SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Numerical Heat Transfer

Journal homepage: https://semarakilmu.com.my/journals/index.php/arnht/index
ISSN: 2735-0142

CFD Modelling and Optimization of Solid Waste Combustion in a 1 MW Fixed Bed Combustion Chamber

Ashraf Abdullah Ahmed[1,*], Pavel Alekseevich Trubaev[2], Rafshan Salmanovich Ramazanov[2]

[1] University of Tikrit, MMH4+876, Tikrit, Salah Al-Din Governorate, Iraq
[2] Belgorod State Technological University named after V. G. Shukhov, Kostyukov St, 46, Belgorod, 308012, Russia

ARTICLE INFO

Article history:
Received 20 May 2024
Received in revised form 19 June 2024
Accepted 22 July 2024
Available online 30 August 2024

Keywords:
MSW; CFD; Incinerator; Excess air coefficient; Combustion chamber; Furnace temperature; Emissions of pollutants

ABSTRACT

The global population and energy consumption grow each year. Therefore, the tendency to use biofuels instead of fossil fuels assist the global requirement. Also, enhancing of the combustion efficiency and minimizing pollutant emissions during the combustion of municipal solid waste (MSW). The present study employed a CFD model to simulate solid fuel combustion in a grate combustion chamber which was commonly used in small-capacity boilers. computational fluid dynamics technique was used to simulate complex solid fuel reactions where 1 MW boiler was supposed for wood and coal combustion. The achievements found that 10%-dried MSW was used as fuel. The results of the study were related to the average gas flow temperatures and composition in the furnace outflow section, as well as the high combustion temperatures of fossil fuels. The results for the average temperature and average chemical molecular fractions (CO, O2, CO2, H2O, and N2) generated at the exit of the combustion process were positive. Thus, it was found that the thermal efficiency of the boiler was significantly affected by the amount of air supplied to the system at a temperature of 273 K and atmospheric pressure. We observed variations in flame morphology, temperature profiles, and corresponding numerical values.

1. Introduction

In contemporary times, the demand for energy leads to enhancing related applications such as boilers, condensers, and other related ones those have an effected role on the thermal power plants performance.

Furthermore, the traditional energy sources such as coal, oil, and natural gas are the predominant means used to meet the energy requirements therefore the essential to improve the boilers performance make an efficient role to augment the overall thermal performance [1,2].

The current status of solid biomass thermal disposal in the energy sector was widely recognized as an important contributor to power generation [3,4]. A number of technologies for thermal waste disposal are known: pyrolysis [5], gasification [6,7]. low-temperature thermolysis [8] etc., but they are all associated with the formation of a large amount of resins [9,10]. and therefore, direct

[*] *Corresponding author.*
E-mail address: ashraf.a.ahmed@tu.edu.iq (Ashraf Abdullah Ahmed)

https://doi.org/10.37934/arnht.23.1.6687

combustion remains the simplest and most effective method. The drawback of burning solid biomass is the formation of pollutants and the release of harmful gases [11,12]. Waste combustion is possible in the form of RDF fuel, which is dried and crushed material [13], and in the form of pressed briquettes or pellets [14]. In recent decades, a marked trend has been achieved among countries that are interested in utilizing solid biomass combustion via grate boilers. Therefore, this approach was considered as useful and more feasible, as it generates fewer pollutants harmful to the environment [15,16]. Furthermore, an exploration of efficient combustion processes was conducted at big scale to meet household energy demands and at a larger scale to cater to the requirements of furnaces and manufacturing industries [17]. Therefore, it is imperative for scientific investigations to continuously examine the factors that influence the combustion of wood residues and household wastes, as well as the production of pollutants within combustion chambers. Where, this was a crucial in order to devise efficient approaches for mitigating the release of these emissions and undesired substances [18]. Tanprasert *et al.,* [19] found a reduction in the emissions and environmental impact during combustion through computational fluid dynamics simulations. Also, the biomass mixing ratio increased the wood particles in the feed, which reduced oxide emissions. Qing *et al.,* [20] found numerically that food and paper waste typically produced a higher content of methane and carbon monoxide compared to yard waste. This was due to the high percentage of carbon in food waste and the high content of volatile matter in paper. While yard waste produced higher H2 content compared to food and paper waste resulting from higher amount of moisture content and lower volatiles that reduce carbon decomposition.

To enhance the efficiency of combustion, it was crucial to ensure complete combustion. The achievement of full combustion relies on the existence of favorable circumstances. For optimal performance, a certain amount of fuel to air, turbulence, temperature and time [21]. Moreover, when combustion occurs, all fuel and air are completely consumed without any remaining surplus while burning refuse-derived fuels (RDF) was usually achieved by increasing the amount of air, atomizing the oxygen, or adding more fuel [22].

The lattice combustion of solid fuel was a widely used method for generating thermal and electrical energy due to its ability to effectively burn a wide variety of fuels, often requiring minimal or even neglectful fuel preparation [23]. Furthermore, the modeling and simulating of the lattice combustion processes in various combustion systems and mechanisms required numerous computational tools [24]. Grate-firing exhibits superior adaptability compared to other solid fuel thermal conversion technologies where this was considered as the prevailing choice for biomass firing [25]. It was found that the combustion of solid waste in high-temperature grate boilers played a significant role in the production of renewable energy [26]. Meanwhile, The predominant application of this process included the generation of heat through the combustion of solid waste (MSW) [27].

The grid thermal boilers specialized in burning wood waste and solid household waste [28]. so as to assist the power generation or district heating [29,30]. The objective was attained the optimal combustion efficiency while minimizing the release of pollutants [31]. Furthermore, the thermal neutralization of wastes improved the almost complete destruction of organic harmful substances under the effect of high levels of temperature, as investigated in several studies [32]. Additionally, it was detected that the temperature requirement was elevated to a minimum of 1100 °C (1373 K) when the burning process included hazardous waste due to halogen organic compounds exceeding 1%. Moreover, it was found that the determination of the boiler's efficiency relied on the amount of excess. Therefore, the evaluation of the ideal excess air coefficient was a critical technical parameter that requires ongoing monitoring [33].

The combustion process employed in high-temperature process boilers and furnaces typically required the incorporation of a moderate quantity of surplus air [34]. Also, In order to create distinct interaction zones, it was investigated combustion processes and systems using diverse computational methods [35]. Where Insufficient air supply led to increased carbon monoxide (CO) emissions and reduced energy efficiency as a result of incomplete combustion of carbon [36]. Furthermore, it was observed that the co-ignition process occurring in various burners was a notable impact on the convection of the boiler walls, resulting in a discernible rise in emissions of carbon dioxide (CO_2) and nitrogen oxides (NO_x) [37].

To investigate the effect of oxygen-enriched combustion on heat transfer and wall temperatures, where a thermodynamic model with zero and one-dimensional characteristics was conducted. This model was achieved to estimate the heat flux to a thermal load and the principal temperatures in both laboratory-scale and industrial-scale furnaces. Moreover, The numerical simulation method was employed to investigate the temperature distribution and NO_x formation in a boiler under various air grades [38].

The basic and most important method of burning solid fuel in boilers of low and medium capacity was primary combustion, in which fuel was fed to the grate from above and blown with blast air supplied from below. Furthermore, the rate of combustion of coal was highly dependent on the density of air supply due to the fact that the rate of combustion of coal is highly dependent on the density of air supply [39]. An empirical investigation was conducted to examine the combustion of individual coal particles under different atmospheric conditions, including air and various oxy-fuel compositions, at multiple time intervals. It was found that the presence of water vapor into the oxy-fuel environment led to an increase in particle temperature during the combustion of coal particles [40]. Also, it was conducted on the co-firing of biomass with coal in a tangentially fired boiler using oxy-fuel combustion where the outcomes referred to an augmentation of oxy-fuel conditions results in an elevation of flame temperature [41].

The objective of this study tends to model the process of solid fuel combustion in a grate boiler and identify the potential strategies for enhancing the combustion efficiency of municipal solid waste (refuse-derived fuel) and reducing emissions of pollutants by using Ansys Fluent software. Moreover, it assesses the impact of various key parameters on the combustion efficiency such as altering the excess air coefficient, the temperature of the air supplied to combustion, the height of the furnace space, and the location and size of the outlet window. Furthermore, a comparative analysis must be examined to evaluate the combustion efficiency under different parameter configurations also addresses the challenges related to simulating the combustion phenomenon within a solid fuel.

2. Computational Fluid Dynamic Analysis

2.1. Model Description

The study utilized a KVM-12 boiler which included a capacity of 1 MW it was built to combust both wood fuel and coal, as depicted in Figure 1. The boiler was equipped with an enormous furnace that features a grate. The outcome gaseous from the furnace directed into a dual-channel tube bundle to facilitate the heating of water where each one movement takes up half of the total width of the boiler.

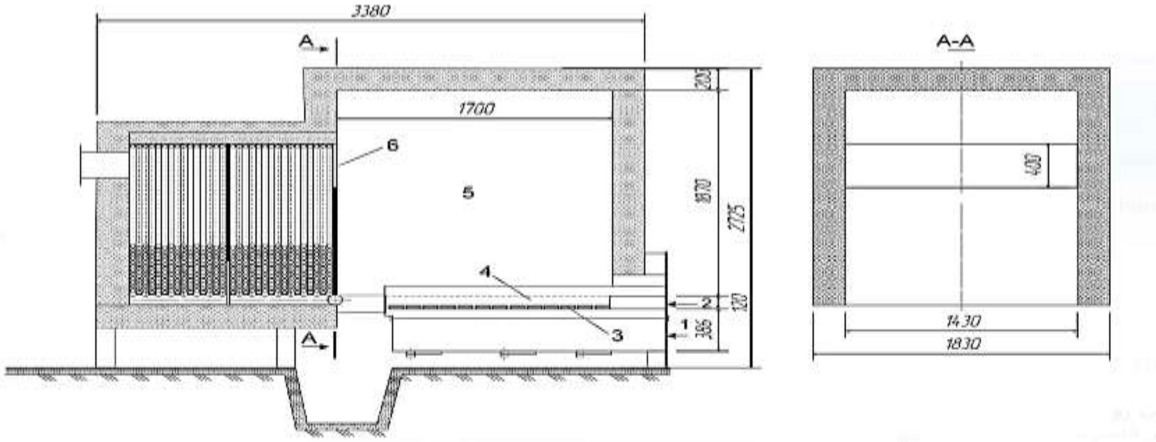


Fig. 1. Boiler KVM-12: 1 – air inlet; 2 – solid fuel inlet; 3 – grate; 4 – layer of fuel; 5 – fire chamber; 6– combustion outlet

It was tended to ascertain the levels of noxious chemicals and the gas temperature at its discharge. To optimize the combustion temperature, the possibility of utilizing a screen less furnace was taken into consideration. Also, it is postulated that the furnace walls are thermally insulated using fireclay material with a thickness of 0.2 units.

2.2. Boundary and Initial Conditions

The supposed domain should be provided with the boundary conditions so as to enhance the perfection of the outcome achievements and make those results more reliable to the real case [42]. the supposed domain of the present study that is shown in Figure 2. And Figure 3. includes rectangular walls where they are assumed to be adiabatic to prevent any heat loss from the core process to the out ambient. Also, the present domain includes an inlet air section that allow for a mass flow rate of air to be flowed with certain value Where the mass fuel flow rate is 0.03665 kg/s constant for each excess air flow rate α. Moreover, the exit section is supposed on the corresponded region of the inlet wall to simulate make better flow for the combusted gases. The inlet air temperature is supposed according to the atmospheric conditions i.e. 25 C and 101.325 Kpa while the outlet temperature of the exhausted gases is determined according to the condition of the combustion process. Furthermore, the present study doesn't have a time variation so that, the supposed solid fuel is assumed to be inserted within the domain under specified mass limit.

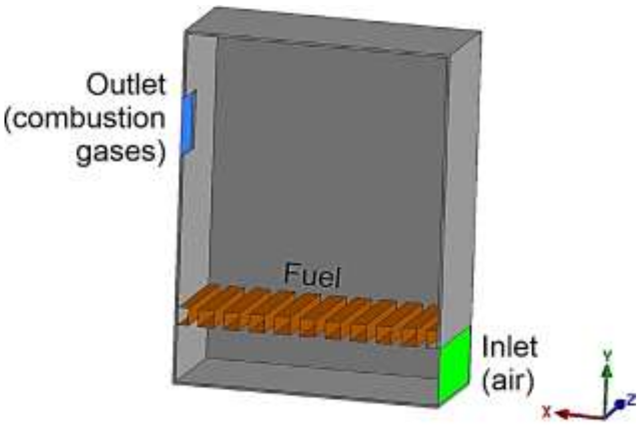


Fig. 2. Longitudinal section of the supposed boiler (Domain)

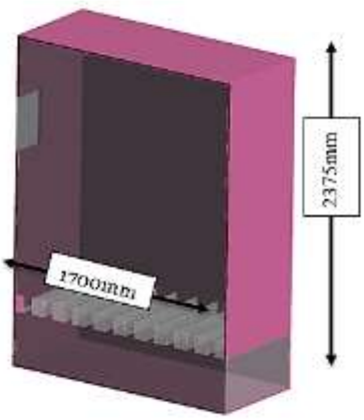


Fig. 3. The dimensions of the studied domain

2.3. Composition of Solid Fuel

There is a large range of variation in both the physical qualities of municipal solid waste (humidity, density, and size) and the chemical properties of MSW (elemental composition, heating value). Therefore, the fuels such as MSW and coal contain varying amounts of carbon, oxygen, hydrogen, nitrogen, Sulphur, moisture, and ash, accurate mass analysis is problematic. The primary components of used solid fuel are destructible blocks and ballast. Combustible mass refers to combustible materials, whereas ballast is composed of debris and slag [43].

The composition of used RDF fuel is shown in Table 1. where these values are computed by depending on equation (1) below [44,45],

$$\text{Fixed carbon in Coal (wt.\%)} = 100-(M\ (wt.\%) + AC\ (wt.\%) + VM\ (wt.\%)) \tag{1}$$

where
M = Moisture content analysis (%)
AC = Ash content (%)
VM = Volatile Matter (%)

Table 1
Composition of fuel

Physical composition of MSW (wt.%)	
Food residue	30
Paper	30
Textiles	5
Wood	5
Ribbon, leather	1
Plastics	15
Non-combustibles	14
Ultimate analysts as received	
C (%)	54.4
H (%)	7.3
O (%)	36.5
N (%)	1.4
S (%)	0.4
Proximate analysis as received by weight	
Moisture content (%)	10.0
Volatile nutter (%)	49.1
Ash content (%)	26.9
Fixed carbon (%)	14.0
Net heat value (kJ/kg)	13 640

The fuel simulations were subsequently established through the utilization of the Coal Calculator dialog. The Coal Calculator dialogue facilitates the automated computation and configuration of pertinent input parameters for the species, Discrete-Phase (DPM), and pollutant models linked to the process of solid fuel combustion. Moreover, the Species dialog of the Species Transfer Model offers the option to select either Eddy-Dissipation or rate-specific/eddy-dispersive disorder-chemistry as shown in the Figure 4.

The mass fraction values for the elements carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and optionally sulfur (S) are inputted for the dry ash-free coal (DAF). The mass fractions in ANSYS FLUENT are normalized to ensure their aggregation into a unit Shown in Table 2. Subsequently, an evaluation is conducted on the estimated coal, specifically focusing on the mass proportions of volatile and fixed carbon, ash, and moisture present in the coal. The ANSYS FLUENT software is employed to standardize these mass proportions and aggregate them within a unified measurement unit. Subsequently, the two-step chemical mechanism was selected. The two-step mechanism comprises the initial reaction involving the oxidation of carbon dioxide by volatile substances, followed by the subsequent reaction involving the oxidation of carbon dioxide to carbon dioxide.

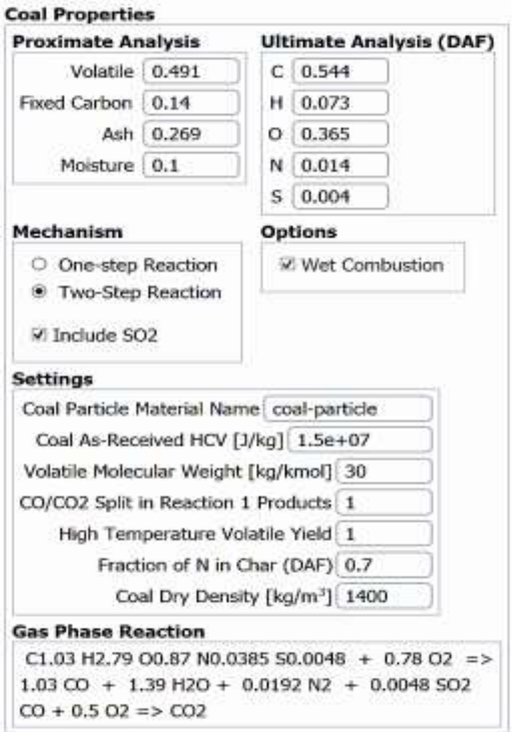


Fig. 4. Fuel characteristics

Table 2
Composition of the studied fuel

Name	Fuel composition (MSF), wt. %
Combustible elemental mass	
Carbon C^g	54,7
Oxygen O^g	36,6
Hydrogen H^g	7,3
Nitrogen N^g	1,4
Sulfur S^g	0
Sum	100
Components	
Ash content A^p	26,9
Humidity W^p	10
Fixed carbon	13,5
Volatiles	49,6
Sum	100

2.4. Modeling the Combustion of a Layer of Solid Fuel on a Grate

The combustion of solid fuels is a heterogeneous reaction where combustion occurs in a diffusion-dependent region during lattice stratification combustion. This is supported by the strong relationship between the rate of combustion of solid fuels and the rate of oxygen supply to the particle surface. Also, the incineration is regarded as a thermal process that involves the oxidation of combustible waste components.

The Figure 5 shows the schematic diagram of the studied boiler where flames are achieved from the fuel under the effect of air flow with the standard contents of oxygen and nitrogen in the atmospheric.

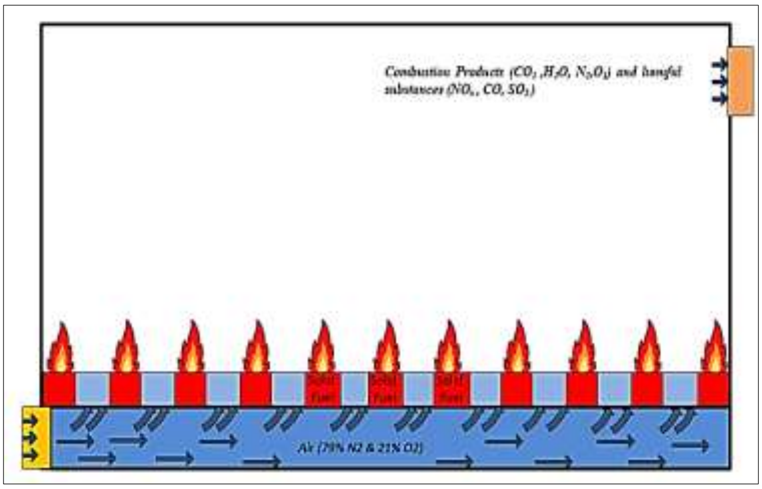


Fig. 5. Diagram showing the fuel combustion process

3. Meshing Process

It is well known that the applying of the numerical analysis upon any studied domain become essential to get on a solution of the governed equations. Moreover, the numerical solution requires subdivision of the geometry for fine elements to get on more accurate achievements. Therefore, the meshing process of the present CFD model involves the use of tetrahedral elements for increasing the connecting among the corresponded elements.

The subdivisions of the geometry for fine elements may be changed according to the total number of those items where the higher mesh number presets accurate results but it requires more time for the analysis. Thus, the mesh independency should be processed to get on the best choice of mesh number that reaches the highest accuracy and lowest processing time. The table below shows the grid independency of the present geometry where the best element number is approached to 1,060,690.

The next major stage involves segmenting the initial 3D geometric model to create a finite element network. Aerodynamics, gases and process flow modeling (CFD modeling) is implemented in the Ansys Fluent software package by using the finite element method. The initial approach involved adopting an adaptive network model, which is mainly composed of polyhedral elements as shown in Figure 6.

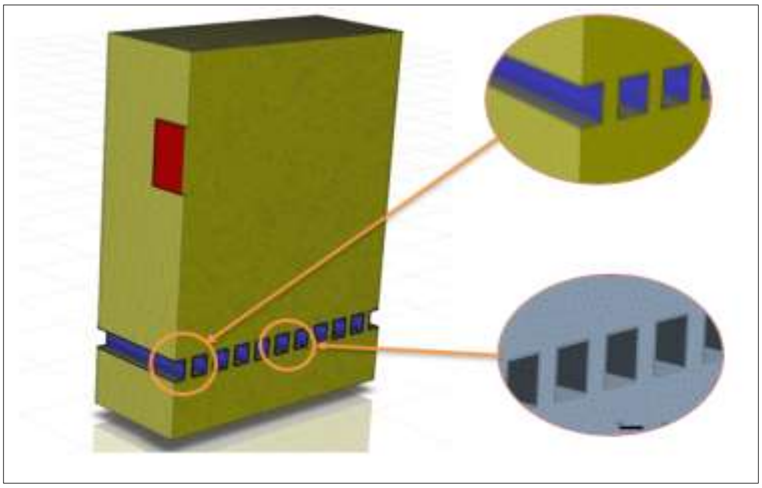


Fig. 6. General view of the domain under the mesh case

To achieve comparability among various simulations, the computational specification of modeling in a network structured with polyhedral cells (polyhedrons) was utilized, and similar settings were employed for each calculation. Nevertheless, it is imperative to modify the configurations to gain access to the affinity. Additional information pertaining to the spatial estimation of gradients, quantities, and hypo-relaxation factors identified in the simulation can be found in Table 3, Table 4 and Table 5.

Table 3
Mesh independency

No	Mesh number	Value of Co_2 at Excess air ratio at 1.6	The best choice
1	765,876	7.65	×
2	799,800	10.23	×
3	865,390	10.98	×
4	976,543	11.1	×
5	1,060,269	11.51	√
6	1,100,653	11.5	×

Table 4
Settings for spatial discretization

Spatial Discretization	Realizable k-ε and DO models	Spatial Discretization	Realizable k-ε and DO models
Gradient	Least Squares Cell Based	Vol	Second Order
Pressure	PRESTO	O_2	Second Order
Momentum	Second Order	CO_2	Second Order
Density	Second Order	H_2O	Second Order
Turbulent Kinetic Energy	Second Order	CO	Second Order
Turbulent Dissipation Rate	Second Order	Pollutant NO	Second Order
Energy	Second Order	Pollutant HCN	Second Order
Discrete	First Order	Pollutant NH_3	Second Order

Table 5
Under-Relaxation factors in CFD

Under Relaxation Factors	Realizable k-ε and DO models	Under Relaxation Factors	Realizable k-ε and DO models
Pressure	0.5	Vol	0.75
Momentum	0.5	O_2	0.75
Density	0.5	CO_2	0.75
Body Forces	1	H_2o	0.75
Turbulent Kinetic Energy	0.75	CO	0.75
Turbulent Dissipation Rate	0.75	Pollutant NO	0.75
Turbulent Viscosity	1	Pollutant HCN	0.75
Energy	0.75	Pollutant NH_3	0.75
Discrete Ordinates	1	Discrete Phase Sources	0.5

4. Results and Discussion
4.1. Investigation of Combustion with a Change in The Coefficient of Excess Air

The study of combustion initially involved the examination of combustion processes under different excess air ratios. Table 6. provides the prescribed values for the surplus air coefficient, the composition of the combustion products, the flow rates of air and combustion products, and the combustion temperature.

Table 6
Composition of fuel combustion products

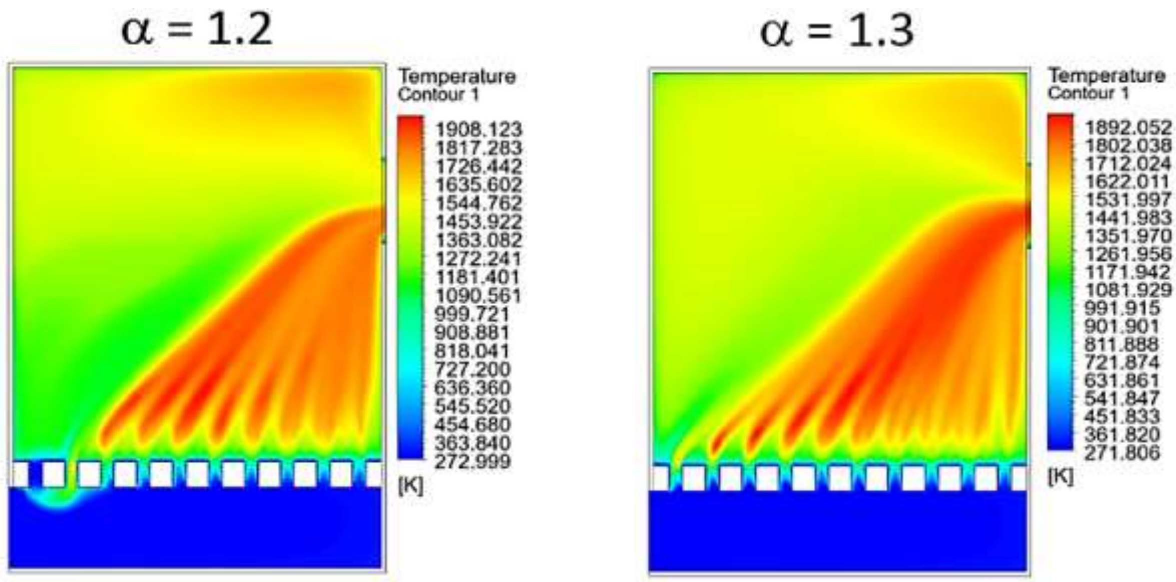
	Excess air coefficient α							
	1,2	1,3	1,4	1,6	1,8	2,0	2,5	3,0
Specific air consumption, m^3/kg								
theoretical	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10
valid	3.72	4.03	4.34	4.96	5.58	6.20	7.75	9.30
Specific volume of combustion products, m^3/kg,								
including	4.35	4.66	4.97	5.59	6.21	6.83	8.38	9.93
CO_2 (vol. %)	14.7	13.8	12.9	11.5	10.3	9.4	7.7	6.5
S_2O (vol. %)	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.02
H_2O (vol. %)	14.6	13.6	12.8	11.3	10.2	9.3	7.6	6.4
N_2 (vol. %)	67.7	68.4	69.1	70.2	71.1	71.8	73.1	74.0
O_2 (vol. %)	3.0	4.2	5.2	7.0	8.4	9.5	11.6	13.1
the flow								
fuel, kg/s	0.0733	0.0733	0.0733	0.0733	0.0733	0.0733	0.0733	0.0733
air, kg/s	0.3526	0.3820	0.4113	0.4701	0.5289	0.5876	0.7345	0.8814
air, m^3/s (at 0°C)	0.27	0.30	0.32	0.36	0.41	0.45	0.57	0.68
combustion products, kg/s	0.41	0.44	0.47	0.53	0.59	0.65	0.79	0.94
Calorimetric combustion temperature, °C	1838	1750	1668	1522	1398	1291	1082	1562

The modeling study yielded findings regarding the maximum combustion temperatures of organic fuels, average temperatures and composition of the gas flow in the outlet section of the furnace was illustrated in Table 7 and Figure 7. These results align with the theoretically calculated values. Additionally, favorable outcomes were observed for the average temperatures and average chemical molecular fractions (O_2, CO_2, H_2O, N_2, and CO) generated during combustion at the outlet. Furthermore, the radial temperature at different excess air proportions introduced to the grate heat boiler was also investigated, yielding satisfactory results.

In addition, as an option to improve efficiency, a mode with an excess air coefficient of = 1.4 was selected, in which a significant proportion of unburned fuel and a high CO concentration were present in the exhaust gases. A search was made for the possibility of increasing the efficiency of combustion not by increasing the excess air coefficient, at which the combustion temperature decreases, but by altering the geometry of the furnace.

Table 7
Parameters in the exit section

Parameters	Excess air ratio (α)							
	1.2	1.3	1.4	1.6	1.8	2.0	2.5	3.0
The amount of unburned fuel								
Mass fraction on vol	0.0256	0.0190	0.0114	0.0049	0.0000	0.0000	0.0000	0.000
Consumption share, %	14	12	7	4	0	0	0	0
The content of harmful components								
a) ppm								
NO_x	10.6	29.2	57.4	132.8	152.9	151.2	117.7	57.5
CO	4769	3438	2253	1114	448	38.6	1.2	0.012
SO_2	563	549	540	505	489	445	361	310
b) flow rate, mg/s								
NO_x	4.5	13.4	28.0	72.9	93.3	101.5	96.9	56.1
CO	1901	1468	1026	571	255	24.2	0.9	0.0
SO_2	526	548	575	606	652	652	649	660
Temperature, K								
average on outlet	1513	1538	1556	1540	1486	1374	1173	1036
maximum in burner	1969	1973	1976	1960	1943	1905	1848	1825
Velocity, m/s	17.7	19.3	20.8	23.1	24.8	25.2	26.4	27.6



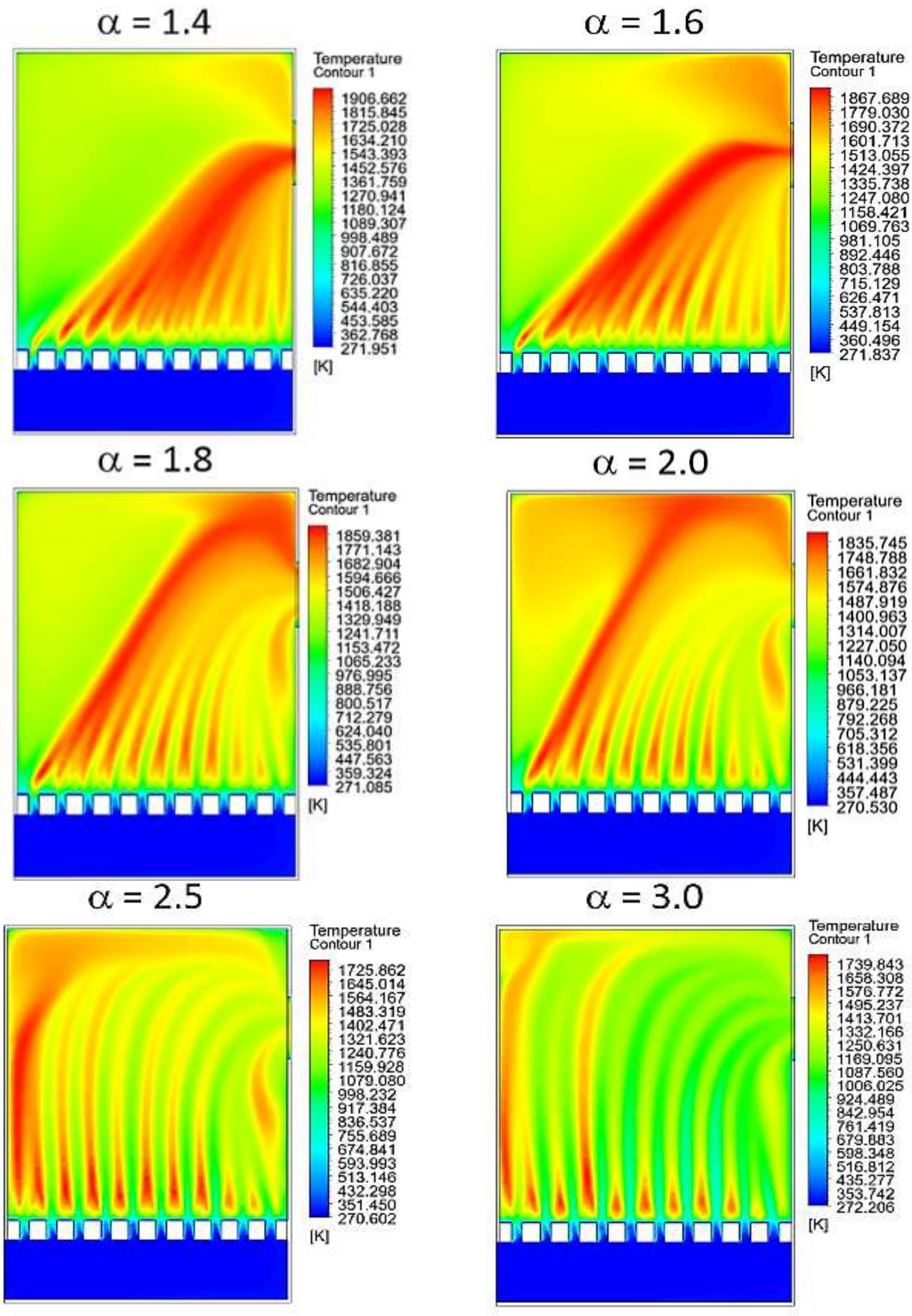


Fig. 7. Temperatures of the gas flow in the boiler section at various coefficients of excess air (base variant)

4.2. Investigation of Combustion with a Change in The Height of the Furnace and The Location of The Exit Window

To investigate the geometric characteristics of the furnace space with regards to combustion efficiency, several options were taken into consideration

Option A (refer to Figure 8). The exit window is situated in the upper plane of the furnace rather than the side wall, while retaining its dimensions of 0.25 x 0.4 meters. The placement of the tube bundle in this design can either be situated above the furnace or connected to it through a flue.

Option B involves the act of increasing the furnace's height from 1.87 m to 3 m, while also preserving the proportions of the exit window at 0.25 x 0.4 m.

Option C. The location of the exit window on the side wall with its width increasing to the width of the wall and located in its upper part (0.715 x 0.4 m). One stroke of the tube bundle must be.

Option D. An additional increase in the height of the exit window by 1.5 times (0.715 x 0.6 m). The air flow rate corresponding to α = 1.40 was established in the computation.

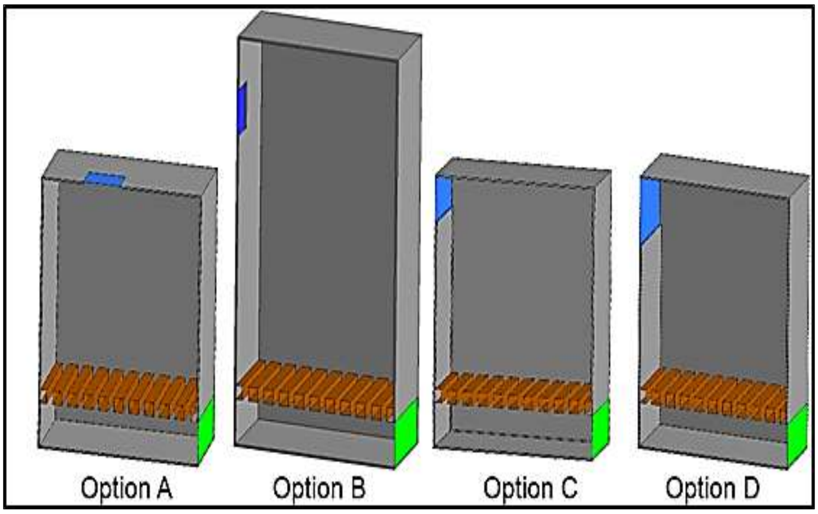
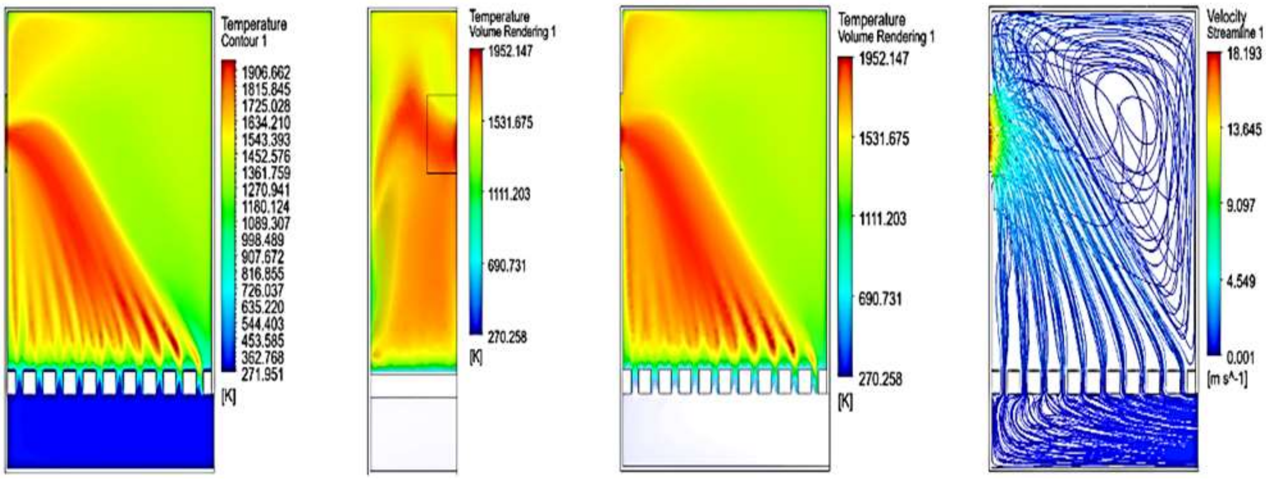


Fig. 8. Scheme of the boiler plant

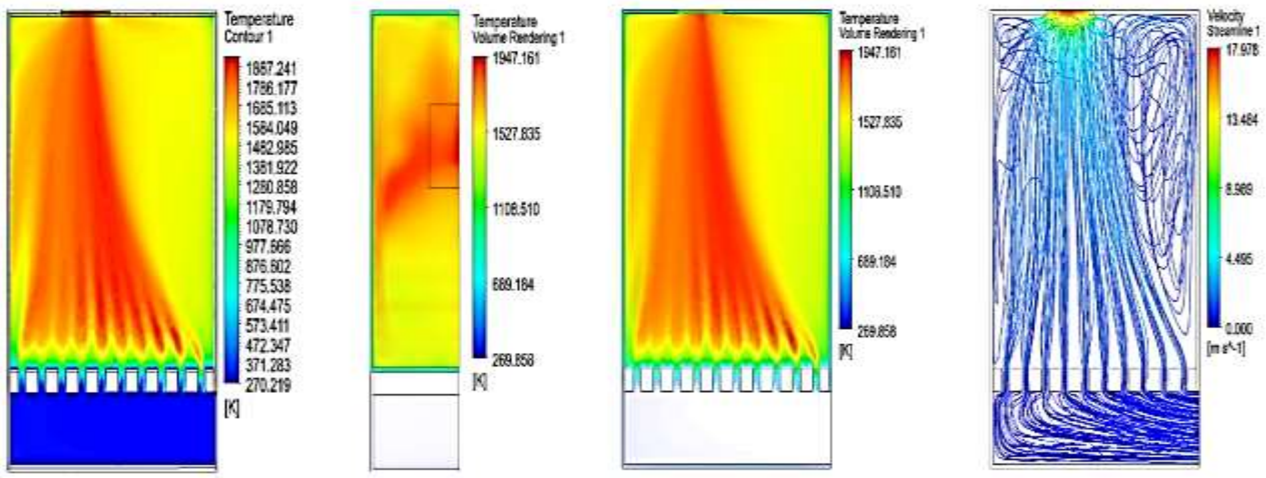
Table 8 presents the primary outcomes derived from the modeling of four alternative designs for the furnace, while Figure 9 illustrates the temperature distributions within the gas flow.

Table 8
Parameters in the exit section (base variant)

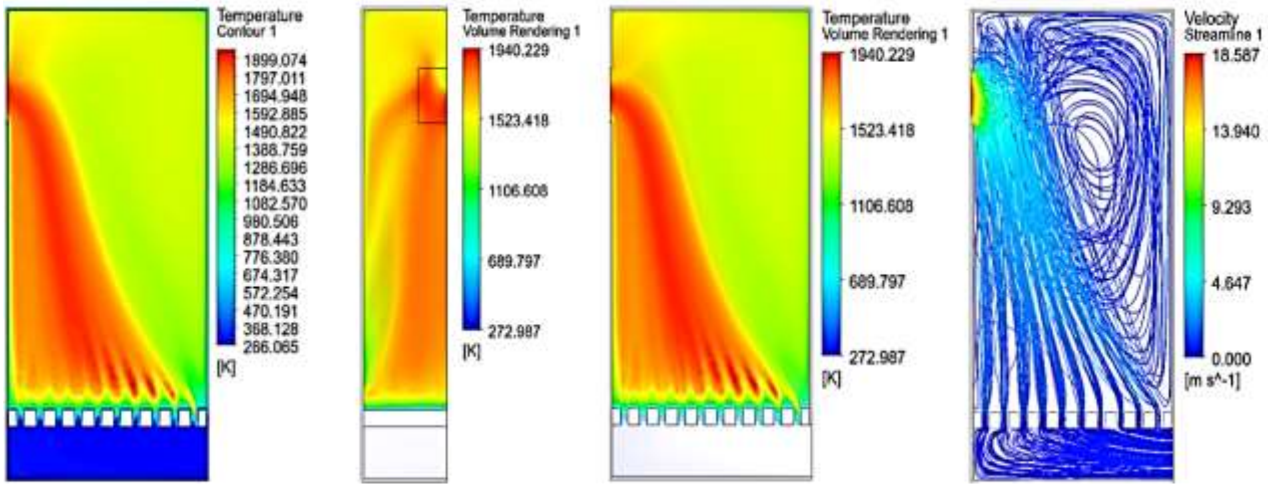
Parameters	Option				Basic option of geometry (α = 1,4)
	A	B	C	D	
The amount of unburned fuel					
Mass fraction on vol.	0.0099	0.0103	0.0101	0.0091	0.0114
Consumption share, %	6.4%	6.6%	6.5%	5.9%	7.4%
The content of harmful components					
a) ppm					
NOx	27.5	35.8	54.4	69.8	57.4
CO	2696	2351	1992	1798	2253
SO2	544	552	544	535	540
b) flow rate, mg/s					
NOx	13.5	17.5	26.5	34.1	28.0
CO	1228	1071	907	819	1026
SO2	580	589	580	570	575
Temperature, K					
Average on outlet	1563	1558	1558	1525	1556
Maximum in burner	1937	1950	1966	1979	1976
Velocity, m/s	20.9	20.8	7.27	4.75	20.8



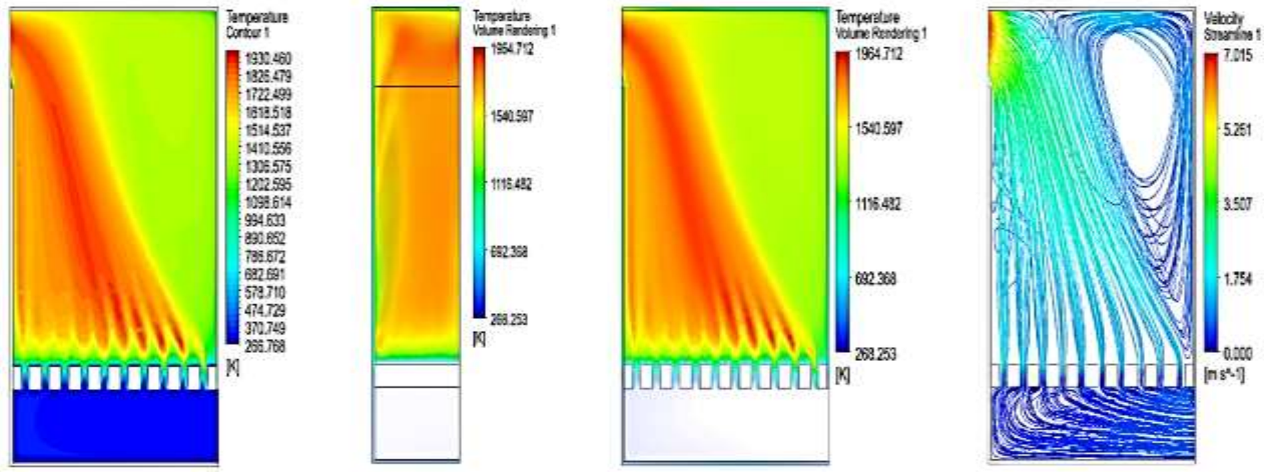
(a)



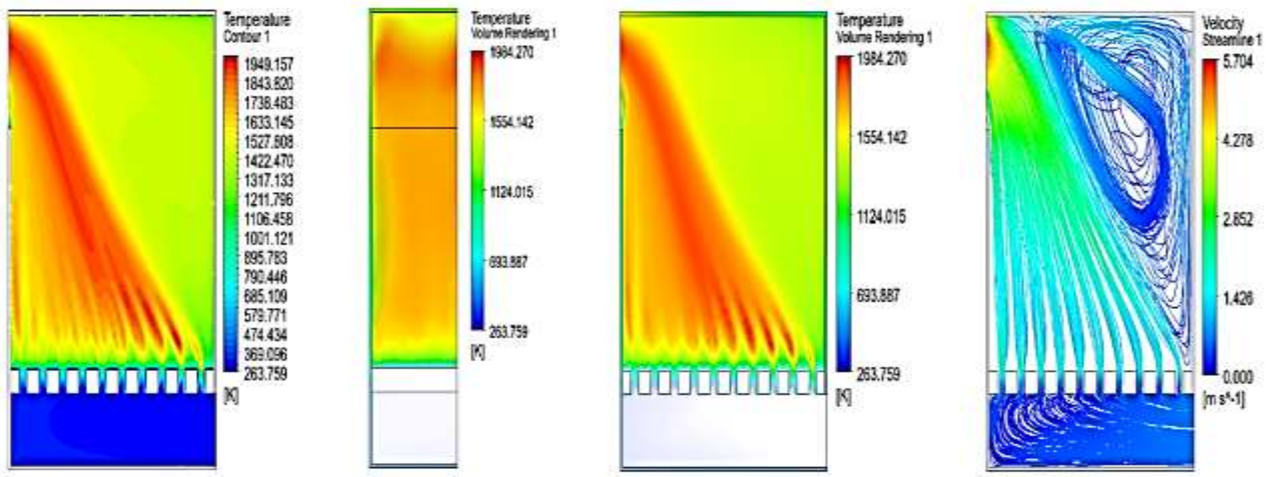
(b)



(c)



(d)

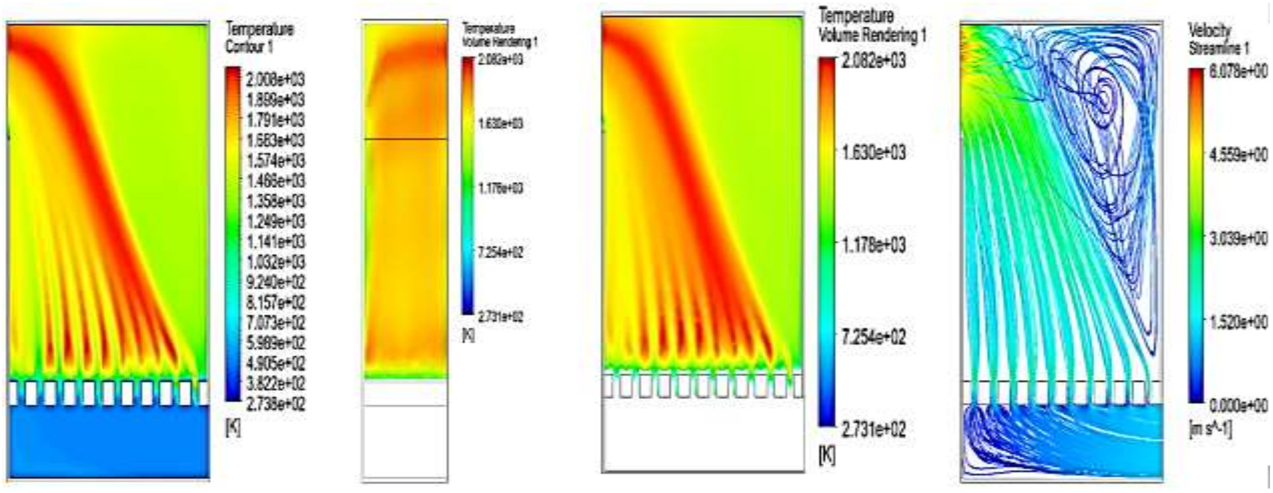


(e)

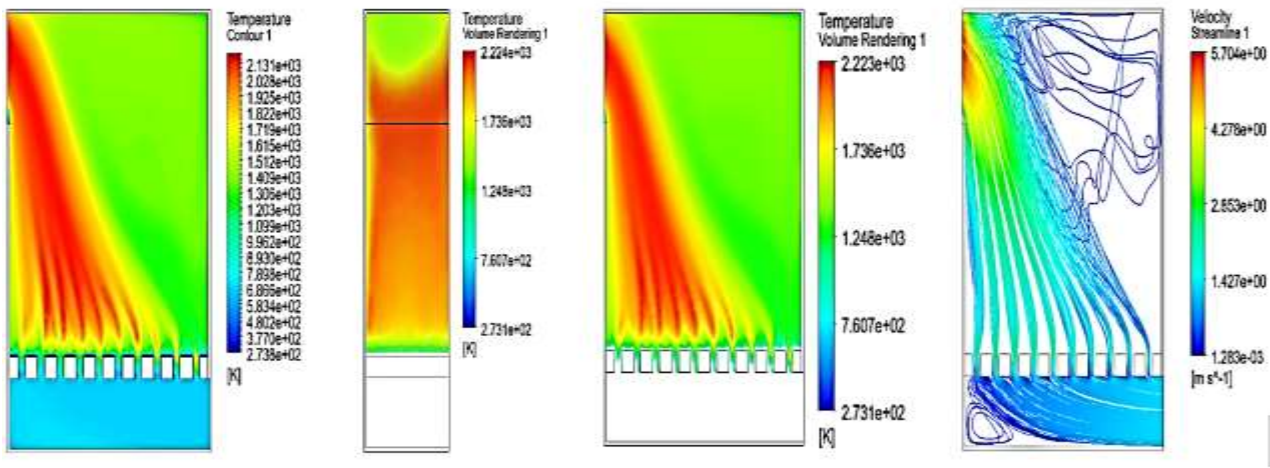
Fig. 9. Temperature and velocity fields in the boiler section (four design options), (a) Basic option, (b) Option A, (c) Option B, (d) Option C, (e) Option D

4.3. Investigation of Combustion with a Change in Air Temperature

In conclusion, this study examined the impact of air temperature on combustion efficiency in a furnace operating at an air flow rate corresponding to α = 1.4. The experimental setup employed the Option D design, with the air temperature fed to the boiler being set at 200 and 400 °C (473 and 673 K). The computation results are displayed in Table 9 and Figure 10.



(a)



(b)

Fig. 10. Fields of temperatures and velocities in the boiler section (when the air temperature changes), (a) t_{air} = 473K (200°C), (b) t_{air} = 673K (400°C)

Table 9
Parameters in the exit section

Parameters	Air temperature t_{air}		Option D, α = 1.4, t_{air} = 273K)
	673K	473K	
The amount of unburned fuel			
Mass fraction on vol.	0.0115	0.0117	0.0091
Consumption share, %	7.4%	7.6%	5.9%
The content of harmful components			
NO_x	266.4	72.2	69.8
CO	1909	2750	1798
SO_2	540	562	535
b) flow rate, mg/s			
NOx	130.1	35.3	34.1
CO	869	1252	819
SO_2	575	599	570
Temperature, K			
average on outlet	1779	1630	1525
maximum in burner	2196	2063	1979
Velocity, m/s	5.5	5.1	4.7

The primary determinant of combustion is the ratio of un-combusted fuel present at the output of the furnace. In the context of Ansys Fluent, the term used to denote this quantity is "mass fraction on volume" (expressed in kilograms per kilogram). The proportion of unburned fuel (F_{uf}) can be determined by utilizing the value of M_{fv} along with the given fuel consumption data:

$$F_{uf} = M_{fv} M_{cp} / M_f \cdot 100\% \quad (2)$$

The amount of unburned fuel at the outflow of the furnace drops as the excess air coefficient increases, reaching zero at an excess air coefficient of α = 1.8, as shown in Figure 11. The alteration of the furnace dimensions, as well as the dimensions and placement of the exit cone, does not exert any influence on the ratio of un combusted fuel, irrespective of the air temperature. Here Mcp and Mf are the mass flow rates of combustion products and fuel, kg/s Table 4.

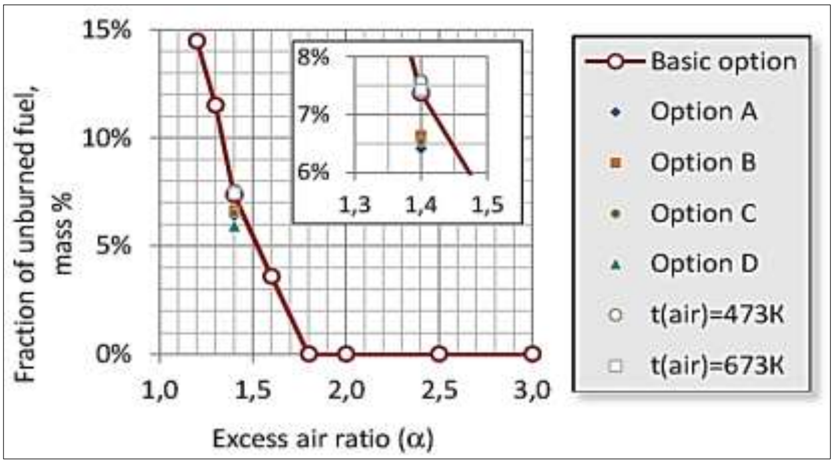


Fig. 11. The proportion of unburned fuel at various excess air ratios

The carbon monoxide (CO) concentration at the furnace outlet is indicative of the degree to which fuel combustion has been achieved. The combustion efficiency is observed to increase as the extra air ratio is increased, resulting in a decrease in its content, as illustrated in Figure 12. The carbon monoxide (CO) concentration reaches zero when the value of the parameter α = 2.

The sulfur dioxide (SO_2) concentration is contingent upon the specific composition of the fuel utilized. Hence, it can be shown that the mass flow rate of sulfur dioxide (SO_2), expressed in milligrams per second (mg/s), is only contingent upon the mass flow rate of the fuel being combusted (as depicted in Figure 12). As the fraction of unburned fuel decreases, there is an observed increase in the mass flow rate of SO_2. Once the proportion of unburned fuel reaches F_{uf} = 0%, the mass flow rate of SO_2 stabilizes and remains constant.

The impact of an excessive amount of air on the generation of nitrogen oxides is characterized by a significant correlation, reaching its peak at α values ranging from 1.15 to 1.25 for oil-gas boilers and α values ranging from 1.4 to 1.5 for pulverized coal boilers. The specific values are contingent upon the burner design and the condition of the combustion chamber [46,47]. It can be postulated that in the case of lower-quality solid fuel, the peak value of nitrogen oxide generation will occur at a higher value of α. The modeling analysis indicated that the highest production of nitrogen oxides during the process of trash incineration will occur at an alpha value ranging from 1.8 to 2.0, as depicted in Figure 12. As the value of α continues to rise, the production of nitrogen oxides starts to decline because of a reduction in the temperature of combustion. It can be concluded that the obtained simulation results are consistent with the main theoretical provisions in the field of fuel combustion.

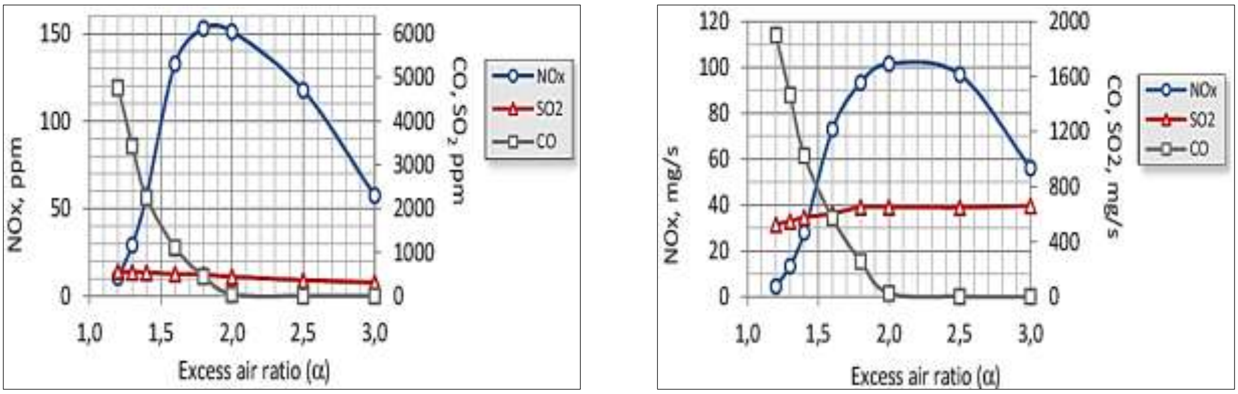


Fig. 12. Average content of NO_x, CO and SO_2 in the furnace outlet window (basic option)

During the simulation, two values of temperatures were determined:

i) is the average temperature of the gases in the cross section of the exit window.
ii) is the maximum temperature in the furnace.

Figure 13 displays the temperatures acquired by modeling, while also presenting the adiabatic flame temperature at varying α values, as depicted in Table 4. The temperature of the combustion products (Tout) is expected to drop with complete combustion of the fuel. However, due to incomplete combustion, the average temperature of the gases at the output of the furnace remains rather stable until the value α =1.6. Once the combustion process reaches its completion, the temperature of the resulting products experiences a decline that mirrors the magnitude of the adiabatic flame temperature (Tad). The dissimilarity between Tad and Tout values can be elucidated by the heat losses that occur through the boiler furnace wall. Outlet temperature (Tout) is the average temperature in the output window; maximum temperature (Tmax) is the utmost furnace temperature; "Tad" is the adiabatic combustion temperature.

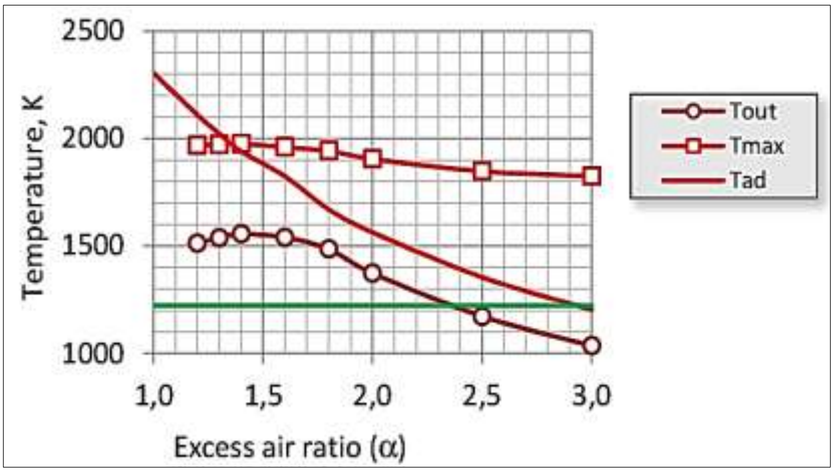


Fig. 13. Temperatures in the boiler when changing the coefficient of excess air

As shown in Figure 14 the temperature within the furnace exceeds the fuel layer in the combustion zone. The result is dependent on the rate of combustion chemical reaction, as well as the pace at which oxygen is supplied to the combustion zone. Hence, in juxtaposition to the adiabatic flame temperature and the mean temperature at the furnace output, its dependence on the surplus air coefficient is minimal. As the value of α increases, the combustion products after the zone of maximum temperature experience a dilution effect due to the presence of surplus air, resulting in a reduction in the average temperature of the gases.

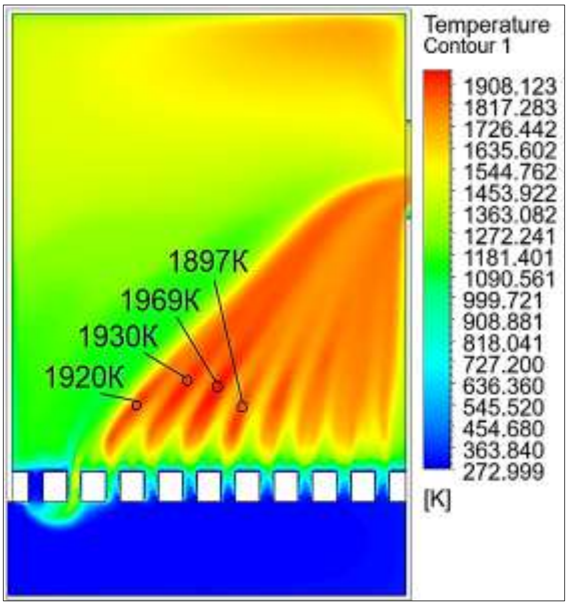


Fig. 14. The position of the maximum temperatures in the furnace (α = 1,2)

The increase of the air temperature provided for combustion results in a corresponding rise in both the maximum temperature within the furnace and the average temperature of the gases at the furnace output see Figure 15. The elevation of air temperature by 200K results in a corresponding rise of approximately 100K in both the maximum and average temperatures seen at the exit of the furnace. The rise in Tout and Tad exhibits comparable characteristics.

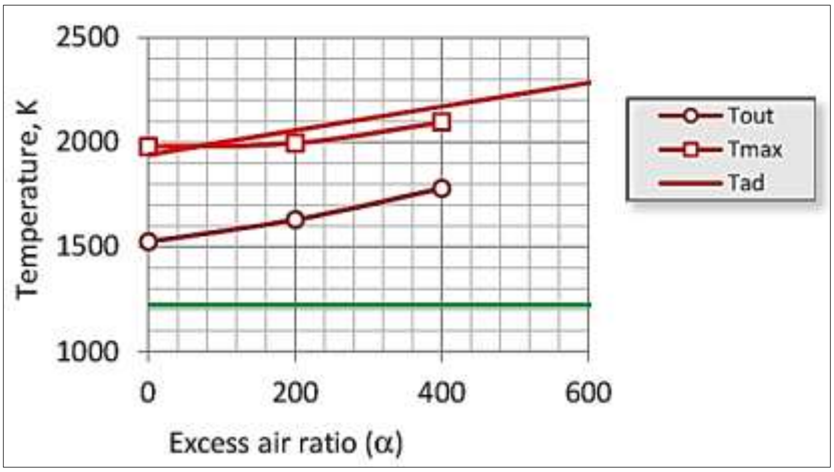


Fig. 15. Temperatures in the boiler when the air temperature changes: "Tout" is the average temperature in the output window; "Tmax" is the utmost furnace temperature; "Tad" is the adiabatic combustion temperature

The temperature at which complete combustion of dangerous substances is attained is indicated by the green line in Figures 12 and 14, corresponding to a value of 850°C (1123K). The temperature of the gases at the exit of the furnace lowers under this limit when α ≥ 2.35.

Based on the simulation results, the following conclusions can be drawn.

i) The outcomes obtained from the computation of the combustion of a solid fuel layer on a grate align with the theoretical principles governing the combustion process, hence indicating the suitability of the created model.
ii) A range of values, specifically α = 2…2.35, has been determined to guarantee the achievement of complete combustion of the fuel, as well as the minimal emission of NO_x, SO_2, and CO. This range is applicable while the temperature of the gases exiting the furnace remains above 850°C.
iii) Modifications such as enlarging the furnace, altering the size and placement of the exit window, and elevating the temperature of the air provided for combustion do not exert any influence on the efficiency of the combustion process. However, a rise in atmospheric temperature facilitates an elevation in the temperature of gases.

5. Conclusion

A comprehensive computational fluid dynamics (CFD) model was utilized to conduct microcomputer simulations and modeling of biomass combustion plants in boilers. The simulations were carried out using Ansys Fluent software, along with theoretical calculations, to assess the combustion performance, temperatures, and emission characteristics that arise from the combustion of solid fuels within the thermal boiler and at the outlet port. The present study involved the examination of a unique three-dimensional model in order to comprehensively evaluate various flow and mixing phenomena. Displacement gases, which possess combustion and generation temperatures that are pertinent to the biomass grid, are produced by considering the eight varied ratios of surplus air that are fed into the convection boiler via the input. Under the experimental settings of atmospheric pressure and a temperature of 273 K, it was discovered that varying percentages of air introduced into the system had a discernible impact on the thermal efficiency of the boiler. This resulted in noticeable alterations in flame morphology, temperature profiles, and corresponding numerical values.

The present study presents a proposed model for the combustion process of a solid fuel layer over a grate, commonly employed in boilers with limited capacity. The analysis of the acquired outcomes indicates a congruence with the theoretical rules governing the combustion process. It has been determined that the combustion efficiency is only influenced by the value of the excess air coefficient α. The establishment of a specific interval, denoted as α, is necessary for the purpose of waste incineration. This interval is crucial in guaranteeing the thorough burning of waste materials and ensuring that the gas temperatures at the boiler outlet meet the necessary environmental standards.

Acknowledgement
This work was realized in the framework of the Program "Priority 2030" on the base of the Belgorod State Technological University named after V.G. Shukhov. The work was realized using equipment of High Technology Center at BSTU named after V.G. Shukhov.

References

[1] Golgiyaz, Sedat, Muhammed Fatih Talu, Mahmut Daşkın, and Cem Onat. "Estimation of excess air coefficient on coal combustion processes via gauss model and artificial neural network." *Alexandria Engineering Journal* 61, no. 2 (2022): 1079-1089. https://doi.org/10.1016/j.aej.2021.06.022.
[2] Harsono, Soni Sisbudi, B. Prayogo, Maizirwan Mel, and Fabrobi Ridha. "Effect of Holes System Designing for Low Energy Stove Using Coffee Husk Bio-Pellet as Solid Fuel." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 51, no. 2 (2018): 215-226.
[3] Dewangan, Satish Kumar, Moode Praveen Kumar Naik, and Vivek Deshmukh. "Parametric study of the non-premixed coal combustion in furnace for heat transfer and emission characteristics." *Journal of Thermal Engineering* 6, no. 6 (2020): 323-353. https://doi.org/10.18186/THERMAL.833556.
[4] Ismail, Ras Izzati, Khor Chu Yee, Alina Rahayu Mohamed, Nik Muhammad Khairi Nik Mustafa, Lee Yit Leng, Nur Lailina Makhtar, and Norawanis Abd Razak. "The Effect of Different Waste Material Binders in Relation to Khaya Senegalensis Solid Fuel Pellet Quality." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 32, no. 3 (2023): 151-164. https://doi.org/10.37934/araset.32.3.151164
[5] Chen, Dezhen, Lijie Yin, Huan Wang, and Pinjing He. "Pyrolysis technologies for municipal solid waste: a review." *Waste management* 34, no. 12 (2014): 2466-2486. https://doi.org/10.1016/j.wasman.2014.08.004.
[6] Safarian, Sahar, Rúnar Unnþórsson, and Christiaan Richter. "A review of biomass gasification modelling." *Renewable and Sustainable Energy Reviews* 110 (2019): 378-391. https://doi.org/10.1016/j.rser.2019.05.003
[7] Kim, Gyeong-Min, Jae Hyung Choi, Chung-Hwan Jeon, and Dong-Ha Lim. "Effects of cofiring coal and biomass fuel on the pulverized coal injection combustion zone in blast furnaces." *Energies* 15, no. 2 (2022): 655. https://doi.org/10.3390/en15020655
[8] Shatalov, A. V., A. N. Maslovskaya, V. A. Shatalov, and U. V. Golubeva. "Disintegrator with intensive action on the ground material." In *Digital Technologies in Construction Engineering: Selected Papers*, pp. 201-207. Cham: Springer International Publishing, 2021. https://doi.org/10.18412/1816-0395-2020-12-11-15
[9] Milne, Thomas A., Robert J. Evans, and N. Abatzaglou. "Biomass gasifier''Tars'': their nature, formation, and conversion." (1998). https://doi.org/10.2172/3726
[10] Xie, Jun, Wenqi Zhong, Yingjuan Shao, Qian Liu, Longhai Liu, and Guoyao Liu. "Simulation of combustion of municipal solid waste and coal in an industrial-scale circulating fluidized bed boiler." *Energy & fuels* 31, no. 12 (2017): 14248-14261. https://doi.org/10.1021/acs.energyfuels.7b02693
[11] Rokni, Emad, Aidin Panahi, Xiaohan Ren, and Yiannis A. Levendis. "Reduction of sulfur dioxide emissions by burning coal blends." *Journal of Energy Resources Technology* 138, no. 3 (2016): 032204. https://doi.org/10.1115/1.4032239
[12] Sukarni, Sukarni, Sumarli Sumarli, Teguh Achmad Firdaus, and Ardianto Prasetiyo. "The Catalytic Impact of MnO Additive on the Selected Municipal Solid Waste Combustion Behavior Determined by Thermogravimetric Analysis." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 71, no. 1 (2020): 50-59. https://doi.org/10.37934/arfmts.71.1.5059
[13] Kulkarni, Bhargavi N., and V. Anantharama. "Solid Waste to Energy: A Prognostic for Sound Waste Management."

Handbook of Solid Waste Management: Sustainability through Circular Economy (2020): 1-33. https://doi.org/10.1007/978-981-15-7525-9_86-1
[14] Glagolev, S. N., V. S. Sevostyanov, T. N. Ilyina, and V. I. Uralskii. "Production modules for combined reprocessing of technogenic materials." *Chemical and Petroleum Engineering* 46 (2011): 556-559. https://doi.org/10.1007/s10556-011-9376-3
[15] Houshfar, Ehsan, Øyvind Skreiberg, Terese Løvås, Dušan Todorović, and Lars Sørum. "Effect of excess air ratio and temperature on NOx emission from grate combustion of biomass in the staged air combustion scenario." *Energy & Fuels* 25, no. 10 (2011): 4643-4654. https://doi.org/10.1021/ef200714d
[16] Rahman, Nik Kechik Mujahidah Nik Abdul, Syamimi Saadon, and Mohd Hasrizam Che Man. "Waste Heat Recovery of Biomass Based Industrial Boilers by Using Stirling Engine." *Journal of Advanced Research in Applied Mechanics* 81, no. 1 (2021): 1-10. https://doi.org/10.37934/arfmts.89.1.112
[17] Holkar, Rajesh, and Omprakash D. Hebbal. "CFD Anlysis of Pulverised-Coal Combustion of Burner Used In Furnace with Different Radiation Models." *IOSR Journal of Mechanical and Civil Engineering* 5, no. 2 (2013): 25-34. https://doi.org/10.9790/1684-0522534
[18] de Jong, Wiebren. "Biomass composition, properties, and characterization." *Biomass as a sustainable energy source for the future: Fundamentals of conversion processes* (2014): 36-68. https://doi.org/10.1002/9781118916643.ch2
[19] Tanprasert, Sorathan, Nuttima Rangton, Warunee Nukkhong, Pitakchon Wises, Pornpote Piumsomboon, and Benjapon Chalermsinsuwan. "Impact of Biomass Fuel Feeding Ratio in Co-firing Circulating Fluidized Bed Boiler: A Computational Fluid Dynamics Study." *Journal of Advanced Research in Numerical Heat Transfer* 17, no. 1 (2024): 44-54. https://doi.org/10.37934/arnht.17.1.4454.
[20] Qing, Nelvin Kaw Chee, Nor Afzanizam Samiran, and Razlin Abd Rashid. "CFD Simulation analysis of Sub-Component in Municipal Solid Waste Gasification using Plasma Downdraft Technique." *CFD Letters* 14, no. 8 (2022): 63-70. https://doi.org/10.37934/cfdl.14.8.6370.
[21] F. Li, Zhang Cao, Lijun Xu, Yixin Xie, Prediction of equivalence ratio in pulse combustor from ion current amplitude spectrum, *Fuel* 218 (2018) 179–187. https://doi.org/10.1016/j.fuel.2018.01.004
[22] Konovalov V, Goncharov A, Fedorov A., Moshkov I, Gostev N, "Combustion of RDF fuel using oxygen blast". Vestn. Belgorodskogo Gos. Tekhnologicheskogo Univ. Im. V G Shukhova 7, no. 10 (2022): 79–86. https://doi.org/10.34031/2071-7318-2022-7-10-79-86
[23] Mahmoudi, Amir Houshang, Xavier Besseron, Florian Hoffmann, Miladin Markovic, and Bernhard Peters. "Modeling of the biomass combustion on a forward acting grate using XDEM." *Chemical engineering science* 142 (2016): 32-41. https://doi.org/10.1016/j.ces.2015.11.015.
[24] Karyeyen, Serhat, and Mustafa Ilbas. "Experimental and numerical analysis of turbulent premixed combustion of low calorific value coal gases in a generated premixed burner." *Fuel* 220 (2018): 586-598. https://doi.org/10.1016/j.fuel.2018.02.052.
[25] Yin, Chungen, Lasse A. Rosendahl, and Søren K. Kær. "Grate-firing of biomass for heat and power production." *Progress in Energy and combustion Science* 34, no. 6 (2008): 725-754. https://doi.org/10.1016/j.pecs.2008.05.002.
[26] Mostafa, Mohamed E., Limo He, Jun Xu, Song Hu, Yi Wang, Sheng Su, Xun Hu, Saad A. Elsayed, and Jun Xiang. "Investigating the effect of integrated CO2 and H2O on the reactivity and kinetics of biomass pellets oxy-steam combustion using new double parallel volumetric model (DVM)." *Energy* 179 (2019): 343-357. https://doi.org/10.1016/j.energy.2019.03.156
[27] Anca-Couce, Andrés, Georg Archan, Markus Buchmayr, Michael Essl, Christoph Hochenauer, and Robert Scharler. "Modelling fuel flexibility in fixed-bed biomass conversion with a low primary air ratio in an updraft configuration." *Fuel* 296 (2021): 120-687. https://doi.org/10.1016/j.fuel.2021.120687.
[28] Liang, Zhanwei, Hongwei Chen, Bin Zhao, Jiandong Jia, and Kai Cheng. "Synergetic effects of firing gases/coal blends and adopting deep air staging on combustion characteristics." *Applied energy* 228 (2018): 499-511. https://doi.org/10.1016/j.apenergy.2018.06.116.
[29] Sun, Rui, Tamer M. Ismail, Xiaohan Ren, and M. Abd El-Salam. "Influence of simulated MSW sizes on the combustion process in a fixed bed: CFD and experimental approaches." *Waste management* 49 (2016): 272-286. https://doi.org/10.1016/j.wasman.2015.12.019
[30] Simanjuntak, Janter Pangaduan, Samsudin Anis, Mochamad Syamsiro, Eka Daryanto, and Bisrul Hapis Tambunan. "Thermal Energy Storage System from Household Wastes Combustion: System Design and Parameter Study." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 80, no. 2 (2021): 115-126. https://doi.org/10.37934/arfmts.80.2.115126
[31] Moon, Cheoreon, Yonmo Sung, Seongyool Ahn, Taekyung Kim, Gyungmin Choi, and Duckjool Kim. "Thermochemical and combustion behaviors of coals of different ranks and their blends for pulverized-coal combustion." *Applied Thermal Engineering* 54, no. 1 (2013): 111-119. https://doi.org/10.1016/j.applthermaleng.2013.01.009

[32] Kasakura, Tadao, and Masakatsu Hiraoka. "Pilot plant study on sewage sludge pyrolysis—II." *Water research* 16, no. 12 (1982): 1569-1575. https://doi.org/10.1016/0043-1354(82)90233-0
[33] Parsa, Mehdi, Ali Vahidian Kamyad, and Mohammad Bagher Naghibi Sistani. "Combustion efficiency optimization by adjusting the amount of excess air." In *2014 5th Conference on Thermal Power Plants (CTPP)*, pp. 103-108. IEEE, 2014. https://doi.org/10.1109/CTPP.2014.7040703
[34] Purvis, M. R. I., E. L. Tadulan, and A. S. Tariq. "NOx control by air staging in a small biomass fuelled underfeed stoker." *International journal of energy research* 24, no. 10 (2000): 917-933. https://doi.org/10.1002/1099-114X(200008)24:10<917::AID-ER685>3.0.CO;2-5
[35] Spliethoff, H., M. Kaltschmitt, and A. Mory. "Energie aus Biomasse: Grundlagen, Techniken und Verfahren." (2001).
[36] Wang, Yu, Yixin Shao, Miodrag Darko Matovic, and Joann K. Whalen. "Exploring switchgrass and hardwood combustion on excess air and ash fouling/slagging potential: Laboratory combustion test and thermogravimetric kinetic analysis." *Energy conversion and management* 97 (2015): 409-419. https://doi.org/10.1016/j.enconman.2015.03.070
[37] Szufa, S., P. Piersa, R. Junga, A. Błaszczuk, N. Modliński, S. Sobek, M. Marczak-Grzesik, and M. Dzikuć. "Numerical modeling of the co-firing process of an in situ steam-torrefied biomass with coal in a 230 MW industrial-scale boiler." *Energy* 263 (2023): 125-918. https://doi.org/10.1016/j.energy.2022.125918
[38] Wang, Yanhong, Xiaoyu Li, Tianqin Mao, Pengfei Hu, and Xingcan Li. "Mechanism modeling of optimal excess air coefficient for operating in coal fired boiler." *Energy* 261 (2022): 125-128. https://doi.org/10.1016/j.energy.2022.125128
[39] Bochkarev, V. A., I. V. Dykus, A. G. Frolov, and V. V. Khan. "Organization of vortex smoke gaz movement over the fuel layer to increase the efficiency of the work boiler unit KVm-2, 5 in the village of Mishelevka, Usolsky district, Irkutsk region." In *IOP Conference Series: Earth and Environmental Science*, vol. 751, no. 1, p. 012003. IOP Publishing, 2021. https://doi.org/10.1088/1755-1315/751/1/012003.
[40] Bhuiyan, Arafat A., and Jamal Naser. "CFD modelling of co-firing of biomass with coal under oxy-fuel combustion in a large scale power plant." *Fuel* 159 (2015): 150-168. https://doi.org/10.1016/j.fuel.2015.06.058
[41] Elattar, H. F., Rayko Stanev, Eckehard Specht, and A. Fouda. "CFD simulation of confined non-premixed jet flames in rotary kilns for gaseous fuels." *Computers & Fluids* 102 (2014): 62-73. https://doi.org/10.1016/j.compfluid.2014.05.033
[42] Zhou, Shiquan, Aragona Patty, and Shiming Chen. "Advances in Energy Science and Equipment Engineering II." In *Proceedings of the 2 nd International Conference on Energy Equipment Science and Engineering (ICEESE 2016)*, pp. 12-14. 2017. https://doi.org/10.14299/ijser.2021.07.02.
[43] Thabit, Qahtan, Abdallah Nassour, and Michael Nelles. "Flue gas composition and treatment potential of a waste incineration plant." *Applied Sciences* 12, no. 10 (2022): 5-236. https://doi.org/10.3390/app12105236
[44] Kornilova, N. V., and P. A. Trubaev. "Analysis of MSW Combustion temperature in a hot water boiler with the low-capacity." In *Journal of Physics: Conference Series*, vol. 1066, no. 1, p. 012003. IOP Publishing, 2018. https://doi.org/10.1088/1742-6596/1066/1/012003
[45] Rasheed, M. A., PL Srinivasa Rao, Annapurna Boruah, Syed Zaheer Hasan, Arpit Patel, Vaidik Velani, and Khamosh Patel. "Geochemical characterization of coals using proximate and ultimate analysis of Tadkeshwar Coals, Gujarat." *Geosciences* 5, no. 4 (2015): 113-119. http://journal.sapub.org/geo.
[46] Blarke, Morten B. "Towards an intermittency-friendly energy system: Comparing electric boilers and heat pumps in distributed cogeneration." *Applied Energy* 91, no. 1 (2012): 349-365. https://doi.org/10.1016/j.apenergy.2011.09.038
[47] Anufriev, Igor S., Evgeny P. Kopyev, Ivan S. Sadkin, and Mariia A. Mukhina. "NOx reduction by steam injection method during liquid fuel and waste burning." *Process safety and environmental protection* 152 (2021): 240-248. https://doi.org/10.1016/j.psep.2021.06.016