Compact Combustor Integrated (CI) with Compressor and Turbine for Perspective Turbojet Engine

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Abstract. For several years, CIAM has conducted comprehensive work on the development of the combustor integrated (CI) with air swirling. This project involved an integrated development of three components: diffuser, combustion chamber and nozzle guide vanes of turbine to reduce their length and, respectively, the length of the engine and obtain high performance elements with low emissions of harmful substances. The new frontal device was proposed for CI combustor. The design optimization of this type combustor was conducted in the compartments and in a full-size combustion chamber. It was shown the possibility of obtaining high combustion efficiency and low NOx emissions at a short length on cruise condition. By a simplified model of the frontal device it was shown experimentally that the proposed device provided a lighting-up and flame spreading in a wide range of equivalence ratio ER (ER > 0.014) at idling. It was shown that short vane diffuser with moderate swirling ensured high parameters of the combustion chamber. The use of residual swirling of the combustion products at the exit of combustor allows reducing the size, or the number of nozzle guide vanes of the turbine. In General, the use of the swirling of the air stream gives a possibility of total length reduction for all three elements by about 20 – 25 %.

1. Introduction
The main element of CI is a new frontal device (FD) [1, 2], consisting of annular V-shaped stabilizer and a large number of inclined radial pylons installed on the upper and lower rows. 3D scheme of CI is shown in Figure 1. For realization of low-emission NOx air mass flow through the FD is quite high – 60...70 % of the total air flow through the combustor. The fuel supply into the chamber is carried out in two places: the pilot - in separation zone behind the annular stabilizer via a number of pneumatic nozzles and the main- behind the each of the radial pylons in outer and inner rows through special pneumatic nozzles. Stable combustion is ensured by the fact that combustion products of the pilot fuel from the reverse flows zone of annular stabilizer are mixed due to convective mass transfer into the separation zone of small dimensions behind radial pylons of both rows, and set fire to the main fuel.
The calculations of three-dimensional viscous flow were performed in the combustor compartment (to reduce calculation time) and in a full-size combustion chamber for definition of CI characteristics, the peculiarities of the flow field and mixing processes in it. All further calculations were performed with the total air parameters behind compressor, corresponding to the cruise condition for perspective turbojet engines – total pressure $P^*a = 1280$ kPa, total temperature $T^*a = 753$ K and the equivalence ratio $ER = 0.357$. Computational analysis of flow and combustion processes within annular combustor CI was built on the basis of the combustor chamber of a conventional type with a smooth diffuser and a modern system of flame tube cooling. Note that the same scheme process has been proposed previously, for example, in a recently published work [3] with the different scheme of the combustor.

2. The method of calculation
The calculation of the flow in the compartment or in a full-size combustor was performed using the commercial software complex Esi Group CFD-ACE+ [4]. The method of calculation is the solution of the iterative method of the Reynolds equations for compressible flow, equations of the $k$-$\epsilon$ turbulence model, transport equations of mixture enthalpy and equations of combustion turbulent model for a combustible mixture. The possibility of using the $k$-$\epsilon$ turbulence model for swirling flows, without amendment, was adopted, related to big object radius and accordingly low value of the centripetal acceleration ($Ut*R^2/g$), where $Ut$ is the tangential air velocity, $R$ - radius of the combustor, $g$ – gravitational acceleration and also with satisfactory results of the calculation of two-phase swirling jet using $k$-$\epsilon$ turbulence model. A recently appeared work [5], in which the weak influence of the swirling jet on combustion acceleration due to the "bubble mechanism of buoyancy" [6] is associated with the presence of a stream of high velocity directed perpendicularly to the centrifugal forces.

The reliability of the scheme CFD-ACE+ was validated in the specific experiments on modern combustion chamber without swirl, including at high pressures and temperatures ($P^*a < 18$ kPa, $T^*a < 800$ K). It was shown that the difference in experimental and calculated values of the emissions index EINOx when using CFD-ACE+ in these conditions was 4…8 %.

The angle of the pylons in rows of the FD with respect to the axis of the combustor was taken equal to the angle 53.5° and it was close to the swirling angle of the flow behind the compressor at take-off. The annular stabilizer fuel drops were supplied along the bottom part of the annular stabilizer. The initial drop diameter was of 30 $\mu$m. The initial drop speed was equal to 30 m/s. For radial stabilizers fuel drops were supplied from the surface of the annular stabilizer along the butt. The initial drop diameter in the calculations was of 40 microns. The initial velocity of the drops was of 40 m/s.

3. The analysis of the flow in the combustor under changing the initial flow swirling
As shown by the calculations, changing the air flow swirling angle $\beta$, the distribution of pressure air within combustor greatly changes.

The total pressure losses ($\delta c$) between the input ($P^*_a$) and the exit from combustor ($P_b^*$)
(\( \delta c = (P_a - P_b)/P_a \)) was equal to \( \delta c = 5, 24\% (\beta = 40^\circ) \) and \( \delta c = 12.2\% (\beta = 60^\circ) \). Thus, from the point of view of total pressure losses, the swirling flow with angle of more than \( (\beta = 40^\circ) \) leads to extremely high total pressure losses.

As one can see, the increase in swirling over \( \beta = 40^\circ \) resulted in incomplete combustion at the exit and increase the uniformity of the temperature field. The magnitude of the temperature field pattern are determined in the usual way: \( \theta_{av} = (Tav - T*a)/(T*g - T*a) \) - rotor factor, where \( Tav \) is the circumferential mass average value of \( T^* \); \( \theta_{max} = (Tmax - T*a)/(T*g - T*a) \) - stator factor, where \( Tmax \) is the maximum value of \( T^* \) in the circumferential direction.

The calculation shows that \( \theta_{av} = 1.017 \) and \( \theta_{max} = 1.147 \) for \( \beta = 40^\circ \) and \( \theta_{av} = 1.21 \) and \( \theta_{max} = 1.23 \) for \( \beta = 60^\circ \). Thus, the increase of the swirling more than \( 40^\circ \) negatively affects all characteristics of the combustor of the said scheme (combustion efficiency, pressure loss, temperature field). Therefore CI cannot be used without the new diffuser with the angle of the swirling flow at the entrance is less than \( 40^\circ \).

### 4. Short optimized combustor

As a result of numerous parametric calculations the main requirements were formulated for the CI combustor which allowed designing a short combustor with the flame tube length of 150 mm. To improve the flame stabilization over the outer row of pylons it was decided to increase the size of the pylons (12\%) by reducing its number (just 120 pylons). The velocity profile at the entrance of the diffuser was accepting uniform with swirling of 20\% clockwise. Optimization of fuel distribution was full field. The best result was obtained in the compartment in which the fuel of the inner row was supplied along the radial pylons from the annular stabilizer (35\%), the fuel of the outer row pylons (85\%) was supplied from the heights of 35\% and 85\% of each pylon height. Fuel was not supplied through the annular stabilizer. To improve the efficiency of cooling the cowls a double-walled plug cooling system was used at the vent area about 25\%.

The amendments led to the improving of combustor performance. The combustion efficiency became \( \eta = 0.995 \), the temperature field stator factor was \( \theta_{max} = 1.12 \), total pressure loses was \( \delta c = 4\% \) and the emissions of nitrogen oxides became minimal (\( \text{EINOx} = 3.7\,\text{g/kg of fuel} \)). In Figure 2 shows that the short combustor gives rapid ignition of the fuel behind the FD and a much more uniform distribution of the gas temperature in the flame tube. This flame tube is about 25\% shorter than the original flame tube discussed earlier.

![Figure 2. Distribution of the total gas temperature within the short flame tube.](image-url)
5. Preliminary experimental study of model frontal device

In scheme CI, the most difficult to implement are two elements: atomization of liquid kerosene on FD due to the large number of nozzles and the organization of the process of flame propagation behind FD.

For an experimental study of flame propagation behind FU a simplified rectangular model was created, which reproduces the aerodynamics of the flow just behind FU. Stabilization grid in a model of FU was set at an angle 34° to the incoming air flow (see Figure 3), providing the adopted angle of the air turning before FD. Given that the model tests were carried out at atmospheric pressure, the air parameters selected for the idle condition with a corresponding pressure drop (3 %). The pilot fuel was fed through two impact pneumatic nozzles along the rear side of the annular stabilizer. The main fuel was fed via pneumatic jet injectors along the butt of the upper and lower radial pylons.

![Figure 3. Experimental setup end view of rear part of FD at work on kerosene (T*a = 500 K, P*a = 1.08*10^5 Pa, ER = 0.55).](image)

Independent research on the dispersion of fuel atomization by adopted injectors using phase Doppler-particle analyzer (PDPA) showed that selected parameters of injectors are sufficient to provide dispersion of drops of 30 - 60 microns at a pressure drop of the air of 3 % and suitable for experimental investigation.

Experiments on combustion were carried out in an open air. Photography of the FD end was produced using the video camera. It was shown that injectors of main and pilot fuels in the experimental setup are working effectively. At T*a = 500...525 K, P*a = 1.08*10^5 Pa and the pressure drop across the injectors of 3 % the spray devices ensure reliable starting of FD at equivalent relation ER ≈ 0.5 from the electrical spark plug. The flame of the primary fuel occurred for all pylons of small transverse size (~ 10 mm) (see Figure 3). The consumption of pilot fuel was (15 - 20 %) of the total fuel consumption. The FD flame blow off were recorded by a full flame extinction behind the pylons and annular stabilizer. Wide range of work was fixed under these conditions until ER = 0.014.

6. Joint analysis of the short vane diffuser, combustor and nozzle guide vanes

The combustion chamber of the developed scheme were further investigated in the integrated setting: 1) the calculation of the combustor characteristics was performed when its input was not smooth and the short blade diffuser was installed, 2) the calculation of the nozzle guide vanes characteristics which installed at the exit of CI was done, using the real parameters of the gas flow behind the CI.

The scheme a new vane short diffuser has been proposed to work in conjunction with the CI. Its outline is shown in Figure 4.
A distinctive feature of the proposed vane diffuser is to integrate the outlet straitening device of the high pressure compressor and vane diffuser in two-row crown with a reduced number of vanes. The dimensions of this vane diffuser are approximately 45% of a smooth diffuser length. In Figure 13 the axial and radial velocities distribution behind vane diffuser are also shown, which were used as the initial in the calculation of the combustor.

The numerical study has shown that the use of blade diffuser and the real properties of the air flow allows to obtain high values of combustion efficiency (\( \eta = 0.992 \)), the total pressure loss (\( \delta c = 4.47 \% \)) and acceptable temperature field rotor and stator factors at the exit of the combustor (\( \theta_{av} = 1.21, \theta_{max} = 1.29 \)), and rather low emission of NOx (EINOx = 4.7 g/kg fuel) at cruise parameters of perspective turbojet engine. Gas parameters at the outlet of the flame tube obtained for this variant represented in Figure 5. As one can see, the use of blade diffuser kept the swirling flow at the outlet of 45...50 °.

These data were used further in assessing the performance of the high pressure turbine (HPT) set behind CI. To evaluate the efficiency of the HPT with nozzle guide vanes, the flow geometry of a modern turbofan high-pressure turbine were used. Turbine was two-stage and cooled.

In the calculation it was used short, modified nozzle vanes, which in a swirling flow creates the same settings as the original blade at the exit. A calculation showed that in swirling flow a modified vane was virtually indistinguishable from the original one according to the total pressure losses. The reduction of the vane length gives the possibility facilitate its cooling.
The calculation of the two-stage turbine showed that the use of the modified nozzle guide vanes and the use of real parameters of the gas flow behind flame tube do not lead to additional losses in the high pressure turbine. Thus, due to the significant reduction of the flow turning in the nozzle guide vanes its axial length can be either slightly reduced (by 15 ... 20 %) without losses in the value of the efficiency of the HPT (see Figure 16); either while maintaining the axial length of vanes its number can be reduced by 15 ... 20% without significant losses in the value of the turbine efficiency.

7. Conclusion
The development of the combustion chamber integrated CI with a swirling of the air flow at the entrance is allowed to determine the main parameters of the combustion chamber and the associated elements of the diffuser and turbine.

The possibility of obtaining high combustion, uniform temperature field at the output and low emissions of NOx (EINOx < 5 g/kg fuel) was shown on small length CI when working on kerosene. It was shown experimentally on the simplified model of the frontal device that the parameters of the proposed frontal device provided the starting and flame spreading behind it in a wide range of equivalence ratio.

It was shown that the creation of a short blade diffuser with a moderate swirling gave rise to a high performance of the diffuser and combustion chamber.

The use of residual swirling of the combustion products allows reducing the size, or the number of nozzle blades of the high pressure turbine.

In General, the use of the air flow swirling gives the possibility of reduction the lengths of all elements diffuser-combustor – nozzle guide vanes of approximately by 20...25 %.

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