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THE ROLLS-ROYCE PLC ULTRAFAN HEAT MANAGEMENT CHALLENGE

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Abstract

This paper describes the design challenges faced in defining the heat management system for the Rolls-Royce plc UltraFan™ gas turbine engine design and explores how new technologies and Systems Engineering can enable a step change in system heat management performance to be achieved at the same time as reducing environmental impact.

2 Background

Over the past 30 years passenger demand for air travel has grown at an average of 5% per annum, with the expectation that future demand will continue to grow. The future is also a place where passengers, airlines and governments want to see air transport grow, but grow responsibly, with a commitment to minimising environmental impact.

Future scenarios of air transport assume propulsion systems with increasing efficiency and reliability coupled with reducing environmental emissions and cost of ownership.

To meet these demands for future propulsion systems, Rolls-Royce has introduced the UltraFan™ engine, a geared, high thrust, high bypass ratio engine at least 25% more fuel efficient than the first generation of Rolls-Royce Trent engines, Figure 1.

3 UltraFan™

The UltraFan™ builds on the core architecture and technologies of the Advance engine concept with the incorporation of a geared IP and low pressure ratio Fan system, both are described in [1 and 2].

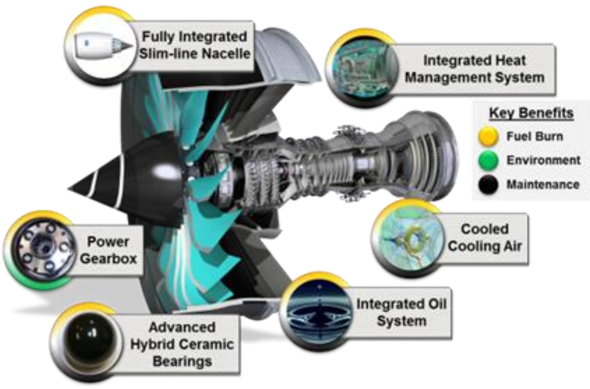


Figure 1, Rolls-Royce plc UltraFan™

The UltraFan™ design presents a new challenge for the heat management systems employed by the engine. The geared design features a high power density power gearbox, low specific thrust Fan system and high efficiency core operating at increased temperatures. These increase powerplant heat loads relative to previous generations of engines, whilst the incorporation of lean burn fuel systems limit the heat sink capability of the fuel system, the traditional sink for heat management (HM) systems.

The UltraFan™ architecture is also destined to be adopted by a family of engines sharing a common architecture, so there is a requirement for the HM system to be scalable from middle of the market sized applications through to the largest twin engine applications resulting in a wide range of heat loads to be managed.

The enabling technologies required for UltraFan™ will be comprehensively demonstrated, both in previously described technology programmes [1 and 2] and in a dedicated UltraFan™ demonstrator engine (UFD). In addition the Rolls-Royce University Technology Centre (UTC) network continues to develop key technologies and capabilities for future UltraFan™ engines, in alignment with the Rolls-Royce policy of continual product improvement and technology insertion.

4 Gas Turbine Heat Management Systems

Typically in large turbofan engines the HM system utilises several working fluids (air, oil and fuel) to collect and transport heat from heat generating sources and reject this heat into a suitable sink, usually the fuel system, with the aim of minimising heat lost to the engine cycle. As heat loads have increased with higher cycle temperatures supplementary air cooling has also been required. Each generation of engine has faced an ever more difficult task to efficiently manage heat loads, retaining as much heat in the cycle as possible. The UltraFan™ presents further complexity due to a significant increase in heat load from the power gearbox and an engine cycle more sensitive to pressure losses in the bypass duct. The challenge for the UltraFan™ heat management system is to manage a significantly increased engine heat load whilst also minimising environmental impact, Figure 2.

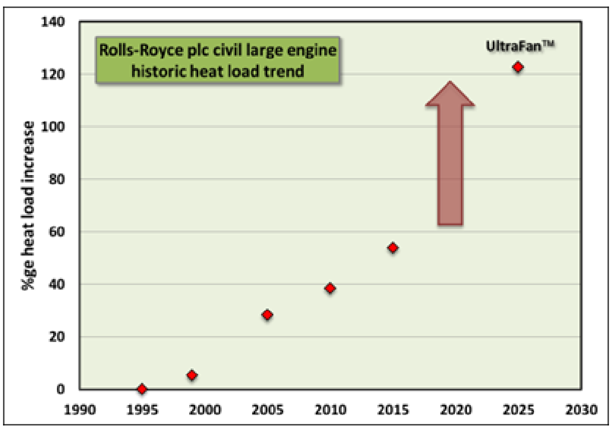


Figure 2, Historic heat load trend

The first step in meeting this challenge is to question the fundamental nature of the heat management system itself. As previously described this is traditionally viewed as the transport of heat within the oil system and subsequent exchange with the fuel system. Using Systems Engineering (SE) techniques this traditional view of the HM system is questioned and challenged. SE prompts us to consider the boundaries and interactions of the system, to identify requirements and hence to capture the required functional attributes.

By exploring the basic requirements of the system and comparing to those of other heat transport systems a holistic view can be derived of all heat management systems required across the whole engine, and then potential synergies between them can be explored. For example by taking this holistic view it can be recognised that; the nacelle ventilation, powerplant anti-icing, secondary air system and cabin bleed systems are all heat management systems, controlling temperatures by transporting or exchanging heat. In addition there are also multiple aircraft systems that manage heat in some way.

5 Defining the UltraFan™ HM System

5.1 Systems Engineering

As has previously been described, extensive use of Systems Engineering has been employed to aid the definition of the UltraFan™ HM system. It is beyond the scope of this paper to explore these principles in detail, but they can be simply summarised as an approach that re-examines the fundamental drivers of the heat management problem comprising several key stages with an emphasis and focus on understanding in the early stages of the Design process;

- Understand the boundary and scope of the HM system and relationship to other systems,
- Understand the stakeholders and functional interactions,
- Understand system requirements,

- Decomposition of functions to understand the cardinal requirements and critical functions.

Figure 3 provides an illustration of a typical SE toolkit used within Rolls-Royce.

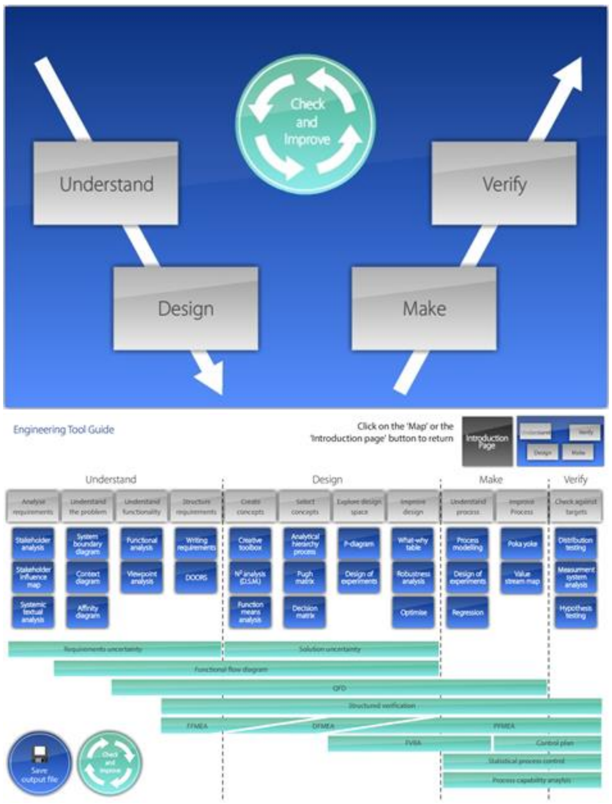


Figure 3, Typical Systems Engineering Toolkit

This structured approach carries an additional overhead in time and resource but enables the detailed solution definition phase to focus on the areas that are most critical to success and also used to explore how existing knowledge and technologies may be combined in a disruptive way, for example;

- Can technologies from other non-Aerospace applications be used ?
- What is the potential for multi-functional designs to increase system efficiency ?
- Can the expertise of Engineers in other disciplines be effectively used to promote innovation ?
- What integration opportunities are there across the powerplant or airframe to optimise system performance ?

Ideas and potential solutions are created using traditional brainstorming techniques as well as more structured approaches such as TRIZ and function means analysis. Idea ranking and comparison is initiated using tools like AHP & function means analysis. Often these steps identify additional requirements or functionality that was not originally captured.

As potential solutions are down selected, functional models of the HM system are created and used in model based SE where design explorations are performed and then optimisation algorithms are used to explore the design space and to identify optimum system configurations. In this stage hybrid solutions can be identified based upon optimisation results resulting in further design iterations. Initially the functional models are simplified but increasingly evolve into more complex representations of the HM system as the definition matures.

5.2 People & Resources

To meet the UltraFan™ challenge also requires the mobilisation of highly skilled people across the Rolls-Royce community, supply chain and UTC's, to interpret requirements, develop technologies, and integrate these as efficiently as possible. The UltraFan™ project team has been staffed by a diverse range of Engineers drawn from across all of the Rolls-Royce aerospace sectors (large civil, small / medium civil and defence) enabling differing viewpoints to be exploited. The team have been based in an environment conducive to creative thought and encouraged to challenge the norm and to constantly question. Within the team innovation was encouraged and generation of new ideas actively supported, as well as identifying which existing or new technologies could be adapted and integrated into the UltraFan™ engine.

A heat management community of practice (CoP) has also been formed that draws experienced Engineers from across the Company to share best practice, technologies and help with problem solving. This CoP has representatives from all Rolls-Royce businesses (Civil Aerospace, Defence, Power Systems, Marine and Nuclear) and shares ideas on diverse technologies.

This CoP also considers how the expertise of engineers in other disciplines across the company could be used in heat management, such as turbine specialists who are expert at devising cooling schemes within high temperature turbine blades. An impartial view is taken of how the different technologies the turbine specialists use (such as impingent cooling schemes and heat transfer enhancement features) can be applied to other applications such as heat exchanger design.

One of the partners helping to explore how new technologies can be developed and exploited is the Rolls-Royce University Technology Centre for Thermal Management at Pusan National University (PNU). The UTC staff work in partnership with Rolls-Royce project staff to understand system requirements and then to explore what tools or technologies are required to be developed. They perform the vital fundamental research necessary to understand and to mature the technology readiness level of new tools and technologies.

5.3 Integration & Multi-functional Solutions

As previously mentioned, one of the key areas in the definition of the HM system has been to understand the functions performed by all secondary systems involved in heat management and to explore the potential for integration. An example of this is the potential for turbine cooled cooling air systems. As described in [1] future UltraFan™ products are likely to adopt the use of CCA to optimise the design of the HPT and cooling system. A CCA solution is likely to incorporate an array of heat exchangers utilising air as the cooling medium packaged in an installation on the engine core, extracting and returning air to the bypass stream. There is therefore a potential synergy where the HM system heat exchanger units could also be located within this installation, minimising bypass duct losses and installation mass. Figure 4 shows a typical CCA arrangement.

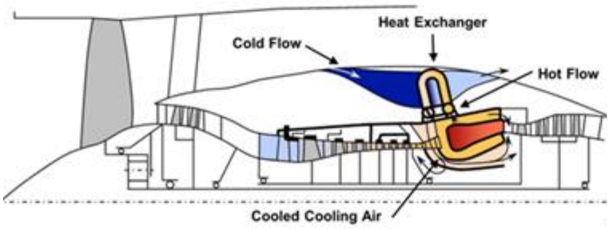


Figure 4, Typical CCA Arrangement

The SHEFAE project is a joint European-Japanese programme with the aim of developing and demonstrating lighter and more compact heat exchanger systems that can more easily be integrated into existing powerplant structures. The first programme demonstrated a structural panel type heat exchanger on a test engine, figure 5, and is succeeded by SHEFAE2 that will build upon the work already performed and will utilise the Centre for Next Generation Heat Exchangers (CNGX) at Pusan, South Korea to demonstrate heat exchanger performance. An example of a potential future panel type heat exchanger is given in figure 6.

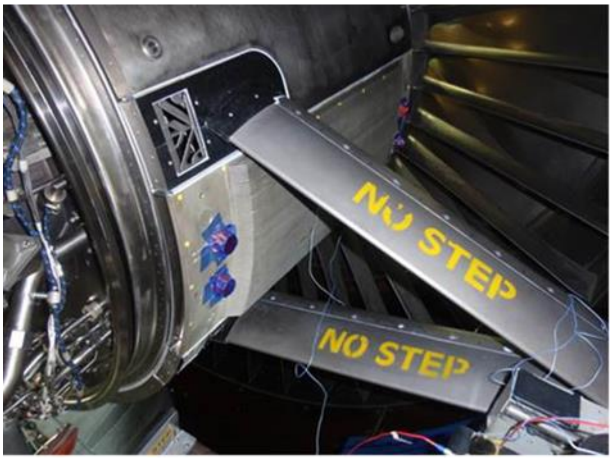


Figure 5, SHAFAE panel type heat exchanger

In addition the use of additive layer manufacturing techniques (ALM) can enable heat exchange devices to be manufactured in shapes not previously possible enabling integration with a greater variety of powerplant structures or as an integral part of a structure or component. The use of ALM is further discussed later in this paper.

Figure 6, Future panel type heat exchanger

The higher bypass ratio and lower Fan pressure ratio of the UltraFan™ means that the aerodynamic losses in the bypass duct are more critical to the overall powerplant efficiency. Minimising them is therefore a key part of the design. There are several systems that draw air from the bypass duct as well as CCA (accessory ventilation, turbine case cooling, turbine tip clearance control system) research has also been performed to explore how these systems can share air off-takes and air management ducting to minimise losses.

Consideration has also been given to the use of secondary surfaces to provide supplementary heat exchange by locating oil carrying units within powerplant ventilation zones or exposed to bypass flows. One of the most obvious components that can provide this capability is the oil tank, which because of its large surface area can be used to exploit additional heat rejection from secondary air flows. Most oil containing units can however also be used to provide some level of secondary heat rejection.

The integration opportunities described so far have only applied within the gas turbine. There are however potential integration opportunities across the whole airframe. Background studies have commenced as part of the European Union Cleansky 2 programme to assess how heat management may be shared across the powerplant / airframe boundary and to explore how a shared heat exchange system could be used at different flight phases.

5.4 Reducing Heat Generation

When defining the heat management system the other key area to explore is that of heat generation, ie avoid generating heat in the first place. It is easy when defining a geared product with such a large heat generating source such as the reduction gearbox to allow this to become the sole focus of the HM system.

As the single most significant source of heat within the UltraFan™ engine defining lubrication and cooling schemes within the gearbox is the key factor in reducing overall heat load. As well as coolant management & optimisation schemes to reduce churning losses, attention is paid to reducing windage losses, and consideration also given to the use of air as a secondary coolant to complement the principal oil cooling.

Oil chemistry is also being explored to ensure the best balance is achieved between heat transport, lubrication, load carrying and shearing losses.

There has also been a strong focus on the rest of the engine sub-systems and modules in order to minimise heat generation. Given the relatively smaller scale of many of the engine heat generating sources, the reductions achieved do not initially appear to be significant. However when multiple small reductions are combined they can yield a meaningful overall reduction in total heat load. Some examples of heat generation reducing schemes that have or are being explored include;

Use of heat dispersant coatings, ceramic brg elements, windage reduction schemes, low leakage air seals.

5.5 Heat Exchanger Design Methodology

This paper has so far principally focussed on the approach used to define the overall HM system along with the potential synergy with other sub-systems. However every HM system requires the use of heat exchange devices whether they are secondary, shared, integrated or traditional style heat exchangers. The definition of these devices, the technology used within in them, and the methodology used to size them is described.

To facilitate more effective preliminary design of high-efficiency heat exchangers required for UltraFan™, a Heat Exchanger Ranking Program (HXRP) was developed by Pusan UTC which is capable of ranking various heat exchanger types in terms of the compactness of the heat-exchanger volume. It was based on a newly constructed database having performance correlations, and uses the ε-NTU method for performance prediction.

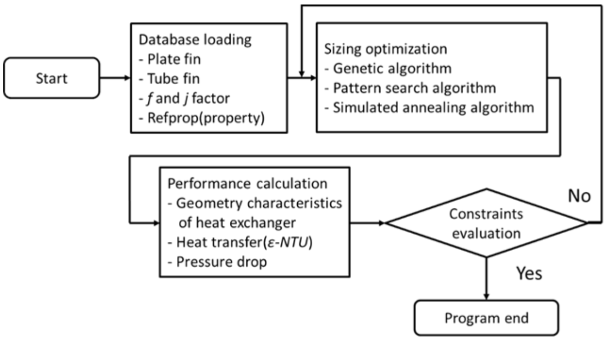


Figure 7, Operating process of ranking program

The operating process of the HXRP is shown in Figure 7. The process can be broken down into three main components: database loading, performance analysis, and optimisation using a design algorithm. The database contains the necessary information required to carry out the performance analysis. The optimisation algorithm uses an iterative method to predict the performance of the intended heat exchanger and provides optimal design information. The program was coded using MATLAB R2011 programming language.

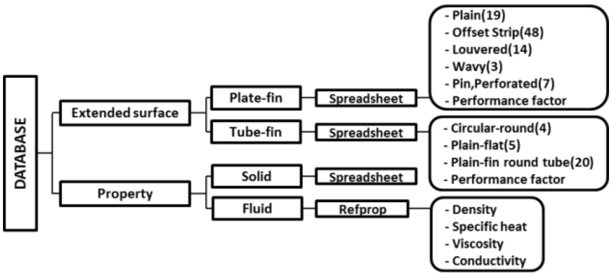


Figure 8, Structure of the heat exchanger database

Figure 8 shows structure of the database of the HXRP. The database contains performance characteristics by core type and shape of heat exchanger. Currently, heat exchanger types can be broken down into plate-fin type and tube-fin type. The contents of the database for each heat exchanger type are: i) geometrical parameters, ii) performance correlations of Fanning friction factor as a function of Reynolds number, and iii) the Colburn j-factor as a function of Reynolds numbers. All information in the database was discretized and summarized in a Microsoft Excel spreadsheet file, and which can be read by the program at execution. All the performance correlations were extracted from the Kays and London data [3].

The program also includes properties of various fluids and solids. Fluid properties were obtained by linking REFPROP v9.1 (Reference Fluid Thermodynamic and Transport Properties Database) from NIST (National Institute of Standards and Technology) to the program, while those of heat exchanger materials (solids) were derived from additional spreadsheet files containing information such as thermal conductivity, specific heat and density.

The heat exchanger is described using the lumped-capacity model, and the pressure drop is calculated using the following general equation:

$$\Delta P = \frac{2 f \rho U_{avg}^2 L}{D_h}$$

where f is Fanning friction factor, obtained from the experimental data provided by Kays and London [3].

The program predicts heat transfer capacity by applying the conventional ε-NTU method. Effectiveness (ε), is defined as the ratio of the actual heat transfer rate to the ideal maximum heat transfer rate.

$$\varepsilon = \frac{q}{q_{\max}} = \frac{C_h\left(T_{h,i} - T_{h,o}\right)}{C_{\min}\left(T_{h,i} - T_{c,i}\right)} = \frac{C_c\left(T_{c,o} - T_{c,i}\right)}{C_{\min}\left(T_{h,i} - T_{c,i}\right)} \quad (1)$$

$$C = \dot{m}c_p \quad (2)$$

Here, subscripts h, c, i, o represent hot-fluid, cold-fluid, inlet, and outlet, respectively. The heat capacity rate, C, is described in equation (2), and Cmin in equation (1) is the smaller heat capacity among the heat capacity rate of hot and cold fluids.

The program also calculates area and volume ‘goodness’ factors in order to evaluate the compactness of heat exchangers.

The general heat exchanger design process is shown in Figure 10. In order to develop a heat exchanger, the heat exchanger type needs to be selected, and then validated using different methods. The purpose of the HXRP is to help its users determine heat exchanger type early in the design phase. For a novel heat exchanger, CFD and experiments can be applied to carry out novel geometry studies, supported by design of experiment techniques. Once the heat exchanger type has been finalized, the HXRP has the optimisation function to evaluate the minimum volume of heat exchanger under design requirements and constraints. This systematic and multi-fidelity design process can enhance the productivity of the heat-exchanger design process by reducing unnecessary rework.

The HXRP is also being integrated with several internal Rolls-Royce programs such as RHEST (Rapid Heat Exchanger Selection Tool) and the SPAN 1-D fluid network analysis code. RHEST is a pre- and post- processor for running heat exchanger codes and enables parametric studies for heat exchanger selection to be performed. The integration of the HXRP with RHEST enables design engineers to efficiently explore design space combining legacy design data with the performance calculation and optimisation algorithms developed by Pusan UTC. Figure 9 shows a flowchart of the operation of RHEST and the integration with the HXRP.

SPAN is a 1-D fluid network solver used for the analysis of fluid systems within Rolls-Royce. The aim of integrating SPAN with HXRP is to allow design engineers to rapidly assess the performance of heat exchanger designs within an entire fluid system. This integration will also enable HXRP to access more realistic fluid boundary conditions and properties that are consistent for each design case analysed, which in conjunction with the REFPROP database already included in HXRP, will enhance the accuracy of the HXRP design tool.

The integration of the HXRP with both RHEST and SPAN enables engineers within Rolls-Royce to perform heat exchanger sizing, selection, and optimisation and to be able to assess their system performance, all within a coherent computational toolset.

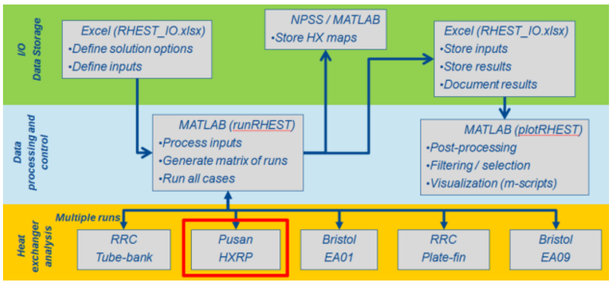


Figure 9, RHEST interfaces and data flow.

Design Maturity

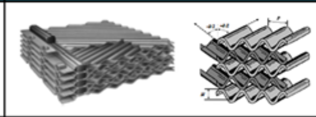
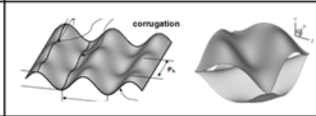
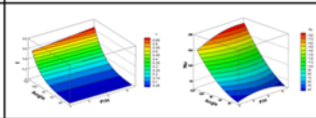
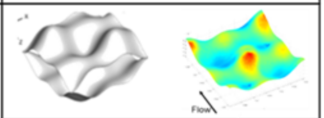
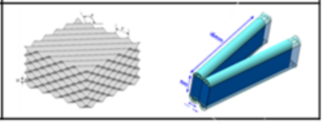
Design Stage	Approach	Method	Output Data	Output Image
HX Type Selection	Knowledge-Based Analysis	▪ HXRP ▪ Literature Survey	Matrix type plate HX	
Novel Geometry Study	CFD / Unit Cell	▪ DNS / LES / RANS ▪ Entropy Analysis ▪ Experiment	Promising candidate of surface geometry	
Design of Experiment	CFD / Unit Cell	▪ RANS ▪ Experiment	Performance correlations (f, j)	
Surface Design Optimization	DOE / Optimization	▪ RSM Model (or RBF) ▪ Entropy Analysis	Optimum surface design values	
HX Sizing Optimization	Optimization	▪ Heat Conduction Code ▪ Flow-Thermal Network ▪ HXRP	**Minimum weight and size of HX module**	

Figure 10, General heat exchanger design process

5.6 Heat Exchanger Technology

To handle the large increase in heat removal required for the UltraFan™ HM system, the development of novel heat exchangers, clearly distinctive from conventional matrix or tubular type heat exchangers, is being researched. Pusan UTC is carrying out a work package to develop new heat exchangers using "biomimetics". Biomimetics or nature-inspired engineering is the imitation of models, systems, and elements from nature for the purpose of solving complex human problems.

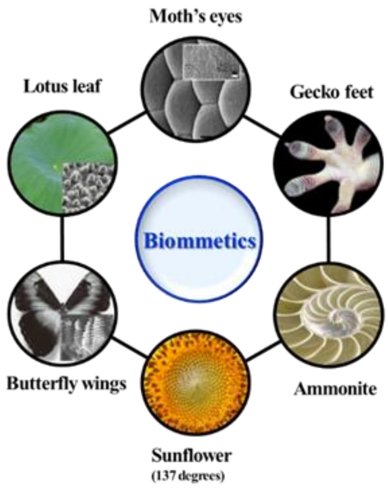


Figure 11, Examples of Biomimetic Engineering

As shown in Figure 11, there are various examples for nature-inspired engineering that can help solve critical aero-thermal problems. For heat exchanger problems, natural structures that have a large surface density (surface-to-volume ratio), such as the lung of animal or gill of fish, are potentially of the main interest.

Manufacturability is a key element in the realisation of biomimetic structures for practical use. Due to its highly complicated three-dimensional design, the manufacturing process needs to be revolutionized. Pusan UTC is building a capability of ALM (Additive Layer Manufacturing) technology for manufacturing of prototype heat exchangers with nature-inspired complicated shapes. This challenging work involves collaboration with key players in metal ALM in Korea, including KITECH (Korea Institute of Industrial Technology), KIMM (Korea Institute of Machinery and Materials) and KIMS (Korea Institute of Materials Science), in order to fully utilise their expertise in powder-bed based and DED (direct energy deposition)-based metal ALM manufacturing technologies. Figure 12 shows typical metallic products manufactured by the ALM technology.

Figure 12, Typical product of metal ALM technology

5.6 Control & Optimisation

The model based optimisation work described previously in this paper identified the optimum HM solution for each design case analysed as well as 'pinch points' in the flight envelope. Each design case usually has its own optimum solution so this work has identified how the system could be configured for each condition and hence what system modulation or variability could be employed to optimise the system.

Research is underway to explore how system modulation could be combined with adaptive control schemes to maximise the efficiency of the system and also to help reduce system size. As also discussed previously, as well as system level optimisation, optimisation is also crucial at component level. For the HM system size of heat exchangers is one of most important constraints.

Therefore, it is essential to optimize the size of heat exchangers to achieve maximum performance in a given volume. The HXRP applies optimization techniques to calculate the optimal size of heat exchangers while reflecting geometrical constraints in the optimization process. Three optimization techniques can be applied within HXRP for size optimization, genetic algorithm, pattern search algorithm, and simulated annealing algorithm, these are illustrated in Figure 13.

- Genetic algorithm (GA) is a search heuristic that mimics the process of natural selection.
- Pattern search (PS) is a family of numerical optimization methods that do not require the gradient of the problem to be optimized.
- Simulated annealing (SA) is a generic probabilistic heuristic for the global optimization problem of locating a good approximation to the global optimum of a given function in a large search space.

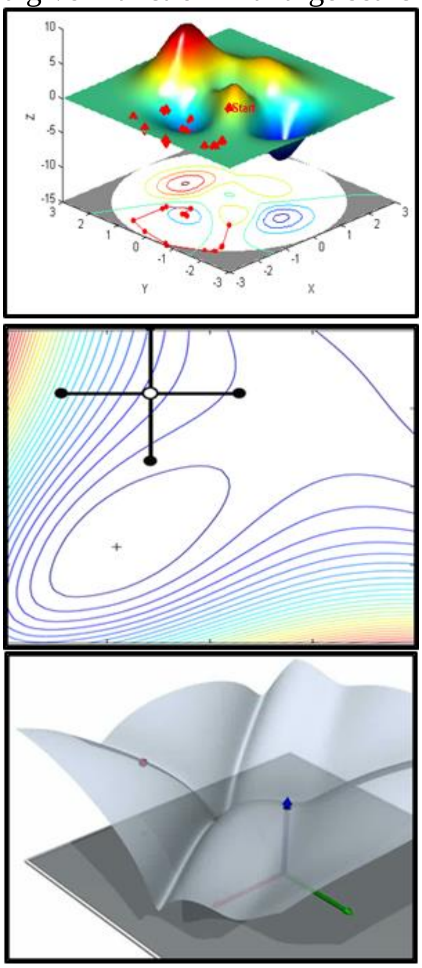


Figure 13 illustration of genetic algorithm, pattern search & simulated annealing

6 Conclusion

This paper has explored how Systems Engineering techniques have guided the definition of the UltraFan™ heat management system by supporting a new way of thinking and has encouraged a diverse team of Engineers, located in a physical and cultural environment conducive to creativity, to explore new ideas.

In this way the UltraFan™ project team have defined the heat management system for the UFD engine and have mapped the technology acquisition and development pathway for future UltraFan™ products, consistent with the policy of Rolls-Royce for continual product improvement. Integration opportunities and multi-function designs have all resulted from the use of Systems Engineering thinking and enabled a HM system to be defined that supports the application of the Rolls-Royce UltraFan™ architecture to the largest potential future product application

Working in partnership with the Pusan UTC has also enabled the identification and development of new technologies, processes and tools to be applied at system level and component level. This paper has also described how a new computational toolset has been used to optimise heat exchanger design and to explore how novel technologies can be used to maximise heat exchanger efficiency.

7 References

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