1. INTRODUCTION

Despite the increasing interest in alternative and renewable energy sources, the proportion of fossil fuels in the world fuel balance remains to be quite appreciable. According to the BP Statistical Review of World Energy (2017), it accounts for about 80%, with coal taking 40% among fossil fuels. Coals of all metamorphic stages are
mined in the world: from brown coal to anthracite — all of them can be used for energy, chemical, household purposes, and in other processing areas (BP Statistical Review of World Energy, 2017).

The main objective of utilizing coal for power generating and industrial purposes is to use its energy resource efficiently and minimize the harmful impact on the environment. It is possible to consider coal as a complex raw material containing not only carbon, which serves as a thermal and chemical energy source, but also the content of ashes in the form of compounds that can be used in construction; as well as rare and rare-earth elements, which are of value for the modern semiconductor industry. In addition, coal often contains high concentrations of sulfur and other chemical elements, and this fact determines the effectiveness of their extraction (Pinchuk and Potapov, 2009).

The technologies of using coal in the form of coal–water fuel (CWF) are most common among various methods of power generation from coal. The experience of their implementation in different countries has demonstrated the prospects of CWF-based technologies for power generation. CWF has a range of advantages (Delyagin et al., 1994; Iegorov et al., 2016), and the main one is the possibility of using the coal preparation waste of various compositions. Storing such waste is cost-ineffective and environmentally unfriendly. Moreover, in the process of CWF combustion, it is possible to use low-grade coals (high-ash coal or/and high-sulfur coal) which are hardly appropriate for direct combustion or using in other technologies. During the direct combustion of low-grade coal, the operation of coal-pulverizing, combustion, and burning equipment becomes rather complicated, and the reliability of boiler units, smoke exhausters, ash catchers, and hydraulic ash removal systems is determined (Beloselskyi and Baryshev, 1989).

In the process of CWF production, the solid fraction, if necessary, can be significantly modified to increase the heat of coal matter combustion. Viscosity reducers and stabilizers, corrosion inhibitors, and other additives can also be used in the process of CWF production (Beloselskyi and Baryshev, 1989; Iegorov et al., 2016; Khodakov, 2007; Serant et al., 2011; Solodov et al., 2003).

The above considerations prove the significance of the research into the CWF fuel combustion processes and the development of technical and technological methods of increasing combustion effectiveness.

2. PROBLEM FORMULATION

At present, a great deal of scientific research is being done with the purpose to provide stable and efficient CWF combustion. For this aim, a variety of methods have been developed. A number of scientific papers focus on the research into CWF combustion with additives of miscellaneous waste in different amounts that are produced by petrochemical, coke chemical, chemical, and wood processing industries (Chen et al.,
Thermal and electromagnetic activation of CWF before combustion allows providing stable ignition and effective combustion of such fuel (Pinchuk and Sharabura, 2015; Pinchuk et al., 2017).

The development of nanotechnologies has made it possible to study the influence of material, concentration, size, and shape of a nanoparticle on the properties of different solids and liquids. In Ghamari and Ratner (2017), it is shown that adding carbon-based micro- and nanoparticles to liquid colloidal fuels increases the fuel combustion rate and shortens the time before its ignition. In addition, this leads to the improvement of heat transfer inside the fuel drop and to the increase in drop combustion temperature.

In the power generation industry, it is advised to use soot additives in fuel production to effectively replace a natural gas and fuel oil by the CWF. This allows the betterment of rheological properties and stability of the CWF. Ecological qualities are also improved in comparison with those of the fuel oil (Staroń et al., 2016). Gu et al. (2008) suggest using the mixture of three different coal grades in the fuel production process to enhance the CWF rheological properties, give CWF certain characteristics, and make the combustion more efficient. One of the ways to raise the calorific value of CWF and its combustion effectiveness is to increase the weight content of solid fraction. However, bigger coal concentration in CWF results in increased viscosity (decreased fluidity). This leads to large energy consumption while transporting CWF through pipes to combustion units and causes significant operational problems (Mukherjee and Pisupati, 2016) determined the influence of extremely various and specific additives on interphase interactions, which leads to fuel viscosity deterioration. This will help to choose the appropriate additive to decrease the fuel viscosity in the case of the weight content of solid fraction increases in certain CWFs.

Zhang et al. (2016) suggest using preliminary absorption of moisture from air to get CWF with a high amount of coal matter and low viscosity. Such technology results in a significant decline in suspension viscosity and yield point.

A number of papers are devoted to experimental research into the CWF drop combustion processes (Burdukov et al., 1996; Kijo-Kleczkowska, 2011; Liu and Law, 1986; Lyrshchikov et al., 2016; Pinchuk, 2015, 2018a,b; Smetannikov and Delyagin, 1965). They have determined CWF ignition temperature and combustion stages. Mathematical models of CWF combustion process have been developed in Sazhin (2017), Starchenko et al. (2012), and Tavangar et al. (2015) based on the results of experimental and theoretical research. However, the models have certain significant allowances because of the complexity of the processes:
characteristic features of physical and chemical changes in coal matter during the combustion process are not considered,

• CWF features distinguishing it as a disperse system are also not taken into account.

The obtained results of experimental and theoretical research are mostly not generalized in the form of equations convenient for further research.

Quite a few papers (Delyagin et al., 1964; Sharabura et al., 2011; Salomatov et al., 2013; Bo et al., 2013) are concerned with the research of CWF combustion in boilers of various capacity and other units designed for flame combustion, combustion in a fluidized bed, and co-combustion with other kinds of fuel. Such an approach reveals general ideas about the fuel combustion process and operation of power generating equipment. Nevertheless, in this case, it is difficult to identify the influence of certain factors on the CWF combustion process.

One other aspect distinguishing the present research and technologies is the focus on utilizing fuel made of high-volatile coal, namely, gas coal, flame coal, and gas–flame coal. It is common to use low-ash coal (with ash content from 8% to 10%) and low-sulfur coal (sulfur content maximum 1%). No matter how identical they may seem, each technology of coal production from different coal grades has its own features due to the physical and chemical characteristics of each coal type. This is reflected in the CWF ignition and combustion processes. That is why it is impossible to apply the results obtained for the fuel made from one coal grade to CWF made from coal of another grade or/and from coal having other characteristics. This is particularly true for CWF produced from low-volatile coal and coal cleaning waste.

Thus an analysis of the literature has shown that at present there is a lot of various works studying the CWF combustion processes with different properties and characteristics. Yet, these researches are unrelated and uncoordinated. This fact does not allow for the systematization of all obtained data into a consistent CWF combustion theory and establishment of physical and chemical mechanisms underlying combustion of the given fuel.

The only possible way to collect the necessary information on the CWF combustion theory development is to study typical features characterizing combustion of a CWF drop. Such research makes it possible to determine the regularities describing the way in which different parameters (temperature, water phase content, mineral impurities content, drop size, etc.) influence the fuel combustion process. The results of such research conducted for fuel drops from different coal grades will serve as a knowledge base for the CWF combustion theory. Data processing will allow obtaining empirical dependences for the description of each combustion stage (heating and emission of volatile matter, volatile matter combustion, coke residue combustion), considering the influence of different physical and chemical parameters, and also to develop a more correct mathematical description of CWF combustion processes.
3. OBJECTIVE AND TASKS OF RESEARCH

The main objective of the research was to determine the influence of the source coal metamorphic stage (coal grade), oven medium temperature, and CWF drop size on the time–temperature characteristics of a single fuel drop combustion process in static air.

In order to reach the objective, the following areas were studied:

- Influence of the source coal metamorphic stage (from brown coal to anthracite) on the characteristics of an individual CWF drop combustion process.
- Influence of oven medium temperature in the range from 550°C to 1000°C on characteristics of an individual CWF drop combustion process.
- Influence of CWF drop size δ in the range from 0.5 to 2 mm on the characteristics of an individual CWF drop combustion process.

On the basis of the obtained data, the regularities of the influence of the above parameters on an individual CWF drop combustion process were established.

4. RESEARCH METHODS

The entire research was conducted by means of a physical experiment. For the purpose of the research, we have used the experimental equipment the layout of which is presented in Fig. 1. It is the same equipment which we used in Pinchuk et al. (2017). The main units of the experimental setup are:

- A laboratory electrical oven SNOL-2.2.1.5/12 (1) with a control module (3), which provides different heating modes. Maximal heating temperature is 1100°C.

FIG. 1: Scheme of the experimental setup: 1) electrical oven; 2) tempered looking glass (quartz); 3) oven control unit; 4) manipulation stand with servo motor; 5) stroke; 6) thermocouple; 7, 8) thermocouples (not used); 9) thermocouple input module EX-9018; 10) computer based registration and control system
• A manipulation stand (4) for a thermocouple (6) with CWF drop moving into and out of the oven.
• PC-based real-time temperature and weight registration system (10).
• Thermocouples (6), (7), and (8) versus Pinchuk et al. (2017). For this research only thermocouple (6) was used. Thermocouples (7) and (8) were removed from the experimental area.

Thermocouples were fabricated manually from a Chromel/Alumel alloy wire of 0.25-mm and 0.1-mm diameter. The 0.25-mm-diameter wire was used for CWF drops of equivalent diameter more than 1 mm. For CWF drops with a diameter less than 1 mm we used wire diameter 0.1 mm. Junction diameters did not exceed 0.5 mm for thick wires and 0.12 mm for thermocouples of thin wires. Although it was described in details, we repeat here some important points regarding the accuracy and error estimation of the experimental facility.

Individual calibration procedures were carried out for each of thermocouples, and individual correlation equations \( t = f(U) \) were established in the temperature range from 250\(^\circ\)C to 1300\(^\circ\)C. The individual calibration procedure allowed narrowing thermocouples systematic error interval to \( \pm 1^\circ\)C. Thermocouples data were collected with TopSCCC's EX-9018 input module operated in the analog input mode. It requests temperature sensors permanently with \( 10^{-1} \) s step. Producer of EX-9018 indicated in the technical datasheet that module's error level is 0.1\% (Pinchuk et al., 2017).

The diameter of drops of coal–water fuel varied from 0.5 mm to 2.0 mm. The process of thermocouple (6) junction covering with a CWF drop was visually monitored. We made a photo of the CWF drop with the help of a digital SRL camera for determining its size. Typical photos of CWF drops and determination of their diameter are presented in Fig. 2.

The form of the CWF drops of medium and small size differs from the form of large drops, showed in Pinchuk et al. (2017). Large drops usually keep a spherical form. Medium and small-sized drops of coal–water fuel have the form close to an ellipsoid of revolution — spheroid. It is clearly visible in Fig. 2. So, we use the equivalent diameter for comparing different drops during the investigation. The equivalent diameter was calculated with the help of a photo. Assuming the spheroid-like form of drop, we can calculate the volume of the drop by using the formula

\[
V_{\text{drop}} = \frac{4}{3} \pi a^2 b - V_{\text{jnc}},
\]

where \( a \) is the equatorial radius of the spheroid; \( b \) is the distance from the center of the spheroid to its pole along the symmetry axis of the spheroid, and \( V_{\text{jnc}} \) is the volume of the thermocouple junction. For the 0.5-mm junction:

\[
V_{\text{jnc}} = \frac{4}{3} \pi (0.25)^3 = 0.06545 \text{ mm}^3.
\]
In accordance with Fig. 2: \(2 \cdot a = 1.3\) mm and \(2 \cdot b = 2.1\) mm.

Thus, the equivalent diameter, hereinafter drop size \(\delta\), can be calculated by the formula

\[
\delta = 2\sqrt[3]{\frac{V_{\text{drop}}}{4\pi}}.
\]

The equivalent diameter values calculated for different drops of CWF are shown in Fig. 2 below the drop example number (I–IV).

Thermocouple (6) was used for measurement of the CWF drop average temperature. All experimental investigations were carried out in the natural convection conditions in order to establish general regularities for CWF drop ignition and combustion. Flue gases left the combustion area through special openings in the oven casing. The temperature of the oven medium (internal oven temperature) varied in the range from \(550^\circ\text{C}\) to \(1000^\circ\text{C}\).

During the experimental routine, we selected at least 7 closest experimental data for generalization and trend determination for each experimental point. The total measurement system error was 2.5–3%. Confidence interval, defined with the confidence level 95%, constituted for time values \(\pm 1.6\%\), for temperature values it was \(\pm 2.8\%\).

The lowest temperature of the measurement range \(t_{\text{oven}} = 550^\circ\text{C}\) was defined by the minimum temperature of the fuel ignition and combustion, while the highest temperature \(t_{\text{oven}} = 1000^\circ\text{C}\) ensured visibility of the fuel combustion process for the purpose of setting up the necessary regularities. It should be mentioned that CWF combustion in actual conditions occurs at \(800^\circ\text{C}–1100^\circ\text{C}\).

The range of CWF drops size change (0.5–2 mm) was determined in view of the possibility of using burners of different design that is capable of ensuring various
levels of atomization. Besides, we took into account the possible coalescence of small fuel drops into bigger ones during atomization.

5. CHARACTERISTICS OF COALS AND COAL–WATER FUEL

CWF samples were manufactured at the A.V. Dumansky Institute of Colloid and Water Chemistry at the Department of Physical and Chemical Mechanics of Disperse Systems (Kiev, Ukraine). Coals of six grades: brown coal, flame (long flame) coal, gas coal, fat (bituminous) coal, nonbaking (lean) coal, and anthracite were used for manufacturing different fuel samples. Hereinafter we will use the following notations for these different coal grades: B for brown coal, D for flame coal, G for gas coal, F for fat coal, N for nonbaking coal, A for anthracite.

The technology of CWF production was developed by Makarov et al. (2007, 2011) and Savitskiy et al. (2012). During the CWF producing process, it was mandatory that the maximum of solid fraction, the minimum viscosity of the composition, and the needed sediment stability of the fuel be provided. The technology included phases of coal wet grinding in a ball mill and cavitation processing. Sodium lignosulfonate (1% of CWF mass) was used as a plasticizer. It provides CWF sediment stability for 8–10 days. The authors of the technology have been carrying out numerous investigations of specific technological parameters for a long time and have acquired a great experience in coal–water fuel production for different purposes. Coal–water fuel samples were additionally mixed before each experiment to avoid stratification.

Basic characteristics of CWF samples are listed in Table 1. Because of the paper size limitations, we do not provide the data here on specific coal characteristics, chemical composition of mineral impurities and coal matter, coal particles size distribution in CWF, and the rheological properties of the fuel, which are thoroughly accounted for in Pinchuk et al., (2017).

### TABLE 1: Basic content of coal for CWF samples (Pinchuk et al., 2017)

<table>
<thead>
<tr>
<th>Source Coal Grade</th>
<th>Dynamic (shear) Viscosity, Pa·s</th>
<th>Solid Fraction, %</th>
<th>Source Coal Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mineral Impurities Fraction $A^d$, %</td>
</tr>
<tr>
<td>B</td>
<td>0.8</td>
<td>58</td>
<td>23.31</td>
</tr>
<tr>
<td>D</td>
<td>1.06</td>
<td>65</td>
<td>36.8</td>
</tr>
<tr>
<td>G</td>
<td>0.73</td>
<td>65</td>
<td>60.8</td>
</tr>
<tr>
<td>F</td>
<td>0.73</td>
<td>70</td>
<td>50.5</td>
</tr>
<tr>
<td>N</td>
<td>0.68</td>
<td>68</td>
<td>18</td>
</tr>
<tr>
<td>A</td>
<td>0.6</td>
<td>70</td>
<td>44.1</td>
</tr>
</tbody>
</table>

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6. RESULTS OF EXPERIMENTAL RESEARCH INTO THE INFLUENCE OF DIFFERENT PARAMETERS ON TIME–TEMPERATURE CORRELATIONS CHARACTERIZING THE COMBUSTION PROCESS OF AN INDIVIDUAL CWF DROP

With a view of establishing time–temperature correlations of an individual CWF drop combustion (for all the above-mentioned coal grades), we conducted experiments on combustion of fuel drops of different sizes at different temperatures of the oven medium $t_{\text{oven}}$.

The following basic parameters were in the focus of our research:

- the rate of fuel samples heating before ignition;
- instantaneous values of drop temperature $t_{\text{drop}}$;
- total time of drop combustion $\tau$;
- the maximum temperature of the drop combustion.

6.1 Influence of the Oven Medium Temperature on the CWF Drop Combustion Process

Figures 3–8 demonstrate the temperature change of CWF drop of 1-mm size from different coal grades during its combustion in air at different temperatures of the oven medium $t_{\text{oven}}$.

From the research, it becomes evident that for the studied drop sizes it is impossible to single out clearly each stage of CWF combustion unlike the case of 5-mm drops (Pinchuk, 2015, 2018a,b). At the same time, it is obvious that combustion of small drops involves the same complex of interrelated physical and chemical processes as in the case of bigger drops.

FIG. 3: Temperature of the brown coal (B) CWF drop dependence on time
It can be inferred from the analysis of the obtained data that the oven medium temperature $t_{\text{oven}}$ is an important factor which determines the combustion of CWF produced from coals of different metamorphic stages.

For instance, the total combustion of a CWF drop from anthracite (Fig. 8) is 2.5 times longer at the oven medium temperature $t_{\text{oven}} = 600^\circ\text{C}$ than at $800^\circ\text{C}$, while the total combustion of a CWF drop from brown coal (Fig. 3) at $t_{\text{oven}} = 550^\circ\text{C}$ is 4.5 times longer than at $t_{\text{oven}} = 800^\circ\text{C}$.
If the oven medium temperature $t_{oven}$ is low, the rate of fuel samples heating to the ignition temperature decreases dramatically. Thus, for CWFs produced from coals of low and medium metamorphic stages, the average rate of fuel samples heating is 45–55°C/s at $t_{oven} = 600°C$, and 100–160°C/s at $t_{oven} = 800°C$. For CWFs produced from coals of high metamorphic stages and anthracite, the average rate of fuel samples heating is 15–30°C/s at $t_{oven} = 600°C$, and 65–90°C/s at $t_{oven} = 800°C$. In most cases, the low rate of CWF samples heating causes drying up of the superficial layer of the fuel drop and formation of a tight membrane. As a result, the fuel does not ignite.
6.2 Influence of the Source Coal Grade on CWF Drop Combustion Process

Figure 9 presents time–temperature correlations characterizing combustion of CWF 1mm drops from different coal grades.

It was found that within the studied temperature range, the total CWF drops combustion time decrease and the temperature $t_{\text{oven}}$ increase are related by a power law. The time of brown coal CWF drop combustion is significantly shorter than the time of anthracite CWF drop combustion, given the combustion conditions are identical.
Volatile yield is one of the indicators of the coal metamorphic stage. According to Table 1, every grade of the source coal in the fuel corresponds to a certain quantity of volatile yield. Processing of experimental data allowed establishing a relationship between the duration of CWF drops combustion and volatile yield in the source coal (Fig. 10).

As an overall trend, it is clear that CWF drops combustion time shortens as the amount of volatiles in the coal used for fuel production increases. Computation of experimental data showed that this dependence can be described by the following law:

\[ \tau = k_f (V^a)^{-0.326}, \]  

where \( V^a \) is the volatile yield of coal–water fuel as fired, \( \% \), and \( k_f \) is the factor considering the oven medium temperature \( t_{oven} \).

This factor has been determined empirically: for \( t_{oven} = 600^\circ\text{C} \), it was \( k_f = 188.78 \); for \( t_{oven} = 700^\circ\text{C} \), \( k_f = 118.86 \), and for \( t_{oven} = 800^\circ\text{C} \), \( k_f = 86.84 \).

The values of \( k_f \) were generalized, which resulted in the following equation:

\[ k_f = \frac{3.2 \cdot 10^4}{t_{oven} - 430}. \]  

Thus, the combustion time of CWF drops produced from coals of different metamorphic stages with characteristics listed in Table 1 can be calculated according to the empirical formula given below, in which the oven medium temperature is taken into account:

\[ \tau = \frac{3.2 \cdot 10^4 (V^a)^{-0.326}}{t_{oven} - 430}. \]  

FIG. 10: Correlation between the time of the complete CWF drop combustion and volatile yield for different medium temperatures
However, since the volatile yield is not the only parameter defining the coal grade, hereinafter, for the purpose of research results generalization, we used empirical modifying factors for each coal grade.

### 6.3 Influence of CWF Drop Size on the Fuel Combustion Process

The fuel drop size is an important parameter influencing the duration of CWF combustion. Figures 11–13 present dependences that describe the temperature change of CWF drops of different sizes during their burn-off in the air at $t_{oven} = 700^\circ$C.

The processes of CWF drops combustion were compared on the basis of the empirical research results for CWF from brown coal (placed at the beginning of the metamorphic rank), from flame coal (belonging to the group of bituminous coals and placed in the middle of the metamorphic rank), and from anthracite, which comes last in the metamorphic rank.

It is obvious that doubling of CWF drop size results in a tripling of fuel drop burn-off time for CWF samples produced from coals of different metamorphic stages.

Figure 14 shows general relationships between the duration of CWF drops combustion in air and their size at an oven medium temperature of 700°C.

Experimental data treatment proved that the dependence of CWF drops combustion time on their sizes is described with power function, which becomes more pronounced as the drop size increases. This dependence was generalized in the form

$$\tau = k \delta^{1.6},$$

where $\delta$ is the size (diameter) of CWF drop, mm, and $k$ is the factor considering metamorphism of the source coal and related to the oven medium temperature $t_{oven}$.

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**FIG. 11:** Comparison of the burning process for coal (B) CWF drop of different sizes
It can be determined from the formula obtained as a result of experimental data handling:

\[ k = \frac{k_m \cdot 10^3}{t_{oven} - 430}, \quad (5) \]

where \( k_m \) is the factor related to the grade of the source coal in the fuel.

For the fuels produced from coal (B) \( k_m = 8.48 \); coal (D) \( k_m = 11.28 \); coal (G) \( k_m = 12.89 \); coal (F) \( k_m = 14.29 \); coal (N) \( k_m = 15.98 \); coal (A) \( k_m = 19.69 \).

It was found that irrespective of the oven medium temperature, source coal grade and CWF composition (Table 1), exponent of \( \delta \) in formula (4) is the same and is equal to 1.6.

**FIG. 12:** Comparison of the burning processes for coal (D) CWF drop of different sizes

**FIG. 13:** Comparison of the burning processes for coal (A) CWF drop of different sizes
Comparative analysis conducted in Babiy and Kuvaev (1986) testifies that the oven medium temperature produces a stronger effect on duration of coal particles combustion in pulverized coal fuel than their size. From the results of the present research, it can be inferred that in the case of CWF combustion, we deal with a reverse process. It is clear from Eqs. (3) and (5) that the exponent of temperature is equal to 1 in absolute value, while in Eq. (4) the exponent of drop size is 1.6. It allows concluding that the time of CWF drops combustion is stronger related to fuel drops size than to the oven medium temperature $t_{\text{oven}}$.

7. CONCLUSIONS

As a result of experimental research, we have defined the effects of the source coal metamorphic stage (grade), oven medium temperature, and CWF drop size on the time–temperature correlations characterizing the process of individual fuel drop combustion in static air.

The obtained data testify that the oven medium temperature $t_{\text{oven}}$ is a meaningful factor in organizing combustion of CWF from coals of different metamorphic stages. The rate of CWF sample heating to the ignition temperature at different $t_{\text{oven}}$ has been determined. When $t_{\text{oven}}$ is low, the rate of fuel samples heating to the ignition temperature significantly decreases (2–3 times), which results in the formation of a tight crust on the fuel drop surface preventing it from igniting.

It follows from the research that the reduction of the total time of CWF drops combustion is related to the oven medium temperature $t_{\text{oven}}$ according to a power
function. Given the conditions of CWF drops combustion are the same, the drop combustion time shortens significantly when the anthracite source coal (A) is replaced by the brown coal (B). We have experimentally established the regularities describing the influence of the fuel drops sizes on CWF ignition and combustion processes. The time of CWF drops combustion increases with the growth of the drop size according to a power function. Unlike the case of pulverized coal fuel particles combustion, the time of CWF drops combustion depends strongly on the drops size and less — on the oven medium temperature $t_{oven}$.

Treatment of experimental data allowed the plotting of empirical dependences describing relations between the time of CWF drops combustion and volatile content in the source, as well as drops sizes. These dependencies take into account the oven medium temperature and the source coal grade.

The obtained results are critical for further generalization and establishing the dependencies for describing each combustion stage, considering the impact of various parameters (temperature, water phase and mineral impurities content, drops sizes, etc.) on the fuel combustion process.

It is known that ensuring the necessary time for the fuel complete burnout is one of the main parameters for the assessment of the combustion chambers and combustors' efficiency. That is why the obtained data are vital for upgrading and designing the equipment for CWF combustion.

REFERENCES


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