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PURIFICATION AND THERMOCHEMICAL CONVERSION OF AMMONIUM SULPHATE: A PATHWAY TO SUSTAINABLE WASTE RECYCLING

Abstract: Ammonium sulphate produced as a by-product of the coke-chemical process at JSC “QARMET” (Kazakhstan) contains impurities such as tarry substances and pyridine-based sulphates. These impurities cause adverse effects, including strong odour, caking, and atypical appearance, while pyridine sulphates also increase acidity ($\text{pH} < 5$). This study investigates the purification of substandard ammonium sulphate to expand its potential applications. Mechanisms for producing complex fertilisers from the purified product were examined. The results provide a fundamental theoretical and technological basis for developing new production lines for chemical products, including compound fertilisers. Thermochemical interactions between potassium carbonate and molten ammonium bisulphate were studied. It was found that at equimolar ratios of $2 \text{ NH}_4\text{HSO}_4$ to K_2CO_3 , ammonium potassium sulphate (NH_4KSO_4) forms in the temperature range of (157-260) °C; above 260 °C, potassium sulphate and ammonium sulphate are produced, with concurrent pyrolysis of ammonium sulphate to ammonium bisulphate and ammonia. Upon cooling, various double bisulphates form, depending on the ratio of potassium sulphate to ammonium bisulphate.

Keywords: waste recycling, obtaining complex fertilisers, ammonium sulphate, potassium carbonate, melt

Introduction

In the Republic of Kazakhstan, despite the availability of a substantial raw material base, a large amount of industrial waste and unsellable by-products are generated, while the chemical industry remains insufficiently developed. The required volume of chemical products is imported from other countries such as the Russian Federation, China, and Uzbekistan. This dependence acts as a constraining factor for the development of various

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technological processes in the chemical industry and agriculture. At the same time, many waste and by-products from metallurgical enterprises contain valuable components and may serve as secondary raw materials for the production of commercially valuable products. However, such materials often remain unutilised due to quality limitations or the absence of appropriate processing technologies [1].

One such by-products is technical-grade ammonium sulphate generated during coke-chemical production at JSC "ArcelorMittal Temirtau" (currently JSC "QARMET"). This product does not meet the requirements of the relevant GOST standards and cannot be directly used as a fertiliser [2]. The effective utilisation of these wastes as a source of ammonia requires purification from organic contaminants, the presence of tarry substance and pyridine bases, which is both a necessary and technically complex process [3]. For these reasons, the manufacturer has faced difficulties in marketing this by-product.

The purification of technical-grade ammonium sulphate aims not only to improve its quality but also to expand its potential applications, including the production of high-purity salts and its usage in the pharmaceutical and electronics industries. Purification methods can generally be classified into physicochemical, thermal, chemical, and membrane-based approaches [4, 5].

The most widely used purification approach is based on differences in solubility between impurities and the main salt. Ammonium sulphate is dissolved in water, followed by filtration and controlled cooling to precipitate a pure product. Recrystallisation can significantly reduce the concentration of soluble impurities. However, it is ineffective method for the removal of volatile and organic contaminants [6-8]. Consequently [9], this method is mainly applied as a preliminary purification step, particularly for the removal of mechanical inclusions, carbonaceous particles, and insoluble impurities, and is often combined with the use of coagulants. Upon heating, ammonium sulphate partially loses ammonia and water, leading to the formation of secondary compounds. However, thermal decomposition begins at temperatures above 250 °C - 300 °C, which limits the applicability of this approach. Thermal drying can be effective for the removal of volatile organic impurities [10].

Chemical purification methods are employed to neutralise acidic or alkaline impurities and to oxidise or reduce specific contaminants. For example, hydrogen peroxide or potassium permanganate can be used to oxidise organic impurities, resulting in improved colour and odour of the product. In addition, precipitating agents such as sodium hydroxide or sodium sulphide are applied to remove heavy metal impurities from ammonium sulphate solutions [11].

Advanced methods capable of achieving a high degree of product purity include ion-exchange and membrane-based technologies. Ion-exchange resins are commonly used to remove iron, copper [12], and zinc ions, while reverse osmosis and nanofiltration are applied to concentrate solutions and eliminate low-molecular-weight impurities. Despite their effectiveness, these methods are often limited by high capital costs and relatively low throughput, which restricts their large-scale industrial application.

Biological purification methods are rarely employed in industrial practice; however, they may be applied at the wastewater treatment stage during ammonium sulphate production from gas emissions to remove organic contaminants (e.g., from flue gas desulphurisation units) [13].

The available literature emphasises that selection of an appropriate purification strategy should be based on the initial composition of the technical-grade ammonium

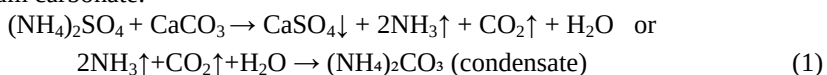
sulphate. For example, ammonium sulphate obtained from caprolactam production typically contains predominantly organic impurities, whereas from coke-chemical processes are mainly contaminated with volatile and sulphur-containing compounds. Combined purification schemes incorporating filtration, chemical neutralisation, and recrystallisation stages have been shown to provide the most effective results, enabling purity levels of 99 % or higher to be achieved.

Thus, the purification of technical-grade ammonium sulphate is a multistage process, the choice of which is determined by the nature of the impurities and the requirements for the final product. Conventional approaches, including recrystallisation or resin-based purification, are often associated with high energy consumption or reagent usage. Therefore, the development of simpler and more cost-effective methods remains a relevant and important research objective.

One promising application involves the synthesis of alkali and alkaline earth metal carbonates, which allows for the simultaneous utilisation of ammonium sulphate - such as that generated as a by-product of caprolactam production or flue gas treatment - while producing valuable carbonate materials for industrial and environmental applications.

The processing of ammonium sulphate to obtain more valuable compounds, such as ammonium carbonate $((\text{NH}_4)_2\text{CO}_3)$, is of interest from the perspective of resource-efficient utilisation and secondary recycling of chemical industry waste. Various approaches have been proposed for the synthesis of complex compounds based on ammonium sulphate. In general, carbonate formation involves the interaction of ammonium sulphate with alkali metal carbonates or bicarbonates (Na_2CO_3 , K_2CO_3), alkaline earth metal carbonates (CaCO_3 , MgCO_3), or with gaseous CO_2 and ammonia solutions [14, 15]. Possible reactions include:

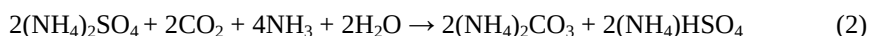
with calcium carbonate:



In aqueous systems, the reaction typically initiates at temperatures above 50 °C, and the reaction rate increases with enhanced evaporation of the ammonia-water azeotropic mixture. It is well established that ammonium carbonate $((\text{NH}_4)_2\text{CO}_3)$ decomposes at temperatures above 60 °C, releasing ammonia, carbon dioxide, and water vapour. As a result, precise control of temperature and pressure is required to obtain the target product in a stable form [16]. Despite its feasibility, this process is characterised by considerable technological complexity and high energy consumption.

According to [17], reactions between ammonium sulphate and calcite (CaCO_3) are thermodynamically feasible at relatively low temperatures of (60-70) °C, particularly in the presence of moisture. Under these conditions, ammonium carbonates are formed and can be recovered by reducing temperature or solution concentration. Such reaction pathways are often considered in the context of agroecosystem modelling and CO_2 capture technologies.

The authors [18] also reported the possibility of reacting ammonium sulphate with solutions saturated with ammonia and carbon dioxide within the framework of the urea cycle:



This approach requires the use of high-pressure reactors and precise pH control. In industrial practise, this process is applied in CO_2 absorption technologies based on

ammonia solutions, followed by the precipitation of ammonium carbonate, which also enables the utilisation of greenhouse gases [19].

However, it should be noted that a significant shift of the equilibrium toward the right-hand side of reaction [18], resulting in the stable coexistence of both products, is unlikely. This is because both compounds are readily hydrolysed, while one exhibits a pronounced alkaline character and the other represents an acidic ammonium bisulphate species.

Ammonium sulphate is also actively used in reactions with magnesium carbonate to produce magnesium-containing carbonate compounds:



Conducting such reactions in an aqueous medium under controlled pH conditions enables the production of basic magnesium carbonates, including magnesite, hydromagnesite, and related phases, which are of interest in pharmaceuticals, particularly as antacid materials [20].

An alternative route for synthesising ammonium carbonate from ammonium sulphate involves its reaction with alkali metal carbonates (Na_2CO_3 , K_2CO_3), during which ammonium carbonate is displaced into the solution or gas phase. These reactions can be carried out in aqueous media under controlled temperature and stirring conditions. In addition, incomplete carbonation has been reported to result in the formation of double salts, such as $\text{NH}_4\text{HCO}_3 \cdot (\text{NH}_4)_2\text{SO}_4$ [21, 22].

It is also possible to obtain rare earth metal carbonates from their sulphate solutions by adding ammonium carbonate derived from $(\text{NH}_4)_2\text{SO}_4$. This approach is applied in the processing and separation of lanthanides [12].

A comparison of the results reported [18, 21, 22] reveals that the investigated reaction are essentially identical and lead to the formation of the same double salt $\text{NH}_4\text{HCO}_3 \cdot (\text{NH}_4)_2\text{SO}_4$ as a common product.

Materials and methods

Experimental procedure

The industrial prototype was designed for a raw material processing capacity of 8 t/day and consisted of the following technological units:

1. A homogeniser for crushing and disintegrating lump inclusions to facilitate the release of tarry substances;
2. A custom-manufactured flotation machine with a chamber volume of 0.08 m³;
3. A decanter and a Nutsch filter complete with a vacuum station and receiver;
4. A drying drum, 400 mm in diameter and 2000 mm in length, heated in two modes: by transferring thermal energy through the drum walls using a gas burner, and by an electric air heater.

The dosing unit was equipped with a bottom slide gate, allowing controlled discharge of the material. The initial ammonium sulphate sample collected from the storage surface exhibited a greyish colouration and contained agglomerated lumps.

For homogenisation, 50 L of a pre-prepared saturated ammonium sulphate brine and 50 mL of a 25 % aqueous ammonia solution were introduced into the homogeniser, the amount of ammonia solution calculated to displace pyridine bases (approximately 100 mL in total).

The mixing was performed at a stirrer speed of 3000 rpm, with the residence time varied between (5 and 15) minutes in the presence of solid lumps up to approximately 40 mm in size. The results indicated that a mixing time of (5-10) minutes was sufficient for complete homogenisation, as no lumps were detected on the sieve. The homogenised suspension was then discharged by gravity into the flotation machine positioned directly below via a ball valve.

The purification of the crude product was carried out in the flotation machine with a volume of 0.08 m³, custom-manufactured at a plant. The optimal air supply rate, determined using rotameter measurements and visual assessment of foam formation, was found to be 5 L/s. The flotation process was conducted for (7-10) min. Once complete separation of the foam-resin fraction was achieved, the contents of the flotation machine were discharged into a decanter through the lower drain valve. During decantation, the supernatant solution containing residual resinous impurities remained above the crystal layer and was removed without passing through the solid phase, thereby preventing secondary contamination of the purified crystals.

The concentration of residual impurities in the circulating solution was sufficiently low to allow its reuse in the process without preliminary filtration. Periodically, the solution was purified using a Nutsch filter.

After 10 minutes of decantation, the moisture content of the crystals was approximately 15.7 %. The wet crystals were transferred into the hopper of a rotary drum dryer using a crane. The hopper was equipped with a screw feeder (auger) that delivered the material directly into the rotating drum. To simplify the design, the screw was fixed to the drum, allowing both components to rotate synchronously at the same speed using a single drive motor. The drum tilt angle and rotation speed were kept to a minimum 2° and 12 rpm, respectively. Drying was periodically interrupted, as a residence time shorter than 45 min resulted in the discharge of wet, non-free-flowing material. The installed capacity of the dryer was approximately 38 kg/h. Consequently, the daily output of the unit was about 912 kg/day, which constituted the limiting factor under the test conditions. The temperature of the material at the dryer outlet was approximately 75 °C.

Physicochemical analysis

As a fundamental basis for obtaining new compounds aimed at expanding the scope of ammonium sulphate applications, a physicochemical analysis of several chemical reactions involving ammonium sulphate was performed.

Thermal analysis of the reaction mixtures was performed using a Q-1000 D derivatograph, F. Paulik, J. Paulik, L. Erdey system, manufactured by the Hungarian company MOM (Magyar Optikai Muvek). This instrument enables simultaneous recording of thermogravimetric (TG), differential thermal (DTA), and differential thermogravimetric (DTG) signals, providing comprehensive information on the thermal behaviour of the investigated substances.

Experimental conditions:

Heating mode: dynamic, with a constant rate;

Heating rate: 10 °C/min;

Sample mass: 450 mg;

Reference substance: calcined aluminium oxide (Al₂O₃);

Atmosphere: inert argon;

Temperature range: up to 350 °C, followed by cooling to 50 °C.

The reaction mixtures were prepared in two ratios: $\text{NH}_4\text{HSO}_4 : \text{K}_2\text{CO}_3 = 1 : 1$ and $2 : 1$. Prior to analysis, each sample was placed in a quartz crucible identical to that containing the reference material. During heating, thermal effects associated with phase transitions, dehydration, thermal decomposition, or interactions between the mixture components were recorded.

The DTA data were interpreted based on the shape, onset temperature, and peak temperature of the effects, as well as by comparing them with mass losses recorded in the TG curves. Exothermic processes (e.g. crystallisation or oxidation) were presented as upward peaks, whereas endothermic processes (melting, dehydration or decomposition) appeared as downward peaks [12, 23].

Results and discussion

Research on the purification of ammonium sulphate

This paper presents the results of a study on the purification of technical-grade ammonium sulphate (AS) obtained from the coke chemistry production of JSC “QARMET”. The work was carried out under industrial prototype conditions at LLP “Innovation”, with the participation of several of the authors. The initial sample from JSC “QARMET” was contaminated with heavy tars and pyridine bases, exhibited a dark colour with reddish inclusions, and had an unpleasant odour (Fig. 1).



Fig. 1. Storage conditions of ammonium sulphate and samples of tarry inclusions (red)

The process flow diagram for processing impure ammonium sulphate and obtaining the commercial product is shown in Figure 2.

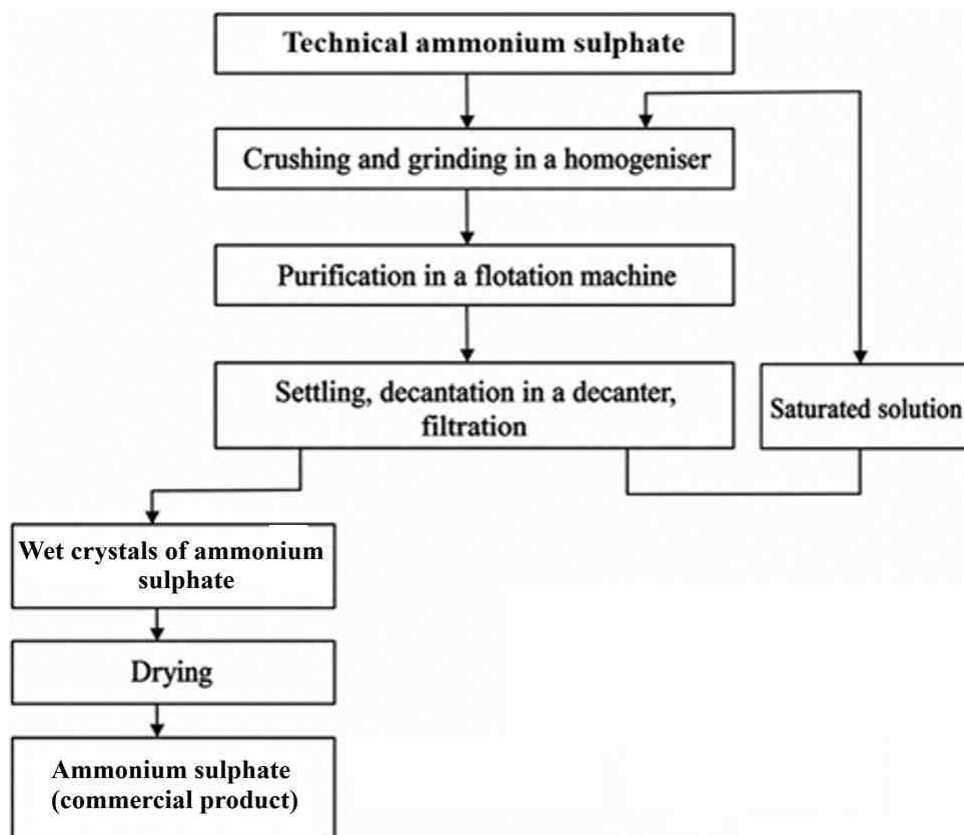


Fig. 2. Process flow diagram for the production of commercial ammonium sulphate

The main indicators of purified ammonium sulphate

Table 1

Parameter	Value
Mass fraction of nitrogen [%]	21
Mass fraction of water [%], not more than	0.2
Mass fraction of free sulphuric acid [%], not more than	0.03
Friability [%]	100
Mass fraction of insoluble impurities [%]	0.02
Appearance (white)	white to grey

Preliminary extraction tests conducted using a laboratory flotation machine demonstrated the feasibility of separating resinous substances. The red coatings and characteristic odour of pyridine compounds were eliminated after displacing the pyridine bases by saturating the solution with an equivalent amount of ammonia, which was subsequently removed and captured during the drying stage of the wet purified product.

During the trials, approximately 2,400 kg of commercial-grade ammonium sulphate was produced, fully complying with all GOST standards [24, 25] (Table 1).

The main optimal parameters of the ammonium sulphate purification technology at the coke-chemical plant of JSC “ArcelorMittal Temirtau” (Table 2).

Table 2

Optimal parameters of the ammonium sulphate purification technology at the coke-chemical plant

No.	Process name	Process duration [min]	Plant capacity [kg/h]
1	Homogenisation	10	200
2	Flotation	10	200
3	Decantation	10	200
4	Brine filtration	15 (batch)	200 and above
5	Drying	79	38

As shown in Table 2, the most limiting stage in the process is drying. Therefore, to increase productivity to 200 kg/h (4.8 t/day), one of the possible optimisation strategies should be implemented. For drying, to use of industrially proven drying units is recommended to ensure efficient utilisation of thermal energy.

The potential for using ammonium sulphate to synthesise more valuable compounds

As illustrated in Figure 3, the overall shape of the DTA curves differs for the two mixtures. For a 1 : 1 ratio of the initial components, a single broad and shallow endothermic effect is observed in the temperature range of 61 °C - 350 °C. In contrast, for the 2 : 1 ratio, this endothermic effect is more gradual up to 235 °C, with the curve nearly parallel to the abscissa. It then rises to 250 °C and, in the 250 °C - 350 °C range, transitions into a second, more pronounced endothermic effect characteristic of ammonium sulphate pyrolysis (Fig. 3a).

For the 1 ÷ 1 mixture, the TG curve indicates a mass loss of 0.69 % of the batch mass up to approximately 210 °C. In the 2 ÷ 1 mixture, slight gas evolution occurs between 170 °C - 235 °C, remaining minimal. Above 235 °C, the formation of gaseous products accelerates, the DTA curve enters the endothermic region, and the TG curve exhibits a sharp drop, indicating endothermic decomposition. These observations correspond to conditions of high instrument sensitivity and small sample mass (20 mg), where the onset of ammonium sulphate pyrolysis is detected at a lower temperature than under the opposite conditions (Fig. 3b).

For mixtures with equal component ratios, thermal treatment up to 350 °C followed by cooling results in gas release of 7.8 % in the first case and 10 % of the corresponding batch mass in the second case. In both reaction mixtures, only 1 mole of K_2CO_3 is present; therefore, the relative increase in mass loss is associated with the higher content of NH_4HSO_4 . How does the consumption of this component affect the yield of condensed and gaseous phases? For a 2 ÷ 1 charge composition, the theoretical mass loss expected from CO_2 evolution alone during the initial interaction stage is 10.87 %. As observed in the TG curve (Fig. 3), the total mass loss at 350 °C is 9.99 %, with gas evolution continuing during cooling until the temperature reaches 255 °C. Pure potassium carbonate is relatively stable and does not decompose at these temperatures in the absence of ammonium bisulphate, which is a strongly acidic polar compound capable of interaction.

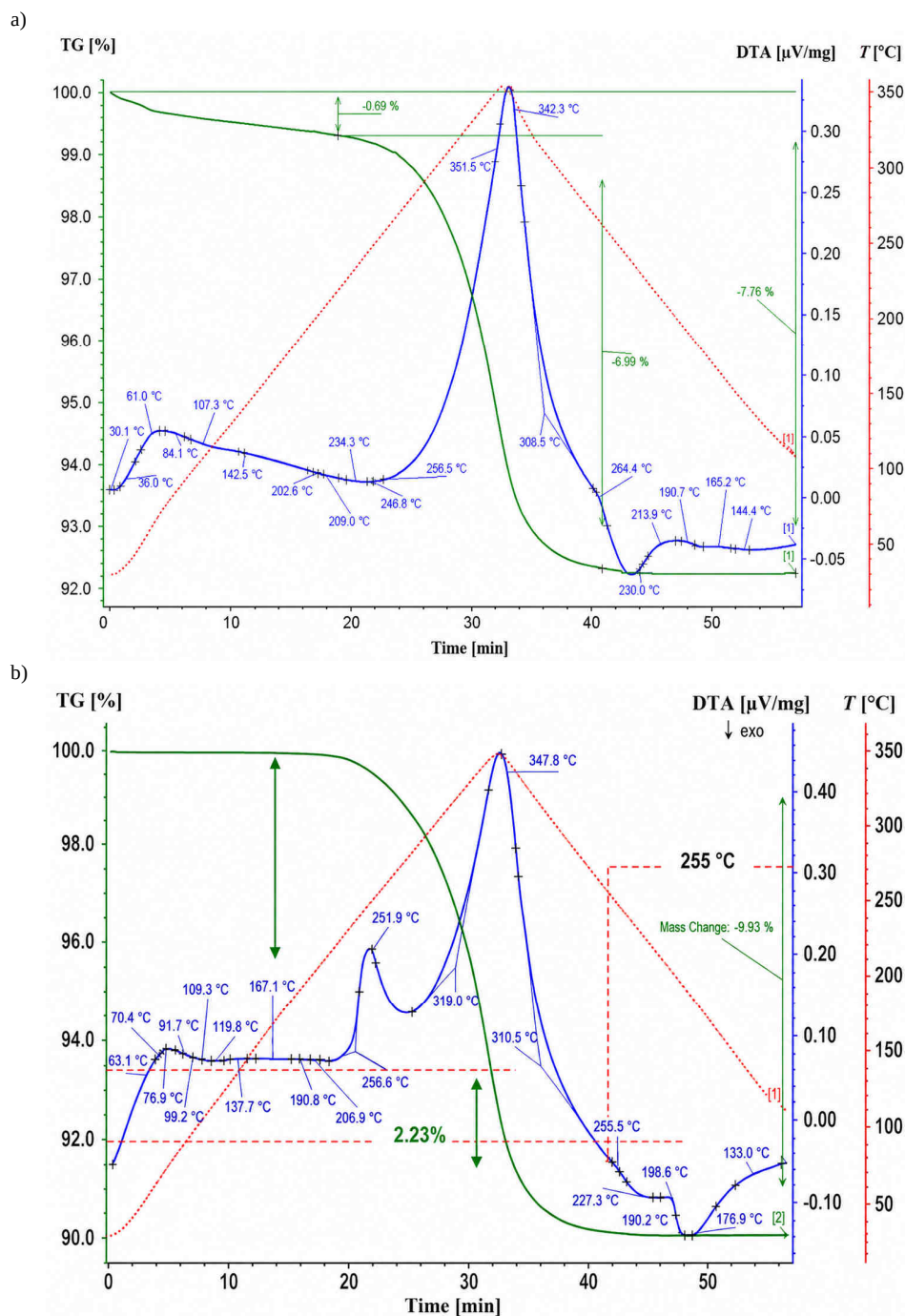


Fig. 3. Derivatograms of the mixtures: a) $\text{NH}_4\text{HSO}_4 \div \text{K}_2\text{CO}_3 = 1 \div 1$; b) $\text{NH}_4\text{HSO}_4 \div \text{K}_2\text{CO}_3 = 2 \div 1$

The results of comparing the thermodynamic probabilities of a series of proposed sequential reactions are presented in Table 3.

As shown in Table 3, the formation of a double sulphate via Reaction 1 is the most thermodynamically favourable. In both mixtures, this reaction predominates; however, at a reactant ratio of 1 ÷ 1, approximately 50 % of potassium carbonate remains in excess. Only after the acidic salt appears as molten ammonium bisulphate via Reaction 3 can the residual potassium carbonate undergo secondary interaction according to Reaction 5, which occurs at temperatures above 250 °C.

Table 3

Results of the analysis of the proposed reactions

No.	Chemical reaction equations	$T [^{\circ}\text{C}]$	Enthalpy, ΔH_{298} [kJ·mol ⁻¹]	Gibbs energy ΔG_{298} [kJ·mol ⁻¹]	Entropy, ΔS_{298} [J·mol ⁻¹ ·K ⁻¹]
1	$2\text{NH}_4\text{HSO}_4 + \text{K}_2\text{CO}_3 = 2\text{NH}_4\text{KSO}_4 + \text{H}_2\text{O} + \text{CO}_2$	-124.0	-34.6	-103.4	-231.5
2	$2\text{NH}_4\text{KSO}_4 = (\text{NH}_4)_2\text{SO}_4 + \text{K}_2\text{SO}_4$	101.0	-27.9	-8.4	-74.5
3	$(\text{NH}_4)_2\text{SO}_4 = \text{NH}_4\text{HSO}_4 + \text{NH}_3$	255.0	113.6	49.9	215.0
4	$2\text{NH}_4\text{HSO}_4 + \text{K}_2\text{CO}_3 = \text{K}_2\text{SO}_4 + \text{NH}_4\text{HSO}_4 + \text{NH}_3 + \text{H}_2\text{O} + \text{CO}_2$	288.0	51.1	-61.9	-91.0
5	$\text{NH}_4\text{HSO}_4 + \text{K}_2\text{CO}_3 = \text{NH}_3 + \text{K}_2\text{SO}_4 + \text{H}_2\text{O} + \text{CO}_2$	26.0	111.1	-61.6	372.0

In [27-29], in their calculations, due to the absence of thermodynamic data for complex compounds in reference sources, the corresponding functions were estimated using the ionic increments method, as summarised in Table 4.

Table 4

Thermodynamic functions of compounds included in the chemical reaction equations, were determined based on reference data and estimated using the ionic increments method [26-28]

Compound	ΔH_{298} [kJ·mol ⁻¹]	ΔG_{298} [kJ·mol ⁻¹]	ΔS_{298} [J·mol ⁻¹ ·K ⁻¹]
NH_4KSO_4	-1292.9	-1104.0	235.1
NH_4KCO_3	-1060.2	-858.3	160.9
$\text{NH}_4\text{K}(\text{HSO}_4)_2$	-2159.2	-1871.2	472.9
$(\text{NH}_4)_2\text{KHS}_2\text{O}_8$	-2313.1	-	477.5
NH_4HSO_4 [26-28]	-1020.2	-834.7	242.4
NH_4HCO_3 [26-28]	-823.5	-666.6	209.4
$\text{H}_2\text{O}(\text{g})$ [26-28]	-241.8	-228.6	188.7
$\text{NH}_3(\text{g})$ [26-28]	-46.2	-16.7	192.6
$(\text{NH}_4)_2\text{SO}_4(\text{cryst.})$ [26-28]	-1180.0	-901.3	220.0
HSO_4^- [26-28]	-887.8	-755.2	128.0
SO_4^{2-} [26-28]	-909.3	-744.0	18.2
NH_4^+ [26-28]	-132.4	-79.5	114.4
$\text{CO}_2(\text{g})$ [26-28]	-393.5	-394.4	213.7
$\text{K}_2\text{SO}_4(\text{cryst.})$ [26-28]	-1433.7	-1316.4	175.7
$\text{KHSO}_4(\text{cryst.})$	-1139.0	1036.5	230.5
$\text{K}_2\text{CO}_3(\text{cryst.})$ [26-28]	-1146.1	-1059.8	156.3
K^+ [26-28]	-251.2	-281.3	102.5
CO_3^{2-} [26-28]	-676.6	-527.6	-56.0
HCO_3^- [26-28]	-691.1	-587.1	95.0
$\text{KHCO}_3(\text{cryst.})$	-942.3	-868.4	197.5
$\text{K}_2\text{NH}_4\text{HS}_2\text{O}_8$	-2431.9	-2141.3	465.6

In [29], the double potassium-ammonium sulphate, KNH_4SO_4 , was obtained, and its thermal behaviour was analysed with holding at (330, 370, and 580) °C. It was established that KNH_4SO_4 decomposes into potassium sulphate and ammonium bisulphate at 330 °C.

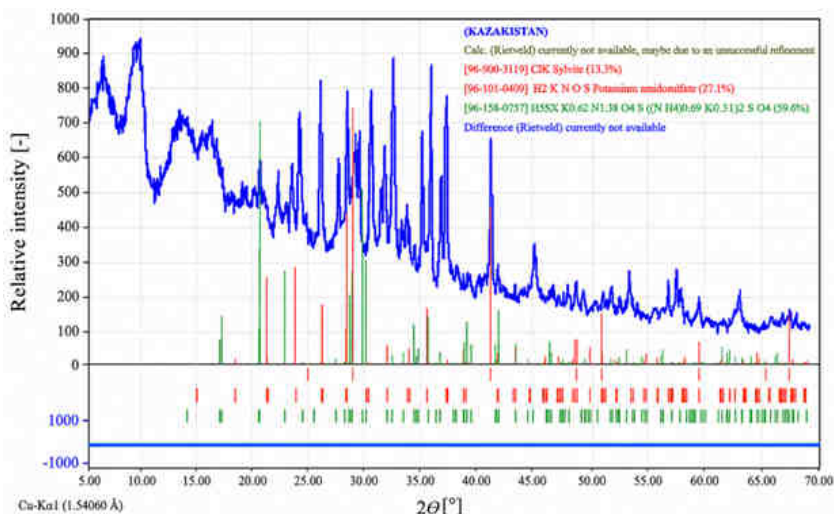
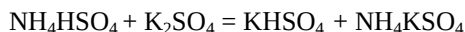


Fig. 4. X-ray diffractogram of the reaction mixture: $\text{NH}_4\text{HSO}_4 \div \text{K}_2\text{CO}_3 = 2 \div 1$

In our previous studies, it was noted that molten ammonium bisulphate, formed during the thermal treatment and subsequently cooled, can react again with metal sulphates [15, 30]. This secondary interaction may lead to the formation of double sulphates or bisulphates, ammonium sulphate, or their mixtures, depending on the ratio of condensed products from the primary reaction [15].

Mass balance calculations based on TG data (Fig. 3) indicate incomplete interaction of potassium carbonate under DTA conditions. In the cooled, condensed reaction products of Reaction 1, XRD analysis confirms the presence of the double sulphate KNH_4SO_4 . This is caused by extensive gas evolution, which promotes separation of the reaction components, resulting in the extraction of potassium carbonate to the surface of the molten ammonium bisulphate. A similar phenomenon was observed in reactions with potassium chloride [15], and it has been established that KNH_4SO_4 decomposes under DTA thermal treatment in the (100-200) °C range into the corresponding constituent sulphates. Above 250 °C, ammonium sulphate undergoes pyrolysis, releasing ammonia and forming molten ammonium bisulphate. Upon cooling, secondary interactions occur between the condensed reaction products, corresponding to the onset of the endothermic effect at 198 °C on the DTA curve. This effect is associated with the formation of potassium bisulphate [30] and ammonium potassium sulphate:



Conclusion

The study confirmed the effectiveness of the purification technology for technical-grade ammonium sulphate derived from coke-chemical production at JSC

“QARMET” implemented using an industrial prototype developed by LLP “Innovation”. The purified ammonium sulphate complies GOST standards, exhibiting a nitrogen content of 21 %, moisture ≤ 0.2 %, free sulphuric acid ≤ 0.03 %, insoluble impurities ≤ 0.02 %, and friability of 100 %.

Purification was achieved through homogenisation, flotation, decantation, filtration, and drying, effectively removing tarry substances and pyridine bases.

The drying stage was identified as the process bottleneck, limiting productivity to 38 kg/h (912 kg/day) and indicating a need for process scale-up.

Thermochemical and thermodynamic analyses of the $\text{NH}_4\text{HSO}_4\text{-K}_2\text{CO}_3$ system demonstrated the potential for secondary processing into valuable compounds, such as carbonates and double salts. The formation of NH_4KSO_4 was confirmed at a 2 : 1 component ratio, with a maximum gas release of 10 % at 350 °C.

These results highlight both the technological feasibility of the proposed purification method and its potential for valorising ammonium sulphate by-products into higher-value compounds.

Acknowledgements

This research was funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP 19677917 “Development of technologies for the synthesis of granular ammonium sulphate in the conditions of KazAzot JSC”).

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