Optimization of thermophysical processes of bottom part of shaft furnace for plasma treatment plant of solid radioactive waste

A Yu Markelov¹,², A A Kudrinskiy³,⁴, S V Anpilov³ and V L Shiryaevsky²

¹ National Research University “MPEI”, Krasnokazarmennaya 14, Moscow, 111250 Russia
² LLC “FINPROMATOM”, Ferganskaya 25/1, Moscow, 109507 Russia
³ M.V. Lomonosov Moscow State University, Lenin Mountains 1, Moscow, 119991 Russia
⁴ National Research Center Kurchatov Institute, the area of Academician Kurchatov 1, Moscow, 123098 Russia

alex.markeloff@gmail.com

Abstract. The task of analyzing various sources of heating in the bottom part of the shaft furnace to optimize thermophysical processes is of interest from both an economic and technological point of view. When replacing the type of heat source, it is necessary to preserve the performance characteristics, primarily high temperatures in the range of 1400-1600 °C for melting minerals. This work aims to substantiate plasma torches replacement by natural gas or diesel burners and to confirm preservation of the utilization process efficiency. In order to do this numerical modeling of thermal processes was used: CFD modeling of a full-sized shaft furnace with a melter, including the distribution of temperature fields in the slag melt layer and external thermal insulation materials. Other possible combinations were also analyzed to optimize heat exchange processes: ohmic heating of the melt, replacement of air with oxygen. The results of numerical simulation show that hydrocarbon burners can be used instead of plasma torches for efficient processing of various types of waste in the slag melt. This can be economically attractive for expanding the application area of waste treatment technology in the slag melt, especially for the housing sector waste processing.

1. Introduction

For the processing of solid radioactive waste (SRW) on the Experimental-Demonstration Decommissioning Engineering Center (ODIC) basis (Rosenergoatom Concern branch) in Novovoronezh the first radioactive waste plasma processing complex in the Russian Federation (RF) was put into commercial operation (called “KPP RAO”). At the heart of the complex are the shaft furnace in which drying takes place, pyrolytic decomposition of the loading waste and gasification of residual carbon, with a bottom part intended for melting the mineral fraction of the waste and discharging the slag melt. Over the years of operation, the technology has shown its economic and environmental efficiency: the volume of solid radioactive waste sent for disposal is reduced almost 50 times.

It is known that technology direct incineration of radioactive waste leads to the formation of ash with concentrated radioactive isotopes that dangerous for transportation, dusty and unsuitable for disposal [1], which is a significant drawback in comparison with the process implemented at the “KPP RAO”.

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The development and optimization of plasma waste treatment technologies extensively uses computer simulation of both physicochemical processes and the dynamics of the gas stream in plasma furnace [2-6]. Plasma treatment of waste is conducted mostly in shaft furnaces. Examples of such furnaces can be found in “Piroliz” and “Pluton” pilot-commercial facilities developed by Radon Research and Production Association, State Unitary Enterprise, for solid radioactive waste treatment [7].

The source of heat in the process of high-temperature waste processing in “KPP RAO” is electric arc plasma torches located in the bottom part of the furnace. The economic efficiency of the process is largely due to the fact that “KPP RAO” buys the electricity needed for the plasma torches at the price of the own needs of the Novovoronezh nuclear power plant, in whose territory the complex is actually located. Considering the efficiency of electric arc plasma torches (not more than 0.6-0.7), it is easy to calculate that for Russia outside the NPP, it is much more profitable to use natural gas instead of the plasma torch, since, for example, for the plasma torch EDP-200 to obtain 120 kW of heat is required 200 kW of electricity, which corresponds to a flow rate of ≈13 m³/h when using natural gas. Consequently, for objects where there is no subsidized or reduced electricity tariff, using natural gas will be more economically advantageous, and the payback period of the complex in the form in which it is implemented in the ODIC will be questionable. This is especially relevant when expanding the areas of application of the technology in question when it comes to waste generated in the housing and utilities sector, where the economy is of paramount importance. A similar situation is relevant not only for Russia, but also for other countries with a large stock of cheap hydrocarbon resources.

Analysis of different heating sources in the bottom part of the shaft furnace to optimise thermophysical processes lies not only in the economic plane, but also in the technical one. The work is devoted to the substantiation of the replacement of plasma torches for natural gas or diesel burners and confirmation of the preservation of the efficiency of the utilization process. To solve this was used numerical modeling of thermal processes: CFD modeling of a full-sized shaft furnace with a melter. Other possible combinations were also analyzed to optimize heat exchange processes: ohmic heating of the melt, replacement of air with oxygen. The results of numerical simulation show that hydrocarbure burners can be used instead of plasma torches for efficient processing of various types of waste in the slag melt.

2. “KPP RAO” shaft furnace brief description
The shaft furnace is the main element of the system, which ensures the implementation of technological processes of the “KPP RAO” Complex (Figure 1).
The shaft furnace consists of the shaft and the melter, which are connected by a water-cooled flange connector. Waste enters the mine through the boot device located above the shaft furnace. The loading unit is protected from the heat flow of the mine by a heat shield. In the upper part of the mine under the loading device there are four nozzles for emergency cooling. Blowing air is supplied to the lower part of the shaft furnace through a manifold. Two plasmatrons are mounted on the top part of the melter and are cooled by water circulating in their cavities and in the plasma torch shields. The shaft furnace is mounted with the help of a metal supporting structure, on which the body of the mine is fixed with supporting legs. Slag is discharged through a drain device located at the end of the melter. Technology parameters for solid radioactive waste treatment on “KPP RAO” are shown in Table 1.

Table 1. Technology parameters for solid radioactive waste treatment on “KPP RAO”.

| Parameter | “KPP RAO” |
|-----------|-----------|
| Facility type | Counter shaft furnace with melter |
| Capacity for solid radioactive waste, kg h⁻¹ | 200-250 |
| Capacity for molten slag, kg h⁻¹ | 50-80 |
| Productivity on pyrolysis gases at the exit of the shaft furnace, kg h⁻¹ | 300-400 |
| Performance of exhaust gases at the outlet of the Complex, normal m³ h⁻¹ | 2000-3000 |
| Melter temperature, °C | 1500-1800 |
| Temperature of the gases leaving the shaft (pyrogas temperature), °C | up to 300 |
| Plasma torch type | Electric-arc plasma torch |
| Plasma torch electric power, kW | 100-150 |

Number of plasma heat sources:
3. Melter heating alternative options analysis

In “KPP RAO”, plasma torches are used to heat the melter within the range of 1500-1800 °C. In industry, this method is rarely used abroad and especially in the Russian Federation. The domestic industrial equipment required for plasma torches is not produced, including power supplies. The use of an industrial complete imported plasma torch system is hampered by the lack of residents in Russia (support and service) and the difficulty of using imported plasma torches.

The purpose of this note is a thermophysical simulation of the heating of the melter by plasma torches, as well as alternative sources of heat that can be used as a replacement for plasma torches.

To ensure the efficiency of the furnace and the required heat output, several approaches can be considered:

- Use of fluxes to lower the melting point of the slag;
- Addition of carbon and air blast for additional heating;
- Use of an air hydrocarbon burner;
- Use of an oxygen hydrocarbon burner;
- Application of ohmic slag heating.

The addition of fluxes (Na$_2$O, CaO, etc.) is widely used in industry, including glass production. So the diagram of the state of Na$_2$O-SiO$_2$ shows the possibility of obtaining a liquid phase at a temperature of less than 1000°C and a 20% fraction of Na$_2$O, while it is necessary to additionally introduce CaO to obtain chemically stable slag.

The adiabatic temperature of hydrocarbon fuel combustion in atmospheric air at room temperature is 1700-1800 °C and decreases with excess air. In industry, preheating of the blast air is used to reduce fuel consumption. Heating air provides an increase in the rate of combustion and the input of thermal power (if not reduce fuel consumption), reduces chemical and mechanical underburning of fuel, reduces the length of the torch. To increase the adiabatic temperature of combustion of diesel fuel from 1700 °C to 2200 °C, it is necessary to preheat the air to 850 °C, this will take about 35 kW, and the input power will increase by the same amount. In the RF industry, air burners with heated blast air up to 900 °C are used.

Table 2 shows a comparison of the parameters of the plasmatron and oxygen burners. For example diesel burners with different degrees of oxygen enrichment for combustion are considered. As can be seen, the burner devices fully correspond to the required design parameters.

| Parameter | Plasma torch | Burner$^a$ (combustion of diesel fuel in oxygen, stoichiometry) | Burner (combustion of diesel fuel in O2 enriched air (40%), stoichiometry) |
|-----------|--------------|---------------------------------------------------------------|------------------------------------------------------------------|
| Exit to the mode (heating/ the furnace), h | 16-24 | 360-720 | 360 |
| Installed electric power of general and special purpose equipment, kW | 1000 | | |
| Facility mode operation | | | |
| continuous work, h | | | |
| routine maintenance, h | | | |
| in the melter | 2 | | |
| in the pyrogas combustion chamber | 1 | | |
| Plasma-forming gas | Air | | |

Table 2. Comparative table of the plasma torch and burners parameters
Thermal power, kW  
70 150 140  
Electric power, kW  
100 - -  
Flame temperature\(^{c}\), °C  
2760 2620 2480  
Design temperature of the melter, °C  
1500-1800  
Actual melter, °C temperature  
1600  
Air flow, normal m\(^3\)/h\(^1\)  
50 470 80  
Oxygen flow, kg/h  
- 43 -  
Fuel consumption\(^{c}\), kg/h  
- 13 12  
Torch/flame length, cm  
40-50 70-80 70-80  

| Exhaust gas flow (stoichiometry), kg/h | 61 | - | 65 | 56 | 113 |
|----------------------------------------|----|---|----|----|-----|
| N\(_2\)                                | 65 | - | 65 | 56 | 113 |
| O\(_2\)                                | -  | - | -  | -  | -   |
| H\(_2\)O                               | -  | 16| -  | -  | -   |
| CO\(_2\)                               | -  | - | 40 | -  | -   |
| Total                                  | 65 | 56| 113|    |     |

\(^{a}\) The burners can work not only on diesel fuel, but also on propane. \(^{b}\) Diesel fuel density \(\sim 850\) kg/m\(^3\). \(^{c}\) Adiabatic temperature with taken into account dissociation

Oxygen burners have several advantages over air burners due to the lack of “ballast” in the form of nitrogen:

- Reduction of harmful emissions into the atmosphere (nitrogen oxides);
- Higher combustion temperatures (adiabatic temperature fuel combustion in oxygen around 2700 °C);
- Use of an oxygen hydrocarbon burner;
- Higher specific heat power and shorter flame length.

In the Russian Federation, industrial air, oxygen burners and oxygen concentrators are offered by foreign and domestic companies. The resource and reliability of burners and oxygen concentrators is determined mainly by the compressor.

For a 150 kW oxygen burner for burning diesel fuel, the consumption of 90% oxygen is about 33 m\(^3\)/h. The compressed air consumption required for the operation of an adsorption oxygen generator is 460 m\(^3\)/h at a pressure of 5-6 atm.

It should be noted that oxygen burners for industrial high-temperature gasification of waste have been used for a long time, for example in Japan more than 20 years ago, 7 plants were built and operated using Thermoselect technology. In general, heating with fuel oxygen combustion is comparable to heating with plasma torches. The issue associated with economic, which is preferable for a particular case, taking into account capital and operating costs, fuel and electricity prices, reliability requirements.

Hearth ovens in a temperature of 1500-1600 °C range are widely used in the glass industry, where problems also arise in maintaining the desired temperature of the liquid phase, which is heated by a flame of burners over a layer of liquid glass. When this occurs, temperature unevenness in depth and cross section of a layer of liquid glass. A widely used method in the industry for additional heating (without increasing the temperature of the torch) is to install electrodes in the lower part of the melter,
which provide additional ohmic heating of the liquid glass mass. The conductivity of liquid glass is
determined by the presence of alkaline earth oxides. The heating system for liquid glass is relatively
simple and consists of bottom or side molybdenum electrodes and a supply transformer.

4. Thermophysical processes numerical simulation of the shaft furnace melter part
For a more detailed preliminary analysis of the options for heating the melter, a 3D thermal model of a
shaft furnace with thermal insulation was built. Using CFD-modeling, fragments of computational
grids were built. The number of cells used to create the grid was about 989 000. The computational
grid is presented in Figure 2. The flow of the medium is described as the motion of a multicomponent
mixture of viscous compressible gases (the Navier-Stokes equations).
The thermophysical properties of gases are temperature dependent. The equation of state is the ideal
gas equation. The turbulence model used is k-ε. Heat losses through thermal insulation are taken into
count (12 W/m²K, 20 °C). In modeling, raw materials are considered as porous media. A “hill” of
porous glass was modeled into the melter under the shaft furnace. SRW - porous medium with
resistance to granular backfill [8]:

\[
\frac{\partial p}{\partial x_i} = \frac{150 \mu (1 - \varepsilon)^2}{D_p^2} \left| \frac{\partial v}{\partial x_i} \right| + \frac{1.75 \rho (1 - \varepsilon)}{D_p} \left( \frac{\partial v}{\partial x_i} \right)^2
\]

where \( \mu \) - gas mixture viscosity, \( D_p \) - characteristic granule diameter, \( \varepsilon \) - backfill porosity. Losses on
heating of SRW in the cylindrical part and phase transition (melting of SRW in the melter) are
specified as permanent sources of heat in the respective areas. The model took into account the
radiation heat exchange between the internal surfaces of the shaft furnace as between surfaces with a
blackness coefficient of 0.9.

**Figure 2.** General view of “KPP RAO” shaft furnace design with a melter. Dimensions in [mm].

10 cm layer of liquid glass was introduced in the melter. CFD-simulation allows to calculate the fields
of temperature, gas velocity, pressure, and others thermal furnace parameters. The model takes into
account heat input, heat loss with the outgoing gas, heat loss through the furnace walls, a heat required
to heat the raw materials, to melt and overheat the slag melt.
### Table 3. Types of heat sources and their parameters.

| Operation mode number | Parameters       | Heat source №1 | Heat source №2 |
|-----------------------|------------------|----------------|----------------|
|                       | Type             | Plasma torch   | Plasma torch   |
| I, IV, V, VI          | Thermal power, kW| 70             | 70             |
|                       | Air flow, normal m³/h | 50          | 50             |
|                       | Temperature of flame, °C | 2760      | 2760           |
| II                    | Type             | Plasma torch   | Air burner     |
|                       | Thermal power, kW| 70             | 150            |
|                       | Air flow, normal m³/h | 50          | 140            |
|                       | Fuel consumption, kg/h | -          | 9              |
|                       | Temperature of flame, °C | 2760      | 2170           |
| III                   | Type             | Plasma torch   | Air burner     |
|                       | Thermal power, kW| 70             | 110            |
|                       | Air flow, normal m³/h | 50          | 100            |
|                       | Fuel consumption, kg/h | -          | 7              |
|                       | Temperature of flame, °C | 2760      | 2170           |

The following operation modes were calculated:

- Heating by two plasma torches;
- Heating by plasma torch and air burner on diesel fuel
- Heating with plasma torch and air burner on diesel fuel with heating of blast air;
- Heating by a plasma torch and an oxygen burner on diesel fuel;
- Heating by two plasma torches with additional ohmic heating of the liquid glass layer.

Some of the options under consideration are shown in Table 3. The calculation results and additional information on the modes are given in the next section.

### 5. Results of shaft furnace melter part thermophysical processes numerical simulation

The results of calculations of the thermophysical model can be summarized by the following Table 4. Quantitative simulation results are shown in this table.

### Table 4. Results of numerical simulation

| Parameter                                      | Operation mode number | I | II | III | IV | V | VI |
|------------------------------------------------|-----------------------|---|----|-----|----|---|----|
| Input thermal power (source №1), kW           |                       | 70| 70 | 70  | 70 | 70| 70 |
| Input thermal power (source №2), kW           |                       | 70| 150| 110 | 70 | 70| 70 |
| of which for burners: - energy of chemical reaction of combustion, kW |               | - | 110| 80  | -  | - | -  |
| - air preheating, kW                          |                       | - | 40 | 30  | -  | - | -  |
| Ohmic heating of the slag layer, kW           |                       | - | -  | -   | 30 | 20| 10 |
As you can see in Table 4, using an air burner with heating of the blast air together with a plasma torch, you can get a higher average slag temperature. This is due to the large amount of thermal energy entering the melter with the gas mixture of the burner. Thermophysical calculations of the shaft furnace in all cases show a significant heterogeneity of the temperature of the liquid slag layer in the melter (about 500 °C). Figures 3 and 4 show temperature fields for operation mode number I.

**Table 4.** Energy balance (heat consumption)

| Total input thermal power, kW | 140 | 220 | 180 | 170 | 160 | 150 |
|------------------------------|-----|-----|-----|-----|-----|-----|
| Heat consumption for heating, melting of mineral fraction and overheating of slag melt, kW | 41 |
| Heat loss to the environment, kW | 50  | 60  | 50  | 70  | 60  | 60  |
| Exhaust gases heat, kW | 50  | 120 | 90  | 60  | 60  | 50  |

**Temperature readings**

| The average temperature of the gas in the melter, °C | 1950  | 1810 | 1690 | 2090 | 2030 | 1980 |
|---------------------------------------------------|-------|------|------|------|------|------|
| Maximum temperature of slag layer, °C | 1630  | 1640 | 1570 | 1870 | 1780 | 1700 |
| The average temperature of the slag layer, °C | 1330  | 1370 | 1280 | 1790 | 1640 | 1480 |
| The minimum temperature of the slag layer, °C | 1160  | 1190 | 1090 | 1490 | 1380 | 1270 |
| Sensor temperature №1 (in the wall), °C | 1420  | 1440 | 1360 | 1690 | 1600 | 1510 |
| Sensor temperature №2 (in the wall), °C | 1430  | 1450 | 1370 | 1700 | 1610 | 1520 |
| Exhaust gas temperature, °C | 1210  | 1490 | 1350 | 1530 | 1420 | 1320 |
| Pressure drop, Pa | 40    | 110  | 70   | 50   | 45   | 45   |

As you can see in Table 4, using an air burner with heating of the blast air together with a plasma torch, you can get a higher average slag temperature. This is due to the large amount of thermal energy entering the melter with the gas mixture of the burner. Thermophysical calculations of the shaft furnace in all cases show a significant heterogeneity of the temperature of the liquid slag layer in the melter (about 500 °C). Figures 3 and 4 show temperature fields for operation mode number I.

**Figure 3.** Operation mode number I. The temperature field of the gas region and the slag melt layer.
Figure 4. Operation mode number I. The temperature field of the gas region, the slag melt layer and layers of refractories and external insulation.

For comparison of different options for heating the melter, the greatest information content and visual results has a temperature field in the melt layer. Figures 5-7 show the temperature fields in the slag melt layer for various operation modes. Obviously that from a thermophysical point of view, the most effective way of additional heating is ohmic heating of liquid slag. So entering 10 kW increases the average temperature of the liquid slag by 150 °C.

Figure 5. Operation mode number I. Slag layer temperature.
6. Conclusions
This work aims to substantiate plasma torches replacement by natural gas or diesel burners and to confirm preservation of the utilization process efficiency. In order to do this numerical modeling of thermal processes was used: CFD modeling of a full-sized shaft furnace with a melter, including the distribution of temperature fields in the slag melt layer and external thermal insulation materials. Other possible combinations were also analyzed to optimize heat exchange processes: ohmic heating of the melt, replacement of air with oxygen. Thermophysical calculations of the shaft furnace in all cases show a significant heterogeneity of the temperature of the liquid slag layer in the melter (about 500 °C). Heating the medium using an oxygen burner is equivalent to heating using a plasma torch. The use of an air burner instead of one air plasma torch allows the liquid slag to be heated to the required temperatures, but this increases the heat loss by the exhaust gas. Entering additional heat using the aerial combustion of diesel (or another hydrocarbon) fuel and heating the combustion air can be used for normal operation technology process. From a thermophysical point of view, the most effective way of additional heating is ohmic heating of liquid slag. So entering 10 kW increases the average temperature of the liquid slag by 150 °C. According to the simulation results, we can conclude that the required parameters for the efficiency of the waste treatment process in the slag melt can be achieved by various heating options. The best option is chosen based on economic conditions and energy resources availability.
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