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OVERVIEW OF THE DEVELOPMENT OF HEAT EXCHANGERS FOR USE IN AIR-BREATHING PROPULSION PRE-COOLERS†

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Abstract—High pressure heat exchangers used in closed cycle rocket engines and air-breathing propulsion pre-coolers are required to work at very high heat transfer rates. They work with high fluid flow rates and are fabricated from tubes or channels which have small hydraulic diameters. This increases the compactness of the unit and therefore reduces its mass. Novel designs of the manifold are required so that the pressure drop remains within acceptable limit. This paper reports on the progress of research work to investigate the manufacture of such heat exchangers and characterise their performance. The investigations centre on a heat exchanger constructed from tube of 0.4 mm diameter with potential heat transfer coefficients of up to 5000 W/m^2/K. The heat exchanger is subjected to pre-cooler operating conditions of 1000 K simulated air external flow and supercritical cryogenic internal flow. It seeks to validate extrapolations of aerodynamic and heat transfer design data under extreme temperatures and high mass flow rates. Due to the small size of the heat exchanger and the thin walls of the tubes, novel manufacturing methods are required. Work is being done to investigate compatibility of various high temperature brazing materials with thin walled tubes and special manufacturing automation processes to allow cost effective constant-quality fabrication of production units. It is concluded that heat exchangers capable of power transfer rates of up to 1 megawatt per kilogram mass are capable of being manufactured and used operationally. This is a technology where production to satisfy future aerospace demands for single-stage-to-orbit and hypersonic propulsion can be envisaged.

Symbols

P	Pressure drop
d	Tube diameter
L	Tube length

1. INTRODUCTION

The technology used today in designing and fabricating tube heat exchangers is based on research developed in the 1960s. The principal reference has been the work of Kays and London [1]. Although much work has been done by subsequent researchers to improve understanding of heat exchangers, little has been done to advance their performance beyond the level established by Kays and London. The reason being that there has been little need. The primary use of high power heat exchangers is in the power generating and the chemical industries. These are terrestrial applications where the technological requirements are different to those of the aerospace industry. Unfortunately, the aerospace industry maintains a very small database on heat exchanger technology that is suited to flying vehicles. High power designs almost always reflect the state of the art from the terrestrial industries and produce units which are very large and have prohibitive masses. The success of any advanced combined cycle rocket propulsion system for the next generation of space and hypersonic transport vehicles depends ultimately on the development of heat exchangers much more advanced than what are available today.

2. COMPACTNESS

Heat exchangers are characterised by their compactness. This is the ratio between the amount of surface area over which the fluids can exchange energy to the total volume which the heat exchanger and fluids occupy.

$$\text{compactness} = \frac{\text{internal surface area}}{\text{total volume}}.$$

The heat transfer rate is proportional to the surface

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area over which it can take place. It is also proportional to the proximity of a fluid element to the surface across which transfer takes place. A higher compactness directly increases these two factors and for a unit volume of heat exchanger, the potential heat transfer rates increase disproportionately for an increase in compactness.

Another advantage of increasing compactness is the "economy of scale" benefit. Packing a unit surface area into a smaller volume better utilises the structure of the exchanger consequently reducing the mass per unit surface area. For a given heat transfer rate a more compact surface becomes progressively lighter. This is an important relationship to consider for a space transport vehicle application where weight reduction is a primary design objective. Heat exchangers used in space applications must demonstrate:

1. low total mass,
2. small volume,
3. ability to operate at very high pressures,
4. high power transfer rates in the region of hundreds of megawatts.

This requires considerable advances in the state of technology used today in terrestrial industries.

Advanced tube heat exchangers which can be custom designed for applications in rocket motors are possible using 1990s technology. This paper outlines the requirements for advanced rocket heat exchangers and the technologies involved to make them a reality.

3. OPERATING CONDITIONS OF THE SKYLON DEEPLY PRECOOLED HYBRID AIR BREATHING TURBO ROCKET ENGINE

The SKYLON Single Stage to Orbit (SSTO) aerospaceplane [2] uses a combined cycle air-breathing and rocket propulsion system called SABRE. While air-breathing it feeds supercritical air into the main rocket engines for the ascent through the atmosphere. On exiting the denser portions of the atmosphere and achieving a velocity of Mach 5 the developed performance of the air-breathing engine begins to decline. The engine then switches to onboard stored liquid oxygen for the injection into orbit. It is a union between rocket motor and gas turbine technologies. The thermodynamics of the cycle require the use of a number of heat exchangers which integrate the air-breathing system with the rocket motors.

The principal unit comprises two heat exchangers called HX1 and HX2. It is an air precooler which reduces the temperature of the collected air from a design entry temperature of 1000°C to a compressor entry temperature of −140°C. The air is then compressed by the turbo-compressor to the rocket motor injector entry pressure of approximately 150 bar.

During operation, this precooler is required to function with a developed power transfer rate of roughly 400 MW using deeply cooled helium to extract heat from the incoming air.

On designing this precooler using established technology [3], the mass of heat exchanger required to achieve this power capability is about 18 metric tonnes. (This is 1.5 times the transport's payload.) Advancing the design to present technological capabilities outlined in this paper, this mass becomes 0.6 metric tonnes: *a reduction by a factor of 30.*

4. THE SABRE PRECOOLER HEAT EXCHANGER

The primary heat exchangers HX1 and HX2 in the SABRE engine form the air precooler. The unit uses helium operating at 185 bar as the internal fluid. This is used to cool the air which enters the engine at a variety of conditions depending on the phase of flight: from ambient conditions when the vehicle is on the runway to the design point of approximately 1000°C and 1 bar at the maximum air-breathing flight speed of Mach 5.5 at 25 km altitude. The heat exchanger appears as a slightly tapered hollow cylinder with the mass of the heat exchanger forming the wall (Fig. 1a).

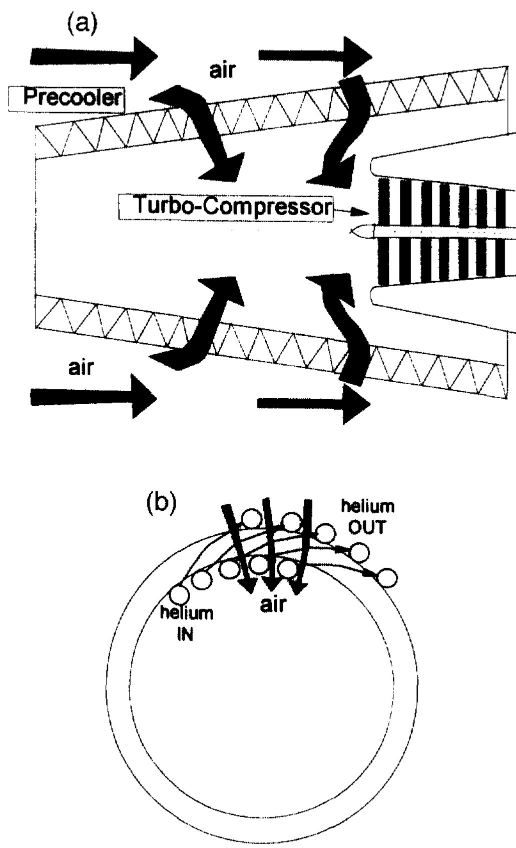

Fig. 1. (a) SABRE precooler side-view. (b) Along the longitudinal axis

Table 1. Dimensions and overall performance of the HX1 and HX2 precooler

Tube diameter	0.9 mm
Precooler length	5500 mm
Average diameter	2500 mm
Thickness	175 mm
Mass	~600 kg
Operating power	~400 MW

Air travels inwards through the cylinder "wall" where it meets the turbo-compressor located along its axis. Deeply cooled helium is supplied to the tube matrix by a series of tube manifolds located along the circumference of the inner "surface". The helium enters the matrix travelling circumferentially and radially outward counterflow to the air current. After exchanging heat with the air, it collects in similar manifolds located on the outer circumference (Fig. 1b). This arrangement takes maximum cooling advantage of the helium (Table 1).

5. HEAT EXCHANGER MANIFOLD DESIGN

Previous considerations of heat exchangers [3,4] for combined cycle engines generally settled on the progeny of Kays and London's [1] experimental work because of the pressure drop limitations associated with developing more compact tube surfaces. The smaller the tubes, the smaller is the hydraulic diameter and for a similar mass flow of fluid, the higher the pressure drop through the matrix.

For the same mass flow rate, the pressure drop in turbulent flow approximately varies with the tube diameter as

$$\Delta P \propto 1/d^{4.8}.$$

Using conventional manifolding techniques, the pressure drop would be prohibitive and the advantages of a lighter matrix are all outweighed by the penalties of the larger pumps required to overcome the pressure losses. This explains to a great extent why many aerospace engineers have been reluctant to use smaller tubes and therefore more structurally efficient compact surfaces. However, with smaller tubes the heat transfer rate increases and thus the tube lengths can be shortened reducing the pressure drop:

$$\Delta P \propto L.$$

Therefore, a smaller tube heat exchanger tends to have a very large number of short length tubes. Trying to plumb this using conventional design techniques is exceedingly difficult. What is needed is a radical departure from the established methods for configuring heat exchanger design. SABRE engine's heat exchangers therefore employ a completely new manifold design philosophy. This makes their appearance seem unconventional. The design takes account of the increased performance of the tube matrix and configures the manifold assembly to allow the exchanger to process a very large amount of fluid through it without incurring prohibitively high pressure losses.

Although the detailed manifold designs (Figs 1 and 3) had been configured many years ago through engineering ingenuity and painstaking trial and error, a systematic design philosophy has been discovered by the authors only recently [5]. The new rationale draws parallel from the designs used in the natural gas exchangers found in biological systems. The SABRE engine's heat exchangers particularly reflect the fish gill flow/manifold structure [6] a portion of which is schematically shown in Fig. 2. Similar to the fish gills, the heat exchangers use a large number of very low pressure loss non-heat exchanging manifolds linked together by very short runs of exceptionally compact high performance tube matrices across which heat transfer occurs very rapidly (Figs 1 and 3).

6. DESIGN OF THE JMHX1 HEAT EXCHANGER

The JMHX1 heat exchanger is a small 8 kW unit designed to test and verify the formulae and empirical extrapolations used to design the SABRE heat exchangers. It forms the principal experimental component used currently at Bristol University.

JMHX1 is not a small-scale representation of the SABRE engine heat exchangers. It represents a small section of the precooler that is cut-out and isolated (Fig. 3) so that small scale tests can be made under similar operating conditions as would occur in the main engine precoolers.

JMHX1 is an amalgamation of the various SABRE heat exchangers. The operating conditions for JMHX1 reflect those of the precoolers (cryogen internal fluids), while the tube size (0.38 mm od.) corresponds to the heat exchangers located on other circuits in the engine. As has been noted in Table 1, the outer tube diameter of the HX1 and HX2 heat exchangers is 0.9 mm. JMHX1 is thus designed to obtain comprehensive experimental data which would be useful for extrapolating heat exchanger performance well beyond what is needed for HX1 and HX2 exchangers. Table 2 summarises the main parameters of JMHX1, and Figs 4 and 5 show the arrangement of tubes.

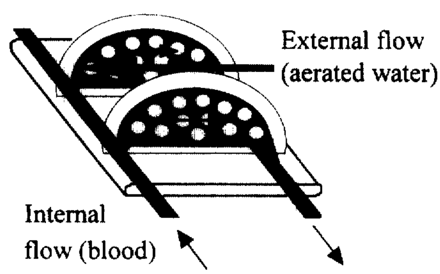

Fig. 2. Schematic diagram of a fish gill

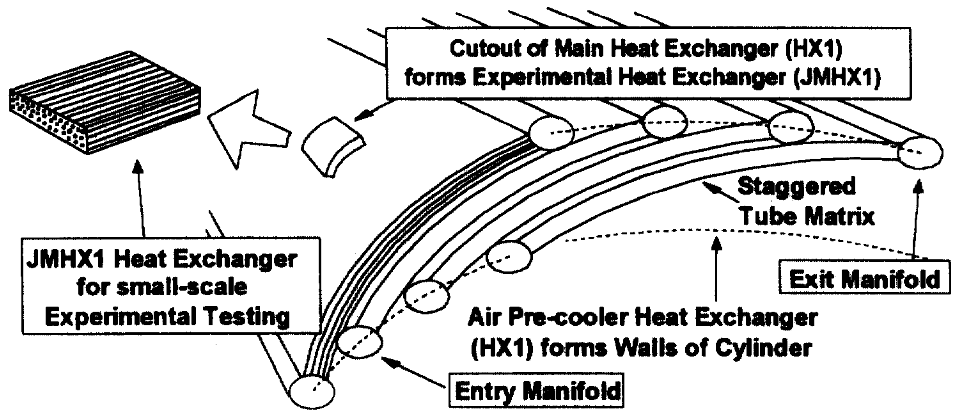

Fig. 3. JMHX1 is derived from a slice of the SABRE precooler

The JMHX1 is a thin square 40 mm × 40 mm staggered tube array (Figs 4 and 5) heat exchanger of 10 rows thickness. Along a row the staggered tube pitch is:

$$X_l = 2.5d$$

and the pitch between rows is:

$$X_t = 1.1d.$$

JMHX1 is designed to facilitate experimental analysis of each of the rows. The internal fluid enters the tube matrix from a common inlet manifold. The fluid from each row is collected on exit into individual manifolds which allow heat transfer and corresponding pressure loss analysis for each of the rows. This builds up a model of the heat transfer performance of the individual rows and produces a complete model of the entire heat exchanger. This data is used to create a mathematical model verifying the applicability of extrapolations of design data from previous working heat exchangers.

7. DESIGN EXTRAPOLATIONS

Current data used in the design of heat exchangers is based on experiments using terrestrial configurations. The lower geometrical limit of all experiments performed to this date currently remains at around 2–3 mm tube diameter. Using this design data for tubes which are an order of magnitude smaller than the smallest tubes used to generate the original experimental data still represents a certain level of risk.

Table 2. Dimensions of the JMHX1

Width	40 mm
Length	40 mm
Thickness	4 mm
Tube out/inside diameter	0.38/0.28 mm
Number of tube rows	10
Total number of tubes	415
Tube material	Stainless 316
Operating Pressure (Design)	
Internal Fluids (N_2 and He)	100 bar abs.
External Fluid (N_2)	1 bar abs.
Operating Temperatures	
Internal	80 K—300 K
External	300 K—1000 K

While it would seem logical to assume that the Reynolds, Nusselt and Stanton Number correlations remain true at these smaller sizes, it appears not to have been experimentally proven. The non-dimensional relations can be calculated for these small tubes and accurate correlations are available. JMHX1 is used to experimentally prove the validity of these dimensional extrapolations. It also does this by using fluids operating at conditions as close to the actual engine operation conditions as possible. This will extend and confirm the boundaries to which the database of experimental data can be confidently applied. Additionally, it would serve to instil confidence in the performance capabilities of the SABRE engine design.

8. MANUFACTURING TECHNIQUES

Tube heat exchangers which operate across a large temperature range are either metallic or made of exotic ceramic materials. They comprise many intricate joints which must be reliably connected together using methods such as welding or brazing. This is a costly, time consuming, and labour-intensive process. Fabrication quality is based on the skills of the fabricator and much of the assembly is done by hand. Although time consuming, the size of the tubes in conventional units allows easy manipulation and joining by hand. This becomes increasingly difficult when the size of the tubes decreases and their number disproportionately increases. Heat exchangers on the SABRE engine consist of 100 000's of tubes. They are made of tubes of 1 mm or less and can no longer be individually manually joined to any satisfactory degree of consistency and reliability. New techniques need to be used and some level of automation must be employed in manufacturing these very compact tube heat exchangers. JMHX1 thus serves as an experimental proving rig to test out suitable procedures for fabricating the SABRE heat exchangers.

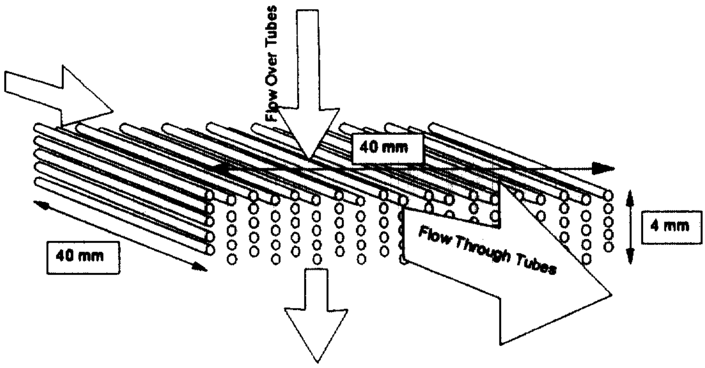

Fig. 4. JMHX1 tube layout

This is enhanced by operating the exchanger under similar fluid conditions as would occur in the engine requiring materials capable of withstanding the temperatures and pressures encountered.

The inlet manifold presented a representative problem being similar to one side of the tube manifolds used in the HX1 and HX2 precooler assembly. The tube geometry forms a staggered arrangement and the manifold surface consists of a matrix of holes drilled into a flat plate. The holes must be spaced to close dimensional tolerance and the inside surface of the holes must be of consistent quality to allow them to be joined to the tubes. For SABRE engine manufacture the holes will most likely be laser drilled. The JMHX1 manifold was NC drilled using a 0.40 mm drill bit. The resulting hole diameters are 0.41 mm consistent over the entire 415 hole matrix. Figure 6 shows a section of the manifold.

The method chosen to join the tubes to the manifolds is brazing. It is a very empirical process. The brazing filler metal must be selected to give suitable strength and corrosion resistance under the working conditions of the joint. The geometry of the joint and the type and metallurgical condition of the parent metals (tube and manifold plate) affect the resulting quality of the joint and also its eventual operational properties. The assembly of the apparatus and the positioning of the filler metal which will flow into the joint gap to make the junction must also be tested. It was quickly realised that many prior experiments were needed before actual assembly of JMHX1 could take place.

Brazing stainless steel invites particular complications due to the very stable oxide layer formed. Suitable techniques are vacuum or hydrogen furnace brazing. To test materials compatibility an experimental hydrogen brazing rig was built at the University.

To maintain structural integrity in the thin wall tubes, a minimum number of grains spanning the wall is required. This, from experience, was specified as 8. A particular nickel–chromium brazing filler metal was selected. This has low aggressivity (does not penetrate too deeply into thin walls), good strength, and resists oxidation up to 850°C.

Figure 7 illustrates a sample experimental result using this material. The tube material is SS-316 of 1 mm od. and 0.16 mm wall thickness. There are at least 10 grains spanning the stainless steel tube wall (top of picture). The penetration of the nichrome filler metal (majority of lower section) is restricted to within the surface grain. The brazing temperature was 980°C.

Brazing techniques are designed to take advantage of the effects of capillary action.

The problem with brazing tubes which have a similar size to the gaps between the joints is that

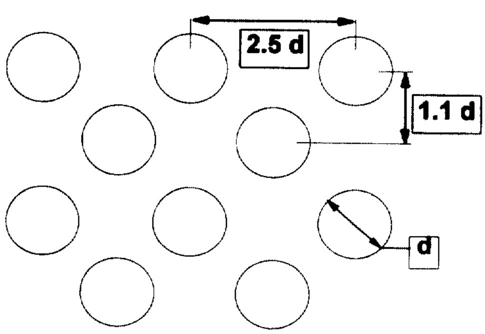

Fig. 5. Diagram of JMHX1 matrix

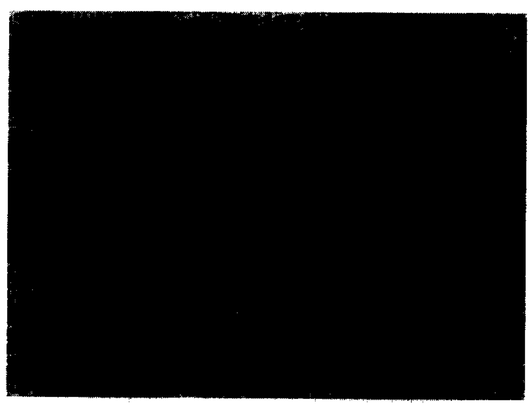

Fig. 6. Manifold holes, magnification 40 ×

Fig. 7. Cross-section of SS 316 tube –90Ni10P braze joint, magnification 260 ×

the filler metal is just as likely to travel up the tube or collect between the spaces between adjacent tubes as it is to be drawn into the tube-manifold gaps. Special attention needs to be paid to how the brazing metal is distributed around the joints. This is difficult because the small size of the piece makes it very hard to position the filler metal in the best places.

The solution to this is to deposit the filler metal onto the manifold surface between the holes by electro-less nickel plating. This technique was originally developed to provide a protective coating for milk churns. By slightly varying the deposit composition, the present application uses the nickel as the filler metal for the brazing operation.

9. VERIFYING DESIGN DATA

Table 3 shows the expected performance of the heat exchanger during design operation. JMHX1 is expected to attain an average internal heat transfer rate of up to 4250 W/m^2/K assuming an average N_2 fluid temperature of 500 K.

Since each row of the tube array is individually sampled, the external flow entry effects can be explored as well. Heat exchangers normally take a few rows before the flow settles down and performance values become stable and repeatable. JMHX1 can be used to quantify this. Aerodynamic effects can be investigated as well to model correlations to friction data subjected to large temperature variations.

In all, JMHX1 provides a versatile unit allowing many performance parameters to be investigated under a variety of flow conditions.

Table 3. Expected performance of JMHX1 during design operation

Internal nitrogen flow	
inlet temperature	80 K
mass flow rate	0.023 kg/s
mass flux	922 kg/m^2/s
External nitrogen flow	
inlet temperature	1000 K
mass flow rate	0.023 kg/s
mass flux	30 kg/m^2/s
Operating power	8000 Watts
Total mass of tubes	6.5 grams
Power/weight performance	1.23 MW/kg

10. ADVANCING THE FRONTIERS OF HEAT EXCHANGER DESIGN TOWARDS THE BIOLOGICAL LIMIT

Current effort has been primarily centred on advancing existing heat exchanger performance by an order of magnitude. This has an immediate direct application in the space transportation industry where efforts to develop economical single stage to orbit transports are in progress. To achieve this, significant work is being done to solve the problems associated with using smaller tubes. During the course of this work, the potential limitations of the technology have been explored and it was found that it is possible practically to build heat exchangers with tube sizes approaching the biological limit. Fabricating tubes of diameters of 10–20 μm has been possible for many years. The exploration into building heat exchangers with them has centred on the manifolding technology; effectively utilising the same design philosophy discovered in use in living organisms [6]: that of minimising the pressure drop through the matrix. The technique is called fractal manifolding: fractal, because the coding used to design the manifolds is based on very simple repetitive formulae [5].

Using this technique, heat transfer coefficients of up to 30 000 W/m^2/K can be achieved due to the very small tube size and power transfer to weight ratios of the resulting heat exchangers can reach 1 GW/kg mass.

11. CONCLUSION

Heat exchangers with power transfer rates of up to 1 megawatt per kilogram mass are capable of being manufactured and used operationally. (This represents an improvement in the power-to-weight ratio by a factor of 30 as compared to conventional technology described, for example, in Perezagua *et al.* [3]) Verification of heat transfer results is seen as a prerequisite to widespread acceptance of the capabilities and adoption of the new technology. Using small tubes to increase the performance of heat exchangers is not a straightforward procedure. Previously, the difficulties associated with the resulting high flow losses have all but negated their advantages. A completely new approach to the design of the manifolds was required to regain the benefits. In addition, new approaches to manufacturing have evolved which no longer make their construction prohibitive. With this completed, it would be possible to build operational units for direct application in the next generation of space transportation and hypersonic propulsion vehicles. There also exists the potential to make systems using micro-tube fractal manifold heat exchangers which give near molecular heat transfer performance. However, this technology, whilst feasible, still requires further investigation.

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