EXPERIMENTAL INVESTIGATION OF FRONTAL DEVICE FOR PERSPECTIVE COMBUSTORS

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ABSTRACT

The purpose of the presented investigation is to obtain deeper understanding of work process of frontal device with swirlers necessary for design of combustors for perspective gas turbine engines with high combustion efficiency and low emission level. Includes the results of experimental investigation of the physical basis of the working process in the frontal device.

SYMBOLS AND ABBREVIATIONS

p - pressure
G - flow rate
a - air
f – fuel
α – the air-fuel coefficient (α = Ga /(Gf L_0), Ga – flow rate air, Gf - flow rate fuel, L_0 - stoichiometric factor, for kerosene L_0 = 14,8 kg air/ kg fuel)
FD – frontal device
CFD - combined flame device
AJM - advanced jet mixer
LPP - lean - premixed - prevaporized

INTRODUCTION

Owing to the higher demands on the thermodynamic efficiency, temperature values of the working process in gas-turbine engines constantly increase.

Increase in the temperature in combustors leads to increased NO_x emission, if the control of this emission remains at the same level. At the same time, the requirements to the emission level of gas-turbine engines, especially in respect of NO_x, become more and more strict. Therefore there is the need in special technologies of combustion organization in combustors, efficient in terms of emission reduction under high-temperature conditions. It is well known that the combustion of premixed lean homogenous mixtures may possibly provide a low NO_x emission level even at high temperature levels of air at the entrance of the combustor. However, when the temperature of air at the entrance is very high, premixing before the combustor, as well as a higher pressure may lead to self-ignition of the mixture.

The analysis of literature data for up-to-date and perspective combustion chambers shows, that the most probable scheme of a low-toxic combustor of a gas-turbine engine, meeting all the necessary requirements, may be a multi-injector combustor. Its modules for a cruising flight shall use a combustion scheme similar to the combustion of a lean homogenous mixture. Improvement of such a combustor scheme is, perhaps, possible on the basis of new data on the mixing processes and kinetics of nitrogen oxide formation.

At the Moscow Aviation Institute a scheme of an annular combustor with fuel supply through a large number of fuel injectors placed in the front section of the combustor is being considered as a possible scheme of a low-toxic combustor enabling to reduce nitrogen oxide formation in combustion products of hydrocarbon fuels.

The frontal device (FD) of such a combustor has two parts: a row of combined flame devices (CFD) in the central part of the combustor and two advanced jet mixer (AJM), encircling the row of the CFD from top and bottom.

Fuel is fed to the frontal device, both to the CFD and AJM. In this scheme the CFD is a snail fuel swirler, a tangential air swirler and a cone branch pipe with a reverse-flow zone inside. In an annular combustor the number of such CFD depends on the diameter of the combustor and in a first approximation can be selected as the number of injectors for common combustors. The role of the AJM in an annular combustor is played by axial vane swirlers.

The main characteristics of such a combustor are as follows:

- Almost all the air and fuel (except for the air cooling the walls) is supplied to the combustor through the frontal device, which provides mixing and combustion of a lean fuel-air mixture at the optimal use of the combustor volume.
- For good fuel and air mixing and producing a homogenous fuel-air mixture, going to the combustor, the fuel is fed to the combustor through a large number of injectors.
- The mixing process in the main flow of fuel and air takes place in the AJM in small channels, which enables to burn the fuel-air mixture at low turbulence within a short distance.
- The air passing through the CFD and AJM is swirled, so that all the flows from the centre to the periphery of the combustor have reverse swirling. This provides generation of big tangential velocity gaps, an increased turbulent level of the flow and accelerated mixing of the fuel and air in the area of flow interaction.

In the proposed scheme the roles of the CFD and AJM are different. The CFD should provide a start-up, stable operation in a wide range and operation of the combustor at the idle mode on the whole. Mixture composition at the CFD outlet may vary within a wide range. The AJM provides operation at afterburning, and thus, the main quantity of fuel and air should go through them. To reach minimum NO_x emission, mixture composition at the AJM outlet should be sufficiently lean (α = 1,3 – 1,6), in order to ensure LPP combustion. Naturally, in this case the composition of the mixture leaving the CFD should also ensure homogenous combustion in the combustor volume. Thus, the given combustor scheme is one of the two-zone combustor schemes with combustion of a lean fuel-air mixture. Different configurations of such schemes are being intensively developed in the world.

MODEL COMBUSTOR

At the initial research stage, taking into account the capability of the experimental facility, it was decided to develop, manufacture and test a CFD and a tubular combustor with a frontal device combining a CFD and an AJM. This combustor is a model combustor. It substantially facilitates an experimental research and significantly reduces the cost of manufacturing of an experimental model.

A tubular model allows studying the main characteristics of both individual elements of the combustor (for instance, the characteristics of a CFD, such as lean and rich flameout) and the most complicated issue of interaction (ignition and flame propagation) of the fuel-air mixture leaving the AJM with the combustion products from the CFD.

Fig. 1 presents a general view of a tubular model combustor.

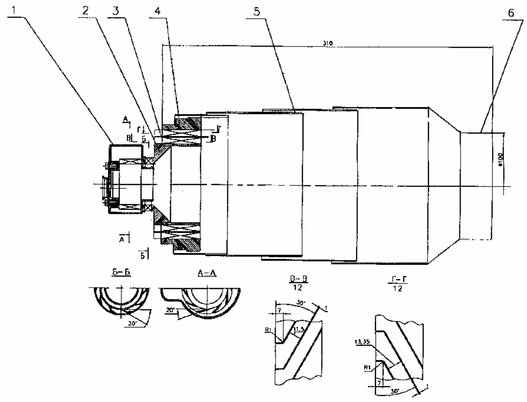

FIG 1. The modeling combustion chamber:
1 - CFD; 2 – outlet cone; 3 - AJM; 4 - ring flame holder; 5 - can; 6 - exit pipe

At the entrance of the combustor there is a CFD dual swirler consisting of a snail fuel swirler and an air swirler. This device should provide start-up modes, operation at the idle modes, as well as combustion stabilization and flame propagation in the mixed flow leaving the AJM. Fuel may be supplied to the CFD both through a receiving branch pipe and a rotary injector placed on the fuel swirler's side.

The CFD fuel swirler is followed by a CFD air swirler with air flow swirling reverse to the fuel swirling direction. The swirling flow results in occurrence of a reverse-flow zone in the centre of the model combustor, where the primary combustion area is stabilized.

Above CFD there are two axial vane swirlers (AJM), swirling of the inner swirler being reverse both to the CFD air swirler and the outer swirler. The AJM should generate a homogenous fuel-air mixture. The flow in both the swirlers is swirled by30^{o} in opposite directions.

The flow through the injectors in this case becomes low, which makes difficult their manufacture and use. Therefore, for a tubular model combustor it is suggested to supply fuel to the AJM by 12 spray injectors into lower channels of the inner swirler oriented at 30^{o} to the inner surface of the inner swirler's outer wall. Such a scheme of fuel supply is explained by the fact, that it is the swirler's outer wall where the maximum velocity of a swirling air flow is observed. A fuel flow gets on the cowling surface under a certain angle, spreads over the surface as a sheet that flows on the channels walls. At the exit of the channel the sheet gets into the zone of interaction of two flows with reverse swirling and breaks up into drops. Thus, fuel atomization in the AJM is performed pneumatically, and there is no need to provide high pressure feed. The experience of using similar atomization systems showed that, having an air pressure drop in an injector of such type, in 3% of cases it was possible to obtain a median size of a fuel drop of 30-50 μm in cold air.

Above the AJM there is an annular flame holder with the transverse dimension 12 mm, which should provide ignition of the fuel-air mixture from the outer side of the AJM.

Next follows a combustion liner with 4 sections of spray cooling, and an exhaust branch pipe.

Selection of spray cooling with relatively high air consumption (as will be showed later) is caused by simplicity of its design and the need to avoid problems related to the thermal conditions during testing of a model combustor.

The main dimensions of the combustion liner and casing were selected on the basis of the capabilities of the facility.

The model combustor is placed in a cylinder casing of 180 mm diameter. No diffuser would be installed before the combustor, and the incoming airflow to the frontal device would be uniform.

DESCRIPTION OF A RESEARCH OBJECT

The scheme of the model frontal device No. 1 is given in Fig. 2.

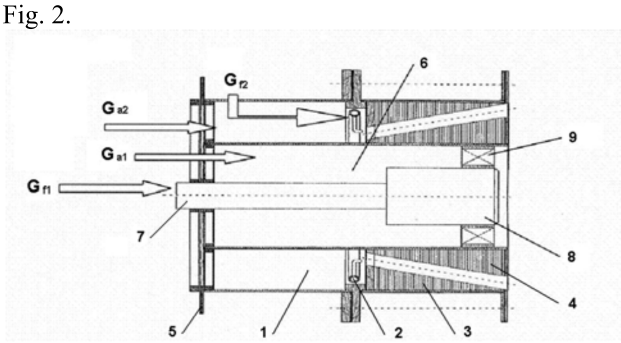

FIG 2

In this FD the inner contour is CFD and the outer contour is AJM.

The outer contour (Fig. 2) consists of air duct 1, fuel manifold of the second contour with jet nozzles 2, set of

milled outer plates 3, set of milled inner plates 4, diaphragm 5 for alteration of the airflow through the second contour.
The inner contour (Fig. 2) consists of air duct 6, fuel pipeline 7, axial centrifugal nozzle 8, vane swirler 9, where the air swirling direction is opposite to the fuel swirling.
The operation principle of the proposed FD is as follows. The air going to the inner contour through the vane swirler is supplied to the central zone. The fuel of the primary (stand-by) zone, which is necessary for engine operation at lower regimes and for ignition of the main fuel during transition to the higher operation regimes, is also supplied to the central zone through the axial centrifugal nozzle. The twist of the primary-zone airflow is opposite to that of the centrifugal-nozzle fuel in this contour, which provides better mixing and facilitates start.
The outer contour has the following scheme. The axial air gets to the outer contour of the FD which consists of 44 ducts 10 mm in diameter, 22 ducts being located in the outer case and 22 in the inner case of the AJM at 30 degrees to the FD axis. It is also possible to vary the angle of the relative position of the ducts (flow exit angle). At the same time the upper and the lower ducts always intersect irrespective of their relative position angle. The geometry of the FD air duct with the fully opened diaphragm 5 (Fig. 2) provides CFD to AJM airflow ratio equal to 0,4.
Fuel is supplied to the outer contour through the axial nozzles located in the air duct of the AJM.
The air duct of the second contour is made by milling of a pack of 60 plates 1 mm thick. The plates can rotate in respect of each other in the plane perpendicular to the FD axis. After the FD assembling the ducts of the second contour make 44 cylindric ducts. The FD design makes it possible to vary the duct exit angles of the second contour, both from the outer and inner case, independently. The exit angle can vary from 0 to 40 degrees from the axis of the initial duct. The exit angles of the upper and lower AJM ducts can be varied independently. The proposed design has the following peculiarity: while changing the duct exit angle, the plates shift in respect of each other, which results in a step between adjacent plates. As was said above, the second contour case contains 60 plates, i. e. the whole inner surface of the ducts, both upper and lower, will constitute a stepped surface with a pitch of 1 mm. This, in its turn, leads to flow turbulization in the duct, deceleration of the flow, better fuel and air mixing and good preparation of the mixture before it gets to the combustion zone. Heat radiation from the outer contour contributes to the fuel evaporation prior to it's to its getting to the combustion zone.
Fig. 3 shows the inner contour of the jet mixing device.
Its outer counter is shown in Fig. 4.
The above frontal device was designed and manufactured at the experimental plant of Moscow Aviation Institute.

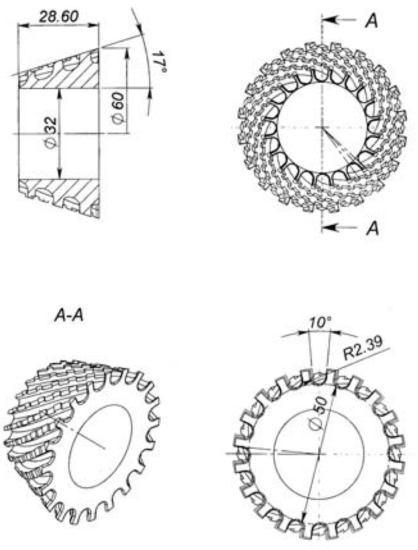

FIG 3

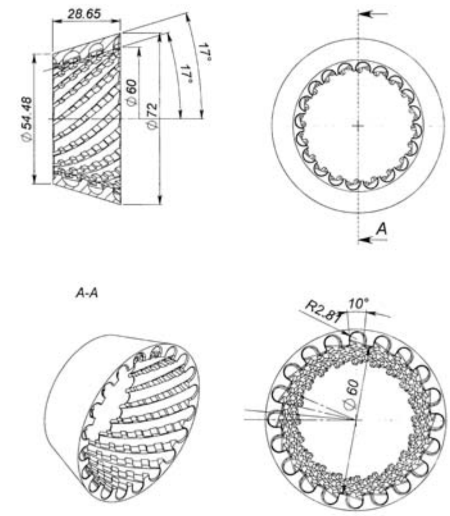

FIG 4

Photos of jet mixing device elements are given in Fig. 5.

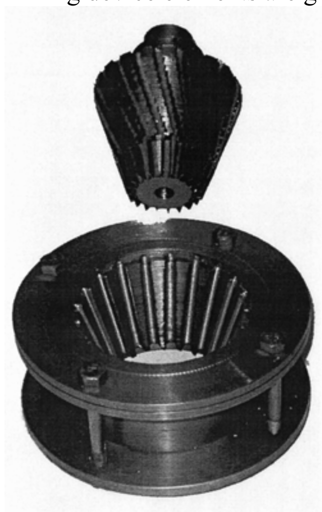
FIG 5

THE EXPERIMENTAL INSTALLATION

Thefrontal device were investigated on experimental installation which scheme is represented in a Fig. 6.

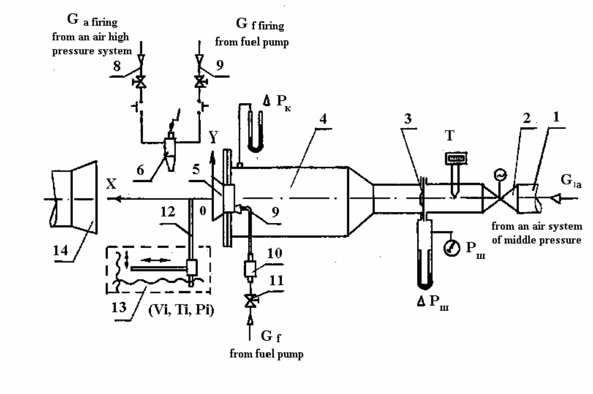

FIG 6. The scheme experimental installation:
1 – air tube; 2 – adjusting valve; 3 – measuring diaphragm; 4 – receiver; 5 – frontal device; 6 – igniter; 7 – system firing fuel; 8 –system firing air; 9 – injector; 10 – flowmeter; 11 – adjusting valve; 12 – measuring instrument; 13 – coordinate system; 14 – exhaust system

Operation principles of the test facility are as follows:
During an air tube with the adjusting valve and measuring diaphragm air income into receiver. On the outlet the researched rotational frontal device are installed. The fuel (kerosene) from an account fuel tank moves through a by-pass cock and flowmeter to the CFD from injector. The ignition of a fuel-air mixture is made by a burning system. Firing fuel and air on appropriate firing systems and through by-pass cocks and the electromagnetic valves move to an electrical igniter, which one gives an intensive plume of a flame.
In a trace behind the FD measuring instruments on coordinate system, have three degree of freedom are installed: longitudinal and transversal transition, and also rotation of instruments.
Concentrations of pollutant emissions analysed with the gas analyser. The gas analyser is designed to determine chemical composition of gas and concentrations of such combustion products as CO, CO_2, NO, NO_2, SO_2, soot etc., as well as temperature.
During experiments the air and fuel consummations were measured. In each experiment the differences of pressure on the researched frontal device (Δp) was measured. Behind FD the fields of axial and environing component velocities, the distribution of velocity, stagnation pressure, intensity of a turbulence and field of temperatures were determined.
Measurement of velocities and pressure were conducted with the help of special instruments. The measurement of temperature for in flame was carried out by cooled thermocouple.
The difference of pressure on the FD (Δp = 4...10 kPa) was selected from a condition of choosing the same velocities as was in the burning located in the real combustion chamber (V ≈ 30...50 m/s). At the same time, the auto modelling of flow in the trace after the burner was preserved (the Re ≈ (2...5) 10^5).

THE ANALYSIS OF RESULTS

Two types of frontal devices were experimentally studied. The working process of the frontal device No. 1 (Fig. 1) was compared to operation of the known frontal device No. 2 whose scheme is given in Fig. 7.

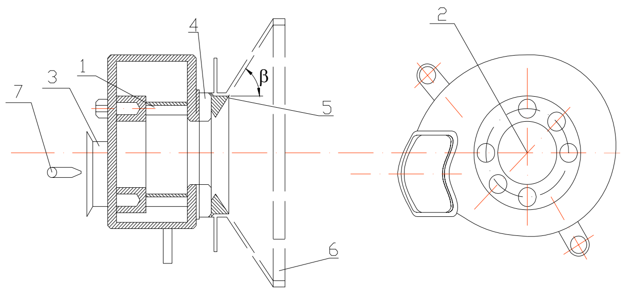

FIG 7. Scheme of the frontal device No. 2:
1 – air swirler of the central zone; 2 – centrifugal fuel nozzle of the first contour; 3 – air intake of the central zone; 4 – air swirler of the second contour; 5 – conical outlet; 6 – cylindrical outlet; 7 – jet fuel nozzle of the second contour

The frontal device No. 2 with opposite twist of air flows. This device has a two-contour air supply and two-contour fuel supply. Air is supplied to the combustion chamber through an inner vane swirler (the first contour); the second contour is a vane swirler with air twist opposite to the first contour. Fuel is supplied through an axial centrifugal nozzle to the first contour and through an axial jet nozzle to the second contour.
The frontal device No. 2 has two swirlers of opposite twist. An attempt to obtain two separate combustion zones has failed as one powerful reverse-flow zone forms in a flow and separation of the combustion process doesn’t take place.
In the experiment, measurements of temperature fields and volume concentrations of NOx in the analysed sample were taken in a trail in sections 50, 100, 160, 280 mm from the axial cut of the frontal device and in sections 10, 20, 40, 50, 60, 70, 80 mm from the axis of the frontal device in the radial direction.
As an example, the tables show some experimental data.

Parameters of a gas flow behind the frontal device No. 1 at G_a = 0,40 kg/s

Table 1

Radial distance, mm	Values of C_{NOx}, ppm			
	Axial distance from the frontal device, mm			
	50	**100**	**160**	**280**
0	2	11	25	18
10	5	11	22	18
20	6	14	19	20
30	9	15	16	24
40	14	19	14	23
50	20	21	7	19
60	22	12	2	17

70	9	5	1	5
80	4	3	1	1

Parameters of a gas flow behind the frontal device No. 2 at G_a = 0,40 kg/s

Table 2

Radial distance, mm	Values of C_{NOx}, ppm			
	Axial distance from the frontal device, mm			
	50	**100**	**160**	**280**
0	6	30	48	54
10	14	24	38	48
20	18	26	30	41
30	22	28	31	38
40	24	34	34	34
50	28	36	36	30
60	14	32	28	24
70	0	18	19	18
80	0	0	4	8

An analysis of the experimental data has shown that operation of the frontal device No. 2 causes more intensive NO_x emissions than that of the frontal device No. 1. Maximum NO_x quantity is observed in the zone of higher temperatures on the border of the reverse-flow zone.

On the basis of the undertaken computational, theoretic and experimental investigations of the frontal device No.2, the chosen concept of fuel combustion in the outer contour using the kinetic principle has been proved; and recommendations on the use of such frontal devices in gas-turbine engines to reduce toxic emissions have been given.

The results demonstrate that the investigated frontal device enables to reduce toxic emissions to the atmosphere as compared to the existing frontal devices with high average temperatures retention.

The use of divergent intersecting conical channels of the second-contour air duct improves mixing owing to intensive turbulization in the channels, which leads to finer fuel drop atomization and supply to the combustion zone of premixed and preheated fuel and air.

In the frontal devices in question the reverse-flow zone forms in the central zone and has small dimensions since air and fuel flows through the inner contour are small comparing to the outer contour. A small reverse-flow zone near the central swirler helps to hold flame at low regimes and serves as a heat source for ignition of the prepared fuel and air mixture from the second contour. The main part of the fuel and air mixture burns in the second contour with the air-to-fuel ratio $\alpha \approx 1,5$ at lower temperature, which reduces NO_x emissions.

CONCLUSIONS

A new scheme of a frontal device is proposed for combustion chambers of air-breathing engines which enables to reduce NO_x emission.

Experimental data on the working process in a model frontal device of the proposed scheme have been obtained. The design of the frontal device provides better organization of the process of fuel and air mixing in the outer jet mixer. This contributes to evaporation of fuel prior to its entry to the combustion zone.

ACKNOWLEDGMENTS

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