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EXPERIMENTAL INVESTIGATION OF HYDROGEN BURNING AND HEAT TRANSFER IN ANNULAR DUCT AT SUPERSONIC VELOCITY

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Abstract

The results of experimental investigations of model axisymmetric scramjet with annular chamber are considered. Conditions of engine working process organization with supersonic velocity in chamber are analyzed. During the tests the position of H_2 injection and equivalence fuel ratio β are varied. These data were a base for preparation to flight test of the same scramjet.

Nomenclature

CE	-combustion efficiency,
F_o	-inlet frontal area,
$\bar{F}_{th}=\bar{F}_{th}/F_o$	-relative throat area,
l	-lenght of section,m,
M	-Mach number,
p	-pressure,Pa,
$\bar{p} = p/p_{t\infty}$	-relative pressure,
T	-temperature,K,
$\bar{x} = x/r_o$	-relative distance along the x axis,r_o=113mm,
β	-equivalence fuel-air ratio,
σ	-total pressure recovery,
τ	-time,sec,

Subscripts

cmb	-combustor,
∞	-freestream parameters,
th	-throat,
t	-total parameters,
o	-inlet entry,
I - V	-fuel injectors row numbers,
1 ,2 ,3	-combustor section numbers,
Σ	-summary value

Introduction

In order to make a propulsion for a perspective aircraft a number of tasks should be carried out including:

1-reliable organization of ignition and stabilization in the combustion chamber;
2-stable joint work of the air intake and the combustor;
3-high combustion efficiency;
4-minimal losses of total pressure along the duct;
5-minimal heat flux in the walls to decrease the requirements to the cooling system;
6-effective work at a wide range of flying speeds, etc.

Most works on the present problem are devoted to the organization proper of the working process in the duct at varying inlet parameters of the flow: M=2-3, $T_{t\infty}$=1000-2200 K and $p_\infty=(0.2-5)\times10^5$ Pa ,but there are considerably fewer tests in the combustion chamber of the engine, i.e. in the duct consisting of inlet and combustor.(1-5)

Stability of the flow in the inlet when it is working jointly with the combustion chamber depends on the place and mode of fuel injection into the combustion chamber (through the walls or through the struts and on the direction of the injection as to the main flow) and on the elements of stabilization (reverse step,cavity,flame ignitor) and the shape of the channel, that influence the hydrodynamics of the flow and disturbance propagation along the boundary layer in particular and the level and profile of the parameters of the flow in the inlet area of the combustion chamber.

The intention of the present paper is to acquire initial data that will enable us to answer the questions mentioned above.

Model scramjet

The subject of the investigation is a model that includes an axisymmetric inlet and an annular combustion chamber.

Main geometric parameters of the model are as follows: inlet frontal area $F_o' = 0,04\ m^2$; relative throat area $\bar{F}_{th}$=0.195, the full length of the model (without the nozzle) is 1130 mm, the removal of the central body from the cowl leading edge is 433 mm (Fig.1,2).

Combined combustion chamber with sections: F_1= const = $0.9\times10^{-2}m^2$, l_1=170 mm, diverging section with inlet frontal area and exit area of $F_2=1.38\times10^{-2}m^2$ and $F_3=1,74\times10^{-2}m^2$, l_2 = 150 mm and F_3 =const, l_3 =330 mm. The total number of points where pressure was measured is 149 . To measure the temperature of the walls thermocouples X-A ⌀ 0.5 mm were used. The total number of points where temperature was measured is 55.

Test facility

The air was heated mostly in the

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flame heater with kerosene.Oxygen was admixed in the inlet frontal area of the heater to compensate its combustion. Sparking-plugs were working during the whole period of running . The period of hydrogen injection of 7-9 sec was limited by the time when the temperature of the walls became maximum, the pressure in the measuring system was stable and the heat flux into the walls became regular.The measuring parameters of the test facility and the model were registered by means of the data acquisition system for PC/AT . The model was surveyed by visual examination with andoscope used between the tests.

The methods of processing of the results of the tests on the basis of static pressure and heat flux into the walls of the channel is founded on the solution to the simple equations of conservation and of state, that hold true for the combustion products of any substance that consists of H, C, O, N and Ar.

Aims of tests

Experiments and calculations of the modes of the flow in the channel without fuel injection were carried out to specify and test the methods.The values of T_t calculated by means of p(x) and $T_{t\infty}$ when ΔT_{cool} is taken into account when compared, showed the difference up to 1%.

The experiments fall into two stages.During first stage the fuel was injected only through the central body.Here the distribution of the flow parameters was not uniform (the so-called "two layerness" was observed).It also holds true for the heat flux into the wall with approximately two-times difference in the values of top and bottom wall pressure.

During the second stage of the experiments an additional fuel injection collector (V row) was installed into the upper wall of the channel and the cross section in the vicinity of this row of H_2injectors was enlarged.

The aims of the experiments were as follows:

1) to determine the optimal mode of fuel distribution among I and V rows of injectors,i.e. for the "supersonic" combustion mode in the combustion chamber;
2) to determine the area of stable joint operation of the inlet and the combustor, i.e. to determine the maximum heat flux for all the variants of the fuel distribution;
3) to determine the peculiarities of the optimization of the working process that consists in the ignition (self-ignition) of the fuel, the stabilization of the combustion, particularly, when H_2 is injected through the V row.

Results and discussion

Joint inlet-combustor work stable region

The results given below consist in the parameters of the non-distorted flow in the inlet frontal area of the model $p_{t\infty}$ =4,9-5,0 MPa, $T_{t\infty}$=1470-1550 K and M_∞ =6,3-6,37. Stoichiometrical coefficient L in the experiment (varying due to O_2 admixture) remained practically constant: L =33,8-34,8. Fig.3 shows the diagram of the working modes of the model and indicates the area of the stable performance of the inlet.

Two groups of modes can be singled out: with β_1 =0,4 and with β_1 = 0,25-0,3 and β_V=var and two other groups: with fuel injection only in the first section of the channel (through I row of the injectors or through I and II rows) and fuel injection only in the diverging section of the combustion chamber (through V row).

If we compare it to the data acquired at the I-st stage of the experiments we shall be able: firstly, to observe an increase in β_{max} in the first section up to 0,55-0,59 as compared to β_{max} =0,35 when H_2 is injected through I and II rows. It is to a considerable extent due to the non-calculated efflux outflow through the wind tunnel nozzle of that increases when fuel is injected into the model as the characteristics of the facility diffusor are perfecting.

Secondly,the total $\beta_{\Sigma max}$ obviously depends on β_1 .Thus at β_1 =0,4 value β_Σ =0,9 and at β_1 =0,28 β_Σ was not registered up to β_Σ =1.

Thirdly,somewhat unexpected fact of non-ignition of H_2 was observed when it was injected only through V row with β_V =0,36-0,9.

The initial distribution of the pressure for the "cold" working mode,that is the working mode without fuel injection (Fig.3) testifies to the fully manifested non-uniformity of the flow parameters, particularly in the first section.

Gasdynamic characteristics of combustor

Average flow parameters in the inlet frontal area of the combustion chamber are $\bar{x}$ =4,2. Closer to the exit section these parameters become more reliable when calculating the flow. The temperatures calculated with the help of simple equations and measured in the heat flow sufficiently coincide, that testifies to the same fact. Mach number alternates from M=3 to M=2 in spite of the more than two-fold increase in the cross-section area. It proves, that total pressure in the combustion chamber greatly decreases (wave,hydraulic losses and so on). The large area of wet surface results in considerable friction losses that amount to 12% of the impulse in the inlet frontal area of the combustion chamber.Though the losses caused by wetting of the three cavity flameholders, reversed step and six struts decrease in the process of heat flux,they are the main reason for the fact that thrust characteristics of the annular combustor are low. Fig.3 shows typical distribution of the relative pressure $\bar{p}$, M and combustion efficiency for the modes with β_{1+II}=0,66.

Total pressure recovery σ_1 in the first section of the combustion chamber with the heat flux is σ_1=0,22-0,23. When this section diverges with $\bar{F}_1$ =1,15 and the flow losses speed from M=3 to M=1,2-1,3 the additional impulse decreases.

The total pressure recovery in the second and the third sections σ_{2-3} =σ_{cmb}/ σ_1 is increased due to heat flux from σ_{2-3}=0,2 for the "cold" mode to σ_{2-3} =0,5 when H_2 is injected, as the speed of the flow in these sections of the chamber is considerably less, thus heat and hydraulic losses are also less. It should be noted that the pressure recovery at the whole investigated range of β_Σ varying from 0,4 to 1 is practically the same that is due to the redistribution of the pressure recovery along the sections of the combustion chamber as a result of the heat flux.

A part of the modes are either the modes of non-combustion in the first section or the modes of its low efficiency. For β_1 > 0,4 such phenomena were not observed that proves a theoretical conclusion that maximum possible heat flux in the first section is required to ensure effective work of scramjets of such models.The maximum fuel expenditure corresponds to a greater than 1 Mach number,that is $M_1 \cong 1,2$.

The results of the experiments enable us to determine the moment of the transition from "supersonic" combustion mode to the "subsonic" one or "fixed" combustion mode, to be more precise-"super"-and "subsonic" combustion. $\bar{M}_3$ = $M^{-}_{x=7.95}$ /$M^{-}_{x=9.93}$ >1 corresponds to the "supersonic" mode and vice versa. It should be noted that the transition coefficient is β_{tr}= 0.48 , when H_2 is injected through I and II rows and β_{tr} =0,71,when H_2 is injected through I and V rows.

Combustion efficiency

Diffusion combustion mode determines the combustion efficiency both in the first section of the combustor and along its whole lenght. That is why with the increase in β value CE decreases (Fig.5), i.e. to increase CE the section where air is admixed into the fuel has to be prolonged. The data of Fig.6 confirms it. For the modes with β_Σ =0,66 the combustion efficiency in the run is greater when β_1 =0.4 than when β_1 =0.28 though the combustion efficiency CE_1shows just the opposite results. Thus for the annular channel with the losses mentioned above maximum heat flux should be ensured as it results, alongside with an increase in speed and consequently, losses, in the lengthening of the mixing section and consequently, in the greater combustion efficiency CE .

Fig.6 shows the combustion efficiency of H_2 injected through V row. It is a result of the supposition of the additive heat flux law ,when H_2 is injected through 1 and V rows at known CE_1 and CE_Σ .

Fig.7 shows maximum heat addition presented as (CExβ) that depends on β_Σ . When fuel is injected in the first section (CE x β)=0,5 and when it is injected through I and V rows, it amounts to 0.7. It should be taken into account that these figures are true for the certain heat flux into the walls of the model and the certain $T_{t\infty}$.

Wall heat transfer in the combustor

The rated heat flux for the irregular heating was calculated with the help of the temperature gradient dT/dτ for the effective wall-thickness determined by grading of the heat transducers (δ_{eff}=6,5 mm). As the heat flux rate is proportional to $p^{0.8}$, the heat flux is maximum in the first section of the combustor and in the diverging section up to the struts(6). If we compare the heat flux rate along the channel acquired in the supposition of irregular heat transfer in the regular mode (β_Σ=0,9) and with the help of Reynolds analogy, we come to conclusion that the coincidence is quite sufficient (the difference is not more than 10%). Thus Reynolds' analogical method can be applied to determine approximate heat flux rate. Fig.8 shows the correlation of the heat flux and the heat emissed in the process of combustion. Alternation of dT/dτ during the whole period of fuel injection accounts for the disruption of the flow in the channel,when β is close to maximum, at the end of the mode, even if at the beginning of the fuel injection the mode was stable. As the model is heated, $dT/d\tau$ decreases, the heat flux in the walls and thus due to constant heat emission in the process of combustion, the flow is drosselled and heat chocking comes.

The analysis of the investigation as to ignition and stabilization of the flame showed when H_2 was injected through I and II rows and the sparking plug in the first section in the run, stable ignition is ensured at the range of β_{I+V} = 0,45-1, i.e. for the "supersonic" combustion mode.

In some experiments there were either no ignition or the combustion was not efficient enough (CE_1=0,2-0,6).

If the process of combustion has begun, the combustion was not disrupted when the sparking plug stopped running. When the injection of H_2 through I row stopped, the flame went out, i.e. it confirms the assumption that the height of spread through V row of injection is not sufficient.

When H_2 is injected only through V row (for the "subsonic" modes) there is no ignition as H_2 doesn't seem to reach the cavity flameholders on the central body. Thus an ignitor that is a spurking plug, should be installed into the upper wall of the channel.

Thrust-economical characteristics are calculated for the conditions of engine nozzle with expansion rate of 2 and 2% losses of impulse in the nozzle for two cases of flow- equilibrium and frozen. The results of this analysis are given in Fig.9.

Conclusions

The results of the investigation lead us to the following conclusions:

1) When H_2 is injected both through I and II and I and V rows of injectors the combustion efficiency CE varies from 0,7 at β_Σ =1 to 0,95-1 at $\beta_\Sigma \leq 0,5$.

2) When H_2 is injected only through V row at the whole range of β_V=0,33-0.9, there is no ignition of the fuel as the dimensions of the flameholders are not sufficient for selfignition under the conditions investigated.

3) When H_2 is injected through I and V rows, as the expenditure of H_2 injected in the first section of the channel increases integral combustion efficiency also goes up and the maximum $\beta_{\Sigma max}$, when the flow in the channel is not disrupted, increases. Thus, at β_1=0.42 $\beta_{\Sigma max}$=0.83 and at β_1=0.36 $\beta_{\Sigma max}$ =0.9.

4) At $\beta_1 \leq 0,28$ there is no disruption of the flow in the inlet area up to β_Σ=1.

5) When H_2 is injected through I and II rows the transition from "supersonic" to "subsonic" combustion mode is observed at β_Σ =0,48, while when H_2 is injected through I and V rows the transition came about at β_Σ =0,6-0,7.

6) At small β_1 (β_1<0,07) instances of non-combustion in the cavity flameholder of the first section are observed.

7) The relative heat flux ratio into the walls at β_Σ=1 is 20-25% from the heat emissed in the result of combustion.

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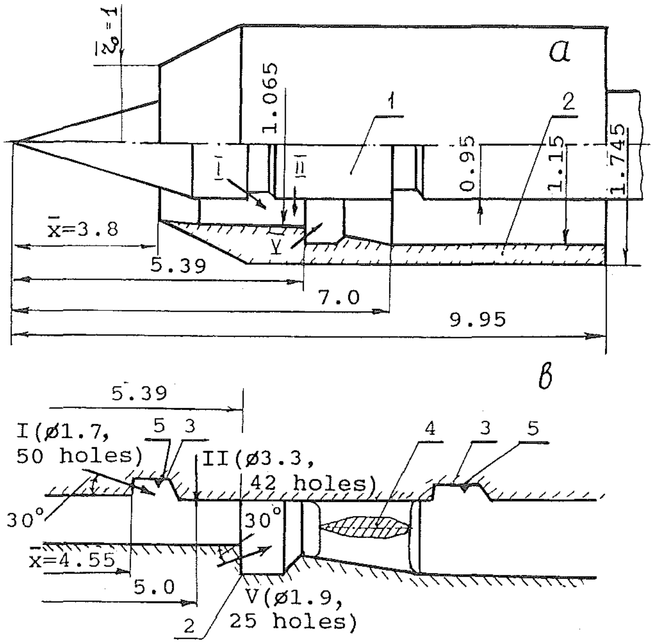

Fig.1. Scheme of model
a-general view, b-positions of fuel injectors in chamber,1-central body 2-cowl,3-cavity flameholders,4-supporting struts,5-sparking plug

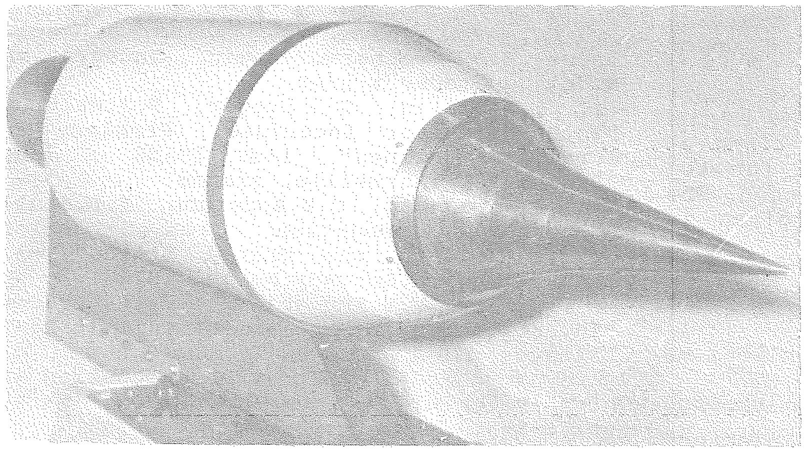

Fig.2. Photo of investigated scramjet

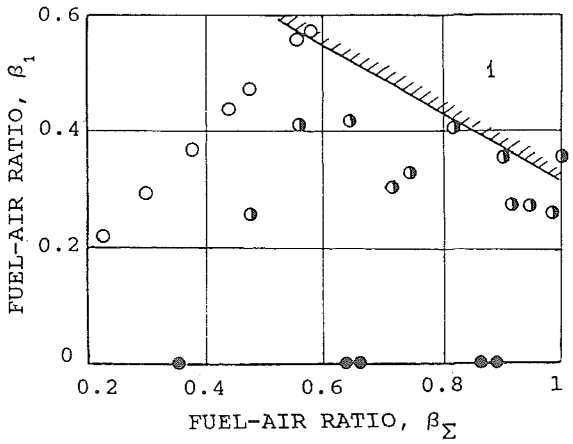

Fig.3. Region of investigated regimes
○ -injection through I or I and II rows
● -injection through V row
◑ -injection through I and V rows
1 -region of unsteady inlet-combustor work

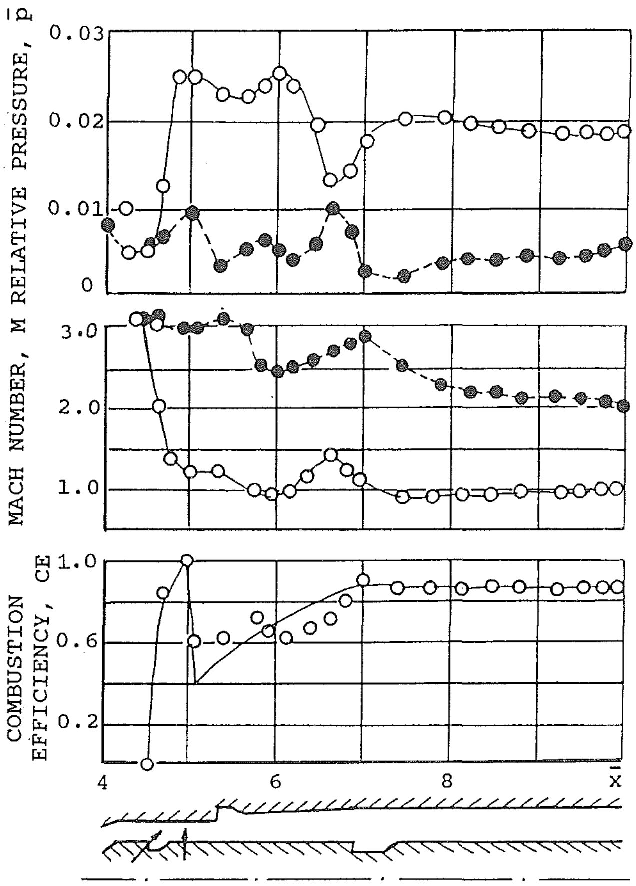

Fig.4. Distributions of relative pressure-$\bar{p}$, Mach number M and combustion efficiency CE along the duct
● -β = 0, ○ -β_{I+II}=0,56

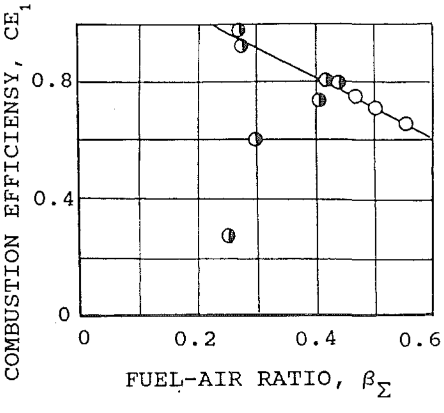

Fig.5. First section chamber efficiency CE_1 (denoted in Fig.3)

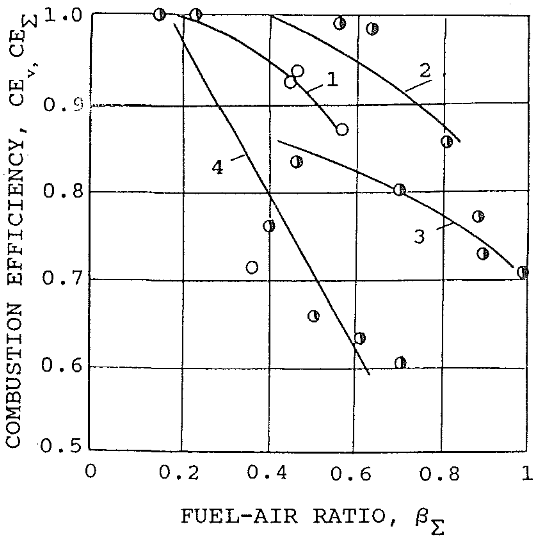

Fig.6. Total chamber efficiency CE_Σ and individual efficiency resulted fuel injected through V row (denoted in Fig.3), 1 ,2 (β_1=0,4),
3 (β_1 = 0,25-0,3)- CE_Σ, 4 -CE_V

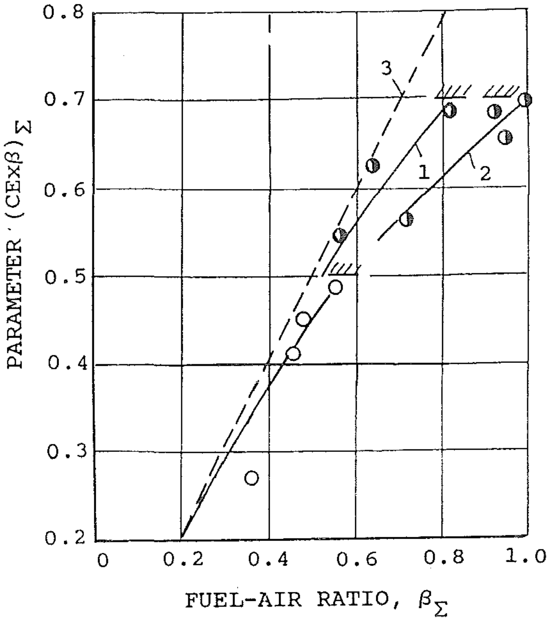

Fig.7. Parameter CExβ vs β (denoted in Fig.3)

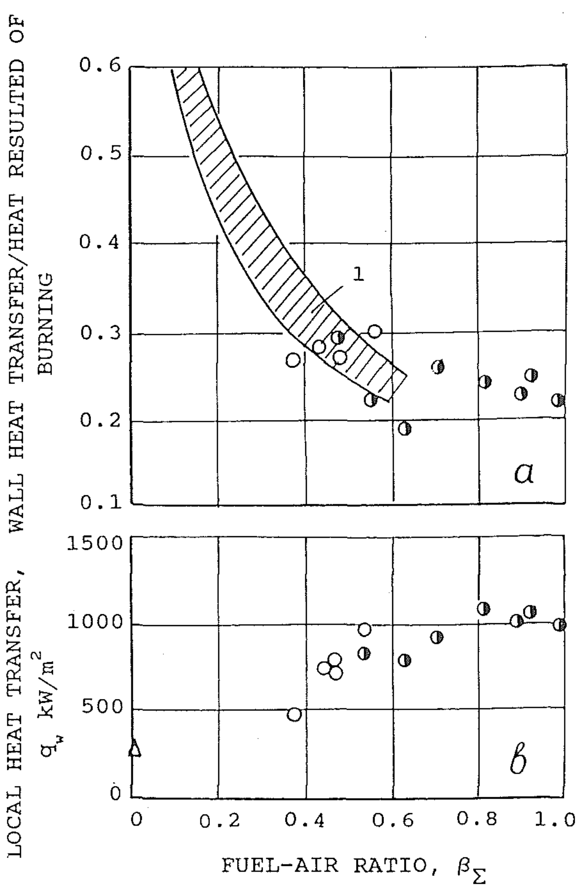

Fig.8. Wall heat transfer/resulted heat burning -a and local heat transfer -b
1 -first stage data, Δ-β=0(next denoted in Fig.3)

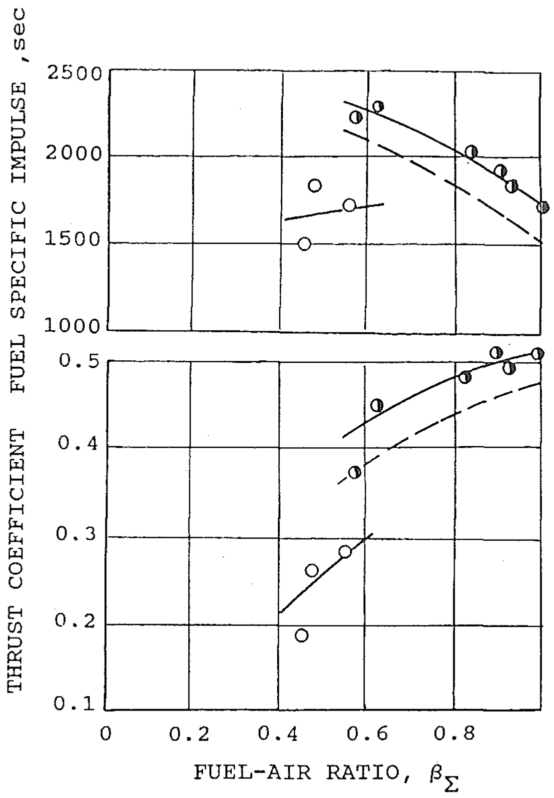

Fig.9. Thrust coefficient and specific impulse vs β_Σ
------- - equilibrium flow
- - - - - frozen flow