Applying heat pipes to a novel concept aero engine

PART 2 – Design of a heat-pipe heat exchanger for an intercooled-recuperated aero engine

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ABSTRACT

With the ever-increasing pressure for cleaner and more fuel efficient aero engines, gas turbine manufacturers are faced with a big challenge which they are bound to accept and act upon. The path from current high bypass ratio (BPR) engines to ultra high BPR engines via geared turbo fans will enable a significant reduction in SFC and CO_2 emissions. However, in order to reach the emission levels set by the advisory council for aeronautics research in Europe (ACARE), the introduction of more complex cycles that can operate at higher thermal efficiencies is required. Studies have shown that one possibility of achieving higher core efficiencies and hence lower SFC is through the use of an intercooled recuperated (ICR) core. The concept engine, expected to enter into service around 2020, will make use of a conventional fin plate heat exchangers (HEX) for the intercooler and a tube type HEX as the recuperator. Although the introduction of these two components promises a significant reduction in SFC levels, they will give also rise to higher engine complexity, pressure losses and additional weight. Thus, the performance of the engine relies not only on the behaviour of the usual gas turbine components, but will be heavily dependent on the two heat exchangers. This paper seeks to introduce a heat pipe heat exchanger (HPHEX) as alternative designs for the intercooler and the recuperator. The proposed HPHEX designs for application in an ICR aero engine take advantage of the convenience of the geometry of miniature heat pipes to provide a reduction in pressure losses and weight when compared to conventional HEX. The proposed HPHEX intercooler design eliminates any ducting to and from the intercooler, offering up to 32% reduction in hot pressure losses, 34% reduction in cold pressure losses and over 41% reduction in intercooler weight. On the other hand the proposed HPHEX recuperator design can offer 6% improvement in performance, while offering 36% reduction in cold pressure losses, up to 80% reduction in hot pressure losses and over 31% reduction in weight. An ICR using HPHEX for the intercooler and recueprator may offer up to 2·5% increase in net thrust, while still offering 3% reduction in SFC and up to 7·7% reduction in NO_X severity parameter, when compared to the ICR using conventional HEX.

NOMENCLATURE

Abbreviations

BPR	bypass ratio
EIS	entry into service
GTF	geared turbo fan
HEX	heat exchanger
HPC	high pressure compressor
HPHEX	heat pipe heat exchanger
HPT	high pressure turbine
IC	intercooled
ICR	intercooled recuperated
IPC	Intermediate pressure compressor
NEWAC	NEW environmental friendly Aero engine Core concepts
LPT	low pressure turbine
OPR	overall pressure ratio
REC	recuperated
SFC	specific fuel consumption
TERA2020	Techno-economic, Environmental, and Risk Assessment for 2020
TET	turbine entry temperature

Roman Symbols

CO_2	carbon dioxide
dP	% pressure loss
NO_X	oxides of nitrogen
x	optimum heat pipe parameter

Greek Symbols

ε	effectiveness
η	efficiency

Subscripts

COLD	cold flow
HOT	hot flow

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1.0 INTRODUCTION

The first part of this work discussed the need for new aero engine concepts and the European medium to long-term development programme, known as NEWAC, which has the aim to develop more efficient aero engine core concepts. Two such concepts are the intercooled (IC) core and the intercooled-recuperated (ICR) core. An alternative design using heat pipes as opposed to conventional heat exchangers (HEX) was proposed for the IC core. The design procedure of the heat pipe heat exchanger (HPHEX) was demonstrated and the performance analysis for the novel IC aero engine was compared with a current high Bypass ratio (BPR) engine. In this second part, the ICR aero engine will be analysed and designs of HPHEX for the intercooler and recuperator are proposed. The performance and weight analysis for each HPHEX is made. An engine performance analysis is also made and compared to the ICR aero engine proposed in earlier work, as well as the IC aero engines from Part 1, and referenced to a current modern high BPR engine.

2.0 THE INTERCOOLED-RECUPERATED CONCEPT

The ICR cycle combines the IC cycle and the recuperated cycle, so that the intercooler and recuperator work in tandem. Following the intercooling process between the low pressure compressor (LPC) and the high pressure compressor (HPC), heat from the exhaust gasses is recovered and transferred to the HPC delivery air prior to entering the combustor. This allows a lower energy requirement to raise the air temperature prior to combustion. Hence a lower fuel flow, and a higher thermal efficiency are expected. The ICR core is considered as a milestone in aero engine development.

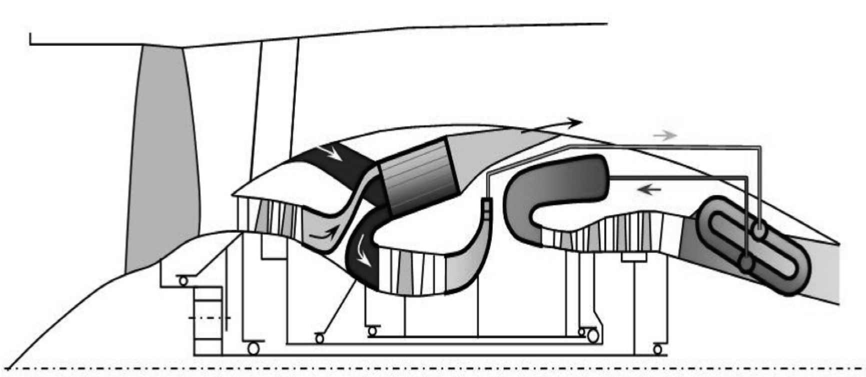

Figure 1. An ICR turbofan as shown in Wilfert *et al* (2007).

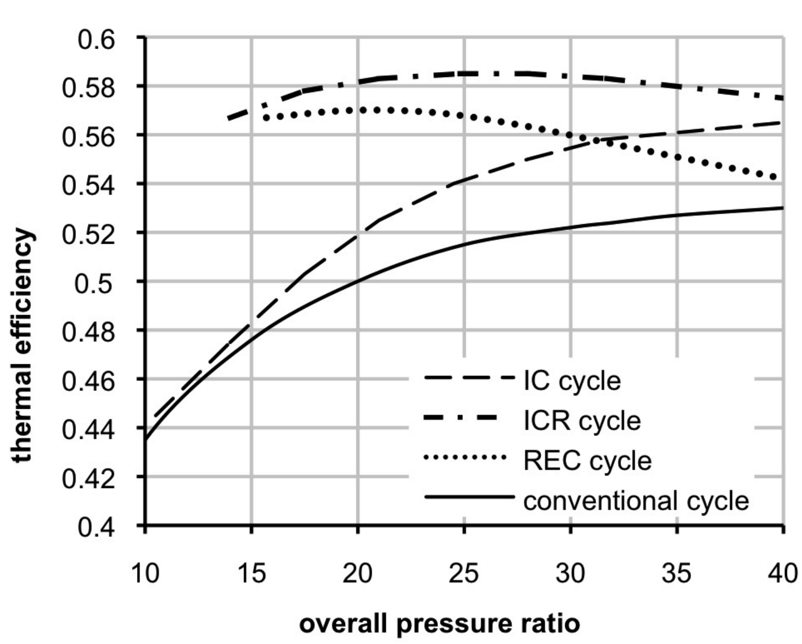

Figure 2. The comparison of the engine core efficiency for the simple cycle, intercooled, recuperated and intercooled-recuperated cycles for a number of OPRs and fixed TET.

Using commercial engine performance simulation software GasTurb, an ICR cycle was modelled and compared to an IC cycle, a recuperated (REC) cycle, and referenced to a simple cycle. Table 1 shows the data used for each of the models. Although the addition of the intercooler and recuperator give rise to additional pressure losses, the thermal efficiency of an ICR is superior to that of other cycles over a range of OPRs. This result compares well with that obtained by Boggia (2002) and Wilfert *et al* (2005).

Table 1
cycle parameters considered in the engine performance modelling

Cycle	simple	REC	IC	ICR
TET		1,750K		
η_C	0·90	0·90	0·90	0·90
η_T	0·93	0·93	0·93	0·93
ICε	–	–	75%	75%
IC dP_{HOT}	–	–	10%	10%
IC dP_{COLD}	–	–	3%	3%
REC ε	–	75%	–	75%
REC dP_{HOT}	–	5%	–	5%
REC dP_{COLD}	–	5%	–	5%

With an increase in OPR, the thermal efficiency of the IC cycle improves. Conversely the thermal efficiency of the REC cycle decreases as the OPR increases. An increase in OPR increases the temperature difference between the IPC delivery air and the bypass air, hence improving the performance of the intercooler. In contrast, the temperature difference between the HPC delivery temperature and the exhaust gasses decrease, consequently reducing the recuperator's performance. On the other hand, the ICR cycle reaches an optimum at an OPR at around 25, with the intercooling effect dominating the cycle at OPRs < 25 while the recuperator dictating the cycle performance at OPRs > 25.

Using GasTurb, a simulation of an aero engine using an ICR core was performed. It could be shown that at the optimum operating conditions, both the SFC and net thrust improve as the intercooling effectiveness and the recuperative effectiveness increase.

3.0 A TECHNO-ECONOMIC ANALYSIS FOR THE ICR AERO ENGINE

The optimum ICR core could potential give a 10% improvement in thermal efficiency when compared to current core designs, thus resulting in lower CO_2 levels. Moreover, as the ICR operates at a lower OPR, NO_X formation will also be reduced. Yet the ICR core is a much more complex and expensive engine. Although it will make use of a smaller compressor it would probably still be heavier due to the additional weight of the intercooler and recuperator. A full techno-economic analysis at an aircraft system level is thus required.

In his work, Whellens *et al* (2003), describes that if an ICR core could be installed in a current turbofan with the same inlet mass flow, BPR and OPR, a performance benefit over conventional turbofans would only exist for engines with low OPRs. This agrees well with the results from the modelling shown above. Whellens *et al* show how a turbo fan engine in the 28kN thrust range, having a bypass ratio of 8 and an ICR core can achieve a 6% reduction in fuel burn when compared to the same engine with a simple core. However, for the same OPR and a similar combustor design, an ICR core would produce approximately 170% more NO_X when compared to a simple core. This is mainly attributed to the high combustor entry temperature. Yet NO_X levels are still lower than those in current high OPR engines.

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Lundbladh and Sjunnesson (2003), performed a feasibility study for an ICR aero engine for medium to long range commercial transport. The study compares the aircraft fuel consumption and operating costs when operated both with an aero engine with simple core, an IC and ICR cores. The engine performance was evaluated for an aircraft with a capacity of 250 passengers, 10,500km range, twin-jet with a cruise speed of M = 0·87. The engine performance was evaluated at mid-cruise conditions when 58% of the fuel remains. Their results show that although the ICR core offers the highest savings, when compared to current engine designs, it may still result in higher operating costs when compared to IC cores. The authors conclude that the improved benefit of an ICR core over an IC core may only start to make economical sense if the price of fuel becomes several times higher, or if new legislations impose high environmental taxes.

Kyprianidis *et al* (2011), utilises an aero-engine multidisciplinary design tool; Techno-economic, Environmental, and Risk Assessment for 2020 (TERA2020), to study the potential benefits from introducing heat-exchanged cores in future turbofan engine designs. The tool allows to predict engine performance, but also to establish the gas path layout for the engine configuration, thus carrying out component thermo-mechanical and aerodynamic design at the appropriate operating conditions, as well as predicting engine weight at component level. The study was performed on an aircraft system level using a twin jet commercial aircraft with range mission of 12,500km and cruise speed of M = 0·87. The authors find that an ultra high bypass ratio (UHBR) with an ICR core and potential entry into service (EIS) 2020, would offer an SFC savings of more than 2%, when compared to a reference conventional EIS 2020 core. The benefits from an IC aero engine are however highly dependent on the set technology targets such as intercooler weight and pressure losses.

4.0 CONVENTIONAL HEAT EXCHANGERS FOR THE INTERCOOLED RECUPERATED AERO ENGINE

The performance of an ICR cycle is very dependent on the effectiveness and the pressure losses resulting from the intercooler and recuperator. In their work, Boggia *et al* (2002), (2005), and Rolt *et al*, (2009), shows how a fin-plate heat exchanger could be used for the design if the intercooler. The intercooler will have an effectiveness of around 70% with a hot pressure loss of around 10% and a cold pressure loss of around 2·5% when operated at mid-cruise conditions. It will be made of 8 modules installed around the core of the engine within the bypass duct. Marx (2007), shows how the weight for such an intercooler will be between 700-800kg. The design of conventional HEX used for intercooling purposes has been already discussed in ‘Part 1 – Design of a heat pipe heat exchanger for an intercooled aero engine’. Hence this section will focus on the use of conventional HEX as a recuperator.

Designing a recuperator for a gas turbine presents tough challenges. The HEX is required to resist thermal and mechanical loads and be protected against hot corrosion. Further more, application in an aero engine requires the HEX to be lightweight and designed to integrate with the rest of the engine thus presenting minimum obstruction to the flow while achieving the highest effectiveness. In their work, McDonald *et al*, (1996) presented a number of possible heat exchanger options for land based gas turbines. Boggia *et al* (2005), and Wilfert *et al* (2005), (2007), shows how a tube type HEX for application in aero engines was developed, with the proposed recuperator consisting of 8 oval HEX modules. Schoenenborn *et al* (2006) shows how each

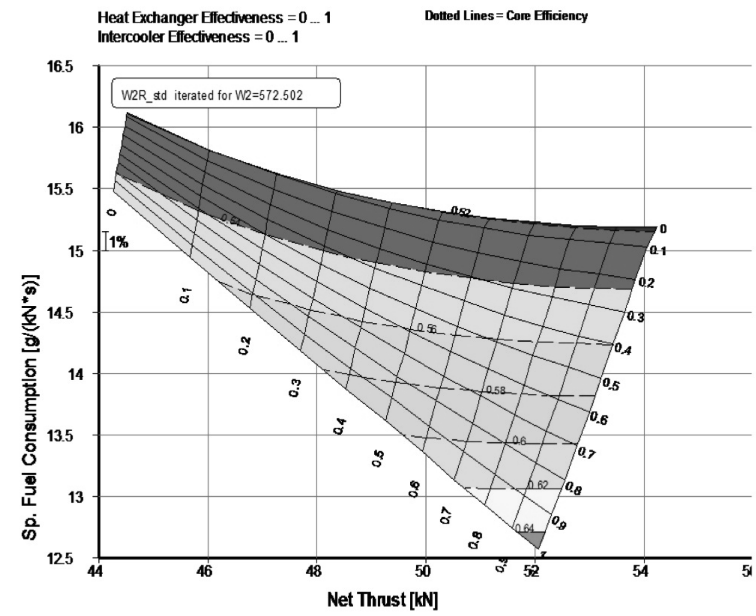

Figure 3. plot showing the relationship between net thrust, SFc and core efficiency for various intercooling and recuperative effectiveness. Simulation performed at fixed TET, BPR, pressure losses and at an optimum OPR.

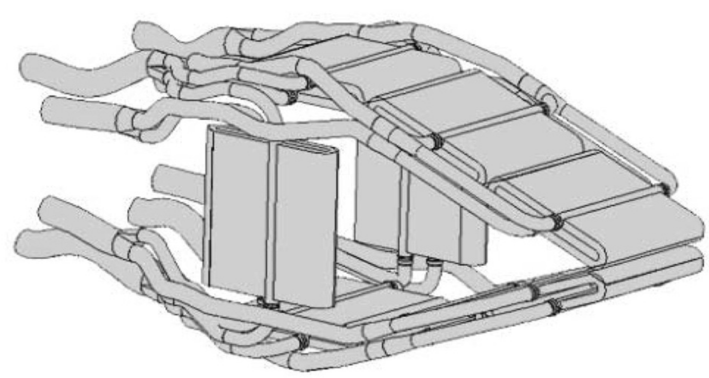

Figure 4. The recuperator design, as shown in Boggia *et al* (2005).

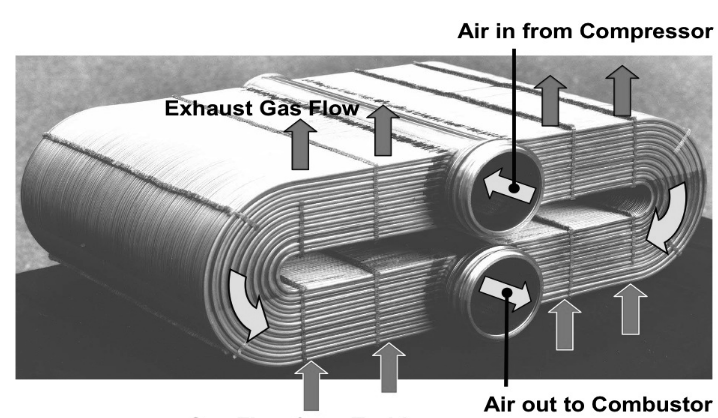

Figure 5. A recuperator module as shown in Boggia *et al* (2005).

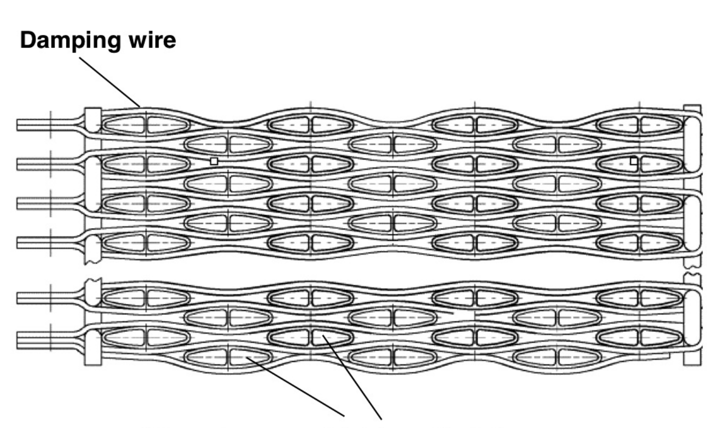

Figure 6. Details of the tubes in each recuperator module, as shown in Schoenenborn *et al* (2006).

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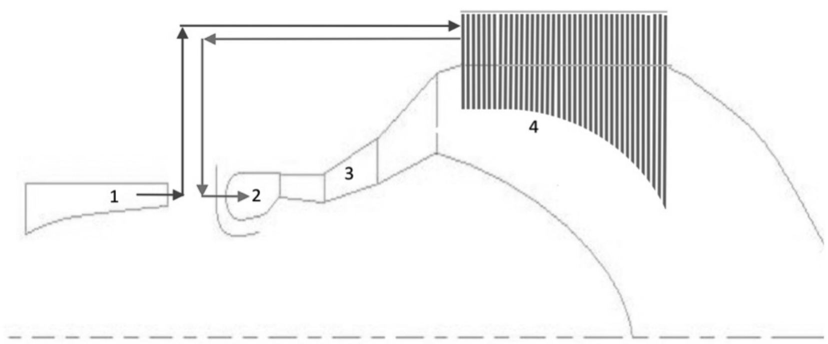

Figure 7. A functional scheme showing the concept of the HPHEX for the intercooler.

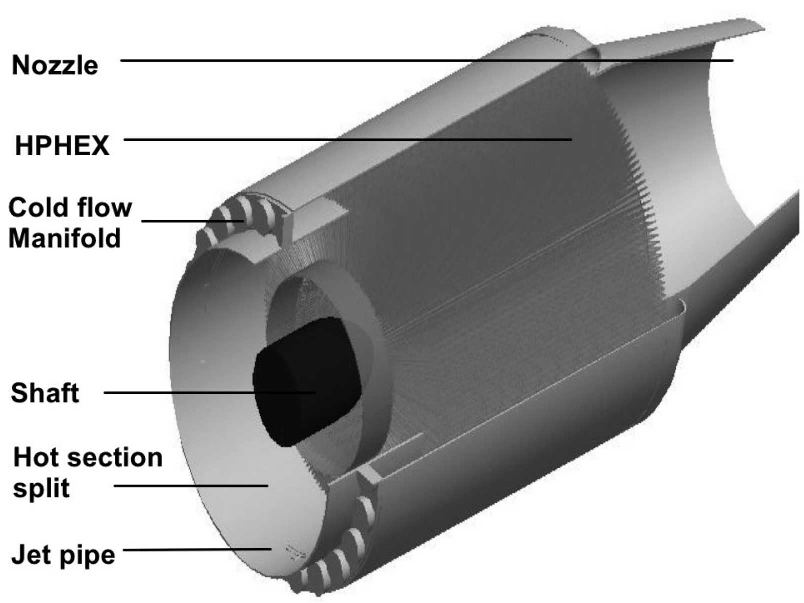

Figure 8. Schematic showing how the HPHEX protrudes from the jet pipe to the cold flow jacket.

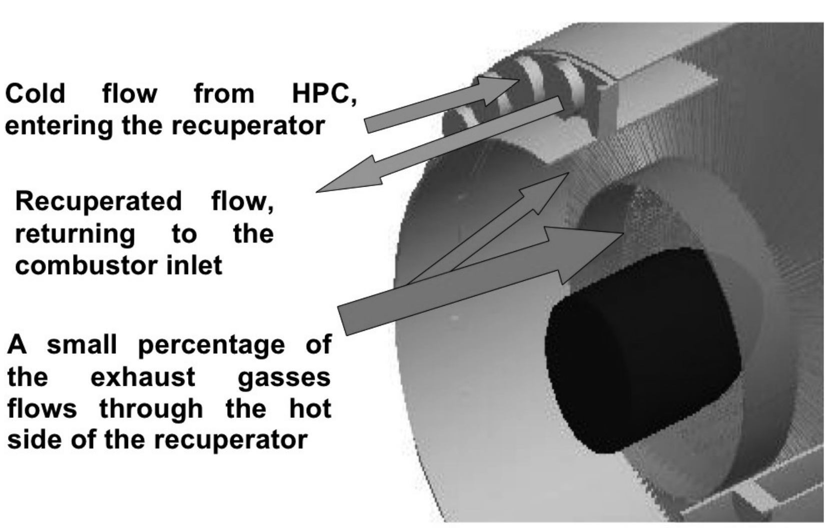

Figure 9. Details of the flows in the HPHEX.

module is shaped using 3,438 tubes which are held together using a woven wiring net. While the cold flow from the HPC is passed through the tubes, the hot exhaust gasses passes over them. The recuperator requires a complex air ducting system, with each module containing two manifolds, one collecting air from the HPC and delivering it into the tubes while the other collects air out and delivers it to the combustor. Hepperle (2007) estimates that a similar recuperator with an effectiveness of around 75% with both hot and cold pressure losses at around 5% will have a length of 3·2m and a weight of 1,100kg.

5.0 HEAT PIPES AND THEIR APPLICATION AS A RECUPERATOR IN THE ICR CORE

The design of an intercooler made from a HPHEX will have a similar design to that discussed in 'Part 1 – Design of a heat pipe heat exchanger for an intercooled aero engine'. Hence this section will focus on the design of HPHEX as a recuperator. Heat pipe heat exchangers used in recuperative applications are not a novel technology. Silverstein (1992) describes how recuperative HPHEX have been applied for industrial gas turbines. However the use of HPHEX in aero engines has never been investigated. Throughout this work, a novel design that takes advantage of the convenience of its geometry is proposed. The HPHEX will be made of a number of miniature elliptical pipes as shown in Part 1, and will contain a number of stages, in radial configuration. The HPHEX will extend from the jet pipe to a 'cold flow jacket'. The cold flow jacket will contain a system of manifolds to deliver the cold flow from the HPC to the recuperator, and return it to the combustor.

Using an engine simulation software GasTurb, it was noted how for a fixed TET and OPR, a 2% increase in recuperative effectiveness would be required to make up for the losses in SFC provided by 1% cold pressure losses. Similarly 6% increase in recuperative effectiveness would be required to make up for the losses in SFC provided by 1% hot pressure losses. Hence a hot section split was introduced in the jet pipe, allowing only a part of the exhaust mass flow to go through the recuperator, thus limiting the hot pressure losses. The figures below show more details of the design of the HPHEX, the flow setup and its integration with the aero engine.

6.0 HPHEX DESIGN TOOL

A tool capable of estimating the performance of HPHEX was developed. The design tool was used to estimate the properties and performance of two HPHEX, one to be used as an intercooler while the other one as a recuperator. The tool makes use of experimental correlations of friction factor and heat transfer characteristics for flow over a tube bank, with varying geometry, configurations and Reynolds number, as performed by Kays and London (1998).

Prior to designing the HEX, GasTurb was used to find the optimum placement for the intercooler. Figures 10 shows how every intercooling effectiveness has an optimum IPR which provides the lowest SFC. Conversely, Fig. 11 shows how a different optimum IPR which provides maximum net thrust exist. Hence a trade-off between the SFC and net thrust has to be made.

Table 2
engine parameters considered in the simulation

TET	1,750K
η_C	0·9
η_T	0·93
IC dP_{HOT}	10%
IC dP_{COLD}	3%
REC ε	75%
REC dP_{HOT}	5%
REC dP_{COLD}	5%

While air properties from the bypass flow and the flow at an IPR = 4 were used to design the intercooler, air properties prior to entering the combustor and the LPT exit were used to design the recuperator. The ε- *Ntu* method as adapted by Silverstein (1992) for designing radial HPHEX was used to compare the various heat pipe geometries and configurations at the appropriate flow conditions. Details of the relationships used to design the HPHEX were shown in part 1.

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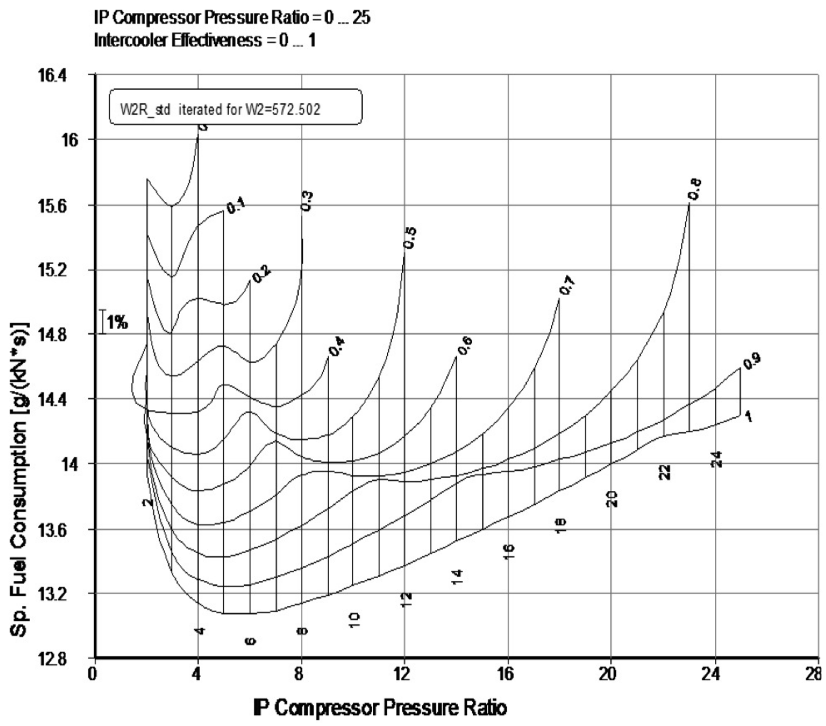

Figure 10. Plot of IPR and IC ε vs SFC for an aero engine with ICR core, fixed REC ε, fixed pressure losses.

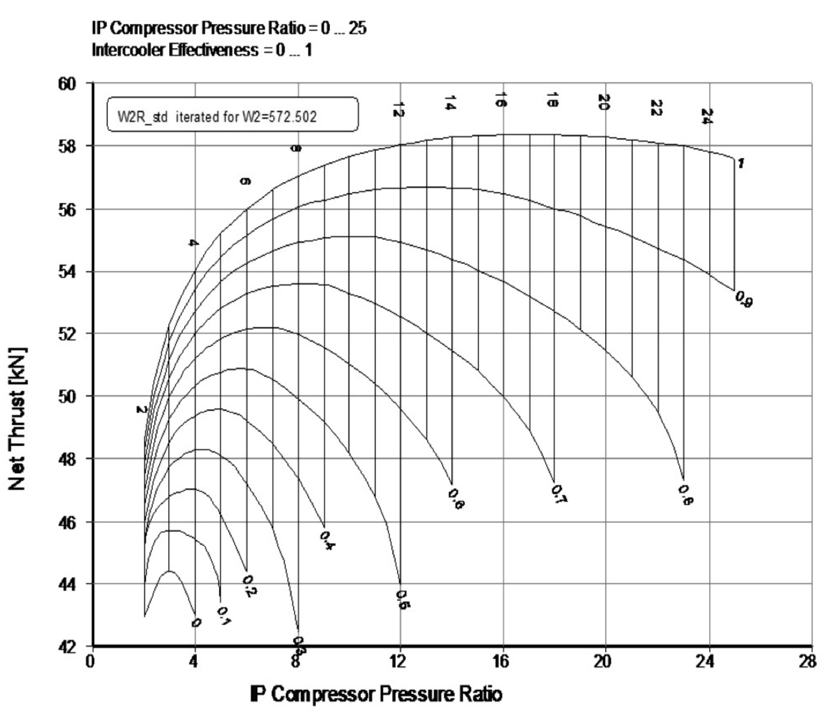

Figure 11. Plot of IPR and IC ε *vs* net thrust for an aero engine with ICR core, fixed REC ε, fixed pressure losses.

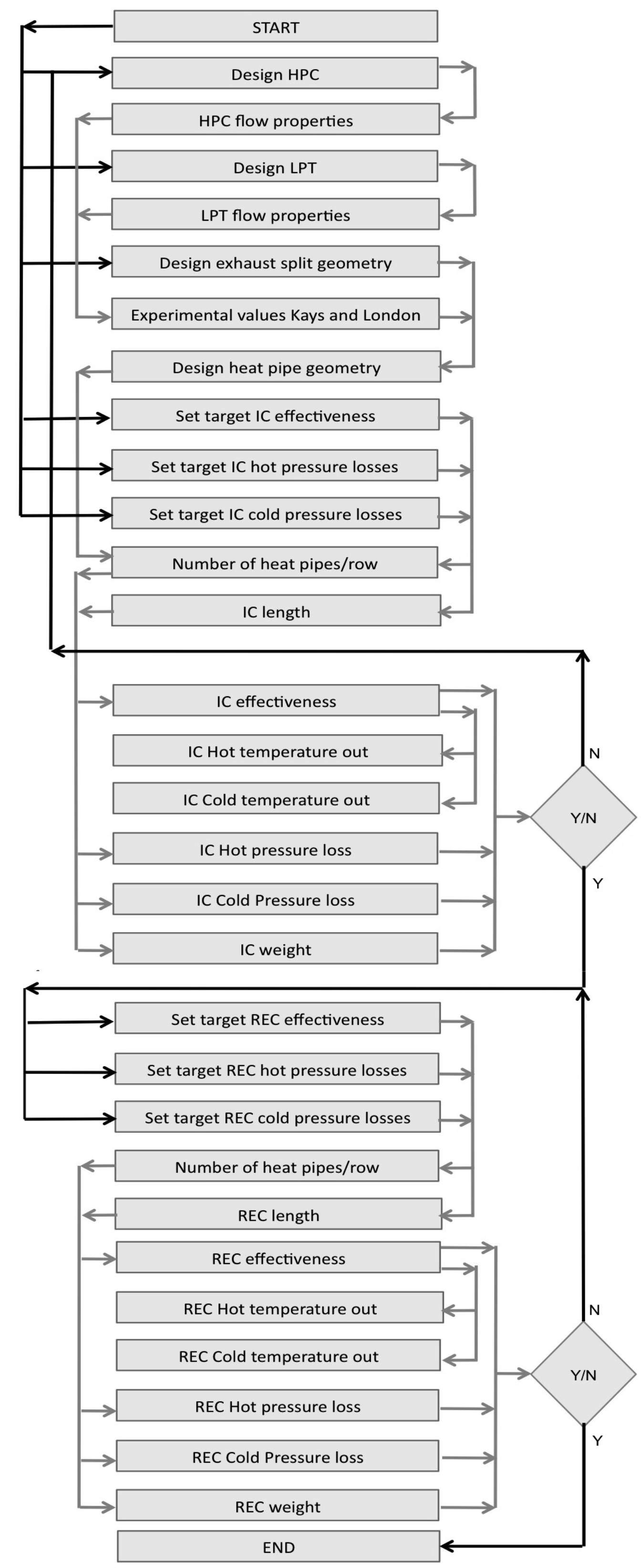

Figure 12. The process flow chart for the HPHEX design software as applied to the ICR aero engine.

7.0 HPHEX PERFORMANCE ANALYSIS

A number of observations on the design of HPHEX could be made:

1. The same heat exchanger effectiveness could be achieved through various combinations of evaporator length, condenser length, flow rate ratios, and number of rows in the HPHEX. Each combination results in different pressure losses and HPHEX weight. The optimum heat pipe (x) parameter defined in part 1 was used to evaluate the effect of the various HPHEX parameters.
2. For a fixed effectiveness and flows, a decrease in evaporator length decreases the hot flow area and the heat transfer surface area surface area. However, this increases the velocity and consequently the heat transfer coefficient. The HPHEX could obtain the same effectiveness with a smaller amount of rows, hence reducing the HEX weight. On the other hand, while the increased velocity increases the hot flow pressure losses, a decrease in evaporator length reduces also the cold flow area, providing also an adverse effect on the cold pressure losses. A reduction in evaporator length increases the x-parameter.
3. Similarly, for a fixed effectiveness and flows, a decrease in condenser length decreases the cold flow area and the heat transfer surface area. However the velocity increases, consequently increasing the heat transfer coefficient. The HPHEX could obtain the same effectiveness with a smaller amount of rows hence the HEX weight is reduced. While increasing cold

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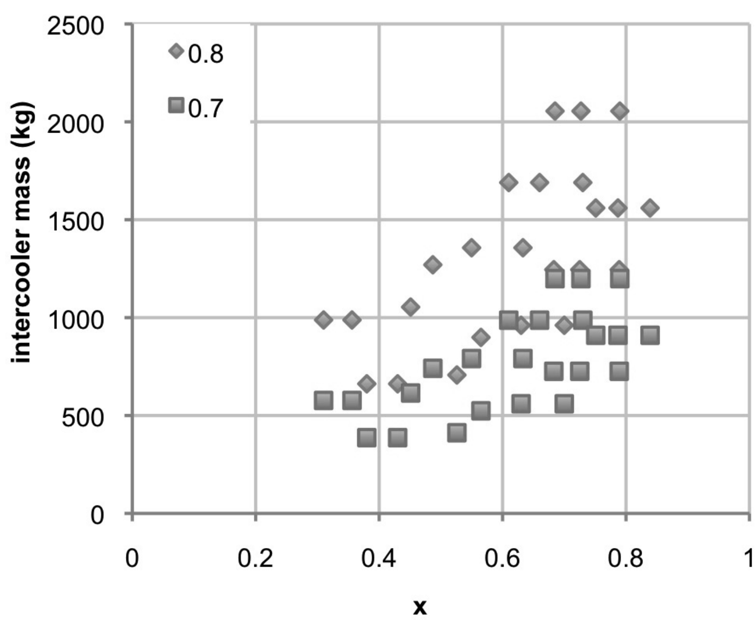

Figure 13. Chart showing values of optimum heat pipe parameter *vs* intercooler mass (kg).

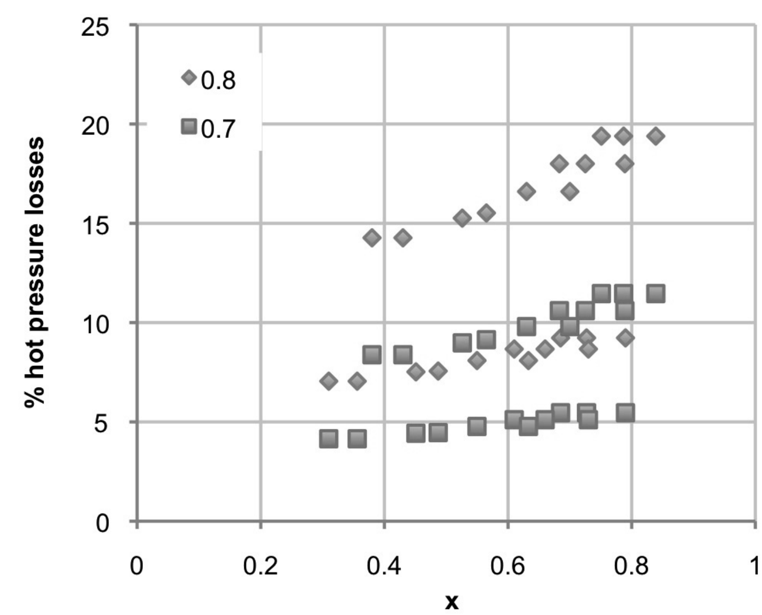

Figure 14. Chart showing values of optimum heat pipe parameter *vs* % intercooler hot pressure losses.

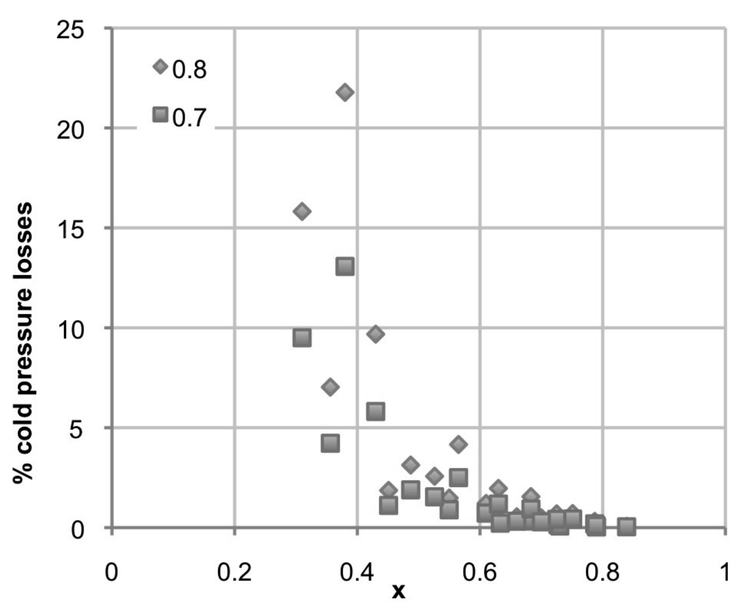

Figure 15. Chart showing values of optimum heat pipe parameter *vs* % intercooler cold pressure losses.

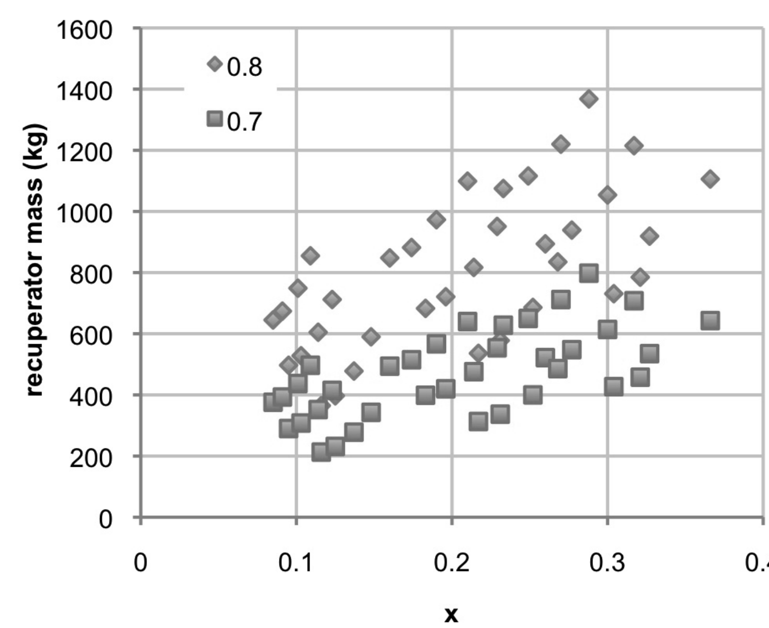

Figure 16. Chart showing values of optimum heat pipe parameter *vs* recuperator mass (kg).

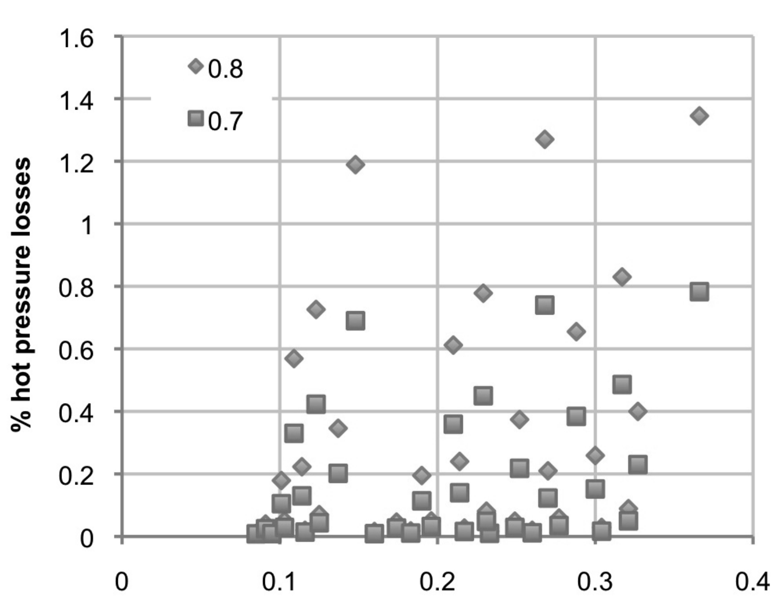

Figure 17. Chart showing values of optimum heat pipe parameter *vs* % recuperator hot pressure losses.

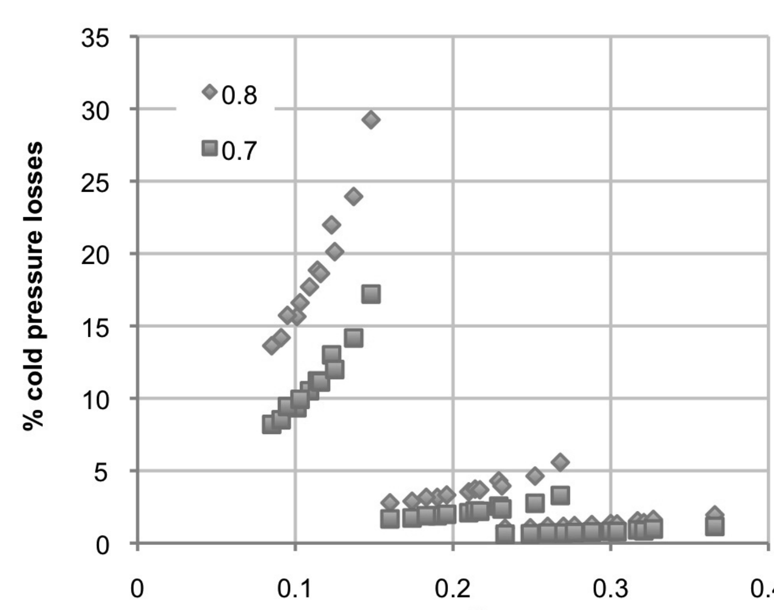

Figure 18. Chart showing values of optimum heat pipe parameter *vs* % recuperator cold pressure losses.

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velocity increases the hot flow pressure losses, the reduction in rows reduces the cold pressure losses. A reduction in evaporator length decreases the *x*-parameter.

4. While the intercooler has a constant hot flow rate, fixed by the engine core flow rate, the cold flow rate in the bypass split was varied. For a fixed effectiveness and pipe geometries, a reduction in cold flow may in some cases mean that the HPHEX requires more rows to achieve the same effectiveness. Hence while a reduction in cold flow always decreases the cold pressure losses, in some cases it increases the HPHEX weight and hot pressure losses. A reduction in cold flow rate decreases the x-parameter.
5. Conversely, the recuperator has a fixed cold flow rate while the hot flow rate in the nozzle split was varied. For a fixed effectiveness and pipe geometries, a reduction in hot flow caused the hot pressure losses to decrease. A reduction in hot mass flow rate causes the x-parameter to decrease.

Figures 13-15 show how the HPHEX intercooler weight and the hot and cold pressure losses vary for different effectiveness values and various x-parameters. It can be seen that that for any ε value, while the x-parameter decreases, both the HPHEX mass and the hot pressure losses decrease, while the cold pressure loss increase. As the HPHEX ε increases, all three properties increase. Hence a decision balancing the HPHEX performance and weight is required. The designs with the most promising performance parameters are shown in Table 3.

The intercooler designs offering the most promising performance figures are shown in Table 3.

Table 3
intercooler *HPHEX* for ε = 0·8 and ε = 0·7

ε	*x*	Mass (kg)	dP hot %	dP cold %
0·8	0·451	1,054	7·52	1·86
0·7	0·526	412	8·98	1·54
0·7	0·430	387	8·39	5·81

On the other hand, figures 16-18 show how the HPHEX rcuperator weight and the hot and cold pressure losses vary for different effectiveness values and various x-parameters. It can be seen that that for any ε value, while the x-parameter decreases, the HPHEX mass, hot pressure losses and cold pressure loss decrease. Similarly, as the HPHEX ε increases, all three properties increase. The most promising recuperator designs are shown in Table 4.

Table 4
recuperator HPHEX for ε = 0·8 and ε = 0·7

ε	x	Mass(kg)	dP hot%	dP cold%
0·8	0·183	683	<1	3·16
0·7	0·183	400	<1	1·89

An engine simulation was run to evaluate each of the HPHEX designs. Although the intercooler design with ε = 0·8 offers a better engine performance, it carries a very large weight penalty, hence the intercooler design with ε = 0·7 and 9% hot pressure losses and 1·54% cold pressure losses was chosen. The HPHEX will have a length of 0·24m and will be made of 68 rows. Each row will have 512 pipes, each one being 0·4m long. The HPHEX will have a weight of 412kg. These values compare very well with the conventional HEX design as proposed for use in an ICR engine in earlier work. For the same effectiveness, the HPHEX offers 32% reduction in hot pressure losses, 34% reduction in cold pressure losses and over 41% reduction in weight.

On the other hand the recuperator design with ε = 0·8 was found to offer the better performance. The HPHEX will have a length of 0·14m and will be made of 39 rows. Every row will have 657 pipes, each one being 0·5m long. The HPHEX will have a weight of 683kg. These values compare very well with the conventional HEX design as proposed for use in an ICR engine in earlier work. The HPHEX recuperator can offer 6% improvement in performance, while offering 36% reduction in cold pressure losses, up to 80% reduction in hot pressure losses and over 31% reduction in weight.

6.0 ENGINE COMPARISON

Using GasTurb, the performance of the ICR core and the ICR core with HPHEX were compared to an IC-core, an IC core with HPHEX, and a current modern high bypass turbofan of the same thrust category, EIS 2007. Table 5 below shows details of the engines modelled, and the resulting SFC, thrust and NO_X levels.

Table 5
details of the engines compared

Engine type	high BPR TF	IC HEX	IC HPHEX	ICR HEX	ICR HPHEX
Net Thrust (kN)	52	51·3	51·7	51·2	52·5
η_C	0·90	0·90	0·90	0·90	0·90
η_T	0·93	0·93	0·93	0·93	0·93
BPR	7·5	13	13	20	20
OPR	35	60	60	28	28
TET (K)	1,850	1,750	1,750	1,750	1,750
IC ε	–	70%	70%	70%	70%
IC dP_{HOT}	–	10%	6·8%	10%	8·98%
IC dP_{COLD}	–	2·5%	1·6%	2·5%	1·54%
REC ε	–	–	–	75%	80%
RC dP_{HOT}	–	–	–	5%	<1%
RC dP_{COLD}	–	–	–	5%	3·16%
SFC (g/KNs)	20·30	13·97	13·94	13·62	13·23
s NO_X	0·614	0·54	0·52	0·44	0·41

7.0 CONCLUSION

The proposed HPHEX designs for application in an ICR aero engine take advantage of the convenience of the geometry of miniature heat pipes to provide a reduction in pressure losses and weight when compared to conventional HEX. The proposed HPHEX intercooler design eliminates any ducting to and from the intercooler, offering up to 32% reduction in hot pressure losses, 34% reduction in cold pressure losses and over 41% reduction in intercooler weight. On the other hand the proposed HPHEX recuperator design can offer 6% improvement in performance, while offering 36% reduction in cold pressure losses, up to 80% reduction in hot pressure losses and over 31% reduction in weight. Moreover the proposed HPHEX designs reduces engine complexity

While the ICR aero engine offers substantial benefits over current turbofan engines, an ICR using HPHEX for the intercooler and recueprator may offer up to 2·5% increase in net thrust, while still offering 3% reduction in SFC and up to 7·7% reduction in NO_X severity parameter, when compared to the ICR using conventional HEX. Moreover, an ICR engine using HPHEX can be up to 35% lighter when compared to an ICR using conventional HEX. While this will offer significant benefits, a mission analysis is required to quantify such effects.

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7.0 REFERENCES

1. ANDRIANI, R., FERRI, L., GHEZZI, U., GAMMA, F. Heat Recovery in Turbofan Engines: A Performance Analysis, 33rd AIAA/ASME/SAE Joint Propulsion & Exhibit, 7-9 July 1997, Seattle, WA, USA.
2. ANDRIANI, R., GAMMA, F., GHEZZI, U. Regeneration in Propulsion, 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 1-3 July 1966, Lake Buena Vista, FL, USA.
3. BOGGIA, S. Intercooled Recuperated Aero Engine, 2002, MTU Report.
4. BOGGIA, S. and RUD, K. Intercooled Recuperated Gas Turbine Engine Concept, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 10-13 July, 2005, Tucson, USA.
5. HEPPERLE, N. Design of a Heat Exchanger for an Intercooled Recuperated Aero Engine, 2007, MSc Thesis, Cranfield University.
6. KRAMMER, P., RUED, K. and TRUEBENBACH, J. Technology Preparation for Green Aero Engines, AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Years, 14-17 July 2003, Dayton, Ohio, USA.
7. KURZKE, J. GasTurb, 2007, available at: http://www.gasturb.de
8. LUNDBLADH, A. and SJUNNESSON, A. Heat Exchanger weight and efficiency Impact on Jet Engine Transport Applications, 16th ISABE Conference, Cleveland, Ohio, USA, 2003-1122.
9. MARX, M. Investigation and optimisation of Intercooling in an IRA Engine, MSc Thesis, 2007, Cranfield University, UK.
10. MCDONALD, C. and WILSONT, D.G. The utilization of recuperated engine cycles for high-efficiency gas turbines in the 21st century, *Applied Thermal Engineering*, **16**, (8/9), pp 635-653.
11. ROLT, A. and BAKER, N.J. Intercooled Turbofan Engine Design and Technology Research in the EU, 2009, Rolls-Royce Plc Report.
12. SAIDI, A., ERIKSSON, D. and SUNDEN, B. Analysis of Some Heat Exchanger Concepts for Use of Gas Turbine Intercoolers, *Int J Heat Exchangers*, 2002, **3**, pp 241-260.
13. SCHOENENBORN, H., EBERT, E., SIMON, B. and STORM, P. Thermomechanical design of a Heat Exchanger for a Recuperative Aeroengine, ASME, 2006, **128**, pp 736-744.
14. SCIALO, S. Performance Simulation and Investigation of an Intercooled Recuperated Aero Engine, MSc Thesis, Cranfield University, Cranfield, UK, 2007.
15. WILFERT, G., KRIEGL, B. and SCHEUGENPFLUG, H. CLEAN – Validation of High Efficient Low NO_X core, a GTF High Speed Turbine and an Integration of a Recuperator in an Environmentally Friendly Engine Concept, 41st AIAA/ASME, SAE, ASEE Joint Propulsion Conference, 10-13 July 2005, Tucson, Arizona, USA.
16. WILFERT, G., SIEBER, J., ROLT, A., BAKER, N., TOUYERAS and A., COLANTUONI, S. New Environmental Friendly Aero Engine Core Concepts, 18th ISABE conference, Beijing, China, 2007-1122
17. WHELLENS, M., TAGUCHI, H., SINGH, R. and PILIDIS, P. Genetic Algorithm Based Optimisation of an Intercooled Recuperated Turbofan Design, 41st Aerospace Science Meeting and Exhibit, 6-9 January 2003, Reno, Nevada, USA.