# Numerical simulation of co-combustion of diesel and pulverized coal fuel in a small-sized furnace

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**Abstract.** The article is devoted to numerical simulation of diesel and pulverized coal flaring in a small-sized furnace with a vortex oil-steam burner. The results of modeling a small-sized combustion chamber with a steam-oil burner operating in combination with diesel fuel and micro-milled coal are presented. The simulation results showed that the combustion chamber with a steam-oil burner works stably in a wide range of coal dust flow rates. The obtained results of a numerical study can be used in the design of a new burner and furnace device, choosing the optimal operating modes to reduce the concentration of harmful emissions and fuel underburning at the output.

## 1 Introduction

The work is devoted to numerical modeling of the co-combustion of diesel and pulverized coal in a small-sized furnace. Partial replacement of diesel fuel with pulverized coal makes it possible to make the operation of small power plants economically viable, which is especially important for power supply to remote areas for which there is a problem of diesel fuel delivery.

The combustion of pulverized coal fuel is organized in large power units, which is justified by the need for a sufficiently long residence time of coal particles in the furnace volume. In small furnaces, coal dust does not have time to go through all the phases associated with coal combustion: heating of particles; yield of moisture and volatile components; burnout of coke residue.

At the Kutateladze Institute of Thermophysics of the Siberian Branch of the Russian Academy of Sciences, a number of technologies has been developed that make it possible to create special burners for flaring pulverized coal. Firstly, it is a technology for preparing micro-milled coal in disintegrator mills. With this technology, the characteristic size of coal particles is tens of micrometers, and coal particles undergo additional mechanical activation, which affects the efficiency of their combustion [1]. Secondly, this is the technology of spray intensification and combustion of liquid fuels [2] using a high-velocity jet of superheated steam for spraying. With this method of burning liquid fuels, the ignition zone is sharply reduced due to intensive evaporation and mixing of the fuel with the oxidizer. The introduction of micro-milled coal particles into the high-temperature liquid fuel combustion zone (~1600°C) promotes the intensive flow of all processes in the coal particle and a sharp reduction in its burnout time. The papers [3] and [4] present the results of numerical simulation, respectively, for the combustion of micro-milled coal and a steam-and-gas burner.

## 2 Mathematical model

In the proposed work, a mathematical model of a device for the joint flaring of diesel and pulverized coal is proposed, which includes a set of interrelated physical and chemical models that describe the turbulent movement of gas and particles (drops of liquid fuel and coal particles), the transfer of radiant energy, the processes of evaporation and combustion of liquid fuel, drying, gasification and burning of coal particles.

In this work, the RANS approach is used to model turbulence. The k-ω SST was used as a model [5]. This model is well known; it is tested for a large number of turbulent combustion problems [6-8] and is considered the most universal of their two-parameter models. The motion of diesel fuel droplets and coal particles was described by the equations of the dynamics of a material point, taking into account the drag force and gravity. Accounting for flow turbulence during particle motion was carried out by introducing random fluctuations of the gas velocity into the equation of motion for particles. The method of discrete ordinates was used to solve the heat radiation transfer equation. The absorption coefficients of the gas were calculated using the model of the sum of gray gases.

The calculation of the combustion of gaseous components was based on the EDC model [9], which makes it possible to use detailed chemical mechanisms in turbulent reacting flows.

Diesel fuel is a complex mixture of hydrocarbons. The uncertainty of the composition of diesel fuel makes it difficult to describe it in detail. Therefore, in this work, diesel fuel was presented in the form of n-heptane

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($C_7H_{16}$). To describe chemical reactions, we used a reduced mechanism with 60 reactions and 35 components developed at the Research Center (ERC) of the University of Wisconsin [10].

The combustion process of a coal particle was considered in the form of the following successive stages [11–14]: the evaporation of moisture from the fuel, the release and combustion of volatile components, and the combustion of coke residue. The reaction rate of the coke residue was calculated according to the provisions of the classical diffusion-kinetic theory:

$$\frac{dm_p}{dt} = -A_p \frac{\rho_p R T_g Y}{M} \frac{k_d k_b}{k_d + k_b},$$

where Y is the mass fraction of the oxidizing agent, M is the molar mass of the oxidizing agent, $k_d$ is the rate constant of diffusion of the reactant gas to the surface of the particle, $k_b$ is the rate constant of the chemical reaction. The rate constant of diffusion of the reagent gas to the surface of the particle was determined:

$$k_d = D_0 \frac{\left[\left(T_p + T_g\right)/2\right]^{0.75}}{d_p},$$

where $D_0$ is the diffusion coefficient of the reactive gas at normal temperature and pressure.

The Arrhenius equation was used to find the rate constant of a chemical heterogeneous reaction:

$$k_b = k_{b0} T^b e^{(E_b/RT_p)},$$

where $k_{b,0}$ is the pre-exponential factor of the carbon burnout reaction, $E_b$ is the activation energy of the carbon burnout reaction.

To describe the reaction processes of solid carbon, the mathematical model includes the reactions of oxidation and steam-air conversion of coal. Reactions and values of kinetic constants are presented in table 1.

**Table 1.** Kinetic constants of heterogeneous reactions.

| Reactions | $k_{b,0}$, kg/ (m$^2$ s Pa) | $E_b$, J/ kmol | β | Degree of components γ |
|---|---|---|---|---|
| $C+0.5O_2 \rightarrow CO$ | 2.3 | $9.23 \cdot 10^7$ | 1 | $[O_2]^{0.4}$ |
| $C+CO_2 \rightarrow 2CO$ | 4.4 | $1.62 \cdot 10^8$ | 1 | $[CO_2]^{0.6}$ |
| $C+H_2O \rightarrow CO+H_2$ | 1.33 | $1.47 \cdot 10^8$ | 1 | $[H_2O]^{0.6}$ |

To describe the process of atomization of liquid hydrocarbon fuel by a steam jet (the speed of which can reach the speed of sound), the following approximation was proposed: the diesel fuel supplied to the furnace is represented by a discrete set of droplets ranging in size from 5 µm to 100 µm. The opening angle of the drop jet was chosen to be 55 degrees, the drop velocity was 30 m/s, and the flow direction corresponded to the direction of the steam jet. Micro-milled coal fuel is represented by a discrete set of particles ranging in size from 10 µm to 50 µm Fig. 1.

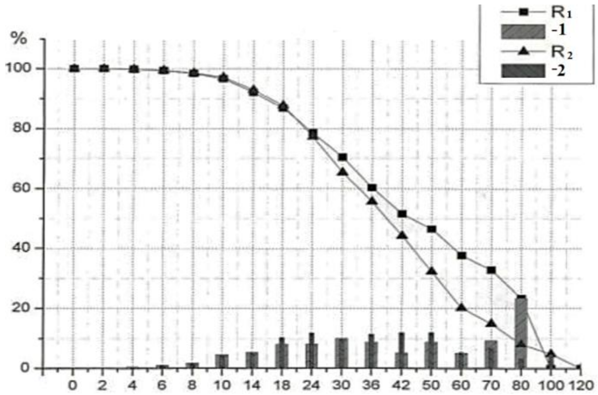


**Fig. 1.** Size spectrum of coal particles (lines) and residue on sieves (columns) after grinding in vibro-centrifugal (1) and disintegrator (2) type mills [1].

Characteristics of coal fuel are given in table 2.

**Table 2.** Characteristics of coal fuel.

| Coal | W % | A % | S % | C % | H % | N % | O % | $Q_r$ MJ |
|---|---|---|---|---|---|---|---|---|
| Kuznetskiy | 12,5 | 13,2 | 0,3 | 58,7 | 4,2 | 1,9 | 9,7 | 22,9 |

As part of the work using the Ansys Fluent CFD package, an adaptation of a complex mathematical model of the process of co-combustion of liquid hydrocarbon fuel and pulverized coal in a steam-oil burner was implemented and based on the experimental data.

Fig. 2 and 3 show, respectively, the schematic diagram of the simulated tangential burner device and the used computational grid.

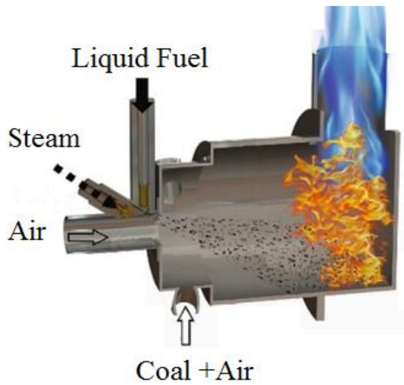


**Fig. 2.** The burner principal scheme.

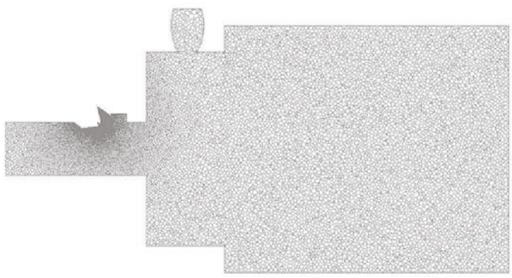

**Fig. 3.** Calculation grid of the burner in cross-section.

The papers [15, 16] present the results of comparing the data obtained by calculation and in an experiment performed at the Institute of Thermal Physics of the

Siberian Branch of the Russian Academy of Sciences when burning diesel fuel [15] and a mixture of diesel fuel and coal [16]. It is shown that the calculation model reproduces the experiment well, both in terms of temperature and gas composition (Fig. 4).

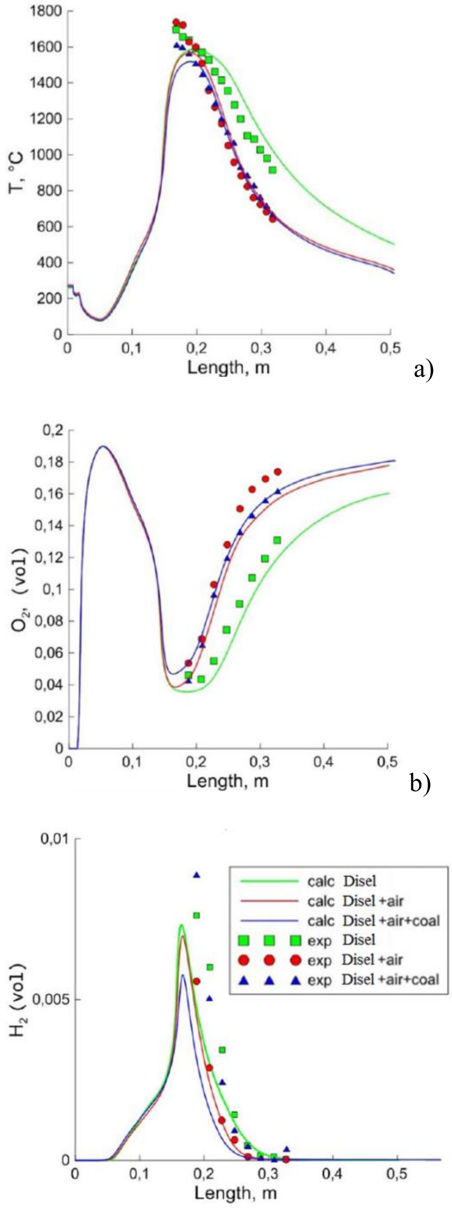


**Fig. 4.** Distribution of parameters on the burner axis: a) temperature, C; b) $O_2$ concentration, $m^3/m^3$; c) $H_2$ concentration, $m^3/m^3$.

## 3 Results

In this article, based on the presented model, options for the co-combustion of diesel and coal fuel in a small-sized combustion chamber with a tangential burner are considered. The combustion chamber is a cylinder with a diameter of 300 mm and a length of 500 mm, in the center of one end side there is a burner, and on the other side there is a chimney. The side of the furnace is cooled with water. Air is supplied to the burner from the end through a nozzle (Fig. 2), steam is supplied in a high-velocity jet, which atomizes diesel fuel. Further, coal fuel and air are tangentially introduced through the nozzles.

Computational studies of the processes in a tangential burner and a small-sized combustion chamber at different coal loads are carried out. Diesel fuel consumption for all options was set the same. 5 options were studied with different combinations of fuel consumption - diesel/pulverized coal in the range of 0.6/0.0 to 0.6/0.6 kg/h. The air flow rate was chosen based on the conditions for optimal combustion of diesel fuel - an excess of 1.05, coal fuel - 1.2. Table 3 shows the consumption characteristics of the studied options.

**Table 3.** Consumable characteristics.

| | | Options, consumption, g/h | | | | |
|---|---|---|---|---|---|---|
| | T,°C | 1 | 2 | 3 | 4 | 5 |
| Diesel | 30 | 600 | 600 | 600 | 600 | 600 |
| Steam | 400 | 500 | 500 | 500 | 500 | 500 |
| Coal | 20 | 0 | 150 | 300 | 450 | 600 |
| Air with diesel | 20 | 7920 | 7920 | 7920 | 7920 | 7920 |
| Air into the nozzle | 20 | 500 | 500 | 500 | 500 | 500 |
| Air with coal | 20 | 0 | 980 | 1940 | 2960 | 3980 |

Fig. 5 and 6 show calculated patterns of temperature and velocity distribution in the burner and combustion chamber.

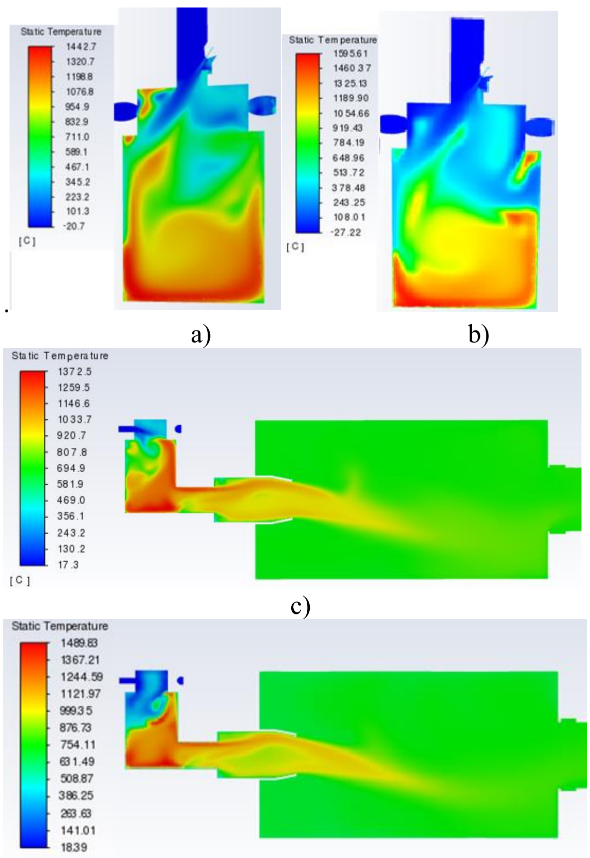


**Fig. 5.** Temperature distribution:in the center of the burner - a), b);in the furnace c),d) when burning diesel - 1.2 kg/h and micro-milled coal. a),c) - 0.15 kg/h, b),d) - 0.6 kg/h.

It can be seen from the figures that a high-speed steam jet intensively atomizes and mixes diesel fuel, which mainly burns in the burner volume, heating and igniting the micro-grinded coal fuel. Coal fuel actively burns out at the burner outlet and at the inlet to the combustion chamber.

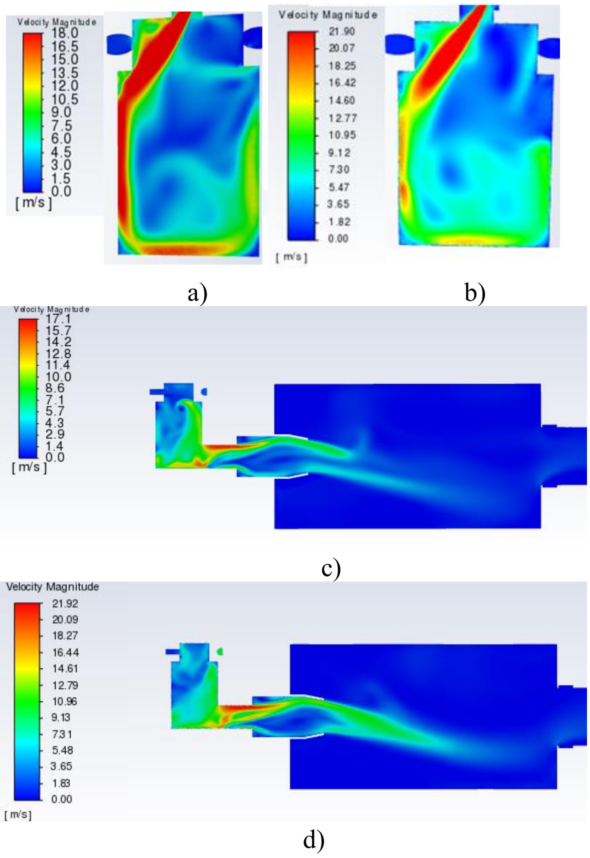


**Fig. 6.** Velocity magnitude: in the center of the burner -a), b); in the furnace c), d) when burning diesel - 1.2 kg/h and micro-milled coal. a), c) - 0.15 kg/h, b),d) - 0.6 kg/h.

In the considered regime options, stable flame combustion and a relatively low, less than 5%, underburning of coal fuel are observed, which allows us to proceed to experimental and laboratory confirmation of such a combustion scheme and, in the future, to the design of specialized burner-furnace devices.

## 4 Conclusions

On the basis of the tested model of co-combustion of micromilled diesel and coal fuel, a computational study of the processes in a steam-oil burner and a small-sized combustion device was carried out. It is shown that the proposed combustion scheme allows combustion of diesel fuel/coal mixtures up to a ratio of 1/1 kg/kg. In this case, stable combustion and good burnout of coal dust are observed. The simulation carried out allows us to proceed to the design of a pilot plant.

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## References

1. A.P. Burdukov, V.I. Popov, V.A. Faleev, T.S. Yusupov. The use of mechanically activated micro-milled carbons in the energy sector. Polzunovskiy Bulletin, No. 1, 93 (2010) (in Russian)
2. E.P. Kopiev, I.S. Anufriev, E.Yu. Shadrin, E.L. Loboda, M.V. Agafontsev, M.A. Mukhina. Study of the characteristics of the flame of a burner device when spraying liquid hydrocarbons with a steam jet // Reports of the Academy of Sciences of the Higher School of the Russian Federation, No. 2 (43), 38 (2019) (in Russian)
3. A.P. Burdukov, O.L. Magdeeva, V.A. Kuznetsov, M.Yu. Chernetsky. Computational study of a 2-stage oil-free burner device based on micro-milled coal. Polzunovskiy Bulletin, **1**(4), 162 (2015) (in Russian)
4. A.V. Minakov, V.A. Kuznetsov, A.A. Dekterev, I.S. Anufriev, E.P. Kopyev, S.V. Alekseenko. Comparative analysis of numerical methods for simulating n-heptane combustion with steam additive. Energies **16**(1), 25 (2023)
5. F. Menter. *Zonal two equation k-w turbulence models for aerodynamic flows*, in 23rd Fluid dynamics, plasmadynamics, and lasers conference. Reston Virigina: AIAA, p. 2906 (1993)
6. A.A. Dekterev, A.A. Dekterev, A.V. Minakov. Comparative study of different combustion models for turbulent gas flames. J. Phys. Conf. Ser. **754**, 062002 (2016)
7. A.S. Lobasov, A.A. Dekterev, A.V. Minakov. Numerical simulation of premixed methane/air and synthesis gas/air flames for turbulence swirling jet. J. Phys. Conf. Ser. **1382**, 012060 (2019)
8. V.M. Dulin, D.M. Markovich, A.V. Minakov, K. Hanjalic, L.M. Chikishev. Experimental and numerical simulation for swirl flow in a combustor. Therm Eng **60**, 13 (2013)
9. B. Magnussen On the structure of turbulence and a generalized eddy dissipation concept for chemical reaction in turbulent flow. Reston, Virigina: AIAA (1981) https://doi.org/10.2514/6.1981–42 .
10. A. Patel, S.C. Kong, R.D. Reitz. Development and validation of a reduced reaction mechanism for HCCI engine simulations. SAE Tech. Pap., SAE International (2004). 10.4271/2004–01–0558
11. A. Gavrilov, A. Dekterev, M. Chernetsky. *Simulation of coal combustion in a pulverized coal-fired boiler*, in Proceedings of CHT‑08 ICHMT Intern. Symposium on Advances in Computational Heat Transfer, 11-16 May 2008, Marrakesh, Morocco, **1** (2008)
12. M.Y. Chernetskii, A.A. Dekterev. Mathematical model for heat transfer and combustion in a pulverized coal flame. Combust Explosion Shock Waves **47**, 280 (2011)
13. A.A. Dekterev, A.A. Gavrilov, M.Yu. Chernetsky, N.S. Surzhikova. Mathematical model of

aerodynamics and heat transfer processes in pulverized coal combustion devices. Thermal processes in engineering **3**(3), 140 (2011) (in Russian)

14. M. Chernetskiy, A. Dekterev, N. Chernetskaya, K. Hanjalić. Effects of reburning mechanically-activated micronized coal on reduction of NOx: Computational study of a real-scale tangentially-fired boiler. Fuel. **214**, 215 (2018)
15. A.V. Minakov, V.A. Kuznetsov, I.S. Anufriev, E.P. Kopyev Numerical analysis of a pre-chamber vortex burner with a steam blast atomizer. Fuel **323**, 124375 (2022)
16. E.S. Tepfer, A.A. Dekterev, V.A. Kuznetsov, Ar.A. Dekterev, E.Yu. Shadrina Numerical simulation of flare burning of coal of a micro-mill in a steam-oil burner. Journal of Siberian Federal University. Engineering & Technologies **16** (4), 462 (2023) (in Russian)