.540	0.581	2.290
10.0	31464	35.0	2.309	0.571	2.295
12.5	31448	35.0	2.095	0.555	2.301
15.0	31436	35.0	1.895	0.533	2.307

Table 3: Optimal design variable values for the lifting system.

Heat transfer, kW	Design thrust, lbf	OPR	FPR	Main BPR	Fuel flow, lbm/s	Lifting work, kW
2.5	31651	35.0	5.000	0.643	2.247	0.62
5.0	31651	35.0	5.000	0.643	2.247	1.94
7.5	31651	35.0	5.000	0.643	2.247	4.24
10.0	31653	35.0	5.000	0.644	2.246	8.00
12.5	31660	35.0	5.000	0.644	2.246	14.18
15.0	31669	35.0	5.000	0.644	2.246	24.67

The lifting system introduces additional thermal energy into the bypass duct, which causes the bypass nozzle to create more thrust than if the airflow was not heated. This slightly positive net thrust effect, coupled with the larger temperature difference possible through the lifting system, counteracts some of the negative effects associated with needing to dissipate more thermal energy. The optimal lifting work values go from 0.62 kW to 24.67 kW across this range of heat transfer requirements. Since we require more heat to be dissipated, much more lifting work is required at each optimal point.

The coupled model does not include many of the realistic considerations that are necessary when measuring total system performance. In particular, we do not account for the weight of the heat exchangers or thermal system components, which is not negligible. Additionally, the actual performance of the ACM may differ than what is modeled here, because we are using an analytic Brayton cycle with assumed efficiencies. We are considering steady-state thermal effects, though heat flow is an inherently transient problem. We would have to integrate this engine-thermal system across multiple time points to accurately evaluate the transient performance.

5. Conclusion

In this work, we constructed a coupled engine-thermal system that models a 3-stream split-flow supersonic engine with a heat exchanger in the secondary bypass duct and an optional heat lifting system. The multidisciplinary model is developed using OpenMDAO and integrates other disciplinary analysis modules. We constructed this model in a modular way to more easily integrate it into a larger vehicle- or mission-level optimization problem.

We first performed analysis sweeps to examine how the model behaves and to ensure that the trends matched physical reasoning. We then performed a series of optimizations across a range of heat transfer requirements. We compared the performance of the engine with and without the thermal lifting system and found that thermal lifting enabled fuel burn reductions of 1.5% for 2.5 kW of heat rejection, to 2.6% for 15 kW of heat rejection. The results presented here are limited in scope, and this model could be used for a variety of other optimization studies.

Future work could optimize the heat exchanger design, examine multiple flight conditions, or introduce more physical trade-offs in the thermal system model that would lead to more realistic results for a given aircraft. This work shows that it is possible to do gradient-based design optimization of a coupled thermal-propulsive system to obtain optimal engine performance under thermal load.

6. Acknowledgements

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7. References

[1] Darcy L Allison, Edward J Alyanak, and Kyle Shimmin. Aircraft system effects including propulsion and air cycle machine coupled interactions. In *57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, page 0671, 2016. doi:10.2514/6.2016-0671.

[2] Edward J Alyanak and Darcy L Allison. Fuel thermal management system consideration in conceptual design sizing. In *57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, page 0670, 2016.

[3] Mark Bodie, Greg Russell, Kevin McCarthy, Eric Lucas, Jon Zumberge, and Mitch Wolff. Thermal analysis of an integrated aircraft model. In *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, page 288, 2010.

[4] Benjamin J. Brelje and Joaquim R. R. A. Martins. Development of a conceptual design model for aircraft electric propulsion with efficient gradients. In *Proceedings of the AIAA/IEEE Electric Aircraft Technologies Symposium*, Cincinnati, OH, July 2018. doi:10.2514/6.2018-4979.

[5] Huikun Cai, Lijun Su, Yidai Liao, and Zeju Weng. Numerical and experimental study on the influence of top bypass flow on the performance of plate fin heat exchanger. *Applied Thermal Engineering*, 146:356–363, 2019.

[6] Stephen F. Clark. 787 propulsion system, 2012. URL: https://www.boeing.com/commercial/aeromagazine/articles/2012_q3/2/.

[7] Justin S. Gray, John T. Hwang, Joaquim R. R. A. Martins, Kenneth T. Moore, and Bret A. Naylor. OpenMDAO: An open-source framework for multidisciplinary design, analysis, and optimization. *Structural and Multidisciplinary Optimization*, 2019. doi:10.1007/s00158-019-02211-z.

[8] Dr. Tristan Hearn, Eric Hendricks, Jeffrey Chin, Justin S. Gray, and Dr. Kenneth T. Moore. Optimization of turbine engine cycle analysis with analytic derivatives. In *17th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, part of AIAA Aviation 2016 (Washington, DC)*, 2016. doi:10.2514/6.2016-4297.

[9] John T. Hwang and Joaquim R. R. A. Martins. A computational architecture for coupling heterogeneous numerical models and computing coupled derivatives. *ACM Transactions on Mathematical Software*, 44(4):Article 37, June 2018. doi:10.1145/3182393.

[10] John P. Jasa, Justin S. Gray, Jonathan A. Seidel, Charles A. Mader, and Joaquim R. R. A. Martins. Multipoint variable cycle engine design using gradient-based optimization. In *57th AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, 2019*, San Diego, CA, January 2019. doi:10.2514/6.2019-0172.

[11] John P. Jasa, Charles A. Mader, and Joaquim R. R. A. Martins. Trajectory optimization of a supersonic air vehicle with thermal fuel management system. In *AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, Atlanta, GA, June 2018. doi:10.2514/6.2018-3884.

[12] Scott Jones. *An Introduction to Thermodynamic Performance Analysis of Aircraft Gas Turbine Engine Cycles Using the Numerical Propulsion System Simulation Code*. NASA, 2007. TM-2007-214690.

[13] WM Kays and AL London. *Compact Heat Exchangers, Third Edition*. McGraw-Hill Book Company, 1984.

[14] Sangkeun Kim, June Kee Min, Man Yeong Ha, and Changmin Son. Investigation of high-speed bypass effect on the performance of the surface air–oil heat exchanger for an aero engine. *International Journal of Heat and Mass Transfer*, 77:321–334, 2014.

[15] Andrew B. Lambe and Joaquim R. R. A. Martins. Extensions to the design structure matrix for the description of multidisciplinary design, analysis, and optimization processes. *Structural and Multidisciplinary Optimization*, 46:273–284, August 2012. doi:10.1007/s00158-012-0763-y.

[16] Zhoujie Lyu, Zelu Xu, and Joaquim R. R. A. Martins. Benchmarking optimization algorithms for wing aerodynamic design optimization. In *Proceedings of the 8th International Conference on Computational Fluid Dynamics*, Chengdu, Sichuan, China, July 2014. ICCFD8-2014-0203.

[17] Raj M. Manglik and Arthur E. Bergles. Heat transfer and pressure drop correlations for the rectangular offset strip fin compact heat exchanger. *Experimental Thermal and Fluid Science*, pages 171–180, 1995. doi:10.1016/0894-1777(94)00096-Q.

[18] Joaquim R. R. A. Martins and Andrew B. Lambe. Multidisciplinary design optimization: A survey of architectures. *AIAA Journal*, 51(9):2049–2075, September 2013. doi:10.2514/1.J051895.

[19] Rebekah Lee Puterbaugh, Jeffrey Brown, and Ryan Battelle. Impact of heat exchanger location on engine performance. In *SAE Technical Paper*. SAE International, 10 2012. doi:10.4271/2012-01-2168.