A Study of Superlean Combustion Modes in a Reverse Flow Combustion Chamber Burning Multicomponent Fuel

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Abstract. Feasibility of using oxidant vortex reverse flow in designing jet burners for prospective combustion chambers fueled with synthesis gas. A complex of experimental studies of the reverse flow burner module fueled with methane with addition of synthesis gas is carried out; steady combustion concentration range is defined.

1. Introduction

One of main problems in creation of promising environmentally friendly combustion chambers for ground-based gas turbine power plants is search for ways to ensure effective processes of fuel mixing, ignition, combustion and flame stabilization in combustion zone of the combustion chamber.

Processes of the fuel feeding and fuel-air mixture preparation occurring in the burner module are of paramount importance for combustion and are an import part of the working process in the combustion chambers. In Russia, similarly to foreign countries, there is an experience of successful creation of combustion chambers in which the burner module uses alternative fuels, including synthesis gas. Application of such chambers in gas turbines is one of the best solutions to the problem of prevention of environmental pollution and efficiency increase. However, currently, both efficient design of such chambers, and adequate, empirically tested calculation and design methods are not known. This defines relevance of the works devoted to designing combustion chambers fueled with synthesis gas and experimental study of the reverse flow burner module fueled with methane-syngas mixture, and also to defining steady combustion concentration range.

Practice of alternative fuels use in gas-turbine plants, including synthesis gas produced by one of the methods of gaseous hydrocarbons thermal decomposition, shows that, today, there are two main concepts of the combustion chamber workflow creation. The first of them involves creation of a pilot flame from burning syngas-air reaction mixture which stabilizes combustion of lean pre-mixed fuel-air mixture implemented with using the known principles of low-emission combustion which are widely implemented in gas turbine technology by many leading domestic and foreign manufacturers. Along with the obvious advantages of this approach consisting in a minimum change of the burner module flow part geometry and combustion chamber as a whole by using a pilot catalytic burner – a synthesis gas generator that extends limits of steady combustion of fuel-air mixtures and reduces emission of nitrogen oxides, there are a number of serious shortcomings. The main of them are due to the fact that, similarly to "classical" combustion schemes of pre-mixed lean mixtures, there is a high probability of backfire in the mixing zone. In addition, in this case the problem is complicated by presence of active
hydrogen in the synthesis gas composition that accelerates kinetics of elementary combustion reactions and leads to increase in mass flow of the fuel burnout rate and, consequently, linear velocity of the flame front in a space toward the incoming flow of the mixture.

The second concept requires complete replacement of all pre-mixing burner modules used in DLN (Dry Low NOx) combustion chambers with synthesis gas RCL (Rich Catalytic Lean-burn) generator modules. In this case, the considered scheme has all the shortcomings of the previous one related to the backfire and low energy efficiency of the unit, but it allows achieving ultra-low emission of nitrogen oxides at high fuel combustion efficiency.

Transition to a principle of combustion in the combustion chamber of a gas-turbine plant not having most of the shortcomings of the lean combustion schemes, including combustion with synthesis gas, is possible on the basis of reverse flow gas-dynamic schemes for mixing and combustion in the chamber that is described in detail in the papers [1-4].

2. Experimental study

Application of a methane catalytic conversion method with the use of synthesis gas generator makes it possible to obtain hydrogen content in the synthesis gas composition up to 32%. The synthesis gas mixing with methane at different percentages made it possible to vary hydrogen volume content in the fuel mixture fed to the reverse flow combustion chamber in the range from 0 to 32%. One of the main characteristics of the methane-syngas fuel mixture is a volume stoichiometric coefficient $V_0$ which characterizes ratio of the actual volume flow of air fed to the combustion chamber and its amount which is theoretically necessary and sufficient for complete oxidation of all combustible fuel components and reaction under the stoichiometric scenario. Its dependence on the volume syngas content $r_{sg}$ in the fuel mixture is shown in Figure 1. In all range of change $r_{sg}$, $V_0$ value decreases according to relationship $V_0 = f(1/r_{sg})$ by 5.19 times, from 8.91 to 1.71. The lightest component of the fuel mixture, hydrogen, has a decisive influence on the stoichiometric coefficient (Figure 2).

The considered dependence has a significant impact on feasibility of changing design of the methane-fueled combustion chamber of a gas turbine engine to fuel it with synthesis gas; for this, essential change in the geometry of the burner modules flow part, pylons for fuel jets delivery to the mixing zone, geometry of the stabilizer flame, modes of the air-fuel mixture flow regarding to the Reynolds number are required and, as a result, change of all thermodynamic parameters of the combustion chamber.

![Figure 1](image1.png)  ![Figure 2](image2.png)

**Figure 1.** Volume stoichiometric coefficient of the mixture versus synthesis gas volume content

**Figure 2.** Volume stoichiometric coefficient of the mixture versus hydrogen volume content

A set of integral parameters of the burner module fueled with methane-syngas mixture is largely defined by mass and volume fuel calorific value. At that, studies have shown that their values vary in a fairly wide range at change in light components percentage being a part of synthesis gas. In addition, a
significant contribution is made by presence in the synthesis gas of inert component - molecular nitrogen which is always present in products of methane catalytic decomposition performed with use of air oxygen as an oxidizer.

Figure 3 shows dependence of mass $Q_m$ (curve 1) and volume $Q_v$ (curve 2) fuel calorific value of the fuel-air mixture on the synthesis gas volume content in its composition.

The analysis allows concluding that $Q_v$ and $Q_m$ decreases linearly with increase of $r_{sg}$. A characteristic feature of the different composition fuel mixtures is that at a small value of the volume content of synthesis gas $0 \% < r_{sg} < 10 \%$ absolute values of mass and volume fuel calorific value differ by more than 1.47 times, while for pure methane, at $r_{sg} = 0 \%$, a ratio of the amount of energy released during the fuel mixture combustion to the corresponding amount of energy obtained during combustion of 1 m$^3$ of the fuel mixture is 1.5 times.

In the range from $r_{sg} = 10 \%$ to $r_{sg} = 100 \%$, mass and volume fuel calorific value are reduced by 5.1 and 4.3 times, respectively. In quantitative terms, $Q_m$ value changes 47232 kJ/kg to 9104 kJ/kg, and $Q_v$ value - from 32320.9 kJ/m$^3$ to 7473.5 kJ/ m$^3$.

As studies have shown, a characteristic feature of the synthesis gas produced by a catalytic conversion method in the presence of air is that the difference between mass and volumetric fuel calorific values is minimal – $Q_m = 9104$ kJ/kg, and $Q_v = 7473.5$ kJ/m$^3$. Curve 3 (Figure 3) shows dependence of the mass fuel calorific values of a mixture consisting of methane and hydrogen on $r_{H2}$, where $r_{H2} = G_{H2} / (G_{H2} + G_{CH4})$. At increasing a hydrogen percentage in the mixture, $Q_m$ rises steadily to values $r_{H2} = 70 \%$, increase is 24 %. In the range of $H_2$ content from 80 to 100 %, the fuel calorific values for a mass unit increases sharply by 1.8 times relative to $r_{H2} = 70 \%$, and by 2.4 times relative to $r_{H2} = 0 \%$ (that corresponds to pure methane). In contrast to adding pure hydrogen in methane (curve 3) causing increase in mass fuel calorific values, adding synthesis gas (curve 1) causes a decrease in the mass fuel calorific values. This is due to the fact that the synthesis gas supplied to the model combustion chamber includes molecular nitrogen at a percentage by volume 49.11 %. As an inert substance, $N_2$ reduces percentage of combustible components ($H_2$ and $CO$) and reduces the amount of energy released during the combustion of a unit mass or volume of synthesis gas.

The purpose of the experimental study is to study features of the processes of mixed and synthetic fuels combustion, as well as to define its blowout and emission characteristics in the combustion chamber of the reverse flow type. To find the optimal operation mode for the combustion chamber at
different percentage of added synthesis gas, a comprehensive study was carried out: the blowout characteristics of the combustion chamber; emissions (volume concentrations of $C_2H_4$, $CO$, $NO_x$ in combustion products). For a complex study of the main integral parameters, a reverse flow burner module (Figure 4) and experimental bench (Figure 5) were used.

Reverse flow burner module operates as follows. The oxidizer (compressed air) is fed through a nozzle into the vortex chamber in the form of an intensely swirling flow. The synthesis gas obtained by the partial methane conversion is fed into the channels of the nozzle inlet of the swirling device. In the pressure gradient field, the mixture of air with synthesis gas in the form of a swirling flow (on the periphery of the vortex chamber) moves to the end of the burner to the place of the main fuel supply (methane). The air-fuel mixture ignites from the spark plug, the combustion products in the paraxial region of the vortex chamber move in the direction of the nozzle-diaphragm and expire from the flow-through zone of the burner. Peripheral and paraxial swirling currents, rotating in the same direction and moving in different axial directions, form a flow structure with aerodynamic reverse flow.

Figure 6 shows the relative air flow $G_{rel}$ through the reverse flow combustion chamber versus the Reynolds number $Re$. A relative air flow rate is the ratio of the actual air flow through the reverse flow combustion chamber to its value at a relative pressure drop of 3% that corresponds to the degree of expansion $\pi^* = 1.03$. This approach allows separating the area of $G_{rel}$ values (Figure 6) to two characteristic ranges $G_{rel} \leq 1$ and $G_{rel} > 1$. The range of values $G_{rel} \leq 1$ corresponds to the acceptable range of variation of the air flow through the combustion chamber of a gas turbine engine. Values $G_{rel} > 1$ characterize extended-range modes of model reverse flow combustion chamber, beyond the area of $\pi^*$ change in combustion chamber of gas-turbine plant.

Figure 7 shows dependence of the concentration limit of stable methane combustion in the "lean" zone, regarding to composition, versus of the mixture flow regime in the reverse flow combustion chamber. Analysis of the obtained experimental data shows a presence of two zones regarding to the Reynolds number with principally different nature of the $\alpha_{max} = f(Re)$ dependence. The first zone is limited to the Reynolds numbers from 12 500 to 44 500. Here, an excess air ratio $\alpha$ corresponding to the "lean" fuel blowout boundary increases sharply by 1.9 times from the near-stoichiometric values $\alpha_{max} < 1.2$ at $Re \approx 10 000$ to the value of $\alpha_{max} = 2.3$ corresponding to $Re \approx 50 000$.

Nature of the obtained empirical dependence can be explained by the fact that, in the range of small the Reynolds numbers corresponding to small pressure differences $\pi^* < 1.1$, gas-dynamic flow mode characterizing with a low quality of mixing the fuel-air mixture components is realized. Also, at a small value of the combustion chamber thermal power which takes place in the considered area of $Re$ number, significantly increases probability of thermal blowout when the amount of energy carried out from the reaction zone due to all forms of heat exchange (convection, radiation, thermal conductivity) exceeds the amount of energy released in the combustion zone. Combination of these factors defines the nature of the $\alpha_{max} = f(Re)$ dependence in this area.

The second range of the Reynolds number, limited to values from 50 000 to 150 000, is characterized by a self-similar mode of behavior of the $\alpha_{max} = f(Re)$ function. Throughout the observed range of $Re$ numbers, the concentration boundary of the "lean" blowout is in the range of...
2.3 < α_{max} < 2.4. In the range of the Reynolds number values from 130 000 to 150 000, excess air ratio corresponding to the boundary of the "lean" blowout decreases by 7 % reaching 2.26 at Re = 150 000. This is due to the fact that the instability process with blowout phenomenon begins to affect the gas-dynamic mechanism, in addition to the thermal mechanism. The gas-dynamic mechanism of the flame front stabilization is characterized by presence of local areas in the flow field where one of the components of the fuel-air mixture flow velocity vector \( \nu_{\text{mixture}} \) is less than or equal to the turbulent propagation velocity of the flame \( U_{c} \), \( \nu_{\text{mixture}} \leq U_{c} \). Analysis of the results of the flow structure numerical simulation for the flow part described in [1] showed that the mentioned conditions are met in the areas on the radial boundary of peripheral and axial vortices interaction characterized by zero value of the velocity vector axial component. If values of the Reynolds number exceed 100 000, time of the elementary volumes of reacting mixture presence in these areas becomes less than the characteristic time of chemical reactions necessary for self-acceleration of oxidation-reduction reactions at combustion of cold portions of the fuel-air mixture and release of sufficient amount of heat to support a thermal mechanism for flame stabilization.

One of the priority issues arising at the stage of gas turbine engine renovation to provide the engine operation with synthetic fuels is an optimal amount of synthesis gas added to methane. To respond to it, a set of experimental studies on combustion of methane-syngas fuel with different volume synthesis gas content in \( r_{sg} \), range from 0 % to 100 % were carried out. The results on influence of the synthesis gas volume content on the boundary of the "lean" blowout were obtained. A summary of the research results is shown in the Figure 8.

The results analysis leads to the conclusion that \( r_{sg} \) essentially influence qualitatively and quantitatively on the combustion thermal physics and kinetics in reverse flow combustion chamber. It can be seen that adding synthesis gas in the \( r_{sg} \) range from 7 % to 80 % causes an abrupt expansion of the steady combustion concentration range by more than 4 times in quantitative terms. This can be explained by active intermediate components presence in the synthesis gas due to development of the chain combustion mechanism and acting as active centers of the local stages intensification due to sum of methane oxidation kinetic processes. Another characteristic factor of \( r_{sg} \) influence on "lean" blowout is the presence of the range of synthesis gas volume content from 80 % to 100 % in which a nonlinear local growth of the excess air coefficient corresponding to the "lean" blowout occurs with a maximum value \( \alpha_{max} \) in the range \( 18 < \alpha_{max} < 19 \) at values \( r_{sg} = 100 \% \).

It should be noted that the considered \( r_{sg} \) range from 80 % to 100 % is characterized by a significant hysteresis of \( \alpha_{max} = f(r_{sg}) \) function and weak repeatability of the steady combustion concentration range which appear in its values scattering in the range from 14 to 19. Analysis of empirical data on \( r_{sg} \) influence on \( \alpha_{max} \) allowed us to conclude that the most suitable from the point of
view of sustainable combustion boundaries expanding at the stage of GTE (Gas Turbine Engines) renovation for synthetic fuels is adding synthesis gas to methane at volume content of 10-15%.

![Figure 8](image)

**Figure 8.** Concentration limit of stable combustion for fuel mixture in the "lean" area, by its composition, versus synthesis gas volume content: 1 – the length of the synthesis gas supply line to the burner was equal to 1 m; 2 – the length of the synthesis gas supply line to the burner was equal to 2 m; 3 – pure synthesis gas of $r_{sg} = 100\%$, the length of the synthesis gas supply line to the burner was equal to 1 m

### 3. Conclusion

Renovation of the combustion chamber for fueling with the synthesis gas requires an essential change in the geometry of the burner modules flow part, pylons for fuel jets delivery to the mixing zone, geometry of the stabilizer flame, modes of the air-fuel mixture flow regarding to the Reynolds number are required and, as a result, change of all thermodynamic parameters of the combustion chamber. A characteristic feature of the synthesis gas produced by the catalytic conversion method in the presence of air is that the difference between mass and volumetric fuel calorific values is minimal - $Q_m = 9104\, \text{kJ/kg}$, and $Q_v = 7473.5\, \text{kJ/m}^3$. Adding synthesis gas in the $r_{sg}$ range from 7% to 80% causes an abrupt expansion of the steady combustion concentration range by more than 4 times in quantitative terms. A characteristic factor of $r_{sg}$ influence on "lean" blowout is the presence of the range of synthesis gas volume content from 80% to 100% in which a nonlinear local growth of the excess air coefficient corresponding to the "lean" blowout occurs with a maximum value $\alpha_{max}$ in the range $18 < \alpha_{max} < 19$ at values of $r_{sg} = 100\%$.

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