International Journal of Latest Research in Science and Technology **ISSN (Online):2278-5299**
Volume 3, Issue 2: Page No34-42 ,March-April, 2014
https://www.mnkpublication.com/journal/ijlrst/index.php

RECOVERY OF HEAT FROM THE WASTE FLOW FORMED IN THE PROCESS OF SODA-ASH PRODUCTION USING A HIGH TEMPERATURE HEAT PUMP

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Abstract- ***Analyses into the operation of the majority of technological processes in chemical industries have shown that considerable loss of energy occurs during the discharge of surplus heat from these processes into the environment, as well as raw materials and other materials associated with the discharge of useful substances into the environment due to their low utilization in the processes. During recent years the authors have investigated the application of a high temperature heat pump in the industrial waste heat recovery. This paper shows the results of waste heat recovery from the soda-ash production process named "DS-solution". The DS-solution is produced in the quantity of 8-11 m^3/t of soda ash, with the temperature between 90-110℃. Waste heat recovery from this industrial flow can be achieved in two stages: the exchange of heat in a heat exchanger by cooling the DS-solution from 95℃ to 68.5℃, and then additional waste heat recovery also using adiabatic evaporation of the DS-solution by decreasing the temperature from 68,5°C to 41,4°C by means of a high temperature heat pump which uses heated water from the previous two stages as a low temperature heat source. In this way the heat potential of water is raised to the level which enables its utilization in the system of high temperature district heating of residential buildings and other facilities. Both stages are component parts of the unique process of DS-solution heat recovery as a waste flow produced in the soda ash process.***

Keywords - industrial waste flow, soda-ash production, DS – solution, heat recovery, high temperature heat pump

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I. INTRODUCTION

Majority of technological processes in chemical industry result in considerable losses of energy due to the discharge of surplus heat energy as well as the losses of matter which are caused by throwing away useful substances due to their low utilization in the processes. Soda-ash production is a huge heat energy consumer, because the consumption of heat energy is 15-20% of total production costs. Moreover, soda-ash process is a great waster of heat energy. The largest heat losses occur in the waste flow termed the DS-solution. This loss is 3.8 GJ/t of soda-ash or approximately 70 – 85% of the total heat introduced with water vapour into the ammonia regeneration plant.

Industrial waste flows which cause energy losses are potential secondary energy resources. Conditionally speaking, secondary energy resources in industry fall in to the following categories:

-high temperature energy sources, t≥150°C, whose heat is used in suitable processes and plants,

-low temperature energy sources, t<150°C, whose heat, as a rule, is not exploited within the basic process plant and is discharged into the environment.

In the basic chemical industry, to which soda ash process belongs, low temperature secondary energy sources comprise 70-95% of all secondary energy sources. This fact becomes even more important if we add the possibility, or impossibility of recovering heat from energy sources. For example, by exploiting the heat of high temperature sources in utilizator boilers we can obtain water vapor with high parameters (pressure and temperature) which is used in the process of or for steam turbine drive. Such or similar solutions, in the case of low energy sources, cannot be applied either by technical or economical principles. The heat with low parameters does not have its consumer within the basic technological unit, therefore the problem of heat energy recovery in low-temperature secondary energy resources becomes even more important.

As a rule, secondary energy sources are corrosion active materials containing suspended solid particles and poorly soluble chemical compounds. The standard heat exchanger and other apparatuses are not suitable for these effluents, therefore the solution of the problem of their utilization is closely connected with design and construction of special apparatuses.

As we have already mentioned, soda-ash production is an example for the whole basic chemistry, being named after a waste flow, namely the DS-solution, which is a typical low-temperature secondary heat source. DS – solution, the waste flow from soda ash process, is formed in the proportion of 8 – 11 m^3/t of soda ash. Inorganic salts which are discarded

Publication History
Manuscript Received : ***4 April 2014***
Manuscript Accepted : ***11 April 2014***
Revision Received : ***16 April 2014***
Manuscript Published : ***30 April 2014***

with the waste flow (primarily $CaCl_2$ and NaCl) also have certain value. Apart from that, DS – solution collected in large landfills, or the so-called “white seas“ is harmful to the environment. Therefore this waste flow often limitates the construction of new soda-ash plants. Heat loss with DS – solution, as it was already stated, is 3.8 GJ/t of soda ash and its utilization is the subject of research shown in this paper.

The palette of technical solutions in which secondary energy sources are used, is limited nowadays, although it is by far wider than that in the 1970s, when the first crisis in energy brought into a focus the necessity of saving energy instead of wasting it as it had been before. There are utilizator boilers for the work with high temperature pure energy sources, freon compressor heat pumps for heat transfer from 5 - 25°C to 50 - 60°C which are also suitable for solid effluents, absorption chrome-lithium cooling aggregates for cooling at the expense of heat source with the temperature of 120°C, air-cooling devices which enable cooling to 35 - 40°C, etc. Recently absorption bromine-lithium aggregates with the capacity of 4 – 20 GJ/h have been developed. Special focus is on the development of plants whose primary aim is operation under difficult circumstances (aggressive environment, gaseous and liquid effluents which containing suspended particles and poorly soluble chemical compounds), as well as efficient heat exchangers which operate at small temperature differences.

The development of compressor heat pumps began with oil crisis when many manufacturers were looking for solutions for the replacement of fossil fuels with other energy resources. Technical solutions and the models of heat pumps from back then did not prove to be very successful. With the rise of the cost of energy, heat pumps are becoming more and more interesting. The development of new technologies, the improvement of operation efficiency, smaller dimensions and mass are also contributing to their greater use. The classic heat pump is a device which transfers heat from fluids of lower temperature to fluids of higher temperature. The principle of operation is based on “removing“ low-temperature energy from a secondary source which is then given to the fluid at a higher temperature level.

A high temperature heat pump, which can be used for the preparation of water for high temperature district heating, is a completely new innovative device and represents a good example of a successful use of knowledge and practical experience. It was developed in 2010 within the EUREKA project. This paper presents the results of the research into the waste heat recovery (DS – solution) from the process of soda-ash production using a high temperature heat pump.

2. THEORETICAL DISCUSSION OF THE DS SOLUTION HEAT RECOVERY

Of all the feasible and practical possibilities of improving the energy balance in the process of soda ash production according to Solvay procedure, the DS–solution waste heat recovery is the most significant and fundamental. The possibilities of using the DS-solution heat are multifaceted to name but a few:

- heat recovery in the production of calcium chloride, if such production is present,

- heat recovery in the ammonia regeneration plant,

- heat recovery in the system of district heating, which is the topic of this paper.

2.1. Properties of DS – solution

DS – solution, which is a waste flow, is formed in the process of soda-ash production, or more precisely in the distillation column (DS). At the bottom of the column the pressure is constant at $(1.33 – 4.00)\cdot10^4$Pa. The amount of DS – solution which is formed in the process of soda-ash production is 8 – 11 m^3 per 1 t of soda ash, whereas the temperature of the waste flow is 95 - 110°C. Chemical composition of DS – solution varies depending on the degree of utilization of NaCl in the process of soda ash production. Its average value, achieved in the soda factory, is shown in Table 1.

Table 1.The average chemical composition of DS – solution

Component	Chemical composition of the solution		Component	The content of suspended particles	
	kg/m^3	% w/w		kg/m^3	% w/w
$CaCl_2$	102.73	8.96	$Ca(OH)_2$	4.5	0.39
NaCl	61.60	5.37			
$Ca(OH)_2$	1.48	0.13	$CaCO_3$	2.5	0.22
NH_3	0.08	0.007			
$CaSO_4$	1.02	0.089	$CaSO_4$	16.0	1.39

During the research itself, as well as in the course of presenting research results, different properties of the DS-solution waste flow were used. Table 2 shows some of the most important physical and chemical, as well as thermodynamic properties of DS – solution.

Table 2. Physical, chemical and thermodynamic properties of the waste flow of DS – solution

Temperature, t	95°C
Density, ρ	1124 kg/m^3
Specific heat, c_p	3.41 kJ/(kg·K)
Viscosity, μ	$5.2\cdot10^{-4}$Pa·s
Heat conductivity, λ	0.65 W/(m·K)

2.2. Fundamentals of the DS – solution heat recovery

The basic principle of DS – solution heat recovery is a combination of adiabatic evaporation and a high temperature heat pump.

Adiabatic vaporization of the DS-solution is achieved by reducing pressure, and, as a result of that, the boiling temperature of DS–solution decreases. The heated DS–solution with the temperature of 95°C-110°C is introduced into the exchanger in which the pressure is much lower, which also decreases the temperature of boiling of the DS-solution which is considerably lower than the real temperature (95 - 110°C). The evaporation of water from DS-solution in the adiabatic evaporator occurs at the expense of the heat which is released by cooling DS–solution from the real temperature (95 - 110°C) to the boiling temperature at the much lower pressure, and based on the following equation:

$$\Phi = q_m \cdot c_p \cdot \Delta t \qquad (1)$$

where:

Φ - heat flow rate (W)

q_m - mass flow of DS solution (kg/s)

c_p - specific heat of DS solution (J/kgK)

Δt - temperature difference of DS solution (K)

The amount of heat released depends on the difference between the starting (the "real") temperature of the DS–solution and the temperature of boiling of the DS–solution at a suitable reduced pressure in the evaporator. The lower the pressure, the greater the difference between the temperatures and this means that more heat will be used for the evaporation of water from DS-solution. Therefore, the amount of water vapour formed by the evaporation form the DS-solution depends on the pressure achieved in the evaporator [1]. Table 3 shows the vapour pressure over DS-solution at different temperatures.

Table 3.Water vapour pressure over DS – solution

Temperature, °C	120	115	110	105	100	95	90	85	80
Water vapour pressure over pure water, bar	2.05	1.75	1.48	1.25	1.01	0.85	0.70	0.58	0.47
Water vapour pressure over DS – solution, bar	1.93	1.65	1.40	1.18	0.96	0.80	0.65	0.55	0.45
Evaporation heat, kJ/kg	2206	2218	2231	2243	2256	2268	2281	2294	2306

The amount of water vapour which is produced in the evaporator from the DS-solution with the decrease of pressure from p_1 to p_2, and the decrease of temperature of the DS-solution from t_1 to t_2, can be determined using the equation (1) and the known value of the evaporation heat under the same conditions (p_2 and t_2). The amount of water vapour formed from DS-solution can be determined from Table 4.

Table 4.The amount of water vapour formed by adiabatic evaporation of DS-solution (kg/m^3 DS – solution)

p_1, bar p_2, bar	1.6	1.4	1.2	1.0	0.8	0.6	0.4
0.4	53.4	47.3	40.6	33.4	25.0	14.1	-
0.6	39.3	33.2	26.4	19.1	10.8	-	-
0.8	28.5	22.3	15.6	8.4	-	-	-
1.0	20.0	13.9	7.3	-	-	-	-
1.2	12.7	6.8	-	-	-	-	-
1.4	6.1	-	-	-	-	-	-
1.6	-	-	-	-	-	-	-

The development of heat pumps started with the great oil crisis. One of the solutions was the use of waste heat from different industrial processes; however technical solutions from those days never gave expected results so they were quickly forgotten. The development of new technologies resulted in new technical solutions and the latest types of heat pumps are nowadays in use, but mainly for the systems of low temperature heating of buildings.

High temperature heat pumps are devices which enable operations with a high added value of heat and they contribute to the reduction of energy dependence. This is due to the fact that they can be applied in all branches of industry. and the soda-ash production as well. They allow an efficient method of heat recovery from low temperature waste flows such as DS-solution. A high temperature heat pump is a device which takes heat from a low temperature heat source such as the DS-solution and uses it to heat the water in the systems of high temperature heating to the temperature of 85°C. It is designed in such way as to enable high values of coefficient of performance COP with the lowest possible energy consumption for the operation of the compressor [2, 3, 4, 5]. A high temperature heat pump is technically, economically and environmentally a very efficient device for heat recovery of the low-temperature sources such as DS-solution.

Working parameters of a high temperature heat pump (temperature, COP, heat flow), as a result of a computer calculation based on programmes specially developed for this purpose, for R717 as a cooling medium, are shown in Table 5 and Figures 1, 2, 3 and 4.

Table 5. Results of the theoretical calculation of the high temperature heat pump

Number of revolutions of the compressor 970 min^{-1}										
Temperature of hot water	Temperature of the source (°C) entrance	15	20	25	30	35	40	45	50	55
	Temperature of the source (°C) exit	5	10	15	20	25	30	35	40	45
65°C	Heat flow (kW)	108.6	136	166.7	200.7	238	278.9	323.2	371.5	423.3
	The necessary strength (kW)	35.3	38.5	41.4	43.9	45.7	46.8	47	46.3	44.4
	COP	3.08	3.54	4.03	4.58	5.21	5.96	6.88	8.03	9.54
70°C	Heat flow (kW)		128.7	158.9	192.5	229.5	269.7	313.6	361	412.1
	The necessary strength (kW)		40.1	43.6	46.7	49.3	51.1	52.1	52.1	51.1
	COP		3.21	3.65	4.13	4.66	5.28	6.02	6.93	8.07
Number of revolutions of the compressor 1450 min^{-1}										
Temperature of hot water	Temperature of the source (°C) entrance	15	20	25	30	35	40	45	50	55
	Temperature of the source (°C) exit	5	10	15	20	25	30	35	40	45
65°C	Heat flow (kW)		207.1	252.3	302.6	357.8	418.5	484.5	555.6	633.3
	The necessary strength(kW)		61.9	66.1	69.6	72.2	73.8	74.1	73.1	70.4
	COP		3.35	3.82	4.35	4.96	5.68	6.54	7.61	9
70°C	Heat flow (kW)			241.2	290.8	345.4	405.2	470.2	540.7	616.5
	The necessary strength(kW)			69.6	74.1	77.7	80.4	81.8	81.9	80.4
	COP			3.47	3.93	4.45	5.04	5.75	6.61	7.67
Number of revolutions of the compressor 1600 min^{-1}										
Temperature of hot water	Temperature of the source (°C) entrance	15	20	25	30	35	40	45	50	55
	Temperature of the source (°C) exit	5	10	15	20	25	30	35	40	45
65°C	Heat flow (kW)		229.4	279.2	334.4	395	461.8	534.4	613.1	698.1
	The necessary strength (kW)		70.1	74.7	78.5	81.3	83.1	83.5	82.3	79.5
	COP		3.28	3.74	4.26	4.86	5.56	6.4	7.45	8.79
70°C	Heat flow (kW)				321.5	381.5	447.2	518.7	596.2	679.5
	The necessary strength (kW)				83.5	87.5	90.4	92	92.1	90.4
	COP				3.86	4.36	4.95	5.64	6.48	7.52

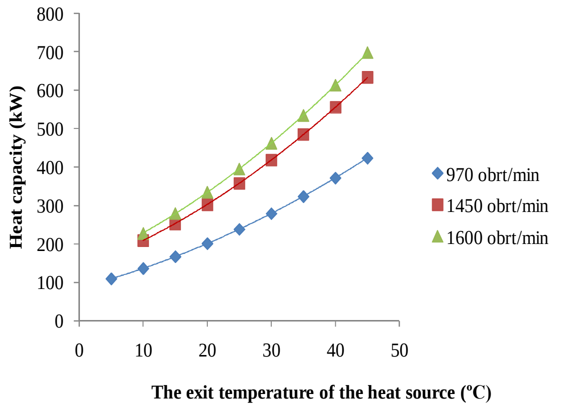

Fig.1. Heat capacity at 970 min^{-1}, 1450 min^{-1} and 1600min^{-1} and the refrigerant condensation temperature of 65°C

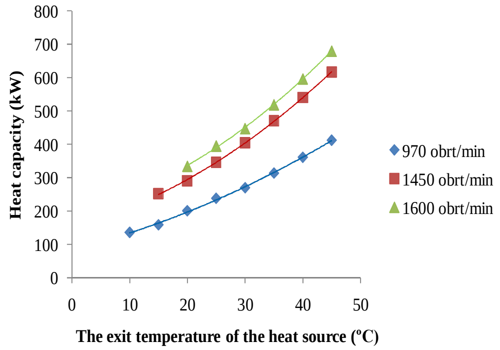

Fig.2. Heat capacity at 970min^{-1}, 1450$min^{-1}$and 1600min^{-1} and the refrigerant condensation temperature of 70°C

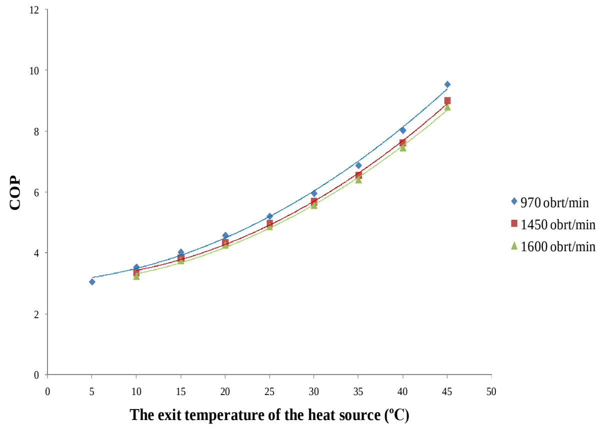

Fig. 3. COP at 970 min^{-1}, 1450 min^{-1} and 1600 min^{-1} and refrigerant condensation temperature of 65°C

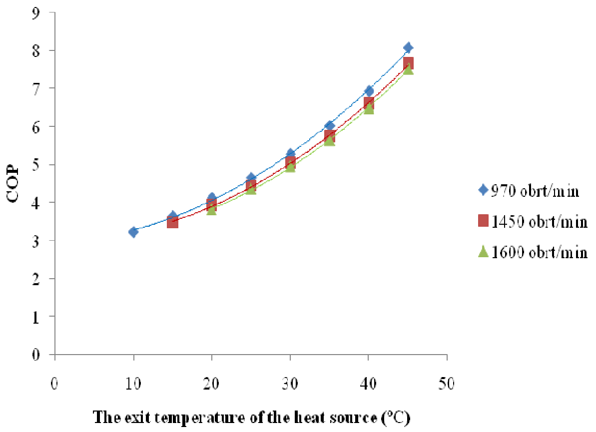

Figure 4. COP at 970 min^{-1}, 1450 $min^{-1}$and 1600 min^{-1} and refrigerant condensation temperature of 70°C

2.3. Characteristics of the system $CaCl_2$ – NaCl – H_2O and the possibility of crystallization

DS – solution formed from the process of Solvay soda-ash production is essentially a three-component electrolytical system $CaCl_2$ – NaCl – H_2O [6]. The synthesis and analysis of different processes in multi-component systems, particularly those tri-component, was a topic of research of several authors [7, 8, 9,10, 11].

We have already stated that the concentration of $CaCl_2$ is 8.96 % w/w and of NaCl 5.37% w/w. A tri-component system like this, in the process of heat recovery, was subjected to adiabatic evaporation where the concentrations of both salts (that of $CaCl_2$ and NaCl) are proportionally increased. The question is whether such adiabatic evaporation and the decrease in temperature of the DS-solution from 95°C to about 40°C cause saturation of the solution in respect to $CaCl_2$ or NaCl or even both salts.

The starting condition of the system $CaCl_2$ – NaCl – H_2O (DS – solution) defined by the concentrations of $CaCl_2$ and NaCl, as well as all other conditions through which the system passes during adiabatic evaporation, can be determined unambiguously in the balance diagram of the system $CaCl_2$ – NaCl – H_2O shown in Figure 5. The minimal number of variable values of the system which is necessary for its complete determination is system parametricity. Parametricity or the number of degrees of freedom of the system, according to Gibbs'phase rule, for an unsaturated tri-component system $CaCl_2$ – NaCl – H_2O is F=3+2-1=4. That is why DS – solution is determined with four degrees of freedom, or:

- pressure,
- temperature,
- $CaCl_2$ content
- NaCl content

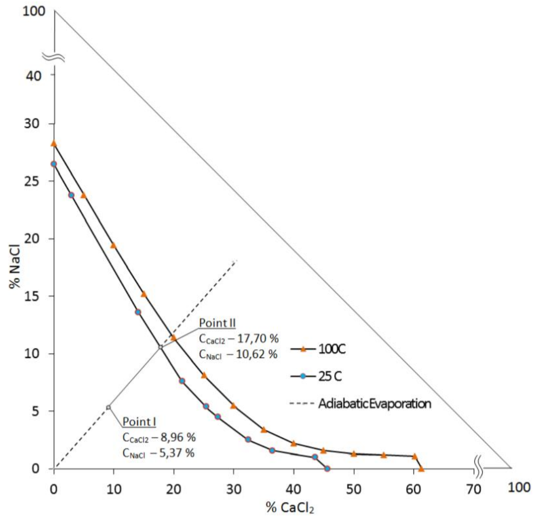

Figure 5.The change of concentration of $CaCl_2$ and NaCl during adiabatic evaporation in the balance diagram of the system of $CaCl_2$ – NaCl – H_2O

Adiabatic evaporation of water from the DS-solution in the process of heat recovery causes the increase of the concentrations of $CaCl_2$ and NaCl in it, therefore it is important to determine whether the condition of a saturated solution is achieved and at which temperature.

Examination of the process of adiabatic evaporation of water from DS-solution (system $CaCl_2$ – NaCl – H_2O) in the balance diagram, Figure 5 (conditions of the system defined by points I and II), can determine the parameters of the system in the point of saturation at the temperature of 25°C:

- the content of $CaCl_2$ 17.70% w/w.
- the content of NaCl 10.62 % w/w.

Based on this analysis of the DS-solution as a tri-component system of $CaCl_2$-NaCl–H_2O, it can be concluded that in the course of the process of heat recovery from DS-solution by adiabatic evaporation of water from the system, the concentration of $CaCl_2$ and NaCl in it increases but it must not achieve the balance concentration of the saturated solution determined by point II at 25°C, Figure 5, in order to avoid NaCl crystallization from the system. This parameter, the value of concentration of $CaCl_2$ and NaCl determined by point II, is the bordering value which defines technical feasibility of DS-solution heat recovery by adiabatic evaporation.

3. DS – SOLUTION HEAT RECOVERY

The soda ash production, as a typical example of a process in basic chemical industry, is a large consumer of energy, especially that of heat. Moreover, it is a large waster of heat energy. The largest loss in heat energy occurs in the DS – solution waste flow. A soda-ash plant with the capacity of 1000 t of soda ash per day produces 424646.0 kg/h of DS – solution (or 370.2 m^3/h). This amount of DS – solution is a basis for the synthesis and analysis of the process DS – solution heat recovery.

We have already stated in this paper that there are several possible methods for DS-solution heat recovery, one of which, the one in calcium chloride production and in the NH_3 regeneration plant [12], has already been considered. The process of heat recovery using a high temperature heat pump in the system of heating buildings is the topic of this paper.

After thorough research and using high temperature heat pumps (HTHP), the authors of this paper suggest the use of recuperated heat from DS-solution waste flow in the systems of district heating. This basic method consists of two stages:

- Adiabatic evaporation of DS-solution, reducing the temperature from 95°C to 68.5°C and transferring an adequate amount of heat to water during which it is heated 25°C to 72.5°C;
- Adiabatic evaporation of DS-solution, reducing the temperature from 68.5°C to 41.4°C and transferring an adequate amount of heat to water during which it is heated 25°C to 55°C, whereas, this heated water in the HTHP is further heated to 90°C and used in the system of district heating.

During the work on the design of the evaporators-condensers in which adiabatic evaporation of DS-solution occurs, it is very important to pay attention to the chemical composition of DS – solution. Certain chemical compounds which are component part of it, particularly $CaSO_4$ and $CaCO_3$, are deposited on the walls of the apparatus and reduce abruptly the total coefficient of heat flow. Therefore, for DS-solution heat recovery, the most suitable method to use is the method of adiabatic evaporation of DS-solution by reducing pressure in the apparatus, which consequently reduces its boiling temperature. Various methods and efforts to recover heat from the DS-solution were investigated earlier, with the first energy crisis [2], however, today they have become particularly important with the discovery of the high temperature heat pump (HTHP).

3.1. The first stage in DS – solution heat recovery

The first stage of DS-solution heat recovery involves adiabatic evaporation of the solution without introducing heat; the temperature of DS-solution is reduced from 95°C to 68.5°C. Adiabatic evaporation [1] is achieved by lowering the pressure and, consequently, decreasing the boiling temperature of the solution. The heat evolved by cooling the DS-solution from 95°C to 68.5°C, through the separated water vapor is transferred to water, heating it from 25°C to 72.5°C. The heated water, depending on the quality, can be transferred to a higher energy level using a high temperature heat pump and it can be used in the system of district heating for various purposes:

- central heating for cities
- preheat boiler feed water
- hot water supply for cities
- swimming-pool heating
- greenhouse heating

The heated DS – solution, produced as a waste flow in the soda-ash production in the quantity of 370.2 m^3/h, with the temperature of 95°C, is introduced into the battery of the evaporator-condenser (I-1 to I-6), in which the pressure drops in cascades from one apparatus to the other, together with the temperature of boiling. The heat flow, used for the evaporation of water from the DS-solution, and obtained by cooling the DS-solution, is calculated according to the equation (1). The amount of heat released from DS – solution (transferred to the production of water vapor which is again used for heating the water by means of condensation) depends on the difference between the starting temperature (95°C) of DS – solution and its boiling temperature at a suitable reduced pressure. In this case it is the temperature of boiling in the last (sixth) evaporator 68.5°C and the suitable pressure 0.279 bar. Figure 6 shows the flow chart of DS-solution heat recovery by heating the water of the system of district heating (I stage). This technical solution involves a six-degree station for adiabatic evaporation of DS – solution. where at the expense of cooling the DS – solution, an adequate part of water vapor is released; this vapor heats the water from the system of district heating in the condenser. Condensers are tubular heat exchangers placed in the upper part of the evaporators, of which they are component part. Vacuum in the evaporators is achieved by means of a vacuum pump or steam nozzle. In the first stage DS-solution is cooled from 95°C to 68.5°C and the water is heated from 25°C to 72.5°C.

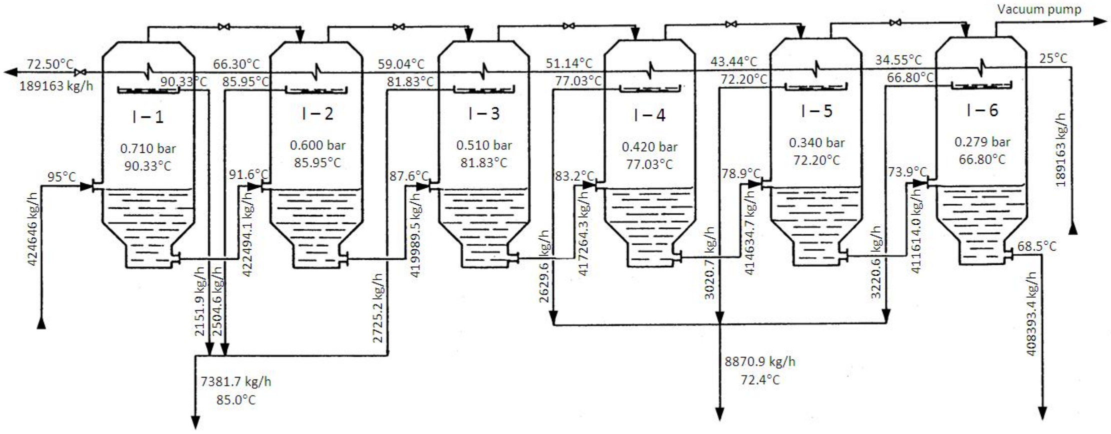

Figure 6. Flow chart of the DS – solution heat recovery plant (I stage)

Material balance of the process is determined based on the DS-solution flow rate which is 424646 kg/h. This waste flow is formed in the production of soda ash with the capacity of 1000 t of soda ash per day. Basic values of the material balance are shown in Figure 6 and Table 6.

According to all we have mentioned earlier, in the first stage of the process we use the heat from the DS-solution by heating the water from the system of district heating, but we also return it into the soda-ash process of the regenerated ammonia. Having in mind this purpose, the condensates formed in the evaporators can be used according to the following scheme:

- Condensate from the first three evaporators-condensers (I-1, I-2, I-3) can be used for washing the filter-cake on filters because it contains the regenerated ammonium from the DS-solution (30 kg/h) and the flow rate of the condensate is 16.2 m^3/h;
- Condensate from the other three evaporators-condensers (I-4, I-5, I-6) can be used in the process of hydration of calcium oxide or for similar purpose in the soda-ash process.

Table 6. Working parameters and basic characteristics of using the heat from the DS-solution by heating water in the 6-phase station of adiabatic evaporation (I stage)

Parameters	Evaporators					
	I-1	I-2	I-3	I-4	I-5	I-6
Pressure, bar	0.710	0.600	0.510	0.420	0.340	0.279
Temperature of vapor, °C	90.33	85.95	81.83	77.03	72.20	66.80
Temperature of DS – solution, entrance °C	95	91.6	87.6	83.2	78.9	73.9
Temperature DS – solution, exit °C	91.6	87.6	83.2	78.9	73.9	68.5
Temperature of water, entrance °C	66.3	59.04	51.14	43.44	34.55	25.0
Temperature of water, exit °C	72.50	66.30	59.04	51.14	43.44	34.55
Mass of the released vapor, kg/h	2151.9	2504.6	2725.2	2629.6	3020.7	3220.6
Mass of DS-solution, kg/h	424646.0	422494.1	419989.5	417264.3	414634.7	411614.0
Mass of water, kg/h	189163	189163	189163	189163	189163	189163
The amount of recovered heat, MJ/h	4909	5743	6276	6090	7032	7539
Surface of the condenser, m^2	100.97	106.28	102.2	90.70	91.04	87.51
Total mass of the released vapor, kg/h	16252.6					
Total quantity of recovered heat, MJ/h	37589 MJ/t (10.441MW)					
Total surface of the condenser, m^2	578.7 m^2					

3.2. The second stage of DS-solution heat recovery

The second stage of DS-solution heat recovery involves heating of water whose heat is used as a low-temperature source of high temperature heat pump [2, 3, 4, 5, 13, 14]. Water is heated using adiabatic evaporation of the DS-solution and its temperature is reduced to 41.4°C, that is to the technically possible reduced pressure of p_k = 0.07954 bar. The temperature of the DS – solution decreases from 68.5°C to 41.4°C. Further DS-solution heat recovery by reducing temperature to 20°C in heat exchangers (either plate or tubular)is not possible due to formation of deposits on the surfaces for heat exchange. This is the reason why the process of adiabatic evaporation is used both in the first and the second stage instead of heat exchange in heat exchangers.

Heated DS – solution in the amount of 408393 kg/h, with the temperature of 68.5°C at the exit of the first stage, is introduced into the battery of the evaporator-condenser of the second stage- there are three of them (I -2 ^{1} to I – 2^3), in which the pressure, and consequently the boiling temperature, drop cascadingly from one apparatus to the other. Heat flow, used for the evaporation of water by cooling DS-solution is determined according to the equation (1). The amount of the heat released from the DS-solution has been indirectly, through evaporation and condensation of water vapor, transferred to water, which is heated from 25°C to 55°C. In this case, in the second stage, the pressure of the DS-solution is reduced to 0.07954 bar and the temperature from 68.5°C to 41.4°C. Heated water from the first stage, as well from the second stage is used as a low-temperature source for the high temperature heat pump. Figure 7 shows a chart of DS – solution heat recovery from the system of district heating (II stage).

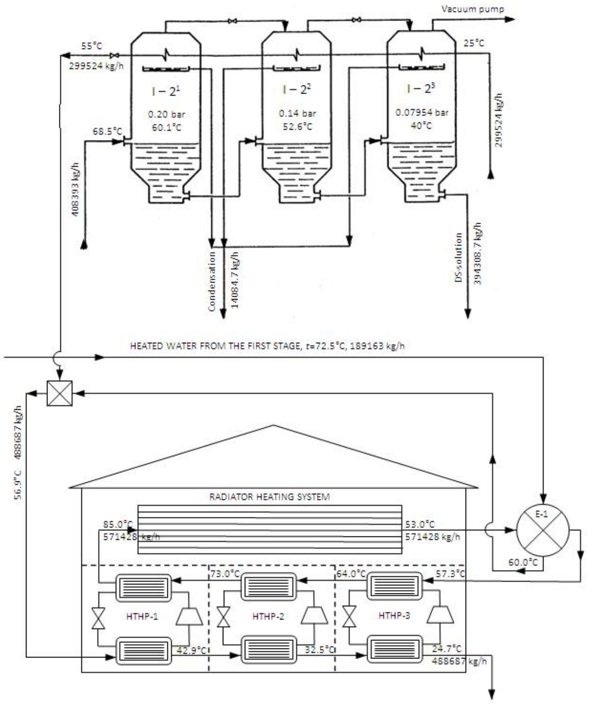

Figure 7. Flow chart of the DS – solution heat recovery plant (II stage)

Evaporators-condensers have the same design as in the first stage. This is important because of certain standardization of the basic apparatus in the total process of DS-solution heat recovery.

Material balance of the second stage of heat recovery was determined based on the flow rate of DS-solution of 408393 kg/h which exits from the first stage at the temperature of 68.5°C. Basic values of material balance are shown in Figure 7 and Table 7. The amount of released heat depends on the temperature of DS – solution at the entrance into the second stage as well as the temperature which enters into every evaporator and the boiling temperature of DS – solution reduced pressure in the evaporator. Water passes through the pipes of the condenser placed in the upper part of the evaporator entering at the temperature of 25°C and exiting it at the temperature of 55°C.

Table 7.Working parameters and basic characteristics of DS-solution heat recovery by heating water in the three-phase station for adiabatic evaporation combined with HTHP (II stage)

Parameters	Evaporators-condensers		
	I-2^1	I-2^2	I-2^3
Pressure, bar	0.20	0.14	0.07954
Temperature of boiling	60.1	52.6	40
Temperature of DS – solution, entrance, °C	68.5	59.5	50.4
Temperature of DS–solution, exit, °C	59.5	50.4	41.4
Temperature of water, entrance, °C	45.0	35.0	25.0
Temperature of water, exit, °C	55.0	45.0	35.0
Mass of DS – solution, kg/h	408393	-	394308.7
Mass of water, kg/h	299524	299524	299524
Total quantity of recovered heat, MJ/h	37740 MJ/h (10.483 MW)		
Total mass of vapor formed (condensate), kg/h	14084.73		

By recovering heat from the DS-solution and using it for heating water which is a low-temperature source for a high temperature heat pump, we would obtain in the second stage, by cooling the DS-solution from 68.5°C to 41.4°C, a heat flow of 10.483 MW. If this were technically feasible, the heat flow would be 15.13 MW if the DS – solution cooled to 30°C, and 19.6 MW if, however, it cooled to 20°C.

DS-solution heat recovery would involve using three high temperature heat pumps with a rotary screw compressor with the nominal heat flow rate of 10.0 MW, whose performance characteristics are shown in Figures 8 and 9.

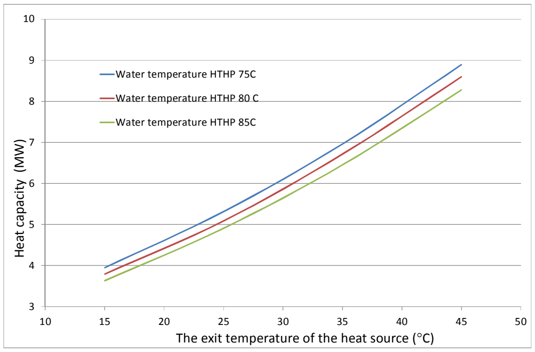

Fig.8. Heat flow of HTHP with nominal capacity of 10.0MW

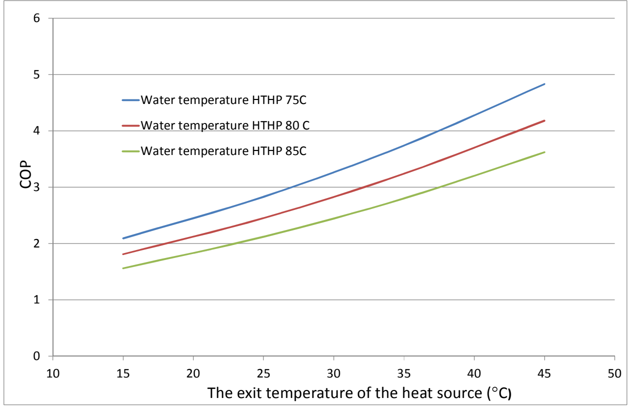

Fig.9. COP of HTHP with the nominal capacity of 10.0 MW

4. CONCLUSION

For a long period of time now, starting from the first energy crisis, the use of low-temperature industrial flows has been a priority. The research conducted previously, particularly concerning waste flow heat recovery in basic chemical industry usually came to the dead end with the insoluble problem of the quality of the recuperated heat and the impossibility of using it either within the process where the waste flow occurred or in other secondary processes. With the development of a high temperature heat pump numerous possibilities opened up concerning the application of recovered (regenerated) heat in the systems of high temperature district heating of buildings and other facilities. The DS – solution is a typical example of a low temperature waste flow formed in the process of soda-ash production. The research whose results are presented in this paper, defines the method of the DS-solution heat recovery consisting of two stages: heat recovery using adiabatic evaporation of the DS-solution in a six-phase evaporation station-stage I, and DS-solution heat recovery using adiabatic evaporation in a three-phase evaporation station by means of a high temperature heat pump (HTHP)-stage II.

The first stage of the DS-solution heat recovery results in a heat flow of 10 441 MW, and 10483 MW for the second stage. The total amount of recovered heat which is technically feasible and which is obtained (regenerated) from the DS-solution industrial waste flow is 20924 MW or approximately 42% of total heat which is necessary for the regeneration of NH_3 in the process of soda ash production.

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