FEASIBILITY STUDY AND PRELIMINARY DESIGN OF A RAM-PULSEJET FOR HYPERSONIC PASSENGER AIR TRANSPORT

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ABSTRACT

In hypersonic aircrafts, the necessity of operating at speed lower than Mach 1.0 obliged the designers to use the complicate propulsion plant of the mixed compression turbojet. Fast commercial passenger transportation will probably shorten the flight time by a factor 5, from the actual 6 hours to 1 hours for the London-NYC flight route. Therefore, the engine will work for a shorter time. The subsonic part of the flight is very limited. For this reason, a possible solution can be to substitute the turbojet with a pulsejet in the ramjet duct. Valveless pulsejets are extremely, simple, reliable, lightweight, fully throttable jet engines. The main limitations of the pulsejet are very low efficiency, relatively low "thrust density" and noise. Noise is naturally reduced as the main working frequency passes from the 150Hz of small pulsejet to the 40Hz of larger ones. Efficiency can be increased inserting the pulsejet in a ramjet-duct. This solution increases the pressure at the pulsejet intake and efficiently recovers heat from the pulsejet walls. Finally, it is possible to decelerate the jet with an ejector exhaust thrust augmenter. The feasibility of this concept is investigated in this paper. For this purpose, it was imagined to develop a transport aircraft with the aerodynamic of the Valkyrie and the new propulsion system. A cruise speed of MACH 3.5@25,000m was simulated with CFD. In this cruise condition the pulsejet works as a combustion stabilizer for the ramjet. Also, the take-off condition was simulated. At take off the thrust is obtained only by the pulsejet.

Keywords: ramjet, pulsejet, thrust, simulation, CFD, hypersonic transportation.

INTRODUCTION

During the Cold War, a deterrent strategy of mutual assured destruction (MAD) from both sides of the Berlin wall. The two superpowers kept some squadrons of Nuclear Strategic Bombers in the air around the clock, orbiting some distance away from their fail-safe points near the "enemy" border. The US developed the North American Aviation XB-70 Valkyrie as a large, six-engined bomber with a payload of 22,500kg capable of reaching Mach 3+@21,000m. The XB-70 would be almost immune to interceptor aircrafts and missiles, due to the combination of speed and altitude. As the strategic role passed from bombers to intercontinental ballistic missiles (ICBMs) during the late 1950s, strategic bombers were obsolete. In February 1954 a RAE (Royal Aircraft Establishment) committee was formed to study the supersonic transport (SST) concept. Soon after, Johanna Weber and Dietrich Küchemann at the RAE published the "slender delta concept" that produces strong vortexes on the upper surfaces at high angles of attack. These vortexes lower the upper wing air pressure, increasing the lift. This vortex effect is maximized by extending the wingspan as much as possible. Therefore, the delta wing configuration has the good supersonic performance inherent to the short span, while offering high lift at low speed at extremely high angles of attack. This concept gave birth to the Concorde project that was contemporary with the Valkyrie project that began also in 1954 and had a delta wing platform. The Valkyrie had a canard surface and a delta wing, which was built largely of fuel cooled stainless steel, sandwiched honeycomb panels, and titanium for Mach 3+ performance. The main addition to the delta wing concept of the Valkyrie is the compression lift, given by two secondary shock wave of the Mach 3 cruising speed generated by central engines frontal splitter plate. These two contra-rotating vortexes effectively prevent the shock front from leaking up over the wing. The compression lift provided five percent of the total lift. At high speed the hinged tip wings were pivoted downward by 65 degrees to improve the use of the high pressure field behind these strong shock waves. This solution also shifted the center of lift to a more favorable position at high speeds. More precious than all, The XB-70's last supersonic flight data of 17 December 1968 were published by NASA on April 1972. In the immediate post-war II period the US and USSR both started rocket research programs based on the German V-2 design. In the USSR, rocket research was centrally organized, although several teams worked on different designs. Early designs from both countries were short-range missiles, like the V-2, but improvements quickly followed. The USSR started in 1953 the Sergei Korolyov's project of a true ICBM that became operational on 9 February 1959. The same R-7 launch platform placed the first artificial satellite in space, Sputnik, on 4 October 1957. The typical ICBM flight is composed by a boost phase that may last at to 5 minutes. In this phase the warhead reaches an altitude from 150 to 400 km. In the following 25 minutes the head follows sub-orbital, elliptical flightpath. The apogee of this curve has altitude of approximately 1,200 km (750 mi). The horizontal semi-major axis is between 3,186 and 6, 372 km. The terminal reentry phase starts at an altitude of about 100km and lasts approximately 2 minutes with a terminal "impact" speed up to 20 Mach. Therefore, an ICBM will take about half an hour to take the payload from Rome to NYC. On the contrary, the record flight time for an aircraft is 4 times more. The SR71's World Record-Speed over a recognized course is 5570 km (New York to London) in less than 2 hours with an average speed of 2900 km/h (Mach 2.72). For comparison, the record flight time for the Concorde is 2 hours 52 minutes while a common airliner averages 6 hours 15 minutes. The cruise altitude of the SR 71 is 22,900m. Concorde had a maximum cruise altitude of 18, 300m. High altitude flight has the main problem of the lack of oxygen due to thinner air. The record altitude in horizontal flight is again of the SR 71 with slightly less than 30,000m. Concorde achieved a record altitude of 20,700m, while cruising at 17,000m. The engines of the SR71 and the Concorde are ram-turbojets (hybrid or mixed compression turbojets). The hybrid intake matches the air flow to the turbojet with afterburner and the ram air. Table-1 summarizes the performance of a propulsion systems of a few high speed aircrafts.

Table-1. Performance of propulsion systems of a few high speed aircrafts.

Engine type	**RAM compression ratio**	**Compression ratio** (engine)	**SFC g/(kN·s)**	**Specific impulse** (s)	**Exhaust velocity** (m/s)
SR71@3.2 Mach J-58 hybrid turbojet	49.4	-	54	1900	19000
EFA@2 Mach Eurojet EJ200	7.3:1	26:1	47-49	2080-2170	20400-21300
Concorde@ 2 Mach Rolls-Royce/Snecma Olympus 593 hydrid turbojet	7.3:1	11.3:1	33.8	3010	29500

In hybrid turbojet engines, the total compression ratio above Mach 2.0, with a supersonic hybrid inlet design, has a high intake pressure recovery that the maximum pressure should be limited to avoid damage to the engine as it happens for the MIG 25 over Mach 2.83. In fact, hybrid turbojets rely heavily on the ramjet part of the propulsion system over Mach 2.0. The necessity of operating at speed lower than Mach 1.0 obliged the designers to use the complicate propulsion plant of the hybrid turbojet. Fast commercial passenger transportation will probably shorten the flight time by a factor 5, from the actual 6 hours to 1 hours for the London-NYC flight route. Therefore, the engine will work for a shorter time. The subsonic part of the flight is very limited. For this reason, a possible solution can be to substitute the turbojet with a pulsejet in the ramjet duct. Valveless pulsejets are extremely, simple, reliable, lightweight, fully throttable jet engines. The main limitations of the pulsejet are very low efficiency, relatively low "thrust density" and noise. Noise is naturally reduced as the main working frequency passes from the 150Hz of small pulsejet to the 40Hz of larger ones. Efficiency can be increased inserting the pulsejet in a ramjet-duct. This solution increases the pressure at the pulsejet intake, efficiently cools down and recovers heat from the pulsejet walls. Finally, it is possible to decelerate the jet with an ejector exhaust thrust augmenter. The feasibility of this concept is investigated in this paper. For this purpose, it was imagined to develop a transport aircraft with the aerodynamic of the Valkyrie and the new propulsion system. A cruise speed of MACH 3.5@25,000m was simulated with CFD. In this cruise condition the pulsejet works as a combustion stabilizer for the ramjet. Also, the take-off condition was simulated. At take off the thrust is obtained by the pulsejet. The "final" assembly of the pulse-ramjet is shown in Figure-1.

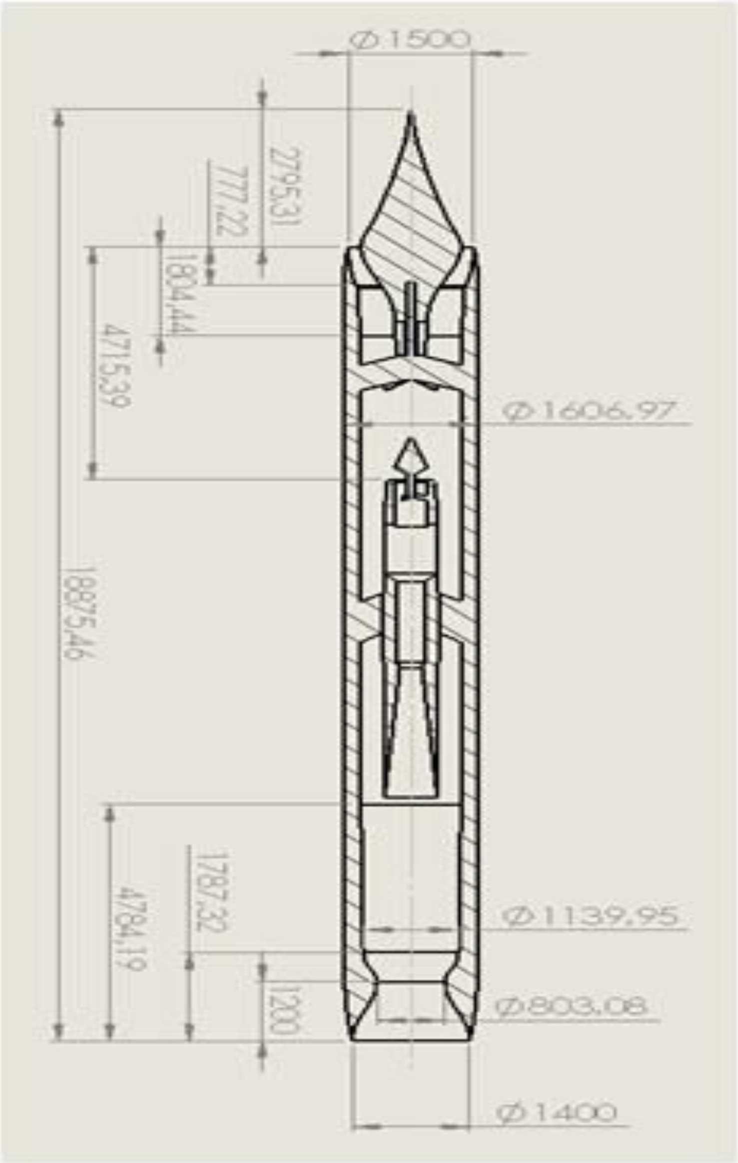


Figure-1. Ram-pulsejet (at take-off). Please turn 90 deg to see measures correctly.

Initial considerations

To simplify the work and to rely on experimental data the air intake of the SR-71 was used. To simplify the analysis the boundary layer control system of the original aircraft was not included in the CAD model. Supersonic inlets are a confusing subject and difficult to explain. The SR-71 uses a mixed compression inlet, designed and patented by D. H. Campbell. This aircraft is capable to cruise at M=3.2 and it achieves a maximum speed of Mach 3.5+ without damage and with acceptable efficiency. This flow in the inlet is called an adverse pressure gradient, since air is pushed downstream into progressively higher-pressure regions. Therefore, the inlet is designed to prevent the airflow from separating from the inlet walls and forming eddies and vortices, which means very gentle turns and slow diffusion. The SR-71 inlet is axisymmetric, mixed compression, translating spike. The preliminary dimensioning of the ramjet requires a few initial assumptions. The target data come from both the North American XB-70 Valkyrie and the Lockheed SR-71 and are summarized in Table-2.

Table-2. Ramjet design data and symbols.

Description	Symbol	Unit	Value
thrust (single-engine)	S	N	35,000
Cruise altitude	z	m	25,000
Cruise velocity	v_m	M	3.5
Temperature	T_a,T_1	K	221.65
Pressure	p_a	Pa	2511.02
Max allow. T	T_4	K	1800
Cruise velocity	v_{ma}	m/s	
Temperature after isentropic inlet compression (ideal ramjet cycle)	T_2	K	
Heat Capacity Ratio	γ		1.4
Pressure after isentropic inlet compression (ideal ramjet cycle)	p_2	Pa	
Nozzle Ramjet temperature Ideal cycle	T_9	K	
Nozzle Ramjet velocity Ideal cycle	u_a	m/s	

$$\delta = \frac{\gamma - 1}{2} = 0{,}2 \qquad (1)$$

$$T_2 = T_a\left(1 + M_a^2 \delta\right) = 764.692[\mathrm{K}] \qquad (2)$$

$$p_2 = p_a\left(\frac{T_2}{T_a}\right)^{\frac{\gamma}{\gamma - 1}} = 191521[Pa] \qquad (3)$$

$$T_9 = T_4\left(\frac{p_a}{p_2}\right)^{\frac{\gamma - 1}{\gamma}} = 521.79[K] \qquad (4)$$

$$u_a = \sqrt{2\left(T_4 - T_9\right)c_p} = 1676.95[m/s] \qquad (5)$$

$$Flowrate = \frac{S}{u_a - v_{ma}} = 55.35\,[kg/s] \qquad (6)$$

Equations (1-6) are referred to the ideal ramjet cycle. Equation (6) makes it possible to calculate the ideal mass flow. In this way it is possible to make a first design of the inlet section (Figure-2). The annulus of external radius 750 and internal 395 is calculated by assuming that the incoming air in this section has the outside mass density. The spike geometry comes from the SR71 inlet design.

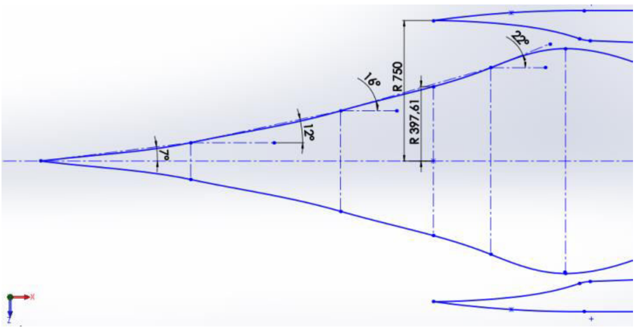


Figure-2. Initial ramjet inlet design.

Figure-3 shows the final intake design that started from a copy of the SR71 and was then refined with Solid Works Flow simulation [1-3].

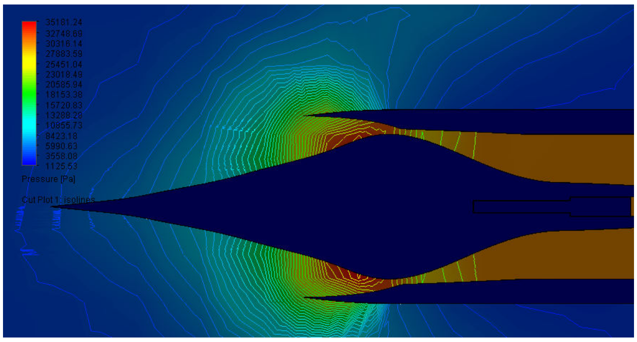


Figure-3. Intake pressure at mach 3.5.

The inlet (spike) configuration of Figure-3 is optimized to cruising at Mach 3.5 (25,000m). To ensure optimum operation throughout the speed range, the spike has to advance and retract, moving along longitudinal guides. This movement allows to vary the air inlet areas, passing by a convergent duct (M> 1) to a divergent (M <1), (Figures 4, 5 and 6).

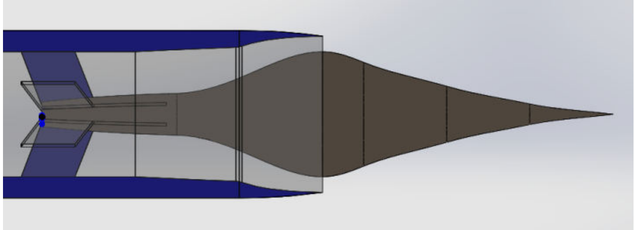


Figure-4. Subsonic spike position (M 0.8).

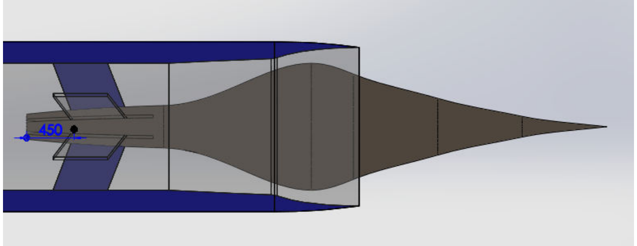


Figure-5. Mach 2 spike position.

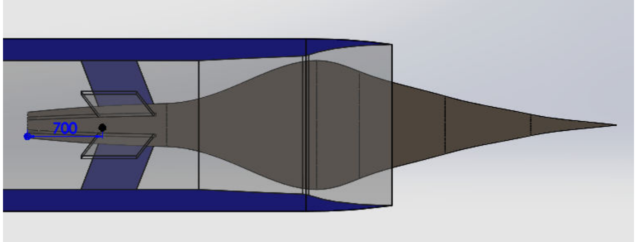


Figure-6. Mach 3.5 spike position

CFD Combustion simulation (Figure-7)

The combustion heat exchange process was modeled using a set of very thin, high temperature laminae, so as to not significantly affect the internal flow, placed longitudinally in the combustion chamber. For simulation purposes, it has been associated to the laminae the maximum allowable temperature T_{4t}=2050 K, (on both surfaces of each sheet), and a coefficient of heat exchange of air equal to 300 $Wm^{-2} K^{-1}$ (forced convection) [4-11].

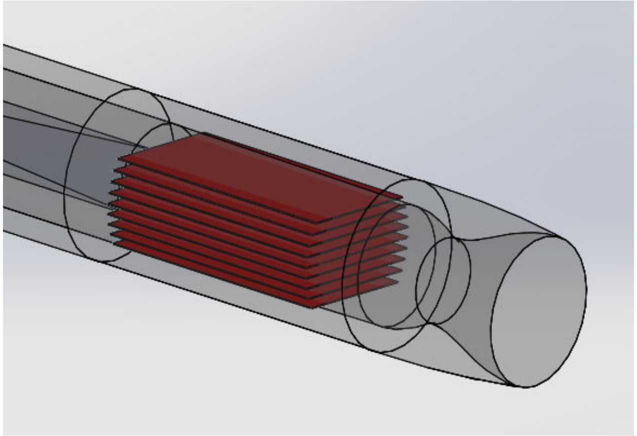


Figure-7. Combustion simulation.

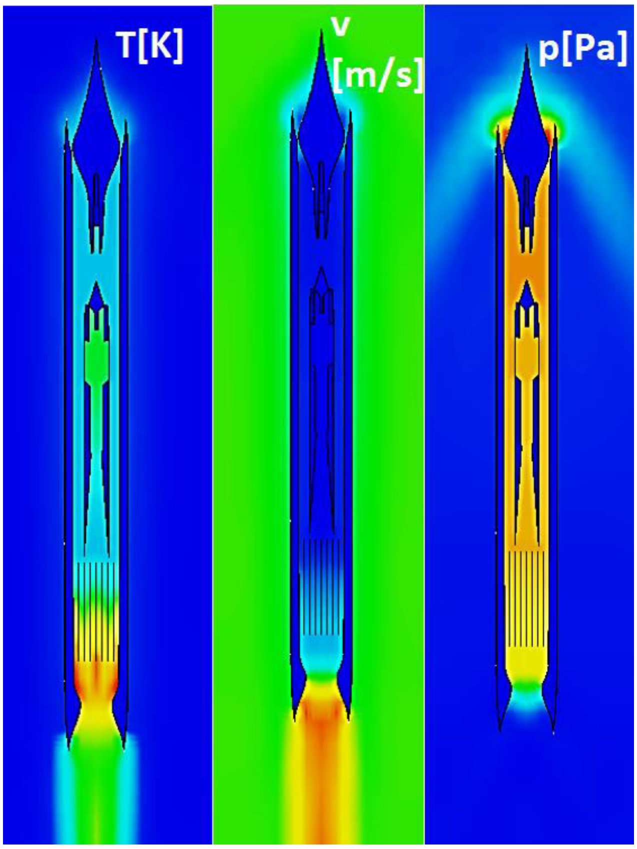


Figure-8. Temperature (Left), Velocity (center) and Pressure (right) of the ram-pulsejet at mach 3.5.

Ramjet cruise simulation results

The simulation results at Mach 3.5 at 25,000 ISA+0 are shown in Figure-8. It can be noted that the spike of the pulsejet it is fully closed (fully forward position) as at this velocity this proved to be the most efficient solution. Therefore, the pulsejet is fully stopped. The spike of the ramjet is positioned in the fully rearward position, as shown in Figure-6. The gas temperature in the combustion chamber is about 2000 K. The maximum speed of the exhaust gas from the nozzle is equal to about 1800 m/s. Therefore, the maximum thrust at cruise speed can be evaluated (7).

$$S = Flowrate\left(u_{at} - v_{ma}\right) + (p_e - p_a)A \approx 40000[kg/s] \quad (7)$$

The results of the simulations showed that it is possible to increase the pressure recovery by intake design optimization and boundary layer control. This process will be introduced in a following paper. However, the ramjet design and the “combustion chamber model” seems to be robust enough to conduct an initial “feasibility” evaluation. The ramjet performance with the pulsejet inside seems to work fairly well. The only shortcoming is the ramjet length that is larger than the original Valkyrie design. However, the lack of high speed moving part seems to render this choice very convenient.

PULSEJET DESIGN

The Pulsejet taken as reference for the design is the valveless model developed by German company Messerschmitt. The choice of this particular model is mainly due to the need to develop a relatively simple machine, with the fewest possible components. The low number of components allows to reduce maintenance costs and to increase the overall reliability of the engine.

The modifications to the original model relate mainly to the air intake and size. With regard to the air intake, the pulsejet spike has the opportunity to move back up to effectively reduce the input stream [12-17]. This operation is performed during the transient pulsejet-ramjet operation at Mach 1.2.

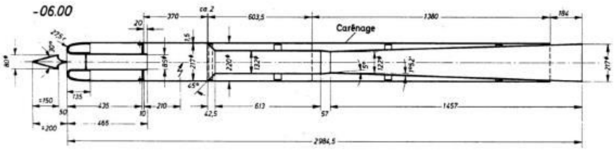


Figure-9. Original Messerschmitt design.

Figure-10. Simplified CAD model.

Figures 9 and 10 show respectively the original drawing and the modified CAD model of the Messerschmitt pulsejet. The pulsejet is inserted inside of the ramjet and it is used to obtain thrust even from 0 to Mach 1.2.The compression is carried out for dynamic pulsating action, without the need for a compressor. The cyclic operation allows achieving higher combustion temperatures compared to other types of engines. The switching frequency is proportional to the size of the engine, from 40 up to 300 Hz. Following numerous simulations, we have chosen to use a switching frequency equal to 43 Hz. This value depends on the engine size. The dimensioning of the Pulsejet was performed in such a way as to allow the aircraft to take off with a defined ground run X_r and at a given rotation velocity v_d. The calculation of the thrust needed for takeoff is calculated from the data of Table-3.

Table-3. Ground run calculation data.

Description	Symbol	Unit	Value
Thrust	Td	N	-
TOW	W	kg	97,000
Ground run	x_r	m	3,900
Rotation velocity	v_d	m/s	83,3
Gravity acceleration	g	m/s^2	9.81
Jet speed at rotation	v_{out}	m/s	600

The thrust was obtained with equation (8):

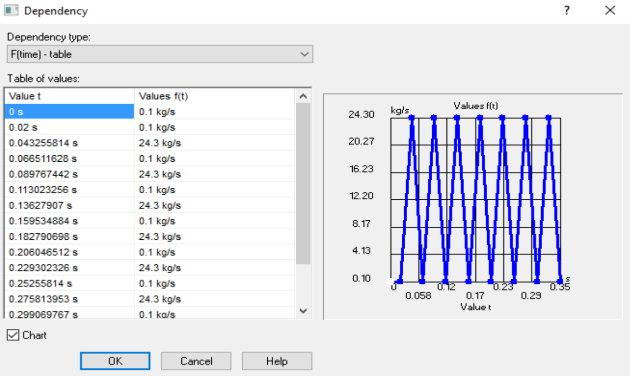
$$T_d = \frac{1}{2}\frac{W(v_d^2 + x_r f \times g)}{x_r n_{jet}} \approx 16000[N] \tag{8}$$

The Valkyrie had 6 propulsion units. With the assumption of a jet speed at rotation of 600m/s, it is possible to evaluate the flow rate (*mflow*) of the single pulsejet at takeoff (9).

$$mflow = \frac{T_d}{v_{out}} \approx 24.3[kg/s] \tag{9}$$

Pulsejet CFD simulation

The pulsating combustion process was simulated by a pulsating heat flux on the pulsejet combustion chamber external walls. This heat flow is introduced into the CFD simulation through a hot fluid flowing through the combustion walls. A pulsating mass flow rate of combustion gases is therefore applied through the combustion chamber walls (Figure-11).



Dependency type:
F(time) - table

Table of values:

Value t	Values f(t)
0 s	0.1 kg/s
0.02 s	0.1 kg/s
0.043255814 s	24.3 kg/s
0.066511628 s	0.1 kg/s
0.089767442 s	24.3 kg/s
0.113023256 s	0.1 kg/s
0.13627907 s	24.3 kg/s
0.159534884 s	0.1 kg/s
0.182790698 s	24.3 kg/s
0.206046512 s	0.1 kg/s
0.229302326 s	24.3 kg/s
0.25255814 s	0.1 kg/s
0.275813953 s	24.3 kg/s
0.299069767 s	0.1 kg/s

☑ Chart

Figure-11. Mass flow rate of combustion gases on the combustion chamber walls.

To minimize the error due to this additional, “unphysical” mass flow, it was assumed to have perfect stoichiometric oxygen combustion. Therefore, the “additional internal flow” is given by the ideal chemical reaction between oxygen and propane gas with the production of CO_2 e H_2O in gaseous form. The data used for the evaluation of the propane mass flow are summarized in Table-4.

Table-4. Pulsejet basic parameters.

Symbol	description	Unit	Value
cp_{C02}	Specific heat capacity at constant pressure of C02	J $kg^{-1}K^{-1}$	1000
cp_{H20}	Specific heat capacity at constant pressure of H20	J $kg^{-1}K^{-1}$	1900
ρ_{C02}	Mass densitiy of C02	kg m^{-3}	1.98
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V_{puls}	Combustion chamber Reference volume	m^3	1
Hf	Lower Heating value Propane	kJ/mol	2229
f	Pulsejet Frequency	Hz	43
R_{gas}	Ideal Gas Constant	J mol^{-1} K^{-1}	8.414
E_{cc}	Energy from combustion per cycle	kJ	
T_{cc}	Additional Flow temperature	K	
p_{cc}	Absolute Peak pressure	Pa	

The use of a complete combustion of propane gas gives equation (10).

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_20 + Energy \qquad (10)$$

In terms of mass (*m*) equivalents, equation (10) becomes equations (411).

$$m_{C_3H_8} + m_{O_2} = m_{CO_2} + m_{H_2O} = m_{tot} \Rightarrow$$
$$44g + 160g = 132g + 72g = 204g \qquad (11)$$

It is then possible to calculate the basic parameters of the pulsating additional heat/mass-flow cycle of Figure-10: the maximum temperature T_{cc} and the maximum pressure p_{cc}. The total mass flow of the propane ($mflow_{C3H8}$) and of the oxygen ($mflow_{02}$) are calculated through equations (12) and (13).

$$mflow_{C_3H_8} = mflow \frac{1000}{m_{tot} f} m_{C_3H_8} \qquad (12)$$

$$mflow_{O_2} = mflow \frac{1000}{m_{tot} f} m_{O_2} \qquad (13)$$

The total energy per cycle E_{cc} obtained by the ideal fuel combustion is given by equation (14).

$$Ecc = Hf \frac{1000}{m_{tot} f} m_{O_2} \qquad (14)$$

From the total energy per cycle it is possible to evaluate the maximum Temperature T_{cc} (15).

$$T_{cc} = E_{cc} \frac{1000}{V_{puls}\left(cp_{CO_2}\rho_{CO_2} + cp_{H_2O}\rho_{H_2O}\right)} \qquad (15)$$

The resulting pressure p_{cc} can be evaluated by the Ideal Gas Law (16).

$$p_{cc} = \frac{1}{2} mflow \frac{1000}{m_{tot} f} \frac{R_{gas} T_{cc}}{Vpuls} \qquad (16)$$

These values can be associated to the additional virtual mass flow to evaluate the thrust from the pulsejet part of the propulsion system. This method has been fully described and validated with experimental data in [1].

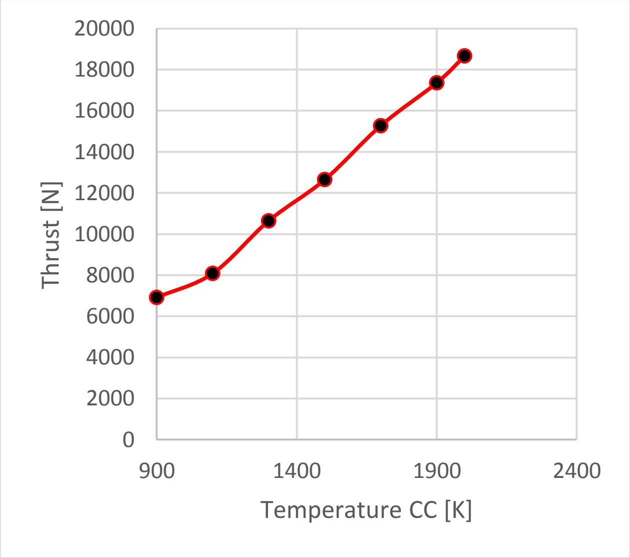

Figure-12. Pulsejet thrust vs. virtual mass flow temperature.

Figure-12 shows the thrust as the virtual mass flow temperature increases. Commercial ramjets that are mainly used for model aircraft run at a reference temperature of about 2000K. The pulsejet thrust estimation is therefore conservative. In any case the pulsejet seems to provide a sufficient thrust for take-off.

CONCLUSIONS

In hypersonic aircrafts, the necessity of operating at speed lower than Mach 1.0 obliged the designers to use the complicate propulsion plant of the mixed compression turbojet. Fast commercial passenger transportation will probably shorten the flight time by a factor 5, from the actual 6 hours to 1 hours for the London-NYC flight route. Therefore, the engine will work for a shorter time. The subsonic part of the flight is very limited. For this reason, a possible solution can be to substitute the turbojet with a pulsejet in the ramjet duct. Valveless pulsejets are extremely, simple, reliable, lightweight, fully throttable jet engines. The main limitations of the pulsejet are very low efficiency, relatively low “thrust density” and noise. Noise is naturally reduced as the main working frequency passes from the 150Hz of small pulsejet to the 40Hz of larger ones [18-26]. Efficiency can be increased inserting the pulsejet in a ramjet-duct. This solution increases the pressure at the pulsejet intake and efficiently recovers heat from the pulsejet walls. Finally, it is possible to decelerate the jet with an ejector exhaust thrust augmenter. The feasibility of this concept is investigated in this paper. For this purpose, it was imagined to develop a transport aircraft with the aerodynamic of the Valkyrie and the new propulsion system. A cruise speed of MACH 3.5@25,000m was simulated with CFD. In this cruise condition the pulsejet works as a combustion stabilizer for the ramjet. Also the take-off condition was simulated. At take off the thrust is obtained only by the pulsejet. This ramjet design and the “combustion chamber model” seems to be robust enough to conduct an initial “feasibility” evaluation. The ramjet performance with the pulsejet inside seems to work fairly well and provides sufficient thrust for the Valkyrie at MAC 3.5/25,000m ISA+0 DEG C. The only shortcoming is the ramjet length that is larger than the original Valkyrie design. However, the lack of high speed moving part seems to render this choice very convenient. Also, the pulsejet seems to provide a sufficient thrust for take-off.

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