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# Physical and chemical processes simulation of organic wastes processing by the method of high-temperature oxidation in the melted slag

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**Abstract.** Recycling of municipal waste is associated with accumulation of significant amounts of sewage sludge. The paper proposes a technology for the thermal utilization of sewage sludge with vitrification of a non-combustible residue. The paper presents the results of numerical simulation of the physical and chemical processes that accompany the high-temperature oxidation of pre-dried and pre-pelleted sewage sludge on the surface of the slag melt in a pilot plant with the melter capacity of up to 100 kg/h pellet. The mathematical model of the melter has been created and numerical calculations of the flow of high-temperature gaseous medium supplied by burner devices in the working volume of the furnace have been made in a stationary approximation taking into account the thermophysical and chemical processes occurring in the raw material, fed in the form of dry pellets (sediment).

## 1. Introduction

One of the key unsolved environmental problems of the Russian Federation (RF) is accumulation of municipal solid waste near water bodies and settlements. Such waste includes sewage sludge, which has a fairly high caloric content. Currently, the sewage sludge in the Russian Federation is mainly disposed in MSW landfill. In foreign countries, the most common technology for its processing is incineration. The disadvantages of this technology are as follows: the risk of emission of supertoxicants, formation of toxic ash requiring burial and special treatment, the absence of domestic equipment manufacturers, and attachment to foreign suppliers.

The authors proposed the technology of vitrification of organic waste in relation to sewage sludge, eliminating the risks of emission of supertoxicants due to elevated temperature of combustion (1400-1600$^{o}$C) [1]. The processed product is vitrified granulated slag, which encapsulates heavy metals and is suitable for use in construction.

The work is devoted to CFD-modeling of physical and chemical processes accompanying high-temperature sediment pellet oxidation on the surface of the slag melt in a specially developed pilot plant for testing technology on real raw material with a melter capacity of up to 100 kg/h with moisture content of 10-15%.

The mathematical model of the melter has been created and numerical calculations of the flow of high-temperature gaseous medium supplied by the burners in the working volume of the furnace have been made in a stationary approximation taking into account the thermophysical and chemical processes occurring in the raw material, fed in the form of dry pellets (sediment).

This paper compares the results obtained with experimental data. The results can be used in the design of the melter of a full-stage installation with a capacity of more than 5 t/h of pre-dried sediment pellets with a moisture content of 10-15%.

## 2. Description of the pilot plant for processing of dried and pelletized sewage sludge

The equipment for vitrification includes a drying unit for the sludge with initial humidity of about 80%. Vitrification is performed by indirect heating with steam (or oil) with heat recovery of flue gases, pelletization of dried sludge with a moisture content of 10-15% and high-temperature oxidation of the obtained pellets in a melter on the surface of the slag melt in oxygen (air) excess at a temperature of 1400-1600$^o$C, while the mineral component of the sediment melts and the organic is oxidized with the release of energy. Exhaust gas is sent to the cleaning system.

The melter consists of the following main structural elements: external enclosing structures made of baddelit-corundum, fireclay and silica refractory materials, screw pellet feeder, burners, additional air supply device, and gas exhaust pipe.

The feedstock in the model approximation consists of carbon, solid mineral inclusions and moisture. During operation of the melter, the raw material is heated, followed by evaporation of the moisture content, oxidation of the carbon component of the raw material and melting of the mineral component. The task of numerical simulation of the installation operation was solved in a stationary approximation: the dynamics of the gaseous medium was simulated, the continuous supply of raw materials was described by the corresponding heat sources and mass sources of gas components distributed in the raw material hill that formed under the loading window. The distribution of heat in solids (furnace walls) was described by the heat equation.

Figure 1 shows three-dimensional model of the pilot plant melter.

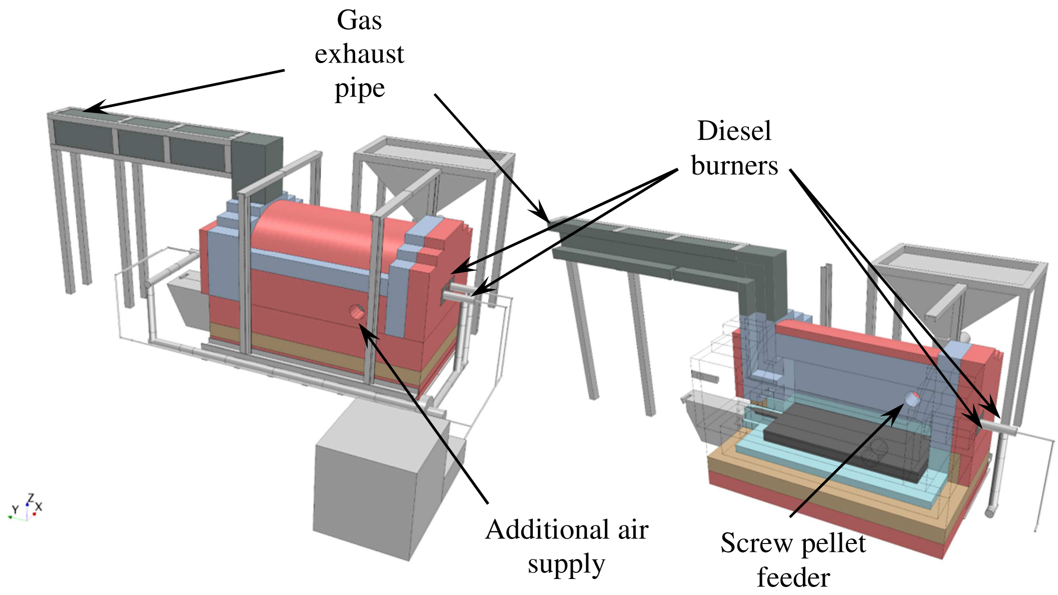


**Figure 1.** 3D-model of the pilot plant melter.

## 3. Numerical simulation of the pilot plant sewage sludge melter operation

Based on the 3D-model of the furnace (figure 1), a three-dimensional volume of flow of the gaseous medium was identified. The final-volume calculation grids are built by the volume of gas movement, the volume of the raw material hill and insulating structural elements (refractories). Using CFD-modeling, fragments of computational grids were built. When choosing the average distance between grid nodes, the expected flow features near the solid boundaries were taken into account. To improve the convergence and increase the accuracy of calculation, the grid is thickened in the vicinity, which significantly affects the flow pattern. To improve the convergence and increase the accuracy of the calculation the grid is thickened near the areas significantly affecting the flow pattern. Preliminary testing of typical fragments was performed. Then, the fragments were merged into a single hybrid grid. For each variant with a change in the geometric parameters, a separate computational grid was constructed. The number of cells used to create the grid was about 800,000.

The gas mixture flow was calculated numerically by solving stationary hydrodynamic equations with Reynolds averaging turbulent pulsations (RANS) [2]. The κ-ω turbulence model was used. The equations were solved numerically using the control volume method [2]. The gas environment was considered as a multicomponent mixture of viscous gases ($O_2$, $N_2$, $CO_2$, $H_2O$) with variable physical properties depending on temperature; the closing relation is the equation of state of an ideal gas. All walls were considered technically smooth and impenetrable.

The problem was solved in a stationary approximation: the dynamics of the gas environment was modeled, the continuous supply of raw materials was described by the corresponding heat sources and mass sources of gas components distributed in the raw material hill formed under the loading window. The distribution of heat in solids (furnace walls) was described by the heat equation; the thermophysical properties of refractories and raw materials are listed in tables 1 and 2, respectively. The characteristic view of the raw material "hill" of pellets is shown in figure 2.

**Table 1.** Refractories thermophysical properties used for numerical simulation.

| The name of refractory materials | Model | The dependence of thermal conductivity on temperature $\lambda(t) = a_i + b_i \cdot t + c_i \cdot t^2$, W/(m·K) | | |
|---|---|---|---|---|
| | | $a_i$ | $b_i \cdot 10^3$ | $c_i \cdot 10$□ |
| Baddelitocorundum | Bakor BK-33 | 2.33 | 0.226 | 0.898 |
| Fireclay (shamot) | ShA-1 | 0.641 | 1.14 | -0.607 |
| | ShL-1.0 | 0.339 | 0.169 | 0.0 |
| Dinas Refractories | Dinas D | 1.152 | 0.393 | -0.0357 |

**Table 2.** Thermophysical properties of components of raw materials used for numerical simulation [3].

| Component | Heat capacity, J/(kg•K) | Heat of evaporation / melting, kJ / kg |
|---|---|---|
| Water | 4200 | 2258.2 |
| Carbon | 2000 | – |
| Minerals | 830 | 510 |

The basis of the developed complex physical and mathematical model is considering in the aggregate:

- Stationary gas dynamics equations with Reynolds averaging of turbulent pulsations (RANS);
- Equations of heat transfer in the gas phase and at the boundary with the melter walls;
- Equations describing the kinetic laws of chemical reactions that take place in the bulk of the raw materials hill between oxygen and carbon contained in raw materials.

- The equations of conservation of mass, momentum, and energy for the gas phase [2] are the equations describing the flow of a multicomponent gas medium.

The volume of the hill formed by the pellets of the raw material was described by the resistance of an anisotropic porous medium [4].

The intensity of evaporation of water, contained in the incoming raw materials, at a temperature above 100°C was calculated by dividing the intensity of heat transfer from the gas to the pellets of the raw material by the heat of water vaporization.

Mass sources of carbon and the gas component corresponding to the process of burning raw material carbon were modeled by the Arrhenius equation describing the oxidation reaction $C + O_2 \rightarrow CO_2$ to produce carbon dioxide at the output without taking into account the formation channels of other possible components. For the preexponential factor, the value of $1.5 \cdot 10^{10}$ [g/m$^2\cdot$h] [5] was used for the activation energy related to *R*, 1984 [K] [5]. Mass sources of $CO_2$ and $O_2$ were asked, based on the stoichiometry of the reaction.

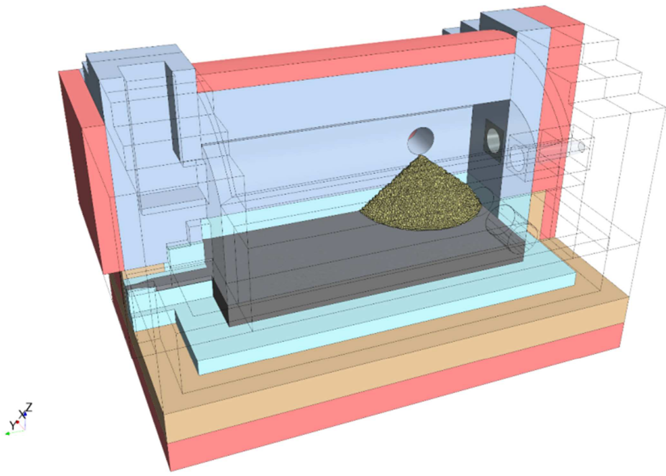

**Figure 2.** The characteristic view of the raw material "hill" of pellets formed under the loading window.

The source of heat released as a result of the reaction was set based on the thermal effect of the reaction 19.579 [kJ/kg]: the specific energy of combustion of the raw material calculated by the dry state.

The melting intensity of the mineral components of the raw material at temperatures above 1200°C was calculated by dividing the heat transfer rate from the gas to the raw pellets by the specific heat of slag melting.

A boundary condition of the third kind (convective heat exchange with ambient air) was set as the boundary condition on the outer surface of the furnace:

$$q = \alpha\left(T_w - T_{air}\right),$$

where α is characteristic heat transfer coefficient, set equal to 12 [W /(m$^2$K)], $T_w$ [K] is temperature of the external surface of the furnace; $T_{air}$ is characteristic ambient temperature taken as 20°C.

In all calculations carried out, the characteristic reduced diameter of the raw pellets was set to 8 mm, the filling porosity was 0.5; the inlet temperature of the raw material and the additional air blast was 20°C, the gas temperature at the burner outlet was 1700°C.

## 4. Results of numerical simulation of operation of the pilot plant sewage sludge melter

Baseline conditions for simulating various modes of operation of the melter are shown in table 3. Figure 3 shows the results of numerical simulation of the temperature distribution in the "hill" of raw materials.

High temperature of raw material “hill” provides the faster and more efficient processes of burning the organic part and melting the non-combustible part of the pellets. From figure 3, it can be seen that the highest temperature of the raw material and the bottom part of the melter (about 1200°C) is achieved only when the burner power is 380 kW and the reduced feed capacity is 25.0 kg/h. In all other cases considered, the bottom part of the melter without additional external thermal insulation does not warm up to the temperature at which the slag melts, and, thus, the functioning of the melter in modes 1-3 does not ensure the effective vitrification of the incombustible components of the sludge. This leads to an increase in fuel consumption, which makes it appropriate to use the external additional thermal insulation materials in the future.

**Table 3.** Simulated modes of operation of the pilot sewage sludge melter.

| Mode number | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Thermal power of burners, kW | 80 | 130 | 230 | 380 |
| Mass flow of heated gas from burners, kg/h | 135 | 212 | 394 | 628 |
| Volume flow of additional air, normal $m^3$/h | 127 | 278 | 185 | 185 |
| Raw material pellets mass flow, kg/h | 37.5 | 37.5 | 37.5 | 25 |

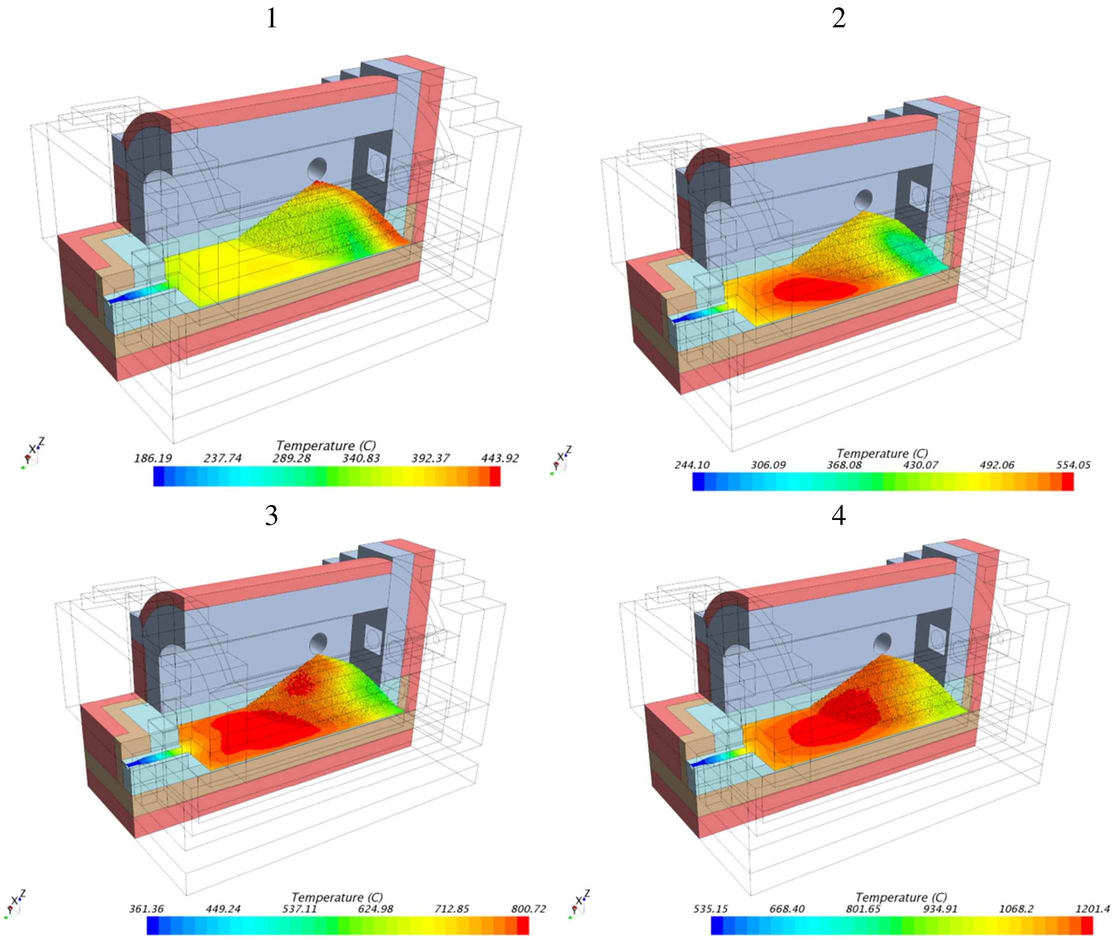


**Figure 3.** Temperature distribution over the raw materials "hill" and horizontal cut of the melter, the number of operating modes of the melter is indicated.

Fuel consumption is important both for the confirmation of technology basis efficiency at the experimental facility and the design of full-scale waste processing facilities. In this regard, the design of industrial melter facilities should be added with the external thermal insulation layers to achieve the lowest fuel consumption. The developed model allows such optimization.

## 5. Conclusions

The technology of thermal utilization of sewage sludge with vitrification of non-combustible residue is proposed. The results of numerical simulation of the physical and chemical processes accompanying high-temperature oxidation of pre-dried and pre-pelleted sewage sludge on the surface of the slag melt at a pilot plant with the melter capacity of up to 100 kg/h pellets are presented. The mathematical model of the melter has been created and numerical calculations of the flow of high-temperature gaseous medium supplied by the burner devices in the working volume of the furnace have been made in a stationary approximation taking into account the thermophysical and chemical processes occurring in the raw material, fed in the form of dry pellets (sediment). It is shown that efficient vitrification of non-combustible components of sewage sludge in a designed pilot melter without additional thermal insulation is possible only with a burner capacity of at least 380 kW for raw materials with productivity of 25.0 kg/h. The results can be used in the design of a melter of an industrial scale plant for thermal processing of dried and pelleted sewage sludge with vitrification of non-combustible residue.

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