# INVESTIGATION OF THE SPRAYING MECHANISM AND COMBUSTION OF THE SUSPENDED COAL FUEL

by

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*This paper presents the results of the suspended coal fuel spraying with pneumo-mechanical sprayers followed by the fuel combustion in a vortex furnace, as continuation of our previous research. It is shown that, during the spraying, two qualitatively different systems of drops are forming. The first one with the "drops" diameter above 80-100 μm is presented by coal particles, the other – by water-coal drops. Different dynamics of temperature variation of the coal particle and water-coal fuel drops during their combustion is founded. The residence time of the burning particles and water-coal fuel drops in the vortex furnace is proportional to their diameter, which permits to provide their effective burn-off.*

Key words: *water-coal fuel, water-coal fuel preparation, combustion stabilization, experimental-theoretical investigations.*

## Introduction

Progress in power engineering and improvement of energy supply security in Russia highly depend on the extensive and effective use of coal as an energy-producing fuel. To reach this purpose, it is necessary, above all, to improve the fuel quality of coal, and also to master the production of alternative coal-based fuels, for the replacement of deficit natural resources such as gaseous and liquid oil fuels. The aforesaid problem can be solved with the aid of the promising works performed both in Russia [1] and abroad: development of the technologies of production and application of coal suspensions which present a disperse system containing a solid phase (fine coal) and liquid medium (water, alcohols, hydrocarbons, petroleum refinery products) [2, 3]. The suspended coal fuel, the water-coal fuel (WCF), is a well-studied and promising trend in the power engineering; the main part of the liquid medium there is water.

The processes of spraying were studied by, for instance, Delyagin [4], Nekrasov [5], and Thambimuthu [6, 7]. The sprayed media properties such as density, viscosity, and surface tension must be known to understand the spraying processes.

We propose a new approach suggesting that the sprayed drops consist of two qualitatively different systems: the first one with the "drops" diameter above 80-100 μm is presented by coal particles, whereas the other contains water-coal drops.

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## Water-coal fuel preparation

Effectiveness of WCF combustion highly depends on the fuel spraying quality. Thus, more detailed study of the mechanisms of WCF drops pulverization and combustion is topical.

In [8] it is noted that the combustion of the water-coal fuel significantly differs from the similar process with powdered coal. The author states that the coal rank leaves the ignition temperature and combustion stability almost unaffected. But the results of the practical application of WCF show that when the WCF is produced from highly-metamorphosed hard coals with low content of volatile, the effective combustion of the sprayed fuel requires the sufficient residence time in the high-temperature area. In this context, we have adopted the following mechanism of WCF spraying with the compressed air or another spraying agent.

As is expected, during the WCF spraying, a poly-disperse flow forms; it contains both the pure coal particles free from the liquid phase owing to the high speed of their escape from the sprayer nozzle, and water-coal drops which contain fine coal particles surrounded by the liquid phase (water). Regarding the coal grain size in the WCF, the quantity of pure coal particles in the sprayed fuel flow may reach 25-30%, which undoubtedly influences the process of fuel ignition and following stable combustion.

Thus, the mechanisms of ignition and combustion of the poly-disperse flow of WCF drops should be considered with due regard to heat transfer and chemical reactions ocurring in liquid-coal drops and normal coal particles.

Spraying of the water-coal fuel with air or water steam consists of two stages. Within the first one, the WCF jet is atomized due to the kinetic energy of the spraying agent. At the second stage, when sprayed particles are accelerated, they are pulverized due to drag forces from the ambient gas medium which has the velocity much lower than the velocity of drops motion. Occurring dynamic action results in drop flattening and pulverizing, whereas the liquid phase with fine coal particles separates from the surface of large coal particles.

Let us consider the mechanism of WCF drops pulverization on the analogy of black-oil fuel [9].

The gas medium pressure $P_1$ on a drop moving in it depends on the action of the friction force $F_{mp}$ on the drop frontal area $S_k$:

$$P_1 = \frac{F_{mp}}{S_\kappa} \tag{1}$$

We neglect the gravity and consider the gas medium action alone, and have that the friction force is equal to:

$$F_{mp} = \psi\, S_\kappa\, \rho V_r^2 \tag{2}$$

where $\psi$ and $\rho$ are the drag coefficient and gas medium density, respectively, and $V_r$ is the relative velocity of the drop in respect to the gas medium.

When substituting eq. (2) in eq. (1), we have $P_1 = \psi \rho V_r^2$.

On the other hand, the pressure going on the drop due to the surface tension forces is:

$$P_2 = \frac{2\sigma}{r_\kappa}$$

where $\sigma$ is the surface tension factor and $r_k$ – the drop radius.

The drop is assumingly pulverized into smaller drops [10, 11] if:

$$P_1 > P_2 \tag{3}$$

In this case, the maximum drop size is reached when $P_1 = P_2$, *i. e.*

$$\psi \rho V_r^2 = \frac{2\sigma}{r_\kappa} \tag{4}$$

From (4) we have:

$$r_\kappa = \frac{2\sigma}{\psi \rho V_r^2} \tag{5}$$

As is seen from eq. (5), the WCF drop diameter highly depends on the surface tension, medium density, and relative velocity of the drop motion. As the temperature rises, when the liquid phase viscosity and the ambient velocity increase, the effectiveness of the liquid fuel spraying rises.

Figure 1 presents the calculation dependence of the diameter of sprayed WCF drops on their motion velocity at various $\sigma$ = 0.040-0.060 kg/s$^2$, $\psi$ = 0.2, and $\rho$ = 1.29 kg/m$^3$.

As is seen from fig. 1, the higher the relative motion velocity, the smaller the maximum diameter of the forming drops. Thus, as the velocity is above 60 m/s, which is realized in practice in industrial WCF sprayers, large coal particles break free from the surface humidity containing fine coal particles, and the maximum diameter of the forming water-coal drops does not exceed 80-100 μm.

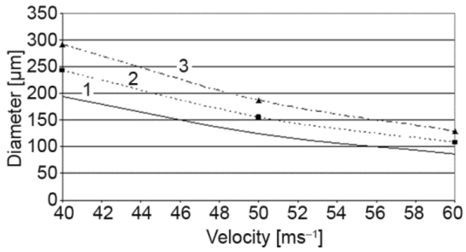


**Figure 1. Diameter of sprayed drops *vs.* their motion velocity (surface tension, *σ:* 1 – 0.040, 2 – 0.050, and 3 – 0.060 kg/s$^2$)**

Since the processes of liquid drops rupture and separation of liquid phase films from the coal particles with high-speed gas flows are comparable [11], it can be assumed that at the current velocity of sprayed fuel motion, no liquid film separated from the coal particles below 80-100 μm.

Hence we can state that the process of combustion of sprayed WCF drops is a combination of combustion of two model systems: coal particles with the diameter $d_k$ > 80-100 μm (drops-particles) and water-coal drops with the diameter $d_k \leq$ 80-100 μm.

## Test bench for WCF spraying

Experimental study of the water-coal fuel spraying with pneumatic sprayers was carried out on a specially fabricated test bench.

The test bench is purposed for "cold"-sprayers tests, estimation of WCF spraying quality, and for the determination of sprayers parameters (fuel flow velocity and pressure, compressed air flow velocity and pressure, dispersity and configuration of the spray cone).

WCF was sprayed onto a dasher with a tray (fig. 2).

The spray cone configuration was detected as follows: the cone was crossed with an aluminum plate at a certain distance from the sprayer; the spray quality was detected by the imprint on the plate.

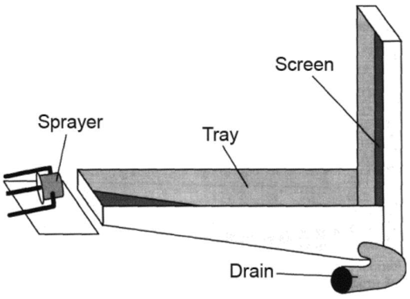


**Figure 2. Test bench for WCF spraying tests**

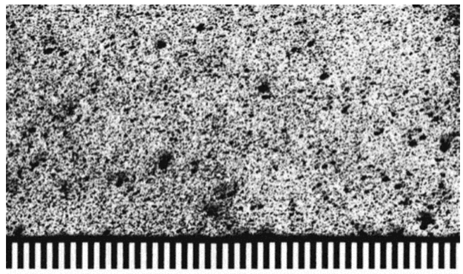

**Figure 3. Imprint of the sprayed WCF**

**Table 1. Distribution of drops (particles) in WCF**

| Drop (particle) diameter [μm] | Drops (particles) quantity [%] |
|---|---|
| > 355 | 4.7 |
| 250…355 | 7.2 |
| 160…250 | 11.9 |
| 71…160 | 23.1 |
| < 71 | 53.1 |

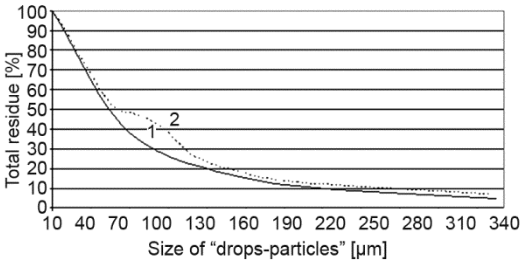


**Figure 4. Integral distribution of coal particles in the initial fuel, and coal-particles system in the sprayed fuel; 1 – size distribution of coal particles in the initial fuel, 2 – similar distribution of the sprayed solid particles and drops of WCF**

As an example, fig. 3 presents an imprint of the sprayed fuel (WCF properties: solid phase fraction is 57%, viscosity at the sliding velocity of 10 $s^{-1}$ is 0.6 Pa·s, particle size lie within 0…355 μm). The figure clearly shows the presence of large coal particles free from the liquid phase.

To analyze the results of WCF spraying, the imprint of the sprayed WCF was processed in the vector editor CorelDraw 9.0, the results are presented in tab. 1 and fig. 4.

The integral curve is based on particles quantitative distribution and drawn accumulated frequency.

As is evident from fig. 4, the integral size distribution of the WCF "drops-particles" has a "hump" within the range from 70 to 120 μm, which proves the considered mechanism of WCF drops pulverization during the spraying.

Hence, the mechanisms of ignition and combustion of the poly-disperse flow of WCF drops should be treated with due regard to the laws of heat and mass exchange and chemical reactions occurring in liquid-coal drops and normal coal particles.

## Experimental and calculation-theoretical investigation of WCF spraying and combustion

Low reactivity of WCF resulting from the presence of the liquid phase (water), increased (about the other liquid fuels) viscosity, as well as the rank of the coal used for the WCF – all these factors are governing in the choice of the effective technology of WCF combustion; this technology must guarantee the needed completeness of the fuel burn-off and minimal possible hazardous exhaust in off-gases. Taking these peculiarities into account, we chose the low-temperature vortex method of combustion (LTVMC) of the suspended coal fuel which was developed by Puzyrev E. M. [12], and realized in various designs of vortex furnace combustion chambers [13-15].

In order to simulate the WCF combustion by the vortex method, numerical investigations were performed.

The calculation was carried out with the aid of program module ANSYS FLUENT, which permits simulating combustion process with due regard to the turbulence, heat transfer, and chemical reactions. The packet GAMBIT, a geometrical and net pre-processing program for FLUENT, was used to design a computational grid in the chamber area.

The computation volume consists of the boiler chamber 1, sprayer 2, blow system 3, and pinch output hole 4 (fig. 5).

In the chamber area, there is a tetrahedral grid of 61,965 cells.

The flow is described by the system of stationary 3-D Navier-Stokes equations, Reynolds-averaged mass and energy conservation equations. Turbulent viscosity is calculated with the aid of a two-parametrical $k$-$\varepsilon$ model. Radiation heat transfer in the two-phase flow is presented in the context of $P_1$ approximation of the spherical harmonics method. The vortex breakdown model (eddy-dissipation model) is utilized as a model of burning of sprayed WCF drops. Thermophysical properties of air are calculated by the polynomial dependence on the temperature. The parameters of WCF drops injection in the chamber are assigned with the "discrete phase model".

The data in tab. 2 were taken as initial parameters.

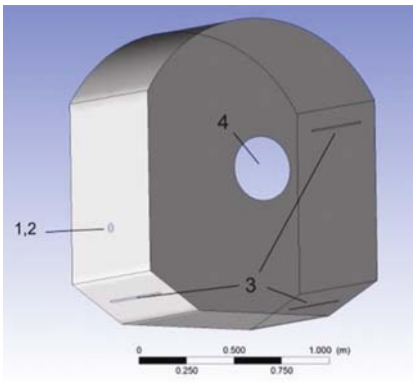


**Figure 5. Geometry of the simulated area**

**Table 2. Initial parameters for the calculation of WCF combustion**

| Parameter | Measurement unit | Value |
|---|---|---|
| Flow rate of WCF through the sprayer | kgh$^{-1}$ | 67 |
| Mass share of solid phase | % | 63 |
| Ash content of coal in WCF | % | 32 |
| Viscosity at the sliding speed of 81 s$^{-1}$ | mPa·s | 1,000 |
| Particle size | μm | 10-160 |
| Velocity of fuel particles | ms$^{-1}$ | 145.6 |

## Calculation results

Figure 6 shows the maximum residence time of "drops" and water-coal drops in the vortex furnace.

The residence time of the burning particles and WCF drops in the vortex furnace is proportional to their diameter, which permits providing their effective burn-off.

Figures 7-10 show the calculation results, respectively: temperature fields, mass rate of liquid phase evaporation in a WCF drop, mass rate of volatile release from the solid phase in a WCF drop, and mass rate of carbon burn-off from the solid phase of a WCF drop.

As is evident from the figures, the escape of the volatile components (fig. 8) starts at the moment of the end of evaporation of the liquid phase of the fuel (fig. 7), which is attended with the temperature increase (fig. 6). At the same time, the process of combustion of the bound carbon in the WCF drop starts, too (fig. 9).

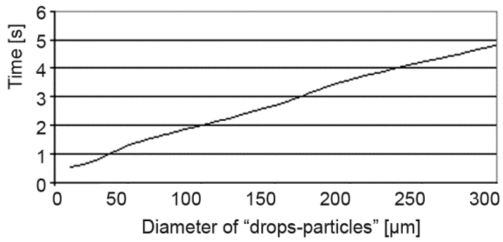


**Figure 6. Maximum residence time of "drops" and water-coal drops in the combustion chamber**

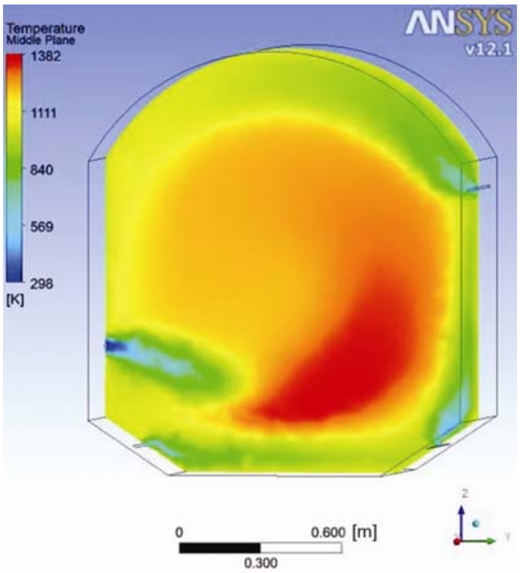


**Figure 7. Temperature field in the sprayer plane**

Figures 6 and 7 show the compared variations in the temperature and volatile content in a coal particle and WCF drop *vs.* the particle and drop path length, respectively.

Analysis of the data presented in fig. 11 reveals that, opposite to the smooth rise of the coal particle temperature (particle 1) during its motion, the temperature of a WCF drop (particle 2), upon its temperature rises up to liquid phase evaporation, remains constant within the whole evaporation process. Then, the solid phase of the WCF drop starts to combust releasing the heat, and dramatic temperature rise is observed.

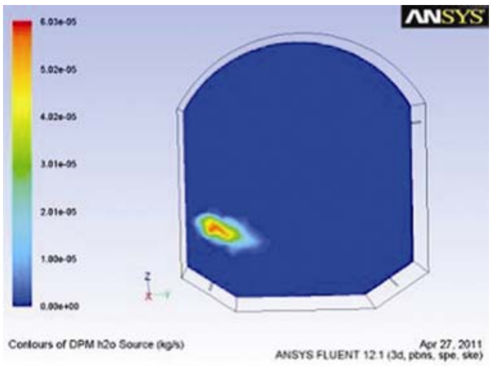


**Figure 8. Mass rate of liquid phase evaporation in a WCF drop, lengthwise cross section of the chamber**

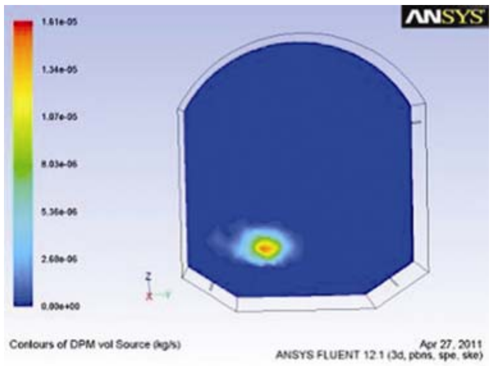


**Figure 9. Mass rate of volatile release from the solid phase in a WCF drop in the lengthwise cross section of the chamber**

As is seen from fig. 12, the volatile content for the coal particle (particle 1) remains constant at the beginning of the process; it decreases only as the particle is heated up to the temperature of the volatile components release. In the WCF drops (particle 2), the volatile components concentration rises due to water evaporation. In the evaporation process, the temperature of the WCF drop solid phase rises, and the volatile content reaches the value similar to that one in the solid coal particle. The process remains stable within the time much shorter because of the increasing temperature of the WCF drop solid phase during water evaporation.

**Table 3. Comparison of numerical simulation and experimental researches**

| Data description | The data obtained in | |
|---|---|---|
| | Numerical simulation | Experiment |
| Thermal power | 247 kW | 258 kW |
| CO output | 101 mg/m$^3$ | 116 mg/m$^3$ |
| $NO_x$ output | 412 mg/m$^3$ | 419 mg/m$^3$ |
| Combustible loss | 7% | 5% |

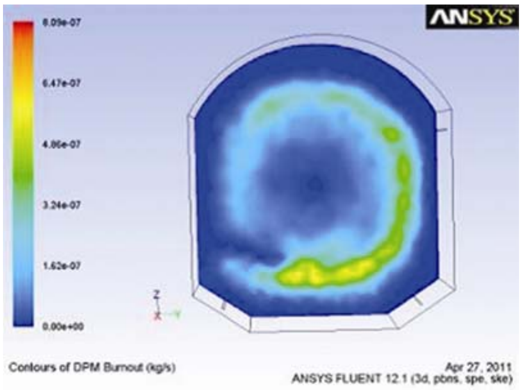


**Figure 10. Mass rate of carbon burn-off from the solid phase of a WCF drop in the lengthwise cross section of the chamber**

## Discussion of investigation results

It is worth noting that the simulation results are in good agreement with the experimental combustion of the test lots of WCF prepared in the demonstration test bench of SPC „Sibekotekhnika“ from coals of various ranks and ash content [16].

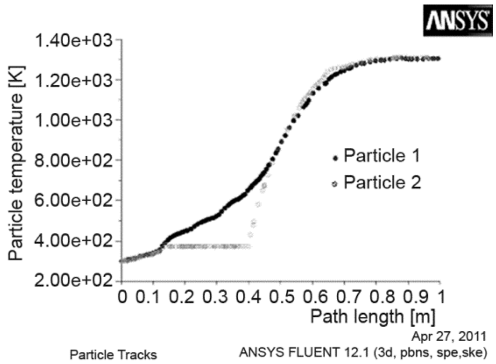


**Figure 11. Comparison of the coal particle temperature variation (particle 1) and WCF drop (particle 2) *vs.* the path length and drop**

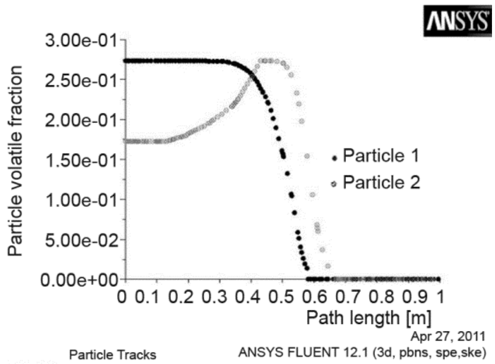


**Figure 12. Comparison of the variation of volatile content in the coal particle (particle 1) and WCF drop (particle 2) *vs.* the path length and drop**

Table 4 presents the results of combustion of test lots of WCF prepared from various coals which prove the effect of the volatile release on the fuel combustion parameters.

**Table 4. Results of combustion of test lots of WCF**

| Kind of water-coal fuel | | Temperature in furnace | | Time of onset of stable independent combustion, [min] |
|---|---|---|---|---|
| | | Ignition | Stable independent combustion | |
| Coal rank D, G | | 450-500 °C | 800-850 °C | 25-30 |
| Coal slime, rank CC | Ash content 22% | 600-650 °C | 850-900 °C | 35-37 |
| | Ash content 36% | 600-650 °C | 850-900 °C | 40-45 |
| Anthracite, rank A | | 750-850 °C | 950-1070 °C | 50-56 |

Analysis of the data presented in tab. 4 shows that the ignition temperature and time of onset of the stable combustion regime of various WCF depend on the coal rank and coal ash content, which also vindicates the performed theoretical investigations.

Hence, computer simulation of the fuel combustion process enables to determine the optimum regimes of WCF combustion and to increase design accuracy of new furnaces, or to improve the design of available ones. Finally, the total cost of the work will be lowered due to the exclusion of expensive experiments.

## Conclusions

Consideration of the mechanisms of spraying and combustion of the suspended coal fuel permits explaining the difference between the ignition and stable combustion of the WCF prepared from coals of different metamorphism stages.

The results of numerical simulation of the WCF combustion process have vindicated the effect of delay of the temperature increase in a drop and particle regarding their path lengths, as well as the influence of the volatile components on the temperature increase velocity in the furnace.

Experimental findings and data of the experimental and industrial tests of the combustion of test lots of the WCF from different coals have also vindicated the results of analytical and numerical calculations.

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