HiSST: 2nd International Conference on High-Speed Vehicle Science Technology
11–15 September 2022, Bruges, Belgium

SABRE Bypass Ramjet Concept Evaluation

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Abstract

SABRE - Synergetic Air Breathing Rocket Engine – combines the advantages of a high specific impulse air breathing engine with a high thrust/weight ratio rocket motor. During air breathing mode, SABRE - operating in a combined turbomachinery based cycle of the core engine and ramjet cycle of the bypass burner - captures the ambient air as oxidizer [1]. To minimize drag, the adjustable air intake system is capable of aligning the shock structure to the free stream Mach number and capturing the maximum possible air mass flow.

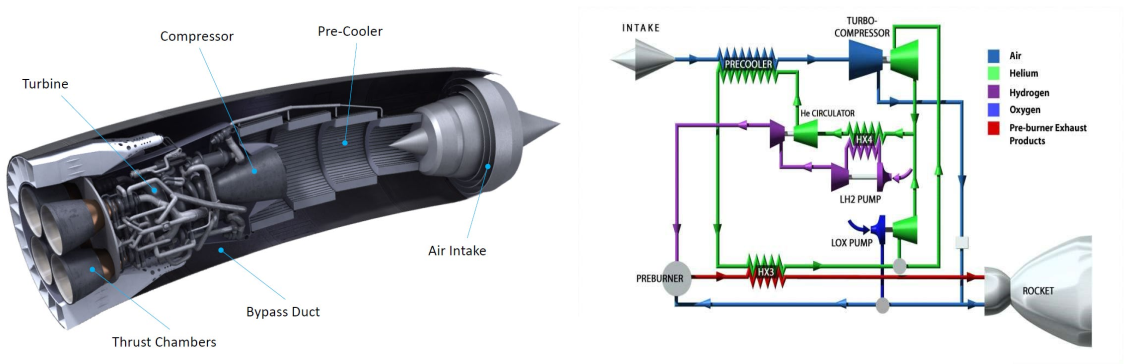

Fig 1. SABRE Engine and simplifies cycle of the core engine

The system is designed in such a way that the core engine is operating under nearly constant conditions – air mass flow, temperature and static pressure – independent from Mach number and altitude. In consequence, a significant percentage of the air mass flow has to be bypassed at low altitudes. This air can be used to generate additional thrust with the excess hydrogen of the core engine cycle in a ring of single ramjet modules [2].

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Independent from the air mass flow through the bypass burner, the system should hold the static pressure of the pre-compressed air at the pre-cooler inlet within a predefined, quite narrow band. In conclusion, the bypass burner system should control the static pressure at the pre-cooler inlet as well as the air mass flow to the core engine while maximizing the thrust.

This paper summarizes the evolution of a design concept for the ramjet bypass burner system.

Keywords: *SABRE, ramjet*

Nomenclature (Tahoma 11 pt, bold)

p – pressure
T – Temperature
n – number
t – times
THR - thrust
$\dot{m}$ – massflow
Γ – constant dependent on gas parameters

Subscripts

PM – Per Module
t – total
total – total / for all modules
fuel – fuel / hydrogen

1. Introduction

The control of both the static pressure and the air mass flow to the core engine can be done in two ways. Either by adjusting the effective overall nozzle throat area or the hydrogen supply to the bypass burner and in consequence the combustion temperature, see Eq. 1.

$$\dot{m}=\frac{p_t}{\sqrt{T_t}}A\Gamma \tag{1}$$

To achieve maximum thrust, the system should be designed in such a way that nearly all of the hydrogen provided by the core engine is used for the combustion. As a result the static pressure at the pre-cooler inlet should be controlled in a cascaded way; a first coarse control loop by adjusting the effective throat area, dependent on the flight conditions, see Fig. 2, and a second fine loop via the hydrogen mass flow.

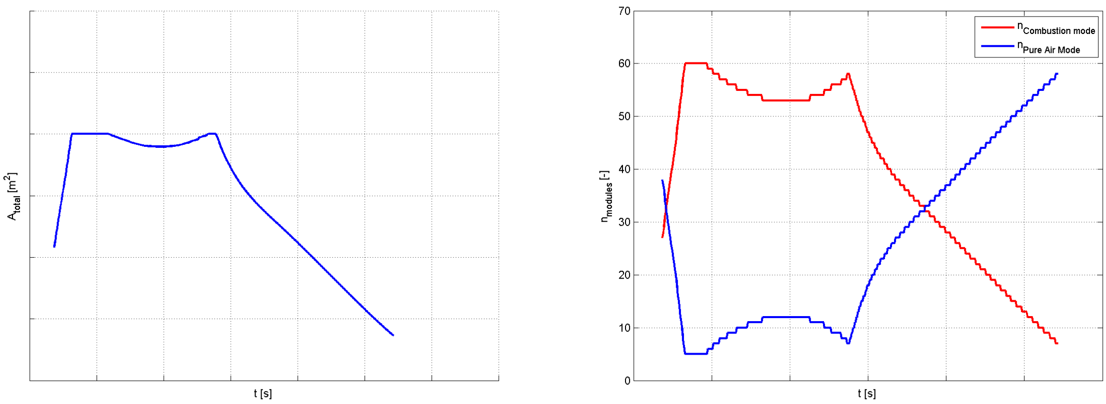


Fig 2. Effective Throat area as a function of time (left hand) and number of modules in combustion mode (right hand - red) and pure air mode (right hand -blue) for discrete module concept

An adjustment of the overall throat area can be done in two ways:

- A continuously adjustable nozzle throat of each single bypass burner module
- A system of single modules which can be switched off resulting in discrete effective area steps (see Fig 2)

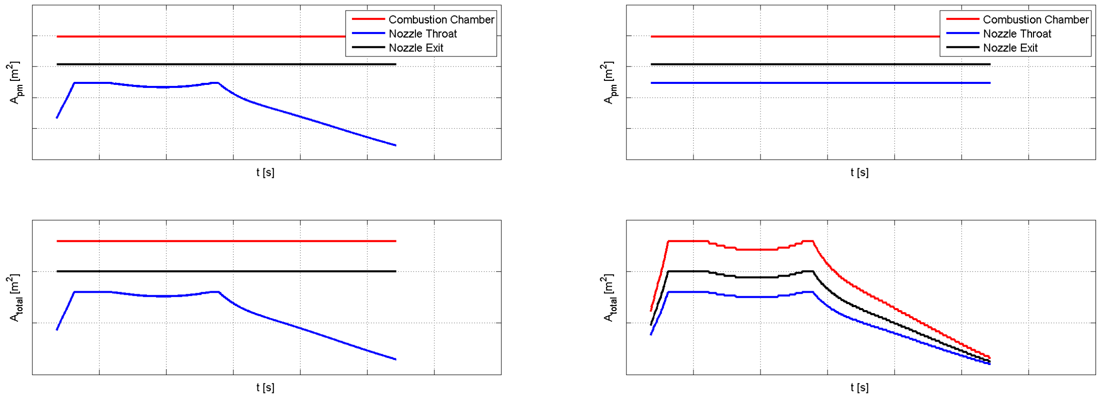


Fig 3. Combustion chamber (red), nozzle throat (blue) and nozzle exit (black) area of each single module (top) or all modules (bottom) for an adjustable nozzle throat system (left hand) and discrete area steps (right hand)

Fig. 3 shows the combustion chamber (red), nozzle throat (blue) and the nozzle exit area (black) of a bypass system with 64 modules. The top graph shows the areas for each module, while the lower graph shows the effective area of all modules. The left graphs are based on a simulation with an adjustable nozzle throat for each module, while the right hand graphs present a system with discrete area steps. As it can be seen, for the first half of the trajectory nearly no module is switched off, which means the two concepts are nearly identical even with respect to the nozzle exit area. Due to the high number of modules the difference in effective throat area are quite small over the complete flight path.

Table 1 gives a first summary of different principle concepts for adjustable nozzle throat and discrete modules. For the adjustable nozzle throat system three principle concepts were found. A first qualitative assessment is given in Table 2.

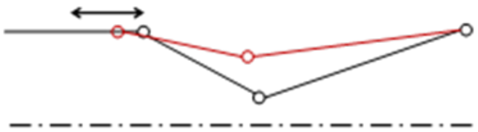
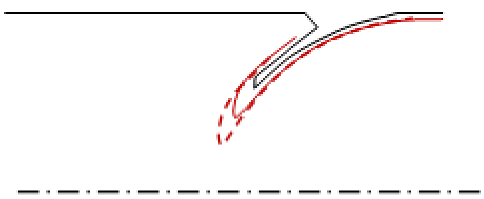
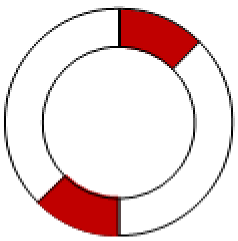
The first concept is a 2D nozzle with two hinged flat panels which form the convergent and divergent part of the nozzle via an axial movement of the nozzle inlet. The main advantage of such a system is the very high specific impulse reached by the adjustment of nozzle throat and nozzle expansion ratio. The main disadvantages of such a system are the very high complexity, e.g. the actuation system as well as the main part of the mechanics have to be placed in the hot combustion gas environment. In addition, a sealing of such a system during reentry including all the hinges and flat panels would be quite difficult. One of the main advantages of an adjustable nozzle concept is the fact that there are no pressure differences between the adjoining ramjet modules. In consequence, the structural elements can be very light. However the flat nozzle panels have to withstand the pressure loads which might compensate the mass savings.

A second concept, described in Table 1, is a concept with a fixed and a rotatable arc. The circular geometry of this concept is beneficial with respect to mass but on the other hand, due to the overlapping parts and the sidewalls of the moving parts the overall system mass is quite high.

The third concept is a kind of plug nozzle with a fixed and a moveable part. Because of the cylindrical structure this concept seems to be the optimum with respect to mass. However it was discarded because the requirement to close the ramjet module during rocket and re-entry mode limits the maximum throat area to a value way beyond the mandatory maximum value.

The last concept is a system of single modules which can be switched off independently. Such a system requires only a limited number of discrete states, therefore the complete actuation system is less complex. The main disadvantages of such a concept are the lower nozzle efficiency due to a fixed nozzle expansion ratio and the fact that each module has to withstand the maximum pressure loads.

Table 1. Nozzle throat adjustment systems

	Concept	Description
Adjustable Nozzle	2D	 • Modular 2D nozzle • Planar hinged convergent and divergent part • Adjustment of throat area via axial movement of 1st hinge
	Moveable Ring-module	 • Ring module plug nozzle • Adjustment of throat area via axially movement of ring module
	Moving Arcs	 • 2D nozzle with constant radius (overlapping part) • Adjustment of throat area via ration of moveable nozzle arc
Discrete Modules	Discrete Module	 • Multiple combustion chamber and nozzle modules • Complete/partial closure of single opposing module pairs in combination with the shut down of the hydrogen supply

The discrete module concept does not need a 2D cross section for adjustable nozzle mechanism like the 2D or moving arcs concept. In consequence, an axisymmetric design with minimum wall thickness can be used to reduce the total system mass. Finally, the discrete modules concept was chosen to be the most promising one due to the lowest complexity and the comparably low structural mass.

Table 2. Qualitative Assessment

Parameter	Adjustable nozzle	Discrete Modules
Specific impulse	++ highest possible specific impulse due to increasing nozzle exit area ratio → adjusted nozzle exit pressure - Maximum throat area reduced due to rectangular nozzle exit (2D and Moving Arcs) → additional base drag	-- low specific impulse due to low nozzle exit area ratio → nozzle exit pressure higher than ambient pressure Significant total pressure losses due to inlet closure mechanism
complexity of the closing mechanism	-- continuously adjustable nozzle throat in hot gas conditions leads to very high complexity (2D and Moving Arcs) o Moderate complexity due to one adjustable ring module with only one actuation system (ring module)	+ low complexity due to three discrete positions (open for combustion mode – partially closed for pure air mode and totally closed for re-entry configuration)
mass	- relatively high mass of adjustable nozzle system expected (2D and Moving Arcs) ++ Low mass due to solely one actuation system and no need for single modules (Ring Module)	o relatively low mass of inlet closure mechanism but significant pressure difference between adjacent modules lead to higher wall thickness
sealing during re-entry	-- significant sealing area (complete nozzle contour) -- requirement to seal the bypass RJ system during re-entry limits the maximum throat area (Moving Arcs and Ring Module)	o simplified sealing of inlet, but combustion chamber has to withstand re-entry conditions
Aerothermal complexity	- actuation mechanism has to be placed in hot combustion gas environment	+ actuation mechanism has not to be placed in hot combustion gas environment - risk of azimuthal combustion instability

2. Discrete Modules Concept

2.1. System Description

Fig 4 shows a discrete module concept consisting of two rings with 32 single modules each. To adjust the total throat area, the inlet to each module can be closed via two rotatable conical covers. Each module can be operated in three different modes: combustion mode, pure air mode and re-entry mode.

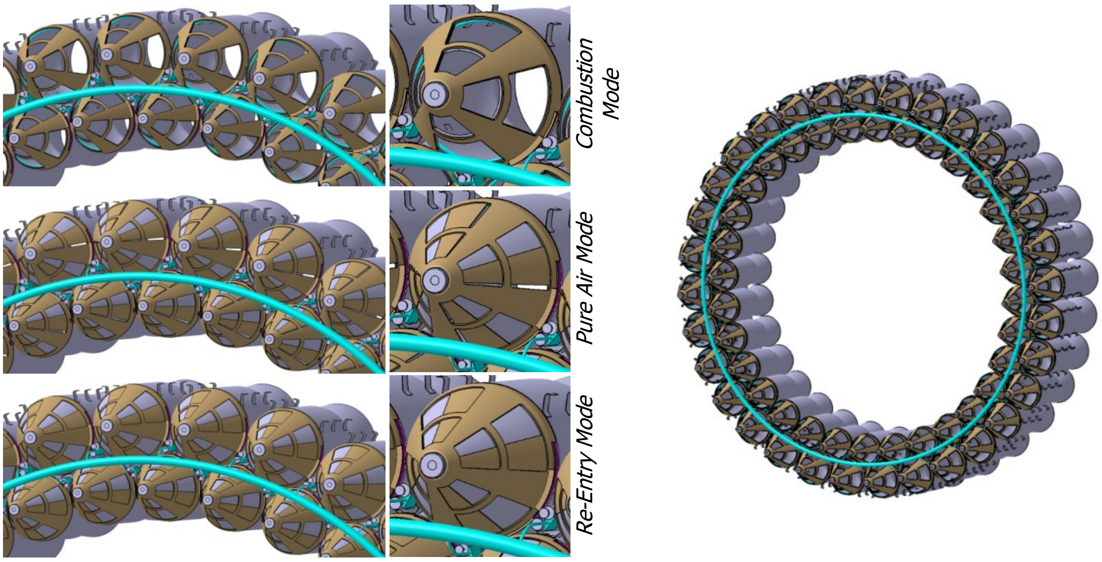


Fig 4. Single modules in combustion mode (top), pure air mode (center) and rocket or re-entry mode (bottom)

In combustion mode, the inlet to the combustion chamber is fully open. To minimize the total pressure losses, two counter-wise rotatable conical covers are used to close the module in order to maximize the inlet area between the four struts. These struts also act as flame holders to guarantee a stable and effective combustion.

To reduce the overall throat area single modules can be switched off. To minimize the base drag of these modules, a small amount of air is allowed to flow through them without combustion: solely pure air without hydrogen. Therefore, the two covers are nearly closed, see Fig 4, and due to the nearly constant pressure at the pre-cooler inlet the air mass flow going through the pure air modules can be defined quite accurately via the exact size of the gap.

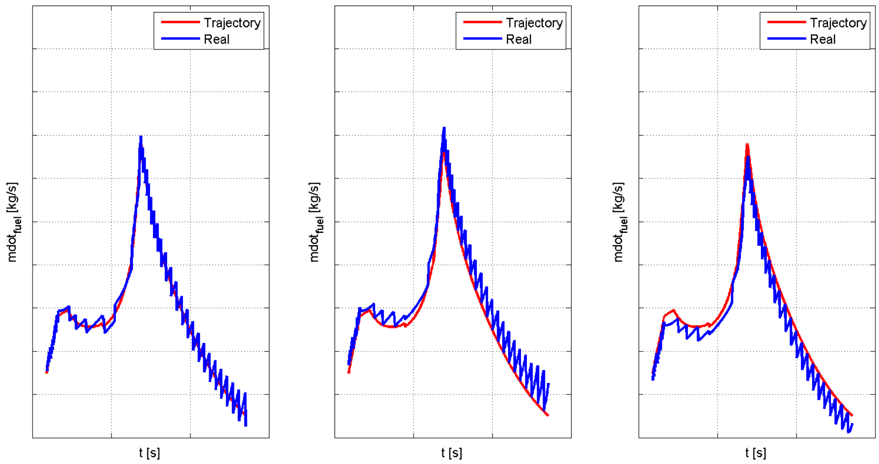


Fig 5. Hydrogen mass flow provided by the core engine (red) and realized mass flow for optimized (left hand), plus (centre) and minus (right hand) logic (30 modules)

The discrete change of the total throat area would result in a sudden pressure step which has to be compensated by the second control loop, the hydrogen supply to the single module, see Fig 5. The exact logic, when a module has to be switched from combustion mode to pure air mode, has significant impact on the total fuel consumption.

- The number of modules in combustion mode is defined in such a way that the difference between hydrogen mass flow provided by the core engine (red) and the mandatory hydrogen mass flow to achieve the required static pressure (blue) is minimized – (optimized - Fig 5 left hand)
- The hydrogen mass flow provided by the core engine is the minimum hydrogen mass flow (plus - Fig 5 centre)
- The hydrogen mass flow provided by the core engine is the maximum hydrogen mass flow (minus - Fig 5 right hand)

Taking into account that the excess hydrogen from the core engine which cannot be used in the bypass burner has to be vented, the total fuel consumption of the minus logic is limited and the specific impulse is also very low if the vented hydrogen is considered. In contrast, all the hydrogen is used for the combustion in case of the plus logic, but the overall hydrogen consumption is higher. In the end, the control logic can be optimized with respect to overall fuel mass and achievable thrust.

2.2. Performance

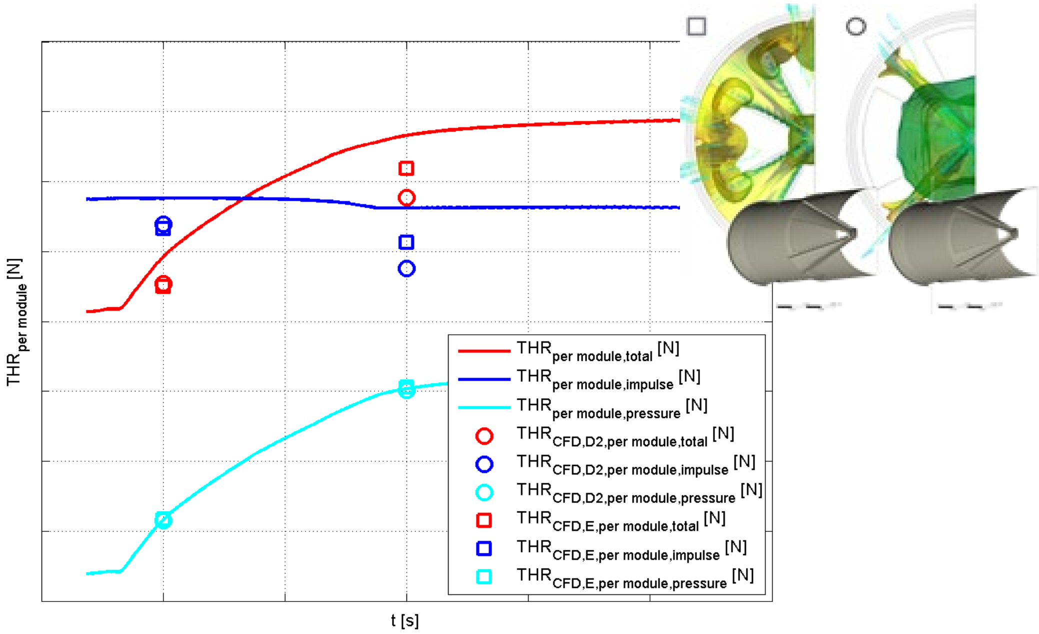


Fig 6. Simulated achievable thrust (total thrust – red, pure impulse thrust component – blue and thrust based on pressure at nozzle exit – cyan) per module based on 1D simulation (solid line) and based on CFD simulations with injection system D2 (circle) and E (square)

Fig 6 shows the simulated total thrust per module (red) as well as the thrust contribution due to the impulse (dark blue) and the static pressure at the nozzle exit (red) based on a simplified 1D simulation using an equilibrium code to define the gas parameters within the combustion chamber. In addition, the graph shows the outcome of a more detailed CFD simulation with two different injection systems. System A with one row of injectors placed in the center of each strut and system B with two rows at each side.

As it can be seen in Fig 7, the injectors of system A are positioned in the plane at the place where the two vertexes caused by the flame holder meet. In consequence, the hydrogen is trapped between these vortexes and no real mixing with the air happens. In contrast, for injection system B the hydrogen is carried away by the turbulent air. Fig 7 shows the combustion temperature on the symmetry plane and on the iso surface with 1% hydrogen mass ratio as well as hydrogen streamlines with the corresponding temperature. Simulation Sim 1 represents the conditions with maximum air and minimum fuel mass flow - minimum equivalence ratio. Simulation Sim 2 covers the other extreme, maximum fuel and minimum air mass flow, maximum equivalence ratio, see Fig 8.

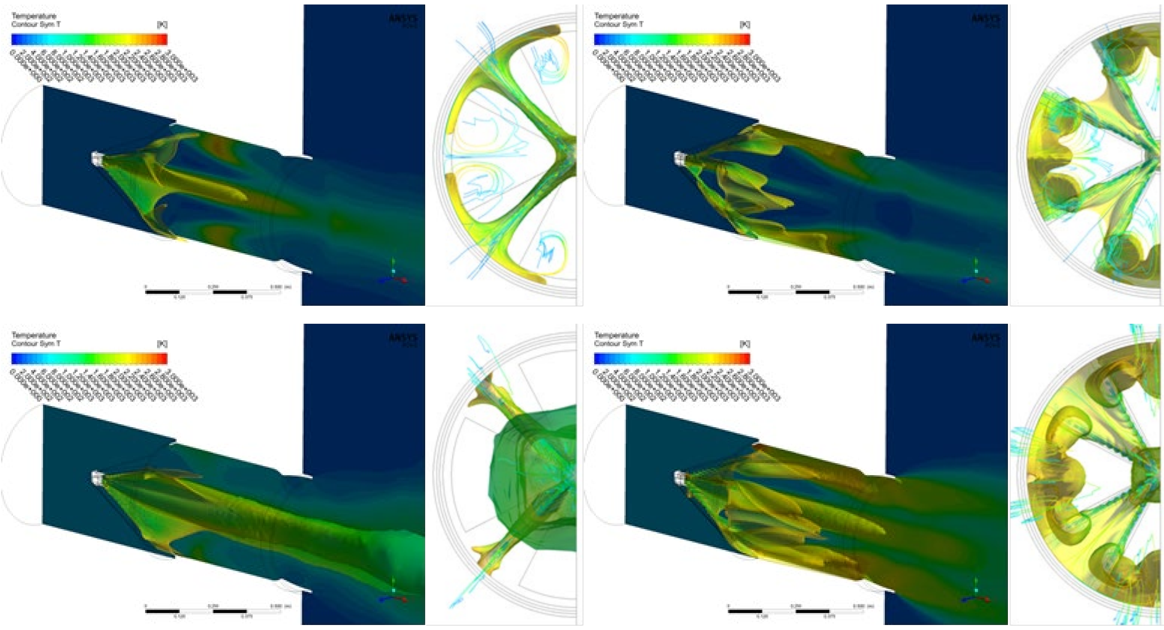


Fig 7. Hydrogen streamlines, iso-surface with 1% hydrogen and resulting temperature for injection system A (left hand) and B (right hand) for Sim1 (top) and Sim 2 (bottom)

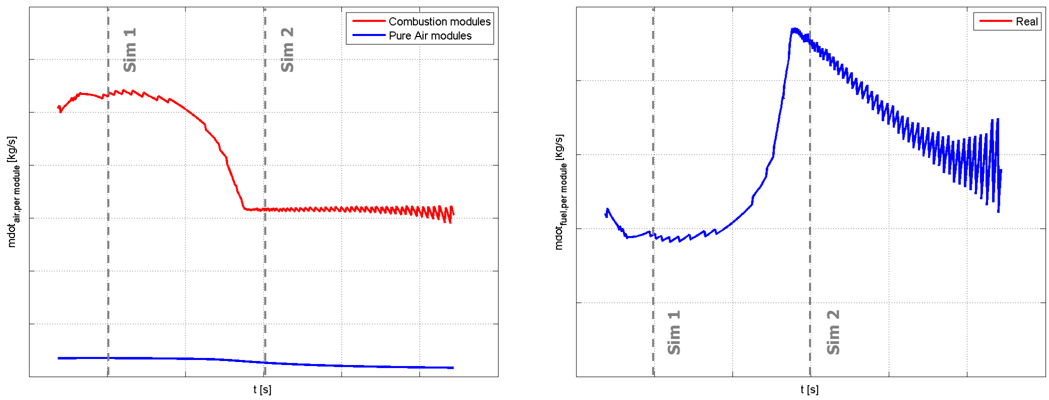


Fig 8. Air mass flow (left hand) in combustion mode (red) and pure air mode (blue) and fuel mass flow rate (right hand) per module

For Sim 1, the achieved thrust for injection system A (circle) is nearly identical to system B (square). Caused by the significant excess of air - mandatory for a complete reaction of the hydrogen - even with the very poor mixing of the hydrogen with the incoming air a more or less 100% reaction can be achieved. For Sim 2, injector system A results in a reasonable amount of unburned hydrogen and in consequence in a lower achievable thrust.

To minimize the base drag, the modules are not completely switched off. In pure air mode, a small amount of air, defined by the gap between the two closure cones, see Fig 4, is streaming through the modules. Fig 9 shows the static pressure in the modules for pure air mode at Sim1 and Sim 2. It can be shown that the drag per module with a small air flow in comparison to a completely closed module can be reduced by up to 85%.

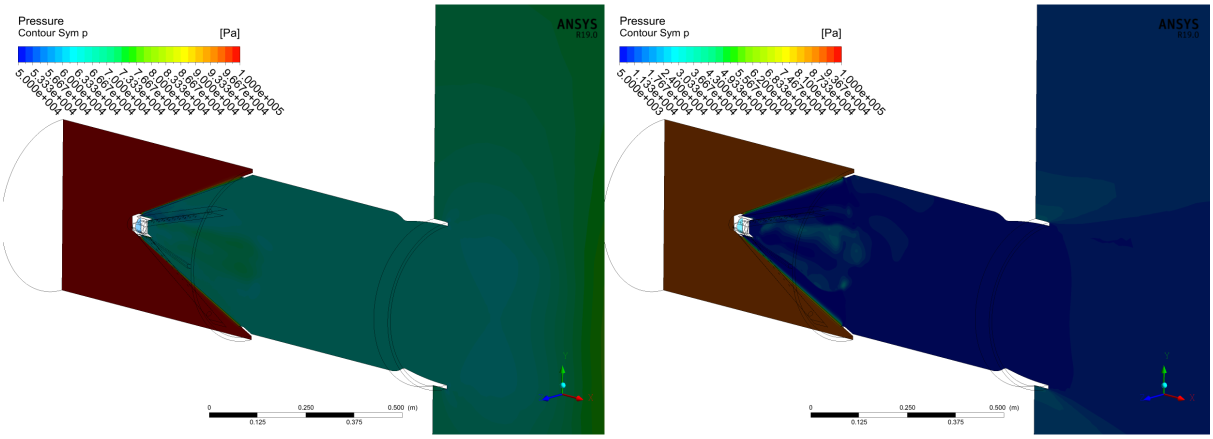


Fig 9. Static pressure for pure air mode Sim1 (left hand) and Sim2 (right hand)

2.3. Structural Analysis

As already mentioned, besides the lower complexity in comparison to the adjustable nozzle concepts the axisymmetric design with minimum wall thickness was the main decision criterion. To minimize the overall system mass, the wall thickness of the cylindrical combustion chamber and nozzle section is reduced to the absolute minimum.

Due to the high combustion temperatures and the external heating during re-entry, a CMC structure for the complete module is assumed. With respect to manufacturability, a design with only four layers with tailored ply orientation is assumed. Because of the very small number of layers the assumption of quasi isentropic material behaviour is not valid.

In consequence, an exact layer design with different ply angles has been modelled. Besides the maximum stresses per layer, also the three failure indices according to Puck were calculated.

- 1st failure index – tensile fiber failure
- 2nd failure index – fiber kinking failure
- 3rd failure index – inter-fibre failure

Fig 10 shows 3rd failure of the third layer for the maximum internal and without external pressure representing the worst case at high altitude conditions. The 1st and 2nd failure indices for this layer design lie below 0.2 and are negligible.

Even under worst conditions including safety margin, the 3rd failure index lies below 1 for the cylindrical part of the combustion chamber while the maximum values can be observed in the convergent part of the nozzle. This gives the indication that with an optimization of the ply orientation and of the nozzle contour, a structure with three to four layers should be able to withstand the internal pressure. The manufacturability of structures with only 3 to 4 layers and the overall dimensions as well as the effect on life cycle and geometrical tolerances has to be investigated but does not seem to be completely unrealistic.

The wall thickness of the conical part including the covers is significantly higher because this part has to bear the high static pressure loads on the pre cooler side in pure air mode. So in contrast to the cylindrical part, a quasi-isentropic material behavior is assumed, see Fig 10.

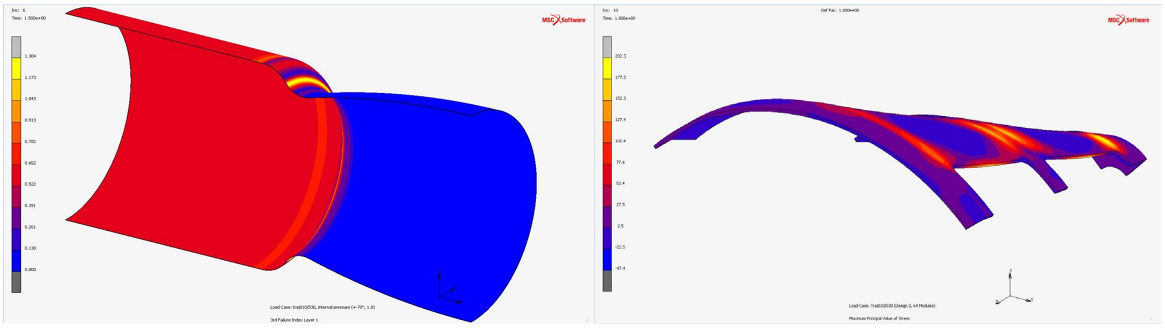


Fig 10. 3rd failure index according to Puck (lefthand) and maximum principle stress at inner closure cone

3. Conclusion

The current paper presents a design concept for the SABRE ramjet bypass burner. Its main objective is to control the static pressure at the pre-cooler inlet as well as the air mass flow to the core engine while maximizing the thrust. In addition, the overall mass of the bypass burner is critical with respect to the overall system performance.

To maximize the efficiency of the bypass burner – maximum thrust with minimum hydrogen consumption – the total throat area of the bypass burner has to be adjusted with respect to the excess hydrogen of the core engine, the capture air mass flow and the air mass flow required by the core engine and the demanded static pressure at the pre-cooler inlet.

To find the optimum solution, different principle concepts – adjustable throat and discrete modules which can be switched off individually – have been investigated. Based on a more qualitative assessment, supported by some simplified studies the discrete module concept was finally chosen as the most promising one. The main reasons are the relatively low complexity due to the fact that only three discrete stages have to be realized and that the estimated mass was the lowest in comparison to the other concepts. This is caused by the facts that both the 2D and the moving arc concept need a 2D cross section in the adjustable nozzle section. Such designs with flat panels lead to relatively high wall thicknesses and in consequence to a higher structural mass.

One of the main disadvantages of the discrete module concept is the fact that the expansion ratio is defined by the low altitude conditions and therefore fixed for all conditions. In consequence the nozzle efficiency is quite low. Another disadvantage is the slightly higher total hydrogen consumption, dependent on the control logic to switch between combustion and pure air mode.

Performance studies based on a simplified 1D simulation showed that in comparison to an adjustable nozzle concept the resulting specific impulse of the discrete module concept is about 5% lower and the fuel consumption 1% higher. But due to the fact that these performance losses are very small, it is assumed that the lower complexity and lower total mass of discrete module concept compensates these shortcomings.

Acknowledgments

The authors would like to thank the European Space Agency, especially Dr. Johan Steelant for their budgetary and technical support within the framework of the GSTP contract No. 4000119831/17/NL/RA and Dr. James Barth and Richard Varvill for their technical support.

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