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A STUDY OF MULTIFUEL BIDIRECTIONAL COMBUSTOR*

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Abstract

The results of experimental studies of the multifuel liquid-gas combustion in the bidirectional vortex combustor are presented. Propane is used as gaseous fuel and kerosene is used as the liquid. The transition between fuels of the different states of matter and molecular mass defines a change in flame geometry and combustion zone length. Depending on the degree of the airflow expansion, the experimentally measured values of the lean limit of stable combustion correspond to the range of the air-fuel equivalence ratio from 3.3 to 7.0. Additionally, the bidirectional vortex combustor provides sufficient stability at the repetitive transitions “liquid-to-gas-to-liquid”. Measured values of the total thermal power of the combustor at five consecutive transitions define a change in the total thermal power of no more than 3%.

Keywords: bidirectional vortex combustor, combustion efficiency, multifuel combustion, kerosene, propane

1. Introduction

The development of energy gas turbines is directed to the improvement of their thermal and electric efficiency. This becomes possible as a result of augmenting gas pressure and temperature at the combustion chamber outlet section. Industrial engines provide the temperature at the turbine inlet at 1600-1700 K. Several projects of high-temperature combustors for industrial and aircraft engines providing turbine inlet temperature 2150 K are currently being developed. The trend of energy development is related to studies of low-emission combustion chambers which should correspond to strict requirements on pollutant emission in wide operational range as well as economic and operational indicators. Mainstream manufacturers such as General Electric, Siemens, Alstom (Khosravy

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el_Hossaini, 2013) offer gas turbine units that provide NO_x and CO emissions less than 25 ppm. An analysis of the development of global energy shows that the most competitive are gas turbines operating on several types of liquid and gaseous fuel. They also provide a transition from primary to secondary fuel with flameout and a decrease in thermal power. This becomes possible as a result of using multifuel burners which form a reaction zone. Their development always requires a study of the dynamic transition between fuel types and the effect of flow structure on the conditions of stable combustion.

The main requirements to multifuel combustors of the industrial gas turbines are high combustion efficiency, a wide range of stable combustion, low pollutant emission, a possibility of dynamic transition between fuel types at constant thermal power, low hydraulic losses, minimal weight and size, and operational safety.

The experimental results have shown that bidirectional swirling flow in a constrained channel allows creating convective cooling of the combustor walls (Munson et al., 2011; Yu et al., 2016), improving mixing efficiency (Gongnan Li et al., 2013) as a result of an increase in residence time in the reaction zone (Evdokimov et al., 2020a, 2020b; Guryanov et al., 2017). These features of the bidirectional swirling flows can be applied to a study of multifuel combustion technologies as an approach to provide complete combustion in a minimal reacting volume. This is one of the main directions to increase the efficiency of energy units operation and primarily heat stress of the combustion zone which is defined as a volumetric amount of heat energy allocated per unit time.

The main goal of the research is to study the operation of multifuel bidirectional vortex combustor which provides burning liquid and gaseous fuel with a dynamic transition between them.

To achieve this goal, a model of multifuel bidirectional combustor were developed and manufactured as well as its experimental research was carried out. The experimental research was directed to find the most stable combustion conditions providing the dynamic transition between liquid and gaseous fuel types.

2. Materials and methods

The bidirectional vortex combustor which is used to study the combustion of gaseous and liquid types of fuel is presented in Fig. 1. Liquid fuel (kerosene) is supplied through a centrifugal atomizer set in the headwall of the combustor. Gaseous fuel (propane) is supplied through a jet nozzle set near the swirler. Previously such geometry of the bidirectional vortex combustor was successfully used for environmentally friendly combustion of single types of fuel: propane (Guryanov et al., 2017), syngas (Guryanov et al., 2019), kerosene (Piralishvili and Guryanov, 2008), and peat (Evdokimov et al., 2020b).

A scheme of the experimental setup is shown in Fig. 2. It operates as follows. Kerosene is supplied into the vortex chamber on its headwall, which has a toroidal shape. At the same time, the airflow is supplied to the combustor through the swirler with three tangential channels and moves in the opposite direction relative to liquid fuel. Both flows are mixed in the vortex chamber and form a toroidal vortex structure. Such structures correspond to the reliable ignition of the air-fuel mixture. Under burning conditions, fuel droplets evaporate and burn, lose their mass and move towards the axis of the combustor, and then they leave the device as a flow of exhaust gases. Propane is supplied into the vortex combustor near the swirler where it starts mixing with airflow. Then both, fuel and air move to the vortex chamber of the toroidal shape where they are ignited, burn, and leave the combustor as exhaust gases.

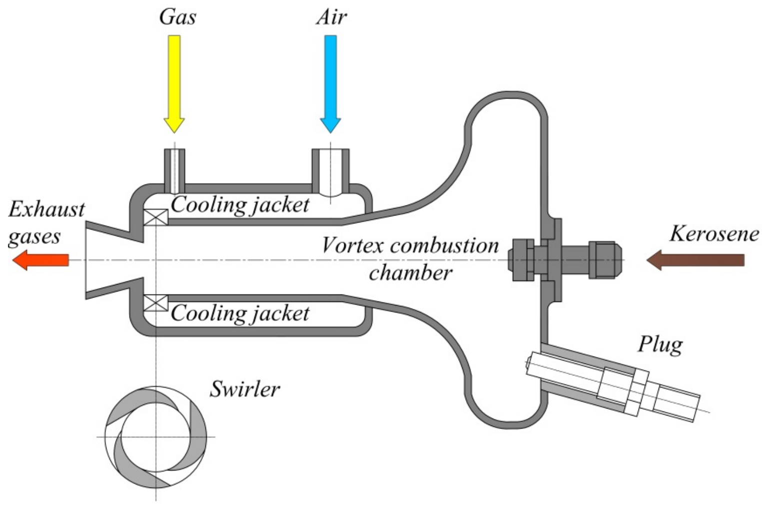

Fig. 1. Bidirectional vortex combustor

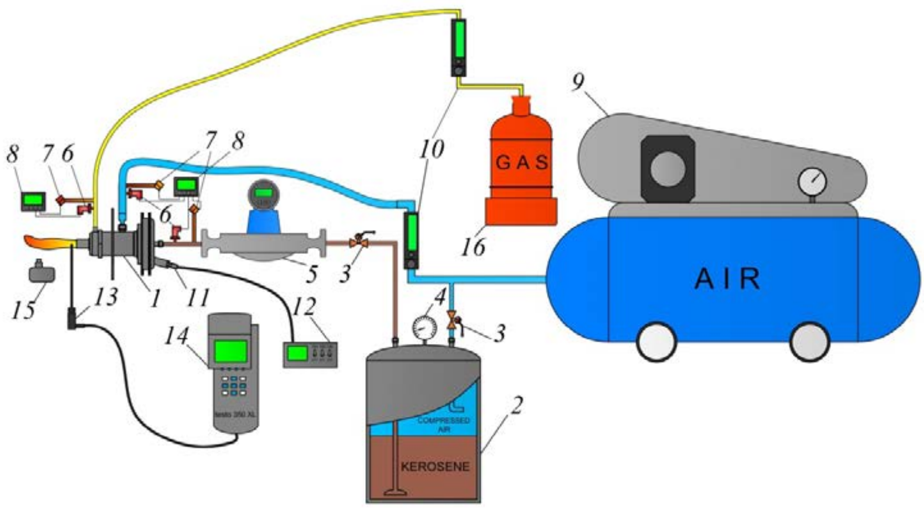

Fig. 2. The scheme of the experimental setup: 1 – vortex bidirectional combustor; 2 – pressure tank; 3 – flow control valves; 4 – pressure control manometer; 5 – Coriolis mass flow meter; 6 – pressure sensors; 7 – K-type thermocouples; 8 – eight-channel pressure and temperature meter-regulator; 9 – air compressor; 10 – Bronkhorst MV306 mass flow meter; 11 – spark plug; 12 – power supply; 13 – gas sampling probe with R-type thermocouple; 14 – TESTO 350XL gas analyzer; 15 – digital camera; 16 – gas cylinder

When analyzing the conditions of multifuel stable combustion, the following parameters are used:

– air-fuel equivalence ratio λ

$$\lambda = \frac{M_{air}}{M_{fuel} \cdot L_0}, \qquad (1)$$

where M_{air} is the air mass flow rate, M_{fuel} is the fuel mass flow rate, L_0 is the stoichiometric coefficient of fuel;

– degree of the airflow expansion π^*

$$\pi^* = \frac{p^*_{air}}{p_{atm}}, \tag{2}$$

where p^*_{air} is the air inlet total pressure, p_{atm} is the atmospheric pressure;

– fuel mass fraction g_i

$$g_i = \frac{M_i}{M_{gas} + M_{liq}}, \tag{3}$$

where M_i is liquid or gaseous fuel mass flow rate (equaled to M_{gas} or M_{liq} respectively), M_{gas} is the propane mass flow rate; M_{liq} is the kerosene mass flow rate;

– thermal power *TP*

$$TP = M_{gas} \cdot LHV_{gas} + M_{liq} \cdot LHV_{liq}, \tag{4}$$

where LHV_{gas} and LHV_{liq} are the low heat values of propane and kerosene respectively. LHV_{gas} = 49.9 MJ/kg; LHV_{liq} = 42.1 MJ/kg.

3. Results and discussion

In order to confirm the possibility of the dynamic transition between gaseous and liquid types of fuel, the experimental research of the bidirectional vortex combustor was performed at multifuel operation modes. The results of the research showed that the problem of multifuel combustion becomes more difficult if fuels of different stoichiometric coefficients are used and the operating mode of the combustor remains unchanged in terms of the degree of the airflow expansion. Fig. 3 shows the values of gaseous and liquid fuel mass flow rates supplied into the combustor under the condition of the “liquid-to-gas” transition. It can be seen that the transition is possible during 30 s and causes the oscillations in thermal power up to 30% of amplitude that may require the use of adaptive automation. At the same time, the oscillations of both gaseous and liquid fuel mass flow rates are observed in the time range from 2 s to 28 s. When starting with liquid fuel, the initial value of the air-fuel equivalence ratio was equal to near-stoichiometric value λ_1 = 1.09 whereas the final ratio at gaseous fuel operation mode corresponded to λ = 1.20.

The change in the air-fuel equivalence ratio is caused by the difference of the stoichiometric coefficients of gaseous and liquid fuel (for propane L_0 = 15.6; for kerosene L_0 = 14.7). In addition, one of the main conditions of the multifuel combustors was performed: the degree of the airflow expansion remained unchanged $\pi^* = 1.03$.

As the experimental results showed, the transition between fuels of the different state of matter and molecular mass defines a change in flame geometry and combustion zone length which are caused by the thermal and flow dynamics in the reaction zone as well as a change in fuel molecular mass. Qualitative changes in the operation of the bidirectional vortex combustor are presented in the photographs shown in Fig. 4.

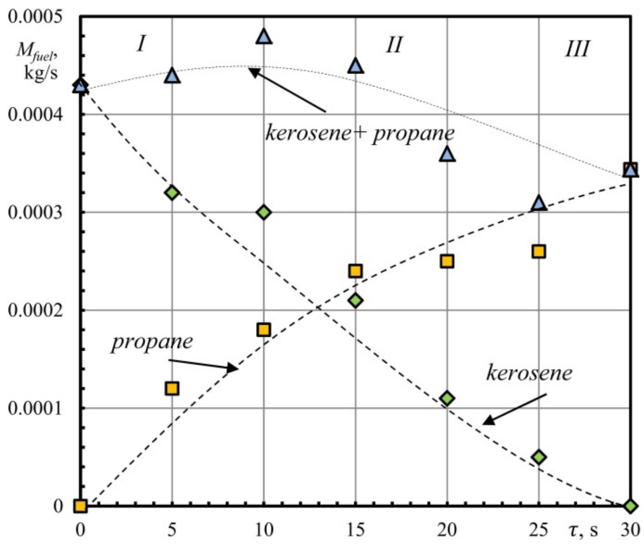

Fig. 3. The dependence of fuel mass flow rate on time for the "liquid-to-gas" transition

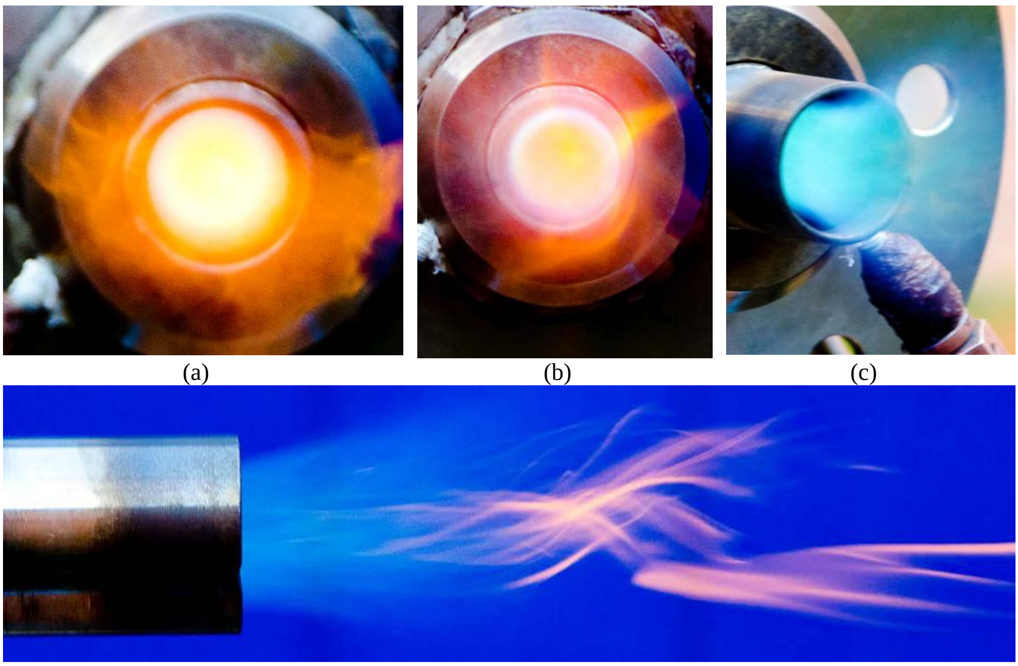

Fig. 4. The photographs of the combustion for the "liquid-to-gas" transition: (a) kerosene combustion; (b) kerosene combustion mainly (g_{ker} = 0.75); (c) propane combustion; (d) propane combustion mainly (g_{ker} = 0.16)

The flame corresponding to kerosene combustion (Fig. 4a) forms a cone-like geometry of expansion angle 120° behind the outlet nozzle. This is caused by centrifugal forces action on reacting kerosene vapor. At the same time, one can observe a strong recirculation zone in the center of the flame which is caused by the ejection of the atmospheric air. It dilutes the near axis part of the flame to the value of the air-fuel equivalence ratio corresponding to the upper limit of stable combustion.

Meanwhile, the reaction zone is shifted in the radial direction to the values of the dimensionless radius of the outlet nozzle from 0.8 to 0.9 in the outlet section.

At the values of kerosene mass fraction $0.34 < g_{ker} < 0.75$ which correspond to the II zone in Fig. 3, the composition of fuel supplied in a liquid form through the headwall and as a gas through the swirler causes the presence of a central reacting core in the flame (Fig. 4b and 4c). This defines the exhaust of reacting kerosene vapor out from the nozzle as a near-axis flow in the range of the dimensionless radius from 0 to 0.6. An intense heat generation occurs from the reacting mixture of gaseous fuel and air supplied through the swirler that leads to a formation of fire wisps in the flame (Fig. 4d). This is accompanied by the qualitative restructuring of the reacting flow and formation of interleaved combustion zones of gaseous and liquid fuel.

The transition to the combustion mode corresponding to $g_{ker} < 0.16$ (the III zone in Fig. 3) provides the burning of liquid fuel as a part of toroidal recirculation zones near the headwall of the combustor. The combustion of gaseous fuel is a volumetric process and occurs over the total length of the vortex chamber and finishes in the externally visible flame which ejects additional airflow from the atmosphere (Fig. 4c).

A special calibration of needle valves set in gaseous and liquid pipes has allowed us to reduce the oscillations of thermal power up to 1.5%. The experimental results for the transition "liquid-to-gas" obtained for this case are shown in Fig. 5 and 6.

Fig. 7 shows limits of stable combustion of lean air-fuel mixtures for the combustor operation on liquid and gaseous fuel as well as their combined supply at g_{ker} = 0.4 and g_{prop} = 0.6. Depending on the degree of the airflow expansion, the lean limit of stable combustion corresponds to the range of the air-fuel equivalence ratio from 3.3 to 7.0.

Another well-known problem of multifuel combustion is related to a high probability of flame blowout at repetitive transitions from the different types of fuel. As the experiments have shown, the bidirectional combustion provides sufficient stability at the repetitive transitions "liquid-to-gas-to-liquid". Measured values of the total thermal power of the bidirectional combustor at five consecutive transitions finishing at the operation mode of two-fuel combustion are given in Fig. 8. It is clearly seen that all the transitions provide a change in the total thermal power of no more than 3%.

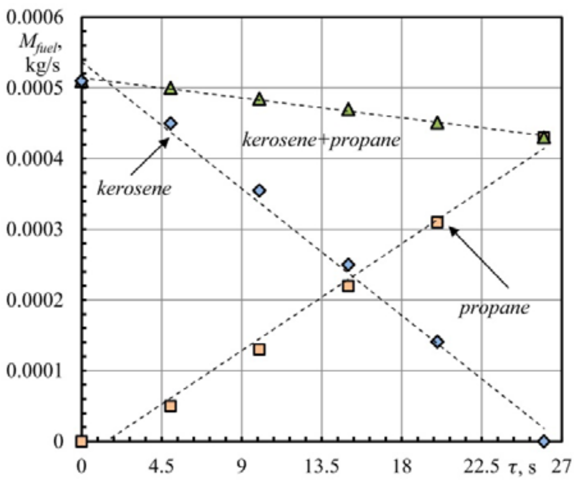

Fig. 5. The dependence of fuel mass flow rate on time for the "liquid-to-gas" transition after calibration of needle valves

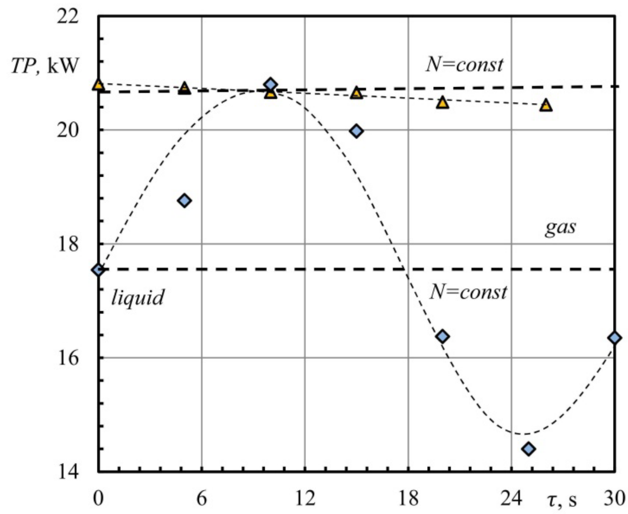

Fig. 6. The total thermal power of the bidirectional vortex combustor for the "liquid-to-gas" transition

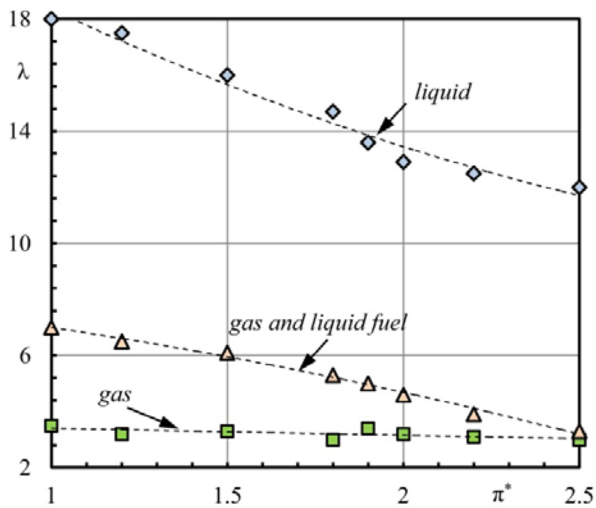

Fig. 7. Lean combustion limits

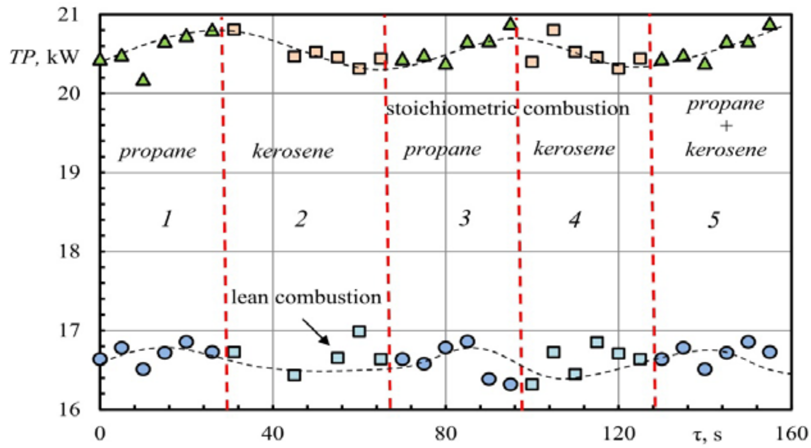

Fig. 8. Consecutive transitions between the multifuel operation modes of the combustor

The stable process and the absence of the flame blowout are observed for all the consecutive transitions corresponding to both stoichiometric and lean combustion.

4. Conclusions

The experimental results of the studies of multifuel combustion in the bidirectional swirling flow have confirmed a possibility of stable combustion when different types of fuel of different state of matter and thermophysical properties are used. This makes it possible to apply bidirectional vortex combustors in multifuel gas turbines of energy use.

Acknowledgments

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