Realizing clean technology principles for the mining and processing industry in the Arctic region

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Abstract. The production of apatite concentrate in the Arctic region of the Russian Federation is carried out using technology developed during the middle of the twentieth century. One of the most energy-consuming and environmentally dangerous stages of this technology is the drying of raw concentrate. Energy for drying is obtained from combustion of fuel oil, which leads to greenhouse gas emissions and environmental pollution. This study analyses the drying step in the apatite production process to optimize the environmental and economic aspects of this process. The characteristics of apatite concentrate during heating was studied through synchronous thermal analysis. Mass loss was determined during each stage. It was observed that drying of apatite concentrate does not require high temperatures, which are achieved in drum chamberthrough fuel oil combustion. Therefore, drying with flue gases is inexpedient. A method that involves dewatering the concentrate, which can be considered a form of clean technology and does not involve fuel oil combustion, is proposed. The results of this study can be used to modernize the current technology for the production of apatite concentrate.

1. Introduction
The Arctic region of the Russian Federation is characterized by high susceptibility to anthropogenic impact and low regenerative properties. Technogenic and human impact factors influence mining and processing of minerals and raw hydrocarbon materials. The environmental management system in some areas of the Russian Arctic has generated highly modified territories [1]. Natural geochemical conditions, exhaustion of biodiversity, soils and vegetation degradation, erosion, and environment pollution have been observed. Therefore, optimization of economic and ecological balance is an important goal.

In these conditions, the urgent task of developing Arctic regions requires striking a balance between economy and ecology. The world is presently transitioning from the traditional model of economic growth to a «green economy» based on resource conservation and clean technologies [2, 3]. Thus, the key task of creating a green economy in the Arctic is the transition to clean processing technologies.

This task is especially important for the mining and mineral processing industries in the Arctic region. The primary strategy for development of promising mining and processing complexes should focus on optimization of technological processes while reducing environmental impact, which corresponds to the principles of the concept of clean technology.

An example of the transformation of production processes towards cleaner technologies is the modification of the apatite concentrate technology in JSC Apatit (Murmansk region, Russia).

2. Analysis of the apatite concentrate technology
JSC Apatit is the world's largest apatite concentrate production enterprise, which develops deposits of apatite-nepheline from endogenous (magmatic) origin ores in the Khibiny Mountain Group [4]. The high-grade apatite concentrate contains 39 % or more of phosphorus pentoxide (P₂O₅), which is used
as the feedstock for phosphate fertilizers and production of feed phosphates [5]. The concentrate, also contains 32.7±3.1 % calcium, 0.57±0.13 % silicium, 0.41 % aluminium, and traces of nonferrous and rare-earth metals [6]. Production output reached 9.5 million tons per year [7].

Figure 1 shows the basic technological scheme of apatite concentrate production. The technological scheme includes the following basic operations: splitting the initial ore, ore grinding, flotation separation of apatite with phosphorus (V) oxide content of not less than 39 %, concentration in thickeners and hydrocyclones, filtration with separation of the filtrate and cake, and final drying of the apatite concentrate.

![Diagram](image)

**Figure 1. Basic technological scheme of apatite concentrate production.**

Apatite concentrate is traditionally dried in rotary-type drum chambers by convection. The drying agent is air heated by combustion gases from fuel oil combustion. The main disadvantage of the traditionally-used rotary chambers is their low efficiency and very high energy consumption. Energy consumption during drying can be reduced using more modern methods.

The use of rotary-type drum chambers has many indirect disadvantages. Condensate formation leads to destruction of buildings during humidification and due to freezing in winter, metal corrosion is activated, and solid micro-particle and convection gas emission during evaporation and drum rotation.

The drying chamber furnaces use M-100 brand fuel oil (high-sulfur), and consumption reaches 10.34 kg per ton of apatite concentrate. Thus, the annual consumption of fuel oil is 97.8 thousand tons, which is a relatively large amount of fuel resources and energy.

The necessity of reducing fuel oil consumption during apatite concentrate drying is obvious. This is being pursued both in the field of resource and energy savings, and directly reduces environmental impacts.

This study analyses the apatite concentrate drying process to improve and optimize the environmental and economic aspects of the production process. A synchronous thermal analysis was carried out using the Netzsch STA 449 F1 Jupiter complex with a Netzsch QMS 403C Aëolos quadrupole mass spectrometer.

Apatite concentrate was obtained at the filtration stage from the apatite-nepheline enrichment factory (JSC Apatit, Murmansk region, Russia) and was used for analysis.
Modelling of apatite concentrate drying was carried out at 30-1050 °C and under argon flow (100 ml/min). Drying was performed in a platinum crucible. The apatite concentrate drying results are presented in Figures 2-6.

![Figure 2. Apatite concentrate moisture content change in argon at various temperatures.](image)

The dependence presented in Figure 2 shows that dehydration of apatite concentrate ends at 60 °C. After this value, the TG-curve runs parallel to the x-axis. This means that drying in the high-temperature regime, which is achieved by fuel oil combustion in air, is not required. The maximum drying rate is observed at 55 °C (downward peak on the DTG-curve). Figure 3 shows the specific heat of the apatite cake within the temperature range presented in Figure 2.

The differential-scanning calorimetry (DSC) signal shows how heat flow is related to the material’s mass. The heat flow is related to a specific phase transition heat and indicates how the material loses weight per unit time. This allows the temperature at which the maximum dehydration rate is observed to be determining. This makes it possible to select the optimal drying parameters.

The DSC signal of apatite concentrate drying indicates an endothermic effect within the investigated temperature range. The latent heat at the phase transition is 2143 J/g. This is slightly below the 2300 J/g enthalpy value of free moisture evaporation.
Figure 3. Phase transition energy of apatite raw concentrate obtained at the filtration stage during.
The results were obtained using differential-scanning calorimetry.

We can suppose that decreased drying enthalpy of apatite concentrate compared to pure water evaporation is due to the influence of surfactants contained in the raw apatite cake obtained after filtration. To prove the supposition that high temperatures do not cause significant changes in apatite concentrate composition, thermo-gravimetric analysis was performed at temperatures up to 1050 °C. These results are shown in Figure 4.

Figure 4. Thermogravimetric analysis of the apatite concentrate during drying.

One can see that subsequent loss of mass at temperatures ranging from 67 to 1050 °C proceeds in two stages. The first stage proceeds at 212 °C, and the second at 757 °C.
The endothermic effects occurring in the apatite concentrate are shown in Figure 5. From this figure, it can be observed that there are two endothermic peaks at 212 °C and 757 °C. The total mass loss is insignificant and is about 0.1%.

During the first stage of heating at 212 °C, crystallized water is released, amounting to 0.05% of the total sample weight. The obtained results confirm the data from similar studies carried out with respect to Moroccan phosphate, which is an analogue of apatite concentrate [7]. In this case, studies have shown the presence of an endothermic peak due to moisture removal in the 100-200 °C temperature range and significant endothermic carbonate peaks at 795-815 °C and 830-890 °C. In contrast to the studies under discussion, two exothermic peaks at 300-400 °C and 730-770 °C were also observed, corresponding to the combustion of organic impurities. Apatite concentrate (Kola Peninsula, Russia) does not contain organic impurities. Therefore, heating up to high temperatures for burning organic matter is not required.

During the second stage at 757 °C, weight loss refers to the release of carbon dioxide (Figure 6). It can be assumed that CO₂ is released due to decomposition of carbonate impurities. Phosphorus and fluorine in the gaseous products formed upon heating to high temperatures were not found.

Thus, the analysis of prior studies has shown that high-temperature drying of apatite concentrate, currently being implemented at JSC Apatit, is impractical, in view of the fact that dehydration ends at 70 °C. In addition, there are no organic matter impurities in the apatite concentrate (Murmansk region, Russia), and this material does not require high-temperature processing. However, in the technology used at JSC Apatit, the temperature of flue gases entering the rotary kiln ranges from 600 to 1000 °C.

An energy calculation showed that about 327 MJ of energy is required to dry 1 ton of crude apatite concentrate. In this case, 10.3 kg of M-100 grade fuel oil are consumed during drying of 1 ton of raw concentrate, which leads to 418 MJ of energy consumption. Thus, when drying each ton of raw apatite concentrate cake, about 91 MJ are lost to the environment, which is about a quarter of the total heat energy produced by fuel oil combustion.
Figure 6. Mass spectrometric determination of carbon dioxide.

The calculated environmental load showed that in addition to the low energy efficiency of the drying process, fuel oil combustion causes significant ecological damage to the ecosystems in the Arctic region. Combustion of high sulfur fuel oils results in the release of greenhouse gases, black carbon, significant amounts of nitrogen and sulfur dioxides, and carcinogenic substances, including polycyclic aromatic hydrocarbons and other toxic compounds [8, 9]. The emission levels and oxygen consumption during heavy fuel oil combustion are presented in Table 1.

Table 1. Specific emissions and oxygen consumption during combustion of high sulfur fuel oil.

|                     | Consumed during combustion, t | Emissions from fuel oil combustion, t |
|---------------------|------------------------------|---------------------------------------|
|                     | Oxygen mass | Air mass   | Carbon dioxide | Sulphur dioxide | Nitrogen oxides | Particulate matter (PM) |
| M-100 high sulfur fuel | 3,1546       | 13,6327 | 3.2296 | 0.07 | 10,4831 | 0.00092 |
| 1 ton               |              |          |                |                 |                 |                         |

The use of clean technology principles requires the introduction of new solutions for the implementation of energy-efficient and environmentally friendly drying technology for apatite concentrate. New apatite concentrate drying technology should consider the following points, justified by the above research results. The greatest energy costs during drying of raw material are noted during the phase transition of liquid water to steam. Thus, clean technology should include drying apatite concentrate without phase transition «water-vapour». This approach will save a significant amount of energy and reduce greenhouse gas and toxic gas emissions caused by fuel oil combustion.

One of the possible technological solutions in this direction is ultrasonic drying. Ultrasonic treatment allows moisture removal in the form of fog (microdroplets) rather than steam [10], which can significantly reduce energy consumption. At the same time, there is no need for energy consumption for heating of heat carriers, elements, and structures in the drying chamber.

To test the effectiveness of ultrasonic drying, laboratory studies were carried out using a laboratory ultrasonic generator with an output of 0.07 kWh. The productivity of the laboratory unit was 2.08 kg/h of apatite concentrate. In this case, the energy consumption per 1 ton of raw cake will be 121 MJ,
which is comparable in energy efficiency to 3 kg of burnt fuel oil. The residual moisture index following ultrasonic drying of the concentrate was 1±0.05%.

An alternative solution may involve using a heat pump system in a water-to-air system, for example, and using a factory recycled water supply as a low-potential heat source. According to the available data, and using JSC Apatit as an example, the circulating water supply amounts to about 70 l/min with a water temperature of 10 to 15°C, which is sufficient to operate the heat pump system in an efficient mode with a heat conversion coefficient of 3-3.5.

3. Conclusion
Analysis of apatite concentrate production showed that one of the most energy-consuming and environmentally hazardous operations is the drying of raw concentrate. This process was studied using synchronous thermal analysis. The results show that the dewatering of the concentrate ends at a temperature of 60°C. With further heating, the mass loss is about 0.1% due to water evaporation and release of carbon dioxide due to decomposition of carbonates. The absence of organic impurities in the apatite concentrate means that high-temperature heating is not required for combustion. It is economically and environmentally expedient to conduct drying without heating to high temperatures. In such conditions, a cleaner water removal technology is possible. The authors have tested the method of ultrasonic drying, which allows one to lower the moisture content of the concentrate to a commercially viable value with much lower energy consumption.

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