A source of thermal energy for roasting phosphogypsum – incinerators flue gas

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Abstract. The existing technologies for phosphogypsum utilization during its handling into building materials have been analyzed. Functioning equipment for joint utilization of municipal solid waste and phosphogypsum has been presented. An additional product of the installation, in addition to electrical and thermal energy, is gypsum. The waste gases from the incinerator are a heat source for roasting phosphogypsum. Fuel for the handling of phosphogypsum into gypsum is not used. A methodology for determining the specific amount of gases from a waste incinerator required for roasting phosphogypsum has been described in the article. The quantitative indicators for the reduction of polluting gases during the joint utilization of two waste types compared with operating independently waste treatment have been presented.

1. Introduction
Phosphogypsum is one of the most multi-tonnage solid wastes of mineral fertiliser manufacturing. There are four types of phosphogypsum in Ukraine: phosphogypsum from apatite concentrate has a shelf life 10-30 years in the tailings; phosphogypsum from phosphorites on the dump with a shelf life of less than ten years; phosphogypsum from phosphorites that was recently formed and dump phosphogypsum from uranium-containing phosphorites obtained. Millions of tons of phosphogypsum accumulated around the world at the moment. The phosphogypsum chemical composition is mainly represented by calcium sulfate dihydrate. This composition determines its using instead of natural gypsum. Scientists around the world have conducted studies that confirm the possibility of obtaining building materials and products from phosphogypsum. But the volume of phosphogypsum is processed into building materials and products from phosphogypsum. But the volume of phosphogypsum is processed into building materials and products from phosphogypsum. But the volume of phosphogypsum is processed into building materials is less than ten percent from total production. The mass phosphogypsum utilization instead of natural gypsum stone is constrained by the lack of cost-effective technological processes for processing these wastes [1-2]. This is explained by the significant consumption of thermal energy for the treatment of phosphogypsum in comparison with natural gypsum [3]. An increase of combustible fuel consumption has often been accompanied by increasing the greenhouse gas emissions, such as carbon dioxide and water vapor.

Technological lines are equipped with a large number of machines, which increases the technology intensity and therefore capital and operating costs. Many different types of technologies for the recycling industrial waste phosphogypsum have been patented in the world [4, 5]. But all of them are economically and environmentally pointless because some proposed technologies have high energy intensity. One of
the most pressing tasks of modern society is the search for ways to reduce emissions of gaseous pollutants into the atmosphere [6-9].

During the experimental studies, it was found that the rational temperature of the gas stream for roasting phosphogypsum is a temperature of 350°C [10]. A hypothesis has been got that the heat flow of the gases from the incinerator should be sent to the roasting phosphogypsum on this basis. A method has been proposed for using the heat of exhaust gases from waste incineration for roasting phosphogypsum as a result [10]. This excludes a need to use fuel. Since fuel is not used for the processing of phosphogypsum into building materials, there are no products of fuel combustion. This means that gaseous pollutants generated by fuel combustion did not pollute the atmosphere.

The purpose of this article is to determine the environmental parameters for roasting phosphogypsum using heat from the household waste incineration.

Operating principle of the installation is as follows. The finely ground phosphogypsum 1 (fig.1) through a hopper with a feeder and a conveyor system is fed to the roller crusher 2. After that, phosphogypsum is sent by a conveyor 3 in a drum-dryer 4. The dried phosphogypsum is sent to the elevator 5, then - conveyor for dry phosphogypsum 7. Wet gases 6 are released into the atmosphere. Dry phosphogypsum 8 is fed to a mill-dryer 9. In the proposed version, a bowl-roll mill-dryer is used, developed at the Department of Mechanization of Construction Processes of Kharkiv National University of Civil Engineering and Architecture. Directly above the mill is a through separator. The mill-dryer 9 is equipped with an external combustion chamber 10.

**Figure 1.** Complex of roasting phosphogypsum with the use of heat from waste incineration.

The fine particles of the material, passing the separator, flow upward into the shaft of the dryer 11, where effective heat exchange takes place in the suspended state. Shaft 11 is also used for further particle
fractionation. From the shaft 11, the flow of the gas with small particles enters the centrifugal cyclone 12, in which the particles are separated from the gas that has received physical moisture from the material. The wet heat carrier through the flue gas line 13, the dust removal system and the smoke exhauster (not shown in the diagram) is discharged into the atmosphere. The dried material, precipitated, is collected in a bunker with a shutter at the bottom. By means of a screw feeder 15, material is fed into the lower part of the gas flue of pre-heating of the dry phosphogypsum 16. The material is picked up by a stream of hot gases that exit the cyclone 22 and is carried upward into the cy-clone 17. At this time the material is heated and dried. In the cy-clone 17, the particles are separated from the wet gases. Gases are discharged through the pipe 18 into the atmosphere, and the hot and absolutely dry particles of phosphogypsum from the cyclone 17 are drained into the dehydrator 20. Here is the transformation of phosphogypsum into hemi water gypsum in a suspended condition in the flow of hot gas. Water is released from phosphogypsum.

During the dehydration reaction, the water molecules are broken with the ions $\text{Ca}^2+$ and $\text{SO}_4^{2-}$ and the water is removed from the crystal lattice in the form of superheated steam. As a result, $\beta$-modification of calcium sulfate hemihydrate is formed. The chemical reaction of this process (dehydration):

$$\text{CaSO}_4 \cdot 2\text{H}_2\text{O} \rightarrow \beta-\text{CaSO}_4 \cdot 0,5\text{H}_2\text{O} + 1,5\text{H}_2\text{O}$$

In cyclone 22, the flow is separated: particles of hemi water gypsum down and collected in hopper 23. Wet hot gases escape up-ward from cyclone 22 to tube 16. The main amount of heat that is used in technology is realized in dehydrator 20 (Figure 1). According to the proposed scheme, this heat is supplied from a municipal waste incinerator (21 on Fig. 1).

2. Quantity determination of exhaust gases from a waste incineration required for roasting phosphogypsum

At the first stage, we must calculate the amount of gas that is produced in the waste incineration (at a specific temperature) will be required to receive 1 kilogram of the semi-hydrate gypsum ($\text{CaSO}_4 \cdot 0,5\text{H}_2\text{O}$- calcium sulphate hemihydrate) from phosphogypsum (calcium sulphate dihydrate - $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). For this we have composed the thermal balance.

2.1. Thermal balance: Heat input (kJ/kg of gypsum).

*With gases from the incinerator:*

\[ q_1 = V \cdot C \cdot t \] \hspace{1cm} (1)

where, \( V \) - the volume of gases emanating from the incinerator, m$^3$ of gas/kg of gypsum; \( C \) - heat capacity of gases; \( t \) - gas temperature.

*With calcium sulphate dihydrate - $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$:*

– a dry raw materials consumption, taking into account the substance losses, kg/kg:

\[ G = \frac{G^T \cdot 100}{100 - a} \] \hspace{1cm} (2)

\( a \) - fraction of dust, which is lost with exhaust gases, %; \( G^T \) - theoretical dry raw materials consumption, kg/kg:

\[ G^T = \frac{100}{100 - LIM} \] \hspace{1cm} (3)

\( LIM \) - loss on roasting of raw materials, %;

– wet raw materials consumption, kg/kg:

\[ G_w = \frac{G \cdot 100}{100 - W} \] \hspace{1cm} (4)

\( W \) - initial moisture content of raw materials, %;

– yield of physical moisture, kg/kg:
4

\[ G_{W}^{f} = G_{W} - G \]  \hspace{1cm} (5)

\[ q_{2} = \left( GC_{C} + G_{W}^{f}C_{H_{2}O} \right) t_{C} \]  \hspace{1cm} (6)

Total heat input:
\[ \Sigma q = q_{1} + q_{2} \]  \hspace{1cm} (7)

Flow structure for calculating thermal balance roasting phosphogypsum with the use of heat from waste incineration is presented in the figure 2.

**Heat Consumption** (kJ/kg gypsum)
- with the evaporation of physical moisture:
  \[ Q_{1} = G_{W}^{f} \left( I_{S} + C_{S} t_{S} \right) \]  \hspace{1cm} (8)

  \[ I_{S} \] - enthalpy of steam; \[ C_{S} \] - heat capacity of steam; \[ t_{S} \] - steam temperature.
- with CaSO₄·0,5H₂O - calcium sulphate hemihydrate:
  \[ Q_{2} = C_{g} t_{g} \]  \hspace{1cm} (9)

  \[ C_{g} \] - heat capacity of gypsum; \[ t_{g} \] - gypsum temperature.
- with the formation of semi-hydrate gypsum:
  \[ Q_{3} = \frac{\Delta H_{298}^{\circ}}{M_{\text{CaSO}_4 \cdot 0,5\text{H}_2\text{O}}} \]  \hspace{1cm} (10)

  \[ \Delta H_{298}^{\circ} \] - reaction enthalpy, J/mol;

  \[ \Delta H_{298}^{\circ} = \sum \Delta H_{298}^{\circ} \text{ reaction products} - \sum \Delta H_{298}^{\circ} \text{ starting materials.} \]
- with exhaust gases:
  \[ Q_{4} = V \cdot C_{w} \cdot t_{w} + V_{v} \cdot C_{v} \cdot t_{w} \]  \hspace{1cm} (11)

  \[ C_{w} \] - the heat capacity of the exhaust gases from the roasting phosphogypsum installation; \[ t_{w} \] - temperature of the exhaust gases from the roasting phosphogypsum installation.
- yield of chemically bound moisture, kg/kg:
  \[ G_{w}^{x} = G_{C} \frac{M_{1,5\text{H}_2\text{O}} \left( \text{CaSO}_4 \cdot 2\text{H}_2\text{O} \right)}{M_{\text{CaSO}_4 \cdot 2\text{H}_2\text{O} \cdot 100}} \]  \hspace{1cm} (12)

  \[ M_{1,5\text{H}_2\text{O}}, M_{\text{CaSO}_4 \cdot 2\text{H}_2\text{O}} \] - respectively molecular weights 1,5H₂O and CaSO₄·2H₂O.
  CaSO₄·2H₂O, the dihydrate gypsum content in raw materials, %.
- total water vapour yield:
  \[ G_{v} = G_{w}^{f} + G_{w}^{x} \]  \hspace{1cm} (13)

  \[ V_{v} = \frac{G_{v}}{\rho_{v}} \]  \hspace{1cm} (14)

  \[ \rho_{v} \] - the density of water vapour, kg/m³.
- heat loss to the environment
  \[ Q_{5} = (0,05...0,1)q_{1} \]  \hspace{1cm} (15)

Total heat consumption:
\[ \Sigma Q = Q_{1} + Q_{2} + Q_{3} + Q_{4} + Q_{5} \]  \hspace{1cm} (16)
2.2. Thermal Balance Equation

\[ \Sigma q = \Sigma Q \] (17)

The volume of gases emanating from the incinerator, \( m^3 \) of gas / kg of gypsum (\( V \)) which must be submitted for roasting phosphogypsum is calculated from the thermal balance equation.

Our calculations showed that the 1.8 m\(^3\) of gases per 1 kg of building gypsum is necessary for roasting phosphogypsum. When the installation productivity for the production of building gypsum from phosphogypsum is 10 t / h, the required hot gases volume from the incinerator is calculated:

\[ 10000 \cdot 1.8 = 18000 \, m^3/hr \]

3. Results. Determination of environmental parameters

When roasting gypsum (using natural gas fuel), the total exhaust gas output [11, 12] during fuel combustion per 1 kg of \( \beta \)-semihydrate gypsum:

- carbon dioxide:
  \[ CO_2 = \vartheta_{CO_2} \cdot \rho_{CO_2} \cdot B_f \] (18)
  \[ CO_2 = 1.036 \cdot 1.977 \cdot 0.040 = 0.082, \, kg/kg \]
  \( B_f \) - fuel consumption for roasting;

- water vapour
  \[ H_2O = \vartheta_{H_2O} \cdot \rho_{H_2O} \cdot B_f \] (19)
  \[ H_2O = 2.01 \cdot 0.805 \cdot 0.04 = 0.065, \, kg/kg \]

- oxygen
  \[ O_2 = \vartheta_{O_2} \cdot \rho_{O_2} \cdot B_f \] (20)
  \[ O_2 = 1.96 \cdot 1.429 \cdot 0.04 = 0.11, \, kg/kg \]
The technological process of phosphogypsum dehydration consists of several technological operations, which is aimed to changing the source material in order to give it the properties of a composite material. In the technology of gypsum binders that is intended for construction, the following main stages of the technological process are mainly used: crushing, drying, grinding or joint drying and dehydration. The recommended workflow depends on the physical properties of the raw materials, the type of equipment needed for dehydration and the quality requirements of the final product.

The method of using the waste gases of the incinerator as a source of thermal energy for roasting phosphogypsum is substantiated. It is shown that the combined disposal of solid waste and phosphogypsum will reduce greenhouse gases and other pollutants into the atmosphere.

4. Conclusions
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