ICAS-92-3.4.3

COMBINED ENGINES FOR HYPERSONIC FLIGHT

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Abstract

For reason of expected increase in air transportation and established 'comfortable' flight time of a passenger not more than 2...3 hours we may infere that in perspective the development of a supersonic passenger aircraft of new generation (M = 2.0...2.5) will be required and far-off future will require air transport ensuring transportation at hypersonic speeds (M = 4...6).

In developing the supersonic and hypersonic propulsion system the main factor, defining its configuration, is a wide range of its operation conditions.

Some types of combined engines - turboramjet and air-turborocket have been considered. The engines performance in different flying conditions have been compared. Their peculiarities and parameters in different flying conditions have been defined.

Investigations into real operation and performance of the TRE were conducted within the programme of development and test bench studies of several versions of the full-scale tyrboramjet demonstrators, created on the base of production TJ. The performance at switching for various operation mode, at ramjet mode with cooling the heat stressed components, operation conditions of rotor supports were studied etc.

The development of an efficient combined engine is one of the most complicated scientific and technical problems of hypersonic aviation, but a progress in aerodynamics, construction materials and technology allows to hope for its solution.

Introduction

The air traffic role in society life is increasingly important. The overall number of air transport passengers per year have exceeded one billion just at the end of last decade. World political and economical situation development broadens relations between countries. One can foresee the tendency to growing share of long range passenger aircraft in the world airliner fleet. Passenger traffic growth at the beginning of XXI century in conjuction with increasing needs in long range transport require more attention to the higher flight speeds [1].

Flight speed increase leads to the flight time reduction and hence improves the travel comfort, particularly on intercontinental routes. However, while the transition from subsonic to supersonic speed of Mach 2 - 3 at flight range of 10.000 - 12.000 km allows to reduce the flight time by 10 hours, a further speed growth up to Mach 5 - 6 results in time saving by about one hour.

For appreciation of maximum flight speed of future passenger airliners let us consider results of modelling of one-day business trip conception [2] (leaving the home not earlier than 7 o'clock and come back at home after a business meeting not later then 24 o'clock at the day). The analysis has shown that even at Mach $\approx$ 6 the overall amount of possible routes between twelve most important political-economical world centres is already approaching the practical limit (Fig.1).

The development of effective aerospace plane (ASP) for commercial loads launch is needed to continue open up the near-Earth space in peacful goals. The key factor of low cost launch is the using of reusable 'launch from Airplane-To-Orbit System' (ATOS) with horizontal take-off/landing and fuel-effective air breathing engine.

The rise of ATOS or TSTO first stage speed from subsonic to hypersonic of Mach 6 - 7 allowes to increase the relative mass load of about 2 - 3 times [1].

The present developments of ATOS on a basis of the subsonic launcher can be considered as precedent for parallel development of advanced hypersonic transport (HST) and hypersonic launcher for ATOS in future (Fig.1). The key problem of development the hypersonic propulsion system (PS) will be better resolved when using the 'double application engine' concept for development an engine of HST and ATOS. In this case the propulsion system for various aviation system missions will keep their distinctions according to the mission, including cooling system, relative size of an inlet and nozzle, integration with airframe, etc.

Combined engine types comparison

In developing the supersonic or hypersonic power plant the main factor, defining its configuration, is a wide range of its operation conditions. Engine efficiency in cruise flight is ensured by optimising thermodynamic parameters, which considerably change depending on flight speed and altitude. On the other hand, a significant requirement to the power plant of a high-speed aircraft is providing high thrust at acceleration, which at high Mach flight number is determined by the air flow. A well-known decrease in turbojet engine output with flight speed increase causes the necessity of changing air-breathing engine (ABE) operation mode at high Mach number to ramjet mode.

Problems of matching the essentialy different operation modes in combination with the more stringent requirements to the noise level, sonic boom intensity and detrimental emmision create a very complicated problem to develop the multimode hypersonic power plant.

There is a need in using variable cycle engines (VCE) to match conflicting ecological and thrust characteristics requirements. Usually VCE is a by-pass engine with variable geometry components. Adding the ramjet to such engine types allows to develop a combined variable cycle power plant with a very wide range of performance.

Selection of one or another type of an engine is to a great extent determined by the requirements to a hypersonic aircraft. The change in these requirements can significantly change the power plant reasonable design. For example, at high aircraft thrust-to-take-off weight ratio and stringent requirements to the specific weight of an engine, power plants with air-turbo-rocket engines (ATR) may have certain advantages; however they have low fuel efficiency, particularly at low flight speed.

Turbocompressor engines of more sophisticated cycles, using hydrogen high cooling and working capacity (air cooling at the engine entry, steam-hydrogen turbine) allow to extend the flight speed range of their using and have higher efficiency, but higher weight too, as compared to the rather simple gasgenerator ATR.

When there is a considerable part of subsonic cruise flight (for instance the flight over populated territory, subsonic hold, emergency situation in case of supersonic or hypersonic transport aircraft) there are severe requirements to providing for high fuel efficiency at the mentioned modes. In this case, the advantageous will be the power plant with the turbojet (TJ) or turbofan (TF) (VCE), whose fuel efficiency at the throttle cruise modes is much more higher as compared to the steam-hydrogen (regenerative) ATR.

The analysis of mission performance and advantages of some various ABE concepts was conducted for two advanced hypersonic aircraft - ATOS launcher with stage separation at Mach 6 and HST with cruise speed Mach 6 (Fig. 2). The climb and acceleration trajectory was practically identical for both missions and the flight at maximum speed was conducted on an altitude out of atmospheric ozone maximum concentration area (Fig. 3). *)

The efficiency criterion of the ATOS power plant was a relative mass of the second stage. For the HST with constant for all variants commercial load mass the criterion was a take-off weight. For the last mission airplane (HST), two flight concepts were considered - only with hypersonic cruise and combined subsonic (about 20 percent of total range) and hypersonic cruise. The combined mission reflects the possibility of flight speed reduction above the populated territory for sonic boom impact elimination.

The liquid hydrogen fuel is used. The using of LH2 provides to consider a wide variety engine concepts as it is of great combustion heat, high cooling capacity and high working capacity when expanding in turbine [3].

The next engine concepts are discussed (Fig. 4).

1. Turboramjet engine (TRJ). TRJ consists of the TJ and RJ parts and has common afterburner-ramjet combustion chamber (ARCC) and ramjet channel with shut-off device. The TJ has a compressor with moderate pressure ratio and high temperature turbine (Tgmax up to 2000 K). The variation of TRJ with separate combustion chamber of RJ part (TRJs) was also considered. The independence of the TJ and RJ parts in TRJs provides a parallel operation of the parts at low and moderate flight speed with higher thrust performance.

2. Turbofanramjet engine (TFRJ), which, in essence, is a high temperature, variable geometry turbofan (VCE). The selection of design by-pass ratio value at higher level improves matching of the TF and RJ sizes and transition of the engine to windmilling fan mode at high Mn.

3. Regenerative Airturborocket engine

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*) Mission performance analysis was conducted by N.P. Doulepov and G. Khartchevnikova, to whom authors express their acknowledgements.

(RATR) with transition to RJ mode at high Mn. Its compressor is driven by turbine working on gaseous hydrogen, heating of which is performed in the heat exchanger, located in combustion chamber. Because of heat regeneration the SFC of the engine is nearly equal to the SFC of the TFRJ at operation with the same maximum fuel-to-air ratio, but RATR has higher thrust-to-weight ratio because of low pumping work of a liquid fuel. The turbine inlet temperature is 1200 K.

4. Airturborocket engine (ATR) with transition to RJ mode at high Mn. The oxygen/hydrogen burner (gasgenerator) provides high pressure fuel rich flow to the uncooled turbine. This fuel rich flow is then mixed with compressor discharge flow and burned in the combustion chamber. The turbine inlet temperature is 1200 K.

The variable geometry inlet and nozzle performance efficiencies are the same for all engine types. Design fan (compressor) pressure ratio in the cases of TFRJ, RATR and ATR was selected nearly the same. For this reason the thrust characteristics of TFRJ and RATR are nearly similar (Fig.5). The SFC of the ATR is higher about 2 - 3 times in comparison with other engine types because of using of onboard oxygen. It was adopted, that all engines operate on RJ mode at flight speed higher than Mach 3.5.

The independent selection of gasturbine part and ramjet part sizes (a fan/compressor inlet area Ac and an ARCC or ramjet burner cross section area Ar) is common feature of the combined engines.

In general:

- a size of inlet area Ai is determined by design thrust value at the maximum flight speed and optimised by influence on the flight range and external drag at the transonic flight speed ;
- a size of the fan (compressor) area Ac is determined bearing in mind ecologycal requirements: namely, by a design thrust at the transonic flight speed (sonic boom limitations) or at take-off (noise level limitations); for engines with lower dry specific thrust (TFRJ) the subsonic cruise thrust can be determinating factor;
- a size of ARCC cross section area Ar is determined by the flight speed at which a transition to ramjet mode is realized and is optimised taking into consideration matching of TJ (TF) and RJ operation modes;
- a size of nozzle exit area An is optimised taking into consideration nozzle efficiency at the maximum flight speed, external drag at the transonic flight speed and nozzle weight.

TFRJ has the highest fuel efficiency on subsonic cruise flight. In accordance with higher propulsive efficiency its dry thrust SFC is lower about 25 - 35 percent in comparison with TRJ and about 2 - 3 times - in comparison with RATR (for very high fuel consumption the ATR engine cannot be a competitor at this flight regimes), (Fig.6). However, the low dry specific thrust of the TFRJ at a minimum SFC condition may lead to decrease of subsonic cruise flight speed and altitude or to increase of engine size and propulsion system weight. It should be noted that the range of a RATR throttling performance is limited by the heat exchanger construction over-heating.

For the engines considered one can recognize some interdependence between the engine thrust-to-weight ratio (TWR) and SFC at the subsonic cruise flight. The ATR has a highest TWR. The RATR has a TWR about 10 - 15 percent lower in comparison with the ATR because of a heat exchanger weight and lower working mediumin flow in turbine. The TRJ and TFRJ have a TWR about 1.5 - 2.0 times lower (Fig.7).

The results of mission performance analysis are presented on Fig. 8, 9. The highest second stage mass corresponds to ATOS launcher with RATR propulsion plant in accordance with good engine TWR and relatively low fuel consumption at maximum thrust rating. The second stage mass lower only about 5 - 7 percent corresponds to the system with TFRJ or TRJ. The lowest second stage mass corresponds to ATR (about 12 - 14 percent lower in comparison with turboramjets) because of worst fuel consumption which cannot be compensated by low engine weight.

The mission performance results for HST are substantially influenced by a presence of subsonic cruise. In case of fully hypersonic cruise the lowest HST take-off weight corresponds to RATR power plant. Other engine types effectiveness is some lower and nearly equal (TOGW is higher by 18...20%), (Fig.9). If combined subsonic and hypersonic cruise is considered (subsonic part is about 20 percent of total range), then turboramjet engines reveal lowest take-off weight (TFRJ gives nearly 5% advantage in comparision with TRJ). Take-off weight with RATR engines is about 1.8 times higher than with turboramjets. Taking into account take-off noise limitations, the advantages of TFRJ are increasing additionally.

Hence, TRJ and TFRJ could be considered as universal multimode engine types for hypersonic (up to nearly Mach 6) aircraft of different missions.

Turboramjet engines (TRE)

Let's consider some peculiarities of operating process of TRE as combined engines.

The TRE features depend on its design. The multitude of TRE types can be split up according to the principle of using the engine gas-turbine part 'free power' to compress air in ramjet part in order to increase the engine thrust at take-off and low flight speed (Fig.10).

The TRE without energy transfer to the ramjet part is just a mechanical combination of turbojet and ramjet engines. If there is a separate combustor in the ramjet part, then the parts are independent. This allows to light on the ramjet at the transonic flight to increase the total thrust of the engine. Thus, in the TRE of this type a simultaneous (parallel) operation of the parts is realized. For better performances of the engine at its operation at ramjet mode the switched-off part should be shut off by special devices such as doors, louvres, moving centre body etc. The most simple and compact in this group of types is the TRJ with separate gas-turbine and ramjet channels (TRJs), especially when using 'stoichiometric' TJ.

A group of TRE types without energy transfer to the ramjet part at low flight speeds includes also the TRJ with ARCC common for TJ and RJ parts. In this case the TJ is intended for charging the ARCC at low and moderate flight speed. According to the consecutive layout of the TJ and ARCC the TRJ operation mode with flight speed increase is changed from gas-turbine mode to the ramjet mode. The TRJ principle feature is impossibility to realize the parts simultaneous (joint) operation mode at low and moderate flight speeds due to the large pressure difference in TJ and RJ parts. Hence the necessity to shut off the ramjet duct at gas-turbine operation mode with a special device takes place. After transition to the ramjet mode the TJ operating mode can be changed to windmilling or idling, which can be used to drive the accessories. The TRJ has advantages from the point of view of dimensions and simplicity.

In TRE with energy transfer to the ramjet part the free power produced by the gas-turbine engine is used to increase pressure of the air supplied to the ramjet. As a result both parts of the engine can be involved in operation within the range of flight speeds and altitudes. These types are essentially the development of the TRJs and TRJ by application of compressor (fan) to increase air pressure in the ramjet part.

The TRE with energy transfer by fan (TFRJ) doesn't differ principally from augmented turbofan with separate primary and secondary flows (TFs) or with mixing flows (TFm). Their feature is the change to the operation mode with fan windmilling at high flight speeds. In this connection the windmilling fan drag presents an important factor. Multimode operation possibility and using windmilling fan to drive accessories are the important advantages of the TFRJ.

Selection of the design by-pass ratio is of important role in developing a multimode engine. The less the by-pass ratio, the closer the TF performance to those of the TJ. At high supersonic flight speed (M > 3.5) the engine must run according to the RJ cycle, which can be realized more simply at the larger dimensions of external low-pressure part, that is the higher the design by-pass ratio. Its increase in this case decreases the demand in variable geometry of the passage. The fuel efficiency at subsonic cruise is also improved.

The design by-pass ratio increase results in engine air flow and its cross dimensions increase. In case of moderate supersonic flight speeds aircraft (M = 2...2.5) this is one of the reasons for selecting low by-pass ratio values. In case of high supersonic flight speeds (M > 3) the cross dimensions of an inlet and diverging nozzle rise considerably (Fig. 11), whereby a significant increase in the by-pass ratio within the range determined by the dimensions of the power plant entry and exit can be possible. The optimum by-pass ratio values depend on the engine cycle parameters, aircraft aerodynamic characteristics, flight parts with supersonic and subsonic speed etc.

Transition from gasturbine (GT) to ramjet (RJ) mode is TRE peculiar operation mode. The TJ and RJ engines have different thrust characteristics in function of flight speed. This determines an existence of the optimum flight Mach number for transition to the RJ mode. If a criterion is the minimum time for airplane climb and acceleration, then the optimum Mach number corresponds to condition when thrust of GT and RJ modes being equal. If a criterion is the minimum fuel consumption for acceleration/climb, then the optimum Mach number corresponds to the condition when SFC related to excess thrust on GT and RJ modes being equal. Therefore, the optimum Mach numbers depend on the engine air flow change at GT and RJ operation modes also [5].

If the TRE air flow on transition mode is limited by ARCC flow capacity and is not limited by the power plant inlet, then the optimum Mach number could be lower than TJ 'degeneration' flight Mach number (when engine's PR => 1). In this case, the adequate control of propultion system is needed to provide a stable operation on transition mode. The curves of Mopt numbers for the minimum of time and for the minimum of fuel consumption at acceleration/climb are shown on Fig.12. The optimum Mach numbers are decreased when rising of ARCC cross section area to compressor inlet area ratio Ar/Ac and are lower than the TJ 'degeneration' Mach numbers.

TRE demonstrators investigations

Investigations into real operation

and performance of the TRE were conducted in CIAM within the programme of development and test bench studies of several versions of full-scale TRE demonstrators, created on production TJ's and their parts. Here some results of the investigations are presented.

TRJ demonstrator (Fig.13) has a ramjet channel with controlled shut off device. There were studied the performances at switching for various operation modes, at ramjet mode with cooling the heat stressed components, also studied operation conditions of rotor supports etc. For the first time there was conducted tests of an experimental TRJ under simulated flight conditions at $M = 3...4$ ($t^{*}e \approx 300 - 600\ ^{\circ}C$) for rather long time (several hours) [6].

Tests of experimental TREngines were conducted at the facility with attached air pipeline, when at the engine entry the air parameters behind the inlet are reproduced (Fig.14). Realized at the facility maximum entry air temperature corresponds to approximately $M \approx 5$, is provided for by heat exchanger and flame heaters (with recovery of air normal composition by oxygen replenishment) and, in case of need, may be increased. Air pressure at the entry reaches 900 kPa. The facility has several hundreds channels for temperature and pressure measuring in static and dynamic modes. The facility dimentions allow to test any current supersonic engine.

Investigations have revealed rather narrow operation interval, inside which power plant stable working process with parallel operation of TJ and RJ parts could be realized (Fig.15). Maintaining the TJ operating parameters with respect of the limitations provides the propulsion system reliability on transition to RJ mode. At transition operation the profile of ARCC inlet flow velosity changes considerably (Fig.16). The transition to RJ-mode is finished with TJ windmilling, which may be used to drive engine accessories.

Inlet air flow capacity limitation is rather inherent for TFRJ propulsion plant on transition to RJ operation mode. In this case a transition to RJ mode consists in the gradual TF switch off in some Mach numbers interval. The propulsion system governing is determined by inlet and engine air flow matching at minimum pressure losses taking into consideration stable operation margin. The transition process begins at Mach number when inlet maximum air flow capacity is reached and finishes with TF attaining the windmilling operation mode (in case of TFRJs with duct burner the primary burner fuel flow gradual switching off is followed by primary nozzle closing) [4]. The example of TFRJ performance characteristics (for engines with common and separate nozzles) at transition to RJ mode is shown on Fig.17. Because of by-pass ratio fast rise SFC is some increasing at the transition process. On RJ mode the propulsion system control is provided by decreasing of nozzle area with flight speed rise; RPM and corrected air flow are decreasing respectively.

At $M = 4...5$ the fan corrected air flow and corrected speed, corresponding to typical relationship of areas Ai/Ar, decrease down to 20-40% of the values at take-off.

Let us consider the peculiarities of the fan operation at low rotation speeds ($Nc < 0.4$). Reducing the counterpressure behind the fan the operating point is shifted to the right down on the characteristic, and this is followed by 'stretching' the velocities triangles, decreasing angle of attack and expended work. At some point the work is equal to 0, that is when the fan is at the mode of free windmilling and represents the 'hydraulic drag' in air flow ($PR < 1$). The combination of such points at various rotation speed gives a line of windmilling mode operation (Fig.18). With further shift of the operation point down on characteristic the fan changes operation to the 'turbine' mode producting a certain power. The expediency of using the fan to drive the power plant accessories at the ramjet mode of operation depends on its efficiency as a 'turbine', values of the work taken-off, thermal condition and other factors. The higher flight Mach number and inlet pressure recovery and the less design fan pressure ratio, the less pressure loss in the fan at windmilling. Experiments on full scale fans and TFRJ models have demonstrated the possibility of RJ mode performance with rather low losses in windmilling fan.

Experimental demonstrator engines investigations are the part of advanced power plants designing methodology created in CIAM - the national scientific centre of the engine industry. CIAM carries out scientific supervision of the work conducted in engine and accessories design bureaus and related research institutes [6]. The principle of this methodology, which assumes stage-by-stage development order, consists of building up scientific-technical base prior with respect to the phase of engine development. This principle includes development of new construction materials and technologies, design and testing methods, design and development of experimental parts, components, gasgenerators, engines with gas-dynamic, duration and cyclic testing. Although this initial phase is characterized by relatively low costs with respect to the total programme it is however very important in providing for new engine high quality and efficiency (Fig.19). Application of the methodology favours aircraft and engine development matching.

CIAM has the largest rigs to investigate engines and their components in altitude conditions. The unique experimental base of CIAM allows to conduct comprehensive tests of engines of practically any thrust and power.

As an example of an up-to-date powerful facility to investigate supersonic engines there is altitude facility with a multimode generator of flow disturbances at the engine entry, automated system to monitor experiment processes, up-to-date means of data processing (Fig.20), which allows to conduct the investigation of non-uniform flow effect on the engine performance under conditions most close to those in flight at steady-state and transient regimes. The facility operation imitates the flight dynamic conditions along the trajectory simulating non-uniformity of pressure distributions and pulsations at the engine entry, which correspond to the inlet operation at different angles of attack and slip.

Solving complicated problems of developing new aviation techniques requires high expenditures. International cooperation in the building up scientific-technical base for abvanced powerplants is one of the important factors to successfully realize the projects of the 21st century air transport.

The authors acknowledge the contributions from collegues during the preparation of this paper and thank the Directorate of Central Institute of Aviation Motors (CIAM) for permission of this publication.

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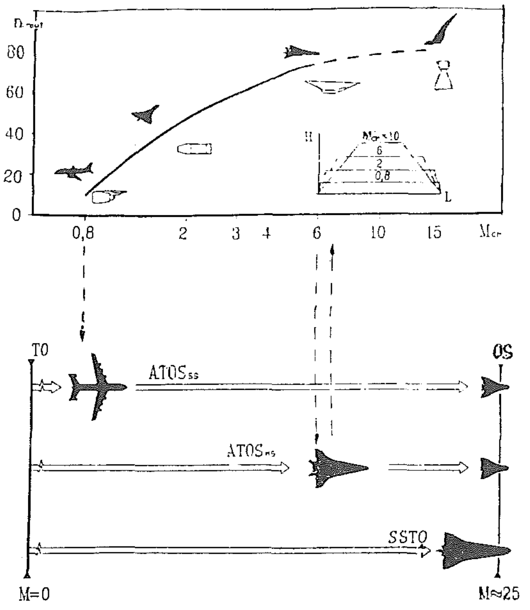


Fig.1. Future airtransport and airspace systems

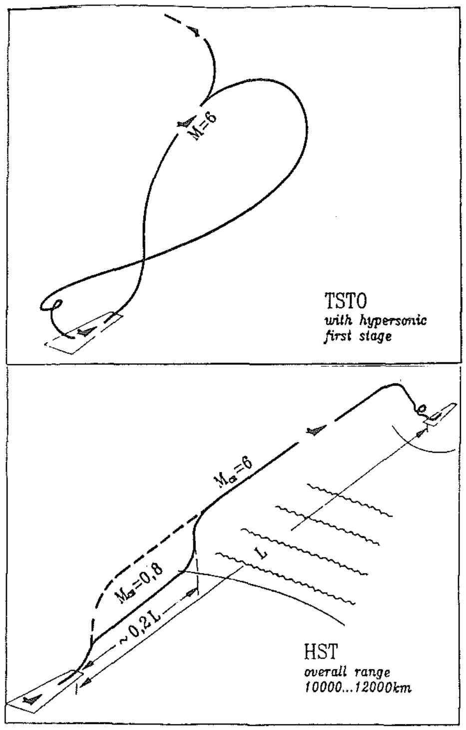


Fig.2. The flight profiles of ATOS (TSTO) and HST

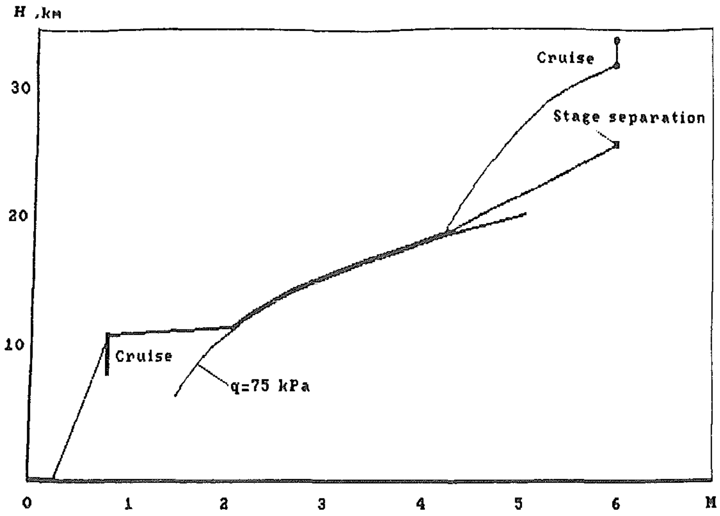


Fig.3. Flight trajectories

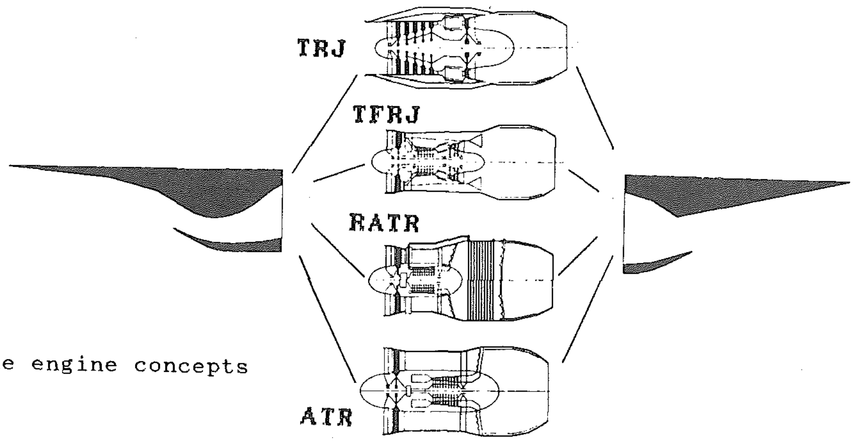


Fig.4. The engine concepts

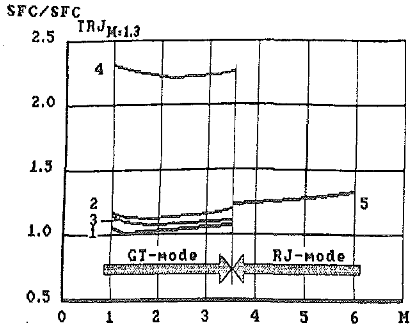


Fig.5. The engine's relative specific fuel consumption
1 - TRJ ; 2 - TFRJ ; 3 - RATR ;
4 - ATR ; 5 - RJ

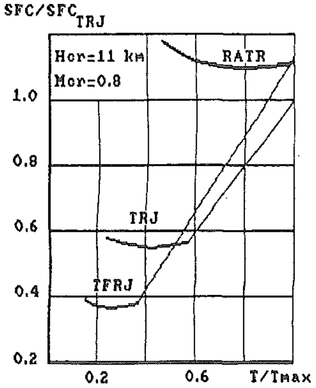


Fig.6. The engine's performance characteristics

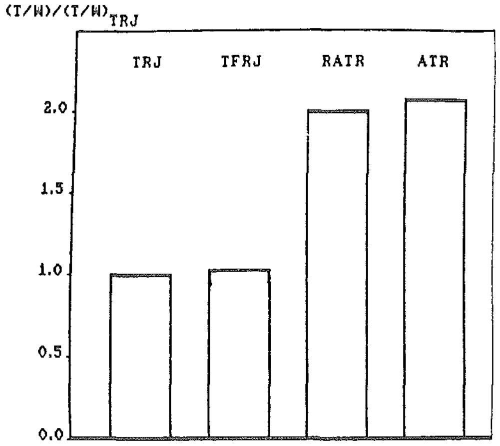


Fig.7. The engine's relative thrust-to-weight ratio at transonic speed

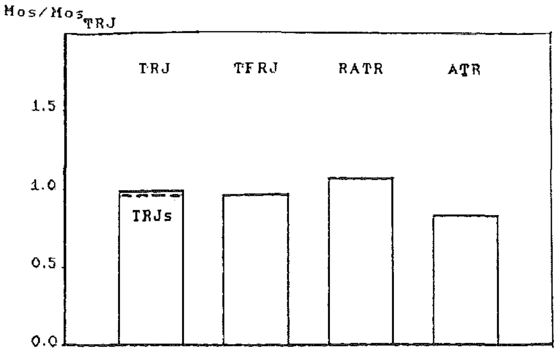


Fig.8. The TSTO second stage relative mass

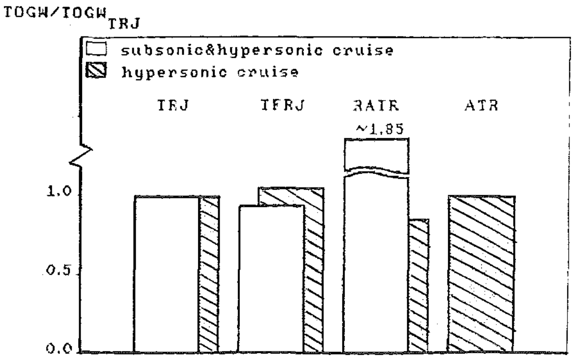


Fig.9. The relative TOGW of HST

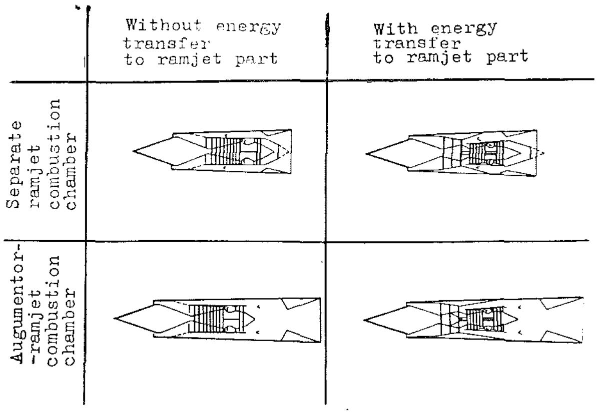


Fig.10. TRE's classification

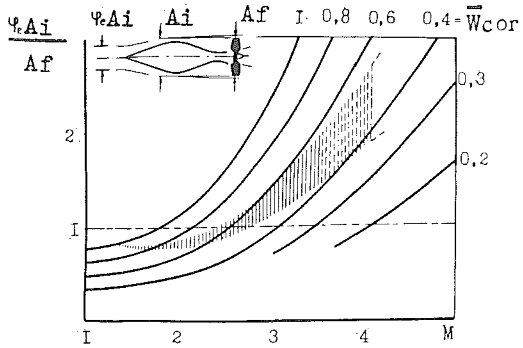


Fig.11. Air inlet flow-to-fan inlet section areas ratio at various flight M and fan corrected air flow

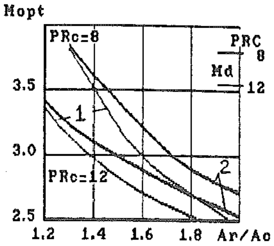
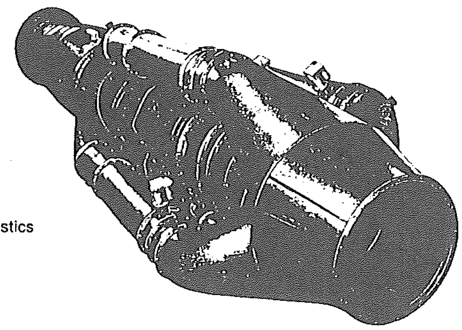


Fig.12. TRJ optimum transition Mach numbers
1 - $Mopt_t$; 2 - $Mopt_\xi$



- Complex Study of operation
- Engines switching modes
- Afterburning and ramjet combustor (ARC) operation
- Ramjet operation mode characteristics (M > 2.5)
- Windmilling mode
- Power output
- Passage hydraulic characteristics
- Structure heat state
- ARC and nozzle cooling at M ≈ 3.5 - 4.5
- Transmission operability
- Cooling system impact on T and SFc

Fig.13. CIAM experimental turboramjet

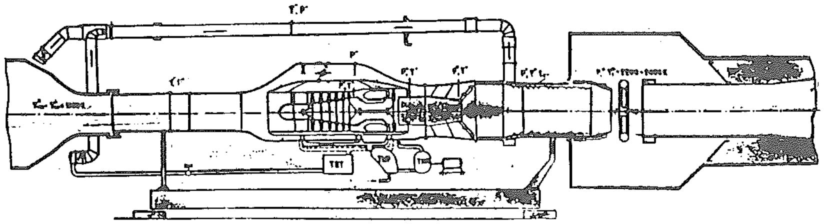


Fig.14. The test facility

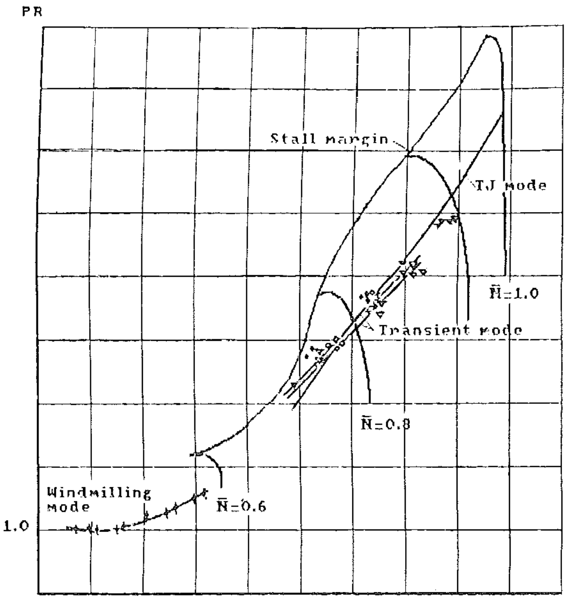


Fig.15. The TRJ compressor performance map

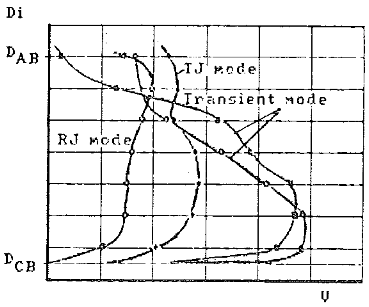


Fig.16. The flow velocity profiles on ARCC entry for different TRJ operation mode

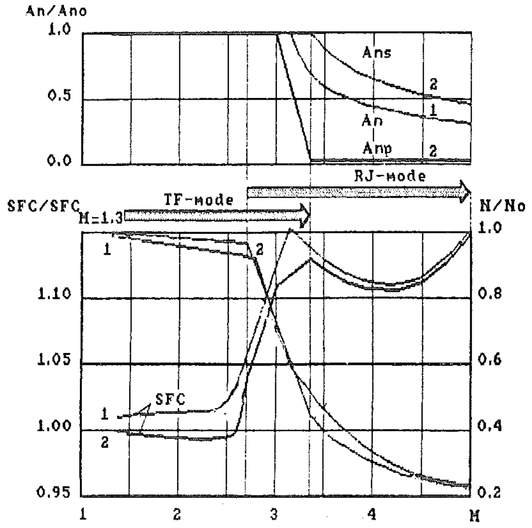


Fig.17. The TFRJ operation parameters variation at the transition mode; 1-TFRJ, 2-TFRJs.

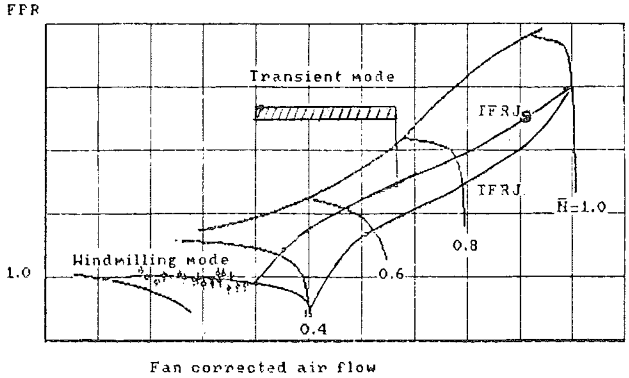


Fig.18. TFRJ fan performance map

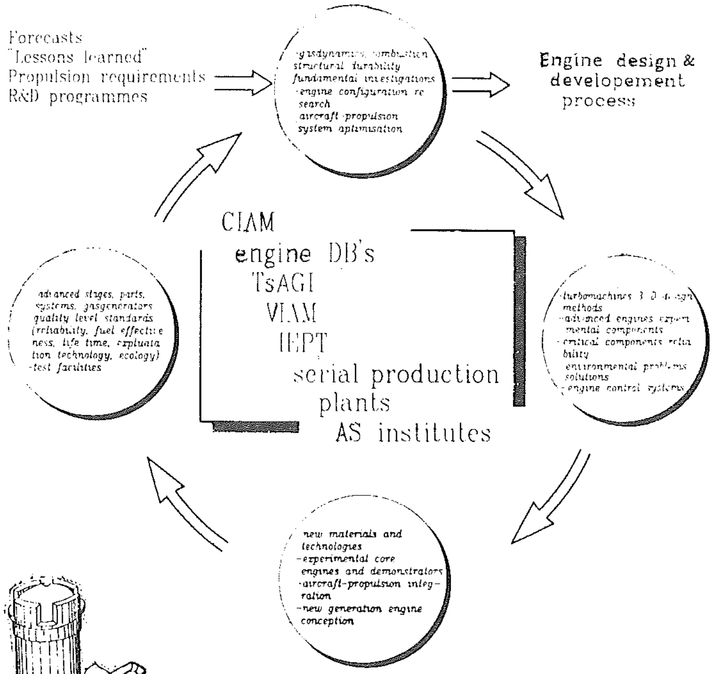


Fig.19. Scientific base for ABE

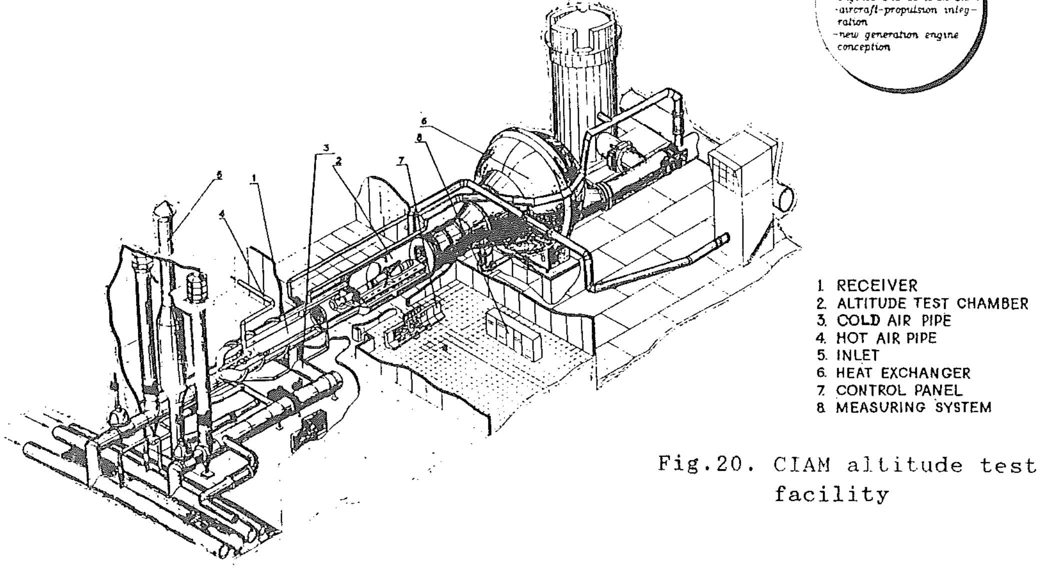


Fig.20. CIAM altitude test cell facility