

Heat exchanger integration with an aero-engine bypass duct

Proc IMechE Part G:
J Aerospace Engineering
2026, Vol. 0(0) 1–15
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Abstract

The development of aero engines with geared fans may require the use of an air/oil heat exchanger (AOHE) embedded within the bypass duct to dissipate heat from the power gearbox of the fan. It is important that the AOHE system is designed and installed to minimise any detrimental impacts on exhaust performance while meeting the heat exchanger (HEX) heat transfer requirements. This paper introduces and demonstrates the capabilities of a coupled mixed fidelity method to model a naturally ventilated AOHE embedded within the bypass duct. The method is demonstrated in this paper by using it to explore and quantify the trade-offs between the HEX design and performance and the impact on the exhaust system. Overall, for the specific example considered, the introduction of the HEX could reduce the cruise thrust by 0.7% while meeting the required heat transfer at maximum take-off. Overall, the work shows how a mixed fidelity method can be used for preliminary design assessments of the integration of the HEX with the bypass duct.

Keywords

computational fluid dynamics, heat exchanger, mixed fidelity methods, design space exploration

Received: 31 July 2025; accepted: 2 March 2026

Introduction

Background

The requirement to reduce the environmental effect of aviation has led to the development of Ultra-High Bypass Ratio (UHBR) aero-engines with geared fans.¹ The mechanical losses within the power gearbox generate heat^{2,3} which introduces a challenge in the form of thermal management of the engine gearbox system.⁴ Heat transferred from the gearbox components to the coolant oil needs to be dissipated. This can be achieved through the integration of a heat exchanger (HEX)⁵ embedded into the bypass duct of the engine (Figure 1) where the heat is rejected to the bypass flow. The beneficial effects of heat addition to the bypass flow are likely to be negligible compared to the penalty due to the pressure loss in the bypass flow due to the introduction of the HEX.⁴ Therefore, it is essential to size, aerodynamically define and integrate HEX systems which minimize the detrimental impacts on the bypass performance while ensuring the HEX heat transfer requirements are met.

The work presented in this paper used computational fluid dynamics (CFD) methods to evaluate the effect of HEX integration on the engine performance. Three different methods are typically used to numerically model HEXs: conjugate heat transfer (CHT),⁶ porous media methods^{7–12} and low order HEX models.¹³ The CHT methods require the detailed geometry and mesh of the HEX. It has been used to

accurately predict the aerothermal performance of aero-engine HEXs⁶ but it is computationally expensive and not suitable for rapid design studies. Alternative methods utilise the porous media approach to model the HEX system but require that the model is well calibrated.^{7–12} Porous media can model the performance of a HEX to a similar level of accuracy as CHT methods⁶ but are limited by the calibration accuracy of the model.

Low order models of HEXs can be integrated into CFD solvers to construct a mixed fidelity method of modelling a HEX system as part of a larger CFD domain and simulation. Such methods have been used for specialised cases in literature.¹³ Mixed fidelity methods can capture the performance of the HEX while improving the CFD solution convergence and at reduced computational costs. These

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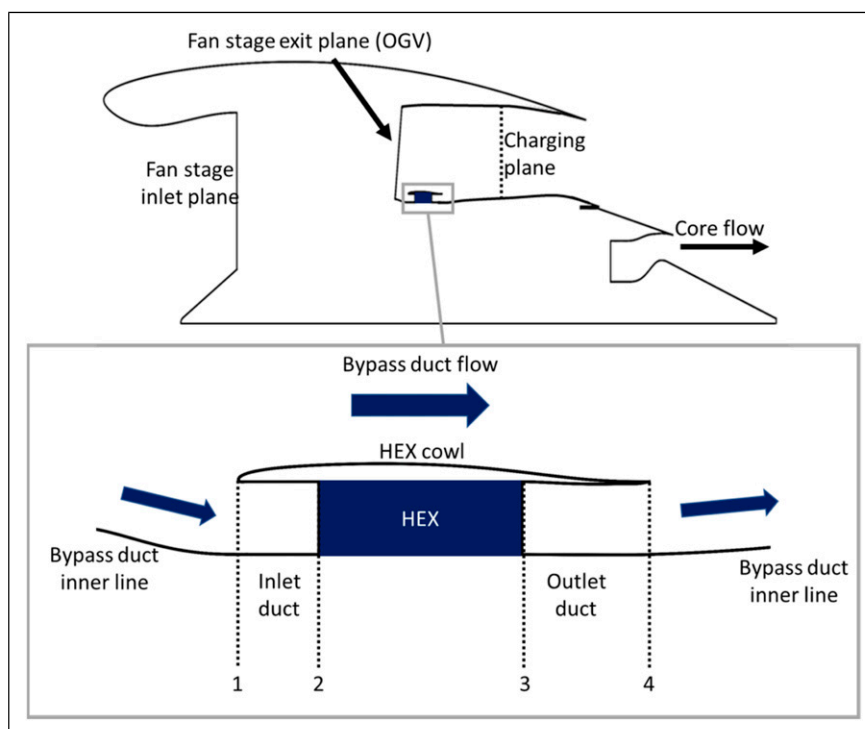


Figure 1. Schematic of a HEX embedded within the bypass duct of an aero-engine. The fan stage exit plane is also referred to as the OGV exit plane in this paper.

methods are also robust and easy to calibrate. Therefore, mixed fidelity methods are suitable for large design space exploration studies of HEX configurations. Although individual tools exist to rapidly assess the performance of a heat exchanger and to simulate the aerodynamic behaviour of an aero-engine, these tools have not previously been used together in a coupled manner. As a result, mixed-fidelity methods for analysing heat exchangers embedded within an aero-engine bypass duct have not appeared in open literature. This work therefore presents the first combined assessment using these complementary tools. In this process, a key challenge was the development of a consistent thrust-accounting formulation able to calculate the overall aero-thermal performance for the integrated HEX-Exhaust system.

Scope and novelty

This work demonstrates the capabilities of a coupled mixed fidelity method to model a naturally ventilated HEX embedded within the bypass duct. An in-house CFD based modelling tool was developed to accommodate the HEX system and was used to conduct the aero-thermal analysis of naturally ventilated, embedded HEX systems integrated in the bypass duct of an aero-engine.¹⁴ This tool parametrically generates full engine geometry. A naturally aspirated HEX modelling approach is used to simulate an embedded HEX system¹⁵ and enable rapid design analyses. A heat exchanger sizing and thermodynamic modelling tool is used to generate HEX low order models based on empirical heat transfer and pressure loss correlations.¹⁶ The tool can model a range of plate-fin type and

tube-fin type heat exchangers. The thrust-drag book-keeping (TDB) method quantified the effect of air-oil heat exchanger (AOHE) integration on the aerodynamic performance of the exhaust system.^{17–19}

Overall, this paper demonstrates for the first time the capability of a mixed fidelity aero-thermal tool for analysis of exhaust aerodynamics, HEX performance, and thrust accounting for the evaluation of embedded HEX systems at an engine level. The paper also explores perturbations in the HEX system geometry including the HEX sizing, AOHE integration with bypass duct, and HEX cowl designs to provide the first quantitative assessment of the overall engine performance at cruise and maximum take-off (MTO) operating conditions.

Methodology

Geometry generation and computational setup

A range of HEX configurations are embedded into the bypass duct of a UHBR engine with a 140-inch fan diameter²⁰ in this study. An in-house tool is used for the design and analysis of engine exhaust systems and consists of an automated workflow for geometry generation, meshing, solving and postprocessing of separate-jet exhausts. The geometry generation approach uses a parametric method defined by intuitive class shape transformation (iCST) functions.²¹ The iCST method is widely used to parameterise geometries for aerodynamic applications.^{21–23} The iCST curve is defined by the product of a class function $C(x)$ and a shape function $S(x)$ with an offset parameter. The class function varies based on

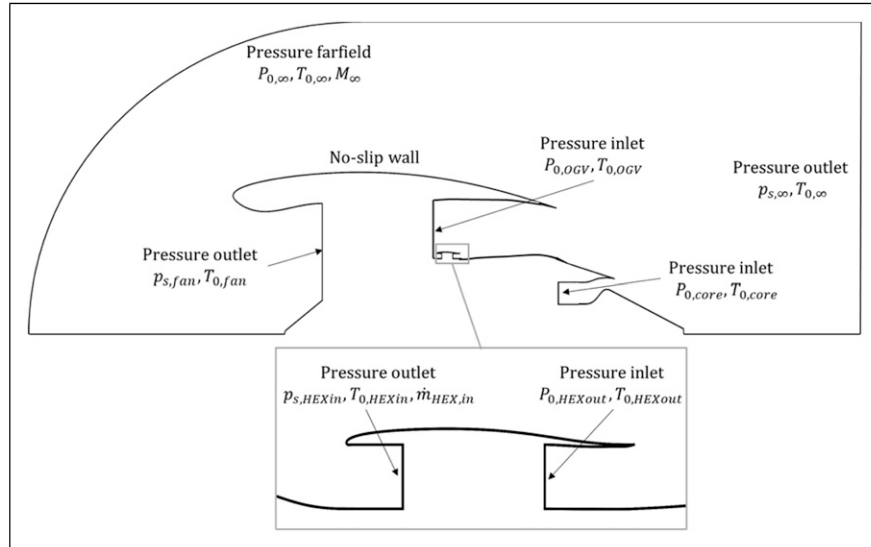


Figure 2. Schematic of the computational domain and boundary conditions for the farfield, engine and HEX.

requirements of the geometry to be generated. The shape function controls the local parameters of the geometry and is constructed from scaled Bernstein polynomials. The iCST method enables parametric aerodynamic shapes to be created based on intuitive design variables.^{24,25}

A 2D axisymmetric computational domain was generated with a semi-circular far-field boundary (Figure 2). A hybrid mesh of 200,000 elements with a y^+ of less than one was used. Mesh independence studies quantified the grid convergence index (GCI) as defined by Roache et al.²⁶ The GCI was less than 0.1% for net thrust and HEX heat load at cruise and MTO conditions. The results of this study are mesh independent. A compressible Reynolds Averaged Navier-Stokes (RANS) solver with the $k-\omega$ shear stress transport (SST) turbulence model²⁷ was used to calculate the flow field. The high Mach number conditions of cruise and MTO was solved using density-based calculations. Second order spatial discretisation was used and the gradients were computed using the Green-Gauss node-based method.

The CFD method to calculate the flowfield in this study was validated against experimental data of the Dual Stream Flow Reference Nozzle (DSFRN).^{17,28} The DSFRN does not have a HEX embedded within the bypass duct. This validation task was done for CFD methods using hybrid meshes. The performance of the DSFRN exhaust was validated by determining the root-mean-square deviation (RMSD) between experimental measurements and numerical predictions of the velocity coefficient (C_v) and bypass duct discharge coefficient (C_d). The RMSD value of C_v and C_d were 0.033% and 0.32% respectively. This was calculated across a fan-nozzle pressure ratio (FNPR) range of 1.4 to 2.8. A similar validation study on the DSFRN was carried out by Otter et al.²⁹ using structured meshing approaches. They also calculated an RMSD between CFD and experiments of 0.03% and 0.37% for C_v and C_d respectively. Therefore, this CFD method for prediction of exhaust performance is suitable for the requirements of this study.

HEX modelling

The HEX modelling method introduced by Bajimaya et al.¹⁵ parametrically generates the geometry of the embedded HEX system, integrates the low order HEX model into the solver and uses the TDB method for an exhaust system with an embedded HEX. A high degree of control is possible for the axial and radial position of the whole HEX system within the bypass duct as well as subsystem components including the intake duct, exhaust duct and the HEX cowl.

The coupling between the low order HEX model and the RANS based CFD solver must be achieved while satisfying mass, momentum and energy conservation. The ventilated HEX model integrated into the CFD requires a priori selection of HEX matrix parameters and oil flow properties. These are used as inputs in the HEX sizing and thermodynamic modelling tool¹⁶ to generate HEX total temperature ($\Delta T_{0,HEX} = T_0^3 - T_0^2$) and total pressure ($\Delta P_{0,HEX} = P_0^3 - P_0^2$) maps as a function of the air mass flow through the HEX ($\dot{m}_{HEX}$). The value of $\dot{m}_{HEX}$ is not known a priori therefore a first guess for $\dot{m}_{HEX}$ is used to determine an initial $\Delta T_{0,HEX}$ and $\Delta P_{0,HEX}$. The effect of $\Delta T_{0,HEX}$ and $\Delta P_{0,HEX}$ is reflected in the CFD solver by updating the HEX boundary conditions in the computational domain. The updated boundary conditions lead to a change in the mass flow through the HEX calculated by the CFD solver. A mass flow convergence check is done and the value of $\dot{m}_{HEX}$ is updated based on the difference between HEX air side mass flow used in the HEX modelling tool and that calculated by the CFD. This updated mass flow is used as the new input in the HEX modelling tool to arrive at new values of $\Delta T_{0,HEX}$ and $\Delta P_{0,HEX}$. The whole process is repeated until mass flow convergence is reached. High values of $\Delta P_{0,HEX}$ leads to low values of $\dot{m}_{HEX}$. This can lead to a flow separation due to streamtube pre-diffusion effects at the intake side of the HEX as discussed in later sections.

An offset strip-fin type crossflow HEX was selected for this demonstrative study due to the high ratio of heat

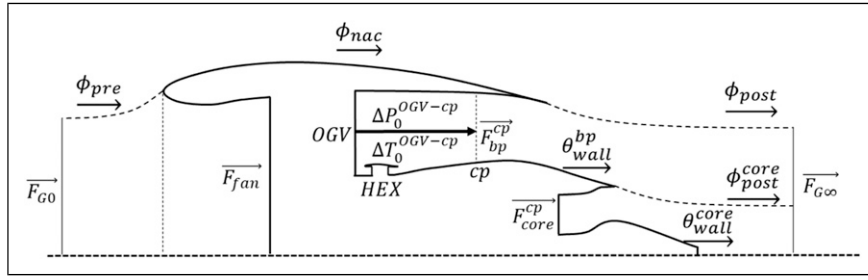


Figure 3. Thrust-drag accounting for aero-engine with a HEX embedded within the bypass duct.

transfer to total pressure loss associated with this type of HEX.³⁰ The total pressure loss (equation (1)) and total temperature rise (equation (2)) across this type of HEX was calculated using empirical correlations Fanning friction factor (f) and heat transfer (h) coefficients described by Manglik et al.³⁰ The air side total pressure drop across the HEX depends on the Fanning friction factor (f), HEX length in the flow direction (L), air density (ρ), channel hydraulic diameter (D_H) and the air flow mass flux (G). The HEX effectiveness (ε), heat transfer coefficient (h), overall heat transfer area (A_{ht}), inlet total temperature (T_0), wall total temperature (T_w), air mass flow rate ($\dot{m}_{HEX}$) and the specific heat capacity of air at constant pressure (c_p) determines the total temperature rise across the HEX. Heat transfer is calculated through the ε -NTU method where the number of transfer units (NTU) of the HEX is determined and the effectiveness (ε) of the HEX is correlated to the NTU.¹⁶ Here, effectiveness is the ratio of the actual heat transfer to the ideal heat transfer rate. The flow rate at the oil side of the HEX was determined based on the heat transfer requirement at MTO condition, specific heat capacity of the oil used, and the maximum oil temperature restrictions. At off-design conditions, oil flow rate was scaled as a function of the engine RPM at each operating condition that was explored. For each operating condition, the oil temperature was assumed fixed based on lubrication system data and was held constant during the analysis.³¹ This assumption reflects a typical control strategy in which oil temperature is maintained within a narrow band for component protection. The mixed-fidelity framework is compatible with alternative oil-system control strategies, including variable oil temperature or flow-rate scheduling, and the fixed-temperature approach adopted here represents one illustrative use of the methodology rather than a limitation of the tool.

$$\Delta P_{0,HEX} = \frac{2fL_{HEX}}{\rho D_H} G^2 \quad (1)$$

$$\Delta T_{0,HEX} = \frac{\varepsilon h A_{ht} (T_0 - T_w)}{\dot{m}_{HEX} c_p} \quad (2)$$

The HEX assessment tool used in this work was validated by Lee et al.³² where they compared the performance of an air-to-air offset-strip fin, crossflow HEX predicted by the HEX model with results from experiments. Hot side flow was at 580 K and 800 kPa with a mass flow rate of 0.81 kg/s and the cold side was at 350 K, 160 kPa at 1.21 kg/s. The cold-side Reynolds number based on the hydraulic diameter

of the HEX channels in the validation case was approximately 200,000. This is comparable to the range of cold-side Reynolds numbers encountered in the present study, which vary between 50,000 and 150,000 depending on operating condition. This broad similarity in flow regime provides confidence that the validation data are representative of the conditions relevant to the HEXs assessed in this work. A maximum difference between the experiment results and the HEX model predictions of 0.7% and 1.85% was calculated for total temperature rise and total pressure loss respectively. Overall, this HEX model is therefore suitable for the purposes of this study. This lower order heat exchanger is coupled with the bypass duct to model an embedded HEX system. This fully coupled embedded HEX configuration has not been validated. However the individual constituent parts have been validated and coupled together ensuring mass, momentum and energy conservation. This method enables rapid design space exploration and sensitivity assessment for naturally ventilated HEX systems embedded within the bypass duct.

Thrust and performance accounting

To quantify the effect of HEX integration on the aerodynamic performance of the exhaust system including the overall impact on net thrust, the TDB method is used (Figure 3).^{28,33} Fluid forces acting in the drag domain and the thrust domain are represented by the terms ϕ and θ respectively. The thrust domain is the region bounded by the engine intake and exhaust streamtubes. Drag domain is the region around the engine not within the intake and exhaust streamtubes. The main impact of the HEX integration is localised within the bypass duct and therefore two assumptions were made to quantify the effect on thrust as the HEX configurations were varied:

- Engine intake mass flow capture ratio (MFCR) is constant therefore there is no effect on nacelle drag.
- Effect of the HEX only arises within the thrust domain.

The main effects of HEX integration can be quantified using the overall net thrust (F_N):

$$F_N = F_{G\infty} - F_{G0} \quad (3)$$

Where $F_{G,0}$ is the intake momentum drag and $F_{G,\infty}$ is the gauge force at the downstream infinity streamtube cross

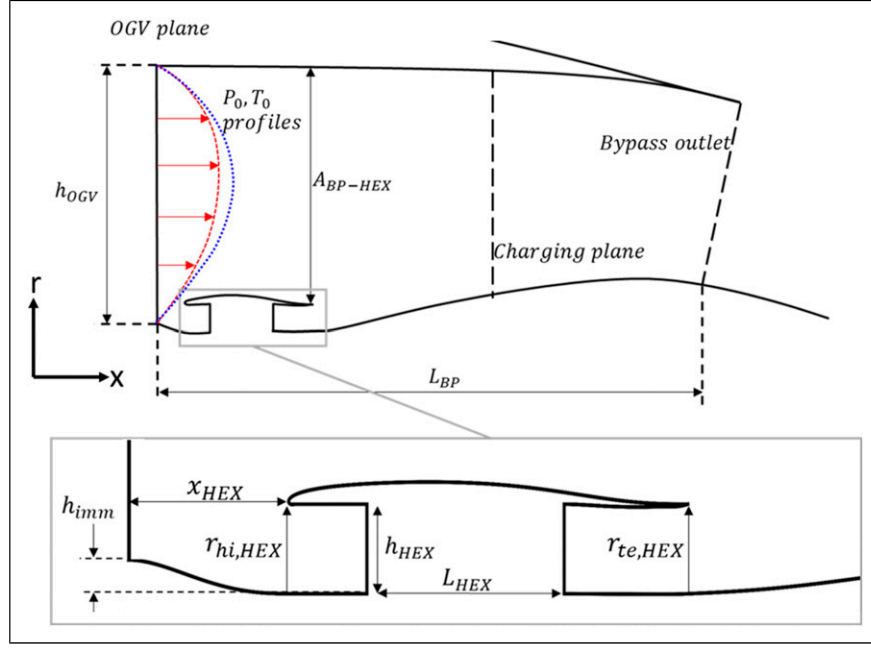


Figure 4. Schematic of exhaust domain with geometric parameters of embedded HEX system including representative P_0 (blue) and T_0 (red) non-uniform profile applied at the OGV exit plane.

section. The integration of the HEX into the bypass duct introduces a blockage effect which affects the mass flow within the bypass duct for the prescribed total pressure at the OGV exit plane. This is a numerical artefact of the computational method and is addressed to allow consistent comparisons between different HEX system configurations. This was achieved by using cycle-based values of mass flow, total pressure and total temperature for post-processing. The total pressure loss and total temperature rise between the OGV exit plane and the charging plane ($\Delta(P_0, T_0)^{OGV-cp}$) is applied to the cycle values at the OGV exit plane ($(P_0, T_0)^{OGV, cycle}$) to get corrected total pressure (P_0^{cp}) and total temperature (T_0^{cp}) at the charging plane (equation (4)). The value of $\Delta(P_0, T_0)^{OGV-cp}$ is defined as $(P_0, T_0)^{cp} - (P_0, T_0)^{OGV}$. The P_0^{cp} , T_0^{cp} , ideal gas constant (R) and the ratio of specific heats (γ) determine the corrected ideal velocity ($V_{ideal}^{cp, cycle}$) (equation (5)).

$$(P, T)_0^{cp} = (P, T)_0^{OGV, cycle} + \Delta(P, T)_0^{OGV-cp} \quad (4)$$

$$V_{ideal}^{cp, cycle} = \sqrt{\frac{2\gamma R T_0^{cp}}{\gamma - 1} \left(1 - \left(\frac{P_{s, \infty}}{P_0^{cp}} \right)^{\frac{\gamma-1}{\gamma}} \right)} \quad (5)$$

The cycle ideal propulsive force (IPF^{cycle}) is calculated from the cycle corrected ideal velocity ($V_{ideal}^{cp, cycle}$) (equation (6)). The velocity coefficient ($C_{v, cp}^\infty$) is defined as the ratio of the gross propulsive force (GPF) to the ideal propulsive force (IPF) (equation (7–9)). The net thrust (F_N) is determined from GPF^{cycle} , engine intake mass flow ($\dot{m}_{intk}^{cycle}$) and flight velocity (V_{flight}) (equation (10)).

$$IPF^{cycle} = \dot{m}_{bp}^{cycle} V_{ideal}^{cp, cycle} + \dot{m}_{core}^{cycle} V_{ideal}^{core} \quad (6)$$

$$C_{v, cp}^\infty = \frac{GPF}{IPF} \equiv \frac{F_G^\infty}{F_G^{ideal}} \quad (7)$$

$$GPF = F_G^\infty = \left(\overrightarrow{F_{bp}^{cp}} + \overrightarrow{F_{core}^{cp}} \right) - (\theta_{wall}^{bp} + \theta_{wall}^{core}) + \phi_{post} \quad (8)$$

$$IPF = F_G^{ideal} = \dot{m}_{bp}^{CFD} V_{ideal}^{cp} + \dot{m}_{core}^{CFD} V_{ideal}^{core} \quad (9)$$

$$F_N = F_{G^\infty} - F_{G0} = C_{v, cp}^\infty IPF^{cycle} - \dot{m}_{intk}^{cycle} V_{flight} \quad (10)$$

Operating conditions and performance metrics

The effect of the HEX integration on changes in net thrust is quantified at the two operating conditions of cruise and MTO. A loss in thrust is generally compensated for through an increase in the fuel flow rate to maintain a constant overall net thrust. This results in an increase in the engine fuel consumption at both cruise and MTO. The increased fuel flow rate at MTO conditions also leads to an increase in turbine entry temperature (TET) which can result in a decrease in turbine life.³⁴

At cruise, a freestream Mach number of 0.85 and a FNPR of 2.2 was identified for an UHBR engine with a bypass ratio of over 15.³⁵ Wolf et al.³⁶ detailed the engine operating conditions at MTO with a FNPR range of 1.3 and 1.4 for a UHBR engine operating within a Mach number range of 0 and 0.4. Nonuniform P_0 and T_0 profiles are applied at the OGV exit plane boundary and are based on typical fan stage aerodynamic studies (Figure 4). The non-dimensional circumferentially averaged radial distributions of total

pressure and temperature were kept fixed across both operating conditions. For each condition, the peak total pressure was scaled to achieve the required area-averaged FNPR, and the corresponding peak total temperature was adjusted accordingly. This approach preserves the characteristic profile distribution while allowing the boundary conditions to match the operating requirements of each case. Given that the purpose of this study is to demonstrate the overall methodology, this level of fidelity was considered appropriate.

The maximum heat transfer requirement for the HEX configurations in this study is at MTO conditions where the engine fan rotation speeds are highest. The value of heat transfer required at MTO used in the work presented in this paper is based on Nikolaidis et al.⁴ They used 0-D engine performance modelling tools and a gearbox efficiency to estimate that the heat transfer requirement at MTO for UHBR scale engines is 150 kW. The fan power for the UHBR engine at MTO and cruise conditions was determined through 0-D engine performance analysis. The fan power and the heat transfer requirement at MTO were used to estimate the efficiency of the power gearbox. The uncertainty in engine modelled parameters results in an estimated gearbox efficiency between 99.5% and 99.9%. This variation in the efficiency of an aero-engine planetary gearbox is considered to be reasonable as Anderson et al.³⁷ reported gearbox efficiencies ranging from 99.1% to 99.4% depending on the operating condition. This corresponds to a variation of 0.3% in gearbox efficiency. This is comparable to the 0.4% variation considered in the present work. For the subsequent analysis, a nominal gearbox efficiency of 99.7% is used, and the sensitivity to variations within this range is also explored.

The gearbox heat generation was estimated using a simplified loss model in which the thermal load was scaled with shaft power using the nominal gearbox efficiency. It is acknowledged that gearbox losses depend not only on rotational speed but also on torque, bearing loads and gear mesh friction. A detailed loss model would require component-level data and a dedicated gearbox model which is outside the scope of this work. However, for the purposes of the present system-level methodology demonstration, this simplified approach was considered sufficient to represent the order of magnitude of the thermal loads. Additionally, the clean-condition heat loads presented in this work do not explicitly include an additional margin for in-service fouling or gearbox efficiency degradation. These effects are expected to increase the required thermal capacity of the heat exchanger, and their inclusion forms an important component of ongoing work beyond the scope of the present parametric study.

Overall, a simplified power loss in the gearbox at cruise is estimated as the product of the gearbox efficiency and the cruise fan power to be 55 kW. Overall, these are approximate values of Q that are used in this study and are sufficient to establish the capabilities and sensitivities of the mixed fidelity HEX model.

Embedded HEX system configuration and geometric parameters

The main design parameters of interest are the length of the HEX (L_{HEX}), the height of the HEX (h_{HEX}), the radial immersion of the HEX into the bypass duct (h_{imm}), the axial position of the HEX (x_{HEX}) and the radial position of the HEX cowl trailing edge ($r_{te,HEX}$) (Figure 4). The five design parameters control the overall size of the HEX and the air mass flux through the HEX which affect the values of $\Delta(P_0, T_0)^{OGV-cp}$. The design parameters are perturbed in a full factorial manner to allow design sensitivity analysis. A single cowl design of sufficient thickness was selected that does not have any adverse flow features such as flow separation or shock formations along the HEX cowl at all operating conditions.

The internal heat-exchanger matrix geometry (including fin spacing, fin thickness, and strip-fin characteristics) is held fixed throughout this study. Variations in overall HEX size therefore correspond to changes in frontal area and flow-passage count rather than changes to fin or tube density. The baseline internal matrix geometry was selected using the optimisation stage of the heat-exchanger design tool described by Ryemill et al.¹⁶ In this design process, matrix performance correlations are first loaded from the database, after which the HEX thermal and aerodynamic behaviour is evaluated using an ϵ -NTU-based performance analysis. An iterative optimisation algorithm then explores candidate geometries and converges on a configuration that provides an appropriate balance of heat-transfer performance, pressure loss and compactness. This optimised matrix design is subsequently held constant while the external HEX dimensions and installation parameters are perturbed in the present study.

Overall, this section has elaborated the individual approaches that have been described in a reproducible manner in past papers. The individual methods have been coupled by enforcing conservation of mass, momentum and energy to build the naturally ventilated, embedded HEX system. The strategy for parametric geometry generation,^{17–19} exhaust aerodynamic analysis method,^{28,29} thrust-drag bookkeeping^{28,32} and the HEX modelling method^{30,31} have been detailed. Each method and the approach used to couple the methods together has been described which proves the viability of the system for similar studies to those presented in this paper.

Results and discussions

Effect of HEX size on F_N , Q and HEX volume

The additional heat dissipated by the naturally ventilated HEX system to the bypass flow increases the enthalpy within the bypass duct and leads to an improvement in thrust. However, the integration of the HEX with the

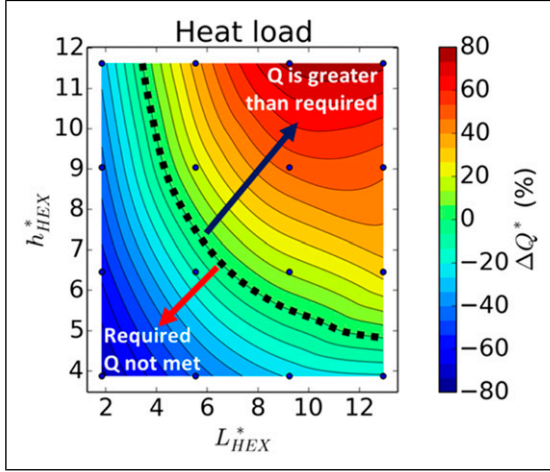


Figure 5. Map of HEX Q variation at MTO due to change in HEX size. Black dashed line represents design that exactly meet the HEX heat transfer requirement. Dots represent the HEX configurations that were analysed.

bypass duct also introduces losses in total pressure which has a detrimental impact on the engine thrust. There is a trade-off in the thermal contribution of the HEX and the aerodynamic effects of the HEX on engine thrust. The effect of variations in L_{HEX} and h_{HEX} on F_N , HEX Q and HEX volume were quantified at cruise and MTO to explore these trade-offs. Generally, only HEXs with specific values L_{HEX} and h_{HEX} will exactly meet the required HEX Q . However, these values are not known a priori. Therefore, perturbations in L_{HEX} and h_{HEX} are explored to identify the required values of these parameters and establish potential design trade-offs. A design sensitivity study enabled the identification of performance trends and design bounds within the HEX system design space (Figure 5). The relative size of the HEX is defined by the parameters $h_{HEX}^* = 100h_{HEX}/h_{OGV}$ and $L_{HEX}^* = 100L_{HEX}/L_{BP}$ which represent the HEX height and HEX length respectively. Non-dimensional HEX heat transfer rate (ΔQ^*) is quantified relative to the required heat transfer rate at the defined operating condition (equation (11)).

$$\Delta Q^*(\%) = \frac{100(Q - Q_{required})}{Q_{required}} \quad (11)$$

The dominant design bounds within the design space are obtained through comparisons of the thrust performance of the exhaust and the thermal performance of the HEX system at cruise and MTO. All explored HEX configurations met the Q requirement at cruise conditions (Figure 6). Fewest number of HEX designs meet the Q requirement at MTO. Therefore, the bound for Q at MTO conditions is identified as the dominant design bound for the configurations considered in this study.

The effect of the HEX size on the net thrust is quantified at cruise and MTO conditions (Figure 7). The non-dimensional change in net thrust ($\Delta F_N^*(\%)$) is quantified relative to the net thrust for a baseline engine without a HEX ($F_{N, clean}$) (equation (12)). As expected, the larger the HEX, the greater the loss in net thrust, albeit with also notable changes in Q . Overall, the ΔF_N^* and HEX Q can vary by up to 1% and 160% respectively across the $L_{HEX}^* - h_{HEX}^*$ design space. The total pressure loss across the HEX is the dominant contributor in ΔP_0^{OGV-cp} as it is two orders of magnitude higher than the total pressure loss in the HEX system intake duct, exhaust duct, cowl and any mixing losses. The only source of total temperature rise between the OGV exit plane and the charging plane is the mass weighted effect of total temperature rise across the HEX.

For the HEX configurations explored, the ΔP_0^{OGV-cp} is more sensitive to h_{HEX}^* than to L_{HEX}^* (Figure 8) (equation (13)). For a naturally ventilated HEX system, the sensitivity of total pressure loss to variations in L_{HEX} and h_{HEX} can be understood from the coupled dependence of HEX mass flow and frictional losses. Increasing L_{HEX} raises the frictional pressure loss within the matrix (equation (1)), but the associated reduction in total pressure at the HEX exit (station 4) lowers the driving pressure ratio for ventilation. This decreases $\dot{m}_{HEX}$, such that the increase in per-unit-mass pressure loss is largely offset by the reduced mass flux. Consequently, the mass-weighted contribution of the

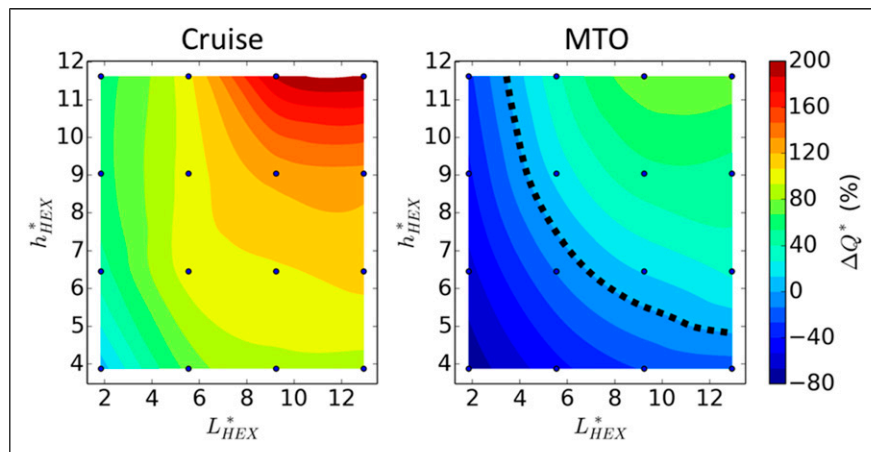


Figure 6. Variation in HEX Q due to change in HEX size at cruise and MTO.

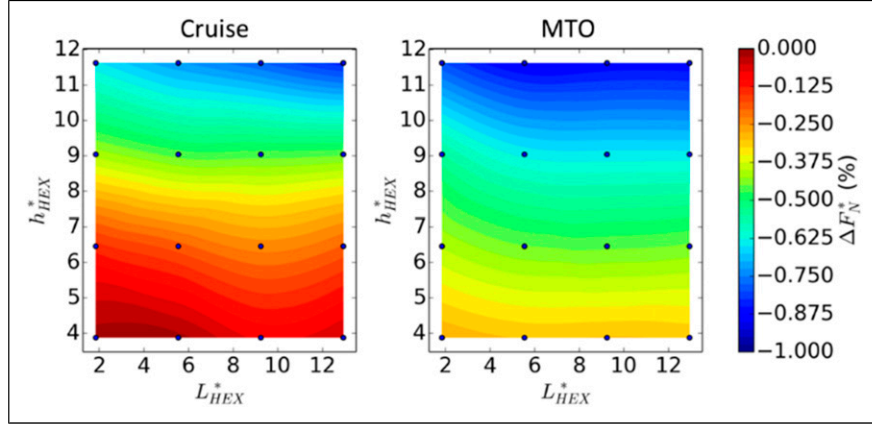


Figure 7. F_N^* map at cruise and MTO as a function of the change in HEX size.

HEX to the bypass-duct total pressure loss remains approximately constant as L_{HEX} varies at fixed h_{HEX} . In contrast, changes in h_{HEX} do not modify the internal frictional loss but directly scale the available flow area and therefore $\dot{m}_{HEX}$. Therefore the mass-weighted total pressure loss and the contribution of the HEX to the bypass-duct total pressure loss increases approximately in proportion to h_{HEX} . The small deviations from these trends across the design space arise from modest shifts in the local static pressure at station 4 as the external geometry of the HEX installation is varied (Figure 8).

The change in net thrust across the design space is mainly due to the ΔP_0^{OGV-cp} . For these examples, the variations in ΔT_0^{OGV-cp} is not large enough to have a significant effect on the change in net thrust (Figure 8) (equation (14)). This explains why an increase in HEX size results in an overall reduction in net thrust. Although both ΔP_0^{OGV-cp} and ΔT_0^{OGV-cp} increase, the magnitude of total pressure loss is significantly higher therefore it is the more dominant metric.

$$\Delta F_N^*(\%) = 100 \frac{F_N - F_{N, clean}}{F_{N, clean}} \quad (12)$$

$$\Delta P_0^{OGV-cp, *}(\%) = 100 \frac{P_0^{cp} - P_0^{OGV}}{P_0^{OGV}} \quad (13)$$

$$\Delta T_0^{OGV-cp, *}(\%) = 100 \frac{T_0^{cp} - T_0^{OGV}}{T_0^{OGV}} \quad (14)$$

The performance maps for loss in cruise net thrust and the distribution of MTO heat transfer across the design space are combined into a single map to identify the main design bounds within the design space (Figure 9). The map of change in net thrust at cruise with change in L_{HEX}^* and h_{HEX}^* determined in Figure 7 is superimposed with the HEX Q requirement bound that was identified in Figure 6. A design bound associated with the HEX intake separation is also identified. For a HEX with a given h_{HEX}^* , an increase in L_{HEX}^* causes the $\Delta P_{0, HEX}$ to increase and the $\dot{m}_{HEX}$ to decrease. The reduction in the $\dot{m}_{HEX}$ for a HEX with constant h_{HEX}^* leads to a reduction in the HEX intake mass flow capture ratio ($MFCR = A_{cs, OGV}/A_1$) (Figure 10). This is characterized by an increased diffusion of the streamtube entering the HEX. The increased streamtube diffusion results in a strong adverse pressure gradient at the HEX intake duct. Flow separates at the intake side of the HEX

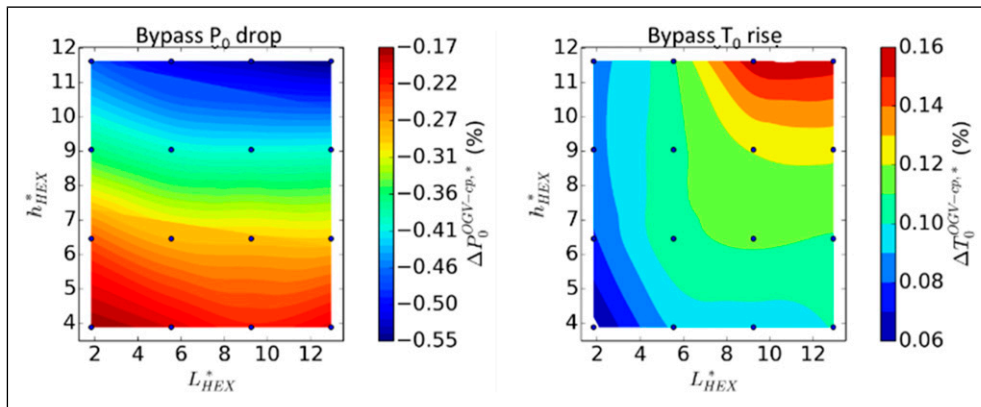


Figure 8. Map of cruise mass-averaged total pressure loss (left) and mass-averaged total temperature rise (right) between OGV exit plane and bypass duct charging plane with variations in HEX length and height.

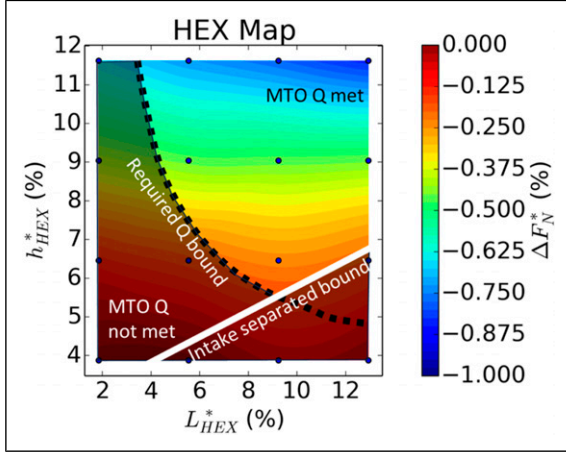


Figure 9. Contour map of F_N^* at cruise with design bounds for HEX Q at MTO and intake separation. Designs below the black dashed lines do not meet the Q requirement at MTO. Designs below the white line feature flow separation at the intake side.

due to this adverse pressure gradient (Figure 10). This combined performance map with superimposed design bounds highlights the regions of the design space that contain HEX configurations that meet the Q requirement at all operating conditions and do not have intake separation. This type of performance maps can be used to identify feasibility bounds in terms of the key HEX design parameters to aid during preliminary design processes.

The general design trend is to make a HEX with low h_{HEX}^* and high L_{HEX}^* if the aim is only to minimise thrust loss and to meet the heat transfer requirement. However, the volume of the HEX should also be taken into consideration during the design process to minimise the potential penalties associated with the practical aspects of HEX integration due to architectural and spatial constraints. The volume of the HEX is reported non-dimensionally relative to the volume of the HEX at the middle of the $L_{HEX}^* - h_{HEX}^*$ design space (equation (15)). The Vol_{HEX}^* is the HEX non-dimensional volume and Vol_{HEX} is the HEX volume per unit azimuth. The

parameters $L_{HEX,avg}^*$ and $h_{HEX,avg}^*$ are the median values of L_{HEX}^* and h_{HEX}^* within the design space. HEX configurations with low L_{HEX}^* and high h_{HEX}^* meet the HEX Q requirements while minimising the HEX volume (Figure 11).

$$Vol_{HEX}^* = \frac{Vol_{HEX}}{L_{HEX,avg}^* h_{HEX,avg}^*}, L_{HEX,avg}^* = 7.4, h_{HEX,avg}^* = 7.8 \quad (15)$$

The HEX system configurations that minimise thrust loss and HEX volume while meeting the heat transfer requirement is a balance between L_{HEX}^* and h_{HEX}^* . HEX systems designs that meet the Q requirement and have a high h_{HEX}^* generally have a larger loss in net thrust (Figure 9) while configurations with high L_{HEX}^* typically have a large volume (Figure 11). A single HEX system design can be downselected from all HEX configurations that exactly meet the Q requirement. The downselection method can vary as it is subjective and is dependent on design requirements and constraints. The downselection criteria applied for this study is based on the rate of change of net thrust with respect to the change in HEX volume ($d\Delta|F_N^*|/dVol_{HEX}^*$). Designs that have a $d\Delta|F_N^*|/dVol_{HEX}^* = 1$ are downselected in this work. This is because designs with values of $d\Delta|F_N^*|/dVol_{HEX}^*$ greater than 1 generally have a larger thrust loss for a small benefit in HEX size compared to designs with $d\Delta|F_N^*|/dVol_{HEX}^* = 1$. The opposite is true for configurations with $d\Delta|F_N^*|/dVol_{HEX}^*$ less than 1 where a small benefit in thrust is traded for a large increase in HEX size.

Overall, while the predicted thrust losses associated with HEX integration are relatively small for this example, this information was not available a priori. The presented coupled mixed-fidelity method can rapidly perform performance analyses to identify the required HEX size. This reduces the possibility of the HEX being oversized and causing significant exhaust performance deterioration or being undersized and not meeting the required Q.

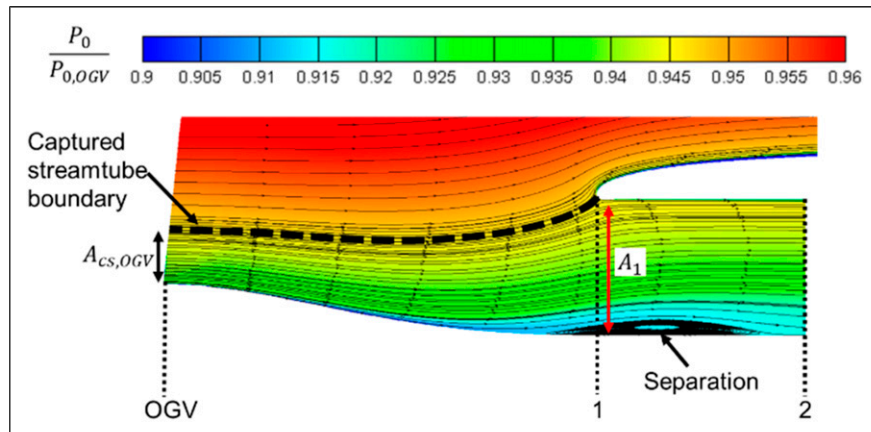


Figure 10. Total pressure contour between OGV exit plane and HEX inlet with separated flow.

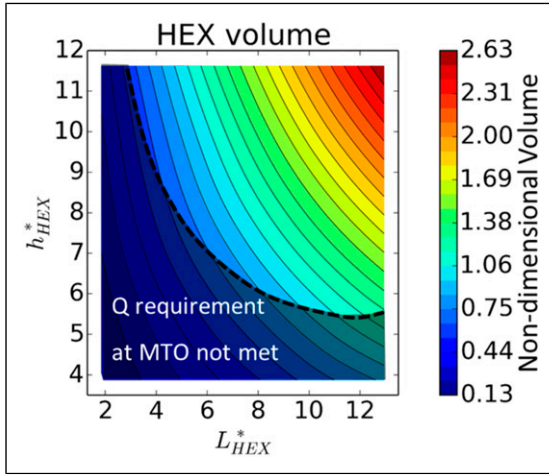


Figure 11. Map of HEX volume as a function of L_{HEX}^* and h_{HEX}^* with the HEX Q design bound at MTO.

Effect of gearbox efficiency on performance trade

The efficiency of the power gearbox was estimated to be within a range of 99.5% and 99.9%. A decrease in the gearbox efficiency from 99.9% to 99.5% results in an increase in the Q requirement at MTO by a factor of 5 (Figure 12). This necessitates an increase in the size of the HEX which leads to an increase in ΔP_0^{OGV-cp} . This results in a decrease in ΔF_N^* by up to 0.6% for the configurations explored in this study. The volume of the HEX required for the gearbox also increases by a factor of 10. This highlights the sensitivity of the HEX system and the bypass duct performance to the gearbox efficiency.

Effect of HEX system radial immersion

One method to reduce total pressure loss across a given HEX is to reduce the air mass flux through the HEX (G) while still meeting the Q requirement (equation (4)). A reduction in the $\dot{m}_{HEX}$ for a given HEX design achieves a reduced G and leads to an increase in $\Delta T_{0,HEX}$ (equation (5)). The reduced value of $\dot{m}_{HEX}$ is compensated for by the increase in $\Delta T_{0,HEX}$ leading to similar values of HEX Q at both high and low $\dot{m}_{HEX}$. The mass flux through the HEX in a naturally ventilated configuration depends on the ratio between the inlet total pressure at station 1 (P_0^1) and the exit static pressure at station 4 (p_s^4) of the HEX system. This pressure ratio can be controlled by changing the static pressure at the HEX cowl trailing edge. The pressure ratio and hence the HEX mass flux is likely to be dependent on the radial immersion (h_{imm}) of the HEX system into the bypass duct (Figure 4). This is because varying the radial immersion of the HEX alters the flow area in the bypass duct which directly affects the pressure field within the bypass duct.

A reduction in the HEX system radial immersion ($h_{imm}^* = h_{imm}/h_{OGV}$) from $h_{imm}^* = 0.0$ to -0.025 results in an improvement in cruise net thrust by up to 0.1% (Figure 13). This is because the static pressure at the outlet of the HEX system (p_s^4) has increased leading to a

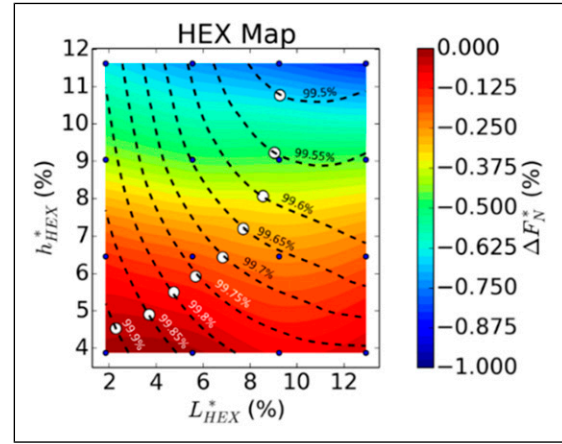


Figure 12. Change in HEX Q boundary at MTO and variation in the downselected design due to the change in HEX efficiency. Dashed lines represent the Q boundaries at MTO and white circles are downselected designs.

reduction in HEX mass flow and therefore a reduction in the total pressure loss between the OGV and the charging plane (ΔP_0^{OGV-cp}). This translates to an improvement in net thrust. The increased curvature of the embedded HEX system intake duct for configurations with reduced immersion into the bypass duct causes the intake flow separation boundary to deteriorate. The HEX Q bound is not significantly affected by HEX radial immersion.

A reduction in the radial immersion of the HEX system into the bypass duct from $h_{imm}^* = 0$ to $h_{imm}^* = -0.015$ results in an improvement in the trade-off between net thrust and HEX volume. This indicates that the total pressure loss across the HEX has decreased due to the change in the static pressure field within the bypass duct caused by the reduction of the radial immersion. An intake separation boundary for configurations with no radial immersion ($h_{imm}^* = 0.0$) is identified. A reduction in h_{imm}^* to -0.015 for the downselected designs results in a 0.07% benefit in net thrust at cruise while still meeting the HEX Q requirement. However, the HEX volume increases by 1-2%. There was no significant thrust benefit in a further reduction of h_{imm}^* to -0.025 . The HEX volume of the downselected design at $h_{imm}^* = -0.025$ increased by 4% relative to the $h_{imm}^* = 0.0$ design.

Effect of HEX system axial position and radial immersions

The static pressure field within the bypass duct varies in the axial direction due to the variation in the flow area of the bypass duct. Perturbation of the axial position of the HEX within the bypass duct will result in a change in the static pressure at station 4 (Figure 4). Although the changes in exit static pressure at station 4 can be relatively small for the naturally ventilated HEX system the resulting variation in the pressure ratio across the HEX system impacts the $\dot{m}_{HEX}$. Understanding the combined effects of perturbations in the HEX system axial ($x_{HEX}^* = x_{HEX}/L_{BP}$) and

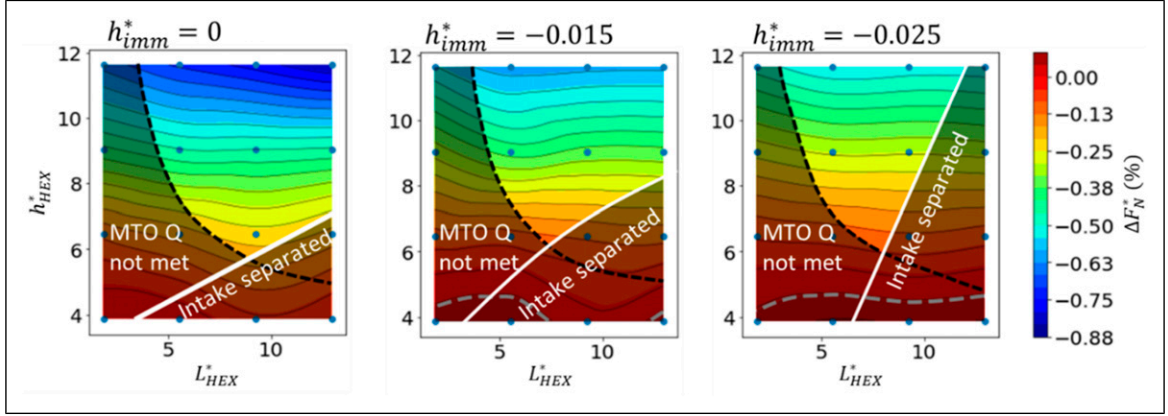


Figure 13. Cruise thrust maps with design bounds at different HEX radial immersions.

radial ($h_{imm}^* = h_{imm}/h_{OGV}$) position on the net thrust at cruise and HEX Q at MTO can be used to develop preliminary design guidelines for HEX integration within the bypass duct. The value of x_{HEX}^* was varied from 0.075 to 0.30 in increments of 0.075. The effect of a change in the x_{HEX}^* on the F_N^* at cruise and Q at MTO was evaluated at two different radial positions of $h_{imm}^* = 0$ and -0.025 . Generally, an increase in x_{HEX}^* and a reduction in the h_{imm}^* results in a significant benefit in net thrust (Figure 14). The baseline configuration with $x_{HEX}^* = 0.075$, $h_{imm}^* = 0.0$ is compared with the updated configuration of $x_{HEX}^* = 0.3$, $h_{imm}^* = -0.025$. There is a 0.3-0.6% benefit in cruise thrust across the design space for updated HEX system configuration relative to the baseline configuration. The intake separation bound is significantly deteriorated for the updated HEX system configurations. There is no significant change in the HEX Q boundary in the design space of the two configurations.

The bypass duct is diffusing between x_{HEX}^* of 0.075 and 0.3 which leads to an increase in p_s^4 as x_{HEX}^* increases

without any significant effect on P_0^1 . This results in a decrease in $\dot{m}_{HEX}$ as x_{HEX}^* increases. A reduction in $\dot{m}_{HEX}$ reduces the HEX MFCR but improves the thrust performance of the system with no significant effect on the HEX Q bound for the HEX system configurations explored in this paper. The low values of HEX MFCR results in flow separation within the diffusing streamtube upstream of the HEX intake duct. Therefore, the HEX intake separation bound within the design space deteriorates as x_{HEX}^* increases. This section has demonstrated the capabilities of the coupled, mixed fidelity method to rapidly analyse HEX system geometries to identify performance trends for naturally ventilated HEX systems.

At all axial positions a reduction in the HEX system radial immersion into the bypass duct generally improved net thrust but also increased the overall HEX size (Figure 15). For example, a benefit of 0.1% in F_N^* is achieved for the downselected design at $x_{HEX}^* = 0.075$ as h_{imm}^* is reduced from 0.0 to -0.025 . The HEX volume increase is insignificant at 3%. A similar analysis at

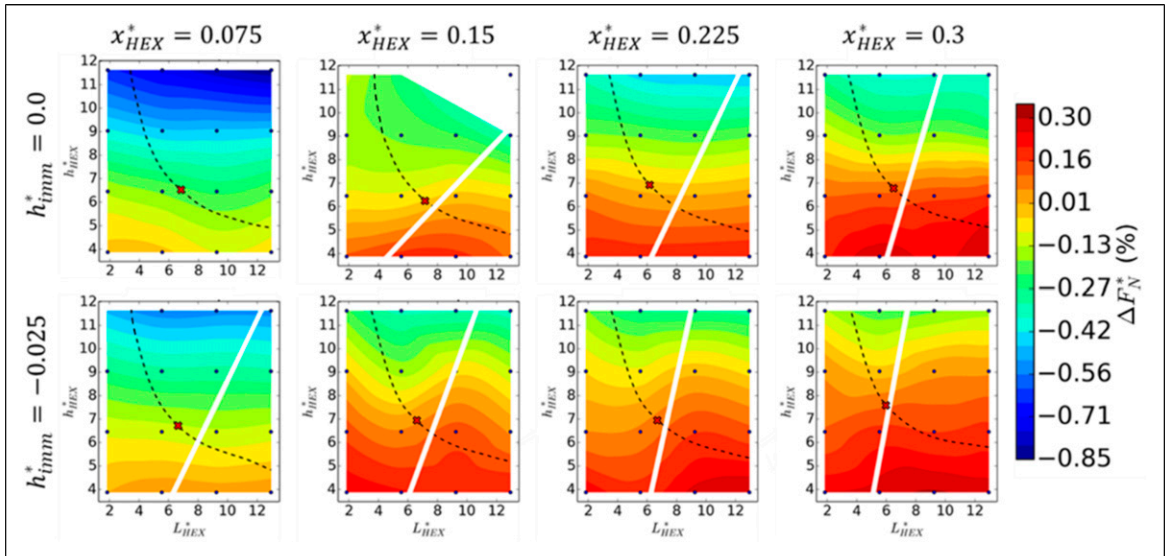


Figure 14. Variations in the cruise thrust performance maps, MTO Q boundaries and intake separation bound due to changes in x_{HEX}^* and h_{imm}^* . The “x” markers define the downselected HEX design in each design space.

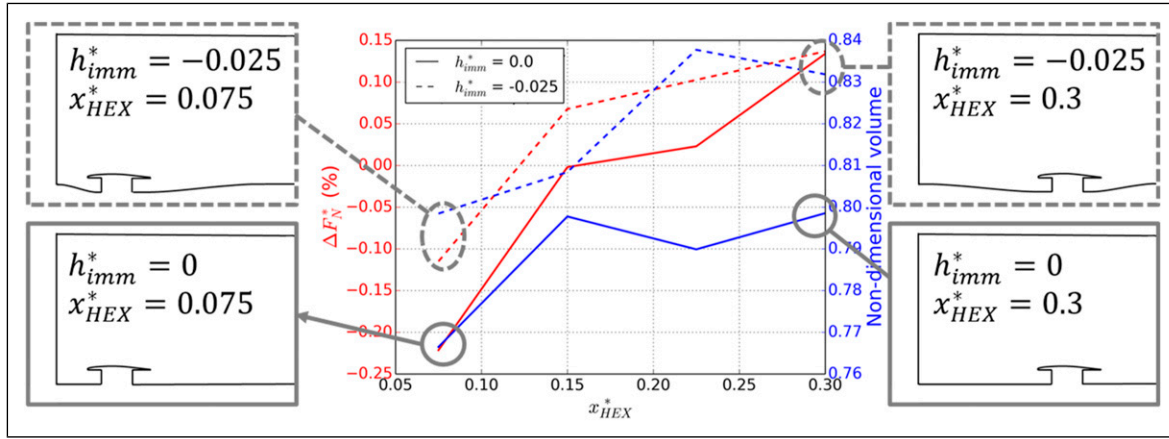


Figure 15. Trade-off between net thrust at cruise and HEX volume with changes in performance of the downselected HEX system designs due to variations in x_{HEX}^* and h_{imm}^* .

$x_{HEX}^* = 0.3$ reveals that the downselected design has no significant benefit in F_N^* as h_{imm}^* is reduced from 0.0 to -0.025 . However, moving the HEX from $x_{HEX}^* = 0.075$ to $x_{HEX}^* = 0.3$ at a constant h_{imm}^* of 0.0 improves the net thrust by 0.35%. This corresponds to a 200N in absolute net thrust for a UHBR scale engine with a nominal standard net thrust of 60 kN.²⁸ Without the mixed fidelity method, the HEX integrated into the bypass duct could have been located at a position where the deterioration in net thrust is as high as 0.7%. Or a design could have been chosen with a high value of net thrust without realizing that those designs have separated flow at the intake.

HEX system trailing edge and axial position

The radial position of the trailing edge of the HEX cowl ($r_{te,HEX}^* = (r_{te,HEX} - r_{hi,HEX})/h_{OGV}$) controls the throat area at the HEX system station 4 (Figure 4). It is expected that an increase in $r_{te,HEX}^*$ will increase the $\dot{m}_{HEX}$ and the Q through the HEX and therefore enable designs of more compact HEX systems with smaller volumes. Conversely, a reduction in $r_{te,HEX}^*$ will decrease the mass flow through

the HEX leading to a reduction in the $\Delta P_{0,HEX}$ which can result in an improvement in the thrust performance without significantly impacting the heat transfer rate. For this study, the radial immersion of the HEX system was maintained at $h_{imm}^* = 0.0$.

The value of x_{HEX}^* has been perturbed in the same manner as introduced in section 3.4. The effect of changes in $r_{te,HEX}^*$ is quantified at three different positions of $r_{te,HEX}^* = 0.025, 0.00, -0.015$. An increase in x_{HEX}^* resulted in downselected HEX system configurations with monotonic improvement in net thrust (Figure 16). Conversely, an increase in $r_{te,HEX}^*$ to a value of 0.025 generally leads to a deterioration in net thrust across all values of x_{HEX}^* . This is because the increase in the radial position of the HEX cowl trailing edge increases the overall HEX air-side flow area at station 4. For this ventilated HEX system, this results in an increase in mass flow through the HEX. Increase in the HEX mass flow results in an increase in the total pressure loss across the HEX and leads to a deterioration in net thrust. The value of net thrust for the designs could vary by up to 0.7% within this design space. The volume

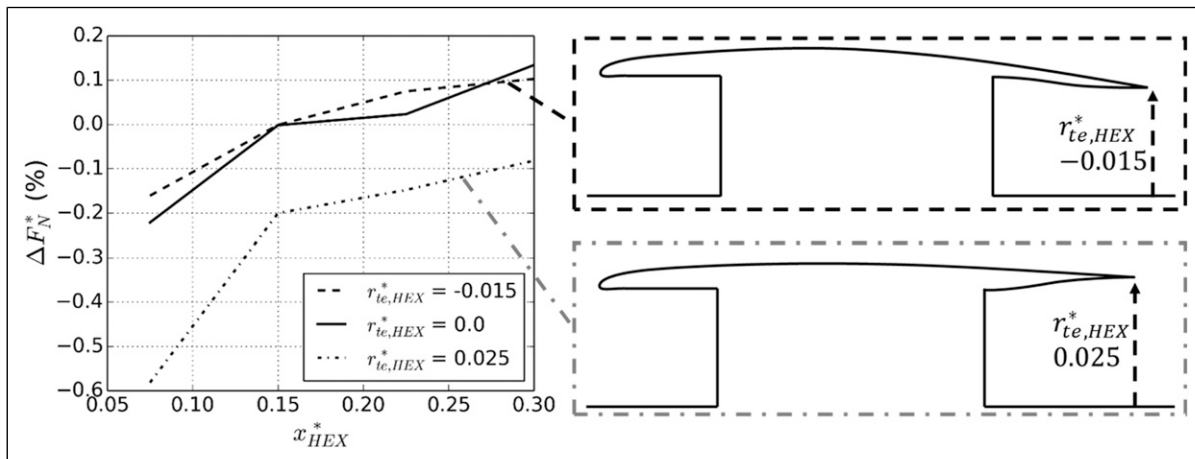


Figure 16. Change in cruise thrust of the downselected HEX system designs as a function of x_{HEX}^* and $r_{te,HEX}^*$.

of the downselected HEX changes by 4% as $r_{te,HEX}^*$ is varied therefore it is not significant. Overall, for this study the HEX system configuration with $x_{HEX}^* = 0.3$ and $r_{te,HEX}^* = 0.0$ is the design that minimizes thrust loss while meeting the Q requirement with attached flow at the HEX intake. The capability of the mixed fidelity HEX modelling method to quantify the performance of the HEX and the bypass has been demonstrated for a large range of HEX system design spaces.

Conclusions

The novelty of this work is the demonstration a robust mixed fidelity method that can be used to systematically explore the effects of integration of a HEX with the bypass duct of a future large UHBR aero-engine. This method enables the evaluation of the sensitivity to the change in design and integration of the HEX in terms of the effect on performance parameters such as net thrust, HEX heat transfer and HEX volume. The performance of the HEX and the bypass is evaluated at cruise and maximum take-off operating conditions. Typically, the effect of HEX integration on net thrust is of interest at cruise while the HEX heat transfer rate is of more importance at the MTO condition. The contribution of the paper is that for the first time the design space of the dominant HEX design parameters is explored to quantify the trade-off in the HEX size, HEX performance and engine performance in terms of HEX heat transfer rate and net thrust. Additionally, a new design and integration limitation associated with pre-diffusion flow separation at the intake side of the HEX system has been identified. This can be used to develop guidelines for the design and integration of HEX systems for future UHBR aero-engines.

Beyond mapping design sensitivities, this study has also clarified the physical mechanisms governing how the embedded HEX influences exhaust-system performance. The trends observed across the design space were shown to arise from a balance between frictional pressure losses within the HEX matrix, the installation-induced modification of the local static-pressure field, and the resulting changes in naturally ventilated HEX mass flux. In particular, increases in HEX length amplify frictional losses but simultaneously reduce the driving pressure ratio, leading to reduced mass flux and an almost constant mass-weighted pressure loss. Variations in HEX height directly scale the mass flow and therefore the total-pressure loss contribution. The onset of intake flow separation was found to be driven by excessive pre-diffusion of the streamtube approaching the HEX, creating an adverse pressure gradient that the boundary layer cannot withstand. Finally, axial and radial placement, as well as the cowl trailing-edge position, were shown to control whether local passages behave in a diffusing or accelerating manner—strongly influencing pressure recovery and thus net thrust.

The impact of the paper is that the design guidelines and trade-off maps can be used to quantify the HEX system

design space and identify potential designs that could improve the performance of the future UHBR engines. For all HEX configurations explored in this paper that meet the Q requirement, the integration of the HEX can affect the value of net thrust at cruise by up to 0.7%. Overall, the capabilities of the mixed fidelity method for modelling the performance of a HEX coupled with the bypass duct has been demonstrated. This mixed-fidelity method can be used to conduct rapid design assessments for embedded HEX systems.

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Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The author is partially funded by the UK Research and Innovation Engineering and Physical Sciences Research Council (EPSRC) under project reference 2268554. Abdessemed was partially funded by UK Research and Innovation under project reference 113263.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

1. Cao H, Zhou ZG and Ye XL. Aerodynamic characteristic comparison of ultra-highly and normally loaded fans. *Aeronaut J* 2021; 125(1293): 2021–2038. <https://doi.org/10.1017/aer.2021.64>
2. Larsson L, Gronstedt T and Kyprianidis KG. Conceptual design and mission analysis for a geared turbofan and an open rotor configuration. *Proceedings of the ASME Turbo Expo: Power for Land, Sea, and Air* 2011; 54617: 359–370. <https://doi.org/10.1115/GT2011-46451>
3. Kyprianidis KG, Gronstedt T, Ogaji SOT, et al. Assessment of future aero-engine designs with intercooled and inter-cooled recuperated cores. *J Eng Gas Turbines Power* 2011; 133(1): 011701. <https://doi.org/10.1115/1.4001982>
4. Nikolaidis T, Jafari S, Bosak D, et al. Exchange rate analysis for ultra high bypass ratio geared turbofan engines. *Appl Sci* 2020; 10(21): 7945. <https://doi.org/10.3390/app10217945>
5. Li H, Huang H, Xu G, et al. Performance analysis of a novel compact air–air heat exchanger for aircraft gas turbine engine using LMTD method. *Appl Therm Eng* 2017; 116: 445–455. <https://doi.org/10.1016/j.applthermaleng.2017.01.003>
6. Kim J, Sibilli T, Ha MY, et al. Compound porous media model for simulation of flat top U-tube compact heat exchanger. *Int J Heat Mass Tran* 2019; 138: 1029–1041. <https://doi.org/10.1016/j.ijheatmasstransfer.2019.04.116>
7. Zhao X and Grönstedt T. Conceptual design of a two-pass cross-flow aeroengine intercooler. *Proc Inst Mech Eng G J Aerosp Eng* 2015; 229(11): 2006–2023. <https://doi.org/10.1177/0954410014563587>

8. Zhao X, Gronstedt T and Kyprianidis K. Assessment of the performance potential for a two-pass cross-flow intercooler for aero engine applications. In: *Proceedings of ISABE 2013*; Busan, 2013. Paper ISABE-2013-1215.
9. Zhao X, Tokarev M, Hartono EA, et al. Experimental validation of the aerodynamic characteristics of an aero-engine intercooler. *J Eng Gas Turbines Power* 2017; 139(5). <https://doi.org/10.1115/1.4034964>
10. Missirlis D, Donnerhack S, Seite O, et al. Numerical development of a heat transfer and pressure drop porosity model for a heat exchanger for aero engine applications. *Appl Therm Eng* 2010; 30(11–12): 1341–1350. <https://doi.org/10.1016/j.applthermaleng.2010.02.021>
11. Pandey S, Kallath H, Choi HY, et al. Numerical study of the effect of flow nonuniformities on the low-pressure side of a cooled cooling air heat exchanger. *Appl Therm Eng* 2022; 217: 119113. <https://doi.org/10.1016/j.applthermaleng>
12. Kallath H, Kohli FK, Jin Q, et al. Numerical study of the flow uniformity inside the high-pressure side manifolds of a cooled cooling air heat exchanger. *Appl Therm Eng* 2021; 189: 116645. <https://doi.org/10.1016/j.applthermaleng.2021.116645>
13. Tokarski M, Ryfa A, Bulinski P, et al. Experimental analysis and development of an in-house CFD condensation hood model. *Heat Mass Tran* 2022; 58(2): 321–336. <https://doi.org/10.1007/s00231-021-03109-7>
14. Goulos I, Stankowski T, MacManus D, et al. Civil turbofan engine exhaust aerodynamics: impact of bypass nozzle afterbody design. *Aero Sci Technol* 2018; 73: 85–95. <https://doi.org/10.1016/j.ast.2017.09.002>
15. Bajimaya R, MacManus D, Abdessemed C, et al. Heat exchanger integration with an aero-engine bypass duct. *Proceedings of the Aerospace Europe Conference (EU-CASS/CEAS)*. EUCASS, 2023.
16. Ryemill M, Bewick C and Min JK. *The rolls-royce PLC UltraFan heat management challenge*. *Proceedings of the 30th ICAS Congress*. ICAS, 2016. Paper ICAS 2016_0344.
17. Goulos I, Stankowski T, Otter J, et al. Aerodynamic design of separate-jet exhausts for future civil aero-engines, part 1: parametric geometry definition and CFD approach. *J Eng Gas Turbines Power* 2016; 138(8): 081201. <https://doi.org/10.1115/1.4032649>
18. Goulos I, Otter J, Stankowski T, et al. Aerodynamic design of separate-jet exhausts for future civil aero-engines, part 2: surrogate modeling and optimization. *J Eng Gas Turbines Power* 2016; 138(8): 081202. <https://doi.org/10.1115/1.4032652>
19. Goulos I, Otter J, Stankowski T, et al. Design optimisation of separate-jet exhausts for the next generation of civil aero-engines. *Aeronaut J* 2018; 122(1256): 1586–1605. <https://doi.org/10.1017/aer.2018.95>
20. Benini E and Mistry CS, and Wadia AR. *Historical developments in fan technologies for aeroengines*. *Proceedings of the ASME Turbo Expo 2023*. ASME, 2023. Paper GT2023-101639. <https://doi.org/10.1115/GT2023-101639>
21. Zhu F. *Geometric parameterisation and aerodynamic shape optimisation [phD thesis]*. : University of Sheffield, 2014.
22. Lane KA and Marshall DD. *Inverse airfoil design utilizing CST parameterization*. 48th AIAA Aerospace Sciences Meeting. AIAA, 2010, pp. 1–14. <https://doi.org/10.2514/6.2010-1228>
23. Christie R, Heidebrecht A and MacManus D. An automated approach to nacelle parameterization using intuitive class shape transformation curves. *J Eng Gas Turbines Power* 2017; 139: 1–9. <https://doi.org/10.1115/1.4035283>
24. Christie R, Robinson M, Tejero F, et al. The use of hybrid intuitive class shape transformation curves in aerodynamic design. *Aero Sci Technol* 2019; 95: 1–13. <https://doi.org/10.1016/j.ast.2019.105473>
25. Sobieczky H. Parametric airfoils and wing. *Notes on Numerical Fluid Mechanics*. Vieweg Verlag, 1999, vol 68, pp. 71–87. https://doi.org/10.1007/978-3-322-89952-1_4
26. Roache PJ. Perspective: a method for uniform reporting of grid refinement studies. *J Fluid Eng* 1994; 116(3): 405–413. <https://doi.org/10.1115/1.2910291>
27. Menter FT. Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA J* 1994; 32: 1598–1605. <https://doi.org/10.2514/3.12149>
28. Goulos I, Otter J, Tejero F, et al. Civil turbofan propulsion aerodynamics: thrust-drag accounting and impact of engine installation position. *Aero Sci Technol* 2021; 111: 106533. <https://doi.org/10.1016/j.ast.2021.106533>
29. Otter J, Goulos I, MacManus DG, et al. Aerodynamic analysis of civil aero-engine exhaust systems using computational fluid dynamics. *J Propul Power* 2018; 34(5): 1152–1165. <https://doi.org/10.2514/1.b36867>
30. Manglik RM and Bergles AE. Heat transfer and pressure drop correlations for the rectangular offset strip fin compact heat exchanger. *Exp Therm Fluid Sci* 1995; 10(2): 171–180. [https://doi.org/10.1016/0894-1777\(94\)00096-Q](https://doi.org/10.1016/0894-1777(94)00096-Q)
31. MIL-PRF-23699F. Performance specification: lubricating oil, aircraft turbine engine. *Synthetic base (NATO code O-156)*. United States DoD, 1997.
32. Lee K, Kim M, Ha MH, et al. Investigation of heat-exchanger-sizing methods using genetic, pattern search, and simulated annealing algorithms and the effect of entropy generation. *J Mech Sci Technol* 2018; 32(2): 915–928. <https://doi.org/10.1007/s12206-018-0142-0>
33. MIDAP Study Group. *Guide to in-flight thrust measurement of turbojets and fan engines*. AGARD-AG-, 1979, vol 237.
34. Cumpsty NA. Turbine inlet temperature. *Jet propulsion: A simple guide to the aerodynamic and thermodynamic design and performance of jet engines*. Cambridge University Press, 2015, p. 65. <https://doi.org/10.1017/CBO9781316223116>
35. Giangaspero G, MacManus D and Goulos I. Surrogate models for the prediction of the aerodynamic performance of exhaust systems. *Aero Sci Technol* 2019; 92: 77–90. <https://doi.org/10.1016/j.ast.2019.05.027>
36. de Wolf WB. *Possibilities and limitations of VHBR and UHBR turbofan simulations in engine/airframe integration wind tunnel experiments*. National Aerospace Laboratory NLR, 1996. NLR TP 96028 U.
37. Anderson NE, Cedoz RW, Salama EE, et al. Advanced gearbox technology final report. NASA-CR-179625; NASA Lewis Research Center, 1987. EDR12909.

Appendix

Nomenclature

Abbreviations

AOHE	Air-to-oil heat exchanger
CFD	Computational Fluid Dynamics
cp	Charging plane
CST	Class-Shape Transformation
FNPR	Fan Nozzle Pressure Ratio
GCI	Grid Convergence Index
GPF	Gross Propulsive Force
HEX	Heat Exchanger
IPF	Ideal Propulsive Force
MFCR	Mass Flow Capture Ratio
MTO	Maximum Take-Off
OGV	Outlet Guide Vanes
RANS	Reynolds Averaged Navier Stokes
TDB	Thrust-Drag Bookkeeping
UHBR	Ultra-High Bypass Ratio.

Greek and roman symbols

A	Area
F_N	Net thrust
G	Mass flux
h_{HEX}	HEX height
h_{imm}	HEX radial immersion
h	Heat transfer coefficient
j	Colborn j factor
l	Fin length
L_{HEX}	HEX length
M	Mach number

$\dot{m}$	Mass flow rate
P_0	Total pressure
p_s	Static pressure
Q	Heat transfer rate
$r_{te, HEX}$	HEX cowl trailing edge radial position
s	Fin spacing
t	Fin thickness
T_0	Total temperature
T_s	Static temperature
x_{HEX}	Axial position of HEX system
ε	HEX effectiveness
θ	Related to thrust domain
ρ	Fluid density
ϕ	Related to drag domain.

Subscripts and superscripts

$(-)_{HEX}$	Associated with HEX
$(-)_{BP}$	Associated with bypass
$(-)_{core}$	Associated with core flow
$(-)_{ht}$	Heat transfer
$(-)_{\infty}$	At freestream
$(-)_f$	Of HEX fins
$(-)^{i-j}$	Between stations i and j
$(-)^*$	Nondimensionalised
$(-)^{cycle}$	Based on cycle values
$(-)_{clean}$	For engines without embedded HEX
$(-)_{wall}$	At walls
$(-)_{post}$	Post-exit terms
$(-)_{ideal}$	At ideal conditions
$(-)_{required}$	Required value
$(-)_{te, HEX}$	At HEX cowl trailing edge.



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2026-12-31

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<https://doi.org/10.1177/09544100261434428>

Bajimaya R, MacManus D, Abdessemed C, et al., (2026) Heat exchanger integration with an aero-engine bypass duct. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, Available online 13 May 2026