ІННОВАЦІЙНЕ ОБЛАДНАННЯ ХАРЧОВИХ ВИРОБНИЦТВ

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THE DETERMINATON OF ENERGY SOURCE OPTIMAL PARAMETERS FOR VACUUM EVAPORATION
ВИЗНАЧЕННЯ ОПТИМАЛЬНИХ ПАРАМЕТРІВ ДЖЕРЕЛА ЕНЕРГІЇ ДЛЯ ВАКУУМ-ВИПАРЮВАННЯ

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There were suggested in the paper the right principle form of the Vacuum Evaporator (VE) optimal parameters determination. The problem studied on the example of the corresponding device for the food juices concentration by the vacuum conditions. It is especially important for the right comparison the VE traditional energy source using (steam from the special boiler or from the turbine) design and the VE with heat pump as energy source using too. There were working out the special method for different variants of VE optimization and using it for the grounded comparison. The VE for tomato juice concentration was used as the optimization object media. There was fulfilled a whole optimization calculations volume. The optimal steam temperature (it saturation pressure), including the summary expenditures value in the optimal temperature) was discovered from these results. It was presented in the paper the author approach and results obtained on it. Besides it, there were obtained the dependency of minimum expenditures on the inlet and outlet concentrations ratio. It was noted, the pointed value significantly decreased with the pointed ratio decreasing. It was concluded, that there are some conditions, when VE with Heat Pump can be considerable better. Besides it, the authors noted, that the Heat Pump using as the energy source for VE will be especially effective in the cases with limited temperature drop between heating and cooling temperatures.

У статті пропонується загальний принцип підходу до проблеми обґрунтованого вибору оптимальних параметрів для Вакуумної Випарної Установки (ВВУ). Завдання розглядається для конкретного випадку підвищення концентрації харчового розчину (томатного соку) у вакуумі для традиційного джерела енергії (тепло) від водяної пари, що подається або з котельної або з відбору парової турбіни. Авторами пропонується вважати, що підхід до обліку вкладу в загальну суму витрат енергії не повинен залежати від джерела виробництва пари, що гріє (котельна або відбір з парової турбіни). Таким чином, реалізується відповідна схема і алгоритм розрахунку і вибору оптимальних параметрів парогенератора. Такі дії, за уявленнями авторів, потрібні для обґрунтування вибору джерела тепла. Відомо, що порівняно з традиційним джерелом (водяна пара, що гріє) можливі і інші варіанти, зокрема використання теплових насосів. Нині, така альтернатива по вибору джерела тепла в апаратах харчової технології відома і розглядається як один з перспективних напрямів вирішення проблем енергозбереження. Кожен з вказаних напрямів має свої переваги і недоліки. На думку авторів, істотною перевагою в порівнянні з іншими мають схеми ВВУ з ТНУ (тепловими насосами), оскільки по останніх є досить представницька і надійна інформація за їх характеристиками і, що не менш важливе, для техніко-економічного порівняння по їх комплектації і вартості. У завершенні автори відмічають, що особливо перспективний перехід на схеми ВВУ з ТНУ при зниженні температурних перепадів між температурами пари, що гріє і температурою конденсації вторинної пари.

Keywords: vacuum evaporation, heat pump, power supply
Ключові слова: вакуум-випарювання, епловий насос, витрати енергії

There are known, that one of the very widely spread energy source for VE is the steam from the boiler or, sometimes it is possible from the vapor turbine extractions. The last case is more useful from the energy saving point of view, as soon as the pointed vapor flow fulfilled some useful work before to be taken for the heating the food solutions with goal their concentration. It is understandable, that than the pointed vapor flow pressure (temperature) lower, than the work already done before the extraction more, but the vapor generator heat transfer surface also increased too. It means that there exists the optimal steam temperature value from the economic point of view. The authors consider, that the pointed principle would be right to take as the key base for the vapor generator parameters choice; using the corresponding information about the specific energy units and materials and thermal equipment prices for formation as main optimal criteria value as the so called as Sum of Expenditures Values.(SEV). It was taken and there were made the next steps in the optimization problem statement and solution.

The VE design parameters determination, including their mass equipment values& prices and expenditures on the collection and their installation and service during every year. Besides it, the next important item definition inside (SEV) have to be done. It was connected with energy expenditures such as the price on the thermal power with respect of the expenditures on the fuel for the boiler work or for the expenditures on the thermal energy production at the power station with vapor turbines and etc. The energy expenditures were summarizes from the product flow initial (inlet) temperature to the boiling temperature, also for the vaporization with key goal to increase concentration soluble premixes from the inlet values to the outlet ones and adding the thermal power losses to the environment. The main design parameters were connected with vapor generator price, including also statement; service and so on. The separate task was connected with secondary vapor flow condenser price and the expenditures on the cooling water flow. It was taken into consideration that in the case there are existed it own optimization conditions and parameters. The initial data list, the calculations formulas, and these formulas using order; it was formed the optimal parameters method determination, there were next:

The initial specific productivity mass values in G_n kg/hr or kg/sec.

The solid elements initial specific concentration in a_n kg/kg.

The outlet elements specific concentration in a_k kg/kg.

The hot vapor pressure at Pa or the corresponding saturation temperature t_{gr} value in K and it range.

The secondary vapor temperature in C and pressure P_{vt} in Mpa.

The vaporization temperature t_{vt} in C and it range.

The product initial temperature t_n in C .

The steam dryness factor or its enthalpy.

The heat exchanger heat transfer surface material and it physical properties.

The fuel kind view, it calorific power value and it unit specific price.

The main equipment elements cost and their surfaces service life.

The product thermo physical properties determination correlations.

The heat carrier thermo physical properties determination equations.

There are especially important determination (position 12) the product property values as different so called temperature depressions, including physical chemical (PCTD); hydrostatical and hydro dynamical. It is required for the first one to know the corresponding empirical formulas. Unfortunately, very often the information usually is absent. Sometimes it is exist. For example, in the case product is tomato juice, the necessary correlation to define (PCTD) exist. It has the next view:

$$\Delta Ph = 0.38 \cdot \exp\,(0.05\ + 0.045 \cdot \mathrm{a_k}) \qquad (1)$$

Here: $\Delta Ph, a_k$ PCTD and outlet concentration value.

There are necessary to know for every product the similar empirical correlations to define PCTD value. As to hydrostatical depression value definition, it is necessary first of all to know the vapor generator design. If it is known, then the simple order calculation has the next view. It is connected first of all with the product liquid height optimal level can be determined with the next equation:

$$l_{opt} = [0.26\ + 0.0014\ \cdot \frac{(\rho_{pr} - \rho_{grk}(tvt)}{kg \cdot m^3}] \cdot m \qquad (2)$$

Here: l_{opt}; $\rho_{grk}\ (tvt)$; $\rho_{pr} -$ - the optimal boiled product level inside vertical vapor generator tubes; the inlet and outlet product densities, correspondingly. Then the average pressure inside evaporator can be defined using the next formula:

$$\mathrm{P_{cp}\ =\ P_{vt}\ + 0.5 \cdot l_{opt} \cdot \rho_{pr} \cdot g} \qquad (3)$$

Then it is necessary to determine the vaporized water mass from the product W_{vt}. It is required to use the next formula:

$$W_{vt}\ =\ G_n \cdot (1 - \frac{a_n}{a_k}) \qquad (4)$$

W_{vt} – is the product mass flow rate value in the kg/hr or kg/sec. Then, it is necessary to determine whole thermal power items. They are consisted from the thermal power for product flow heating from the initial temperature to the vaporization one Q_1; thermal power for the product partial vaporization Q_2 ; the thermal power connected with thermal power losses Q_{op} and whole thermal power value Q_0 .

The equations system these items defition has the next view:

$$Q_1 = G_n \cdot C_p\ \cdot (t_S\ -\ t_n\ ) \qquad (5)$$

$$Q_2 = W_{vt} \cdot r_{vt} \qquad (6)$$

$$Q_{op} = 0.05 \cdot (Q_1 + Q_2) \tag{7}$$

and

$$Q_0 = Q_1 + Q_2 + Q_{op} \tag{8}$$

The temperature drop inside the vapor generator can be determined on the next base:

$$\Delta t_i = t_{gri} - t_S \tag{9}$$

Here: Δt_i; t_{gri}; t_S – temperature drop; steam temperature; the saturation temperature, correspondingly.

The next steps into calculations connected with the heat transfer coefficient and specific heat flux inside vapor generator determination. In the first turn it is consisted from the separate heat transfer coefficients from the boiling product side on the generator tubes external surfaces and from the heat carrier (steam) condensation inside these tubes. The first heat transfer coefficient by the product solution boiling on the heated tubes external surface, proposed to be made, using the next formula:

$$\alpha_2 = \left(\frac{\lambda_1}{\delta_1}\right) \cdot 3.25 \cdot 10^{-4} \cdot \left(q_{1f} \cdot \frac{\delta_1 \cdot C_1 \cdot \rho_1}{r_1 \cdot \rho_2 \cdot \lambda_1}\right)^{0.6} \cdot \left(g \cdot \frac{\delta_1^3}{\nu_1^2}\right)^{0.125} \cdot \left(P_1 \cdot \frac{\delta_1}{\sigma_1}\right)^{0.7} \tag{10}$$

Here

$$\delta_1 = \sqrt{\frac{\sigma_1}{(\rho_1 - \rho_2) \cdot g}} \tag{11}$$

$$q_{1f} = \propto_2 \cdot \Delta t_2; \tag{12}$$

$$\Delta t_2 = t_{gri2} - t_S \tag{13}$$

The other values are depicted

The product thermal physical properties: λ_1; r_1; ρ_2; ρ_1; ν_1; σ_1; C_1; P_1 – the product liquid heat conductivity, latent heat; product vapor density; product liquid density; product liquid cinematic viscosity; product liquid surface tension value; the product liquid specific heat capacity ; product vapor pressure, correspondingly.

It was suggested to use for the average heat transfer coefficient by the heated vapor condensation inside the generator tubes the known formulas for quick movement vapor flow condensation inside the long smooth tubes.

$$\frac{\alpha_1 \cdot d}{\lambda_1} = C_{10} \cdot Re_1^{0.8} \cdot Pr_1^{0.43} \cdot [1 + X_{cp} \cdot (\rho_1/\rho_2 - 1)]^{0.5} \tag{14}$$

Here: $\propto_1$; d_1; C_{10}; Re_1; Pr_1; X_{cp}; ρ_1; ρ_2; λ_1 – the average heat transfer coefficient along condensation surface by quick moving vapor inside tube with average mass flow vapor content equal X_{cp}; the tube internal diameter; the semi empirical coefficient; average Reynolds Number; liquid condensate Prandtl Number; average mass flow vapor content; liquid condensate density; steam density; liquid condensate heat conductivity, correspondingly. Average Reynolds Number has the next view:

$$Re_1 = q \cdot d_1/r_1 \cdot \mu_1 \tag{15}$$

Here q - average whole internal condensation surface specific heat flux; r_1; μ_1 –latent heat, condensate dynamic viscosity, correspondingly. The thermal resistance from the boiling product side on the external tube generator surface has to include itself, besides the boiling heat transfer item the wall material thermal resistance and the deposits on the product boiling surface, what, as a rule, to appear on it. So it means that:

$$R_\Sigma = (\delta_W/\lambda_W + R_{\text{зar}}) \tag{16}$$

Here R_Σ ; δ_W; λ_W; $R_{\text{зar}}$ – whole thermal resistance from the boiling surface side; tube wall thickness, it heat conductivity; the deposits specific thermal resistance, correspondingly. The last value it is necessary to take on the base of service experience information. Therefore, the heat transfer intensity calculation has to be made on using common decision as specific heat flux determination as from product boiling process on the external generator surface, both as from water vapor condensation inside in the heated tubes. There is leading to the necessity solution two transcendent equations system or two degree equations with the next views:

$$\propto_2 = Z11 \cdot \Delta t_2^{1.5} \tag{17}$$

and

$$1/k_2 = 1/\alpha_2 + \delta_W/\lambda_W + R_{\text{зar}};\ q_2 = k_2 \cdot \Delta t_2 \tag{18}$$

Here:

$$\mathrm{Z11} = \delta_1^{1.675} \cdot \lambda_1 \cdot \left(C_1 \cdot \rho_1/\rho_2 \cdot \frac{1}{r_1}\right)^{1.5} \cdot (\rho_1/\sigma_1)^{1.75} \cdot g^{0.3125} \cdot (\nu_1)^{-0.625} \tag{17a}$$

α_2; Δt_2; q – heat transfer coefficient from the liquid product boiling side on the heated external surface, the temperature drop from the side and specific heat flux from the side. The parameter Z11 is any complex, containing from the liquid product thermal physical properties values, pointed higher, it is necessary to account the values dimensions with respect of the formula empirical base. Naturally, to account here other thermal resistances, connected with wall thickness and deposits as the boiling product result. From the other side, the specific heat flux had to be the same.

That is:

$$q_1 = \propto_1 \cdot \Delta t_1;\ \Delta t_1 = t_{gr} - t_{W1}; \tag{19}$$

and $$q_1 = q_2\,;\ t_{gr} - t_{W1} = t_{vt} - \Delta t_2; \quad (20)$$

The analysis these equations with all their details shown, that the steady state heat transfer processes intensity can be determined using one quadratic equation the next form:

$$t_{W1}^2 - 2\cdot t_{W1}\cdot t_{gr11} - \frac{Z111}{Z122^2}\cdot t_{W1} + t_{10}\cdot\frac{Z111}{Z122^2} + t_{gr11}^2 = 0 \quad (21)$$

Here: $t_{W1};\ t_{gr11};\ t_{10}; Z111; Z122 -$ the determined average heating surface temperature; the steam saturation temperature; the secondary vapor saturation temperature; the complexes, combined itself as the thermal physical liquid product heated water vapor and condensate properties and properties of the heat transfer surface, including all connected with it geometry and physical properties.

There were on the base determined for the every variant the vapor generator surface, it mass, including container, different auxiliary elements and other parameters, what have to be known for technical and economic analysis. Estimated on it, the whole cost and connected with it capital expenditures. Besides it, there were estimated the financial expenditures, connected with expenditures on the energy consumption, with respect of the heated vapor energy potential. It allows to obtain the optimal vapor temperature value. Lower most typical results of the approach and base on it method, presented in the next pictures. There was for example, the VE for the concentrated tomato juice obtain.

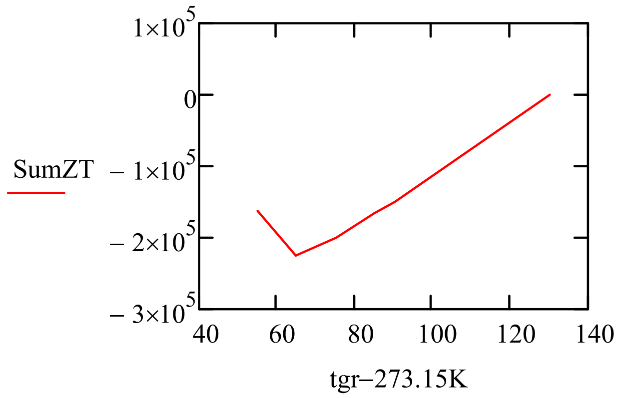

Fig. 1 – The total expenditures SumZT dependency, determined on the above prescribed optimization method base, on the steam temperature t_{gr}

There were taken the next positions in the author approach to the VE design optimal parameters definition:

1. The key optimization function the problem is total money expenditures, including as capital expenditures both energy losses and expenses during year or service time. It was taken, that it will be right to consider the similar initial position in the approach when as energy source the heated vapor flow, obtained from the vapor extraction turbine and from the usual boiler. The corresponding energy expenditures could be estimated with account possible power value to obtain from the vapor flow. Than vapor extraction temperature (pressure) lower, then more the power that could be obtained on turbine. The part of the total expenditures form was calculated as the corresponding money expenses over value electric power multiplied on the electrical power unit price.

2. The other part of total expenditures was connected with main equipment cost. There were the VE vapor generator to evaporate required amount of concentrated solution. That was, in author case, tomato juice flow with any initial concentration, what had to be evaporate to the required final concentration.

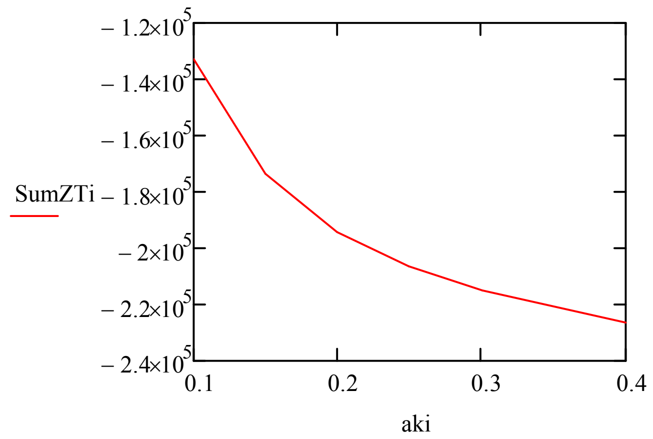

Fig. 2 – The minimum total expenditure $Sum\ ZT_i$ dynamic dependence on the final concentration value a_{ki}, by one the same initial concentration 5 %

The total expenditures part, related to the key equipment element expenses was estimated over the next steps. It was taken: every heat exchanger cost can be determined, using it surface (founded from the pointed calculations). Knowing surface, can be found it mass value, using the exchanger material mass unit price can be defined it total cost and so on. Corresponding items, connected with equipment expenditures were defined with mention approach account, including amortization input and service expenses. Therefore, total expenditures values were defined for every calculation variant. These calculations main results presented lower in the graphic view in figures. The optimization objects were as steam temperature for the vapor generator VE, both water flow rate for the secondary vapor condenser.

There were presented lower pointed above optimization results of the steam saturation temperature.

Here the initial dry media concentration was 5 % and the final one was 40 %. The expenditure value in the minimum point were equal $- 2.265 \cdot 10^5 grn.$

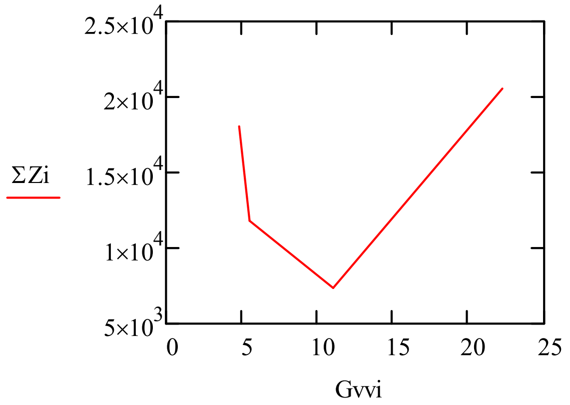

Fig. 3 – The total expenditures $\sum Z_i$ dependency on the cooled water flow rate G_{vvi} by the optimization design for the secondary vapor condenser

The special direction of authors analysis and investigations were devoted the problem energy saving in VE by the application heat pump as the heat source instead steam flow. Namely with right decision of the problem, it is necessary to determine optimal parameters for every compared variants. That is why, was developed and realized for any example prescribed here approach and base on it optimization method. The authors were known, that there exist another possible version of substitution traditional heat source (steam) some other, for example vapor ejector (TVR) or vapor compressor (MVR) application with goal to compress secondary flow and using the flow return into the main part of VE. Unfortunately, the reliable the problem study significantly complicated it is connected with absence reliable information about these devices prices and characteristics. This position for the heat pump is significantly better and reliable.

Concluding notes and remarks

1.The perspective directions of the energy saving in the food technology relating different food solution admixtures concentration, using their vaporization in VE installation, may be connected with heat pump application.

2. The suggested approach to the problem and base on it method could be useful and grounded for right decision.

3. The real decision reliability extremely depended on the right and reliable information for equipment cost, energy, and fuel unit prices.

4. The heat pump application effectiveness will increased by the temperature drop between heating and cooling temperatures decreasing.

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