doi: 10.5937/SimTerm24316E

Results of the Temperature Variation in Experimental Research of the Kolubara Lignite Drying Process in Fluidized Bed

Milić D. Erić [a] ***(CA), Zoran Marković*** [b]***, Danka Kostadinović*** [c]***, Rastko Jovanović*** [d]***, Ivan Lazović*** [e] ***and Mihajlo Gigov*** [f]

[a] *Vinca Institute of Nuclear Sciences – National Institute of the Republic of Serbia - University of Belgrade, RS, milic@vinca.rs*
[b] *Vinca Institute of Nuclear Sciences – National Institute of the Republic of Serbia - University of Belgrade, RS, zoda_mark@vinca.rs*
[c] *Vinca Institute of Nuclear Sciences – National Institute of the Republic of Serbia - University of Belgrade, RS, dankak@vinca.rs*
[d] *Vinca Institute of Nuclear Sciences – National Institute of the Republic of Serbia - University of Belgrade, RS, virrast@vinca.rs*
[e] *Vinca Institute of Nuclear Sciences – National Institute of the Republic of Serbia - University of Belgrade, RS, ivan.lazovic@vinca.rs*
[f] *AMG Chemtech Solutions, Belgrade, RS, mihajlo.gigov@amgchemtech.rs*

Abstract: Of all the fossil fuels in the world, the largest coal reserves are the most evenly distributed, and their mass exploitation ensures a stable and relatively low price on the international market, but coal contributes significantly to total greenhouse gas emissions. Reducing carbon dioxide emissions by increasing the energy efficiency of converting fossil fuels, especially coal, into electricity is known as Clean Coal Technologies. Particular attention is paid to low-grade coals with high moisture content, including lignite, which has significant reserves worldwide. Against this background, intensive efforts are being carried out to increase the energy efficiency of electricity generation from low-grade coal with high moisture content in the thermal plant by developing and introducing the process of pre-drying using the thermal energy available in the thermal plant. The drying process was investigated under fluidized bed conditions. Experimental investigations of the drying process in the fluidized bed were carried out at two different fluidization velocities and three different air temperatures measured at the front of the sample. The experimental results obtained and the influence of the above parameter values show that the drying rate of the sample increases with increasing temperature, while the drying time of the sample decreases.

Keywords: Convective drying, Temperature, Lignite, Moisture, Fluidized bed.

1. Introduction

Lignite from the Kolubara and Kostolac open-pit mines will remain the most important source of energy in Serbian power plants in the future, mainly because it is the most abundant and cheapest fossil fuel and lignite from Kolubara is the most commonly used coal in the Republic of Serbia. Kolubara lignite is the most commonly used coal in the Republic of Serbia. It is a low-quality coal with a moisture content between 45 and 52%, which reduces the friability of the coal and has a negative impact on the quality of grinding and pneumatic transportation of pulverized coal. A lower moisture content in the coal leads to a higher efficiency of the power plant, a lower need for ash disposal and lower pollutant emissions [1].

It is well known that conventional convective evaporative drying involves complex transport phenomena consisting of three successive processes. The first is the movement of moisture (in liquid phase) in solids, which occurs from the moist interior to the gas-solid interface (internal pores, particle surface, etc.). This process is slower for larger solids and/or materials with low moisture content. The second process is evaporation, which is facilitated by heat (energy) that is either supplied from the outside or extracted from the solid and used to convert liquid to vapor. The last process is the movement of the vapor into the surrounding gas by diffusion and convection. The slowest of these processes determines the overall drying rate ([4-5] etc.).

Prediction of falling-rate drying kinetics by theory alone is very difficult. Thus, accurate small-scale experiments are required instead. It is possible to estimate drying rates under different conditions by applying concepts such as the "characteristic drying curve" or the "drying coefficient".

At the Vinca Institute of Nuclear Sciences, Laboratory for Thermal Engineering and Energy, a series of experiments were carried out in the field of convective drying. After the first step, drying in a packed bed, the research was continued with drying in a fluidized bed, which has a much wider range of applications.

Drying in a fluidized bed allows intensive contact of the gas required to achieve the fluidization state (heated air, flue gases or steam) with the particles of the material to be dried, whereby the gas flow must be sufficient to achieve the fluidization state (overcoming the weight of the particles and transferring the particles to the suspended state).

2. Experimental work

The experimental studies on the convective drying process in the fluidized bed of Kolubara lignite had the following objectives:

- determination of the drying kinetics curve of Kolubara lignite,
- analyse the drying process and the influence of the drying agent (hot air),
- determination of the influence of the parameters of the drying agent (temperature),
- determination of the influence of the particle size of the material,
- validation of the mathematical model.

The decrease in moisture content of the Kolubara lignite samples was determined by measuring the air mass flow balance at the dryer inlet and the dryer outlet. The following measured parameters were used for the calculations described above: Volume flow rate at the inlet, temperature and relative humidity of the air at the inlet and outlet of the experimental apparatus.

The drying experiments with Kolubara lignite samples in the fluidized bed were carried out using the Sherwood Tornado M501 fluidized bed dryer with a 5-litre sample container, Figure 1.

The basic elements of the device are: a fan, an air heater, a thermocouple for temperature measurement, a glass container with a plastic housing, a probe for measuring humidity and temperature and a control unit. The control unit is used to regulate the air flow and the air temperature upstream of the sample and to set the test duration. It can be used as a stand-alone device or connected to a computer using the Fluid Bed Drier Controller software. The software enables the test sequence to be controlled, the data to be monitored and all relevant measurement parameters to be recorded. The following parameters were recorded at the output of the test device: fan load, air temperature upstream of the sample and air temperature and relative humidity at the probe location.

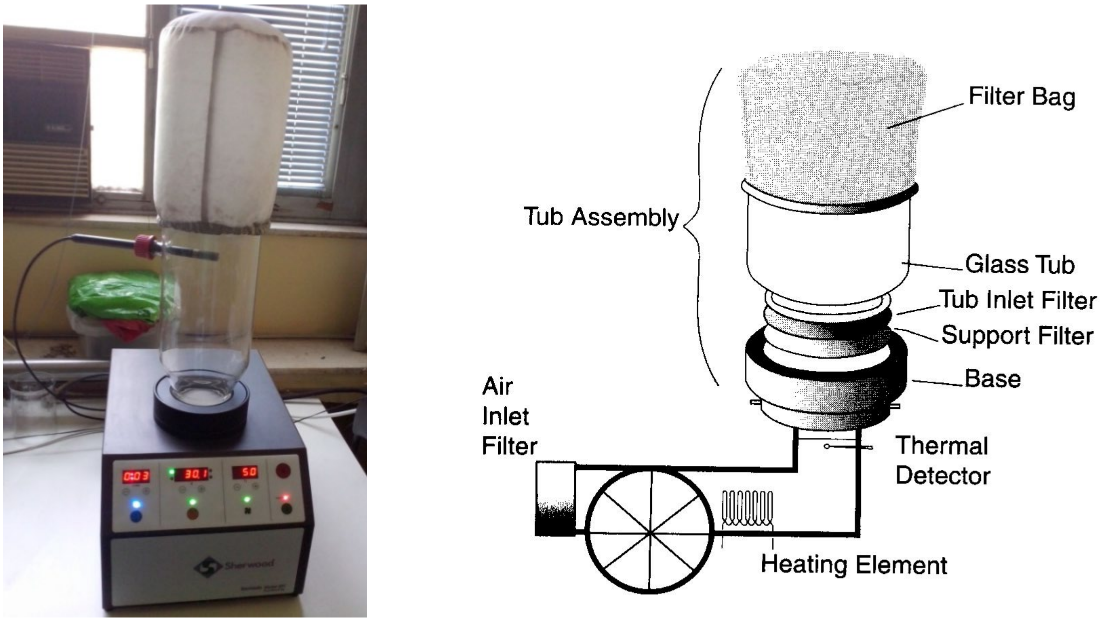

Figure 1. Sherwood Tornado M501 dryer [6]

The experimental apparatus was upgraded with additional equipment for measuring the air flow, Figure 2. The orifice plate with suction tube is installed at the device inlet and complies with the standards SRPS EN ISO 5167-1: 2012 and SRPS EN ISO 5167-2: 2012 "Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full", Part 1: "General Principles and Requirements" and Part 2: "Orifice plates".

Figure 2. Dryer Sherwood Tornado M501with built-in orifice plate [1]

The measuring accuracy of the orifice plate was checked as follows. The accuracy measurement of the volume flow with the orifice plate method was carried out simultaneously with the measurement of the volume flow with a hot-wire anemometer. The probe for measuring the flow rate with a head with an inner diameter of 7 mm was placed on the stand. Due to the small inner diameter of the inlet nozzle of 55 mm, the measurements were carried out with the orifice plate in the center of the cross-section, in accordance with the SRPS ISO 10780: 2010 standard "Measurement of velocity and volume flow rate of gas streams in ducts". Control measurements were carried out at the flow inlet of the device using a hot-wire anemometer. The results obtained were in good agreement. The results of the volume flow rate measurements with orifice and anemometer differed by less than 5 % at five different fan loads: 20 %, 40 %, 60 %, 80 % and 100 %.

The duration of the drying process had to be determined experimentally, as the drying of the coal to a moisture content of zero is very different for the two following methods:

- use of the air mass flow scale at the inlet and outlet of the dryer,
- measuring the mass of the coal sample on the scale immediately before and after the drying process.

The greatest agreement between the results obtained with these two methods was achieved when the sample was dried from the initial moisture content to the equilibrium moisture content of the sample. It was assumed that the experiment was successful if the difference in the amount of moisture removed from the sample by the two methods was less than 2%.

3. The basic properties of the coal sample

For the drying process in the fluidized bed test, the most commonly used domestic lignite from the Kolubara opencast mine (referred to in the following text as Kolubara lignite) was selected, which has a relatively low calorific value and a very high moisture content..

The samples of Kolubara lignite were collected in the bunkers of units A1, A2 and B1 of the Nikola Tesla thermal power plant in Obrenovac [7-10]. The basic properties of the collected coal samples are listed in Table 1. The collected coal samples were ground to a fine grain size suitable for the drying process.

The moisture content of the samples was determined in the laboratory immediately after opening each sample container before the experiments were conducted with the selected coal particle size (grain size). The coal sample was dried in a Binder ED-53 drying oven at 105°C. The mass of the coal sample was measured before and after the drying process in the drying oven on the Mettler AE200-S analytical balance with a working range of 0-205 g and an accuracy of 0.0001 g. Both instruments were calibrated regularly. Both devices were calibrated regularly. Both devices were calibrated regularly. Both devices were calibrated regularly.

Table1. Basic characteristics of Kolubara lignite samples - raw coal parameter [1]

Unit	Carbon [%]	Hydrogen [%]	Oxygen [%]	Nitrogen [%]	Sulfur [%]	Ash [%]	Moisture [%]	LCV [kJ/kg]
A1	25.90 - 27.17	2.17 - 2.19	10.86 - 11.32	0.31- 0.33	0.34 - 0.38	10.29 - 13.15	47.24 - 48.34	8776 - 9343
A2	19.40 - 22.78	1.75 - 1.99	8.54 - 9.74	0.27 - 0.30	0.27 - 0.30	17.02 - 18.37	47.87 - 51.39	7635 - 6167
A2II	20.89 - 23.37	1.86 - 2.01	9.38 - 9.72	0.28 – 0.30	0.30 – 0.35	15.06 - 17.38	49.19 - 49.91	6789 - 7203
B1	23.86	2.08	9.31	0.81	0.14	13.86	49.94	7861

4. Results of the experimental research

The drying process in the fluidized bed of Kolubara lignite samples was investigated for three different coal samples with mean particle diameters: 1.5 mm, 2.57 mm and 3.95 mm and three different air temperatures before the sample: 60°C, 90°C and 120°C. The minimum fluidization velocity was determined for all three sample sizes and all three air temperatures upstream of the sample. The determined values of the velocity parameter were in the following range: 0.63 m/s -1.60 m/s, Table 2. This parameter is of utmost importance for the correct selection of the air flow size and for determining the required blower load for the drying process in the fluidized bed.

Table 2. Minimum fluidization velocity $v_{G,mf}$ for different air temperatures [1]

Air temperature $T_{G,in}$ = 60°C		
d_S = 1,50 mm	d_S = 2,57 mm	d_S = 3,95 mm
$v_{G,mf}$ = 0,63 – 0,73 m/s	$v_{G,mf}$ = 0,99 – 1,13 m/s	$v_{G,mf}$ = 1,32 – 1,50 m/s
Air temperature $T_{G,in}$ = 90°C		
d_S = 1,50 mm	d_S = 2,57 mm	d_S = 3,95 mm
$v_{G,mf}$ = 0,63 – 0,74 m/s	$v_{G,mf}$ = 1,01 – 1,16 m/s	$v_{G,mf}$ = 1,36 – 1,55 m/s
Air temperature $T_{G,in}$ = 120°C		
d_S = 1,50 mm	d_S = 2,57 mm	d_S = 3,95 mm
$v_{G,mf}$ = 0,63 – 0,75 m/s	$v_{G,mf}$ = 1,03 – 1,19 m/s	$v_{G,mf}$ = 1,40 – 1,60 m/s

The results of the experimental investigation of the drying process of Kolubara lignite in the fluidized bed for different temperatures upstream of the sample, for the same sample masses and the three different sample particle sizes are shown in Figures 4-9, which show the drying curves of the tested sample. The results for coal drying in a fluidized bed at a fluidization rate slightly above the minimum are shown in Figures 4 to 6. For more intensive fluidization, where the air velocity in front of the sample is increased by about 50 %, the test results are shown in Figures 7 to 9.

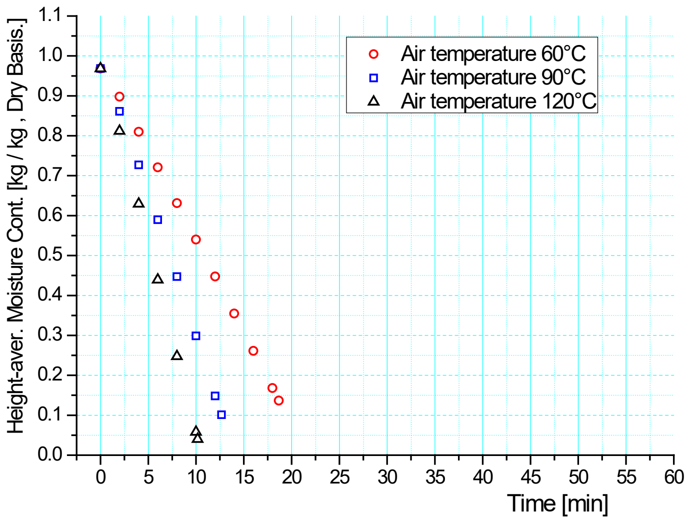

Figure 4. Experimentally determined kinetics of lignite drying in the fluidized bed;
$T_{G,in,30}$ = 60ºC, $T_{G,in,31}$ = 90ºC, $T_{G,in,32}$ = 120ºC, $v_{G,in}$ = 1.3 m/s; d_S = 1.50 mm, m_{S0} = 210g, X_0 = 0.969, Y_0 = 0.007

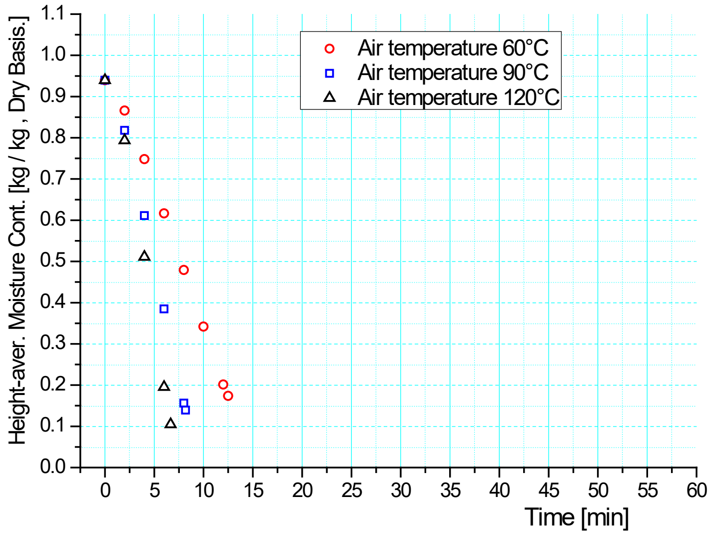

Figure 5. Experimentally determined kinetics of lignite drying in the fluidized bed;
$T_{G,in,42}$ = 60ºC, $T_{G,in,43}$ = 90ºC, $T_{G,in,44}$ = 120ºC, $v_{G,in}$ = 2.0 m/s d_S = 2.57 mm, m_{S0} = 210g, X_0 = 0.939, Y_0 = 0.009

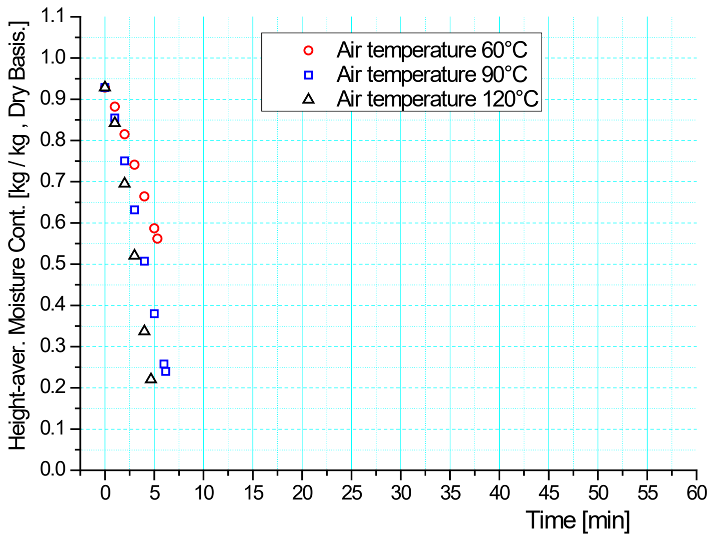

Figure 6. Experimentally determined kinetics of lignite drying in the fluidized bed;
$T_{G,in,53}$ = 60ºC, $T_{G,in,52}$ = 90ºC, $T_{G,in,54}$ = 120ºC, $v_{G,in}$ = 2.1 m/s d_S = 3.95 mm, m_{S0} = 210g, X_0 = 80.928, Y_0 = 0.008

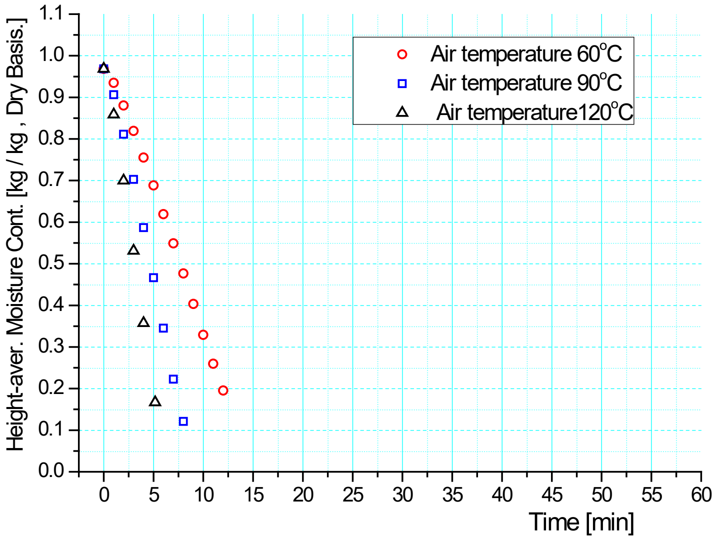

Figure 7. Experimentally determined kinetics of lignite drying in the fluidized bed;
$T_{G,in,33}$ = 60ºC, $T_{G,in,34}$ = 90ºC, $T_{G,in,35}$ = 120ºC, $v_{G,in}$ = 1.9 m/s d_S = 1.50 mm, m_{S0} = 210g, X_0 = 0.969, Y_0 = 0.007

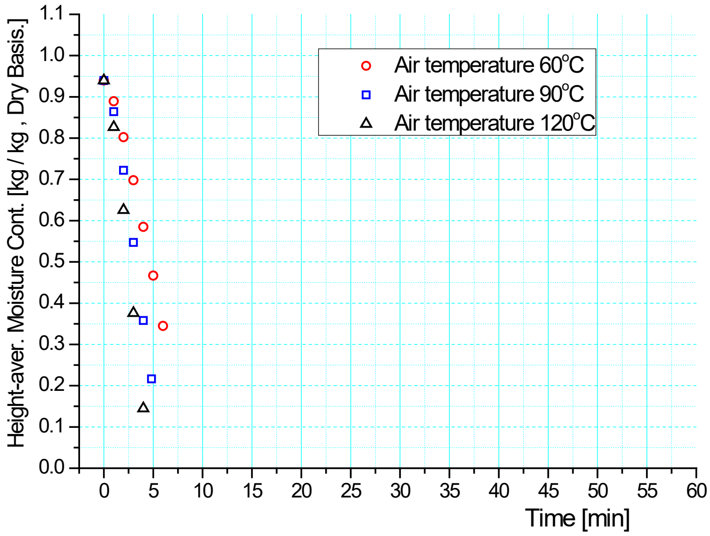

Figure 8. Experimentally determined kinetics of lignite drying in the fluidized bed;
$T_{G,in,45}$ = 60ºC, $T_{G,in,46}$ = 90ºC,$T_{G,in,47}$ = 120ºC, $v_{G,in}$ = 2.9 m/sd_S = 2.57 mm, m_{S0} = 210g, X_0 = 0.939, Y_0 = 0.009

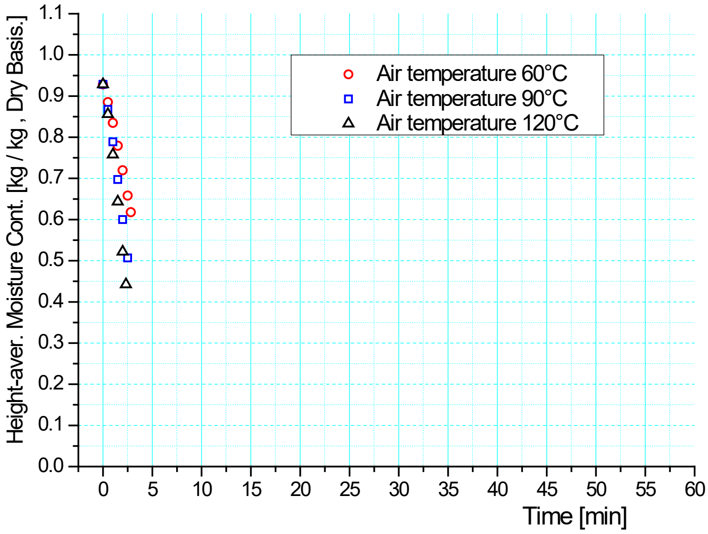

Figure 9. Experimentally determined kinetics of lignite drying in the fluidized bed;
$T_{G,in,56}$ = 60ºC, $T_{G,in,57}$ = 90ºC,$T_{G,in,55}$ = 120ºC, $v_{G,in}$ = 3.1 m/s d_S = 3.95 mm, m_{S0} = 210g, X_0 = 0.928, Y_0 = 0.008

6. Conclusions

The tests were carried out with the Sherwood 501 fluidized bed dryer for drying granular and powdered materials with air in a packed and fluidized bed, which is additionally equipped with devices for measuring the air flow rate, temperature and relative humidity at the inlet of the device, supplemented by automatic control and data logging. All measuring devices are calibrated in approved, accredited laboratories, where the accuracy of each measured parameter is determined. The control measurement of the air flow was carried out by parallel measurement with a standard orifice and a glow wire anemometer at the inlet of the device. In this way, all relevant parameters required to determine the change in average moisture content in the material during the drying tests were measured as accurately as possible.

The measurement and calculation of the change in absolute moisture of the material during the drying process based on the balance of the air mass flow at the inlet and outlet of the device was verified by direct measurement of the mass of the sample on a digital scale before and after each test.

It is obvious that the drying process is faster with smaller pieces of coal, as the resistance inside the particle is lower and the specific surface area of the material is larger, which leads to a more intensive transfer of moisture from the surface of the material to the ambient air. The influence of the particle size on the drying kinetics is not clearly recognisable in the Kolubara lignite fractions used in the tests. The reason for the minor influence of particle size on the drying process is to be found in the small fractions of lignite particles, which differ relatively little in size and whose mean equivalent diameters are as follows: 1.50 mm, 2.57 mm and 3.95 mm, which is due to the unequal particle size in the sample for the same fraction as well as their clearly irregular, mostly needle-like shape, so that one dimension of the particle is significantly larger than the other two. In addition, a smaller number of particles were fragmented during the drying process.

On the other hand, drying is faster at a higher temperature of the heated air, as the difference between the partial pressure of the water vapor (moisture) on the surface of the material and the partial pressure of the water vapor in the ambient air (humidity) is greater.

The influence of the temperature of the heated air can be observed well for all coal granulates for drying in the fluidized bed for both tested flows, i.e. the material dries much faster at a higher temperature of the heated air.

Looking at the drying kinetics curves of Kolubara lignite for three different air temperatures (60 ºC, 90 ºC and 120 ºC), a similar character of the change in moisture content in the material can be observed, i.e. how the drying process of the coal is significantly faster with increasing air temperature.

The experiments were carried out up to a predefined moisture content of the material (on a dry basis) of about 0.2. Of course, coal can be dried to a final moisture content below this value, up to the equilibrium value of the moisture content, which depends on the parameters of the air used to dry the material. Drying the coal for longer to reach the equilibrium moisture content makes little sense from the point of view of the profitability of the entire process, including post-combustion. After the drying process, the coal is mixed with hot flue gases and ground in mills, where it dries further. It is then fed into the boiler in an air mixture with flue gases and water vapour at a temperature of 150 ºC to 200 ºC via the burners, where it losing an additional few percent of its moisture content.

Nomenclature

Latin symbols

d	–	Mean particle diameter, in [mm].
m	–	Sample mass, in [g].
T	–	Temperature, in [°C].
X		Sample height-average moisture content, in [kg/kg, dry basis].
Y		Air height-average moisture content, in [kg/kg, dry basis].
v	–	velocity [ms^{-1}].

Subscripts

0	–	Initial.
G	–	Gas (air).
in	–	Inlet, in the front of.
S		Solid.

Acknowledgments

The research was funded by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract Annex: 451-03-66/2024-03/200017). The authors are very grateful for the support of this work by the Joint Stock Company Elektroprivreda Srbije.

References

[1] Milić Erić, DRYING PROCESSES OF LIGNITES WITH HIGHMOISTURE CONTENT IN PACKED ANDFLUIDIZED BED, Doctoral Dissertation, University of Begrade, Mechanical Faculty, Belgrade, 2016
[2] van Meel, D.A., Adiabatic convection batch drying with recirculation of air, Chemical Engineering Science, 9(1958), pp. 36-44
[3] Tsotsas, E., Measurement and modeling of intraparticle drying kinetics: A review, Proceedings of the 8th International drying symposium (IDS ’92), Montreal, 1992, pp. 17-41
[4] Luikov, A.V., Drying theory, 1st ed., Energiya, Moscow, 1968 (in Russian)
[5] Milojević, D., Stefanović, M., Convective drying of thin and deep beds of grain, Chemical Engineering Communication, 13 (1982), pp. 261-269
[6] The Laboratory Fluid Bed Drier, Sherwood Scientific Limited, 1 The Paddocks Cherry Hinton Road, Cambridge, Issue 2, ECN 412, August 2006.
[7] Erić M., Stefanović P., MarkovićZ., Dragan Živić, Željko Ilić, Reduction of Particulate Matter Emission by the Modernization of the Electrostatic Precipitators at Unit B1 of the TPP Kostolac B, Proceedings of 17th Symposium on Thermal Science and Engineering of Serbia, Sokobanja, Serbia, October 20–23, 2015, pp. 569 – 576, ISBN 978-86-6055-076-9
[8] Stefanović P., Erić M., Marković Z., Particulate Emission Guarantee Test B of the Upgraded ESP at Unit B1 of TPP "Nikola Tesla", Technical report NIV LTE 548, Version 2.0, Institute of Nuclear Sciences "Vinča", Vinča, March 2014.
[9] Erić M., Stefanović P., Marković Z., Periodic measurement of pollutants emissions in air at units A1, A2 and A3 of TPP "Nikola Tesla", Technical report NIV LTE 559, Institute of Nuclear Sciences "Vinča", Vinča, December 2014.
[10] Erić M., Stefanović P., Marković Z., Periodic measurement of pollutants emissions in air at unit A2 of TPP "Nikola Tesla",second series of measurements, Technical report NIV LTE 560, Institute of Nuclear Sciences "Vinča", Vinča, December 2014.