Maisotsenko cycle applications in multi-stage ejector recycling module for chemical production

D O Levchenko¹, A E Artyukhov², I V Yurko³

¹Department of Technical Thermal Physics, Sumy State University, 2 Rymskogo-Korsakova st., 40007 Sumy, Ukraine Sumy Ukraine
²Processes and Equipment of Chemical and Petroleum-Refineries Department, Sumy State University, 2 Rymskogo-Korsakova st., 40007 Sumy, Ukraine Sumy Ukraine
³TRIZ Ltd., Mashinostroiteley 1 St, Sumy, Ukraine

E-mail: d.levchenko@kttf.sumdu.edu.ua

Abstract. The article is devoted to the theoretical bases of multistage (multi-level) utilization modules as part of chemical plants (on the example of the technological line for obtaining nitrogen fertilizers). The possibility of recycling production waste (ammonia vapors, dust and substandard nitrogen fertilizers) using ejection devices and waste heat using Maisotsenko cycle technology (Maisotsenko heat and mass exchanger (HMX), Maisotsenko power cycles and recuperators, etc.) is substantiated. The principle of operation of studied recycling module and prospects for its implementation are presented. An improved technological scheme for obtaining granular fertilizers and granules with porous structure with multistage (multi-level) recycling module is proposed.

1. Introduction
The problem of the ecological safety of chemical production is becoming more urgent. The main environmental problems are: pollution of water, atmospheric air, production waste increasing and consumption, etc.

The production of granular products (including granules of nitrogen fertilizers - ammonium nitrate, carbamide and granules of porous ammonium nitrate for the needs of mining industry) is a major sector of the chemical industry.

Improving the quality of nitrogen fertilizers and indicators for energy consumption and environmental safety of their production to the level of world requirements is an important task for manufacturing enterprises. Increasing the efficiency indicators of production and improving the quality of products is proceeding in two directions: change in technology and processes; increasing of energy and environmental efficiency of equipment in existing production facilities.

In the process of production of granules of ammonium nitrate in vortex granulators [1-3] there is an intensive separation of gaseous nitrous oxide (concentration in the exhaust gases in the range 0.005-0.01 kg / m³), small unconditioned granules and dust of ammonium nitrate (approximately 1% of the capacity of the vortex granulator on the finished product, the size is less than 0.5 mm), ammonia (concentration in the exhaust gases within 0.003-0.005 kg / m³). In this context the issue of transfer of nitrous oxide (I) and thermal decomposition of substandard ammonium nitrate with the formation of higher oxides and their return to the technological process is of great practical interest. This innovation
will increase the efficiency of the nitrogen conversion cycle in the enterprise and reduce the emission of nitrogen-containing compounds into the atmosphere.

2. Main methods of utilization of wastes from the ammonium nitrate production

The basic technological schemes for ammonium nitrate production function in such way (Figure 1) [4,5]. Process air is fed by gas blowing to the air heater, where it is heated for further use as a coolant and liquefying agent to create a vortex weighted layer. The heated air is fed to the vortex granulator I. After contact with the melt of ammonium nitrate, the gas leaves the volume of the granulator. Granules of finished products are discharged from the lower part of the granulator and enter the cooler of fluidized bed, they are cooled there by means of air supplied to the apparatus by gas blowers; then the granules are removed from the cooler and sent to the packaging. Contaminated air leaving the granulator as well as gas from the fluidized bed cooler contain dust, small granules of ammonium nitrate, nitrogen oxides and ammonia. It enters the lower part of the absorber II, where its absorption cleaning takes place. The variant of circuit, shown in Figure 1 (b), provides for an additional cyclonic purification of the off-gases II [6,7].

![Figure 1. Basic schemes for the granular ammonium nitrate production in vortex-type granulators: (a) - with the unit of absorption purification of waste gases; (b) - with the unit of cyclone and absorption purification of exhaust gases; I - vortex granulator; II - absorber; III – cyclone.](image-url)
follows: a mixture of waste gases from the granulator and decomposition products of substandard ammonium nitrate are sent to a bubbling chamber where they are cooled and purified from ammonia and mechanical inclusions; Then the purified cold gas is supplied by a passive flow to the ejector, where the active (ejecting) stream is oxygen. A mixture of nitrous oxide and oxygen passes through the ejector diffuser path through a heated spiral coated with a catalyst bed and is oxidized to higher nitrogen oxides. The resulting gas passes through a coiled heat exchanger and is cooled to the liquid transition temperature. The resulting product is sent to a storage tank or closes the cycle for the production of nitric acid. Such wasteless technology allows to increase the specific energy efficiency of the plant and to reduce the emission of nitrogen-containing compounds into the atmosphere.

![Diagram of the process](image)

**Figure 2.** The scheme for obtaining granular ammonium nitrate in vortex-type granulators using an ejection module [9].
3. Theoretical basics and results

The considered methods of ammonium nitrate production wastes utilization do not provide for the presence of heat recovery units for the drying and cooling agent. The receipt of additional energy by utilizing the heat of waste gases will reduce the amount of external heat, for example, at the stage of reactive decomposition of substandard ammonium nitrate. The authors of this article propose a comprehensive scheme for waste products processing from the ammonium nitrate production in the granulation stage with simultaneous utilization of the heat of the fluidizing agent (drying agent in the granulator and cooling agent in the fluidized bed cooler).

Since the ammonium nitrate production line contains many processes fulfilled with wet and dry flows of hot/warm air, the question of heat recovery arises dramatically. Considering that some units of the line consume considerable amount of energy in form of electricity and/or burned fuel (natural gas / methane, propane etc.), application the heat and mass exchangers (HMX) that utilize Maisotsenko cycle (M-cycle) become very beneficial. Moreover, integration Maisotsenko power cycles and M-cycle HMX recuperators into technological line of ammonium fertilizer production could provide by energy most of the technological processes of the line, reduce cost per tonne of the product and produce additional products like heat water and/or heating, electricity for inner or exterior consumers.

Describing M-cycle main principles and perspective one should refer to the profound paper as “Overview of the Maisotsenko cycle – A way towards dew point evaporative cooling” by Muhammad H. Mahmood, Muhammad Sultan, Takahiko Miyazaki, Shigeru Koyama and Valeriy S. Maisotsenko [10]. So, the M-Cycle is a thermodynamic process which captures energy from the air by utilizing the psychrometric renewable energy available from the latent heat of water evaporating into the air. It combines thermodynamic processes of heat transfer and evaporative cooling to facilitate product temperature to reach the dew-point temperature of the ambient air [11]. The basic principle and features of the M-Cycle can be explained from Figure 3 (a) and Figure 3 (b) representing the partial extraction of air and product air cooling M-Cycle, respectively [10]. The psychrometric representation of both variations of M-cycle is shown in Figure 3 (c). It consists of two kinds of primary channels named as wet and dry channels.

Product Air Cooling arrangement keeps working and product dry channels separated. Partial Extraction of Air arrangement fractions a portion of the dry channel as usable product. Both arrangements are psychrometrically identical while arrangement in Figure 1 (b) with product channel has essential advantages as compared to arrangement in Figure 1 (a). Thus, any gas or liquid matter (for example hot waste product) can be used as a product flow in arrangement in Figure 1 (b) while arrangement in Figure 1 (a) is limited to the same gas for both channels. Moreover using the product channel allows reducing pressure drop in the system. Another advantage of arrangement in
Figure 1 (b) compared with Figure 1a would be a possibility to use the product channel as a condenser for gas dehumidification [12].

For example, ambient air (1) is flowed into the dry-channel where it is sensibly cooled at constant humidity to cycle point (2) by transferring the heat to the wet-channel. The operational principle of M-Cycle is based on diverting the cooled air (2) to the wet-channel in order to use as working air. It results in subsequently decrement of effective dry-bulb (1 - 2a; 2b; 2c; 2) and wet-bulb (1w - 2a,w; 2b,w; 2c,w; 2dp) temperatures of the working air in the wet-channel as shown in Figure 1d. Sequential decrement of dry-bulb temperature in the wet-channel brings the effective wet-bulb temperature to be ideally equal to the dew-point temperature. Hence for an ideal heat transfer surface, the product air can be sensible cooled to the dew-point temperature of the ambient air. Moreover, saturated hot air (3) is rejected from the wet-channel equivalent to the evaporated water and recovered heat. This hot and wet air could be used in Maisotsenko power cycles hence increasing the overall energy recovery index.

Utilization of hot and humid air after HMX using Maisotsenko power cycles will increase thermal efficiency of the fertilizer production line. Using the modern gas turbine engines, based on well-known open Brayton cycle [13, 14], has overall disadvantage of the cycle as the significant amount of waste heat discharged into the atmosphere which results in poor thermal efficiency [15]. In this regard, inverse Brayton cycle [16] have been investigated with different configuration in order to increase the overall cycle performance [17-22]. In this cycle heated working medium at atmospheric pressure is initially expanded in the gas turbine. After that the working medium heat is recovered by the heat exchanger, and finally the cooled gas is sucked by the compressor to the atmospheric pressure. The cycle works below the atmospheric pressure and referred as sub-atmospheric cycle [15]. It is believed that the reverse Brayton cycle is not commercially feasibly because of the greater compressor size and employed higher operational energy [15]. On the other hand, the M-Cycle as an innovative humidifying recuperator can significantly improve the cycle performance by providing extremely saturated hot air to the combustion chamber (before turbine) and cooled air to the compressor (after turbine) simultaneously [15, 23-25]. Consequently, it will improve the fuel combustion efficiency as well as compressor efficiency at the same time. Furthermore, simple designs of atmospheric combustion chamber and cheaper materials could be employed in the turbine industry [15]. The Maisotsenko sub-atmospheric Brayton (M-SAB) cycle conception was realized recently by Maisotsenko et al. [24, 25] in which the authors proposed various possible configurations of M-SAB cycle. On the basis of available literature, the present study discusses two kinds of M-SAB cycle which are based on: (1) compressor [15], and (2) ejector [23]. The compressor based M-SAB cycle is similar to the conventional reverse Brayton cycle.

![Figure 4](hervicong+pumps-2017) Schematic diagram of the compressor based M-SAB cycle, reproduced from [10, 16, 24, 25].
Khalatov et al. [15] analyzed the compressor based M-SAB cycle while recovering the turbine waste heat. The schematic diagram of the cycle is shown in Figure 4 [15, 24, 25]. The cycle configuration is similar to the [24, 25], however an additional low grade heat source unit is proposed for pre-heating (process 1-2) in order to improve the cycle efficiency. The air is heated and humidified simultaneously by the M-Cycle assembly (process 2-3) while recovering the turbine waste heat (process 5-6). The saturated hot air improves the combustion efficiency as well as reduces the NOx emission when used in combustion chamber (process 3-4). The combusted hot gases at atmospheric conditions are expanded in the gas turbine (process 4-5). The energy from the hot gases at state (5) is recovered before it goes to the compressor by means of M-Cycle assembly (process 5-6) and an additional heat exchanger (process 6-7), which consequently improves the compressor efficiency. Analysis showed that the M-SAB cycle can achieve the thermal efficiency of 0.45-0.82 at preheating (T2) and combustion temperature (T4) of 40–90 °C and 160–340 °C, respectively. It is worth mentioning that the preheating shows significant improvement in thermal efficiency by the M-SAB cycle because of the versatile features of M-Cycle at higher temperature. Unlike open Brayton cycle the higher regeneration rate promotes the thermal efficiency of the M-SAB cycle. The study concluded that the M-SAB cycle possesses higher efficiency as compared to conventional open Brayton cycle at certain conditions.

**Figure 5.** Schematic diagram of the ejector based M-SAB cycle, reproduced from [10, 23]

Buyadgie et al. [23] proposed the ejector based M-SAB cycle and investigated its performance for various applications. The schematic diagram of the turbo-ejector based M-SAB cycle is shown in Figure 5 [23]. The principle operation of the cycle is similar the one based on compressor as explained in Figure 4 [10, 15, 24, 25], though the compressor is replace by the steam-air ejector. Each process of the cycle is labelled on the Figure 5 which gives the detail insight of the cycle. However, solar thermal collector 3 could be replaced by high grade heat source or used as recuperator in technological processes of ammonium nitrate production. According to the results the replacement of mechanical
compressor with the steam-air ejector results in 2-4 times higher power generation, and yields 15–20% capital cost reduction of the system. In addition, the electricity used to operate the fans for the M-Cycle assembly decreases two times per power unit. The authors concluded that the turbo-ejector M-SAB cycle design is the optimum choice when the electricity price is high and heat price is low. Furthermore, it is more beneficial when the power generation and low temperature cooling is required simultaneously despite of the available heat cost. From the above prospective the present study concludes that the M-Cycle possesses huge energy recovery potential in various power producing gas turbines. It addition to provide hot and humidified air for combustion, the M-Cycle recovers the turbine waste heat efficiently as compared to conventional heat exchangers. Furthermore, the nature of the M-Cycle helps to provide the cooled air to the compressor simultaneously, which increases the compressor efficiency. Another silent feature of the M-Cycle is the pollution control by reducing NOx formation during combustion which can lead towards an environment friendly gas turbine power cycle.

Figure 6 represents the proposed technological scheme of fertilizer production line which contains ejector recovery module UM1 (for N₂O acidification), number of HMX recuperators (for heat recovery, hot-water and heating supplying) and recovery module UM2 which includes M-SAB cycle plant (for electricity and/or cold production).

![Figure 6. Schematic diagram of technological scheme of fertilizer production line.](image)

The essential role in all M-cycle applications plays M-cycle HMX which conceptual design represented in Figure 7. There is a direct relation between M-cycle heat exchanger’s performance and evaporating cooling efficiency which is directly affected by factors such as the type of wet surface material, surface area, mass flowrates of air, moisture evaporation rate from the wet surface, pad efficiency, dryness of the air and relative humidity of air passing through the wet channels and volume of water used. Hence selection of wet surface media requires careful attention.
A wide range of materials have been commonly used as the heat/mass exchanging medium. However, it is almost impossible to choose one all-mode material for various M-cycle heat exchanger applications. Additionally, one should notice that porous medium for HMX within fertilizer production line has much more strict requirements, comparing to porous materials for other field of M-cycle application, as the flows possess high corrosiveness. That is why research activities aimed to improve ability of wet channel surface to retain a water film become very important. Such improvement will play a key role in development new high-performance recovery modules.

4. Conclusion
In the article the advanced scheme of recovery-recycling module for chemical productions is represented on the basis Maisotsenko cycle and ejector technologies. The conceptual scheme of fertilizer/porous ammonium nitrate production and new design of M-Cycle HMX are developed. Using of this technical solution will increase thermal efficiency of the granulated materials production, reduce cost per tonne of the product and produce additional products like heat water and/or heating, electricity for inner or exterior consumers.

However, future spreading of the proposed recovery technology connected with its reliability and performance improvement. On its turn, HMX design, using appropriate material in wet channels, plays the key role in the improvement of overall M-cycle technology. Thus, the forthcoming research efforts will be directed to careful investigation of HMX optimal design and wet medium properties.

References
[1] Artyukhov A E, Sklabinskyi V I 2015 Chemistry & chemical technology 9(2) pp 175-180
[2] Artyukhov A E, Sklabinskyi V I 2015 Chemistry & chemical technology 9(3) pp 337-342
[3] Artyukhova N A, Shandyba A B, Artyukhov A E 2014 Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 1 pp 92-98
[4] Artyukhov A E, Sklabinskyi V I 2013 Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 6 pp 42-48
[5] Artyukhov A E, Fursa A S, Moskalenko K V 2015 Chemical and Petroleum Engineering 51(5-6) pp 311-318
[6] Artyukhov A 2016 CEUR Workshop Proceedings 1761 pp 363-373
[7] Artyukhov A, Sklabinskiy V, Ivaniia A, Moskalenko K 2016 CEUR Workshop Proceedings 1761 pp 374-385
[8] Prokopov M G, Levchenko D A, Artyukhov A E 2014 Applied Mechanics and Materials 630 pp 109-116
[9] Artyukhov A E 2014 Chemical and Petroleum Engineering 49(11-12) pp 736-740
[10] Mahmood M, Sultan M, Miyazaki T, Koyama S, Maisotsenko V 2016 Renewable and sustainable energy reviews 66 pp 537-555
[11] Miyazaki T, Akisawa A, Nikai I 2011 Energy and Buildings 43 pp 2211-18
[12] Pandelidis D, Anisimov S, Drag P 2017 Energies 10(4) pp 577
[13] Cengel Y, Boles M 1994 Thermodynamics: An Engineering Approach. New York: McGraw-Hill
[14] Cohen H, Rogers G, Saravanamuttoo H 1996 Gas Turbine Theory-4th Edition. Reading MA. Addison Wesley Longman
[15] Khalatov A, Severin S, Brodetsky P, MaisotsenkoV. 2015 Reports of the National Academy of Sciences of Ukraine 1 pp 72-79
[16] Wilson D, Korakianitis T 1984 The design of high-efficiency turbomachinery and gas turbines. London, England: MIT Press Cambridge
[17] Besarati S, Atashkari K, Jamali A, Hajiloo A, Nariman-zadeh N 2010 Energy Convers Manag 51 pp 212-217
[18] Zhang W, Chen L, Sun F 2009 Appl Therm Eng 29 pp 2885-2894
[19] Alabdoadaim M, Agnew B, Potts I. 2006 Appl Therm Eng 26 pp 1448-1454
[20] Agnew B, Anderson A, Potts I, Frost T, Alabdoadaim M. 2003 Appl Therm Eng 23 pp 953-963.
[21] Zhang W, Chen L, Sun F. 2012 Sci Iran 19 pp 1638-1652
[22] Zhang Z, Chen L, Sun F. 2012 Sci Iran 19 pp 1279-1287
[23] Buyadgie D, Buyadgie O, Drakhnia O, Brodetsky P, MaisotsenkoV 2015 Int J Low-Carbon Technol 10 pp 157-164
[24] Maisotsenko V, Gillan L, Heaton T, Gillan A 2006 US Patent No. US7007453B2
[25] Maisotsenko V, Gillan L, Heaton T, Gillan A 2004 US Patent No.US20040103637A1

Acknowledgments
This work was carried out under the project «Improving the efficiency of granulators and dryers with active hydrodynamic regimes for obtaining, modification and encapsulation of fertilizers», state registration No. 0116U006812. The authors thank researchers of department "Processes and Equipment of Chemical and Refining Industries", and department of Technical Thermal Physics, Sumy State University, for their valuable comments during the article preparation.