The Use of Plate Heat Exchangers for Energy Saving in Phosphoric Acid Production

Petro Kapustenko, Stanislav Boldyryev, Olga Arsenyeva, Gennadiy Khavin
AO "Sodrugestvo–T", Krasnoznamenniy per. 2, k. 19, Kharkiv 61002, Ukraine; Tel.: +380577202278 e-mail: kap@kpi.kharkov.ua

Abstract

The principles, algorithms and software for energy saving retrofit of phosphoric acid production process are discussed. The essential feature is replacement of tubular heat exchangers with plate ones and installation of units on the new placements to increase heat recovery. The main problem in product behavior during heating or cooling is high intensity of heat transfer surface fouling due to precipitation of gypsum and fluorides from a solution. Intensity of fouling, besides other factors, such as heat exchanger type, its design and parameters of work, in many ways depends on content and structure of impurities in a solution of a product, quantity and the sizes of particles. Despite of the specified difficulties and heavy operation conditions, plate heat exchangers of a various design find the application in these processes.

For such corrosively active environment as a phosphoric acid the Hastelloy G30 alloy is used as a material of plates. The minimal thickness of plates from Hastelloy G30 is 0.6 mm. It is necessary to apply synthetic rubber EPDMCT as a material for inter plate gaskets for work with a phosphoric acid. The direction of flow of heat-carriers is counter-current. Calculations were made in view of a 10% margin. It is possible to install M10-BFM units with diameter of collectors 100 mm. The analysis of data shows, that using mixed grouping of plates in the unit allows to satisfy heat exchange requirements fully. Thus, the number of plates (the heat transfer area) is minimal and the condition of pressure drops on heating and heated up heat-carriers is completely satisfied.

The software was developed for calculations of units working both with liquid, and with gaseous streams: liquid – liquid; steam/liquid – liquid (condensation); steam/liquid – liquid/steam (condensation – boiling).

1. Introduction

The main aim of this research is development of principles, algorithms and software for energy saving retrofit of phosphoric acid production process. The essential feature of work is replacement of the old equipment of factories with more effective new one. In particular, the replacement of tubular heat exchangers with plate ones and installation of units on the new positions which allow to increase heat recovery.

The chemistry of phosphoric acid production from apatite concentrate by wet method is sufficiently developed and rather well described in literature (see e.g. Evenchik et al. [1]). The typical process flowsheet of phosphoric acid production by dehydrate method is presented on Figure 1. This process enables to obtain weak acid with concentration 26-32% of P_2O_5 and should be followed by evaporation unit to obtain acid with higher P_2O_5 concentration (see Figure 2).

The plate heat exchangers are one of the most efficient types of heat transfer equipment. The principles of their construction and design methods are sufficiently well described elsewhere (see e.g. the books by Hesselgreaves [2], Shah and Seculic[3], Tovazshnyansky et al [4]). This equipment is much more compact and require much less material for heat transfer surface production than conventional shell and tubes units. It makes feasible and economically efficient to produce plates from expensive sophisticated alloys and metals, which can work with highly corrosive substances, such as most of the process streams in phosphoric acid production.

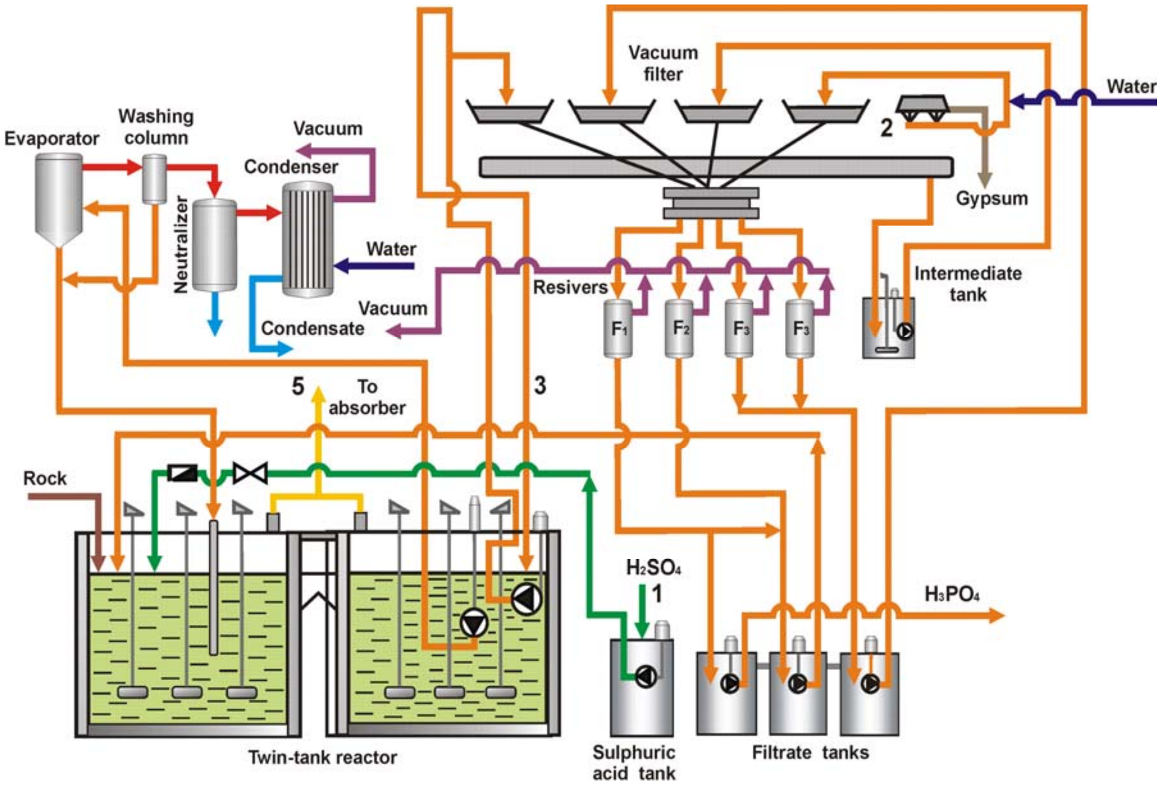

Figure 1. The typical process flowsheet of phosphoric acid production by dehydrate method

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

The main placements for application of heat exchangers in manufacturing of phosphoric acid, proceeding from presented process flowsheet, are:

- Cooling of sulfuric acid solution 78 - 98% H_2SO_4 – plate heat exchanger (position 1 on Figure 1);
- Cooling of weakly concentrated phosphoric acid (3%) after washing of the filter sediments – plate heat exchanger (position 2 on Figure 1);
- Heating of 30 % phosphoric acid before sulfate sedimentation – spiral or plate heat exchanger (position 3 on Figure 1);
- Cooling of phosphoric acid (final product) with 40 – 42% or 50 – 54% P_2O_5 concentration after evaporation – plate or spiral heat exchanger (position 4 on Figure 2);
- Cooling of scrubber acid (8 – 11% H_2SiF_6) (position 5 on Figure 1);
- Evaporation of a phosphoric acid (position 6 on Figure 2);

- Cooling the water, which irrigates barometric condensers on an evaporating station (position 7 on Figure 2).

For calculation of heat exchanging units on these positions under the set conditions of operation it is necessary to develop software based on modern algorithms for design of plate heat exchangers.

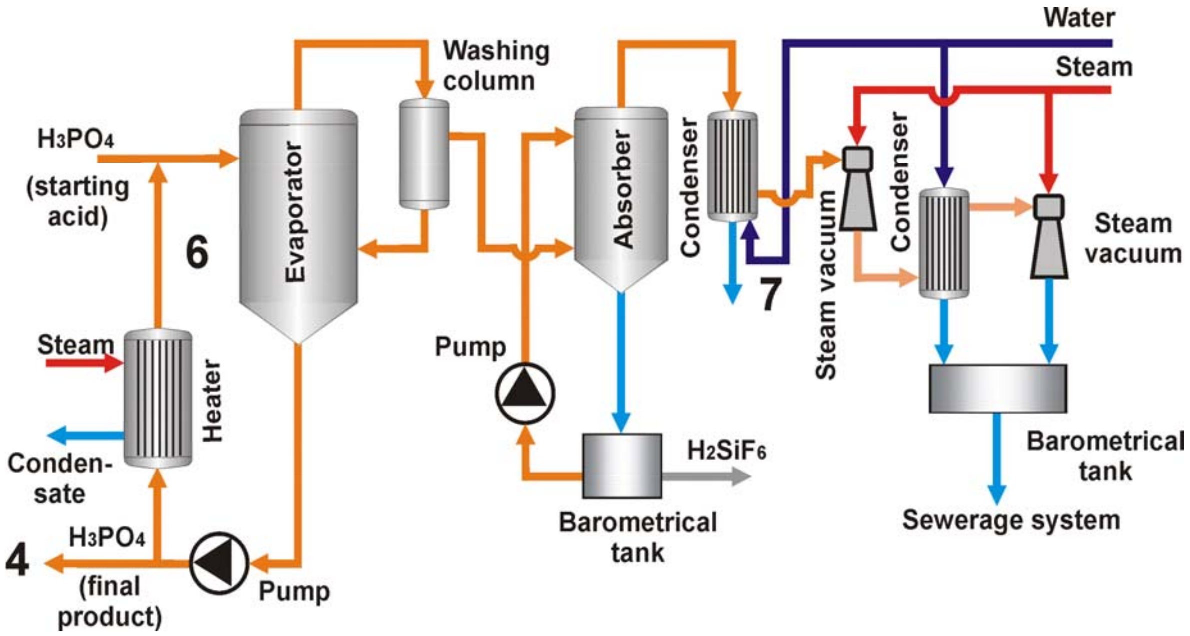

Figure 2. Flowsheet of concentration unit

3. Calculation of plate heat exchangers with channels of different geometry in wet process of phosphoric acid production

It is possible to identify following processes of cooling and heating of streams with various concentration of phosphoric acid:

- Heating of stream which contains 30% P_2O_5 from 20ºC up to 40ºC;
- Cooling of stream with 54% P_2O_5 from 85ºC to 55ºC;
- Cooling of stream with 54% P_2O_5 from 55ºC to 25ºC.

The important feature of stream heating or cooling is high intensity of fouling on heat transfer surfaces due to gypsum and fluorides precipitation from a solution. Intensity of fouling, besides such factors, as heat exchanger type, its design and parameters of work on a rated duty, in many ways depends on structure of impurity in a solution of a product, quantity and the sizes of particles. Despite of the specified difficulties and heavy operation conditions, plate heat exchangers of a various design find the application on these positions. The accounting of fouling was discussed by Gogenko et al. [5].

There are different types of units that can be used for heating or cooling of the concentrated phosphoric acid: plate-and-frame heat exchangers and spiral ones. The choice is determined by the structure and quantity of gypsum in a product. Besides, presence of other impurities substantially influences the choice of heat transfer area material. It should be selected depending on acid concentration, temperature range and presence of chlorine, iron and other impurities. It is recommended by Alfa-Laval the use of Hastelloy G30 or graphite for concentration 50% P_2O_5 at temperature lower than 85 °C and in presence of $1\% HF, Fe_2O_3, Al_2O_{3,} 4\% H_2SO_4, 600\ ppm\, HCl$. The synthetic rubber EPDM can be used as gaskets material.

The alloys AISI 316L, 904L, 254 SMO, Sanicro 28, C-276, G30 are also used as a heat transfer surface material of spiral heat exchangers depending on specific conditions, see table 1.

Table 1. 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

Cooling of phosphoric acid with concentration about 3% P_2O_5 by water after washing the filter deposit should be made from 50°C down to 25-30°C and it require heating of water from 20°C up to 30-35°C. For such conditions the plate heat exchanger with plates from AISI 316 or SMO alloy and gaskets from synthetic rubber EPDM can be selected. The margin of 10% should be accepted in the design to account for possibility of fouling and recommendation to maintain wall shear stress not less than 50 Pa must be followed.

The cooling of a finished product of 54 % P_2O_5 concentration by a phosphoric acid of 30 % P_2O_5 was considered for calculation of plate heat exchangers with different plates geometry. The cooling is usually made in two stages. At first the concentrated acid is cooled from temperature 85°C down to 55°C and the diluted acid with concentration of 30% heats up from temperature 20°C up to 40°C. The content of components in both streams is presented in table 2.

Thermo physical properties for phosphoric acid of different concentrations at various temperatures has been taken from literature data and approximated. Intermediate values were calculated by means of linear interpolation of adjacent values.

Data for calculation of the first stage are presented in table 3. Further there is a cooling of the concentrated phosphoric acid from temperature 55°C up to 25°C at the second stage, thus the diluted acid with concentration of 30 % heats up from temperature 20°C up to 40°C. Physical properties of streams for 54 % and 30 % concentration for a considered temperature range are presented in table 4. Data for calculation of the second stage heat exchanger are presented in table 5.

Table 2 – Composition of phosphoric acid aqueous 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 3 - Data for calculation of the first stage heat exchanger

Heat load	Q = 866.8 kW	
Flow	Cooling	Heating
Medium	Phosphoric acid (54% P_2O_5)	Phosphoric acid (30% P_2O_5)
Working pressure, MPa	$P_1 = 0.5$	$P_2 = 0.5$
Flow rate, kg/h	$G_1 = 40\,000$	$G_2 = 40\,000 - 60\,000$
Inlet temperature, °C	$T_1 = 85$	$T_3 = 20$
Outlet temperature, °C	$T_2 = 55$	$T_4 <= 40$
Pressure drop, MPa	$\Delta P_1 \leq 0.1$	$\Delta P_2 \leq 0.1$

Table 4 - Physical properties of phosphoric acid for 54 % and 30 % concentration

Medium 1 (cooling): physical properties for three temperatures – phosphoric acid 54% P_2O_5			
Temperature, ^0C	$T_1 = 85$	$T_2 = 70$	$T_3 = 55$
Density, kg/m^3	1335	1346	1357
Specific heat, кJ/(kg·^{0}K)	2.659	2.639	2.612
Heat conductivity, W/(м^{0}C)	0.546	0.535	0.520
Dynamic viscosity , centipoises	1.122	1.506	2.753
Medium 2 (heating): physical properties for three temperatures - phosphoric acid 30% P_2O_5			
Temperature, ^0C	$T_1 = 20$	$T_2 = 30$	$T_3 = 40$
Density, kg/m^3	1181	1176	1171
Specific heat, кJ/(kg·^{0}K)	3.237	3.262	3.284
Heat conductivity, W/(м·^{0}C)	0.533	0.47	0.560
Dynamic viscosity, centipoises	2.996	2.310	1.738

Table 5 - Data for calculation of the second stage heat exchanger

Heat load	Q = 861.2 kW	
Flow	Cooling	Heating
Medium	Phosphoric acid (54% P_2O_5)	Phosphoric acid (30% P_2O_5)
Working pressure, MPa	$P_1 = 0.5$	$P_2 = 0.5$
Flow rate, kg/h	$G_1 = 40\,000$	$G_2 = 40\,000\text{-}60\,000$
Inlet temperature, °C	$T_1 = 55$	$T_3 = 20$
Outlet temperature, °C	$T_2 = 25$	$T_4 <= 40$
Pressure drop, MPa	$\Delta P_1 \leq 0.05$	$\Delta P_2 \leq 0.05$

For such corrosively active media as a phosphoric acid the Hastelloy G30 alloy is used as a plate material. Its main feature is the highest content of nickel and chrome, high enough presence molybdenum. The minimal thickness of plates from Hastelloy G30 is 0.6 mm. It is necessary to apply synthetic rubber EPDMCT as a material for plate gaskets. The direction of flow of heat carriers is counter-current. Calculations were made in view of a 10% margin on a heat transfer coefficient.

It is possible to install M10-BFM units with diameter of collectors 100 mm on both stages. Results of calculations for the first stage with various combinations of plates in the unit are presented in table 6. As one can see the use of plates with different geometry of corrugation in one heat exchanger allows the reduction of heat transfer surface area in comparison with of only one plate type in a heat exchanger. The plates have corrugations with different angle to vertical axis and to main flow direction. Plates of H type have corrugations with bigger angle (about 60^0) and form the channels H with higher intensity of heat transfer and hydraulic resistance. Plates of L type have lower angle (about 30^0) and form the channels L with lower heat transfer and hydraulic resistance. Combined together these plates form channels MH or ML with intermediate characteristics (see Figure 3).

From results presented in Table 6 it can be recommended to install one pass unit (8.4 м^2, 37 plates, grouping 1*(5*MH+13*L) / 1*(15*ML+13*L)) for cooling of the concentrated phosphoric acid at the first stage.

Channel L formed by L-plates | Channel ML-MH formed by L- and H- plates | Channel L formed by H-plates

Figure 3. Channels formed by combining plates of different geometry

Table 6 - Results of calculation for heat exchangers with different plate types combinations for the first stage

Plate combina-tion	Grouping	Number of plates	Area, m^2	Pressure drop (hot side), kPa	Pressure drop (cold side), kPa
MH/L–ML/L	1×(3MH+9L)/1× (3ML+9L)	25	6.0	61.3	85.8
MH - ML	1×15MH/1×15ML	31	7.44	61.8	87.1
H - H	1×25H/1×25H	51	12.24	59.1	95.0
L - L	1×15L/1×15L	31	7.44	36.0	58.3

Results of calculations for the second stage with various combinations of plates in one unit are presented in table 7. 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-passes heat exchanger is needed due to operating conditions. From the presented results of calculations it is possible to recommend for installation two-passes unit with the area 50.8 м^2 (213 plates) and grouping 2*(42*H+11*MH)/2*(42*H+11*ML).

Table 7 - Results of calculation of heat exchangers with various plates combinations for the second stage

Plate combina-tion	Grouping	Plates number	Area, m^2	Pressure drop (hot side), kPa	Pressure drop (cold side), kPa
H/MH–H/ML	2×(24H+18MH)/2×(24H+18ML)	169	40.56	33.5	47.7
MH - ML	3×39MH/3×39ML	235	56.4	37.3	48.2
H - H	2×52H/2×52H	209	50.16	34.2	49.0

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 to satisfy heat exchange requirements fully. Thus, the number of plates (the heat transfer area) is minimal and the condition of pressure drops on one of streams is completely satisfied.

The application of algorithm for calculation of mixed grouping plate heat exchangers allows to implement following advantages:

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

4. Software for plate heat exchangers calculation

To design plate heat exchangers working at different conditions at phosphoric acid production processes the software was developed which enables to calculate heat transfer area, the number and grouping of the plates and to select an optimal heat exchanger for the specified duty. The software permits 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 basis for calculation algorithms development was described earlier in papers by Tovazshnyansky et al. [6], [7], [8]. 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 vapor content and others, along the channels length, which was accounted using one dimensional mathematical model of combined heat and mass transfer. The software was developed at AO Sodrugestvo-T and is used for calculation of plate heat exchangers which are produced by this company in Ukraine from plates supplied by Alfa-Laval.

5. Conclusions

In this paper the possibilities of plate heat exchangers application and their placement in phosphoric acid production process are discussed. The high corrosive activity of heat exchanging streams requires the use of highly corrosion resistant materials for plates manufacturing. The possible choice of alloys is presented.

To minimize the surface area of plate heat exchangers the reliable methods and algorithms for their design are needed. It is shown that one of the possibilities to minimize heat transfer area is the principle of combination in one heat exchanger of plates with different geometry of corrugations on their heat transfer surface.

In case of phase change in plate heat exchanger channels (condensation or boiling) for reliable calculations it is necessary to take into account the change of all process parameters along the channel length. The software which accounting all mentoned features of plate heat exchanger design and enables accurate calculation of heat transfer area for heat exchanger, the number and grouping of plates, has been developed. It facilitate the use of plate heat exchangers in phosphoric acid production to increase energy and material saving potential.

Acknowledgments

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