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The use of plate heat exchangers to improve energy efficiency in phosphoric acid production

Petro Kapustenko [a,*], Stanislav Boldyryev [a], Olga Arsenyeva [b], Gennadiy Khavin [b]

[a] National Technical University "Kharkiv Polytechnic Institute", ul. Frunze 21, 61002 Kharkiv, Ukraine
[b] AO "Sodrugestvo–T", Krasnoznamenniy per. 2, k. 19, 61002 Kharkiv, Ukraine

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ABSTRACT

This paper originated as a part of a comprehensive research project designed to develop ecologically sustainable, environmentally friendly, resource- and energy-saving industrial process technology for the production of a wide class of phosphorus containing substances. The essential feature of the research was designed for the replacement of tubular heat exchangers with Plate heat exchangers (PHEs) and for the installation of these units in new locations in the processes to optimally improve energy efficiency and to prevent pollution. Despite the severe operating conditions in the production of phosphoric acid PHEs of various designs find the application in these processes. For such a corrosive environment as a phosphoric acid production plant, the Hastelloy G30 alloy is used as the material for the plates and synthetic rubber EPDM is used as the material for inter-plate gaskets. The analysis of the data shows, that using mixed groupings of plates in the unit allows one to obtain optimal solutions. The simulation of barometric mixing condenser recycled water cooling with plate heat exchanger shows the possibility of an application which minimizes the waste water pollution by closing the condenser cooling water circuit. Software was developed for calculations of units working both with liquid and phase changing streams.

1. Introduction

Most of the technology in the phosphorus chemical industries is outdated and unable to 'solve' the problems of waste minimisation and full utilization of material and energy resources. New research and innovation strategy for the phosphoric acid industry are being developed within the EC supported FP6 INCO ECOPHOS Project. It is designed to develop ecologically sustainable, environmentally friendly, resource- and energy-saving industrial process technologies for the production of a wide class of phosphorus containing substances, for details see Seferlis et al. [1,2], Papadopulos et al. [3]. In this article, findings are presented from the part of the project concerned with the replacement of tubular heat exchangers with PHEs and installation of such units in the new placements to increase heat recovery.

The chemistry of phosphoric acid production from apatite concentrate by the wet method is sufficiently developed and rather well described in the literature (see e.g. European Fertilizer Manufacturers' Association EFMA Best Available Techniques [4], Evenchik and Brodskii [5], Abu-Eishah and Abu-Jabal [6]). According to these literature sources, the typical process flowsheet of phosphoric acid production by the dehydrate method is presented in Fig. 1. This process enables one to obtain weak acid with concentration 26–32% of P_2O_5 which should be followed by an evaporation unit to obtain acid with higher P_2O_5 concentration (see Fig. 2).

Considerable improvement in process energy saving and pollution reduction can be achieved with the use of pinch technology and process integration approach, which shown good results in many industrial applications (see Linnhoff et al. [7], Smith [8], Varbanov et al. [9]). With this technique considerable reduction of energy consumption in phosphoric acid production by wet process, up to 25–30%, was shown by Tovazshnyansky et al. [10]. To fully evaluate the energy-saving potential and impact on environment the new tools should be used, as described by Perry et al. [11] and Klemeš et al. [12]. At the same time the importance of receiving economically optimal solutions with correct accounting for cost and energy prices (see Taal et al. [13]) can substantially limit the possibilities of energy saving, counting that highly expensive materials are required for heat transfer surfaces production. This fact can wear responsibility that in a lot of phosphoric acid production plants, which are now in operation, few process

* Corresponding author. Tel.: +380 577202278.
E-mail address: kap@kpi.kharkov.ua (P. Kapustenko).

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Nomenclature

Q	heat load, kW
t	temperature, °C
F	heat transfer area, m^2
K	overall heat transfer coefficient, $W/(m^2\,°C)$

Subscripts

inlet	cooling water inlet
out	cooling water outlet
outlet	barometric condenser water outlet
all	total heat transfer area

Abbreviations

PHE	plate heat exchanger
EPDM	ethylene–propylene synthetic rubber
EFMA	European Fertilizer Manufacturers' Association
SHE	spiral heat exchanger
H	high
L	low
M	medium
SW, NG	types of inter plate channels
M10B	Alfa Laval PHE with 100 mm collectors, low depth corrugation B
M15M	Alfa Laval PHE with 150 mm collectors and high depth corrugation M
T20M	Alfa Laval PHE with 200 mm collectors and high depth corrugation M
M30M	Alfa Laval PHE with 300 mm collectors and high depth corrugation M
WG200	Alfa Laval PHE with wide gap channels and 200 mm collectors
Alfa Cond 600	special Alfa Laval plate condenser with 600 mm collectors

integration and heat recuperation opportunities are used. To overcome this obstacle for achieving possible gains, the less material consuming, compact heat exchangers, can be used instead of conventional shell and tube ones.

The PHEs are one of the most efficient types of heat transfer equipment currently available. The principles of their construction and design methods are sufficiently well described elsewhere (see e.g. Hesselgreaves [14], Wang et al. [15], Shah and Seculic [16], Tovazshnyansky et al. [17]). This equipment is much more compact and requires much less material for heat transfer surface production, thus, there is a much smaller footprint than with conventional shell and tube units. It makes it feasible and economically efficient to produce plates from expensive, sophisticated materials. PHEs have a number of advantages over shell and tube heat exchangers, such as compactness, low total cost, less fouling, flexibility in changing the heat transfer surface area, accessibility, and what is very important for energy saving, close temperature approach – up to 1 °C. The main limitations for their use are pressure and temperature restrictions imposed by gaskets. The comparison of capital cost data for both PHEs and shell and tube exchanger units for a wide range of thermal duties, evaluated by Edwards and Stinchcombe [18]. They found that, for many cases stainless steel plate units are even cheaper than shell and tube units made from lower cost carbon steel. They also noted that, on average, the all stainless steel tubular unit would be about four times as expensive as PHEs. A similar conclusion was made by Shah and Seculic [16].

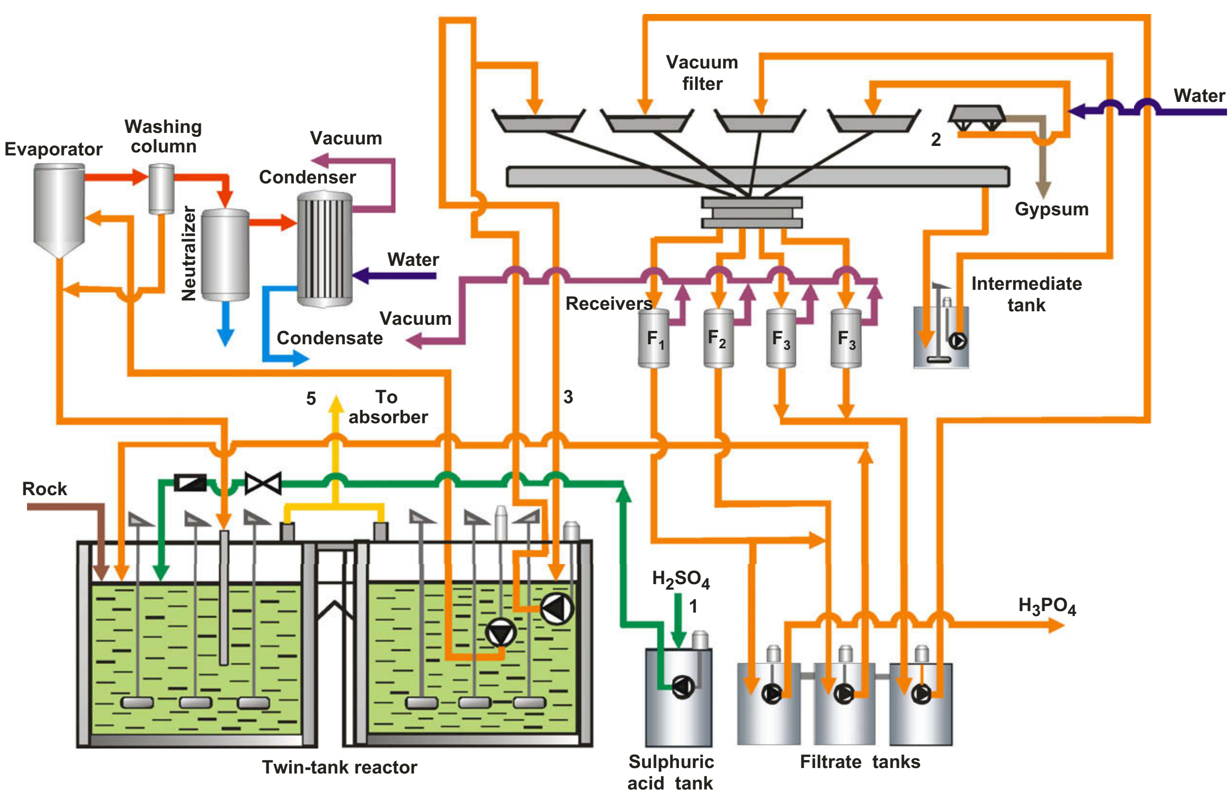

Fig. 1. The typical process flowsheet of phosphoric acid production by the dehydration method.

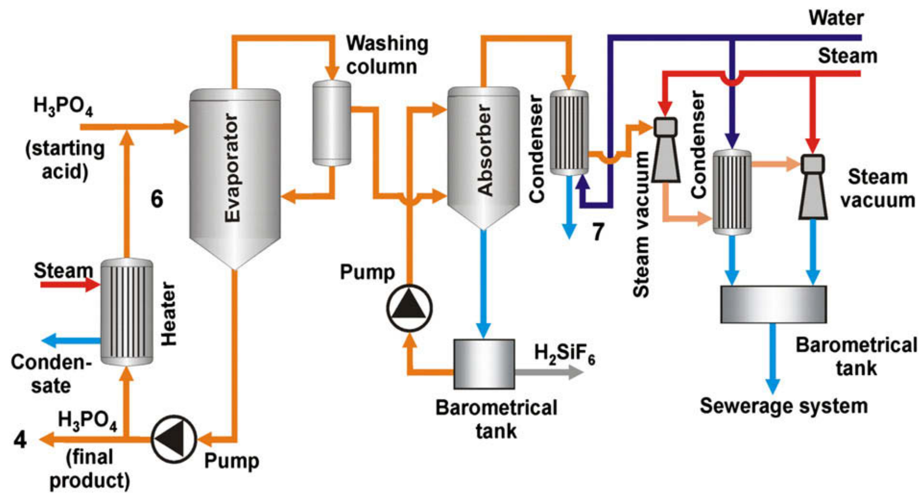

Fig. 2. Flowsheet of the concentration unit.

This advantage is magnified when specialised and expensive metals are used for PHEs. Such material is needed for the heat transfer plates used in the phosphoric acid production process.

2. Placement of heat exchangers in wet process of phosphoric acid production

The main placements of heat exchangers in the manufacturing of phosphoric acid include: (see Figs. 1 and 2)

Cooling of sulphuric acid solution 78–98% H_2SO_4 (Position 1 in Fig. 1);
Cooling of weakly concentrated phosphoric acid (3%) after washing of the filter sediments (Position 2 in Fig. 1);
Heating of 30% phosphoric acid before sulphate sedimentation (Position 3 in Fig. 1);
Cooling of phosphoric acid (final product) with 40–42% or 50–54% P_2O_5 concentration after evaporation (Position 4 in Fig. 2);
Cooling of scrubber acid (8–11% H_2SiF_6) (Position 5 in Fig. 1);
Evaporation of a phosphoric acid (Position 6 on Fig. 2);
Cooling the water which irrigates barometric condensers in the evaporating station (Position 7 in Fig. 2).

The content and temperature conditions of streams, the types of heat exchangers that can be used and heat transfer surface materials are presented in Table 1. The materials for the gaskets for PHEs are also presented in Table 1. The pressures of all streams are under 10 bar, which is much lower than the upper limit for this type of heat exchangers (usually 25 bar). This means that the pressure is not limiting PHEs application in this process.

For accurate calculations of heat exchange units with the different phases of the process, it is necessary to develop software based on modern algorithms for the design of PHEs.

3. Calculation of PHEs with channels of different geometries for use in phosphoric acid production

The following streams of the phosphoric acid production process require cooling or heating:

Heating of streams that contain 30% P_2O_5 from 20 °C to 40 °C;
Cooling of streams with 54% P_2O_5 from 85 °C to 55 °C;
Cooling of streams with 54% P_2O_5 from 55 °C to 25 °C.

Table 1
Requirements for heating and cooling in phosphoric acid production process.

Position, Figs. 1 and 2	Destination	Type of HE	Process stream			Material	Gaskets
				t_{in}, °C	t_{out}, °C		
1	Taking the heat off dilution	PHE	Cooling 98–78% H_2SO_4	80	30	Diabon F100, NS1 or NS2	EPDM
2	Weak phosphoric acid cooling	PHE	Cooling 3% P_2O_5	50	25	AISI 316L, 254 SMO	EPDM
3	Heating of 30% phosphoric acid prior to sulphate precipitating	PHE	30% P_2O_5	20	40	Hastelloy G30, Grafite	EPDM
4	Cooling of 40–42% or 50–54% (final product) phosphoric acid after evaporation	PHE	54% P_2O_5	85	55	AISI 316L, 904L, 254 SMO, Sanicro 28, C-276, G30	MS2000 (klingersil), PTFE
4	Cooling of 40–42% or 50–54% (final product) phosphoric acid after evaporation	PHE	54% P_2O_5	55	25	Hastelloy G30, Grafite	EPDM
5	Cooling of scrubber acid	PHE	H_2SiF_6, 8–11%	50	37	254 SMO and C-276	EPDM
6	Evaporation of phosphoric acid	Shell and tube	30–54% P_2O_5	85 °C	90 °C	Grafite	–
7	Cooling water of barometric condenser	PHE	Water	38	25	Hastelloy G30	EPDM

The important feature of stream heating or cooling is the high intensity of fouling on the heat transfer surfaces due to gypsum and fluoride precipitation from the solution. The intensity of fouling depends on the structure of the impurities of the product solution, the quantity and sizes of the particles, the flow velocities and the temperatures. In spite of these challenges, and severe operating conditions, PHEs of different types can be safely used in these process phases. The detailed study of calcium sulphate deposition from phosphoric acid solution in tubular heat exchangers was made by Jamialahmadi and Muller-Steinhagen [19]. They identified the key variables in deposition rates of fouling to be: a) the concentration of the fouling substances, b) the surface temperatures, c) the flow velocities. In the first effect evaporators, the range of temperatures was from 83 °C to 97 °C and the predominant fouling mechanism is calcium sulphate dehydrate formation. Jamialahmadi and Muller-Shteinhagen [19] noticed significant increase of fouling thermal resistance with temperature and fouling substance concentration, as well as inverse influence of flow velocity. This is the reason why in this paper PHEs are not considered for the first effect evaporators.

At lower temperatures (see Table 1) and cleaner acid solutions PHEs can be used to benefit from their lower susceptibility to fouling (see e.g. Hesselgreaves [14], Wang et al. [15], Kukulka and Devgun [20]). The accounting for fouling in PHE design was discussed by Gogenko et al. [21].

The presence of different impurities substantially influences the choice of heat transfer material. It should be selected depending on acid concentration, temperature range and presence of chlorine, iron and other impurities. It can be recommended the use of Hastelloy G30 or graphite for 50% P_2O_5 at temperatures lower than 85 °C and in the presence of 1% of HF, Fe_2O_3, Al_2O_3, 4% of H_2SO_4 and 600 ppm HCl. The synthetic rubber EPDM can be used as the gasket material. The alloys of AISI 316L, 904L, 254 SMO, Sanicro 28, C-276, G30 are also used as heat transfer surface materials for PHEs, depending on the specific conditions, see Table 2.

The cooling of the end product of 54% P_2O_5 concentration by a phosphoric acid of 30% P_2O_5 was considered for calculation of PHEs with different plate geometries. The cooling is usually done in two stages. The concentrated acid is cooled from 85 °C to 55 °C and the lower concentrated (30%) acid is heated from 20 °C to 40 °C. The composition of phosphoric acid aqueous solution in both streams is presented in Table 3. Thermo physical properties for phosphoric acid of different concentrations at various temperatures are derived from literature data. Intermediate values were calculated by means of linear interpolation of adjacent values.

Software has been developed within the EC ECOPHOS project (Seferlis et al. [1,2]) on the basis of a PHE mathematical model. The heat exchanger effectiveness and the number of heat transfer units (ε-NTU) approach are employed to design the liquid–liquid PHE with multiple pass arrangements and mixed grouping of plates with different corrugation geometries in one pass (see Tovazshnyansky et al. [17,24]). The coefficients of correlations for estimation of film heat transfer coefficient and hydraulic resistance are used as model parameters. These parameters are identified with the numerical experiment technique, by comparing results of model solutions to those obtained for the same heat exchanger and its performance by the PHE producer Alfa Laval. After identification of mentioned parameters, the discrepancies of results on the PHE heat transfer surface area and plate arrangements with those of Alfa Laval did not exceed two plates. This permits one to use software for multi-variant calculations in calculating the optimal solution for heat exchanger networks or for separate heat exchanger for specific process. However the final calculations on ordering the PHEs should be made by its exchanger producer.

Data for calculation of the first stage are presented in Table 4. Further, there is a cooling of the concentrated phosphoric acid from 55 °C to 25 °C while the 30% acid is heated 20 °C to 40 °C. The physical properties of the streams of the 54% and the 30% acid for their respective temperature ranges are presented in Table 5. Data for calculation of the second stage heat exchanger are presented in Table 6.

For corrosive media such as phosphoric acid, the Hastelloy G30 alloy is used as the heat exchanger plate material (see Table 2). The minimal thickness of the plates from the Hastelloy G30 is 0.6 mm. In conjunction with this, it is necessary to use synthetic rubber EPDM as the material for the gaskets. The direction of flow of heat carriers is counter-current. The calculations were made, accounting a 10% margin for heat transfer coefficient.

It is possible to install M10B units with the diameter of connections 100 mm on both stages, as biggest velocity in connections equal to 1.438 m/s and not exceed permissible limit 5 m/s. Results of calculations for the first stage with various combinations of plates in the unit are presented in Table 7. From the comparison of the table rows, the use of plates with different geometries of corrugation in one heat exchanger allows to reduce the heat transfer surface area in comparison with the use of only one plate type in the heat exchanger. The plates have corrugations with different angles to the vertical axis and to the main flow direction. Plates of H type have corrugations with bigger angles (about 60°) that form the H channels with higher efficiency of heat transfer and higher hydraulic resistance. Plates of L type have a lower angle (about 30°) and form the L channels with lower heat transfer and hydraulic resistance. Combined, these plates form channels MH or ML with intermediate characteristics (see Fig. 3).

Table 2
Composition of alloys for heat transfer surface manufacturing.

Alloy	Metals, %				
	Cr	Nickel	Mo	Cu	Others
AISI 316	17.0	12.0	2.0	–	–
Avesta 254 SMO	20.0	18.0	6.1	1.7	N 0, 2
Alloy C276	15.5	58.0	16.0	–	W
Hastelloy C22	21.0	44.0	17.5	–	W 3, Fe 2–6
Hastelloy G30	29.5	40.0	5.0	1.7	W 2,5, Fe 18–21
Hastelloy D205	20.0	64.5	2.5	2.0	Si 5, Fe 6

Table 3
Composition of aqueous phosphoric acid solutions.

Main elements, %	30% P_2O_5	54% P_2O_5
P_2O_5	29.8	53.0
H_2SO_4	1.9	2.0
SO_3	1.6	2.5
Fe_2O_3	0.15	0.24
F	0.9	0.4
SiO_2	0.3	0.03
Cl, ppm	755	165

Table 4
Data for calculation of the first stage heat exchanger.

Heat load	$Q = 866.8$ kW	
Stream	Hot	Cold
Medium	Phosphoric acid (54% P_2O_5)	Phosphoric acid (30% P_2O_5)
Working pressure, MPa	0.5	0.5
Flow rate, kg/h	40,000	48,000
Inlet temperature, °C	85	20
Outlet temperature, °C	55	39.93
Pressure drop, MPa	≤0.1	≤0.1

Table 5
Physical properties of 30 and 54% phosphoric acid.

Medium 1 (hot): physical properties for three temperatures – phosphoric acid 54% P_2O_5			
Temperature, °C	85	70	55
Density, kg/m^3	1335	1346	1357
Specific heat, kJ/(kg °C)	2.569	2.605	2.612
Heat conductivity, W/(m °C)	0.546	0.534	0.520
Dynamic viscosity, centipoises	1.122	1.729	2.753
Medium 2 (cold): physical properties for three temperatures – phosphoric acid 30% P_2O_5			
Temperature, °C	20	30	40
Density, kg/m^3	1181	1176	1171
Specific heat, kJ/(kg °C)	3.237	3.262	3.284
Heat conductivity, W/(m °C)	0.533	0.547	0.560
Dynamic viscosity, centipoises	2.996	2.310	1.738

From results presented in Table 7, it can be recommended to install one pass unit (6.48 m^2, 27 plates, grouping 1 * (9MH + 4L)/1 * (9ML + 4L)) for cooling down the concentrated phosphoric acid at the first stage.

Results of calculations for the second stage with various combinations of plates in one unit are presented in Table 8. Advantages of using the various plate types in one unit on the second stage are seen even more clearly, in spite of the fact that two-pass heat exchangers are needed due to operating conditions. From the results of calculations, it is possible to recommend installation of the two-pass units with an area of 50.16 m^2 (209 plates) and channel arrangement of 2 * (49H + 3MH)/2 * (49H + 3ML).

The analysis of data shows that the use of mixed grouping of plates in one heat exchanger (type H/MH–H/ML and MH/L–ML/L) allows satisfying the heat exchange requirements fully. Thus, the number of plates (the heat transfer area) is minimal and the condition of pressure drop on one of the streams is completely satisfied.

To obtain an optimal solution in this work, the concept of PHE design with fixed allowable pressure drop (in the sense defined by Wang and Sunden [22]) is used. With this approach, the objective function is the heat transfer surface area, which for PHE corresponds to the minimal capital cost; which is mostly due to the fact that the PHE is in contact of with aggressive media and should be manufactured from expensive alloys. The principle of combining two plates with different corrugation geometries, introduced over three decades ago (see Marriott [23]), provides a new dimension to PHE design. In effect, by selecting proper proportion of H and L plates, it allows changing the thermal and hydraulic characteristics of the plate pack with the level of discreteness equal to one plate in a pack. This makes the mathematical problem for designing the PHEs essentially a continuous process that can be solved using the continuous algebraic equations derived from the mathematical model of heat exchangers (see Tovazshnyansky et al. [24], Wang and Sunden [22]), and softening the objection to this specified by Polley [25]. The advantages of this technique are obvious for heat exchanger network optimization, where it allows to obtain continuous mathematical model of the system and to optimize pressure drop at the target stage (as it is described in paper [22]).

Table 6
Data for calculation of the second stage heat exchanger.

Heat load	Q = 861.2 kW	
Stream	Hot	Cold
Medium	Phosphoric acid (54% P_2O_5)	Phosphoric acid (30% P_2O_5)
Working pressure, MPa	0.5	0.5
Flow rate, kg/h	40,000	48,000
Inlet temperature, °C	55	20
Outlet temperature, °C	25	39.81
Pressure drop, MPa	≤0.05	≤0.05

Table 7
Results of calculations for heat exchangers with different plate type combinations for the first stage.

Type of plates	Arrangement of channels	Number of plates	Area, m^2	Pressure drop (hot side), kPa	Pressure drop (cold side), kPa
H–L	1 × (9MH + 4L)/1 × (9ML + 4L)	27	6.48	65.93	98.45
H–L	1 × 13MH/1 × 14ML	28	6.72	79.5	98.91
H–H	1 × 24H/1 × 25H	50	12.00	61.96	93.22
L–L	1 × 20L/1 × 21L	42	10.08	21.6	31.42

Application of the algorithm for calculation of mixed grouping PHEs makes it possible to achieve the following advantages:

To intensify the process of heat transfer and to reduce the heat transfer area;
To select one pass units;
To completely utilize the available pressure drop;
To eliminate unproductive pressure losses in comparison with multi-pass heat exchangers.

4. Improvement of the barometric condenser unit with circulation system implementation

In operating evaporation plants the secondary steam should be condensed to create a vacuum in the evaporation units. With that steam the fluorine is released (see Kopylev [26]), which can be partly recovered as a commercial by-product (fluosilicic acid 20–25%), but its reminder passes to the condenser. It is producing liquid effluent that contains mainly fluoride and a small amount of phosphoric acid (see Ref. [4]). These substances can cause severe damage when discharged to the environment. To avoid this, it is possible: a) as recommended by EFMA [4] to arrange closed loop water system with barometric mixing condenser or b) to use surface condensers. Let us examine both options for the case of evaporation unit with production capacity 120 tons of 54% P_2O_5 per day.

Fig. 4 demonstrates the basic flowsheet of barometric condenser with recycled water circulation. In summer, the water inlet temperature in the mixing condenser is about 25 °C and the outlet temperature is 38 °C. Plate heat exchangers of Alfa Laval were calculated for the location of recycled water cooling. Plates are made from alloy Hastelloy G30 with a thickness of 0.6 mm and gaskets made from EPDM synthetic rubber. The calculation was done accounting for a 20% margin for possible plates' heat transfer surface fouling during process operation. The value of shear stress on the plate's wall was controlled at not less than 50 kPa. This ensures stable operation of the heat exchanger between the scheduled maintenances [17]. Data of the calculations are listed in Table 9.

Fig. 3. Channels formed by combining plates of different geometries.

Table 8
The results of calculation of heat exchangers with various plate combinations for the second stage.

Plate combination	Arrangement of channels	Number of plates	Area, m^2	Pressure drop hot side, kPa	Pressure drop cold side, kPa
H–L	$2 \times (49H + 3MH)/2 \times (49H + 3ML)$	209	50.16	34.5	48.33
H–L	$3 \times 41MH/(2 \times 41ML + 1 \times 42ML)$	248	59.52	37.45	46.84
H–H	$2 \times 53H/(1 \times 53H + 1 \times 54H)$	214	51.36	35.25	49.27
L–L	$(1 \times 38L + 3 \times 39L)/4 \times 39L$	312	74.88	40.44	49.29

Three unit types were obtained from the design process (two of them are couples assembled in parallel):

a) Traditional plate-and-frame PHEs;
b) Spiral heat exchangers;
c) Wide gap PHEs (with the wider channel on the side of the cooled, recycled water of barometric condenser).

Table 10 shows the results of calculations for the main parameters.

Analysis of data from Table 10 gives the following conclusions. The installation of one M30M unit or of two T20M heat exchangers in parallel is most suitable. Although the installation of two units is more expensive, it provides reserve capacity. It allows for increasing the cold heat carrier flow rate, to clean one unit without stopping the other one or to work with one unit at decreased capacity under emergency operation conditions.

It is possible to install M15M units, but they are two-pass heat exchangers, which have a strong tendency for plate's fouling and cleaning them is a more difficult process because both frame plate and pressure plate have connections. It requires dismounting of piping on moving frame plate when disassembling PHE for mechanical cleaning. The same can be said about three-pass wide gap heat exchanger WG200, which also has much bigger heat transfer surface area and is about twice more expensive than M30M. Although use of SHE 1H-L-1T spiral heat exchanger provides stable operation with minimal heat transfer surface fouling, this type of unit has a considerable heat transfer surface and, consequently, very high price (about 4 times more expensive than wide gap heat exchanger and 8 times more expensive than traditional units).

The increase of cooling water temperature can occur during operation in the summer time; therefore, it is essential to take into account such situations during the design stage. It is possible to provide heat exchanger capacities at the design stage in two ways. Firstly, to provide for cooling water flow rate increasing across the heat exchanger, and secondly, to design the unit with possible closest temperature approach. In this case the cooling water inlet temperature should be defined as near as possible to outlet temperature of the barometric condenser, which equals 25 °C according to design conditions (Table 9). The decreasing of the temperature approach leads to increasing of heat transfer surface area of the unit. Eventually, the heat transfer surface increases so that such heat exchanger design becomes unreasonable in terms of cost and technical aspects. Fig. 5 shows the dependence of the total heat transfer surface area F_{all} of M30M heat exchanger from cooling water inlet temperature t_{inlet}, when other calculation parameters are constant (see Table 9) and margin is equal to zero. When the cooling water inlet temperature is equal to 21 °C, then the total heat exchanger surface area must exceed 200 m^2. The further approach of t_{inlet} to 25 °C leads to sharp increase of the heat transfer surface area. Fig. 6 shows the change of cooling water outlet temperature t_{out}, barometric condenser water outlet temperature t_{outlet} and heat transfer coefficient K dependence from the value of external circuit cooling water inlet temperature.

Increasing the cooling water flow rate across the heat exchanger causes significant difficulties. First of all, phosphoric acid production enterprises are mostly located in regions with water supply deficits, especially in summer. Secondly, increasing the flow rate requires installing heat exchangers with headers and connections for high input. Taking this into account the selection of M30M heat exchanger or two T20M units in parallel is the right choice. But one M30M unit costs less. Thirdly, whichever heat exchanger is installed, if cooling water temperature exceeds 24 °C, then the requirement of cooling the barometric condenser water to the temperature of 25 °C cannot be satisfied.

The current trend for chemical production plants is to replace mixing condensers by surface condensers, and especially by plate units [5]. It relates first of all to the following positive aspects of such replacements:

Installation of plate condensers provides a faster response to changes in the barometric condenser system; one may also compare this system with shell and tube heat exchangers (for the

Table 9
The initial data for design of heat exchangers for cooling of recycled water of barometric mixing condensers.

Flow	Duty parameters				
	t_{inlet}, °C	t_{outlet}, °C	Flowrate, m^3/h	Pressure drop, kPa	Margin, %
Barometric condenser water	38	25	368	150	20
Cooling water	20	30	475	150	20

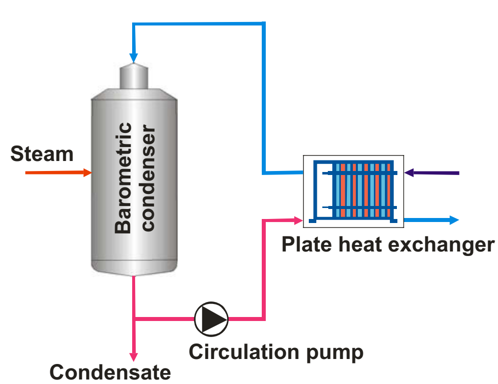

Fig. 4. The barometric condenser unit with water cooled in external heat exchanger.

Table 10
Data for heat exchangers designed for barometric mixing condenser recycled water cooling (Fig. 4), when water is the cooling medium.

Type of PHE	Number of units	Channel arrangement for one PHE type or or spiral unit	Total surface area, m^2	Pressure drop, kPa		Margin, %
				Hot side	Cold side	
M15M	2	$2 \times (37MH + 7L)/2 \times (37ML + 7L)$	215.4	92	145	21
T20M	1	$1 \times 135H/1 \times 135H$	230.4	55.5	92.4	20
T20M	2	$1 \times 68H/1 \times 68H$	234.6	50.5	81.8	20
M30M	1	$1 \times (32H + 24ML)/1 \times (32H + 24MH)$	204.2	86.9	146	20
WG200	2	$3 \times 14SH + 4 \times 15SH/1 \times 33NH + 2 \times 34NH$	322.4	149	79	21
SHE	2	1H-L-1T	572.6	137	143.6	20

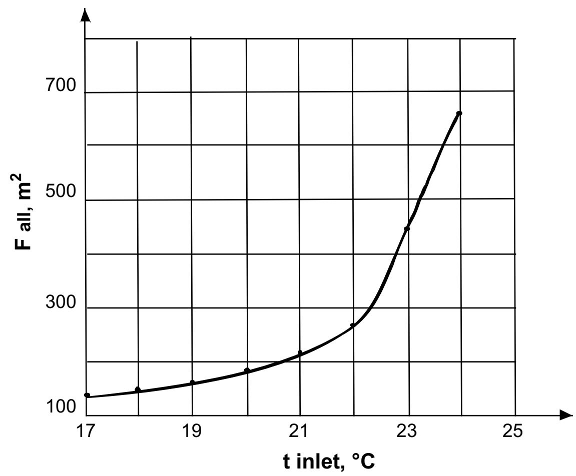

Fig. 5. Dependence of total heat transfer surface area from the cooling water inlet temperature.

comparison of PHE and shell and tube heat exchanger's dynamic behavior in fouling conditions see Georgiadis and Macchietto [27]).

Save fresh water;
Compactness of the unit, ease of maintenance and operation.

The disadvantages are that the plates will accumulate surface fouling during operation, removal of non-condensing gases and the requirement to provide low pressure drop in units operating at a vacuum.

The calculations of surface condenser are made for the same evaporation unit capacity and cooling water parameters as for the mixing barometric condenser (see Table 9). The steam pressure is 9.7 kPa, temperature 45 °C and flow rate 6314 kg/h. Special condenser AlfaCond 600 with a steam connection diameter 600 mm, for high steam throughput, has total surface area 72.8 m^2 and one pass channel arrangement 1 * 51SW/1 * 52NG. Pressure drop of steam is equal to 2.8 kPa and that of cooling water is 37.2 kPa. The plates from Hastelloy G-30 are welded in pairs on the steam side for more reliable operation under a vacuum.

The comparison with the case (a) of closed loop barometric mixing condenser shows significant reduction (up to 3 times) of heat transfer surface area. These advantages of surface condensers

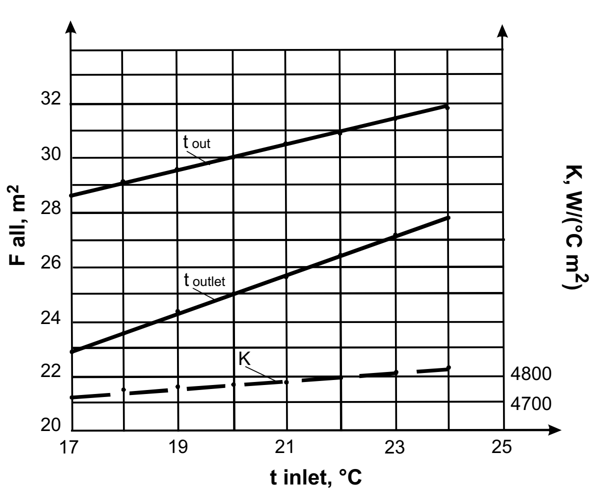

Fig. 6. Dependence of cooling water temperature t_{out}, barometric condenser water outlet temperature t_{outlet} and heat transfer coefficient K from the value of the inlet temperature of the external circuit cooling water.

application make this option preferable in both grass root and retrofit projects for evaporation units in phosphoric acid production.

5. Software for PHEs calculation

To design PHEs for working under different conditions in phosphoric acid production processes, software was developed which enables one to calculate the heat transfer area, the number of plates and arrangement of channels and to select an optimal heat exchanger for the specified duty. The software enables one to calculate heat exchangers working with different conditions of the streams, namely:

Liquid–liquid;
Steam/liquid–liquid (condensation);
Steam/liquid–liquid/steam (condensation–boiling).

The calculation algorithms were developed on the basis of research results for heat and mass transfer in PHE channels reported earlier in papers by Tovazshnyansky et al. [28–30], with the use of coefficients in correlation with heat transfer and with hydraulic resistance obtained for single phase flow in the same inter plate channel, as described earlier in this paper.

The main feature of the processes with phase change, like condensation and boiling, is considerable variation of the process parameters, velocity of the stream and vapour content and others, along the channel length, which was accounted for by using a one dimensional mathematical model of combined heat and mass transfer.

6. Conclusions

The PHEs application and their placement in the phosphoric acid production process are analysed in this paper. The highly corrosive activity of the heat exchanging process streams requires the use of highly corrosion resistant materials for heat transfer surface manufacturing. The cost of such materials makes it complicated to implement economically energy-saving methodologies including advanced pinch analysis and process integration. The use of PHEs, requiring much less material for their production than conventional shell and tube units makes such solutions economically sound. It is possible to increase heat recuperation and to save up to 25–30% of energy consumed in the process of phosphoric acid production.

The possible choice of alloys for manufacturing of the plates is presented. To minimize the surface area of PHEs, reliable methods and algorithms for their design were developed. It is shown that one of the possibilities to minimize the heat transfer area is to use the principle of combining the plates with different geometries of corrugations on the heat transfer surfaces in one heat exchanger.

The current trend is to replace mixing condensers with surface condensers and especially with plate units. The simulation was carried out for the unit of recycled barometric mixing condenser water cooling with plate heat exchangers. It clearly shows the possibility of the application of surface condensers instead of mixing condensers. Proposed engineering solutions are suitable for phosphoric acid concentration stages for different processes of production.

For reliable calculations for cases of phase changes in plate heat exchanger channels (condensation or boiling) it is necessary to take into account the changes of all process parameters along the channel length. Software has been developed accounting for all the features of plate heat exchanger design for enabling accurate calculations of heat transfer area for the heat exchangers, the number and grouping of plates. It facilitates the use of PHEs in phosphoric acid production to increase energy and material savings and to make the production environmentally cleaner.

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