DEVELOPMENT AND TESTING OF ADVANCED HEAT EXCHANGERS FOR IN-FLIGHT OXYGEN COLLECTION SPACE LAUNCHERS

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Abstract

In the scope of an ESA-funded theoretical and experimental study (in the GSTP3 programme) on heat exchangers intended to provide in-flight oxygen collection capability to a reusable or a semi-reusable TSTO launcher with an oxygen collection phase in supersonic cruise, two subscale models of an air-hydrogen precooler and a test set-up are currently being developed in Belgium and in Spain. The vehicle we foresee for this application is described in previous conference papers as well as the work on our ESA-funded airborne air separator, which is the other critical element of the oxygen collection plant. This current paper is concentrating only on the theoretical but mainly the technological and experimental aspects of such an air precooler.

The experimental and technical aspects include choices and main trade-offs that have had to be made during the design process by the different partners (Techspace Aero, the von Karman Institute, Iberespacio, University of Liège, Royal Military Academy of Belgium and University of Brussels).

After we fixed the requirements at system level and at the precooler level, a simulation work of generic heat exchangers is presented including the problem of frost formation and its influence on the heat exchanger performance. A few advanced heat exchanger designs are analysed resulting in a more detailed parametric and performance analysis of two advanced configurations. A detailed study of the most advantageous heat exchangers materials is shown resulting in the selection of the alloys for the two breadboards.

The manufacturing processes for these two breadboards are defined, based on trials on small scale models inspired from the two technology candidates.

Perspectives are also given for the mechanical and thermodynamic testing of the two breadboards.

Nomenclature

CR	Collection ratio (mass of LEA produced per unit mass of LH_2 consumed)
Cox	Oxygen mass fraction in the flow (by default, in the LEA flow)

GDA	Gaseous (oxygen) Depleted Air
LCP	LOX/LEA Collection Plant
LEA	Liquefied (oxygen) Enriched Air
LEO	Low Earth Orbit
LH_2	Liquid Hydrogen
LOX	Liquid Oxygen
SSTO	Single-Stage-To-Orbit
TSTO	Two-Stage-To-Orbit
η_{sep}	Separation efficiency (O_2 mass fraction recovered in enriched flow from incoming flow)

Indices:

c	cold side
h	hot side
1	first stage of TSTO
2	second stage of TSTO

1. Introduction

Belgium, starting in the mid 90's and through a large level of ESA support through its FESTIP programs [1], has been investigating the concept of a 2 stage launcher based on a hydrogen fuelled turbofan engine powered first stage carrying a second pure rocket orbital stage. The attractiveness of this project rested on the large reduction in total vehicle take-off weight by in-flight collection of the oxygen for the second stage, being its largest mass component. Oxygen collection technology, trajectory optimisation, and stage separation have been key technical points requiring definitive and practicable if not straight-forward answers.

Two concepts of TSTO's using in-flight oxygen (LOX) collection will be presented with in both cases a reusable air-breathing 1st stage launcher. The first one is with a high supersonic separation (staging) of the 2nd stage and the other one with a subsonic staging. The second case study seems not very appropriate concerning the delta V obtained for the orbiter but the advantage is somewhere else, i.e. the almost direct applicability of the solution in a near future and the flexibility of the solution concerning the orbit and the launch azimuth.

After the presentation of these two concepts, the technology developments started in Belgium a bit more than 2 years ago will be explained.

2. System studies

2.1. General Framework

In Belgium, research activities on air-breathing and other advanced launchers conducted with universities started in 1994 together with a company called VDK Systems. The activities were mainly focussed on ram- & scram simulations and vehicle sizing & trajectory calculations.

From 1996, with the support of the Belgian Space Delegation, a concentration of the activities on a particular topic has been clearly marked towards the Oxygen Collection Cycles and Vehicles, also called ACES for Air Collection & Enrichment Systems. Three studies have been completed until now : first a Belgian funded ESA feasibility study, then a study on ACES SSTO's in FESTIP I and, finally, a last one on ACES supersonic and subsonic staging TSTO's in FESTIP II. In FESTIP I & II, experimental work has also been accomplished by the University of Liège on air separation through vortex tubes by the team of Ph. Ngendakumana [Figure 1].

An example of an analysed launcher is shown hereafter. Other studies on TSTO with a subsonic staging have been also performed [2].

2.2. TSTO with supersonic collection case study

The ACES TSTO with supersonic staging and collection at supersonic speed has been deeply studied by Techspace Aero (Prime Contractor), RMA and VKI during the ESA FESTIP II Technology program.

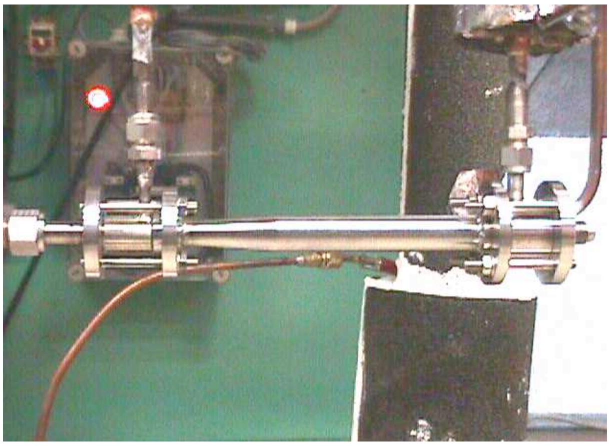


Figure 1: Vortex Tube O_2-N_2 Separator Set-Up

This In-Flight LOX Collection concept has been the subject of studies and technology demonstrations since the 60's. It consists in collecting air during the atmospheric phase of a launch, to enrich its oxygen content by separating and rejecting the nitrogen and to store the liquefied oxygen enriched air in the tanks for a subsequent rocket propulsion phase. Air pre-cooling and liquefaction are realized in heat exchangers thanks to the high cooling capacity of hydrogen fuel. This concept is here applied to a TSTO in a rather different way than what has been proposed by the USAF in the 60’s and early 90’s.

With a staging (separation) Mach number between 4 and 5, it can provide a very interesting launcher solution, even if the collection phase takes place in cruise only, at a relatively "low" cruise Mach number (about 2.5) and with a "moderate" Collection Ratio (i.e. the ratio of collected LOX mass flow rate per kilo of hydrogen used in the launcher, e.g. CR=3 or less, even though values around 5 are frequently quoted in the literature). Indeed, the ACES TSTO concept allows to take-off with a much lighter vehicle (no LOX in the tanks) which induces a lighter landing gear, a lighter propulsion plant, a quicker climb phase (with less drag) and, last but not least, a lower planform area (Spf1) (which means a lighter structure) for a given planform loading at take-off. The second stage can be reusable or expendable making the whole transportation system fully reusable or semi-reusable.

The launcher 1st stage is propelled by gas turbine engines from take-off up to Mach 3.8. It is followed by ramjet propulsion up to the staging Mach number (e.g. Mach 5.0). Three aspects of the launcher were studied : 1st stage propulsion (von Karman Institute), LOX Collection Plant (LCP) pre-design (Techspace Aero) and integration of the results of these two studies in a pre-design tool used to evaluate the performance of such a launch vehicle (RMA) [2].

One of the challenges of this study is to integrate propulsion and LCP. Indeed the LCP requires an air intake, a compressor to overcome the high pressure losses in the heat exchangers and in the N_2-O_2 separator, and a nozzle to reject the oxygen depleted air and recover a part of the collection drag. As these elements are already present for the air-breathing propulsion of the first stage, an interesting idea is to integrate the LCP with the propulsion engines by using the bypass flow of a turbofan engine (LBPR) as the incoming air to the collection plant during the collection phase of the flight. The outer part of the LP compressor is also the LCP compressor. The depleted air is reintroduced into the bypass to be mixed with the engine core flow and expanded in the main nozzle with the possibility of afterburning. This could decrease the additional drag induced by LOX collection and reduce the total mass. The system is represented in the schematic of Figure 2.

The feasibility of this original system has been analyzed through cycle studies and examination of performance in design and off-design engine operation. Different engine configurations and LCP variants were investigated and their performance along the entire trajectory calculated. One difficulty is that the sub-systems and the vehicle studies interact strongly with each other. For example, the hydrogen used in the LCP has to correspond to the fuel consumption of the engines that produce the thrust required by the vehicle. For such an advanced launcher concept, a vehicle sizing & trajectory calculation tool such as the one developed at RMA [3] is absolutely required.

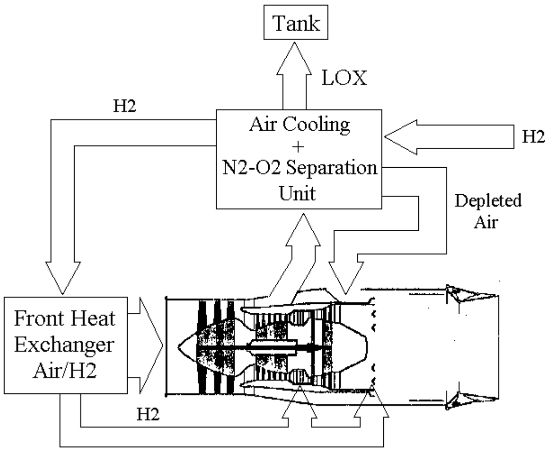


Figure 2: Integrated propulsion LOX collection engine

The iterations between TA, VKI and RMA leaded to a vehicle with the front part of the turbofan engine with a ring pre-cooler system as sketched in Figure 3.

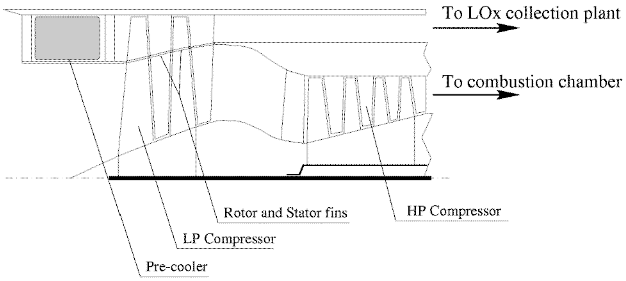


Figure 3: The ring pre-cooler system

The first stage flies at a constant dynamic pressure trajectory of 43 kPa. Its mission is mainly an acceleration mission from take off to staging at Mach 5 although a cruise is needed at Mach 2.5. This cruise phase provides the necessary time for LOX collection and ensures a stable on-design operation of the LCP for a large part of the collection phase.

The turbo-engines must be used from take off to Mach 3.8 while ramjet propulsion ensures the final acceleration, the pull-up for separation and the first part of the return flight, before gliding. LOX collection can take place within the 1.8 to 3 Mach number range, including the cruise at Mach 2.5 or only in cruise. The total thrust capability of the 8 combined engines equipped with the ring pre-cooler system is given in Figure 4 for stoichiometric reheat.

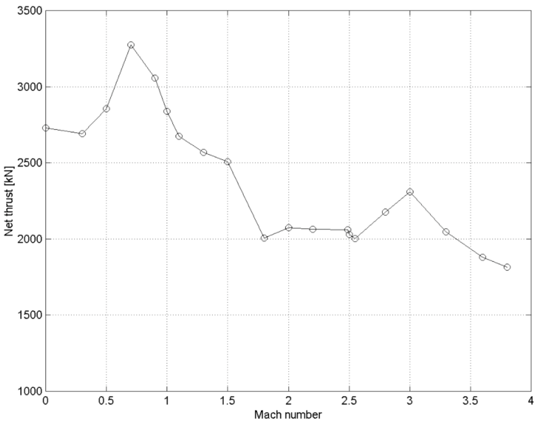


Figure 4: Maximum thrust capability (Turbofan engine with ring pre-cooler system)

The thrust diminution when collecting is due to the lower oxygen quantity available for afterburning and to the necessary throttle-down to reduce the LP rotational speed.

Different options were also investigated for the location of the heat exchangers, including the calculation of the LCP performance. An option is sketched on Figure 5.

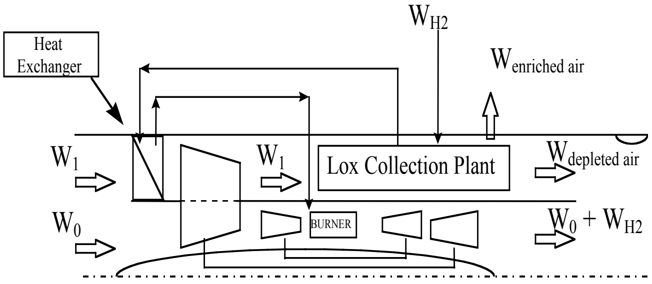


Figure 5: Integrated LCP-engine architecture

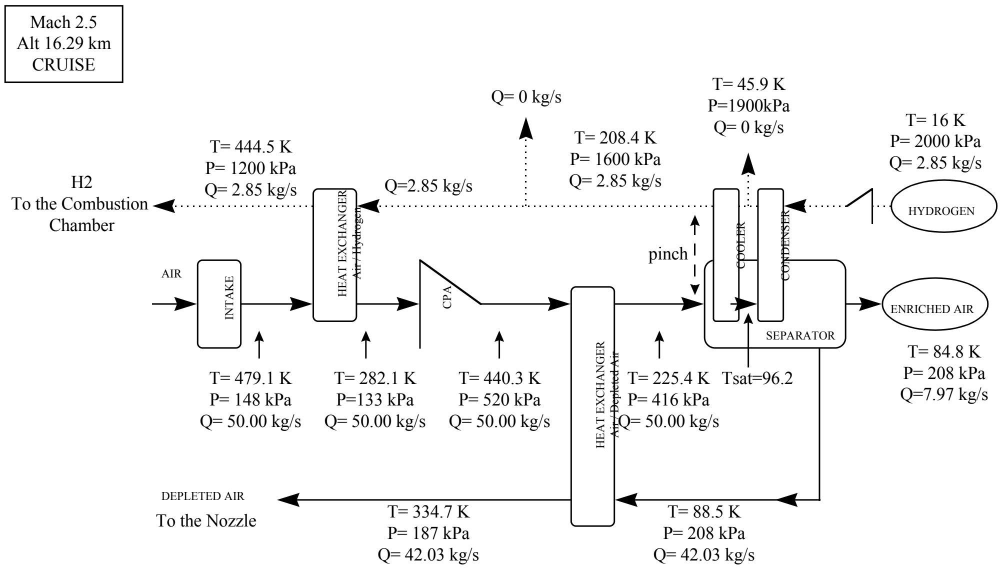


Figure 6: Ring heat exchanger configuration, LCP main parameter

The input parameters of the LCP thermodynamic calculations are adapted to the data provided by the propulsion plant study presented above. These data correspond to an 8 engines first stage launcher. The air processed through the LCP for each engine is approximately 50 kg/s and the enriched air (LOX) production is about 8 kg/s. The main data provided by the propulsion study are the outer fan pressure ratio and the bypass air mass flow rate. An example of the LCP simulation is shown for a Mach 2.5 cruise collection phase on Figure 6. The most important result of this simulation is certainly the value of the collection ratio CR, here equal to 7.97/2.85 or 2.8.

The results of the sub-system detailed studies are then introduced in a pre-design vehicle-sizing tool which integrates the propulsion, aerodynamics and in-flight LOX collection aspects using the results provided by the sub-system studies with a complete vehicle trajectory calculation and a mass & volume model of both stages.

Table 1 is for a fully reusable HTOHL (Horizontal Take-Off Horizontal Landing) TSTO staging at Mach 5.0 and a CR of 2.8. Collection takes place in acceleration (between Mach 1.8 and 3.0) but mainly in cruise (at Mach 2.5, 16.7 km altitude).

Sizing Parameter	**Cox = 95%**	**Cox = 92%**	**Cox = 90%**
TOGW (t)	333.4	353.0	369.2
$Wdry_1$ (t)	185.0	195.4	203.9
Cruise (s)	2279	2409	2507
τ_o (-)	0.0523	0.0510	0.0500
$W_{LH2,1}$ (t)	90.6	96.9	102.2
$Vppl_1$ (m^3)	1264	1352	1426
$LOGW_2$ (t)	178.1	189.2	198.5
$Wdry_2$ (t)	30.1	31.7	33.0
τ_2 (-)	0.0764	0.0743	0.0727
W_{LOX2} (t)	122.1	130.3	137.2

Table 1: ACES TSTO – Influence of stored LOX purity

(Indices 0, 1 and 2 refer respectively to the whole vehicle, the 1st stage and the 2nd stage)

It is shown that, with a LOX purity of 90%, the launch of a payload of 7 tonnes on an equatorial LEO (ESA FESTIP requirement) requires a TOGW as low as 370 t with a 1st stage dry mass of 200 tonnes for a fully reusable TSTO taking off from Kourou. In all these launch vehicles, the collection plant mass represents only less than 2% of the 1st stage dry mass. The specific mass of the collection plant (and thus mainly of the different heat exchangers) is therefore not critical, like it is in a SSTO with in-flight LOX collection or in the USAF studies of the 60's and '80's [4, 5, 6].

3. Required technology

Two developments are necessary in order to be able to implement such a new launcher concept: the air separator and the heat exchangers. The N_2/O_2 separation device based on a rotary distillation concept has been presented in other papers [7, 8, 9]. This paper will be focused on the heat exchangers and especially the first air/hydrogen heat exchanger of Fig. 6, the precooler.

3.1. Preliminary Precooler design

A first design of the precooler has been performed based on simple assumptions. The objective has been from the beginning to integrate the precooler as much as possible with the

turbofan. A solution has been to design a circular ring-shape precooler located around the engine intake.
This design and a first series of calculation results is given in Figure 7.

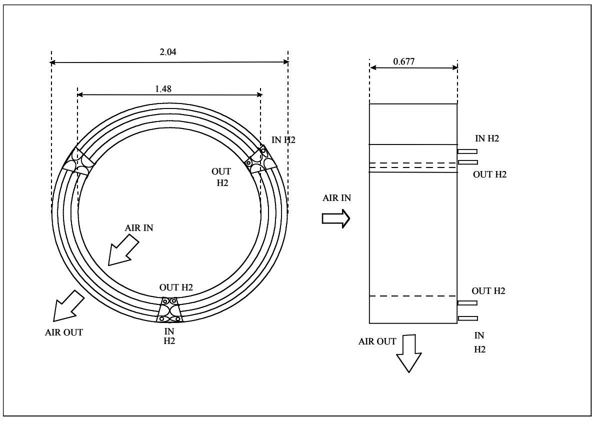


Figure 7 – Ring-shape precooler and its dimensions

	GSTP1	GSTP2
Cold fluid (-)	$H_{2\ para}$	$H_{2\ para}$
Cold mass flow rate (kg/s)	3.01	**3.65**
Cold inlet temp (K)	208.4	**157.0**
Cold inlet press (bar)	16.0	16.0
Cold outlet temp (K)	444.5	**414.7**
Cold outlet pres (bar)	12.0	12.0
Hot fluid (-)	Air	Air
Hot mass flow rate (kg/s)	52.8	**55.0**
Hot inlet temp (K)	479.1	479.1
Hot inlet press (bar)	1.48	1.48
Hot outlet temp (K)	282.1	**222.6**
Hot outlet pres (bar)	1.33	1.33
Heat rate (kW)	10600	**14342**
Heat exch. efficiency (-)	0.872	**0.800**
Log-mean temp diff (K)	51.7	**65.0**

Table 2 – Preliminary working parameters of the precooler

Two sets/specs of working parameters for this preliminary design of the air/hydrogen precooler are shown in Table 2 (the difference between the cases GSTP1 and GSTP2 is just related to the value of the CR, respectively equal to 2,8 and 2,4).

3.2. Precooler designs

This preliminary concept has been refined. Two configurations were analysed in details : a shell and tube and an alternate configuration. The non-conventional configuration that has finally been selected is a plate-fin curved configuration with different types of fins, as offset strip fins or wavy fins (Figure 8) and even straight fins, with low pressure losses.

Figure 8 – View of off-set strip and wavy fins and their geometry

Those two precoolers are represented in Figures 9 and 10, which are respectively with four air passes and three air passes.

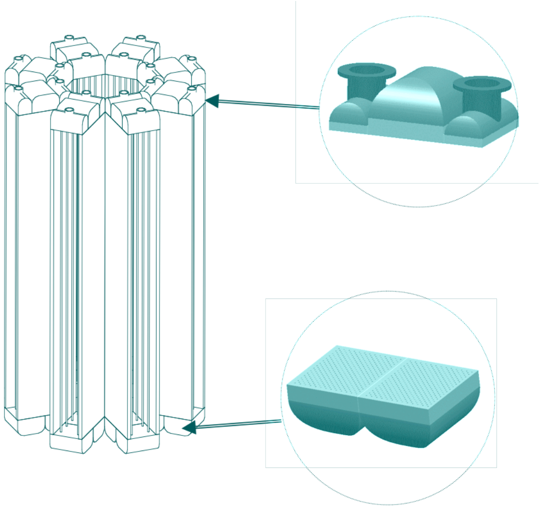


Figure 9 – Shell and tube "flower configuration" precooler

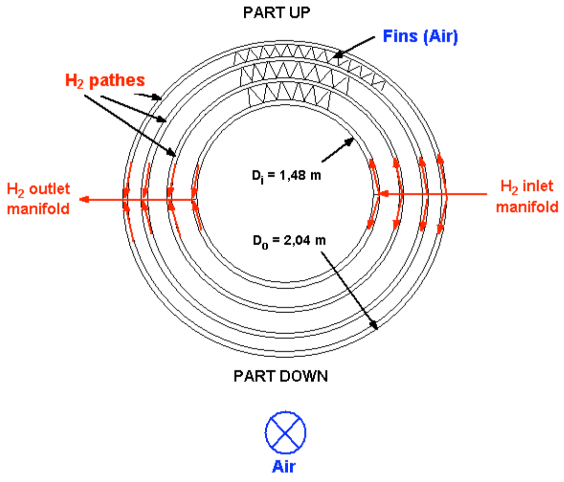
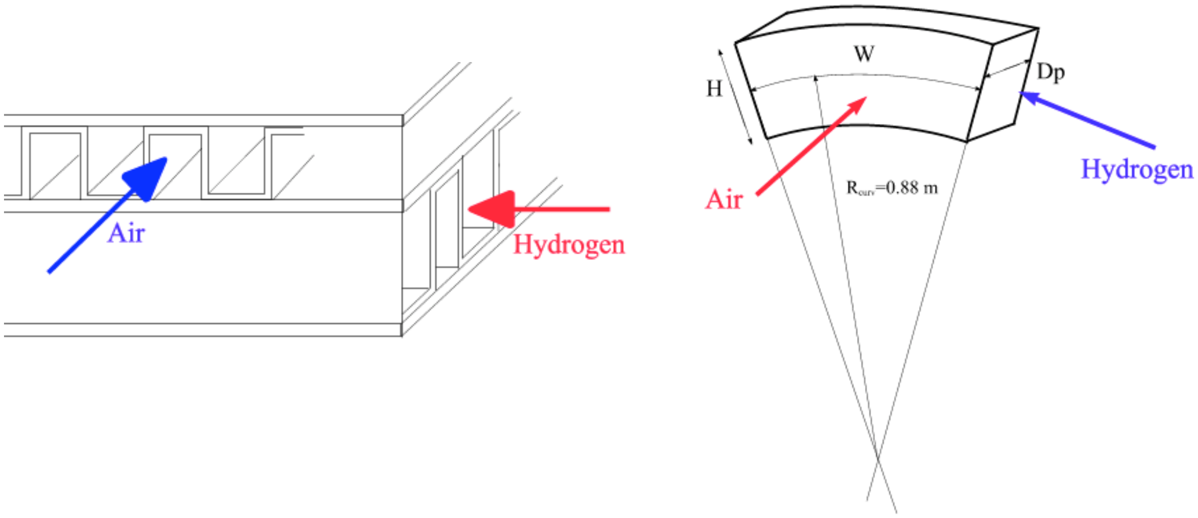


Figure 10 – Plate-fin curved precooler

3.3 HEX breadboard designs

Based on the type and geometry of the two full size precoolers, two breadboards (BB) for each configuration have been calculated and designed. They will be built in aluminium alloys. One of the BB of the P&F configuration based on offset strip fins as represented in Figure 8 is shown with some of its characteristics and simulated testing conditions in Figure 11.



	fin spacing *s* [mm]	fin height *h* [mm]	offset pitch *l* [mm]	thickness *t* [mm]
Air side	3	8.75	10	0.2
Cold side	3	1.65	10	0.2

Air	**supply temperature**	**[K]**	**479.1**
	supply pressure	**[bar]**	**1.48**
	exhaust temperature	**[K]**	**282.1**
	max exhaust pressure	**[bar]**	**1.33**
n-Hydrogen	**supply temperature**	**[K]**	**208.4**
	supply pressure	**[bar]**	**16**
	exhaust temperature	**[K]**	**444.5**
	max exhaust pressure	**[bar]**	**12**

Figure 11 – Plate-Fin brazed BB

4. Conclusions

The in-flight oxygen collection concept is under study in Belgium for ESA since the late 90's. The preferred option is the TSTO with a supersonic collection in cruise at Mach 2.5 and constant altitude and a supersonic staging at Mach 4.5-5.0.

The air / hydrogen front heat exchanger or precooler is under study. Two different configurations for the full size precooler are under consideration. Based on those designs, two breadboards of each configuration have been designed and are under construction at the moment in order to be tested before the end of the study in order to characterize them and check their tightness after cycle loadings.

Acknowledgments

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