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# Modeling of Pyrolysis in a Stage Scheme of Low-Grade Solid Fuel Gasification

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Additional information is available at the end of the chapter

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## Abstract

This paper is concerned with the development of a model of wood pyrolysis in a screw reactor as the first stage of the multistage gasification process. In terms of design, the pilot pyrolyzer represents a recuperative heat exchanger where the heat carrier is represented by a mixture of exhaust and recirculation gases. To prevent clinkering of particles and thermal inhomogeneities, screw-type transportation is used to transport fuel. In order to describe kinetics of pyrolysis and transport of volatiles within the wood particles and their transition to the gas phase, we carried out the studies using a complex of synchronous thermal analysis. The original techniques for the interpretation of measurements were developed for this complex, including the techniques for technical analysis of fuels and identification of detailed kinetics and mechanism of pyrolysis. A detailed numerical modeling of pyrolyzer was performed using the Comsol Multiphysics software, which makes it possible to optimize the design and operating parameters of the pyrolysis process in a screw reactor.

**Keywords:** pyrolysis of low-grade solid fuel, multistage gasification, screw reactor, CFD modeling, thermal analysis

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## 1. Introduction

One-stage processes of fuel gasification have been developed and thoroughly studied in Russia and other countries throughout the twentieth century. They remain the basis for the creation and design of modern gasification equipment. Numerous studies showed that the one-stage gasification processes had already achieved the limit of perfection beyond which a considerable improvement in their operating characteristics turned out to be impossible or unprofitable.

The gasification technology meeting the contemporary level of technology development should correspond to the following criteria: (1) the gasifier should operate in automatic, mainly unmanned mode, (2) the gasifier operation should be stable and provide insignificant variations in gas composition and flow rate that randomly occur over time, (3) it should produce the minimum amount of liquid and solid waste, (4) the conversion process should be, if possible, little sensitive to changes in the properties of fuel biomass, that is, moisture content and size of particles, and (5) the efficiency of converting fuel chemical energy into gas chemical energy should reach 80–85%.

The staged gasification technology meets the current technical requirements most completely. In the first stage of the process, the allothermal pyrolysis of biomass is organized using producer gas heat and exhaust gases of an engine unit. In this stage, the volatiles (gas and tar) are produced from the fuel. In the second stage, tar is decomposed under the action of heated air and steam outside the fuel bed. Further, the formed steam-gas mixture reacts with the charcoal in the third stage of the process.

## 2. A review of technologies for multistage solid fuel gasification

One of the first multistage gasifier was developed and patented by Antoine de Lacotte in the 1940s [1, 2]. Oxidative pyrolysis took place in the upper part of fixed-bed reactor. Its gaseous products were taken from the space above the fuel bed and were sent to the external combustion chamber. The oxidation products of the tarred gas returned to the middle part of the fuel bed. One-third of these products were recycled in the pyrolysis stage and two-thirds were involved in the coal-char gasification.

The obtained producer gas was very clean. Diesel internal combustion engine that used this gas could operate without capital maintenance for 30 years [3].

The reactor similar to that designed by Antoine de Lacotte was proposed and patented by the Greek researcher Lampros Elefsiniotis [4]. He installed an air supply to the zone of oxidative pyrolysis in the shaft of a gasifier. Such an improvement makes it possible to control the amount of recycled gas coming from the combustion chamber [5]. A downside of the gasifiers invented by de Lacotte and Elefsiniotis is the low efficiency of gasification, which is caused by high heat losses of the external combustion chamber. There is experience of accommodating this chamber inside the fuel bed [6]. In this case, heat coming from the chamber is used in the pyrolysis process and is not dispersed into the environment.

An interesting design of the multistage gasifier is proposed at the Technical University of Denmark [7, 8]. It differs in that the stage of pyrolysis is separated and takes place in a separate screw reactor whose duct is connected to the space above the fuel bed of the downdraft fixed-bed gasifier. In this space, part of pyrolysis gases is oxidized in the air blow. The combustion products come to the coal-char bed in the third stage of the process. A distinctive feature of this multistage process is an active use of the producer gas heat and exhaust gases of the internal combustion engine to heat the air blow and fuel in the screw pyrolyzer. Chemical efficiency of such an allo-autothermal process reaches 93%, whereas in the autothermal conditions it does

not exceed 75–80% [9, 10]. Moreover, the tar content in the unrefined gas is at the level of 15 mg/nm<sup>3</sup>. Such gas can be used after its conditioning without additional cleaning. The Technical University of Denmark has created a pilot plant Viking with a capacity of 20 kW (E). Its scaled-up version with a capacity of 200 kW (E) was implemented by the Weiss energy company in Denmark [11]. The Viking gasifier can be used to process fuel with a moisture content of up to 30%. An additional screw reactor of the Weiss cogeneration plant intended for fuel drying makes it possible to convert biomass with a high moisture content (up to 60%). The successful design of the Viking gasifier of the Technical University of Denmark inspired some teams to develop and create similar plants. The Tomas Koch group (company TK Energy) simplified the design of the multistage gasifier by refusing from heating the screw reactor and using a complex system of heat recuperation [12]. The air is blown to the pyrolyzer, thus providing partial fuel combustion and operation of this reactor in the autothermal conditions. The pilot plant with a capacity of 2.3 MW (t) is established in the city of Gjol (Denmark).

A pilot plant similar to the Viking gasifier is manufactured by the team from the Institute of Qingdao (China) [13, 14]. They use pelleted biomass as a fuel, and the capacity of the plant makes up 800 kW (t). The researchers from Shanghai Jiao Tong University (China) are developing a multistage gasifier with a capacity of 430 kW (f) for rice straw processing [15]. In the pyrolyzer of this gasifier, there is a fuel piston instead of screw machine. The researchers from the De Cocody University are studying the work of a screw pyrolyzer embedded in the multistage gasifier [16].

However, the gasifier of the Technical University of Denmark and its analogs have one common drawback. The high degree of biomass combustion is reached only for the sized fuel (chipped wood) prepared from solid species of wood. Such a fuel travels across the screw reactor with minimum destruction of particles, their crushing, and abrasion. Moreover, the char bed in the third stage is effectively and stably gasified. There is no critical packing of the char due to accumulation of coal powder and ash. The processing of the polyfraction or pelleted fuel is characterized by its considerable unburned amount. For example, the degree of fuel carbon conversion in the gasifier of the Jiao Tong University makes up 75–80%. Mass fraction of the lost char residue in the plant of the TK energy reaches 3–10%. Such a considerable amount of unburned fuel leads to a decrease in the gasification efficiency and requires measures for its further processing and utilization.

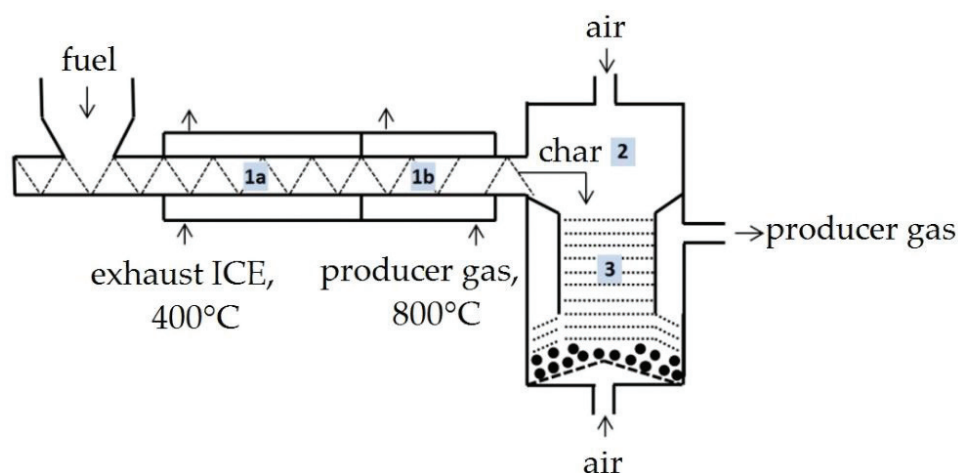
It is worth noting that to date none of the created plants has been scaled-up and reached the stage of commercial production despite its successful demonstration and a large amount of patents. It is also possible to state that the multistage gasification technology is developed much more slowly than the one-stage gasification technologies in the 1990s, even despite a considerable rise in the fossil fuel prices. There are technical difficulties hindering the widespread adoption of the technology, for example, (1) The number of operating parameters that have an effect on the gasifier operation exceeds 11. This circumstance complicates optimization of its operating conditions. (2) Low temperature of the third stage of the process prevents complete combustion of the residual coal, thus leading to a decline in the gasification efficiency and formation of a great amount of solid waste. (3) Operation of the modern gas-fired equipment (internal combustion engine, fuel cell, gas microturbine, etc.) requires additional removal of tars from gas to the level of 5–100 mg/nm<sup>3</sup>. Fine gas cleaning makes the technology much

more expensive. Optimization of the second and third stages of the process is required to obtain an almost tar-free gas.

Thus, the development of a promising low-tonnage technology for staged gasification of wood biomass should rest on a detailed research into thermal physics and chemical kinetics of the processes that occur in the equipment components.

In this research, we propose a new concept of staged gasifier, which suggests apart from the use of a screw pyrolyzer the application of a hybrid fixed-bed reactor combining both down-draft and updraft processes. In this case, the tangential air supply is used, which provides good mixing of pyrolysis gases with oxidizer, and, consequently, a high speed and complete decomposition of tar. Such an organization of the process makes it possible to gasify char not only by the entrained flow of incomplete oxidation products of pyrolysis gas obtained in the first stage but also by heated air blow in the process countercurrent with respect to the fuel motion. A block diagram of the developed multistage reactor is presented in **Figure 1**.

This paper presents the results of the research into the first stage of the multistage gasification, that is, allothermal wood pyrolysis in a screw reactor.



**Figure 1.** A block diagram of the plant for multistage gasification. Notations: 1—screw pyrolyzer heated by the internal combustion engine (ICE) exhaust gases; 2—space above the fuel bed, producer gas combustion chamber; 3—a two-stage fixed-bed reactor.

### 3. The methods for CFD modeling of wood biomass pyrolysis process

In the last years, there has been continuous evolution of the calculation models of pyrolysis plants. The research presented in [17] shows a mathematical description of the pyrolysis process. The authors devised a calculation model for the plant designed by them. The model consists of a set of stages of drying, thermal decomposition, interphase transitions, and cooling. Thus, the total duration of the wood feedstock decomposition  $\tau_m$  process was represented by a set of stages: heating  $\tau_{mv}$ , drying  $\tau_d$ , thermal decomposition  $\tau_{td}$ , and cooling of char coal  $\tau_c$ . This method allowed the common model to be decomposed into submodels suitable for practical implementation that have different degrees of detail and respective form of equations (ordinary differential or in partial differential). A distinctive feature of this problem statement is the use of a

one-dimension representation of distribution of parameters in the space of pyrolyzer chamber. Change in the temperature of gas phase during its passing through the fuel bed was determined from the following equation:

$$\frac{\partial T_1}{\partial \tau} = \frac{\alpha \Delta T F}{(\rho c) V} - w \frac{\partial T}{\partial z}, \quad (1)$$

Solving Eq. (1) and equation of heat conductance for a solid fuel particle made it possible to take into consideration interphase heat exchange:

$$\frac{\partial T_f}{\partial \tau} = \frac{1}{c p x^g} - \frac{\partial}{\partial x_f} \left( x^g \lambda \frac{\partial T_f}{\partial x_f} \right), \quad (2)$$

Moisture content in a fuel particle was determined by the authors [17] from the following expression:

$$\frac{dW}{d\tau} = \frac{\beta(p_p - p)}{\rho V_2}, \quad (3)$$

Solving Eqs. (2) and (3) with the calculation of partial pressure made it possible to determine the duration of a drying stage.

In the same way, the authors of [17] describe all the above-enumerated stages. The only assumption in their model was the absence of nonuniform distribution of parameters in the cross section. To verify their model, the authors of [17] made an experimental bench since in their case, as in many other studies, verification of the constructed mathematical models is based on the unique experimental data. This complicates a comparative analysis of the proposed approaches to the selection of the best description of the processes that occur in similar plants.

A more thorough study on partial gasification, on the basis of a numerical modeling and application of thermogravimetric analysis, is presented in the recent publications [18, 19]. For example, in the research [20] the authors applied a three-dimensional (3D) representation of the calculated region, which made it possible to more accurately determine variation in temperature profiles and gas motion velocities along the modeled furnace. Thus, a good correspondence was achieved between the calculated data and the experimentally measured process of fuel conversion. The model in [21] included the following equations:

$$r = k^f \prod_{i=1}^N c_i^v = A^f T^f \exp(E_a^f / R_g T) \prod_{i=1}^N c_i^v, \quad (4)$$

$$\rho C_p \frac{\partial T}{\partial \tau} + \rho C_p u \nabla T = \nabla \cdot (k \nabla T) + Q, \quad (5)$$

$$-n \cdot (-K \nabla T) = \varepsilon (G - \sigma T^4), \quad (6)$$

$$\rho \frac{\partial u}{\partial \tau} + \rho u \cdot \nabla u = \nabla \cdot \left[ -p I + \mu \left( \nabla u + (\nabla u)^T \right) - \frac{2}{3} \mu (\nabla \cdot u) I \right] + F(a), \quad (7)$$

$$\frac{\partial \rho}{\partial \tau} + \nabla \cdot (\rho u) = 0, \quad (8)$$

The analysis of the numerical modeling results that was carried out by the authors allowed them to make a conclusion on the effect of heat generated in the gasification process on 3d temperature fields and gas velocities inside the furnace. Thus, the detailed three-dimensional representation of an object in the numerical models is a necessary condition for the successful description of complex adjoining processes that occur in the course of gasification.

A thorough analysis of mathematical models was presented in [20]. Large sizes of the plants do not allow us to construct highly detailed aerodynamic models. Therefore, special attention is paid to the development of various closing relationships, in particular the equations of kinetics of chemical reactions. As in the majority of other studies, these authors apply the relationships of the form

$$k_v = A_v \exp\left(-\frac{E_v}{RT_s}\right), \quad (9)$$

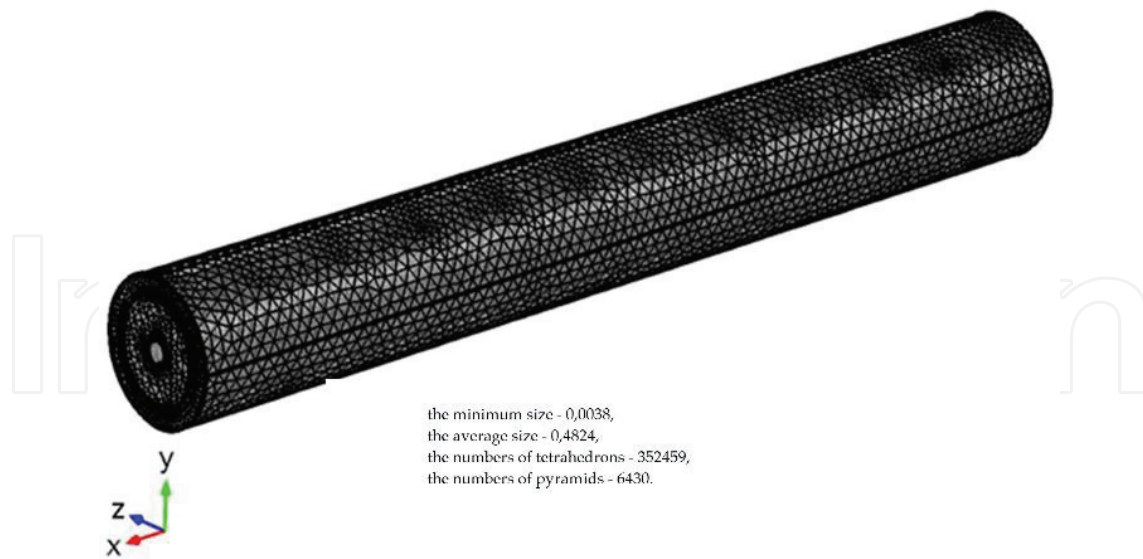
$$r_{\text{dry}} = k_v \rho Y_{\text{H}_2\text{O}}, \quad (10)$$

One of the main parts in each similar research is the determination of a required list of conditions that determine the relationship between the reaction rates and parameters of state, for example, temperature. The authors of [21] properly note that such a method can only be applied to certain ranges of temperatures, whereas for high values (above 475K) it gives absolutely unreal estimates of the rate of solid fuel drying. It is possible to conclude that the application of Eqs. (9) and (10) without consideration of conservation laws naturally creates conditions for such problems to arise. Also, the authors of [21] indicate that the CFD models that refer to a continuous porous medium are very attractive in terms of their possible implementation.

Thus, the analysis of the existing studies shows the necessity to consider the detailed modeling of spatially distributed processes of heat-mass exchange, including the equations of kinetics of chemical reactions, considering natural constraints that follow from the laws of conservation. The most promising seems to be the representation of heat-mass exchange equations in a 3D form. In this case, the problem of a correct consideration of closing relationships in such a statement is not an exceptional characteristic of such detailed descriptions due to insufficient information on multi-parameter models that describe pyrolysis process. Thus, each new mathematical model requires verification involving results of multi-factor experimental studies.

#### 4. Mathematical model

The geometry used for modeling a screw pyrolyzer is presented in **Figure 2**. The interior space is filled with a solid mass by 40%, which should provide easy circulation of the produced gases around the screw. The screw represents a spiral with a wall, 3 mm thick, which is wound on a hollow shaft. The interior space of the pyrolyzer with solid fuel and formed products is separated from heating gases by a wall, 5 mm thick. The screw represents a geometrically complex structure. There are 11 complete spiral turns with a pitch of 139 mm on the hollow



**Figure 2.** Calculation mesh.

steel shaft. An external diameter of the spiral made up 139 mm, and the shaft diameter was 38.6 mm. In the calculation, we took into account the body of the screw, shaft, and external coating. All the objects are constructed from cylinders. The construction of all these objects caused the emergence of surfaces and regions of small size at the point of their intersection. The total number of components in the calculation mesh equals  $N$ . Optimal distribution and sizes of mesh cells were calculated using the Comsol Multiphysics Software on the basis of corresponding algorithms that ensure good convergence for the differential equations applied. The calculation mesh includes different number of cells:

For gas part, it includes hot gas from internal combustion engine and gas inside the screw above the porous medium.

For a surface of solid elements, it includes all solid surfaces.

For the others, it includes solid volumetric parts such as screw, spiral, coating, and so on.

The Comsol Multiphysics Software is used as a simulation environment. Heat exchange in the process of pyrolysis is simulated considering physical properties (porosity, permeability, etc.) of the medium:

$$\frac{\rho}{\varepsilon} \left( (u \cdot \nabla) \frac{u}{\varepsilon} \right) = \nabla \cdot \left[ -pI + \frac{\mu}{\varepsilon} \left( \nabla u + (\nabla u)^T \right) - \frac{2\mu}{3\varepsilon} (\nabla \cdot u) I \right] - \left( \frac{\mu}{k} + \beta_F |u| + \frac{Q_{br}}{\varepsilon^2} \right) u + F, \quad (11)$$

Eq. (11) differs from the model in [21] in the consideration of solid fuel porosity  $\varepsilon$ . In the equation, the changes in masses  $Q_{br}$  correspond to the gas masses formed in the course of the solid fuel decomposition. Then, the equation of continuity has the following form:

$$\nabla \cdot (\rho u) = Q_{br}, \quad (12)$$

Heat exchange in pyrolyzer is calculated using the effective heat transfer coefficient:



$$\rho C_p u \cdot \nabla T + \nabla \cdot (-k_{\text{eff}} \nabla T) = Q, \quad (13)$$

In the area of high-temperature heads, we took into account the radiation heat transfer:

$$q = c_0(T_2^4 - T_1^4), \quad (14)$$

The equation of a diffusion barrier for the plane separating the porous solid body from the gas space in the pyrolyzer is set as follows:

$$\begin{aligned} -nD_{s,i} \nabla c_{i,u} &= \frac{D_{s,i}}{d_s} (c_{i,u} - c_{i,d}) \\ -nD_{s,i} \nabla c_{i,d} &= \frac{D_{s,i}}{d_s} (c_{i,u} - c_{i,d})' \end{aligned} \quad (15)$$

where  $d_s$  is the barrier thickness, mm;  $D_{si}$  is the diffusion coefficient,  $\text{m}^2/\text{s}$ . In the calculations, we assumed a bed thickness of 5 mm and a diffusion coefficient of  $1\text{e}-6 \text{ m}^2/\text{s}$ .

The boundary conditions chosen to solve the problem are as follows:

- An inlet temperature of fuel is  $20^\circ\text{C}$ ;
- An inlet temperature of heating gases is  $600^\circ\text{C}$ ;
- A velocity of fuel flow in pyrolyzer is 1 mm/s;
- An inlet velocity of heating gases is 0.1–1 m/s.

## 5. Modeling results

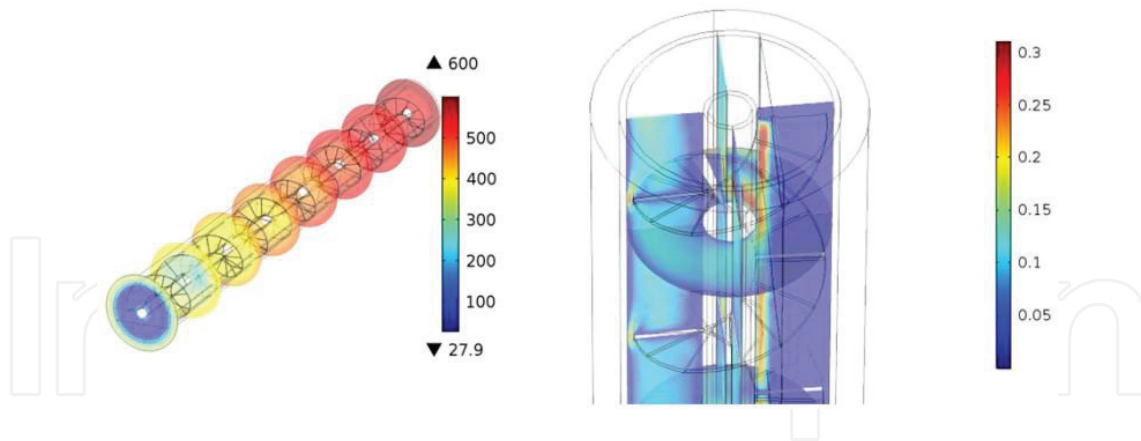
### 5.1. Calculation of the fields of temperatures and gas flow velocities

The calculated fields of temperature, velocities, densities of media, streamlines, and other derivative data were obtained by using the mathematical model of heat and mass transfer processes in the screw pyrolyzers by using the Comsol Multiphysics software. **Figure 3** presents the calculated temperature values in the vertical sections along the pyrolyzer and also the values of formed gas flow velocity in the orthogonally directed planes. The calculation example demonstrates a sufficiently high degree of fuel heating and an adequate pattern of gas flow over the porous medium around the screw.

**Figure 4** demonstrates successful heating of solid fuel providing the condition for its presence at the temperature of above  $500^\circ\text{C}$  for 20 min at the fuel motion velocity of 0.001 m/s.

### 5.2. Parametric calculations

The parametric calculations are an essential part of the optimization study which is intended for determination of the most promising stepwise gasification technology of low-grade solid fuel. The parametric calculations can be made on the stable calculation model allowing the variation of parameters in the solution, that is, boundary conditions, over a sufficiently wide range. The Comsol Multiphysics software makes it possible to calculate steady-state conditions specifying different laws of change in the boundary conditions.



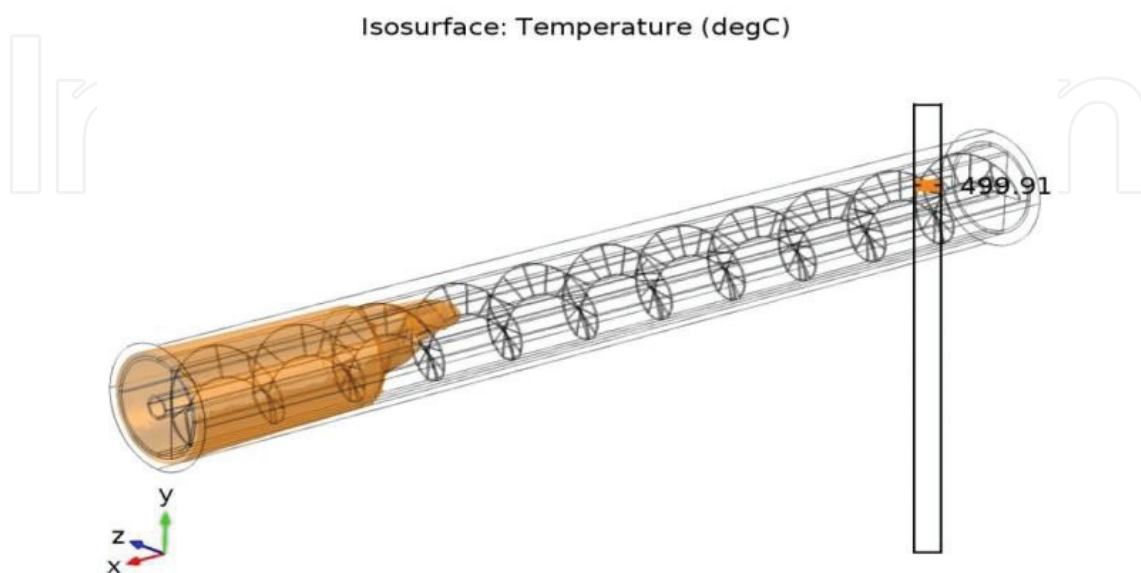
**Figure 3.** The example of calculations performed to determine the fields of temperatures and the motion velocities of pyrolysis products. The heating gas velocity at the inlet section is  $w=0.1$  m/s.

The developed calculation model of the screw pyrolyzer was tested on the basis of the following parametric studies:

- A. the heating gas temperature at the pyrolyzer inlet was set from 770 to 910 K with a step of 20 K;
- B. the heating gas velocity at the pyrolyzer inlet was set from 0.1 to 0.9 m/s with an interval of 0.2 m/s.

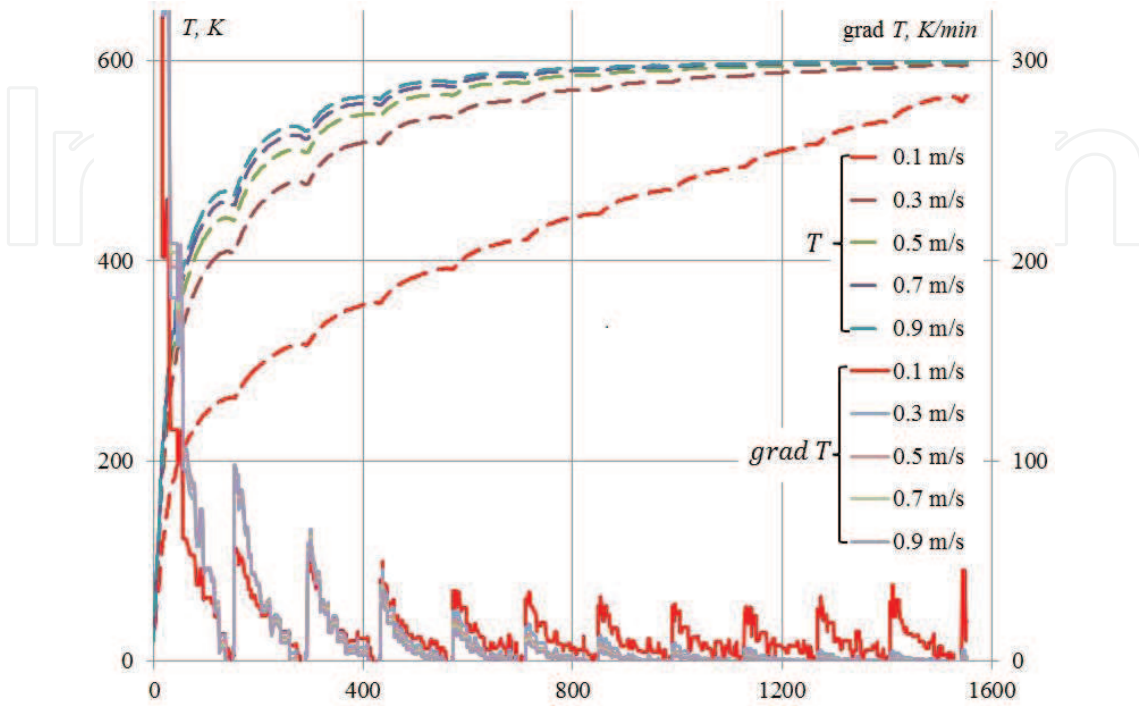
The results of testing (see **Figures 5 and 6**) confirmed the solution reliability and stability with practically full convergence of numerical solutions and as a result the equal time spent on each calculation variant. The other variants of parametric studies are quite possible and seem to be the least problematic from the viewpoint of numerical solution stability, since the current tasks in solving the numerical problems are aimed first of all at the achievement of stability to the initial and boundary conditions.

The parametric calculations with the changing heating gas flow rate reveal an asymptote in the solutions of temperature distribution; as far as starting with 0.3 m/s, the calculated values do

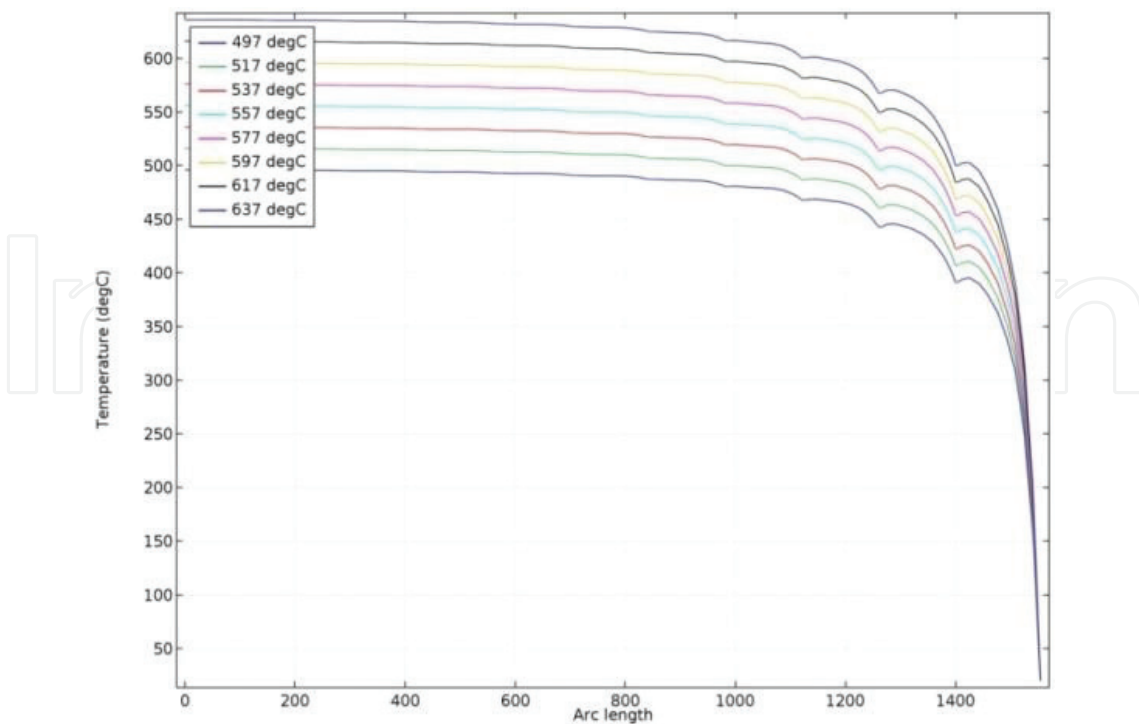


**Figure 4.** The surface formed by the isotherm at 500°C.

not change considerably at further increase of gas velocity values (**Figure 5**). This result enables the supposition about the existing optimal ratio between the working parameters of the developed stepwise gasification scheme in the forthcoming optimization study.



**Figure 5.** Distribution of the temperature and its gradient in the pyrolyzer space for different heating gas flow rates.

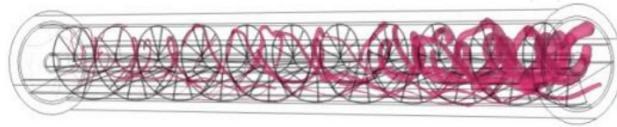


**Figure 6.** Temperature distribution in the pyrolyzer space for different assigned values of heating gas temperature.

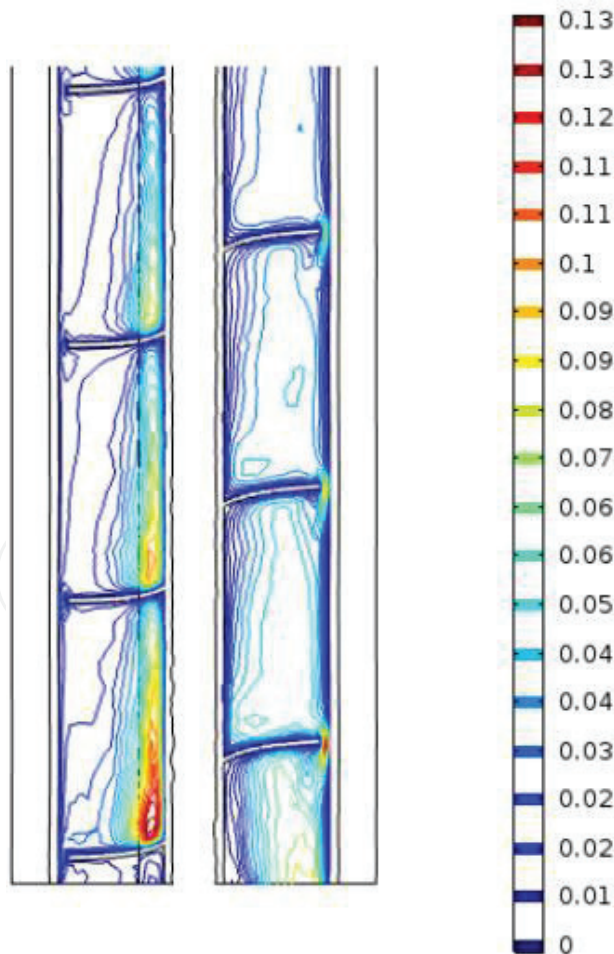
### 5.3. Analysis of the calculated values of gas flow velocity

**Figure 7** illustrates a screwed character of the gas streamlines along the pyrolyzer axis which arranges the mixing of formed fractions (steam, etc.) in the gas space. As a result, the efficiency of the heating process and the uniformity of temperature fields are secured, avoiding the zones with irregular reaction rates.

The calculated fields of the gas phase velocity  $u$  in the longitudinal cross section of the screw reactor are presented in **Figure 8**. The highest values of  $u$  are observed over the surface of filled low-grade solid fuel.



**Figure 7.** The calculated streamlines of the formed gases in the process of low-grade solid fuel heating in the pyrolyzer. The color indicates the calculated temperature values.



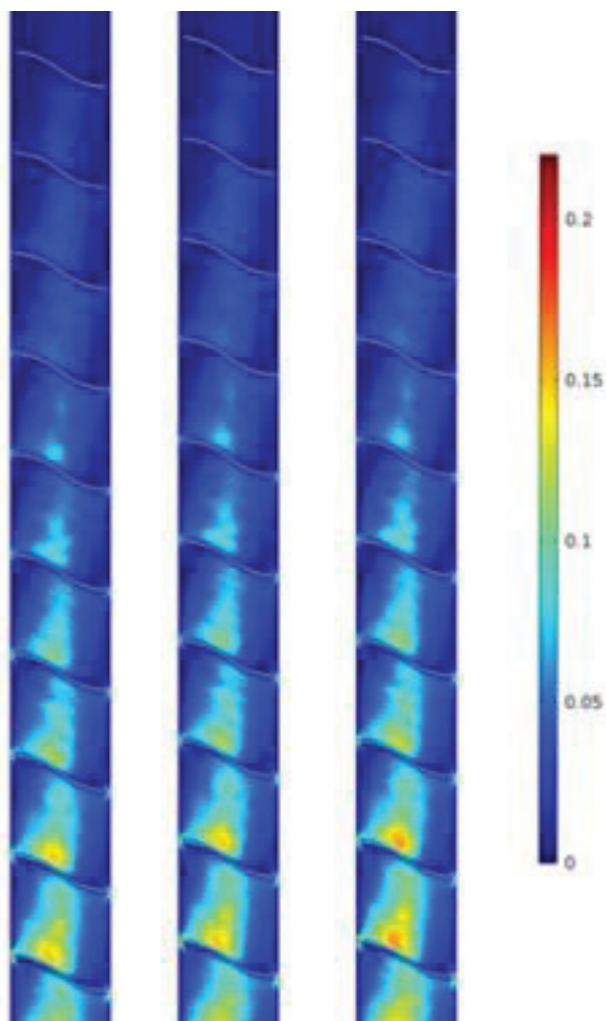
**Figure 8.** The calculated isolines of velocity.

Markedly distinct velocity fields and as a consequence the diffusion coefficients characterizing transfer of the gas phase from the porous mass to the free space can be formed for different operating conditions.

**Figure 9** presents instantaneous values of gas flow velocities through the surface of the filled solid fuel mass. The effect of heating gas temperature on the diffusion processes of formed gas yield was analyzed. The calculations show a negligible effect of the boundary conditions on motion of the media in the region modeled by the diffusion thin bed. This fact suggests feasibility of using the constant coefficients to describe gas transition from the porous medium to the space free for gas flow in the screw reactor. The maximum change in the velocity was equal to  $\sim 1\%$  at the change of the heating gas temperature by 140 K at the pyrolyzer inlet. Thereby, the general distribution type of values in the velocity field did not change.

#### 5.4. Application of the model for distribution of the formed substance concentrations

The validity of applying the stationary thermophysical dependences to the determination of tree properties in the pyrolysis process was analyzed. For this purpose, the temperature



**Figure 9.** The fields of gas flow velocity on the surface.

gradient values in the fuel medium along the motion of solid particles were determined. Taking into account the velocity of fuel mass motion with respect to the pyrolyzer, it is possible to compare the temperature gradient with the heating rates of experimental samples. The conclusion confirmed feasibility of using the equations of chemical kinetics which were determined at  $dT/d\tau = 30$  K/min.

The applied approach to determination of the fields of concentrations of substances formed in the course of substance reaction demonstrated satisfactory results of the calculation example (**Figure 10**). The highest concentration of steams formed during drying is observed in the zone of intensive heating—in the initial part of the screw reactor, and as they flow along the reactor the concentrations level off in the sections.

Because of inhomogeneity of heating, the steams formed in the process of solid fuel mass heating substantially differ in concentrations on the initial part of the screw reactor (**Figure 9**). **Figure 9** shows that the share of formed steams essentially depends on the operating factors. For example, more steam is formed inside the porous bed at the lower values of heating gas temperature at the pyrolyzer inlet. Because of the obvious nonphysical character of these results, the following explanation is advisable: in the available model of fraction formation, there are no constraints on the quantity of substances formed. As was mentioned in the work [21], the direct application of the Arrhenius-modified models leads to the similar effects. The correct analysis of physical constraints requires more strict descriptions of the laws of concentration distribution which are based not only on the values of gas temperatures and velocities. One of the methods to solve this problem is to specify the initial concentration of associated water. Then, the equations describing change in concentrations will have the following form:



**Figure 10.** The calculated fields of steam concentrations.

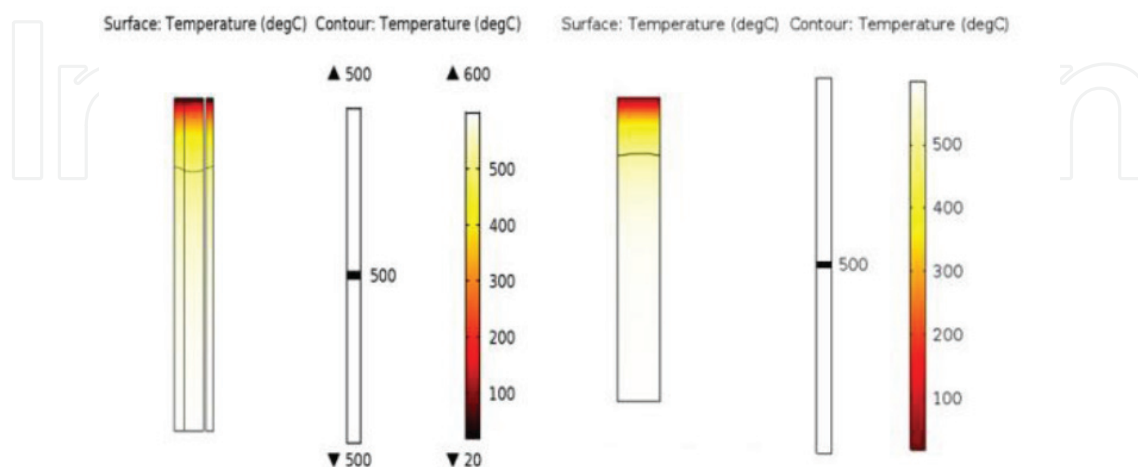
$$\begin{cases} \nabla \cdot (-D_1 \nabla c_1) + u \cdot \nabla c_1 = R_1 \\ \nabla \cdot (-D_2 \nabla c_2) + u \cdot \nabla c_2 = R_1' \end{cases} \quad (16)$$

where indices 1 and 2 correspond to concentrations of the steams and associated water, respectively.

### 5.5. Analysis of contribution of radiation heat transfer

Optimization calculations even for stationary mathematical models with concentrated presentation of the description of processes need huge computational resources. It is not surprising that the numerical calculation of the three-dimensional fields of velocity, temperature, and others by using the server Xeon CPU E5606 (8 cores, 256 gigabyte of the random access memory) of one condition required 24.5 working hours. Therefore, it is topical to reduce the mathematical model by the addition of assumptions allowing the number of equations to be decreased. From this point of view, the statement that the contribution of radiation heat transfer is unessential seems to be the most attractive. The identical operation conditions of the screw pyrolyzer were calculated considering the radiation heat transfer and without it. The calculation results (**Figure 11**) demonstrate invariability of the key isotherm and the temperature field. The contribution of radiation heat transfer, which amounted to less than 5% of the total energy exchange balance, was also estimated. If the radiation heat transfer is excluded from the general model, the computation time can substantially be decreased from 24.5 working hours of the server with the indicated configuration up to 30–40 min.

At the same time, it should be noted that the conclusion about inessential contribution of radiation heat transfer to the whole heat exchange contradicts the results of the work [21], which poses the question on deeper experimental study of this problem.



**Figure 11.** The calculation results of temperature field and isotherm position at  $T=500^{\circ}\text{C}$  by the models, which account for the radiation heat transfer (a) and without it (b).

## 6. Conclusion

The model of heat transfer and aerodynamics of the pyrolyzer was developed for express optimization calculations. The temperature distribution in the pyrolyzer reactor was obtained in a wide range of operating conditions. Moreover, it is confirmed that in the considered thermal conditions the process of fuel conversion proceeds to completion. Inclusion of the kinetic block in the model of heat transfer made it possible to determine the concentration fields of the formed substances (steam, etc.). Numerical experiments confirmed the possibility for the application of this model to optimization calculations.

Possible use of stationary experimental dependences for the determination of the rate of change in solid fuel density, yield of volatiles, and so on is shown for the range of considered working conditions. The results of parametric study demonstrated the existence of the asymptote for the optimal amount of heating gases which ensures the first stage of pyrolysis.

## Acknowledgements

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## Nomenclature

$A$	pre-exponent factor (1/s)
$c_p$	specific heat capacity of the gas mixture (KJ/kgK)
$D_{si}$	diffusion coefficient (m <sup>2</sup> /s)
$E$	activation energy (J/mol)
$F$	surface area (m <sup>2</sup> )
$k$	kinetic rate constant (1/s)
$P$	gas pressure (Pa)
$p$	partial pressure (Pa)
$Q$	heat transfer to wood chips by convection and radiation (W/m <sup>3</sup> )
$R$	universal gas constant ~8.314 (J/molK)
$r$	reaction or process rate (kg/m <sup>3</sup> s)
$T$	temperature (K)
$\tau$	time (s)
$u$	velocity vector (m/s)
$V$	volume (m <sup>3</sup> )
$W$	moisture (%)
$x$	coordinate (m)



**Greek letters**

$\alpha$	heat transfer coefficient (W/m <sup>2</sup> K)
$\beta$	mass transfer coefficient (kg/m <sup>2</sup> sPa)
$\varepsilon$	porosity (-)
$\lambda$	thermal conductivity (W/m K)
$\mu$	air viscosity (kg/ms)
$\rho$	density (kg/m <sup>3</sup> )
$\sigma$	normal stress tensor (Pa)
$\omega$	flow rate (m/s)

**Subscripts**

f	fuel
g	gas
s	solid phase

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