Improvement of Spent Liquor Evaporation at RUSAL Krasnoturyinsk

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Abstract

The spent liquor evaporation unit at RUSAL Krasnoturyinsk uses four-effect counterflow - straight-flow evaporation trains equipped with natural circulation and rising film evaporators. These evaporating trains have a number of significant drawbacks due to the fact that boiling of liquor takes place in heater tubes which causes high abrasive and erosion wear on the tubes and consequently a decrease in service life. In the course of operation, sodium carbonate and aluminosilicate scale builds up in the heater tubes. It should be noted that superheated steam is supplied to the evaporators from turbine pressure steam (TPS). These drawbacks lead to decrease in capacity utilization and production rate of the evaporation train, increase in steam consumption, as well as reducing the service life of heat exchanging tubes. The paper presents technical, structural and process solutions to improve technical and economic efficiency of evaporators.

Keywords: evaporation, efficient heat exchangers, reduction in steam consumption.

1. Introduction

In alumina production used as raw material for aluminum smelting; evaporation process is of great importance. Aluminate (so-called spent) liquors resulting from precipitation of aluminum hydroxide from alkaline aluminate liquors formed in the process of bauxites digestion with caustic soda undergo evaporation. In the course of evaporation, water fed into the process for dilution of autoclave slurry to improve red mud separation is removed from spent liquors; caustic soda contained in liquors is concentrated and crystal sodium carbonate is extracted. The formed solid phase is separated from liquor on filters and fed to alumina production by sintering. Filtered strong evaporated liquor is fed to bauxite grinding [1.2]. At domestic alumina refineries processing bauxites by Bayer process, one of the major components in alumina cost is the cost of thermal energy [3]. Hence, an important objective is to minimise energy consumption during the evaporation process and to improve operation efficiency [3].

In alumina production of RUSAL Krasnoturyinsk, the evaporation process includes four-effect counterflow - straight-flow evaporation trains comprising natural circulation and rising film evaporators [4]. The practice of operation of these multi-effect evaporators has shown that these evaporators have a number of essential design faults caused by boiling of liquor in heater tubes. In the course of operation soda and aluminosilicate scale intensively grows in the heater tubes. Besides, scaling of heater tubes with salt reduces heat exchange intensity that leads to considerable decline in production of the evaporator train. Boiling of liquor in tubes of evaporators causes enhanced abrasive and erosive wear of heating tubes, service life of tubes achieves about 1.5 - 2 years, then they need to be replaced which requires significant labor costs [5].

Process flowsheet has also a significant impact on operational and power data of evaporators. Evaporators used for concentration of spent liquors comprise some countercurrent elements. It is caused by a reverse nature of solubility of sodium hydroaluminosilicates [6].

Besides, a system of liquor heating has a significant impact on power consumption and capacity of evaporators. Shell and tube type heaters are an integral part of the evaporation train and are inclined to intensive scaling with aluminosilicates. Some modification were carried out in the past on the multiple-pass heaters of liquor to one-pass heaters. It reduced somewhat blockages with scale, but led to manifold decrease in intensity of heat exchange and deterioration of evaporator train performance in general. Therefore, an important objective is to improve heaters design to provide longer life and intensive operation [7].

In alumina production at RUSAL Krasnoturyinsk steam is fed to evaporators from TPS at pressure of 0.5 - 0.6 MPa (5 - 6 kgf/cm^2) and temperature 230 - 260 °C, obtained as a result of reduction of high pressure steam selected from turbines.

Thus, superheated steam is fed to heating chambers of evaporators. As a result, intensity of heat transfer from steam to the wall of heat-exchanging tubes leads to decrease in productivity of the train as a whole. Besides, heating of evaporators with superheated steam leads to increase in thermal stresses in heating chambers decreasing service life of heat-exchanging tubes. They fail and should be replaced

Therefore, to avoid the specified negative effects it is necessary to cool steam to the temperature close to saturation before feeding to a heating chamber. It allows to reduce to some extent specific consumption of steam for evaporation and raise evaporator capacity and, most important, to increase by 1.5 - 2 times service life of heat-exchanging tubes of evaporators fed with cooled steam [8].

The above shortcomings in operation of the existing evaporators at RUSAL Krasnoturyinsk lead to significant increase in cost of evaporation of spent liquors. Aiming to eliminate these shortcomings, work was carried out to determine conditions for application of equipment for heating of liquor and cooling of steam. Optimum designs were chosen of liquor heater for evaporators and cooler of steam directed to the evaporator, comparison was made of the proposed designs with the existing ones on the basis of hydraulic simulation, scale growth in tubes was assessed.

2. Design Description of the Existing Heaters

A one-pass shell and tube heater with tubes of 6 m long and diameter of shell 1.2 m is installed in the evaporator. The number of tubes in this device is 192, and heat-exchanging surface area (by average diameter of tubes) is 193.5 m^2. There are also heaters with tubes 5 m long in the evaporation area. The number of tubes is 254 and 236, and the area of heat-exchanging surface (by average diameter of tubes) is respectively 213 and 198 m^2.

Originally, the evaporators were equipped with four-effect heat exchangers. However, the heaters scaled excessively . As a result, hydraulic resistance increased so that transfer pumps failed to pump liquor via heaters to evaporators. Therefore, heaters were shut off, liquor bypassed the heaters, and evaporators operated without them.

Coefficient of a heat transfer of such heaters, makes 250 – 600 W/(m^2×K), depending on heating steam pressure.

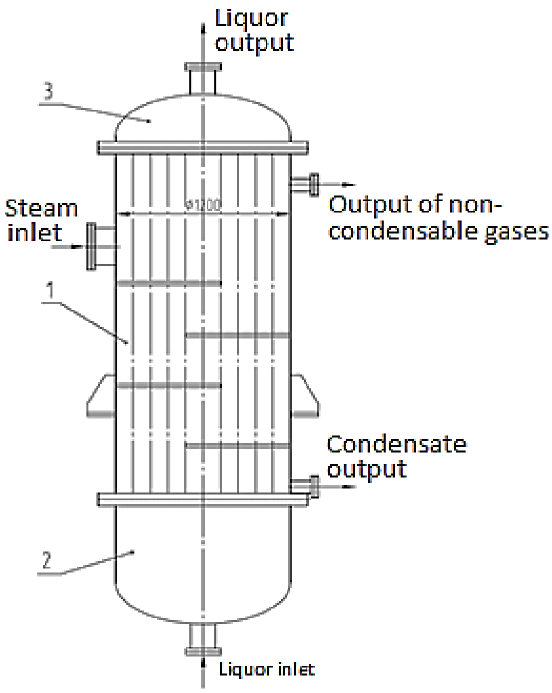

Figure 1. The existing aluminum liquor heater of evaporators.
(1-heat-exchanging chamber; 2 - liquor inlet chamber; 3 - liquor output chamber)

The analysis of modes and operating conditions of the existing liquor heaters in evaporators showed the following. In heaters, liquor leaving the third evaporator effect and enters the first effect (evaporator). Under these conditions (temperature increasing at constant concentration of liquor) solubility of sodium hydroaluminosilicates decreases.

Increased scale formation in tubes of heaters is promoted as well by low liquor slow flowrate that is 0.07 - 0.1 m/s. The previous investigations showed that at such flowrate in 30 – 50 % of tubes liquor flows in the opposite direction and there are stagnant zones that increase further scale growth. Besides, increased scale formation arises due to great difference of temperature between heat carrier – steam and the heated liquor, reaching 60 – 90 °C. At the same time temperature increases in the wall-adjacent layer at a surface of tubes that causes formation of scale having reverse solubility

It was demonstrated that increased scale growth in tubes of the existing heaters is caused both by conditions of operation in evaporators and structural imperfection, but still there are opportunities to reduce scale growth. And to achieve this goal some measures shall be taken to solve the issues mentioned above.

3. Choice of Basic Technology Solutions on Improvement of Evaporating Train of Alumina Production

Considerable influence on power consumption and capacity of evaporators as well as on stabilization of their operation has a system of liquor heating. One should bear in mind that spent liquor has a propensity for scaling due to availability of sodium hydroaluminosilicate that has an inverse relationship between temperature and solubility. Processing and heating of liquors causes serious problems due to scaling on the heat-transfer surfaces of equipment [7].

In Figure 2 silica solubility curves are presented for aluminate liquors processed in hydrometallurgical productions [9]. Silica is available in aluminate liquors as sodium hydroaluminosilicates and can precipitate during production of alumina. The liquors with $\alpha_K = 2$ (α_K is Na_2O/Al_2O_3 molar ratio) shown in the curves should be heated before bauxite digestion, and liquors with $\alpha_K = 3 - 4$ - at evaporation of spent liquor. From the curves one can see the inverse relation between silica solubility and temperature in the temperature range that requires heating of liquors at evaporation and digestion.

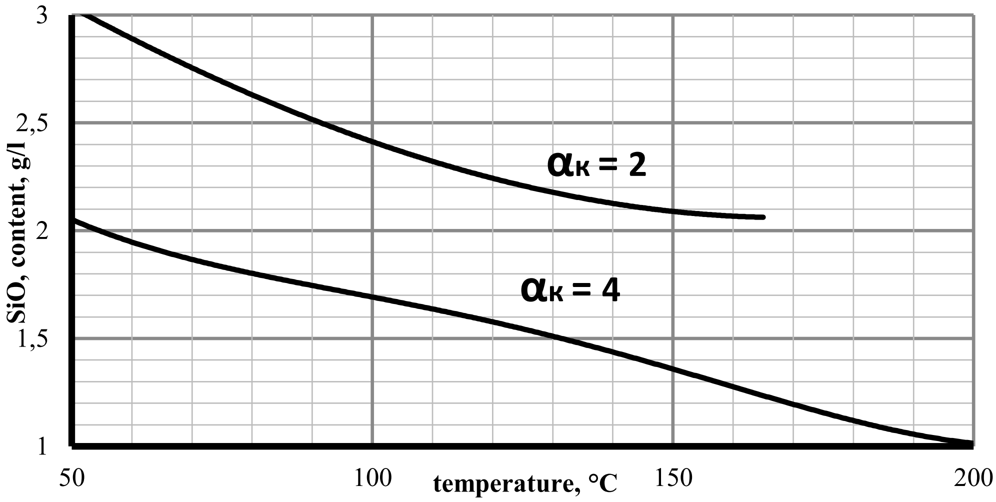

Figure 2. Solubility of silica in aluminate liquor depending on temperature.

Figure 2 shows that silica solubility decreases with increase in temperature and silica scale is formed on the tubes. As a result of scaling the efficiency of the process requiring heating of liquors decreases considerably that leads to extra energy consumption. Evaporators are especially sensitive to insufficient heating of liquor due to scale formation in heaters. For these installations, as calculations showed, using an effective system of heating, it is possible to lower specific heat consumption by 10 – 15 % without altering heat exchange area of evaporators and number of effects (evaporators), and to increase productivity almost by 10 – 15 %.

In existing heaters of alumina production flowrate in tubes usually does not exceed 1 m/s [10]. Even a small increase in flowrate gives considerable reduction in scale formation and improves heat transfer

To achieve all positive results from application of liquor heating superficial heaters are required. The results from investigations demonstrate that shell and tube heat exchangers should be used as heaters. However, they should be designed in such a way as to avoid multiple passage of liquor and to provide hydraulic modes of liquor flow in tubes enabling to maximise heat transfer and to reduce scaling.

With that in mind, heat exchangers are proposed comprising several elements in which liquor flows at the required rate vertically upwards. According to experimental data for salts with reverse solubility, the ascending movement considerably reduces scaling in tubes as compared to descending movement.

A basic design of such heater designed by LLC Khimtekhnologiya taking into account the principles stated above is shown in Figure 3.

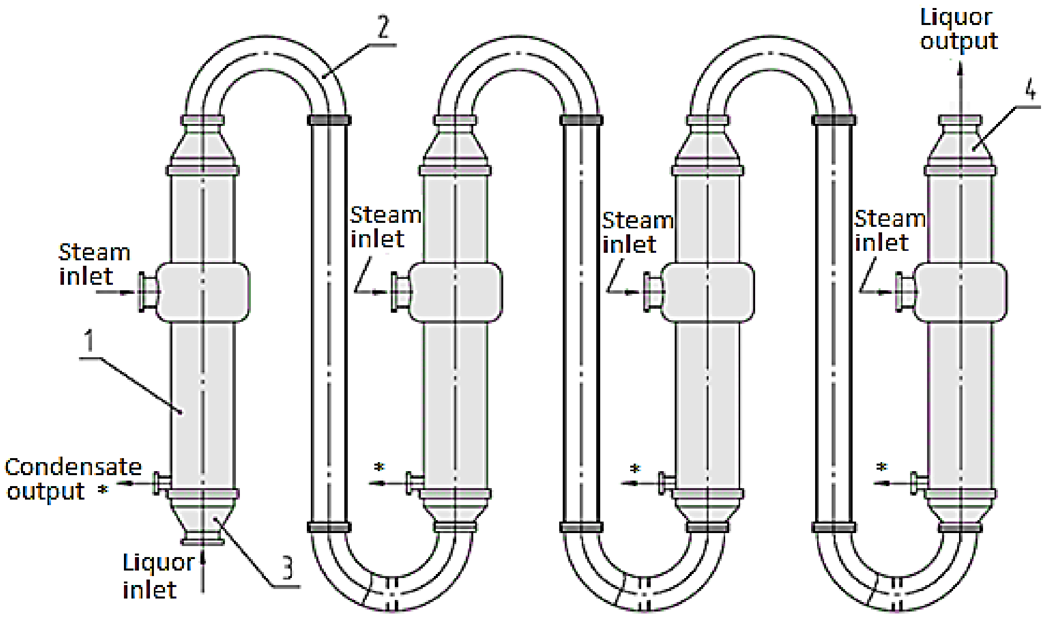

Figure 3. Four-element shell and tube heater.
1-element heater; 2-overflow pipe; 3-inlet liquor chamber; 4-output liquor chamber.

Figure 4. Assembled element shell and tube heater.

In the design of this heater, developers implemented their ideas to provide optimal hydrodynamic conditions for heating of liquor to achieve high and uniform flowrate in tubes. Besides, this device has a certain liquor volume in which removal of supersaturation takes place by a scale forming component. Flowrates in tubes are chosen in such a way that for the period of liquor passing through tubes the scale would not be able to form on the surfaces of tubes.

Also note that in this heater there is an opportunity to use steam with different potential as heating agent for different elements to avoid critical liquor overheating causing scaling. In particular, part of elements can be heated with steam of high potential, for example, heating steam having pressure of 0.6 MPa, and the other part – with secondary steam having pressure 0.3 MPa. As a result temperature difference between liquor and steam and, consequently, wall-adjacent overheating of liquor in heat-exchanging tubes will be reduced [11].

As previously stated, steam of TPS fed to evaporators is superheated in respect to saturation temperature at this pressure. As a result of supply of that kind of steam to evaporators part of heat exchange surface is used for cooling of steam without condensation with very poor heat exchange intensity. It lowers capacity of the evaporator. Besides, heating of the device with superheated steam, causes accelerated wear of heating tubes, due to additional mechanical tension formed as a result of heating evaporators with overheated steam of TPS.

An efficient way to increase service life of tubes of evaporating devices is to lower the temperature of superheated steam of TPS supplied to evaporators. To this end, for cooling, finely dispersed condensate should be injected into the flow of steam. At that, steam should be cooled as much as possible to the temperature, the closest to saturation temperature. Thus, it is possible to gain the greatest effect of cooling steam for evaporator. [12].

Figure 5. Steam cooler.

The tests of the installation for steam cooling allowed to record decrease in specific heat consumption for the evaporator by desuperheating the steam.

4. Results of Hydraulic Simulation of Operation of Heaters of Various Designs

Assessment and comparative analysis are carried out of hydraulic operating conditions of heaters of various designs based on the data of numerical simulation of flows in tube side. Operation of spent liquor heaters is considered, in particular, of the existing one-pass shell and tube heater, as well as of the proposed elemental heat exchanger. At that, process conditions of heaters operation are accepted on the basis of operation data of evaporators.

For assessment of flowrate distribution in heat-exchanging tubes by cross section numerical simulation of flows in the existing and proposed heat exchangers was carried out to determine the design which would provide the most uniform flowrate distribution in tubes to decrease formation of scale.

Numerical simulation was carried out with the use of SolidWorks FlowSimulation 2014 on the basis of Ural Federal University. Equipment 3D models were developed for carrying out calculations, properties of actual spent liquor and operating conditions of equipment are

simulated. Calculation was carried out by analysis of data of a vertical component of liquor flowrate by cross section perpendicular to heat-exchanging tubes.
By consideration of specific cases, one should bear in mind that simulation is carried out by numerical solution of Navier-Stokes equation in enclosed volume for some probabilistic flowrate distribution of liquid, which, often, can be nonsteady by the nature. Thus, the picture of flowrate distribution is true for a specific case, but not statistically, it there can be free of symmetry inherent in the system, however the obtained data sufficiently reflect the regularities connected with system geometry.

4.1. Hydraulic Simulation of Flows in the Existing One-pass Heater

A 3D model was developed for simulation of the existing one-pass heater according to Figure 1. Technical characteristics of this heater required for simulation are given in Table 1.

Table 1 - Technical characteristics of the existing one-pass heater.

Parameter	Value
Heat exchange surface area, m^2	193.5
Number of tubes, pcs.	192
Number of passes	1
Liquor consumption, m^3/h	130
Medium flowrate of liquor in tubes, m/s	0.096

Distribution of absolute liquor flowrates by tubes of the heater is shown in Figure 6. In Figure one can see distribution of liquor flows in the device, and the picture of flowrates. One can see that fed in tube side of the one-pass heater, the main flow of liquor enters to the central part of the device. At that, in a large portion of tubes flowrate of the liquor does not reach even 0.02 m/s, and in some tubes the flow moves in the opposite direction. Such flowrate distribution in tubes leads both to decrease in heat transfer, and to increase in scaling of heat-exchanging surfaces.

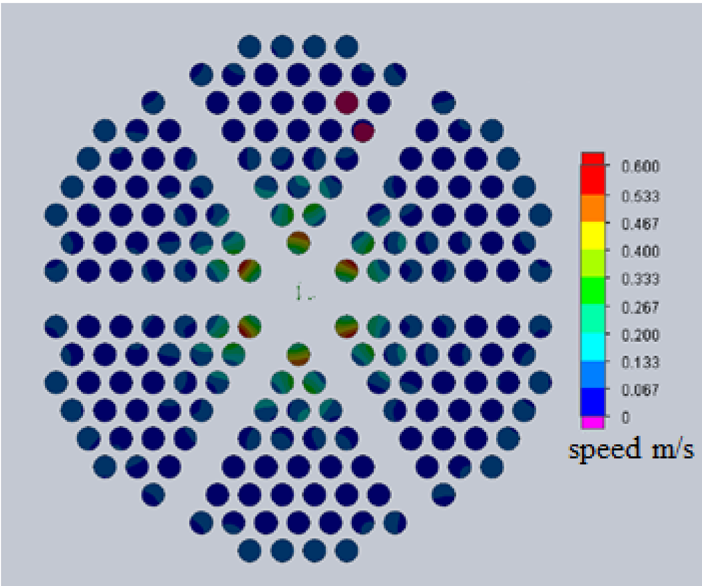

Figure 6. Distribution of absolute liquor flowrates in the existing one-pass heater.

4.2. Hydraulic Simulation of Flows in an Elemental Heater

A hydraulic simulation of flows in the elemental heater preliminary calculation showed that calculation field can be reduced to simulation of two segments, due to similarity of liquor flow in other elements. In view of considerable repeatability of the obtained data, this restriction is not crucial, and the obtained data exhibit high degree of reliability. It should be noted that in the course of simulation of this device the existence was considered in the inlet liquor chambers of elements of the distributing device that provides more even distribution of liquor in tubes.Technical characteristic of the elemental heater is given in Table 2.

Table 2. Technical characteristics of the elemental heater.

Parameter	Value
Heat exchange surface area, m^2	162.6
Number of tubes in a segment, pcs.	27
Number of tubes, pcs	162
Number of elements	6
Liquor consumption, m^3/h	130
Medium flowrate of liquor in tubes, m/s	1.56

Figure 7 shows the section obtained from a hydraulic simulation of the heater that reflects a real picture of liquor flowrates in tubes of the first two passes.

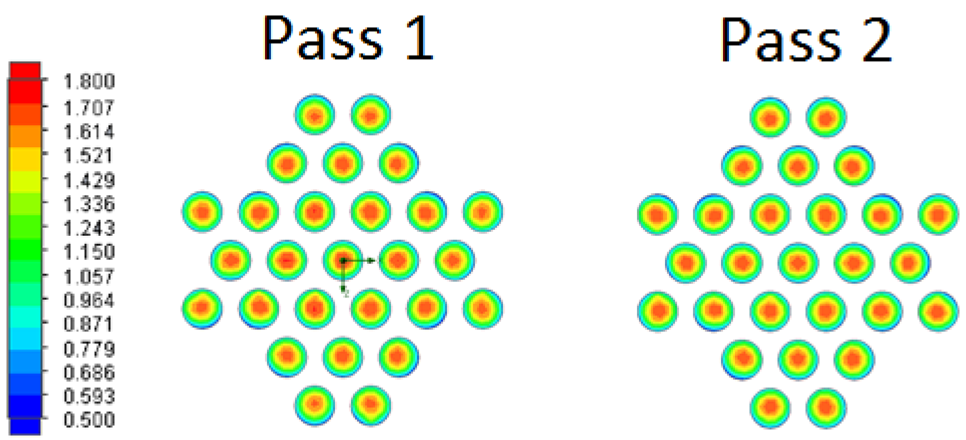

Figure 7. Picture of absolute liquor flowrates in the first two passes of the elemental heater.

As it can be seen in Figure 7, the flow of liquor is distributed by tubes of each pass of the heater rather evenly in the whole section of the device.

Thus, on the basis of the given results of hydraulic simulation, it is visible that though distribution of flowrates and temperatures in the elemental heater is much more uniform than in the existing one, however it also has a certain insignificant unevenness of liquor flow in tube section causing wall-adjacent overheating of liquor and scaling.

4.3. Comparison of Results of Hydraulic Simulation of Flows in various Heaters

The higher is flowrate of liquor in tubes of the heater, the less is the width of a wall-adjacent zone, in which flowrate is minimal. For the existing one-pass heater having the lowest flowrate, distribution of flowrates changes evenly from minimum to maximum in tube section. For elemental heaters distribution of flowrates in the section of a tube corresponds to distribution in a turbulent flow of liquid at which there is distinctly expressed flow core with flowrate close to average. Due to this reason the width of wall-adjacent area in a tube decreases and, consequently, overheating of liquor causing supersaturation of liquor with sodium aluminosilicates and scale formation on walls of tubes.

Temperature distribution in the section of tubes of heaters is inverse to liquor flowrates distribution. At that, the higher is flowrate in tubes, the less is the width of area of high overheating of liquor, where increased scaling takes place, and the higher is flowrate, the lower liquor temperature near the wall. Moreover, for the one-pass heater high temperature area in tube section is considerably larger, than that for the element heater, that indicates that the probability of scaling of this device much higher.

Taking into account flowrates and temperatures of liquor in tubes, a certain supersaturation with sodium aluminosilicates occurs in the considered heaters. The higher is supersaturation, the more vigorous is scale formation on tubes surfaces. From there, it is clear that elemental heaters have the least supersaturation with aluminosilicate. In addition, due to heating of half of elements with lower potential secondary steam of the first effect, the considered value for this device decreases even more, and has the minimum values. The one-pass heater has the most considerable supersaturation. Therefore, it will have maximum scale formation. Thus, on the basis of the above results of hydraulic simulation, it is demonstrated that the most preferable, in terms of decrease in scale formation on tubes walls, are element heaters. Upon that, in the furtherance of this goal, this device should be heated with both TPS steam, and secondary steam of the first effect of the evaporator.

5. Experimental

During preliminary and pilot testing of the liquor heater and of the steam cooler, evaporator train No. 1 at RUSAL Krasnoturyinsk operated with the following parameters:

- productivity up to 150 m^3/h;
- vacuum in the separator of the last effect of the evaporator- 0.75 kgf/cm^2;
- concentration of initial (spent) liquor was lower than standard and made 126 g/dm^3 Na_2O_{caust}.

In the course of pilot testing the heater of liquor and the cooler of steam operated as a part of the evaporator for three full inter-washing periods of operation of the evaporator (IWP); during this period recording was made of operating conditions, both of new equipment, and the existing devices of evaporator No. 1. Besides, tests of evaporator No. 1 were carried out with switching-off the heater of liquor and the cooler of steam, within two IWP; during this period operation parameters of the existing devices of the evaporator were also recorded.

By the results of pilot tests satisfactory operation of both - liquor heater, and steam cooler was marked. At that, steam cooler operated in an automatic mode. Decrease in specific consumption of TPS heating steam for evaporation of 1 tonne of water was also marked.

6. Results Analysis

Key parameters (average) of operation of the evaporator are specified in Table 3 where one can see that during operation of the evaporator with the heater of liquor and the cooler of steam specific steam consumption per tonne of evaporated water was 0.296 t/t as compared to 0.332 t/t without the heater and the cooler, i.e. 12 % less.

Thus the use of the heater of liquor and the cooler of steam enables to lower considerably specific costs of steam evaporation.

Table 3. Average consumption of main process media in evaporator.

Operation conditions of evaporator			**Liquor heater & Steam cooler in service**	**Liquor heater & Steam cooler switched off**
Parameter	Unit.	Way of stating.	Parameter value (average for 3 IWP)	Parameter value (average for 2 IWP)
Spent liquor consumption	m^3/h	Measured	146,0	159,5
Steam consumption	t/h	Measured	21,2	30,8
		Calculation.	23,7	30,6
Evaporated water	t/h	Calculation.	79,9	92,0
Specific steam consumption	t/h	Calculation.	0,296	0,332
Condensate consump-tion for steam cooling	m^3/h	Measured	1,37	-
		Calculation.	1,43	-

Let us consider performance indicators of the liquor heater recorded in testing. Liquor was heated in the heater from 87 – 90 °C to 149 – 151 °C, i.e. by more than 60 °C. Simultaneously, liquor was heated by secondary steam of the first effect in 4 - 6 elements to 122 - 127 °C, i.e. almost by 55 - 60 % of the total value of heating. Thus, application of the heater of liquor and the cooler of steam as part of the evaporator leads to decrease in specific steam consumption in the evaporator. The tests showed that the heater of liquor had the following heat transfer coefficients: in the first three sections - 3060 $W/m^2 \times K$, and in the subsequent ones – 2860 $W/m^2 \times K$. The flowrate of heated liquor in tubes of the heater was 1.35 - 1.5 m/s.

At the same time, some decrease recorded in production of the evaporator at the tests with the heater and the cooler is explained by the fact that during this period the evaporator worked at low vacuum due to hot weather, low content of alkali in the initial liquor and high content of carbonates (30 – 50 % more than usually).

7. Conclusions

Tests of the liquor heater and the steam cooler demonstrated higher performance indicators and characteristics as compared to those put in the project. These devices operated steadily as a part of the evaporator.

Automated control of the new devices and the evaporator provides a required control of process parameters and maintenance of set process conditions.

The results of pilot testing of the liquor heater and of the steam cooler as a part of the evaporator demonstrated that due to the use of the new equipment specific consumption of steam for evaporation per tonne of water is reduced by 12 %.

Heaters of liquor and coolers of steam are recommended for application as a component of other evaporators at RUSAL Krasnoturyinsk.

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