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ENERGY EFFICIENCY OF INDUSTRIAL CONCENTRATORS WITH EJECTOR THERMOCOMPRESSION

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A b s t r a c t: Research on the energy characteristics of systems with ejector thermocompression applied in industrial concentrators is presented in this paper. Ejector thermocompression achieves a significant increase in energy efficiency. The heat pump cycle in ejectors is realized through the compression of a portion of the waste steam from the solution being concentrated, which, together with motive steam from a boiler or another heat generator, is used as the driving steam for the concentration process. Thermocompression realized with thermal energy can represent a significant advantage over mechanical thermocompression. A setup for the production of concentrated sodium hydroxide (NaOH) solution with two ejector thermocompressors is presented, as well as a polygeneration system with a gas engine – electricity generator, and an ejector thermocompression system. The proposed solutions have high energy efficiency. By implementing thermocompression systems in the production of concentrates, the energy production costs are significantly reduced, which positively affects the cost of the produced concentrate. The surplus of electrical energy, as well as steam not used in the thermocompression processes, is used to supply energy for the needs of consumers in the production facilities.

Key words: industrial concentrators; NaOH solution; polygeneration thermal systems; energy efficiency; gas engine – electricity generator; thermocompression

ЕНЕРГЕТСКА ЕФИКАСНОСТ НА ИНДУСТРИСКИ КОНЦЕНТРАТОРИ СО ЕЈЕКТОРСКА ТЕРМОКОМПРЕСИЈА

А п с т р а к т: Во трудот се презентирани истражувања на енергетските карактеристики на системи со ејекторска термокомпресија применети во индустриски концентратори. Со ејекторска термокомпресија се постигнува значително зголемување на енергетската ефикасност. Топлинскиот пумпен циклус кај ејекторите се реализира со термокомпресија на еден дел од отпадната водна пареа од растворот кој се концентрира, која заедно со примарна пареа од котел или друг генератор на топлина се користи како погонска пареа за процесот на концентрирање. Термокомпресијата реализирана со топлинска енергија може да претставува значајна предност во однос на механичката термокомпресија. Презентирана е постројка за производство концентриран раствор на натриумов хидроксид (NaOH) со два ејекторски термокомпресора, како и полигенеративен систем со гасен мотор – електрогенератор, и систем со ејекторска термокомпресија. Предложените решенија овозможуваат постигнување висока енергетска ефикасност. Со имплементација на термокомпресорски системи во производството на концентратот значително се намалуваат производните трошоци за енергија, што позитивно влијае врз цената на произведениот концентрат. Вишокот на електричната енергија, како и на пареата која не се користи во процесите на термокомпресија, се користи за снабдување со енергија за потребите на потрошувачите во производните погони.

Клучни зборови: индустриски концентратори; раствор на NaOH; полигенеративни термички системи; енергетска ефикасност; гасен мотор – генератор; термокомпресија

1. INTRODUCTION

The decrease in traditional energy resources, their increasing prices, as well as the current issues related to global warming and ozone layer depletion, have necessitated the development of technical solutions for rational energy use and increased utilization of alternative energy sources. Increasing energy efficiency is a vital component of sustainable development, and it is a particularly relevant topic that has sparked numerous research and development activities in the field of thermotechnics and thermoenergetics.

Thermocompression systems, presented in this paper, are considered as high-energy efficiency thermal systems. Ejector thermocompression systems utilize thermal energy, and their implementation in modern technologies represents a significant component in the energy sector research [1, 2, 3].

Energy consumption during the production of a specific product significantly contributes to the product's cost. Therefore, achieving a high-quality product while minimizing energy costs per unit of product is a top priority in the industrial processes. This work presents research focused on increasing the energy efficiency of industrial concentrators through the use of ejector thermocompression systems. Industrial concentrators find applications in various technological processes across the process industry (food, pharmaceutical, chemical, inorganic, and other industrial sectors). They are characterized by high energy consumption. Hence, it is essential to find solutions aimed at reducing energy consumption.

In ejector thermocompression systems, primary steam from a boiler or another heat generator (waste heat from industrial processes, solar, geothermal energy, etc.) is utilized. Using thermal energy to realize the thermocompression process can be highly advantageous compared to mechanical thermocompression, especially when waste heat is employed in the production of primary steam [4]. The use of high-temperature heat pumps with ejector thermocompression, where waste heat (water vapor from the solution) from the concentrator plant is elevated to higher pressure and temperature using primary steam from the boiler (or other heat generator) and is used as a driving steam for realization of the concentration process is a promising technical solution [5]. Utilization of waste heat in high temperature heat pumps with mechanical and ejector thermocompression in the process industry and also for HVAC&R of buildings is subject of many research and development activities in recently published papers [6, 7, 8, 9].

The evaporation temperature is a crucial parameter for the production of concentrates of certain products since maintaining the material's essential properties during concentration requires treatment at proper temperatures. In concentrators using ejector thermocompression, this requirement represents an alternative advantage over classical systems. The implementation of ejector thermocompression systems results in significant energy savings, contributing to the reduction of the production cost of concentrates.

Depending on the required temperature lift to be achieved by the thermocompression process and the ratio between the amount of heat (waste steam from the solution being concentrated) and the primary steam from the boiler, relatively high coefficients of thermotransformation (COP_e) can be obtained. COP_e is the most relevant parameter for the plant's efficiency.

The concept of dispersed electricity generation using a natural gas engine – electricity generator, and the implementation of an ejector thermocompression system for the production of technological steam and hot water, using the energy from the combustion products and engine cooling, represents a highly energy-efficient solution.

2. EJECTOR THERMOCOMPRESSION HEAT PUMP PROCESS IN INDUSTRIAL CONCENTRATORS

Thermocompression in ejector systems is achieved using steam from a steam boiler. Steam production from a boiler relies on thermal energy, which can provide a significant advantage over mechanical thermocompression, especially when waste heat is used for steam production.

A scheme of a concentrator with ejector thermocompression is presented in Figure 1. The figure also includes a pressure-enthalpy ($p – h$) chart showing the thermocompression processes, as well as the supersonic steam/steam ejector.

In the main heat exchanger (evaporator/condenser) of the concentrator, the water content in the concentrator solution evaporates, utilizing the energy from the driving steam from the ejector. Preheating of the solution to the evaporation temperature occurs in the subcooler using the heat from the cooling condensate. The heat pump cycle is implemented by thermocompressing a portion of the waste steam contained in the solution, from the evaporation pressure p_e and temperature $T_{er} = T_e + \Delta T_r$, to a higher pressure p_c (corresponding to the condensation temperature T_c), to achieve an effective temperature difference ΔT_e between the temperature of the driving steam T_c, that condenses inside the pipes, and the solution's evaporation temperature T_{er} ($\Delta T_e = T_c – T_{er}$). The increase in the boiling (evaporation) temperature of the solution (T_{er}) above the boiling (evaporation) temperature of water (T_e), for a given pressure (p_e), ($\Delta T_r = T_{er} – T_e$) depends on the thermodynamic and thermos-physical properties of the solution. For higher concentrations of dry matter x in the solution, ΔT_r is larger.

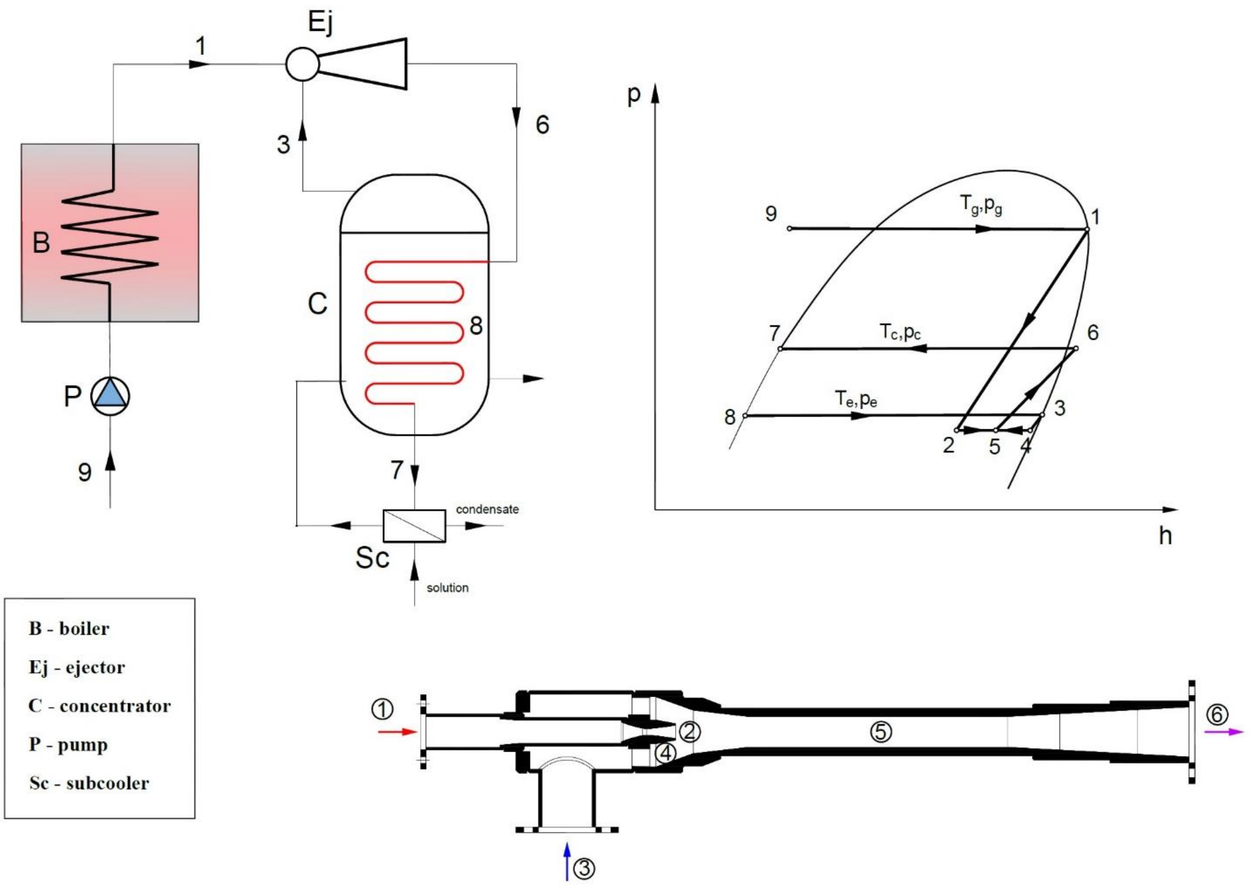

Fig. 1. Ejector thermocompression concentrator, *p* – *h* chart and ejector

The increase in the boiling temperature of the solution ΔT_r from sodium hydroxide (NaOH) depending on the concentration of dry matter *x* is given in Table 1.

T a b l e 1

Dependence of the increase in boiling temperature of the solution ΔT_r from the concentration of dry matter x [11]

x (kg/kg)	10	15	20	25	50
ΔT_r (K)	3.5	7.5	11.5	15	40

The temperature difference ΔT_e has a significant impact on the consumption of boiler motive steam in the ejector thermocompression and on the optimization of the main heat exchanger (evaporator/condenser). Additional optimization criteria can be defined based on the properties of the concentrate. For certain concentrates, low-temperature treatment in the concentration process is crucial for obtaining a high-quality product. Moreover, high temperatures can cause issues on the heat exchange processes related to fouling of the heat exchanger surfaces, increased aggressive and corrosive properties of the solution, and more.

In some concentration processes, it's necessary to install a vacuum pump to achieve and maintain a vacuum in the concentrator.

The energy efficiency of ejector thermocompression heat pumps is estimated using the coefficient of thermotransformation Ψ_e, or COP_e.

$$\Psi_e = COP_e = \frac{Q_c}{Q_p} = \frac{M_c}{M_p}$$

The coefficient of thermotransformation Ψ_e represents the ratio between the obtained thermostransformed heat Q_c and the consumed heat Q_p for the production of primary boiler steam M_p, by which a portion of the waste steam (waste steam M_e') in the ejector is transformed from pressure pe and temperature t_e to higher pressure pc and temperature t_c. The obtained driving steam M_c, which condenses while performing the thermal concentration process, is calculated as:

$$M_c = M_e' + M_p.$$

The performance of the ejector highly depends on the operating conditions of the thermocompressor system in the concentrator. The compression ratio Π and the temperature lift $\Delta T = T_c - T_e$, achieved by the ejector thermocompressor, primarily depend on the entrainment ratio ω.

$$\omega = \frac{M_s}{M_{pr}} = \frac{M_e'}{M_p}.$$

The coefficient of thermotransformation Ψ_e (COP_e) of the ejector's heat pump cycle is approximately:

$$\Psi_e = COP_e = 1 + \omega.$$

For various operating conditions, i.e., different values of the temperature lift ΔT_e, different ω values are obtained, resulting in varying Ψ_e or COP_e. With optimal design of the flow field of the ejector components (primary nozzle, secondary nozzle, mixing chamber, diffuser, etc.), high Ψ_e or COP_e can be achieved under given design operating conditions.

3. INDUSTRIAL SODIUM HYDROXIDE (NAOH) CONCENTRATOR

Scheme of a two-stage industrial concentrator for sodium hydroxide (NaOH) with an ejector thermocompression system is provided in Figure 2. An original technical solution is implemented by the authors [3]. This system is installed at Zeolite Inc. – Probishtip, a company primarily involved in the production of various zeolites and water glasses. In one phase of the technological process, a 5% NaOH solution is obtained as a by-product, while a 25% NaOH solution is used in another phase, necessitating concentration of the solution.

The concentration of the 5% solution takes place in two stages, within two plate heat exchangers located in a cylindrical vessel. Thermocompression is achieved with ejector thermocompressors TC1 and TC2 for the first and second stages of the concentrator, respectively.

Based on defined parameters of the concentration process, calculations, dimensioning, and manufacturing of the two ejector thermocompressors have been carried out. The facility is equipped with industrial measurement instruments. The data provided in Figure 2, as well as the calculated coefficients of thermotransformation Ψ_e, correspond to a steady-state operation of the concentrator. The significant impact of raising the boiling point temperature (evaporation) of sodium hydroxide (above the corresponding boiling point temperature of water) on the performance of the thermocompression system and the concentrator has been highlighted.

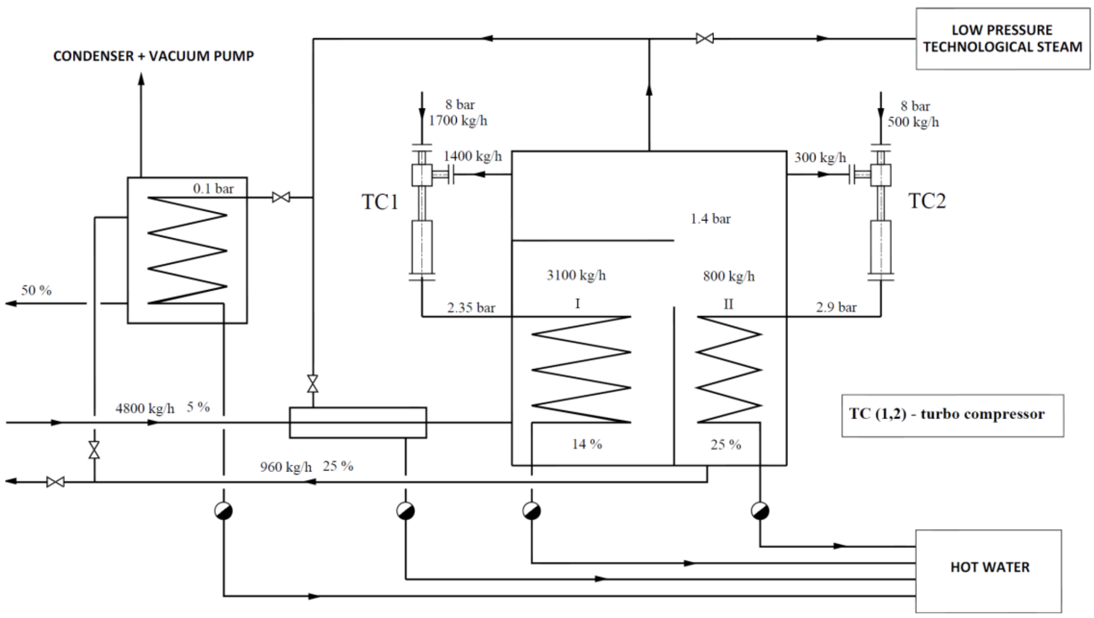

Fig. 2. Scheme of industrial NaOH concentrator

The total temperature lift achieved with TC1 is ΔT = 16 K, but only ΔT_e = 9 K is an effective temperature difference, while $\Delta T_{er} \approx 7$ K (for a concentration of x = 14%) is lost due to the elevated boiling point temperature. The total temperature lift achieved with TC2 is ΔT = 23 K, but ΔT_{er} = 15 K (for a concentration of x = 25%) is lost, and only ΔT_e = 8 K is an effective temperature difference. The thermotransformation coefficients are Ψ_{e1} = 1.8 and Ψ_{e2} = 1.6. The evaporated water in the concentrator (reboiler) that is not thermocompressed is used as process steam. A proposed additional third stage, a vacuum concentrator, is suggested where the NaOH solution is concentrated to 50%. During the concentration process, fouling of the heat exchange surfaces occurs, negatively affecting the heat transfer process and the concentrator's lifespan. Cleaning procedures according to appropriate methods are planned to address this issue.

4. SYSTEM FOR PRODUCTION OF ELECTRICITY AND TECHNOLOGICAL WATER VAPOR WITH EJECTOR

In the industrial systems in the process industry, steam is typically produced in steam boiler facilities. With the development of clean production concepts and strategies to increase energy efficiency in thermal processes and technologies, alternative methods for steam production are proposed, utilizing waste heat from industrial thermal systems, and applying new technologies like high-temperature heat pumps and thermal steam compression / recompression. This topic has sparked special scientific interest and research activities [10]. Using thermal energy to realize the thermocompression process can offer a significant advantage over mechanical thermocompression, especially when waste heat is employed for primary steam production. Compared to classic systems that use motive energy from a steam boiler for the realization of ejector thermocompression, this solution uses waste energy from a motor-generator.

Below is the presentation of an original technical solution of a polygeneration system for production of electrical energy, technological water vapor with defined parameters (pressure and temperature) and technological and sanitary hot water, that uses a gas engine – electricity generator, for electrical energy production and ejector thermocompression (Figure 3).

The input energy from the natural gas (NG) (100% HHV – Higher Heating Value of natural gas) in the gas engine is transformed into mechanical energy (GEN) at 34% and thermal energy at 66%. In the electric generator (ELG), 32% of the input energy from natural gas is converted into electrical energy (power).

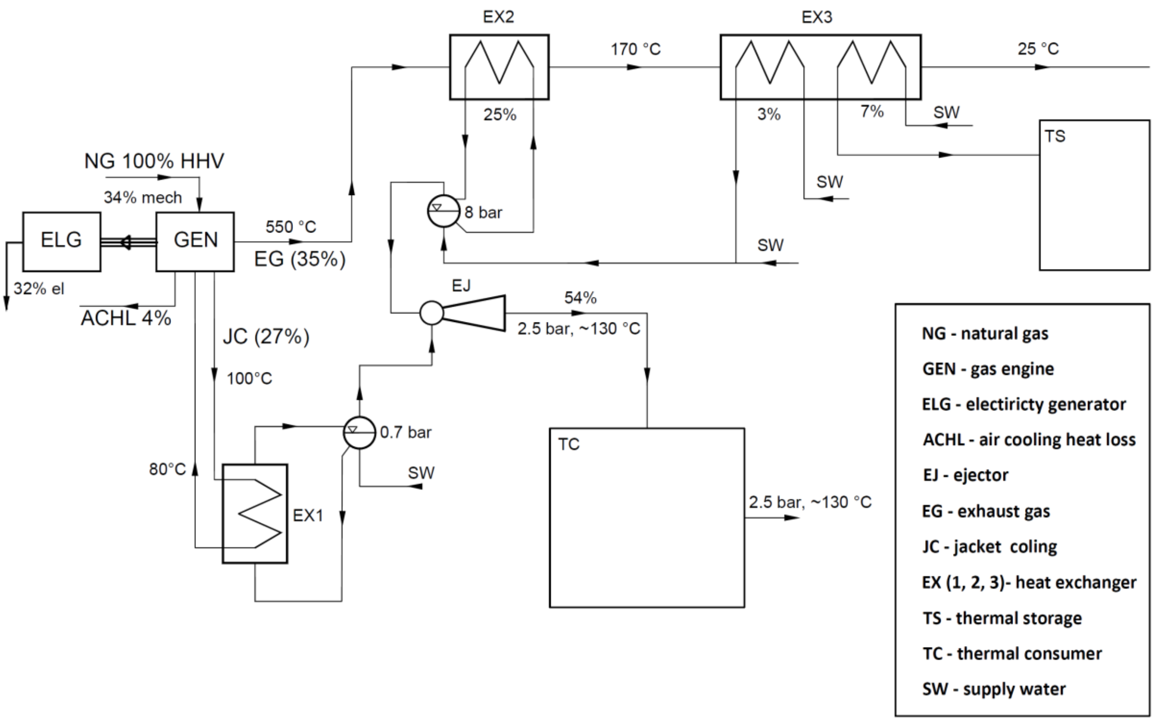

Fig. 3. Gas engine – electricity generator, and ejector thermocompression system

Approximately 4% represents heat losses to the environment, including heat losses in the turbocharger-intercooler (ACHL).

In heat exchanger EX1 (27% HHV), waste heat from engine cooling jacket (JC) is used to produce low-pressure, saturated water vapor with a pressure of 0.7 bar and a temperature of approximately 90°C, which is then thermally compressed to the required pressure using ejector thermocompression.

In heat exchanger EX2 (25% HHV), waste heat from engine exhaust gases (EG) is used to generate saturated water vapor with a pressure of 8 bar and a temperature of approximately 170°C, which is used as primary steam in ejector thermocompressor EJ. With the implemented ejector thermocompression, 52% HHV saturated water vapor at a required pressure of 2.5 bar and a temperature of approximately 130°C is produced.

In heat exchanger EX3 (10% HHV), waste heat from engine exhaust gases is used to produce sanitary and technological hot water STTW (7% HHV) and to prepare supply water SW (3% HHV).

CONCLUSIONS

The significance of the new concept in sustainable development in the energy sector lies in thermocompression systems and their optimal implementation in high-energy efficiency thermal technologies, such as industrial concentrators. Solutions for energy-efficient concentrators are presented, utilizing ejector thermocompression systems. Ejector thermocompression is achieved using primary steam from a boiler or another heat generator, which, along with waste steam from the solution, serves as the driving steam. The use of ejector thermocompression systems results in high values of the coefficient of thermotransformation, which positively impacts energy consumption and the production of high-quality products at lower costs. Thermal characteristics of a sodium hydroxide (NaOH) concentrator, consisting of two ejector thermocompressors, are presented. A concept of an energy-efficient system with a gas engine-electric generator and ejector thermocompression is introduced, which ensures independent power supply for manufacturing facilities' electricity needs and provides thermal energy for the concentrator and other thermal energy consumers.

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