THE STUDY OF TURBORAMJETS IN CIAM

Mikhail Tskhovrebov*, Valentin Solonin*, Vladimir Palkin*, Pavel Kadjardouzov*
*Central Institute of Aviation Motors (CIAM), 2, Aviamotornaya St., Moscow, Russia, 111116

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Abstract

In the second half of the fifties there was a significant growth of interest to advanced technologies for high speed flight. The CIAM began fundamental studies of combined air-breathing engines whose operation process is based on evolution of the concept of the bypass engine with reference to flight conditions at high supersonic speeds. At the same time, the foundation of their theory was laid.

In period 1970…1980-s the wide testing program of full-scale TRE demonstrators of different types has been performed at CIAM. The TRE demonstrators, using a kerosene as fuel, have been assembled from components of produced turbojet and turbofan engines. At the testing, the flight conditions, corresponding to the Mach numbers up to 4.0 have been simulated at the test cell.

In this paper essential technical requirements and design features of the TRE demonstrators, designed and developed at CIAM for carrying out of their testing, are shown. The some results of the TRE demonstrators testing including the engine parameters at transition to the ramjet mode (RJ-mode), variation of the parameters in the windmilling mode (RJ- mode), and the flow characteristics in the afterburner-ramjet combustor are presented. A matching of the TRE characteristics at the transition from gasturbine mode (GT-mode) to RJ-mode and a variation of the parameters when TRE transition to the windmilling mode are discussed.

Nomenclature

A - area
C - velocity
F - thrust
M - Mach number
P – pressure
T - temperature
V - flight speed
W - airflow
β - relative airflow in ramjet or turbofan duct

Abbreviations

AB - afterburner combustor
ARC - afterburner-ramjet combustor
BP - bypass ratio
GT - gasturbine engine
PR - total pressure ratio
PS - propulsion system
RJ - ramjet engine
SFC - specific fuel consumption
TF - turbofan engine
TJ - turbojet engine
TJAB - turbojet engine with afterburning
TRE - turboramjet engine
TRJ - TRE based on TJ with common AB
TRJs - TRE based on TJ with separate RJ.
TFAB - turbofan engine with mixing of flows and common AB
TFRJ - TRE based on TF with mixing of flows and common ARC
TFABs- turbofan engine with
TFRJs - TRE based on TF with duct ARC

Subscript

c - compressor
col - cooling system, cooling air
cor - corrected parameter
e – external
ex - exit
f - fan
g - gas
i - internal
in – inlet

n - nozzle throat
0 - design mode
r - ramjet duct
s - screen
t - turbine
u- tangential component
*- total parameters

1 Turboramjet engine types

There are the many types of TRE and their selection depends on the vehicle mission. The multitude of TRE types can be split up according to the principle of using the gasturbine part "free power" to press air in ramjet part and on a type of ARC – common or separate [1-5].

1.1. TRE without energy transfer to the ramjet part

The TRE without energy transfer to the ramjet part is just a mechanical combination of turbojet (turbofan) and ramjet engines (Fig. 1). Their thrust are obtained by adding altogether the performances of gasturbine and ramjet parts.

At the GT-mode, that is when the ramjet part is switched off (β=0), such an engine has the TJAB or TFAB characteristics, while at the RJ-mode, when the TJ (TF) is switched off (β=1) it has the ramjet engine (RJ) characteristics. If there is a separate combustor in the ramjet part then the parts are independent. This allows to switch on the ramjet at the transonic flight to increase the total thrust of the engine (TRJ_S and $TFRJ_S$ in Fig. 1). Thus, in the TRE of this type a simultaneous (parallel) operation of the parts is realized.

For improvement of engine characteristics at operation on the RJ-mode the switched-off part should be overlapping by special devices such as doors, louvers, moving centre body etc.

The drawback of the TRE types with separate combustor and without energy transfer to RJ part consists in larger dimensions, complexity and higher structure weight, which is necessity for parallel arrangement of two combustors with variable nozzles. The more simple, compact and advanced in this group is the TRJ with separate gasturbine and ramjet ducts (TRJ_S), 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 common ARC for TJ and RJ parts. In this case, the TJ is intended for charging the ARC at low and moderate flight speeds. According to the consecutive layout of the TJ and ARC, the TRJ operation mode with the flight speed increase is changed from GT-mode to the RJ-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 passages. Hence, the necessity to shut-off the ramjet duct at the GT-mode by a special device and special control at the transition mode when switching to RJ takes place.

Necessity to isolate the switched-off TJ at high M numbers may be consisted in the influence of kinetic heating on structure. Hence, if structure durability and oil system operability are sufficient, then along with switching to RJ-mode, it is possible to transfer the TJ to windmilling or flight idling and use it for driving of the accessories. Usually at this mode only small part of airflow passes through TJ part ($\beta \rightarrow 1$) and difference in thrust characteristics from a pure RJ is rather small. The TRJ has advantages from the point of view of dimensions, weight and simplicity.

1.2. TRE with energy transfer to the ramjet part

In the TRE with energy transfer to the ramjet part (Fig. 1), the free power produced by the GT 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 whole range of speeds and altitudes of flight. These types are essentially the development of the TRJs and TRJ by application of blade (or jet) compressor to increase air pressure in the ramjet part.

In the TRE types with energy transfer by ejector the active operating fluid is the airflow from the fan or turbine. These TRE types in principle do not need the shut off device for RJ part duct. For effective operation at take-off and low flight speeds the conditions in which one can obtain some effect from ejection using, it is necessary to make up some constructive measures. Among these there are: lowering the turbine or fan passage exit area for maintaining high active gas parameters; using narrowed mixing chamber and special mixer for lowering the losses; using ARC with large cross-section for losses lowering and, consequently, using the diffuser with large area ratio before ARC. The necessity on these features, consisted with engine complexity, higher weight and dimensions, is conditioned by low efficiency of jet compressor when limiting its dimensions. As a result, the TRE types with ejection have no practical advantages before the types with energy transfer to RJ part by turbofan.

The TRE with energy transfer by fan (TFRJ or $TFRJ_S$) does not differ principally from augmented turbofans with separate primary and secondary flows $TFAB_S$ or with mixing flows TFAB (Fig. 1). Their feature is the transition to the RJ-mode with turbofan windmilling at high flight speeds ($\beta \rightarrow 1$). In this connection, the windmilling turbofan drag presents an important factor. Multimode operation possibility and using windmilling turbofan to drive the accessories are the important advantages of the $TFRJ_{(S)}$. In case with rather high design fan pressure ratio, which worse windmilling characteristics, or, if the TF should be isolated from kinetic heating at RJ-mode as a result of reliability requirements, it is necessary to include into the engine structure the passage around the fan for bypass the airflow at high flight M number. For the same reasons as in the case of TRJ, this passage should be closed by special device in low flight speed conditions.

The TRE types with energy transfer and separate combustor of RJ part inherently have compact configuration because of both parts parallel arrangement. But these types require closing of gasturbine passage exit at RJ-mode for maintaining the thrust characteristics. The TRE types with common ARC do not need such closing, but it is longer and needed a wider range of nozzle flaps moving.

The expediency of using the TRE based on TJ or TF is defined by the vehicle mission. If the high fuel efficiency at low flight speeds and a good performance at the cruise flight with M_{max} are required the TF as the basic engine is preferable. If the main requirement is the high performance at maximum flight speeds, then it is expedient to analyze the possibility of using the TRE types based on the TJ too. It is possible to make up the TFRJ structure with slightly lower length and weight than of the TRJ with equal design thrust.

The main advantages of the TFRJ are following:

- effective performance in wide range of flight condition;
- lower noise level at take-off and low flight speed condition;
- wide range of thrust variations at constant airflow.

2 TRE dimensions and design parameters

The independent selection of both the gasturbine part and the ramjet part sizes (a fan / compressor inlet area A_f or A_c, and an ARC or ramjet burner cross-section area A_x) is common feature of the combined engines (Fig. 2).

In general:

- an intake area A_{in} is determined by design thrust value at the maximum flight speed and optimized by influence on the flight range and external drag at the transonic flight speed;
- a fan (compressor) area A_f (A_c) is determined in mind ecological 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 determining factor;
- the ARC cross-section area A_x is determined by the flight speed at which

a transition to RJ-mode is realized and is optimized taking into consideration matching of TJ (TF) and RJ operation modes;

– a nozzle exit area A_{ex} is optimized taking into consideration nozzle efficiency at the maximum flight speed, external drag at the transonic flight speed and nozzle weight.

Selection of the design bypass ratio is of important role at the development of a multimode engine. The less of the bypass ratio, the closer of the TFAB characteristics to those of the TJAB. With bypass ratio rising the TFAB properties are approaching those of the RJ [1-3].

When rising the design bypass ratio at given cycle parameters the optimum fan pressure ratio and engine core airflow are decreasing. This decreasing leads to increasing of summary engine airflow at supersonic flight speeds. As a result, the relative engine thrust at the maximum augmented ratings (F/F_0) increases.

Corresponding SFC also increases, but usually this does not leads to a significant rising of required fuel amount, because of simultaneous increasing of excessive thrust and higher acceleration rate. At high supersonic speed flight (M>3.5) the engine must run according to the RJ cycle, which can be realized more simply at the larger dimensions of the external low-pressure passage, that is the higher the design bypass ratio. Its increase in this case decreases the demand in special mechanization of the passage and in additional bypass duct. The fuel efficiency at subsonic cruise is also improves.

An increasing of design bypass ratio results in increasing of both an engine airflow and its cross dimensions. In case of aircraft of moderate supersonic flight speeds (M=2.0÷2.5) this is one of the reasons for selection of the low bypass ratio values. In case of high supersonic flight speeds (M>3) the relative cross dimensions of an intake and a diverging nozzle are raised considerably, whereby a significant increasing of the bypass ratio within the range determined by the dimensions of the PS is possible.

As to subsonic cruise part of flight, which is inherent to heavy-weight supersonic vehicles, the fuel economy considerations also require the choice of higher bypass ratios, but with upper limit about $m_0 \leq 4$ because of substantial falling of the engine dry thrust.

The typical TFRJ characteristics should be considered when making the choice of design bypass ratio. In this case, the "critical" factor is the engine dry thrust at subsonic cruise. The requirements for the design take-off (or transonic) thrust and thrust value at cruise with maximum speed are providing for by corresponding design dimensions of intake, fan, and ARC in the whole considering range of engine parameters. With higher design bypass ratios a fan dimension increases, but this does not influence on fuel efficiency at high speed cruise, slightly reflects on engine weight and leads to higher fuel efficiency at subsonic cruise. However, subsonic dry thrust decreases. Increasing bypass ratio higher than some limiting value would be bringing to higher engine dimensions and weight and to engine oversizing relatively to other flight conditions In this case, the maximum bypass ratio, at which the dry thrust corresponds to required level, is the expedient design value [1, 4].

Then, for the engines of multimode flight vehicle with high supersonic flight speed adoption of relatively high design bypass ratios may be rational decided. The optimum bypass ratio values depend on the engine cycle parameters, aircraft aerodynamic characteristics, distances of flight parts with supersonic and subsonic speed, etc.

It is possible to use the similar approach when defining the optimum correlation between the dimensions of RJ and TJ parts of TRJ. This correlation one can express as the ratio of the ARC section area to the area of compressor inlet. The choice of each of them is to some extent mutually independent, and is defined by required thrust values at RJ and GT modes of operation (for example, at take-off). At rather, low A_X/A_C ratio the engine will be oversized for GT-mode of operation, while at the high values – for RJ-mode. At some ratio value the both areas and engine weight are of minimum, and it is possible to consider this value as an optimum.

3 The CIAM experimental turboramjets

The large programs of the studies of engines for high speed flights were carried out in Russia in 60…80-ties years (series of 5-years programs). In the framework of these programs the studies of advisable engine concepts, cycle parameters, control modes of TRE were conducted. In this period, the program of development and testing of full-scale TRE of various architectures in real simulated flight conditions was carried out at CIAM. The experimental TRE were assembled from components of produced TJ and TF. Within the tests, the flight conditions corresponding to the Mach numbers M=4.0 were simulated on the test facility.

For simple solving of the problems of maintainability, preparation, manufacturing, and controlling, the unified ram-duct with a shut-off devices with remote control was used. The ram-duct consist of front and back manifolds and four connecting side tubes; replaceable nozzles which provided different exit areas used too (Fig. 3).

To study a heat state of ARC the TRJ was equipped by perforated screen along ARC length, distribution system of manifold fuel supply and separate air cooling system. This cooling system could provided variable parameters of cooling air (W_{col}, P^*_{col}, T^*_{col}) into cooling duct, i.e. into space between external case and perforated screen of ARC.

The bearing supports of TRJ were reconstructed. To provide an operability of bearing at high Mach numbers, thermo-protective screens were mounted over the support cases. Air cooling system with variable parameters (W_{col}, P^*_{col}, T^*_{col}) and oil system with variable oil feed were used for bearing support cooling.

The main goals of the tests were following:

- complex study of operating process;
- ARC operation;
- engines switching modes and operation stability;
- windmilling and RJ-modes characteristics;
- passage hydraulic characteristics;
- power output possibilities;
- ramjet combustor and nozzle cooling at M=3.0÷4.0;
- cooling system impact on TRE characteristics;
- structure heat state and transmission operability.

Tests of experimental TRE were carried out on the CIAM-branch test facility with direct connected pipeline which permitted to simulate the flight conditions corresponding to the Mach numbers M=4.0 (Fig. 4). The entry air temperature realized at the facility was provided for by heat exchanger and combustion heaters (with recovery of air normal composition by oxygen replenishment). Air pressure on the inlet was reached up to 900 kPa. The facility has several hundreds channels for both the temperature and the pressure measurements in static and dynamic modes. This test cell was equipped also with injector exhaust system. Test cell was equipped by separate air cooling and oil systems with controlled parameters.

The parameters of airflow at the engine inlet changed in range:

- P^*_{in}=0.1÷0.2 MPa;
- T^*_{in}=270÷900 K.

The variable parameters of cooling air for ARC cooling changed in range:

- T^*_{col}=400÷900 K;
- P^*_{col}/P^*_{ARC}=0.95÷1.40;
- W_{col}/W_x=0.03÷0.23.

The bearing cooling air pressure was varied in range up to 0.5 MPa and oil pressure on entry of bearing supports was changed in range p_{oil} = 0.16÷0.22 MPa.

The air mass flows through ram-duct and ARC cooling air tube were controlled by the change of shut-off devices damper angles.

Engine continuous operation time at M=4.0 was about 3 hours.

3.1 An experimental studies of TRJ transition to RJ-mode

The transition from gasturbine to ramjet mode (also windmilling mode) is the great interest for TRJ. The first part of testing was directed just to these modes. Some results of these investigations will be discussed [1, 2, 4].

The rational value of flight speed for transition to RJ-mode depends on the design cycle parameters, the TJ control mode and the dimensions correlation between typical PS passage areas. The transition Mach number usually is changed in the range 2.5÷3.5 [3, 4].

The operating lines on the compressor map for different modes of operation are shown in Fig. 5. The GT-mode corresponds to the A curve. The joint operation of TJ and RJ is realized at the transition mode. In these conditions, pressure behind turbine is higher than one at ram-duct inlet. If shut-off device become to open, the control system of TRJ must response by such way that the stable operations of the intake and an engine are provided [1, 4].

The RJ starting mode corresponds to zero airflow through ram-duct. The curves B and C (Fig. 5) correspond to this mode for different values of turbine exit duct area (this area for curve C is higher than one for curve B). To this condition at the selected turbine exit area the certain engine nozzle throat area is corresponding.

The region locating above the curves B and C corresponds to the reverse flow of the gas part from behind the turbine to the inlet of an engine. Such reverse flow realizes if the engine nozzle throat area A_n is less than the value A_{n0} corresponding to the curve $W_{rd}=0$. With lower values of A_n unstable operation of TRJ and propulsion system is possible.

The points locating below the curves $W_{rd}=0$ correspond to the direct airflow through ram-duct. Such flow realizes if the engine nozzle throat area A_n is bigger than the A_{n_o}. If A_n is increased additionally, there is the increasing of airflow through ram-duct at practically the same airflow through TJ. The experimental points at the joint operation mode are located nearly the curves B and C.

At the definite values of the corrected RPM the curves $W_{rd}=0$ cross the curve A and approach to curve of compressor stall. But usually for the TRJ the corrected RPM for the beginning of transition to RJ-mode locate right of the curves crossing point. Therefore, an error of control at the beginning of transition to RJ-mode (shut-off device premature opens) presents the danger rather for stable operation of intake. The forestalling of shut-off device opening leads to lowering of TJ inlet corrected airflow with corresponding consequences. It was confirmed by some testing of TRJ [3, 4].

The rational control of engine at the transition to RJ-mode must provide not only a stable operation of PS but also the thrust proceeding without significant drops.

The studies were revealed rather narrow operation interval, inside which PS stable operability with parallel operation of TJ and RJ parts could be realized. Maintaining the TJ cycle parameters with respect of the limitations provides the propulsion system reliability at the transition to RJ-mode. The transition to this mode is finished with TJ windmilling, which may be used to drive engine accessories.

At the transient mode, the structure of flow on the ARC entry is strongly changed (Fig. 6). The results of TRJ testing show that ARC inlet flow velocity increasing at the constant rotation speed approximately in proportion to the increasing of engine nozzle area. In this case, a considerable distortion of flow take places. For example, at the GT-mode the distortion of flow is not more than 10÷20 % (the curve A in Fig. 6), but at the engine parts joint mode the maximum flow speed can exceed the mean flow velocity about 2.0÷2.4 times (the curves B and C in Fig. 6). Therefore, the special measures possibly would be demanded for stable combustion in ARC at the transition mode.

3.2. The RJ-mode of TRJ with windmilling of TJ core

At the RJ-mode TRJ can operate with either opened or closed gasturbine part of engine. The curve A on Fig. 6 corresponds to the windmilling mode of TJ turbocompressor.

The pressure losses in TJ at windmilling very strongly depend on compressor corrected air flow (the curve A in Fig. 6 with the ram-duct closed). At the RJ-mode the TRJ pressure losses do not exceed 5÷7% if TJ is closed (the curve C in Fig. 6) or is operated at the windmilling mode (the curve B in Fig. 6). The application of TJ windmilling mode provides the increase of airflow through engine as the additional part of airflow passes through TJ and gives some possibilities for accessories drive. However, expediency of the possibilities depend on the TJ efficiency on the windmilling mode.

At the RJ-mode the ARC inlet flow has a rather little distortion of speed. At the beginning of transition mode the region of maximum speeds locates in central part of ARC, and very strong distortion take place, but at the windmilling mode it replaces to peripheral part of ARC (the curve D in Fig. 6). The unevenness of ARC inlet flow decreases if the corrected airflow is decreasing too.

3.3 TFRJ performance on the RJ-mode

The engine performances and control laws of TRE based on TF core (TFRJ and TFRJs) at the high flight Mach numbers (transition and RJ-modes), including some results of tests with imitation of these conditions, are considered below.

3.3.1 Fan performance on the RJ-mode

For maintaining rather low losses in the air intake with an increase of flight Mach number the fan corrected airflow should be decreased, as it follows from equality of airflows in the stream at infinity before an air intake and in the fan inlet at the areas ratio ($f_{in} \cdot A_{in}/A_f$).

Let us consider the peculiarities of the fan operation at low rotational speed (n_{cor}/n_{cor_0} <0.4). The typical fan characteristic at low RPM (curve A) shown in Fig. 7. At point 1 the flow angle of attack at mean radius is of some positive value, the difference of tangential velocity components $\Delta C_u > 0$, fan expended work is positive and the fan pressure ratio value is near 1. Reducing the counter-pressure 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 of angle of attack, ΔC_u, expended work and PR_f. The point 2 corresponds to the case when the ΔC_u and expended work values are equal to 0, i.e. the fan operates at the free windmilling mode and presents the hydraulic drag in airflow ($PR_f < 1$). The combination of such points at various rotational speeds gives a line of fan windmilling mode operation (curve B). With further shift of the operation point down along the characteristic (up to exit section choking) the transition to "turbine" operation mode takes place. At point 3 the ΔC_u and expended work values are negative, and the fan is possible to give some power.

The example of zero work (free windmilling) performance lines for the fans with different design pressure ratio values is shown in Fig. 8. The less PR_{f0}, the less pressure losses and is wider the range of airflow in the fan on windmilling mode. At design pressure ratio values 2.0÷2.5 and $(W_{cor}/W_{cor_0})<0.4$ the total pressure losses in windmilling fan is of the same order that the pressure losses in the separate ramjet duct of the TRE [1, 3, 4].

At the RJ-mode the airflow in the TRE inner part (gasturbine core) is near to zero. In this condition, the LP turbine becomes the consumer of power produced by the windmilling fan. The turbine resistance to rotation is defined by so called ventilation losses, which arise as a result of energy feed to the airflow in the turbine flowpath and also by the turbine disc friction losses. The analysis of TF operating in typical RJ-mode condition has showed that because of low RPM an additional pressure decrease in fan driving the turbine is usually small [1, 4].

The windmilling fan is possible to use for engine accessories driving at the RJ-mode. The expediency of using the fan to drive the PS accessories at the RJ-mode depends on its efficiency as a "turbine", values of a taken-off power, thermal condition and so on. When loading the windmilling fan by the external energy consumers the operating points on the fan map dispose beneath of the zero work line.

However, at the RJ-mode of TFRJ this deflection is usually insignificant and it is possible to adopt the zero work line as an operating line for the engine ramjet operation mode. In some case when the fan design pressure ratio is rather high it is possible for the TFRJ thrust improving at RJ-mode to arrange the bypass duct around the fan case with corresponding controlled shut-off device.

The possibility to use the windmilling fan to drive the accessories at the ramjet operation mode is significant advantage of the TFRJ(s).

3.3.2 TFRJ(s) transition to RJ-mode

The characteristics of TFRJ(s) engines at the transition to RJ-mode are shown in Fig. 9 and 10. The points B and E correspond to the beginning and the finish of the transition to RJ-mode; the point W corresponds to the beginning of fan windmilling mode.

The engine transition to RJ-mode in essence consist in switching-off the gasturbine part without engine thrust loss. For the TFRJ(s) the gradual transition process is typical which takes place in some range of flight Mach numbers. The transition process is began at the Mach number M_B when the engine airflow at maximum rating approaches the intake maximum airflow capacity (point B in Fig. 9) and finished at flight $M=M_E$ when the whole (or practically whole) airflow is feed through the outer (ramjet) engine part (β=1). Along the flight speed increase in the range of $M_B<M<M_E$ it is necessary to decrease gradually the fan corrected airflow. For the lowering of the TF airflow it is necessary to decrease the engine RPM. It is expedient to use rather simple method of RPM lowering by gradual decreasing of the turbine inlet temperature up to engine going out to windmilling mode. In this case, the nozzles throat areas or the common nozzle throat area decreasing become necessary just after the combustor fuel supply cessation.

For selected TFRJ$_S$ (solid lines in Fig. 10) the inlet maximum airflow capacity is reached at the M=2.7. The inner and outer nozzles throat areas (An_1 and An_2) at first time are maintained constant. As a result, at $M>M_B$ the temperature ratio T^*_g/T^*_{in} and the turbofans RPM quickly decrease. Maintaining the maximum ARC flow capacity in conjunction with decreasing of the airflow in the gasturbine part leads to the quick increase of the bypass ratio and the β value, i.e. the engine operation mode draws near the ramjet operation mode. As a result, the overall heat addition in the engine increases because of maintaining the ARC rating at the minimum air-to-fuel ratio. However, is found that a decreasing of the engine nozzles expanding ratios is a prevailing factor, and as a result, the engine specific thrust is slightly decreased. On this reason an increasing of the thrust rate is somewhat lower when $M>M_B$; the SFC increases simultaneously (the section B-W in Fig. 9 and 10).

After going out to windmilling mode (point W at M=3) the engine control is provided by optimum variation of the nozzles throat areas. At the flight conditions, corresponding to M_W, the β value is equal approximately to 0.9, i.e. about 10% of the overall airflow goes through the engine inner part (Fig. 10). When the flight M number is higher than M_W it is expedient to decrease the airflow in the engine gasturbine part and its drag by decreasing of the A_{n1}. For this purpose it is possible to use, for example, the inner nozzle central body shifting. The nozzle area decreases which corresponds to the intake-engine matching with minimum pressure losses, and the outer nozzle throat area being constant as is shown in Fig. 10 (section W-E in Fig. 9 and 10).

At the An_1 decrease the turbine expanding ratio and work become lower, which leads to both the fan RPM and the pressure ratio decrease (Fig. 10). When the flow in the LP turbine becomes under critical, the inner nozzle area decrease provides the HP turbine work decrease along with core RPM and corrected airflow lowering. As a result, the engine airflow redistributes in favor of ramjet part, and with full gasturbine part shut-off (A_{n1}=0, β=1). At this moment (M=3.4 in Fig. 10) the transition to RJ operation mode is being completed. The corresponding operating point on the fan map is located practically on the zero work line (point E on Fig. 9 and 10).

At the decreasing of inner nozzle area an engine specific thrust is increased because of the core losses decrease and increase of the overall heat addition. For this reason in the range M_W-M_E engine thrust rises, and SFC varies slightly. At the flight conditions corresponding to $M=M_E$ the TFRJs parameters differ from the "pure" RJ parameters by the value, corresponding to the additional pressure losses in the windmilling fan.

At the ramjet operation mode ($M>M_E$) an intake-engine matching is provided by corresponding decrease of the ramjet part nozzle throat area (An_2). The fan RPM and pressure losses are gradually decreasing ($PR_f>1$), and the engine thrust performance is approaching the RJ performance.

Now let us consider some peculiarities of the TFRJ operating process when the transition to RJ-mode is carried out using, as an example, the engine with the same cycle parameters and transonic (M=1.3) to high speed (M=4) thrust ratio as discussed above. For this condition the area ratio A_{in}/A_f would be some higher than for the TFRJs engine type (in correlation of transonic specific thrust values).

The TFRJ cycle parameters variation peculiarities are conditioned mainly by mutual influence of gas and airflows in common ARC inlet. As a result, the core pressure ratio decrease vs. flight speed, which does not compensated by the fan duct outlet pressure variation, the LP turbine specific work is decreased. Because of the fan duct flow influence the fan operating line on the fan map deflects down from the corresponding line for $TFRJ_S$, and bypass ratio vs. flight M number rises more rapidly (Fig. 10). Meanwhile corrected airflow variation vs. flight M number is approximately the same as for the $TFRJ_S$. At the higher A_{in}/A_f ratio in the PS with TFRJ the maximum intake capacity conditions is approached at some higher flight M number than in $TFRJ_S$ (Fig. 10), and corresponding fan pressure ratio is nearer to 1. Then, at the beginning of transition to RJ-mode the TFRJ operation mode is more near to RJ-mode. The turbine inlet temperature lowering at $M>M_B$ leads to β value rise up to almost 1, when TFRJ approaches the windmilling mode. The corresponding fan operating point lies practically on the fan zero work line. Then, in case of TFRJ the completion of transition to RJ-mode practically coincides with the moment of ceasing the fuel feed into the combustor. As a result, M_E number for TFRJ is lower than for $TFRJ_S$ (in the example considered respectively M_E=3.1 against 3.4, Fig. 10).

Rather fast TFRJ transition to RJ-mode is a consequence of simultaneous effect of turbine inlet temperature decrease and gasdynamic influence of fan duct flow on the gasturbine part capacity.

TFRJ thrust variation vs. flight M number is nearly the same as in the case of $TFRJ_S$. Some difference is connected with fan efficiency decrease and higher fan duct pressure losses. At RJ-mode ($M>M_E$) the intake-engine matching is provided by corresponding nozzle area decrease, and this is accompanied by decreasing of RPM and the engine flowpath pressure losses (dotted lines in Fig. 9 and 10).

When analyzing engine parameters variation at transition to RJ-mode it was assumed that the intake operates at maximum capacity rating. This approach, although does not account of possible intake capacity limitations when $M<M_{max}$, yet permits to simplify the analysis and to reveal the main correlations. The account of real characteristics of variable geometry intake would not change the engine parameters variation on principle, but in case of lower intake capacity the transition flight M numbers range would be displaced to the lower flight speeds.

The TRE thrust differences at the RJ-mode from that of the "pure" RJ are conditioned mainly by additional pressure losses in the engine flowpath. The TRE characteristics aggravation in comparison with "pure" RJ at high flight speeds is possible also in connection with higher airflow or other agent expenditure for engine structure cooling.

Some engine thrust aggravation is also possible in connection with the part of airflow energy using for auxiliaries driving. In this case, the using of windmilling turbofan would be possible. When the power take-off is low, the auxiliaries driving by this way would be expedient in spite of rather low fan efficiency when running in turbine mode.

4. The cooling of ARC

ARC and nozzle are one of the most heat loaded units of the TRE operating on the ramjet mode. To provide the reliability of these units, it is naturally to use an air cooling system in which a part of air taken away from engine flowpath to ARC cooling duct (i.e. a space between ARC case and perforated screen). In experimental TRJ for cooling of ARC an air cooling system with perforated screen and for cooling of nozzle – the slot system were used.

The experimental investigations of heat state and operability of high heat loaded TRJ units were carried out at the RJ-mode with windmilling of gasturbine core and simulation of Mach number in range of 2.5÷4.0.

4.1 Operation of ARC cooling system on the RJ-mode

The operation of TRJ is characterized by wide range of ARC inlet parameter change with significant distortion of inlet total pressure fields. The value of inlet total pressure distortion depends on operation mode and value of corrected airflow through engine. In course of the experimental investigations of TRJ the ARC inlet parameters of flow were characterized by values:

T^*_x = 450÷900 K, M_x = 0.1÷0.25.

The radial distortion of ARC inlet total pressure was 6÷12% with the gasturbine core windmilling and 7÷14% with the closed gasturbine core. Nozzle flaps location and cooling air blowing through perforated screen faintly influence on shape of total pressure fields in nozzle throat section. The distortion of inlet total pressure is decreased along the ARC on the modes without burning and in the throat nozzle section is not more 2÷3% when combustion takes place.

The ARC combustion efficiency in these conditions depends mainly on the air excess coefficient and locates in range typical for afterburners.

The length of combustion zone significantly influences on distribution of cooling air along perforated screen of ARC. Combustion zone length one can characterize indirectly by the static pressure drop on the ARC screen measured along the ARC. As experiments have shown the fuel combustion is finished on the distance less than 2/3 of ARC length [2, 4].

The cooling airflow variation and its distribution along the ARC are defined by very complex processes in ununiform flow with combustion in ARC. The hydraulic characteristic of ARC cooling duct depends on discharge coefficient of holes and duct pressure loss coefficient. These factors variation was examined in the course of the tests [2].

The analysis of cooling air parameters in ARC cooling duct has revealed that the cooling air temperature along cooling duct changes faintly. When the total pressure ratio is $P^*_{col}/P^*_x<1$ the cooling air temperature at duct exit is 20÷30% higher than the value of duct inlet temperature. This temperature variation is explained by penetrating of hot gas into cooling duct through the holes of perforated screen at part of the duct. However, the change of cooling air temperature in this case is not large too. It should be noted, that small change of T^*_{col} along the ARC has no practical influence on hydraulic characteristic of ARC cooling duct, and it is possible to use an assumption about constant value of cooling air temperature along the ARC cooling duct.

The results of tests showed that distribution of cooling air along ARC perforated screen depends on a variation of both the cooling air and the ARC gas parameters in wide range is rather weak. In the tests the variations of the corrected airflow into the cooling duct and the gas flow in ARC in dependence of the ratio of total and static pressures in the characteristic cross sections was obtained. The results of testing allowed to obtain a hydraulic characteristic of the cooling duct and ARC at the joint operation (Fig. 11). In this case, the next reasons as a base were adopted:

– characteristic for pressure defining the cross section which is located on approximately half length of ARC was adopted; in this section the combustion is mainly completed and main part of pressure losses is realized;

– air total pressure into cooling duct is taken equal to the mean value between the values for inlet and exit of cooling duct; ARC total pressure is taken equal to the ARC exit total pressure.

– one part of cooling air from cooling duct blows out through perforated screen and other part of cooling air is used for nozzle cooling.

The hydraulic characteristic of ARC and its cooling system was obtained by means of test data and calculation in the form of dependence of the corrected airflow in the cooling duct and gas flow in ARC ratio on the corresponding total pressures ratio. The curves are given at constant values of corrected flow density in the duct and ARC. The obtained hydraulic characteristic promotes to form the principles of governing of coolant flow. The hydraulic characteristic of cooling system showed, that when the total pressures ratio is near to 1, the mass flows ratio changing is rather small in wide range of both ARC and cooling duct parameters variation.

4.2 ARC Heat state

The heat state of ARC, which is characterized by the perforated screen temperature T_W, depends on engine operating mode, flight conditions, parameters, and flow of cooling air. Using the hydraulic characteristic of air cooling system, one can consider the correlation between relative cooling airflow W_{col}/W_X, mean screen temperature T_{Wm} and flight M number bearing in mind, for example, the non controlled cooling system of ARC without conditioning of cooling air ($P^*_{colin}=P^*_X$, $T^*_{colin}=T^*_X$). The two possible laws of PS control at RJ-mode are characteristic:

– with constant value of engine inlet corrected airflow, which corresponds to the constant value of ARC inlet Mach numbers M_X independently on flight conditions;

– with decreasing value of inlet engine corrected airflow vs. flight Mach number which corresponds to the decreasing of ARC inlet Mach numbers; in this case the airflow through engine is limited by inlet maximum productivity.

The variation of mean screen temperature and relative cooling airflow are shown in Fig. 12 in dependence on flight Mach numbers at RJ-mode and air exceed coefficient equal 1.2.

As it follows from Fig. 12, the relative cooling airflow changes feebly, although the change of TRJ parameters for these two laws of PS control is significant. At the flight Mach number M=4.0 the mean screen temperature is T_{Wm}=1150÷1230 K and the relative cooling airflow is 12% approximately.

The results of full-scale TRJ tests in simulated flight conditions at the Mach numbers M=2.5÷4.0 have shown, that in uncontrolled air cooling system of ARC with perforated screen in non-design flight conditions (lower flight Mach numbers or engine throttling at the M=4) the relative cooling airflow is significantly higher than required value. This leads to the thrust performance aggravation on these modes. Improving the performances is possible by choosing rational cooling air parameters and using the controlled cooling air system.

5 Bearing Support Heat State in RJ-mode (Windmilling of Core)

The bearings used in the supports of the TRJ gas turbine core define the engine's reliability to a high degree. Reliable and long-term operation of the bearings is possible only when the bearing details temperature is lower on 40÷50°C than the tempering temperature of the bearing's material.

For cooling and lubrication of the aero engine bearings usually the synthetic oils are used. Rising flight speed leads to increase of inlet engine air temperature and heat loads on the units and structure elements of an engine. The heat flow into the engine's supports grows since for cooling is used an oil with limited operating temperature. When flight speeds are higher than M>2.5, operability of GT supports should be achieved by using special structure measures. One of the most effective methods to ensure bearing supports operability is the use of active thermoprotection. In essence, it is the setting up of a protective screen over the support case under which cooled air from the engine cooling system is supplied. The layout of the experimental TRJ support is shown in Fig. 13. All supports of the experimental TRJ had an autonomously controlled oil supply and a thermoprotective screen under which cooling air with controlled parameters was supplied.

The summary value of the heat flow into the oil cavity of the supports depends on 1) heat of friction in bearings and seals, 2) heat flux through the details of bearing supports, and 3) heat flux from hot air, which penetrates from engine flow path through seals into the oil cavity.

The experimental investigations of the TRJ supports heat state showed that along with the TRJ transition to the RJ-mode with windmilling of core the redistribution of the relative values of each of the afore mentioned heat components takes place. It has been determined that part of the friction heat in the bearings decreases because of the decrease of both the rotor RPM and the axial forces. Heat flux through the details of supports and heat coming from hot air penetrating into the oil cavity components is increased because of the inlet temperature increase and aggravation of the seals operating condition. The total heat flux into the supports, as compared with the GT-mode is increased (approximately twice), so the support exit oil temperature also rises and reaches its limit at some flight Mach numbers (Fig. 14). Autonomous oil supply to each support of the engine in combination with air cooling supply have allowed the investigation of the influence of both oil and cooling air parameters on TRJ support operability. The experimental data of relative cooling airflow and relative support exit oil temperatures dependences vs. relative cooling air pressure are shown in Fig. 15. At the pressure ratio (P^*_{col}/P^*_{in})>1.7 the rising cooling airflow is stopped, and the decrease of support exit oil temperature is also stopped. The cooling air supply under the screen space significantly lower the support exit oil temperature and ensures the engine transmission operability at the flight Mach numbers M>2.5÷3. The use of the thermoprotective screen, under which the cooling air is supplied, ensures the engine supports operability up to M=4.0.

Conclusion

In the framework of the wide program of study of the engines for high speed flight vehicles which was performed in Russia in 1960…1980-ties years, was defined the TRE are a universal variable cycle engines among of various ABE types being installed on future high speed flight vehicles with cruise and acceleration parts of trajectory of flight.

The experimental full-scale TRE of different types assembled from the components of production gasturbine engines were tested on the CIAM test facility at simulated flight conditions, corresponding the Mach numbers up to 4.0.

The results of theoretical investigations and testing of TRE have allowed to define:

- the rational methods of the transition from GT- to RJ-modes;
- the conditions of stable operation of the PS with TRE at the transition mode;
- the characteristics and pressure losses at the windmilling mode for TRJ and TFRJ turbocompressors;
- the expediency of the application of windmilling mode at the RJ-mode;
- performance of ARC at the distortion of ARC inlet total pressure fields;
- conditions of operation of ARC with air cooling system and hydraulic characteristics of cooled ARC;
- influence of ARC air cooling on the TRE thrust performance;
- heat states of ARC with perforated screen and engine bearing supports;

– possibilities of heat protection of bearing supports by controlled oil and cooling air supplies.

The theoretical and experimental results achieved in TRE study program give the initial base for the next steps to developing TRE for future high speed flight vehicles.

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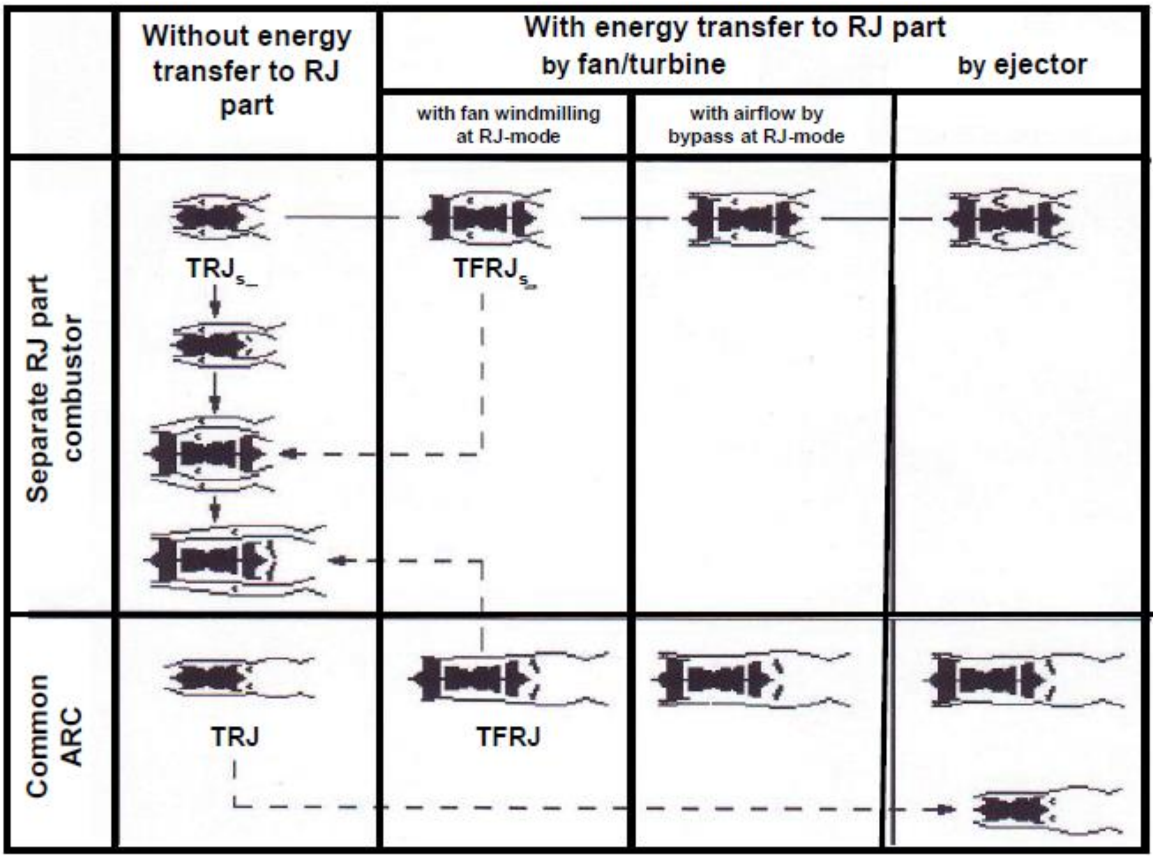

Fig. 1. Classification of TRE

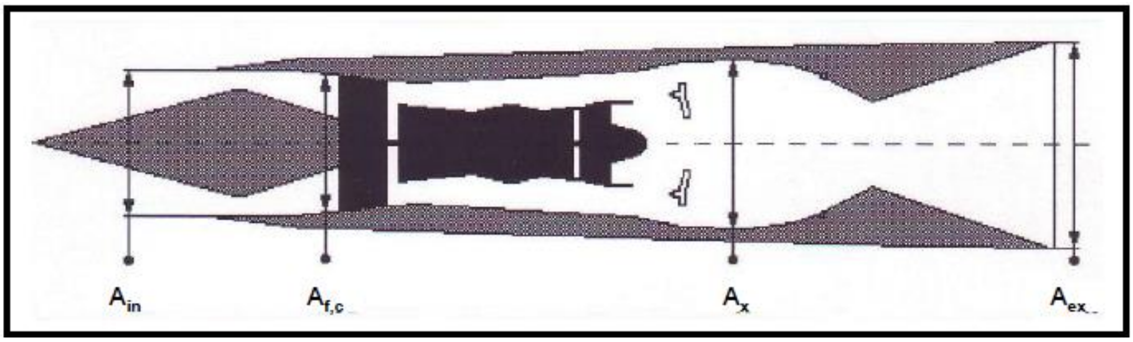

Fig. 2. Characteristically cross-section of propulsion system with TRE

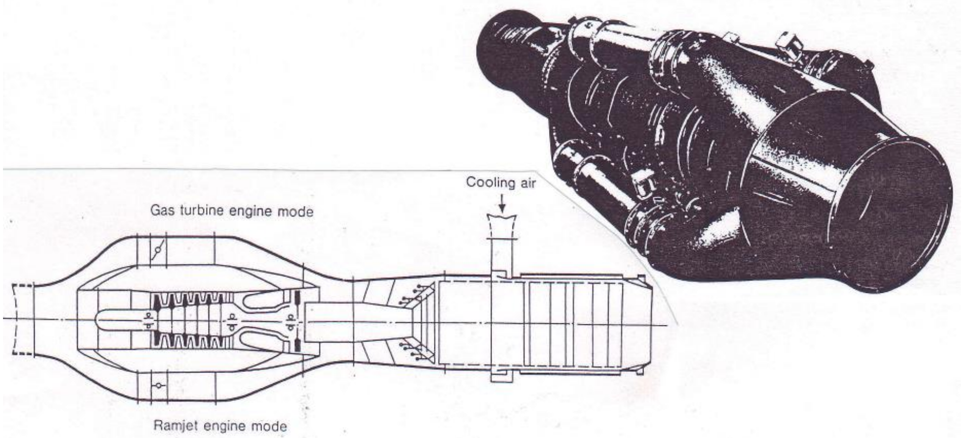

Fig. 3. CIAM's experimental turboramjet

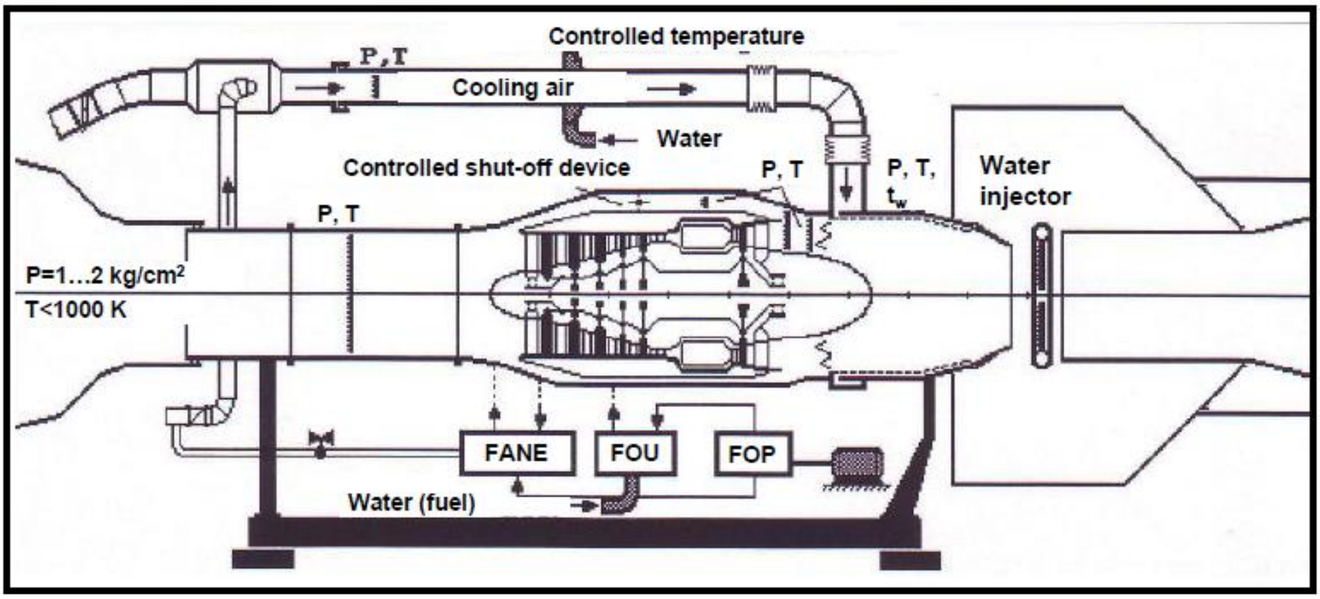

Fig. 4. Layout of CIAM test facility
(FAHE - fuel-air heat exchanger, FOU - fuel-oil unit, FOP - fuel-oil pump)

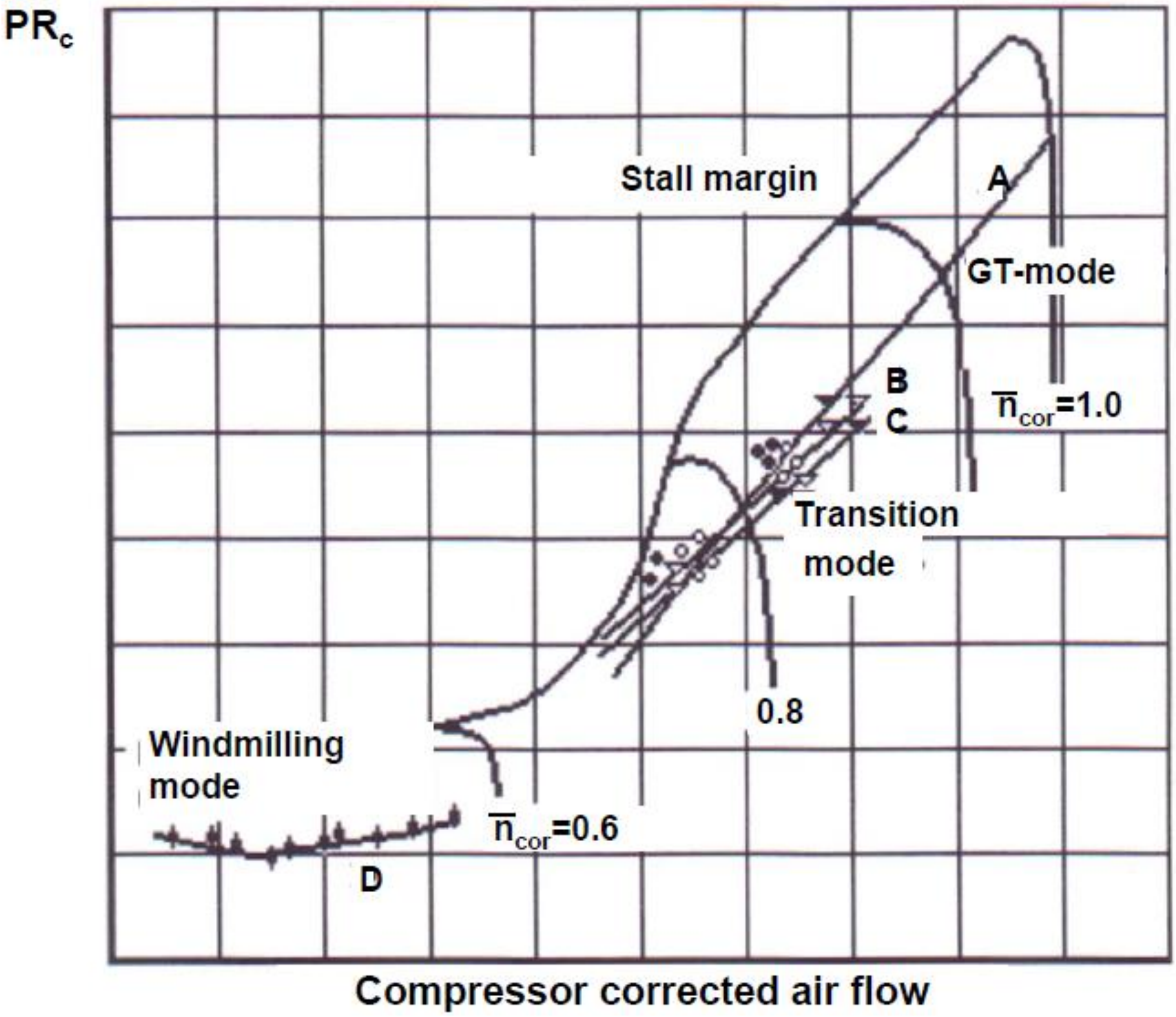

Fig. 5. Compressor map of experimental TRE

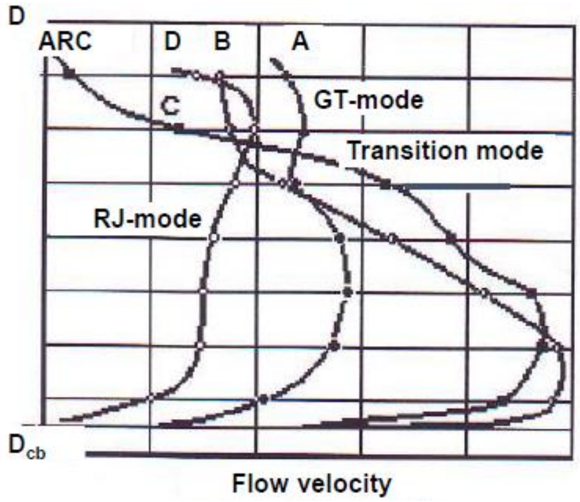

Fig. 6. Distribution of flow velocity on the ARC inlet

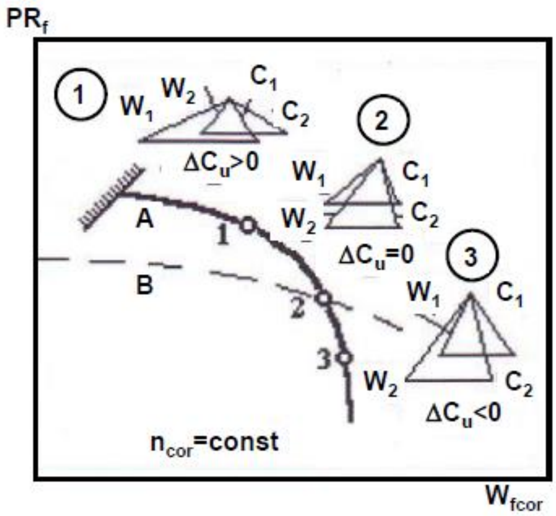

Fig. 7. Fan stage parameters variation along n_{cor}

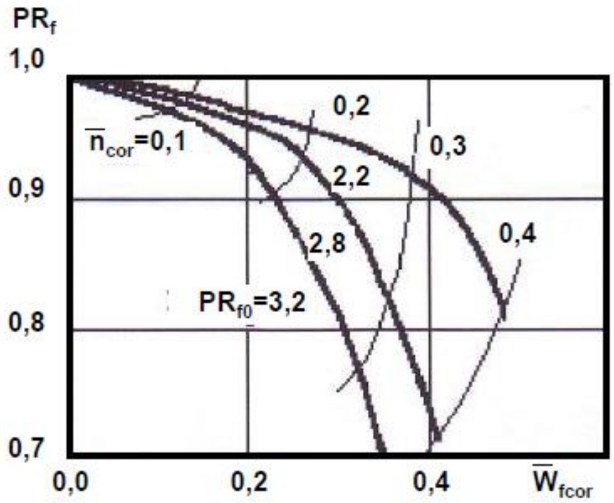

Fig. 8. Fan zero work lines vs. design fan line pressure ratio

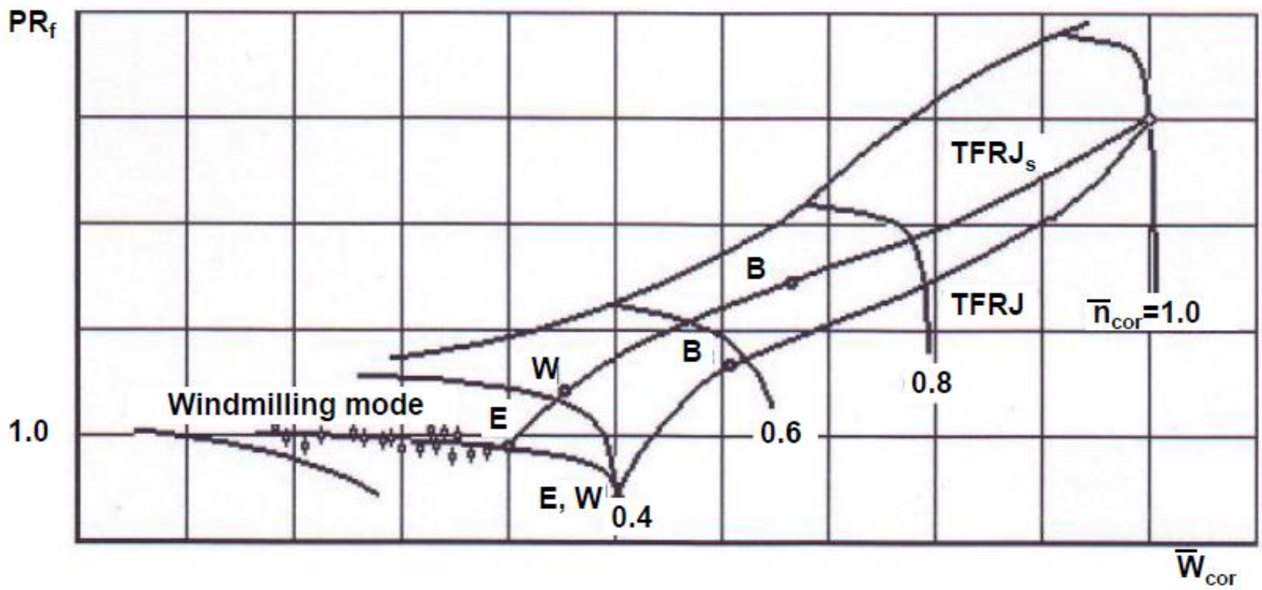

Fig. 9. Fan map

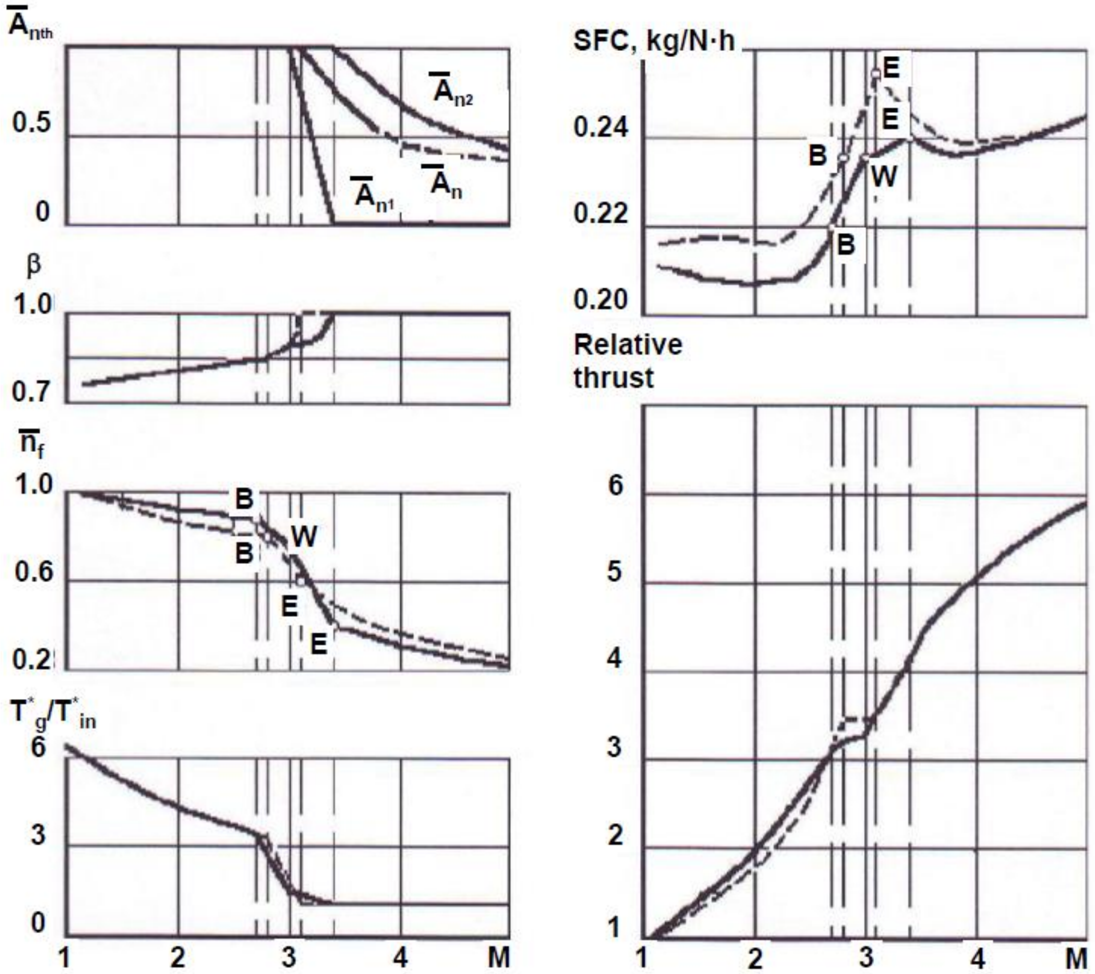

Fig. 10. Characteristics of turbofan-ramjet engines at the transition to ramjet moode
__________ TFRJS — — — — TFRJ

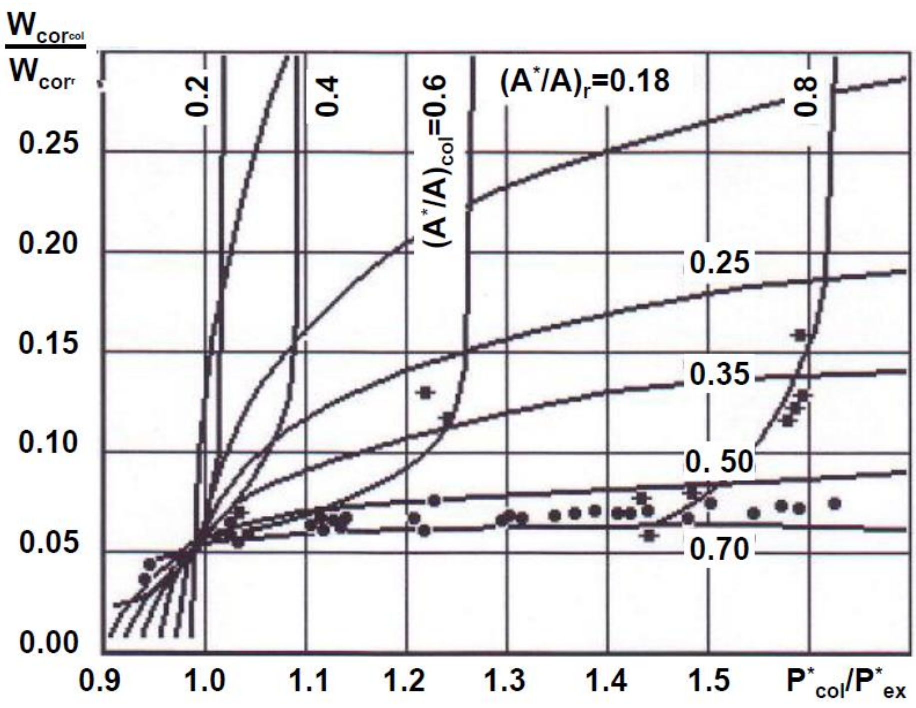

Fig. 11. Hydraulic characteristics of ARCC cooling duct

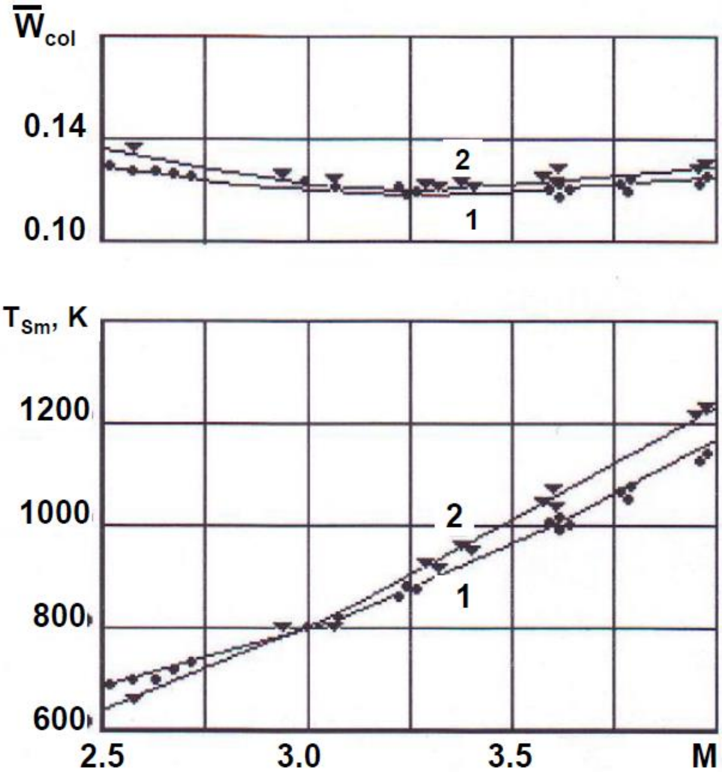

Fig. 12. Relative cooling airflow and mean screen temperature vs. flight Mach numbers

1 - $\overline{W}_{Xcool}$ = const, 2 - $\overline{W}_{Xcool}$ = var

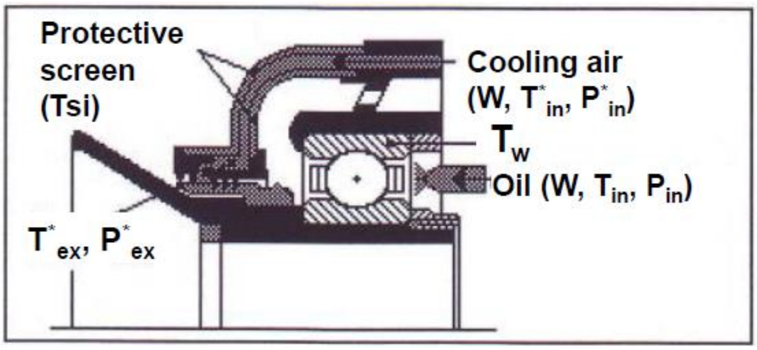

Fig. 13. Layout of bearing unit

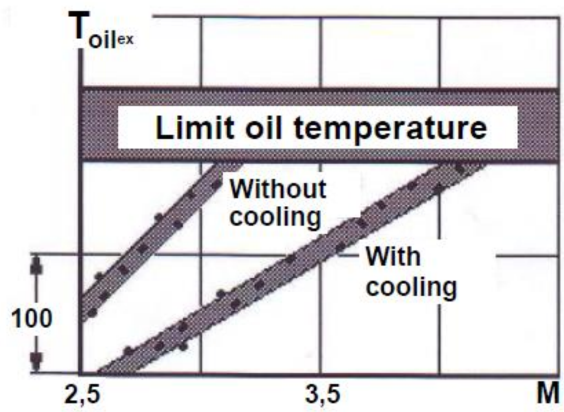

Fig. 14. Support exit oil temperature vs. flight Mach numbers

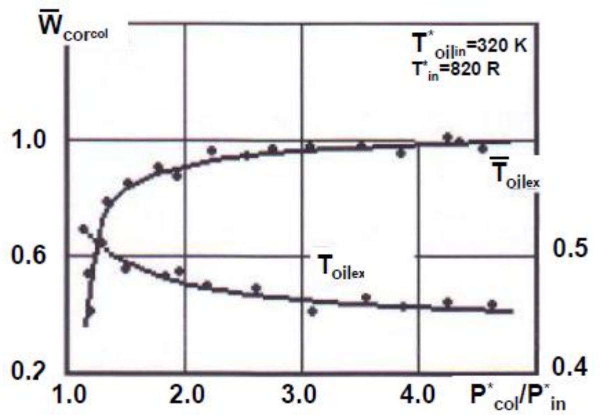

Fig. 15. Relative support exit oil temperature and cooling airflow vs. air pressure ratio