UDC 662.93
DOI: 10.15587/1729-4061.2020.209762

ON USING THE ANSYS FLUENT SOFTWARE FOR CALCULATING THE PROCESS OF BURNING A MIXTURE OF PARTICLES FROM DIFFERENT TYPES OF SOLID FUELS

M. Nekhamin
PhD*
E-mail: nmark@i.ua
I. Beztsennyi
PhD*
E-mail: coalenergy@i.ua
N. Dunayevska
Doctor of Technical Sciences, Senior Researcher*
E-mail: dunayevskani@ukr.net
V. Vyfatnuik
Engineer
Department of atomic station and heat physics
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
Peremohy ave., 37, Kyiv, Ukraine, 03056
E-mail: vefatnuk@kbenergo.com.ua
*Department of Energy Technology Use of Solid Fuels
Coal Energy Technology Institute of the National Academy of Sciences of Ukraine
Andriyivska str., 19, Kyiv, Ukraine, 04070

The use of binary mixtures in TPP steam generators as fuels is caused by various reasons, such as improvement of ignition conditions and the possible environmental benefits of burning binary mixtures. Since the existing boilers of TPP were calculated for burning a single type of solid fuel, the relevance of numerical modeling of the combustion processes of binary mixtures is obvious. Among the software widely used to estimate the operation of energy devices is the ANSYS FLUENT program, whose specification does not include the procedure for using it in order to simulate the combustion of solid-fuel mixtures.

To apply the software for this purpose, in the first approach, the mixture of solid fuels is replaced by one fuel with averaged characteristics. Such a model is approximate because it is impossible to reproduce the interaction among the components of the mixture. The second approach makes use of the ANSYS FLUENT software's feature to take into consideration additional (liquid or gas) fuel to replace it by the second solid fuel.

The application of these approaches to the description of the combustion process of anthracite and gas coal mixtures in different ratios and with different particle sizes has shown the proximity of parameters in the furnace. At the same time, the use of a second approach demonstrated the effect exerted by a bituminous coal additive on the fields of anthracite burning intensity, consistent with the known fact of intensification of the combustion process of a less active component of the mixture with the addition of a more active one.

To test the simulation in line with a second approach, the processes in the furnace of the TPP-210A boiler were calculated in three-dimensional approximation when replacing the lean coal with a mixture of bituminous coal and anthracite. The proximity of the resulting parameters is consistent with the known test data and confirms the sufficient correctness of the simulation of the combustion of the mixture of coals

Keywords: Ansys Fluent, CFD modeling, solid fuel, combustion, blend, bituminous coal, lean coal, anthracite

Received date 10.06.2020
Accepted date 24.07.2020
Published date 31.08.2020

1. Introduction

Coal is one of the most important primary energy sources in the generation of heat and electricity. In recent years, there has been a growing interest in the processes of co-combustion in the furnaces of pulverized coal boilers of mixtures of various solid fuels. As numerous studies show, the combustion of such mixtures is difficult to predict due to the multifactorial interaction between the two fuels. It is possible to take into consideration the mutual influence of two solid fuels when they are burned together only by CFD modeling.

2. Literature review and problem statement

There are reported calculations of the processes of co-burning of different types of solid fuels, mainly coal with biomass, by using various software: CFX [1], AVL Fire [2, 3], as well as programs by the authors of works [4–6]. The use of the ANSYS FLUENT software is widespread [7–9]. The technology for the use of dried biomass is explored in [7]; it is shown that this could significantly increase the share of biomass in the fuel. The emphasis of [8] is on the difficulty of reflecting the biomass burning kinetics in the model and the feasibility of accounting for the effect of the shape and size of its particles on the combustion process. The authors of [9] draw attention to the potential of the co-burning of coal with lightweight biomass (with a density of about 150 kg/m^3).

However, the authors of papers [7–9] did not consider it necessary to address the issue of assigning the composition and properties of the two solid fuels. This process is difficult to recognize as obvious as the documentation for the software, while indicating the applicability of liquid or gas fuel additionally to solid fuel, misses the possibility of using a second solid fuel.

3. The aim and objectives of the study

The aim of this study is to develop ways to use the ANSYS FLUENT software to simulate the combustion process of solid fuel mixtures.

To accomplish the aim, the following tasks have been set:

– to formulate approaches to modeling the combustion process of the mixture;

– to perform calculations and compare the results of these approaches;

– to simulate the combustion process of coal mixture in an industrial boiler and evaluate the results of modeling.

4. Approaches to modeling the combustion of mixtures in the ANSYS FLUENT software

The Discrete Phase model used in ANSYS FLUENT makes it possible to introduce to the estimated area dust of several coals with different types, consumption, particle distributions by size, the technical and elemental analysis data, and combustion heat. In this case, the combustion process is described by the non-Premixed Combustion model, in which the thermochemical interaction between fuel and oxidizer is formed by a mixture fraction parameter in one of two possible modifications – a single mixture fraction, or two mixture fractions. Simulation of particulate combustion is possible using any of these modifications.

However, the second one operates two different compositions – primary (for coal, coke), and secondary (volatile substances), while the single mixture fraction modification the only composition describes a mixture of coke and volatile substances. The single mixture fraction model is considered less accurate but has the advantage that the second of two possible mixture fractions (secondary) remains untapped. Therefore, it can be used if necessary (as indicated in the software documentation) to assign the composition of a second gaseous or liquid fuel. As regards its applicability for assigning the composition of a second type of solid fuel, the ANSYS FLUENT documentation keeps silent. Because the dependence of a mixture fraction parameter on coal characteristics prior to the start of the main simulation is estimated and tabulated in a separate file (the so-called PDF file), this file typically fails to match the parameters of a mixture of two different coals.

An obvious, though clearly approximate, approach to resolving this issue is to use the weighted average composition and properties of the coal mixture. In this case, when calculating the PDF file, corresponding to the mixture of two coals in the required mass ratio, data on the technical analysis are assigned, as well as the elemental composition and combustion heat, as the weighted average, taking into consideration the mass fractions of components in the coal mixture. Thus, the mixture of different coals is replaced by one coal with average characteristics.

Another approach is possible under the assumption that the secondary mixture fraction can be used to set the composition of not only liquid or gaseous fuel but also a second brand of solid fuel (technically, the software allows such a task). In this case, one can expect a more correct description of the processes in the furnace. This approach hereafter is referred to as a more accurate one or a simulation of the burning of a “real mixture.”

This paper examines, in a two-dimensional approximation, the combustion process of a coal mixture in a rectangular estimated region: the inlet of air and pulverized coal on the left, the outlet on the right, a horizontal wall from above, and the plane of symmetry from below. The height is 0.5 m, the length of the flow is 6 m, the size in the third direction is considered by default to equal 1 m. Solid fuel consumption in all estimated variants corresponds to the thermal power of 200 kW, the air parameters at a temperature of 573 K are selected from the condition that at the inlet the excess oxidizer factor is 1.2. The contribution of radiation is determined by the *P*-1 model, the degree of blackness of particles is accepted equal to 0.8. To reduce the effect of the wall on the flow parameters (as it is a secondary factor in the plan of the problem under consideration), the wall is set adiabatic with a zero blackness degree. The aerodynamic structure of the gas phase is described by the k-epsilon model. The burning of anthracite, bituminous coal, as well as their mixtures, with different ratios on thermal power, at the same (but varied) size of particles, is considered.

The elemental composition per dry ash-free basis (DAF), as received basis, as well as the heat of combustion of the coals considered, are given in Table 1.

The ANSYS FLUENT software makes it possible to take into consideration the difference in the total amount of volatile matter in fuel (accounting for the high-temperature output of volatile matter, exceeding by *K* times the value of a standard analysis). It is accepted that, for anthracite, *K*=2.4, for bituminous coal, *K*=1 [10]. The kinetic coal constants for use in the software are determined by comparing particle combustion rates in line with models reported in [11, 12].

Table 1

Coal characteristics

Fuel	*C*	*H*	*O*	*N*	*S*	V^r	A^r	W^r	Q_i^r, MJ/kg
Anthracite	0.930	0.017	0.019	0.009	0.015	0.024	0.229	0.01	25.02
Bituminous coal	0.800	0.055	0.085	0.014	0.046	0.276	0.230	0.01	24.24

5. Results of modeling the combustion of a mixture of solid fuels

First, let us analyze the results of using a first approach. The gas-phase temperature fields in the estimated region, at a particle size of 120 µm, for different compositions of the mixture are shown in Fig. 1. There has been a marked shift in the maximum temperature region against the flow and its decrease with an increase in the share of bituminous coal. This indicates an earlier ignition of bituminous coal particles due to its greater, relative to anthracite, reactive capacity [13].

Since this approach actually reproduces the behavior of one coal, the results derived cannot claim to reflect the processes associated with the reciprocal influence of the components of the mixture, an important aspect of the use of mixtures. One can expect this only from the results of modeling using a second approach, a “real mixture”, which we turn to.

The temperature fields in the estimated region at different compositions of the mixture for particles measuring 120 µm are shown in Fig. 2. In the presence of quantitative differences, there are similarities with the results from the first approach.

The quantitative effect of a bituminous coal additive on maximum temperatures according to Fig. 2 are shown in Fig. 3. There is also a tendency to reduce the maximum temperature as the particle size increases.

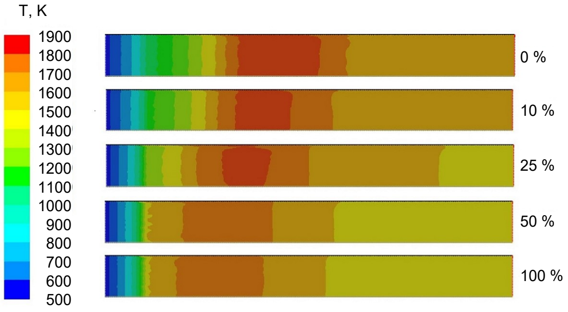


Fig. 1. Gas-phase temperature fields at a particle size of 120 μm based on the results of simulating the mixture considering it coal with average characteristics (the proportion of bituminous coal in the mixture is shown on the right)

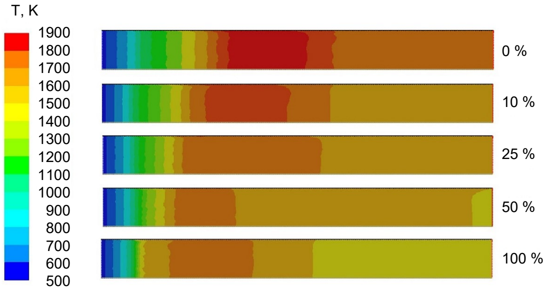


Fig. 2. Gas-phase temperature fields at a particle size of 120 μm according to the simulation of the "real mixture" for the different compositions of the mixture (on the right are the proportions of bituminous coal)

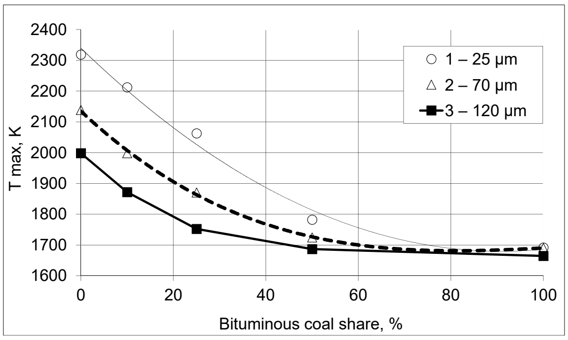


Fig. 3. Maximum temperatures in the calculated region, depending on the composition of the mixture at different particle sizes

The character of the distributions of the rate of mixture burnout manifests that it is determined by the imposition of combustion parameters of two processes, often mismatched in space, – the burning of anthracite and bituminous coal. This is explained in Fig. 4 that shows the combustion rate of the mixture and its components using an example of one of the modes. In those regions of the flow where bituminous coal does not burn (at distances from the inlet $x<0.1$ m and $x>0.53$ m), the rate of combustion of the mixture is the same as that of anthracite. At $x=0.1...0.53$, when both coals burn, the rate of combustion of the mixture is greater than each of the components of the mixture and is close to their sum.

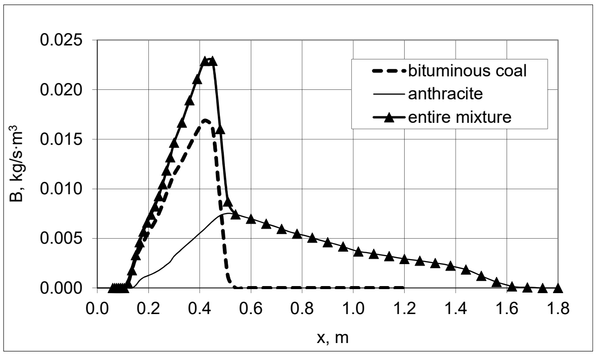
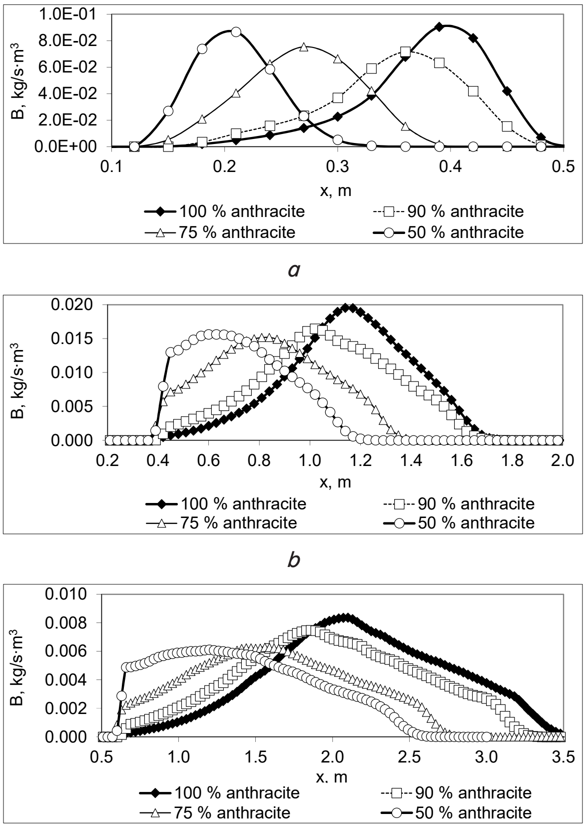


Fig. 4. The distribution of the burnout intensity of anthracite coke, bituminous coal, and the entire mixture with 50 % of bituminous coal at a particle size of 70 μm along the length of the flow

In general, the effect of the composition of the mixture and the size of the particles on the distribution of burnout intensity of the components of the mixture along the length of the flow is illustrated in Fig. 5, 6. There is a tendency to increase the maximum intensity of burnout of the components of the mixture with the growth of their share in the mixture composition. At the same time, the localization of the maximum burnout intensity for anthracite shifts along the flow, and for bituminous coal – against the flow. Increasing the size of particles leads to a decrease in the magnitude of these maxima.

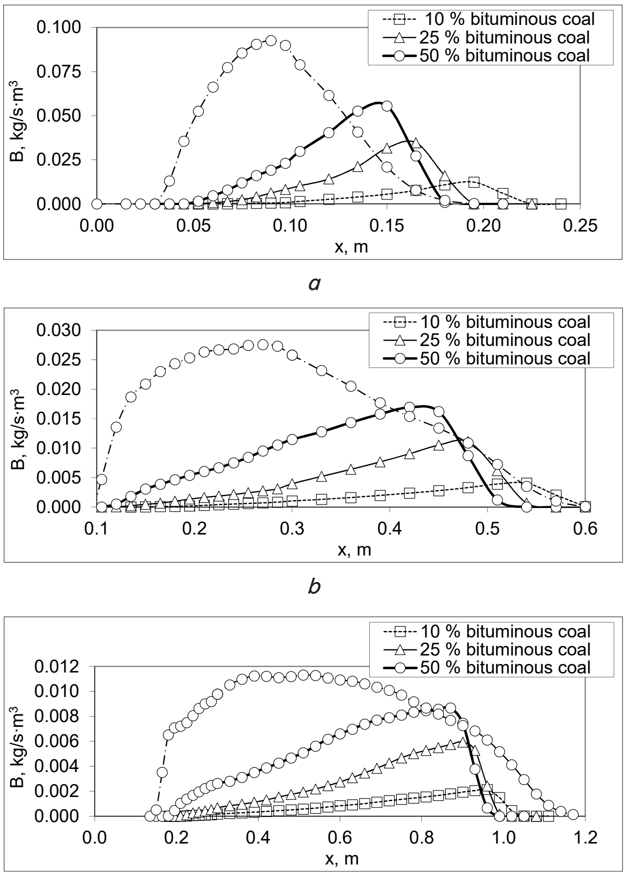


a

b

c

Fig. 5. The distribution of the burnout intensity of anthracite in the mixture at its specified compositions and a particle size of *a* – 25 μm; *b* – 70 μm; *c* – 120 μm, along the length of the flow



a

b

c

Fig. 6. The distribution of the burnout intensity of bituminous coal in the mixture at its specified compositions and a particle size of *a* — 25 μm; *b* — 70 μm; *c* — 120 μm, along the length of the flow

Fig. 7 shows an example of the reciprocal arrangement of the regions of volatile substance discharge and the burnout of coke in the mixture of the coals examined.

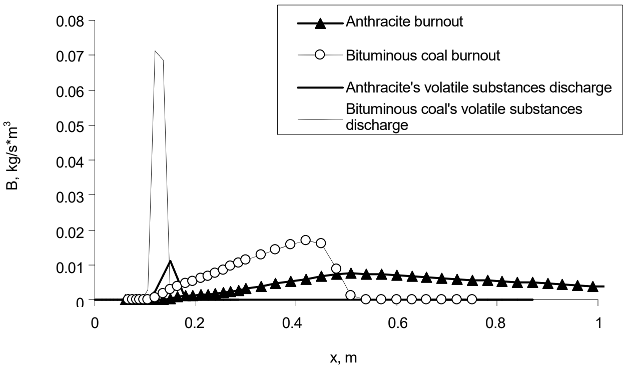


Fig. 7. Reciprocal location of the regions of the volatile matter evolution and the burning of coal coke for a mixture with 50 % of bituminous coal at a particle size of 70 μm

One can see that the burning regions of each type of coal are located lower along the flow relative to the respective regions of the evolution of volatile matter. At the same time, the corresponding regions of bituminous coal are the first to be located along the flow. This is consistent with the idea of the intensifying role of bituminous coal in the ignition of anthracite and the evolution of its volatile matter.

6. Simulation of the burning of a mixture of coals in the furnace of the TPP-210A boiler

It is known [14] that the processes in the furnace, when replacing the lean coal with a mixture of anthracite with bituminous coal, are almost unchanged. It is possible, by comparing the estimation parameters when using these solid fuels in the boiler, to assess the simulation results. At the same time, the consumption of components of the mixture of bituminous coal with anthracite is advisable to choose from the conditions that are the same to the variant of burning the lean coal mass consumption of volatile matter and the thermal combustion power. Below, the volatile matter share, taking into consideration their high-temperature output, is marked by symbol V with indices *B*, *L*, or A, respectively, for the parameters of bituminous, lean coal, and anthracite. At the mass share of bituminous coal in the mixture $k_B=m_B/(m_B+m_A)$ the balance of the consumption of volatile matter yields

$$m_T V_T = m_G V_G + m_A V_A \tag{1}$$

where symbol *m* with indices indicates the mass consumption of the respective coal grads, hence, it follows:

$$m_G = \frac{V_T}{V_G + (k_G - 1)V_A / k_G} m_T. \tag{2}$$

A condition of the balance of thermal capacity

$$m_T Q_i^r{}_T = m_G Q_i^r{}_G + m_A Q_i^r{}_A \tag{3}$$

produces the following equality:

$$m_G = \frac{Q_i^r{}_T}{Q_i^r{}_G + (1 - k_G) Q_i^r{}_A / k_G} m_T. \tag{4}$$

It follows from (2) and (4):

$$k_G = \frac{1}{1 + \dfrac{V_G Q_i^r{}_T - V_T Q_i^r{}_G}{V_T Q_i^r{}_A - V_A Q_i^r{}_G}}. \tag{5}$$

Based on the value of k_G, one can find m_G from (2), and then

$$m_A = (1 - k_G) m_G / k_G. \tag{6}$$

The characteristics of the coals considered are given in Table 2.

Table 2

Coal characteristics

Fuel	W^r	A^r	V^r	C	H	O	N	S	Q_i^r
	%	%	%	% DAF					MJ/kg
Lean coal	5	23.8	10.7	88.1	4.4	2.4	1.3	3.9	24.2
Anthracite	8.5	22.9	2.4	93.0	1.7	1.9	0.9	2.5	22.6
Bituminous coal	8	23	27.6	80.0	5.5	8.4	1.4	4.6	22.0

For these conditions, the k_G value was 0.31.

The high-temperature volatile matter evolution parameter for lean coal is accepted equal to K=1.3. Fig. 8 shows the temperature fields in the cross-section of the furnace of the TTP-210A boiler, operated on lean coal and a mixture of anthracite with bituminous coal. One can note that the replacement of lean coal with a mixture of coals does not significantly affect the field of temperatures.

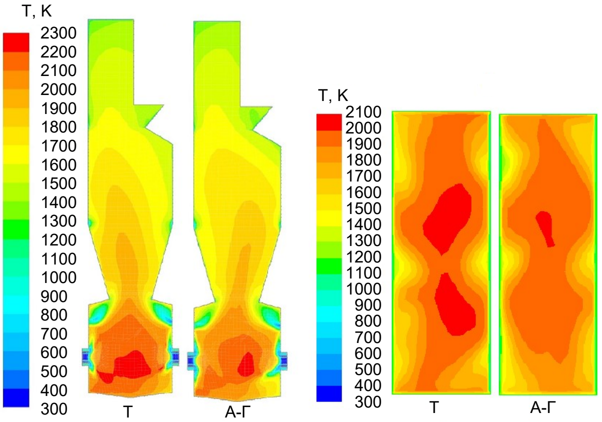


Fig. 8. Temperature fields when using lean coal and a mixture of anthracite with bituminous coal: *a* — in the vertical cross-section of the furnace of the TTP-210A boiler; *b* — in the horizontal cross-section of the lower clamp

To quantify the effect of replacing lean coal with a mixture of anthracite with bituminous coal, Fig. 9 shows the distributions of the average flow temperature for the height of the furnace under these modes. The difference that does not exceed 45 K can be considered small.

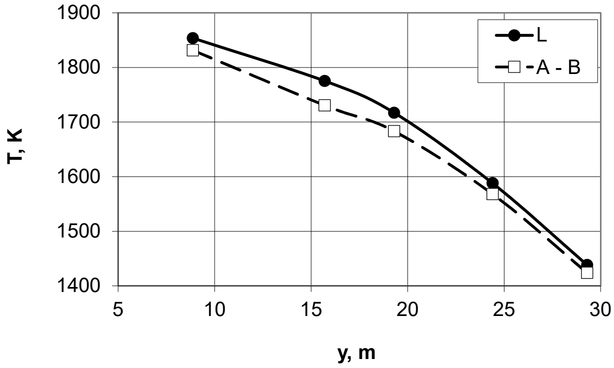


Fig. 9. Change in average flow temperature for the height of the furnace based on the calculation results when using lean coal and a mixture of coals

According to the calculations, the unburned carbon loss in the furnace when using a mixture of bituminous coal with anthracite, which was 1.6 %, is quite close to the value for lean coal (1.1 %).

Thus, the calculations reveal practical convergence of the results when using lean coal and a mixture of bituminous coal with anthracite, which is consistent with the experience of industrial tests [14]. This can be interpreted as a confirmation of the correctness of the considered approach to modeling the combustion of a mixture of coals.

7. Discussion of results of modeling the process of burning a pulverized coal mixture

The two proposed approaches to modeling the process considered, notwithstanding the similarity of the resulting temperature fields, differ significantly both in their essence and in the individual characteristics of the results. The first approach, implying the consideration, instead of a mixture of different fuels, one fuel with the properly averaged parameters, is fundamentally simpler. It fits fully into the capabilities of the ANSYS FLUENT software but it cannot take into consideration the important factor of interaction between the components of the mixture; in this respect, it is clearly approximate. Another approach uses the software's suitability to describe the burning of solid fuel particles with a second liquid or gaseous fuel when they are replaced with a second solid fuel. In this case, the interaction among the components of the fuel mixture (Fig. 7) is similar to that described in paper [14]. This approach is used to simulate the three-dimensional combustion process in the furnace of the TPP-210A boiler of a mixture of anthracite with bituminous coal with a total amount of volatile matter and thermal capacity similar to that of lean coal. The parameters, obtained under these modes in the furnace, are similar: the temperature difference (Fig. 9) does not exceed 45 K, unburned carbon loss 0.5 %, which is consistent with study [14], and confirms the correctness of the considered approach to modeling the combustion of the fuel mixture. This, of course, does not contradict the expediency of further research into the processes of modeling the combustion of solid-fuel mixtures in the furnaces of boilers and comparing their results with experimental data, which may become the task of further work.

8. Conclusions

1. Two approaches to modeling the combustion process of a solid-fuel mixture by the ANSYS FLUENT software have been formulated: an approximate one, reduced to the replacement of a mixture of different fuels with one fuel with averaged parameters, and a more accurate one, based on the hidden capabilities of the software.

2. Simulation of the combustion process of anthracite mixtures with bituminous coal at the variation in their mass ratio and particle size has shown the proximity of temperature fields obtained under different approaches. However, the second ("more accurate") approach demonstrates the mutual location of the regions of discharge of volatile substances and the intensities of combustion of the mixture components, consistent with the combustion intensification of a less active component by adding a more active one, known from the scientific literature. This confirms its advantage.

3. A more accurate approach is used to simulate the three-dimensional combustion process of the anthracite-bituminous coal mixture in the furnace of the TPP-210A boiler in comparison with the results from modeling the process of burning lean coal. Insignificant differences of the resulting temperature fields (up to 45 K) and unburned carbon loss (0.5 %), consistent with known test data, confirm the correctness of modeling the process of burning a fuel mixture.

References

1. Ghenai, C., Janajreh, I. (2010). CFD analysis of the effects of co-firing biomass with coal. Energy Conversion and Management, 51 (8), 1694–1701. doi: https://doi.org/10.1016/j.enconman.2009.11.045
2. Bhuiyan, A. A., Naser, J. (2015). CFD modelling of co-firing of biomass with coal under oxy-fuel combustion in a large scale power plant. Fuel, 159, 150–168. doi: https://doi.org/10.1016/j.fuel.2015.06.058
3. Bhuiyan, A. A., Naser, J. (2015). Computational modelling of co-firing of biomass with coal under oxy-fuel condition in a small scale furnace. Fuel, 143, 455–466. doi: https://doi.org/10.1016/j.fuel.2014.11.089
4. Tabet, F., Gökalp, I. (2015). Review on CFD based models for co-firing coal and biomass. Renewable and Sustainable Energy Reviews, 51, 1101–1114. doi: https://doi.org/10.1016/j.rser.2015.07.045
5. Gungor, A. (2013). Simulation of co-firing coal and biomass in circulating fluidized beds. Energy Conversion and Management, 65, 574–579. doi: https://doi.org/10.1016/j.enconman.2012.09.023
6. Rokhman, B. B., Matviichuk, A. S. (2012). Modeling and Numerical Study of the Thermochemical Processing of Biomass and Coal in the Furnace Devices. 1. The Fixed Bed. Energotehnologii i resursosberezhenie, 2, 4–10.
7. Li, J., Brzdekiewicz, A., Yang, W., Blasiak, W. (2012). Co-firing based on biomass torrefaction in a pulverized coal boiler with aim of 100% fuel switching. Applied Energy, 99, 344–354. doi: https://doi.org/10.1016/j.apenergy.2012.05.046
8. Backreedy, R. I., Fletcher, L. M., Jones, J. M., Ma, L., Pourkashanian, M., Williams, A. (2005). Co-firing pulverised coal and biomass: a modeling approach. Proceedings of the Combustion Institute, 30 (2), 2955–2964. doi: https://doi.org/10.1016/j.proci.2004.08.085
9. Zhang, X., Ghamari, M., Ratner, A. (2013). Numerical modeling of co-firing a light density biomass, oat (Avena sativa) hulls, and chunk coal in fluidized bed boiler. Biomass and Bioenergy, 56, 239–246. doi: https://doi.org/10.1016/j.biombioe.2013.05.006
10. Yan, B.-H., Cao, C.-X., Cheng, Y., Jin, Y., Cheng, Y. (2014). Experimental investigation on coal devolatilization at high temperatures with different heating rates. Fuel, 117, 1215–1222. doi: https://doi.org/10.1016/j.fuel.2013.08.016
11. ANSYS FLUENT Theory Guide (2012).
12. Hzmalyan, D. M., Kogan, Ya. A.; Hzmalyan, D. M. (Ed.) (1976). Teoriya goreniya i topochnye ustroystva. Moscow: Energiya, 487.
13. Beztsennyi, I. V., Bondzyk, D. L., Shchudlo, T. S., Pliusnova, L. P., Dunaievska, N. I. (2011). Doslidzhennia vyhoriannia sumishei antratsytu i hazovoho vuhillia. Naukovi visti Natsionalnoho tekhnichnoho universytetu Ukrainy “Kyivskyi politekhnichnyi instytut”, 5, 27–30.
14. Chernyavskiy, M. V., Provalov, O. Yu., Beztcennyj, I. V., Moyiseenko, O. V. (2016). Development of Methods and Practical Experience in the Preparation and Pulverized Combustion of Anthracite and Bituminous Coal Mixture at Zmiev TPP. Energotehnologii i resursosberezhenie, 4, 3–13.