

PL - Production lines - example

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Simplified calculation of sugar juice evaporator and examples of its optimisation

Given data:

Design an evaporator with 4 effects for thin juice concentration. The 1st and 2nd effects are the Robert type (circulating type), other with falling film (3° a 4°). Following parameters are given:

Amount of thin juice	$M_{J0} = 120 \text{ t/h}$
Saccharisation (concentration) of thin juice	$S_{J0} = 15,0 \text{ \% DM}$
Saccharisation of thick juice	$S_{J4} = 68,0 \text{ \% DM}$
Heating steam temperature in 1st effect	$t_{s1} = 135 \text{ °C}$
Vapour temperature in 4th effect	$t_{v4} = 80 \text{ to } 95 \text{ °C}$
Take-off of heating steam to technology	$O_0 = 5,8 \text{ t/h}$
Take-off of 1st vapour to technology	$O_1 = 16,0 \text{ t/h}$
Take-off of 2nd vapour to technology	$O_2 = 15,8 \text{ t/h}$
Take-off of 3rd vapour to technology	$O_3 = 8,9 \text{ t/h}$
Take-off of 4th vapour to technology	$O_4 = 3,1 \text{ t/h}$

The flow sheet of the evaporator is in the following figure (Fig.1).

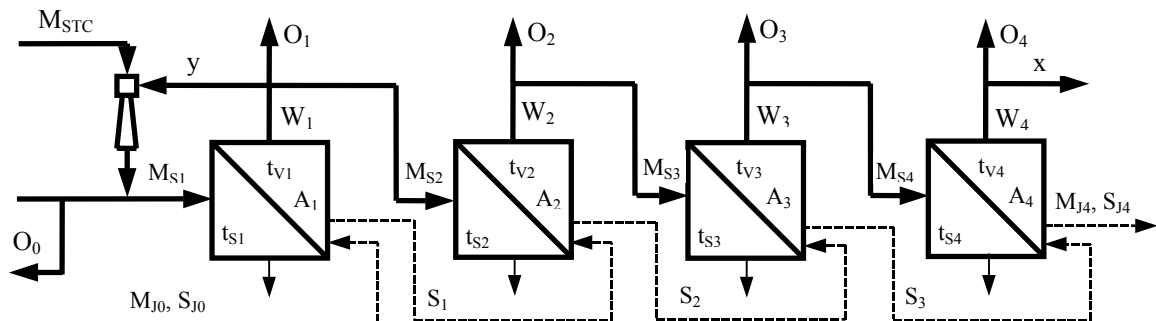


Fig.1: Flow sheet of the evaporator with 4 effects
 ——— steam, vapour - - - - - juice ——— condensate

Task:

- Work an approximate balance of the evaporator (considering that 1 kg of condensing steam evaporates 1 kg of vapour from juice). An expansion of superheated juice (+), condensate expansion, various evaporation heats and heat losses (-) will not take into account.
- A heating steam consumption M_{S1} and the 4th vapour loss to condensation x .
- Juice saccharisations of juice after all evaporator effects (S_i).

- Specification of heat transfer areas of all evaporator effects (A_i)

1. Process of calculation

1.1. Evaporator balance

Taking into account above mentioned simplifying presumption following equations are valid:

Total amount of evaporated water W is derived from a mass and dry mass balance:

$$M_{J0} * S_{J0} = M_{J4} * S_{J4} \quad \text{balance of dry matter in evaporator} \quad (1)$$

$$M_{J0} - M_{J4} = W \quad \text{balance of mass in evaporator} \quad (2)$$

The wanted total amount of evaporated water W is calculated from the two equations.

$$W = M_{J0} * (1 - S_{J0} / S_{J4}) = 120 * (1 - 15 / 68) = 93,5 \text{ t/h}$$

Before we will do next calculations we have to look at the evaporator flow sheet - steam/vapour system. In the last effect (4th) an amount of evaporated water W_4 has to be equal to the amount of a 4th vapour taken off to technology O_4 plus an unknown 4th vapour loss to condensation x . ($W_4 = O_4 + x$). An amount of evaporated water W_3 in the 3rd effect has to be equal to the amount of evaporated water in the 4th effect plus the amount of the 3rd vapour taken off to technology O_3 ($W_3 = W_4 + O_3$). The amount of vapour evaporated from juice in the 3rd effect (W_3) heats the 4th effect (there it condenses \rightarrow vapour W_4) and has to supply required 3rd vapour take-off (O_3).

Similarly an amount of evaporated water in the 2nd effect is determined ($W_2 = W_3 + O_2$) and finally in the 1st effect too. Here the amount of evaporated water has to be equal to the amount of evaporated water in the 2nd effect plus required 1st vapour take-off O_1 plus alternatively a take-off to a thermo-compressor y ($W_1 = W_2 + O_1 + y$). The total amount of evaporated water has to be equal to a sum of the amounts of evaporated water in all effects ($W = \sum W_i$).

The considerations are written in following equations (3)

$$\begin{aligned} 4^\circ \quad & W_4 = x + O_4 \\ 3^\circ \quad & W_3 = x + O_4 + O_3 \\ 2^\circ \quad & W_2 = x + O_4 + O_3 + O_2 \\ 1^\circ \quad & W_1 = x + O_4 + O_3 + O_2 + O_1 + y \approx M_{S1} \end{aligned} \quad (3)$$

$$\Sigma \quad W = 4*x + 4*O_4 + 3*O_3 + 2*O_2 + O_1 + y$$

Only the 4th vapour loss to condensation x is an unknown parameter in these equations (TK is not installed so that the 1st vapour take-off to TK is $y = 0$). Than we can set the loss from an equation

$$\begin{aligned} x &= (W - O_1 - 2*O_2 - 3*O_3 - 4*O_4) / 4 \\ x &= (93,5 - 16,0 - 2*15,8 - 3*8,9 - 4*3,1) / 4 = 1,7 \text{ t/h} \end{aligned} \quad (4)$$

The amounts of evaporated water in the evaporators' effect are

$$\begin{aligned} 4^\circ \quad & W_4 = 1,7 + 3,1 & = 4,8 \text{ t/h} \\ 3^\circ \quad & W_3 = 1,7 + 3,1 + 8,9 & = 13,7 \text{ t/h} \end{aligned}$$

$$\begin{array}{rcl}
2^\circ & W_2 = 1,7 + 3,1 + 8,9 + 15,8 & = 29,5 \text{ t/h} \\
1^\circ & W_1 = 1,7 + 3,1 + 8,9 + 15,8 + 16,0 & = 45,5 \text{ t/h} \approx M_{S1} \\
\hline
\Sigma & W = & = 93,5 \text{ t/h}
\end{array}$$

An amount of heating steam is equal (for above mentioned presumptions) to the amount of water evaporated in the 1st evaporator effect. Than it is

$$M_{SEVAP} = M_{S1} \approx 45,5 \text{ t/h}$$

An amount of thick juice leaving the evaporator to a boiling house

$$M_{J4} = M_{J0} - W = 120,0 - 93,5 = 26,5 \text{ t/h}$$

Now we can set saccharisations of juice after every effect (from dry mass balance).

$$\begin{aligned}
S_{J1} &= S_{J0} * M_{J0} / M_{J1} = S_{J0} * M_{J0} / (M_{J0} - W_1) \\
S_{J1} &= 15,0 * 120 / (120 - 45,5) = 24,2 \%
\end{aligned}$$

$$\begin{aligned}
S_{J2} &= S_{J0} * M_{J0} / M_{J2} = S_{J0} * M_{J0} / (M_{J0} - W_1 - W_2) \\
S_{J2} &= 15,0 * 120 / (120 - 45,5 - 29,5) = 40,0 \%
\end{aligned}$$

$$\begin{aligned}
S_{J3} &= S_{J0} * M_{J0} / M_{J3} = S_{J0} * M_{J0} / (M_{J0} - W_1 - W_2 - W_3) \\
S_{J3} &= 15,0 * 120 / (120 - 45,5 - 29,5 - 13,7) = 57,5 \%
\end{aligned}$$

$$\begin{aligned}
S_{J4} &= S_{J0} * M_{J0} / M_{J4} = S_{J0} * M_{J0} / (M_{J0} - W_1 - W_2 - W_3 - W_4) \\
S_{J4} &= 15,0 * 120 / (120 - 45,5 - 29,5 - 13,7 - 4,8) = 67,9 \% \approx 68 \% = S_{\text{thick juice}}
\end{aligned}$$

The calculated juice saccharisation \approx given (a difference is caused by a rounding to 1 decimal place).

1.2. Determination of evaporator's heating areas

For the calculation of heat transfer areas of the evaporator we need to know values of overall heat transfer coefficients k_i and boiling temperatures in all effects t_{Bi} . A choice of the boiling temperature is limited by requirements to temperatures of vapours taking off to technology (e.g. juice heating) and requirements to an optimal evaporator's operation. These requirements are a maximal temperature of heating steam in the 1st effect (juice browning, sugar decomposition) and a temperature (under-pressure) in the last (4th) effect (good operation of a vapour condenser – cooling water temperature and possibility of the last vapour utilisation). In Czech sugar factories temperature of a 3rd vapour higher than 102 - 103 °C is used (a good utilisation in a boiling plant). We choose following temperatures of boiling (vapours) in the evaporator's effects.

$$\begin{array}{ll}
t_{S1} = 135 \text{ }^\circ\text{C} & \text{given} \\
t_{V1} \approx 126 \text{ }^\circ\text{C} \approx t_{S2} & \\
t_{V2} \approx 116 \text{ }^\circ\text{C} \approx t_{S3} & \\
t_{V3} \approx 102 - 104 \text{ }^\circ\text{C} \approx t_{S4} & \\
t_{V4} \approx 80 - 90 \text{ }^\circ\text{C} &
\end{array}$$

Note: As a value of overall heat transfer coefficient is lower for higher saccharisation and lower temperature higher temperature differences are used in last effects. In the case

is a total heat transfer area of an evaporator lower (capital cost saving).

For a calculation of an overall heat transfer coefficient in circulation type evaporator's bodies (Robert type) so-called Swedish formula is used. A constant in the formula is modified from my multiyear measuring of Czech sugar juice evaporators. So I recommend using the following empirical formula for an i- effect:

$$k_i = K * t_{ji} / S_i = 440 * t_{ji} / S_i \quad (5)$$

Analogous I set for a falling film type evaporator's bodies the following empirical formula:

$$k_i = K * t_{ji} / S_{i\phi} = 500 * t_{ji} / S_{i\phi} \quad (6)$$

These formulas take into account a fouling on a heat transfer surface. A juice temperature is a vapour temperature plus boiling point elevation (BPE) plus an effect of a hydrostatic pressure (it depends on a liquid level in an effect – for falling film evaporators there is no). The BPE is given by the vapour temperature and an average concentration = saccharisation of the juice in an evaporator effect. The BPE is listed in tables. For circulation type evaporator's bodies (Robert type) it is calculated for an outlet juice concentration (saccharisation), for falling film type evaporator's bodies it is set for an average concentration (an another advantage of these bodies). For our data we set following boiling point elevations:

$$\Delta_1 = 0,6 \text{ }^\circ\text{C}; \quad \Delta_2 = 1,3 \text{ }^\circ\text{C}; \quad \Delta_3 = 1,9 \text{ }^\circ\text{C} (\phi 48,8 \text{ } \%); \quad \Delta_4 = 3,8 \text{ }^\circ\text{C} (\phi 63,3 \text{ } \%)$$

(for Robert type effects it would be $\Delta_3 = 3,1 \text{ }^\circ\text{C} (57,5 \text{ } \%); \quad \Delta_4 = 5,4 \text{ }^\circ\text{C} (68,0 \text{ } \%)$)

Than average juice temperatures in effects are:

$$t_{j1} = t_{v1} + \Delta_1 = 126 + 0,6 = 126,6 \text{ }^\circ\text{C}$$

$$t_{j2} = t_{v2} + \Delta_2 = 116 + 1,3 = 117,3 \text{ }^\circ\text{C}$$

$$t_{j3} = t_{v3} + \Delta_3 = 104 + 1,9 = 105,9 \text{ }^\circ\text{C}$$

$$t_{j4} = t_{v4} + \Delta_4 = 90 + 3,8 = 93,8 \text{ }^\circ\text{C}$$

Now we can set values of overall heat transfer coefficients in effects. We use eq. (5) a (6).

$$1^\circ \text{ CI} \quad k_1 = 440 * 126,6 / 24,2 = 2302 \text{ W/m}^2\text{K}$$

$$2^\circ \text{ CI} \quad k_2 = 440 * 117,3 / 40,0 = 1290 \text{ W/m}^2\text{K}$$

$$3^\circ \text{ FI} \quad k_3 = 500 * 105,9 / 48,8 = 1085 \text{ W/m}^2\text{K}$$

$$4^\circ \text{ FI} \quad k_4 = 500 * 93,8 / 63,3 = 741 \text{ W/m}^2\text{K}$$

Amount of heat transferred in an i- effect is set from this equation:

$$Q_i = W_i * r_i \quad (7)$$

Various latent heat of evaporation are taken into account in these equations

$$1^\circ \quad r_1 = 2185 \text{ kJ/kg} \quad Q_1 = 45500 * 2185 / 3600 = 27616 \text{ kW}$$

$$2^\circ \quad r_2 = 2213 \text{ kJ/kg} \quad Q_2 = 29500 * 2213 / 3600 = 18134 \text{ kW}$$

$$3^\circ \quad r_3 = 2245 \text{ kJ/kg} \quad Q_3 = 13700 * 2245 / 3600 = 8543 \text{ kW}$$

$$4^\circ \quad r_4 = 2283 \text{ kJ/kg} \quad Q_4 = 4800 * 2283 / 3600 = 3044 \text{ kW}$$

Necessary heat transfer areas of effects are set from following equations:

$$Q_i = k_i * A_i * (t_{Si} - t_{ji}) \quad (8)$$

$$A_i = Q_i / k_i * (t_{Si} - t_{ji}) \quad (8a)$$

$$1^\circ \quad A_1 = 27616000 / 2302 * (135 - 126,6) = 1428 \text{ m}^2$$

$$2^\circ \quad A_2 = 18134000 / 1290 * (126 - 117,3) = 1616 \text{ m}^2$$

$$3^\circ \quad A_3 = 8543000 / 1085 * (116 - 105,9) = 780 \text{ m}^2$$

$$4^\circ \quad A_4 = 3044000 / 741 * (104 - 93,8) = 403 \text{ m}^2$$

For a case of plate evaporators it is possible to manufacture effects with required areas. But for a case of tubular effects we have to choose proper effects from a type range of manufactured effects. For our example we choose following heat transfer areas (HTA) of the effects:

$$A_1 = 1600 \text{ m}^2; \quad A_2 = 1800 \text{ m}^2; \quad A_3 = 800 \text{ m}^2; \quad A_4 = 400 \text{ m}^2$$

Note: We have to choose proper areas not only from a point of view of results stated above but from a point of view of possible of an increasing of a sugar factory capacity etc. too. In this example are effects chosen with a small reserve. An oversized effect has a low specific heat flux q (W/m^2) and it follows that the effect works badly (it boils worse). That is why recommended ranges of specific heat flux for effects 1, 2, 3 etc. are determined (for Robert type bodies).

Because chosen heat transfer areas are different than calculated ones temperatures in effects will be different from calculated ones too. The change is given by an equation (8), $Q_i = k_i * A_i * (t_{Si} - t_{ji})$. For the same performance (Q_i) and value k_i and changed A_i , $(t_{Si} - t_{ji})$ has to change too. That is why we have to do a recalculation of the evaporator for these selected areas of effects. Similar procedure is used for an existing evaporator monitoring or optimisation.

1.3. Determination of temperatures in effects for selected heat transfer areas and given vapour take-off

For better lucidity we will show all given data and results from previous calculations that we will need for next calculations. As differences between the chosen and calculated HTA are small we can suppose that temperatures in the evaporator incl. boiling point elevation will be similar. So we can suppose that latent heat of evaporation and newly calculated amounts of heat (performance) Q_i will be similar too. **Effects of boiling point elevation owing to hydrostatic pressure (Δ_{Hi}) and pressure losses of vapours in pipes between effects ($\Delta_{\Delta Pi}$) are taken into account in the new calculation.** Than a new data for the new calculations are:

$$t_{S1} = 135 \text{ }^\circ\text{C}$$

$$Q_1 = 27616 \text{ kW}$$

$$A_1 = 1600 \text{ m}^2$$

$$S_1 = 24,2 \text{ } \%$$

CI

$$K_1 = 440$$

$$\Delta_1 = 0,6 \text{ }^\circ\text{C}$$

$$\Delta_{H1} = 0,5 \text{ }^\circ\text{C}$$

$$Q_2 = 18134 \text{ kW}$$

$$A_2 = 1800 \text{ m}^2$$

$$S_2 = 40,0 \text{ } \%$$

CI

$$K_2 = 440$$

$$\Delta_2 = 1,3 \text{ }^\circ\text{C}$$

$$\Delta_{H2} = 1,0 \text{ }^\circ\text{C}$$

For Robert type is

$$Q_3 = 8543 \text{ kW}$$

$$A_3 = 800 \text{ m}^2$$

$$S_{3\phi} = 48,8 \text{ } \%$$

FI

$$K_3 = 500$$

$$\Delta_3 = 1,9 \text{ }^\circ\text{C}$$

$$\Delta_{H3} = 0 \text{ }^\circ\text{C}$$

$$\Delta_3 = 3,1 \text{ }^\circ\text{C}$$

$$Q_4 = 3044 \text{ kW}$$

$$A_4 = 400 \text{ m}^2$$

$$S_{4\phi} = 63,3 \text{ } \%$$

FI

$$K_4 = 500 \text{ (W}\%/\text{m}^2\text{K)}$$

$$\Delta_4 = 3,8 \text{ }^\circ\text{C}$$

$$\Delta_{H4} = 0 \text{ }^\circ\text{C}$$

$$\Delta_4 = 5,2 \text{ }^\circ\text{C}$$

$$\Delta_{\Delta P1} = 1,0 \text{ }^{\circ}\text{C} \quad \Delta_{\Delta P2} = 1,5 \text{ }^{\circ}\text{C} \quad \Delta_{H3} = 1,0 \text{ }^{\circ}\text{C} \quad \Delta_{H4} = 1,0 \text{ }^{\circ}\text{C}$$

$$\Delta_{\Delta P3} = 1,5 \text{ }^{\circ}\text{C} \quad \Delta_{\Delta P4} = 1,5 \text{ }^{\circ}\text{C}$$

In the case (contrary of the mass balance) we go in our solution from the 1st effect to the last one. We use known data and relations among them (eq. (5), (6) a (8)).

$$Q_i = k_i * A_i * (t_{Si} - t_{Ji}) = (K_i * t_{Ji} / S_i) * A_i * (t_{Si} - t_{Ji}) \quad (9)$$

After modification we get a quadratic equation

$$t_{Ji}^2 - t_{Si} * t_{Ji} + Q_i * S_i / K_i * A_i = 0 \quad \text{with roots} \quad [x_{1,2} = (-b \pm \sqrt{b^2 - 4*a*c}) / 2*a]$$

$$t_{Ji} = (t_{Si} \pm \sqrt{t_{Si}^2 - 4 * Q_i * S_i / K_i * A_i}) / 2$$

One root of the equation is a wanted juice temperature t_{Ji} , the second is a temperature difference $(t_{Si} - t_{Ji})$. Than following temperatures of juice, vapours and steam are:

$$t_{J1} = (t_{S1} + \sqrt{t_{S1}^2 - 4 * Q_1 * S_1 / K_1 * A_1}) / 2 \quad (10)$$

$$t_{J1} = (135 + \sqrt{135^2 - 4*27616000*24,2 / 440*1600}) / 2 = 127,6 \text{ }^{\circ}\text{C}$$

$$(t_{S1} - t_{J1}) = (135 - \sqrt{135^2 - 4*27616000*24,2 / 440*1600}) / 2 = 7,4 \text{ }^{\circ}\text{C}$$

$$t_{V1} \approx t_{J1} - \Delta_1 - \Delta_{H1} = 127,6 - 0,6 - 0,5 = 126,5 \text{ }^{\circ}\text{C} \quad (126 \text{ }^{\circ}\text{C}) \quad \text{O.K.}$$

$$t_{S2} \approx t_{V1} - \Delta_{\Delta P1} = 126,5 - 1,0 = 125,5 \text{ }^{\circ}\text{C}$$

$$t_{J2} = (125,5 + \sqrt{125,5^2 - 4*18134000*40,0 / 440*1800}) / 2 = 117,7 \text{ }^{\circ}\text{C}$$

$$(t_{S2} - t_{J2}) = (125,5 - \sqrt{125,5^2 - 4*18134000*40,0 / 440*1800}) / 2 = 7,8 \text{ }^{\circ}\text{C}$$

$$t_{V2} \approx t_{J2} - \Delta_2 - \Delta_{H2} = 117,7 - 1,3 - 1,0 = 115,4 \text{ }^{\circ}\text{C} \quad (116 \text{ }^{\circ}\text{C}) \quad \text{O.K.}$$

$$t_{S3} \approx t_{V2} - \Delta_{\Delta P2} = 115,4 - 1,5 = 113,9 \text{ }^{\circ}\text{C}$$

$$t_{J3} = (113,9 + \sqrt{113,9^2 - 4*8543000*48,8 / 500*800}) / 2 = 103,9 \text{ }^{\circ}\text{C}$$

$$(t_{S3} - t_{J3}) = (113,9 - \sqrt{113,9^2 - 4*8543000*48,8 / 500*800}) / 2 = 10,0 \text{ }^{\circ}\text{C}$$

$$t_{V3} \approx t_{J3} - \Delta_3 - \Delta_{H3} = 103,9 - 1,9 - 0,0 = 102,0 \text{ }^{\circ}\text{C} \quad (104 \text{ }^{\circ}\text{C}) \quad \text{cca O.K.}$$

$$t_{S4} \approx t_{V3} - \Delta_{\Delta P3} = 102,0 - 1,5 = 100,5 \text{ }^{\circ}\text{C}$$

$$t_{J4} = (100,5 + \sqrt{100,5^2 - 4*3044000*63,3 / 500*400}) / 2 = 89,8 \text{ }^{\circ}\text{C}$$

$$(t_{S4} - t_{J4}) = (100,5 - \sqrt{100,5^2 - 4*3044000*63,3 / 500*400}) / 2 = 10,7 \text{ }^{\circ}\text{C}$$

$$t_{V4} \approx t_{J4} - \Delta_4 - \Delta_{H4} = 89,8 - 3,8 - 0,0 = 86,0 \text{ }^{\circ}\text{C} \quad (90 \text{ }^{\circ}\text{C}) \quad ? \text{ to review it and ev. increase } A_4$$

Note: For CI bodies instead FI in the 3^o a 4^o would be temperatures in the effects :

$$t_{J3} = (113,9 + \sqrt{113,9^2 - 4*8543000*57,5 / 440*800}) / 2 = 99,9 \text{ }^{\circ}\text{C}$$

$$(t_{S3} - t_{J3}) = (113,9 - \sqrt{113,9^2 - 4*8543000*57,5 / 440*800}) / 2 = 14,0 \text{ }^{\circ}\text{C}$$

$$t_{V3} \approx t_{J3} - \Delta_3 - \Delta_{H3} = 99,9 - 3,1 - 1,0 = 95,8 \text{ }^{\circ}\text{C} \quad (104 \text{ }^{\circ}\text{C})$$

$$t_{S4} \approx t_{V3} - \Delta_{\Delta P3} = 95,8 - 1,5 = 94,3 \text{ }^{\circ}\text{C}$$

$$t_{J4} = (94,3 + \sqrt{94,3^2 - 4*3044000*68,0 / 440*400}) / 2 = 79,5 \text{ }^{\circ}\text{C}$$

$$(t_{S4} - t_{J4}) = (94,3 - \sqrt{94,3^2 - 4*3044000*68,0 / 440*400}) / 2 = 14,9 \text{ }^{\circ}\text{C}$$

$$t_{V4} \approx t_{J4} - \Delta_4 - \Delta_{H4} = 79,5 - 5,2 - 1,0 = 73,3 \text{ }^{\circ}\text{C} \quad (90 \text{ }^{\circ}\text{C})$$

A fouling formation in an evaporator depends on a juice (sugar beet) composition. And sugar beet composition depends on weather during growing season (temperatures and rain

falls), fertilisation and soil. From it follows that the fouling formation and consequently an overall heat transfer coefficient k in the evaporator alternates according a locality and year.

With an exaggeration we can say that k value depends on weather. We have to calculate with the uncertainty during our design of lines in the food industry. The food industry works with a biological material that underlies to various changes.

The equation introduced above for calculation of k value is used in the sugar industry. The equation is simple and the calculation with it is simple too (quadratic equations). For some other cases especially for falling film evaporators various equations for α values for boiling and condensation are shown. Than a k value has to be calculated from a following equation

$$k = 1 / (1 / \alpha_B + s_T / \lambda_T + \Sigma s_i / \lambda_i + 1 / \alpha_C) \quad (11)$$

For a practical using of such equations we have to verify their validity, it is for what conditions they were set, how long lasts experiments (fouling), what liquids were tested etc. These all affects using for example of a criteria equation (that theoretically has to be generally valid but that was deduced only from experiments with water and low concentrated pure solutions). Another important question is fouling formation (s_i / λ_i). Actual measured k values are often $\frac{1}{2}$ or $\frac{1}{3}$ (and sometimes any lower) than theoretical ones. The k values changes during campaign too. On the campaign end they fall till 50 - 60 % of an initial value. We have to calculate with these all incl. a possibility of a future increasing of a line capacity.

Evaporators were designed by way of a procedure mentioned above till c. 1985 (and they have worked till now well). With a development of computers and requirements to prepare more variants of a solution evaporators are now calculated more accurate. Calculations take into account variant latent heat of evaporation, heat losses, pressure losses of vapour during its flow from a vapour chamber of one effect to a condensing chamber (calandria) of a next effect, utilisation of vapours expanded from condensate in receivers etc. The solution needs a program.

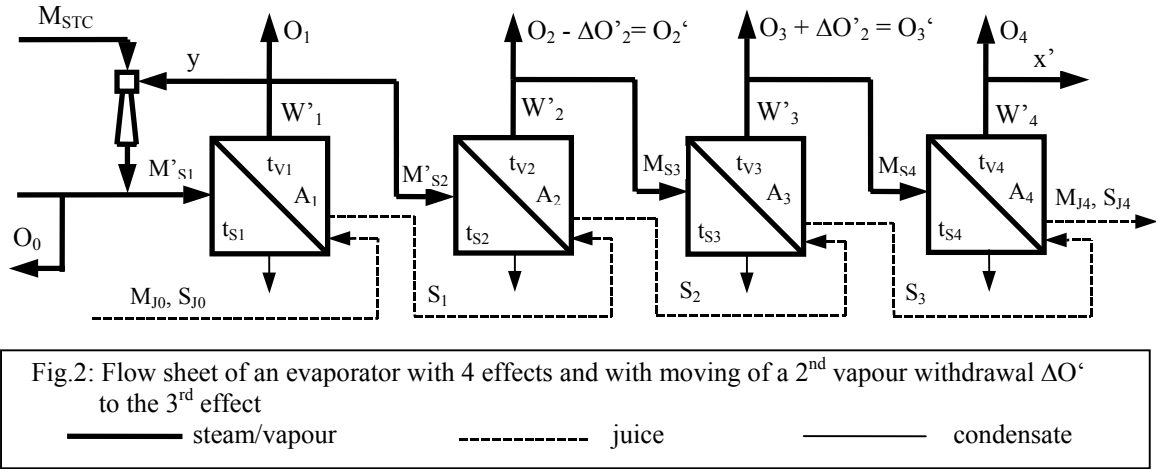
2. Optimisation of the evaporator (or an existing evaporator)

Prevalent way of an existing evaporator optimisation is a better utilisation of vapours in a technology. For example plate HE can work efficiently with a temperature difference between heating vapour and heated up juice c. 3 – 5 °C. Tubular HE usually need the difference c. 10 – 15 °C (effect of higher k value in plate heat exchangers). From it follows that for a juice heating we can use a vapour with lower temperature (for example from a 3rd effect instead from a 2nd effect). Other possibility is using of heat from superheated condensate or vapours going to a condensation. We will talk over some possibilities.

2.1. Moving of a vapour withdrawal ΔO_i from an effect i to $i+1$

As it is said above the effect has for example a replacement of a tubular HE with a plate HE. An existing withdrawal of, for example a 2nd vapour in amount of $\Delta O_2 = 4,7$ t/h is moved to a 3rd vapour. A flow sheet of the evaporator is on the next page – Fig.2.

Analogous to the first part of the example we do the evaporator balance. We use eq. (3). Further we derive a general relation and then calculate an effect. Other given data are the same, it means that the total amount of evaporated water is the same too.



$$\begin{aligned}
 4^\circ \quad W'_4 &= x' + O_4 \\
 3^\circ \quad W'_3 &= x' + O_4 + O_3 + \Delta O' \\
 2^\circ \quad W'_2 &= x' + O_4 + O_3 + \Delta O' + O_2 - \Delta O' \\
 1^\circ \quad W'_1 &= x' + O_4 + O_3 + \Delta O' + O_2 - \Delta O' + O_1 + y' \approx M'_{S1} \\
 \Sigma \quad W &= 4*x' + 4*O_4 + 3*O_3 + 3*\Delta O' + 2*O_2 - 2*\Delta O' + O_1 + y'
 \end{aligned} \tag{3'}$$

Vapour loss to condensation is

$$\begin{aligned}
 x' &= (W - O_1 - 2*O'_2 - 3*O'_3 - 4*O_4) / 4 \\
 \underline{x'} &= (W - O_1 - 2*O_2 - 3*O_3 - 4*O_4 - \Delta O') / 4 = \underline{x - \Delta O' / 4}
 \end{aligned} \tag{12}$$

Amount of heating steam to evaporator is

$$\begin{aligned}
 M'_{SEVAP} &= M'_{S1} \approx x' + O_4 + O_3 + \Delta O' + O_2 - \Delta O' + O_1 + y' \\
 M'_{SEVAP} &= x - \Delta O' / 4 + O_4 + O_3 + O_2 + O_1 \\
 \underline{M'_{SEVAP}} &= \underline{M'_{S1}} \approx \underline{M_{SEVAP} - \Delta O' / 4}
 \end{aligned} \tag{13}$$

It follows from these equations that a 4th vapour loss to condensation and amount of heating steam to evaporator is lowered about 1/4 of a value of moved withdrawal. Generally it is possible to set a following relation for effect of ΔO moving:

$$\underline{\Delta M_{SEVAP}} = \underline{\Delta x} \approx \underline{\Delta O * (\text{about how many effects a withdrawal is moved}) / (\text{number of effects})}$$

For our case it is $n = 4$, moving about 1 effect. Then the eq. (3') are

$$x' = (93,5 - 16,0 - 2*11,1 - 3*13,6 - 4*3,1) / 4 = 0,52 \text{ t/h}$$

$$\begin{aligned}
 4^\circ \quad W'_4 &= 0,52 + 3,1 &= 3,62 \text{ t/h} \\
 3^\circ \quad W'_3 &= 0,52 + 3,1 + 13,6 &= 17,22 \text{ t/h}
 \end{aligned}$$

$$\begin{array}{rcl}
2^\circ & W'_2 = 0,52 + 3,1 + 13,6 + 11,1 & = 28,32 \text{ t/h} \\
1^\circ & W'_1 = 0,52 + 3,1 + 13,6 + 11,1 + 16,0 & = 44,32 \text{ t/h} \\
\hline
\Sigma & W = & = 93,5 \text{ t/h}
\end{array}$$

An amount of heating steam has to be equal (for above mentioned presumptions) to an amount of evaporated water in the 1st effect. Than it is

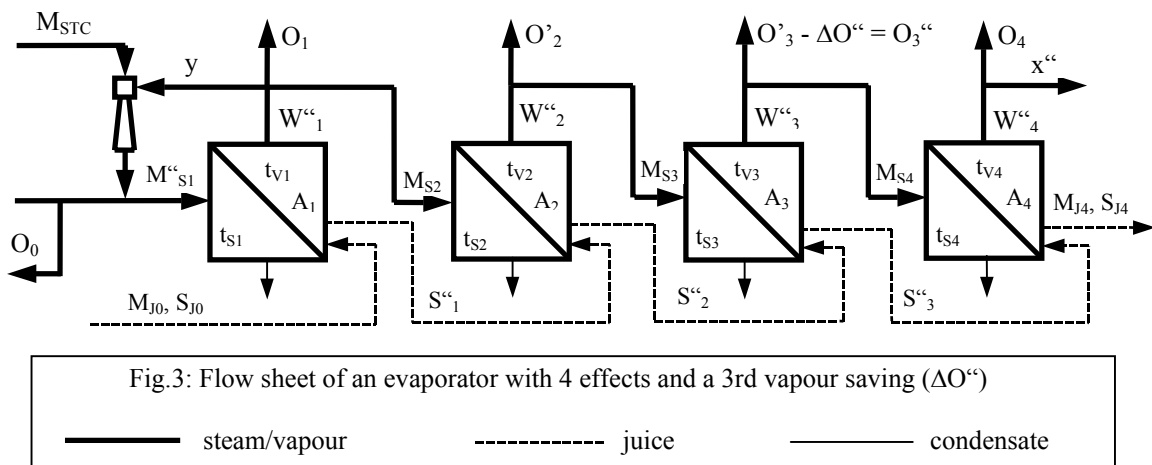
$$M_{S1} \approx 44,3 \text{ t/h}$$

The measure saves c. 1,2 t/h of steam. For 80 days of campaign and steam cost c. 320 Kč/t (c. 150 Kč/GJ, $r_{P1} = 2,16 \text{ GJ/t}$) is a campaign savings

$$1,2 * 24 * 80 * 320 \approx 737 \text{ 000,- Kč.}$$

2.2. Substitution of withdrawal $\Delta O''$ with a waste heat

We suppose the previous variant but with using a waste heat. For example a part of juice heating before liming (with the 3rd vapour) is substituted by a heating with a condensate (plate HE raw juice - condensate). The 3rd vapour withdrawal will be lower by $\Delta O'' = 5,9 \text{ t/h}$, it means that instead of $O'_3 = 13,6 \text{ t/h}$ it is only $O''_3 = 7,7 \text{ t/h}$. The evaporator flow sheet is than (Fig.3.):



The evaporator balance is similar like in previous calculations

$$\begin{array}{rcl}
4^\circ & W''_4 = x'' + O_4 & \\
3^\circ & W''_3 = x'' + O_4 + O'_3 - \Delta O'' & \\
2^\circ & W''_2 = x'' + O_4 + O'_3 - \Delta O'' + O'_2 & \\
1^\circ & W''_1 = x'' + O_4 + O'_3 - \Delta O'' + O'_2 + O_1 + y'' \approx M''_{P1} & (3'') \\
\hline
\Sigma & W = 4*x'' + 4*O_4 + 3*O'_3 - 3*\Delta O'' + 2*O'_2 + O_1 + y'' &
\end{array}$$

Vapour loss to condensation is

$$\underline{x''} = (W - O_1 - 2*O_2 - 3*O_3 - 4*O_4 + 3* \Delta O'') / 4 = \underline{x + 3 / 4 * \Delta O''} \quad (14)$$

Amount of heating steam to the evaporator is

$$M''_{SEVAP} = M''_{P1} \approx x'' + O_4 + O_3 - \Delta O'' + O_2 + O_1 + y'$$

$$M''_{SEVAP} = M''_{P1} \approx x + 3 / 4 * \Delta O'' + O_4 + O_3 - \Delta O'' + O_2 + O_1$$

$$\underline{M''_{SEVAP} = M''_{S1} \approx M_{SEVAP} - \Delta O'' / 4} \quad (15)$$

From these equations results that a 4th vapour loss to a condensation is higher about 3/4 of the value of saved withdrawal and an amount of heating steam to evaporator is lower about 1/4 of the value of saved withdrawal. It is done by this that we have to have the same concentration of the thick juice. A following relation for a specification of a heating steam saving owing to a vapour withdrawal saving ΔO is valid:

$$\underline{\Delta M_{SEVAP} \approx \Delta O - \Delta O * (\text{effect where a withdrawal is saved}) / (\text{number of effects})}$$

Ex.: We save ΔO on the 3rd vapour $\Delta M_S \approx \Delta O - \Delta O * 3/4 = 1/4 * \Delta O$
 We save ΔO on the 2nd vapour $\Delta M_S \approx \Delta O - \Delta O * 2/4 = 1/2 * \Delta O$

Note: If we do other moving of vapour withdrawals or install thermo-compressor (TC) etc. so that vapour loss to condensation will not increase than for a such case is $\Delta M_{SEVAP} \approx \Delta O$. Similar combinations are done during existing evaporators optimisations.

For our case it is $n = 4$ and we save the 3rd vapour. We suppose, that the variant improves previous variant ('), it is that we start from its results. Then balance equations are (3'')

$$x'' = (93,5 - 16,0 - 2*11,1 - 3*7,7 - 4*3,1) / 4 = 4,95 \text{ t/h}$$

$$4^\circ \quad W''_4 = 4,95 + 3,1 = 8,05 \text{ t/h}$$

$$3^\circ \quad W''_3 = 4,95 + 3,1 + 7,7 = 15,75 \text{ t/h}$$

$$2^\circ \quad W''_2 = 4,95 + 3,1 + 7,7 + 11,1 = 26,85 \text{ t/h}$$

$$1^\circ \quad W''_1 = 4,95 + 3,1 + 7,7 + 11,1 + 16,0 = 42,85 \text{ t/h}$$

$$\Sigma \quad W = \quad = 93,5 \text{ t/h}$$

Amount of heating steam (for above mentioned presumptions) has to be equal to the amount of evaporated vapour in the 1st evaporator effect. Then it is

$$M''_{SEVAP} = M''_{S1} \approx 42,85 \text{ t/h}$$

This measure saves, compared to the previous variant, c. 1,45 t/h of steam. For 80 days campaign and cost of steam c. 320 Kč/t (c. 150 Kč/GJ, $r_{S1} = 2,16 \text{ GJ/t}$) an another campaign saving is

$$1,45 * 24 * 80 * 320 \approx \mathbf{890\ 000,- \text{ Kč.}}$$

2.3. Thermo-compressor (TC) installation

We suppose a TC installation to the previous variant. The TC is designed so that to the vapour loss to the condensation will be $x''' = 0$. The evaporator flow sheet is similar like for the previous variant (Fig.3), but the 1st vapour withdrawal (y) to the TC is not zero. The amount of evaporated water in the 1st effect is much higher for the variant. Therefore the 1st effect has to be designed with the larger heat transfer area (HTA) or a new effect is added to an existing one (for example in parallel from the point of view of steam, in series from the point of view of juice). The evaporator balance is then:

$$\begin{aligned}
 4^\circ \quad W'''_4 &= 0 + O_4 \\
 3^\circ \quad W'''_3 &= 0 + O_4 + O''_3 \\
 2^\circ \quad W'''_2 &= 0 + O_4 + O''_3 + O''_2 \\
 1^\circ \quad W'''_1 &= 0 + O_4 + O''_3 + O''_2 + O_1 + y''' \approx M'''_{P1}
 \end{aligned} \tag{3'''}$$

$$\Sigma \quad W = 4*O_4 + 3*O''_3 + 2*O''_2 + O_1 + y'''$$

$$y''' = W - (4*O_4 + 3*O''_3 + 2*O''_2 + O_1) = 4 * x'' \tag{16}$$

$$x''' = 0 \quad x'' = (W - 4*O_4 - 3*O''_3 - 2*O''_2 - O_1) / 4$$

As the part of the 1st vapour y''' comes back to the 1st effect the total amount of heating steam has to be lower about the part. The amount of heating steam (going to the 1st effect) is a driving steam to the TC plus exhaust steam mixing with a compressed steam from the TC. Then a heating steam consumption is

$$\underline{M'''_{SEVAP} = M'''_{S1} - y'''} \approx \underline{W'''_1 - y'''} = O_4 + O''_3 + O''_2 + O_1 = M'''_{S1} - x'' \tag{17}$$

Approximately it is possible to say that an TC installation can save most a such amount of a heating steam that is equal to an existing (or calculated for a variant) vapour loss to condensation. An amount of vapour withdrawal to a TC (y) is approximately equal to an existing vapour loss to a condensation times amount of evaporator effects (for presumption that a thick juice concentration is for both variants the same.

A size of TC as well as an amount of withdrawn vapour has technical limits (an available amount of driving steam, HTA of a 1st effect, temperatures in an evaporator and thermodynamic management of a process in a too big TC).

We do a balance according eq. (16) and (3''') for our given data:

$$y''' = 93,5 - (4*3,1 + 3*7,7 + 2*11,1 + 16,0) = 19,8 \text{ t/h}$$

$$\begin{aligned}
 4^\circ \quad W'''_4 &= 0 + 3,1 &= 3,1 \text{ t/h} \\
 3^\circ \quad W'''_3 &= 0 + 3,1 + 7,7 &= 10,8 \text{ t/h} \\
 2^\circ \quad W'''_2 &= 0 + 3,1 + 7,7 + 11,1 &= 21,9 \text{ t/h} \\
 1^\circ \quad W'''_1 &= 0 + 3,1 + 7,7 + 11,1 + 16,0 + 19,8 &= 57,7 \text{ t/h}
 \end{aligned}$$

$$\Sigma \quad W = \quad \quad \quad = 93,5 \text{ t/h}$$

The steam consumption to the evaporator according (17) is

$$M'''_{SEVAP} = 57,7 - 19,8 = 37,9 \text{ t/h}$$

This measure saves in comparison to the previous variant c. 4,95 t/h of steam. For 80 days campaign and cost of steam c. 320 Kč/t (c. 150 Kč/GJ, $r_{s1} = 2,16 \text{ GJ/t}$) an another campaign saving is

$$4,95 * 24 * 80 * 320 \approx 3\ 041\ 000,- \text{ Kč.}$$

A realisation of all 3 mentioned variants of vapour withdrawals optimisation (and a system of juice heating indeed) saves during one campaign **c. 4 668 000,- Kč**. It needs expenses to installation of 2 plate HE and a TC. As the installation of the TC causes an increase of the amount of evaporated water in the 1st effect from an original value $W_1 = 45,5 \text{ t/h}$ to $W'''_1 = 57,7 \text{ t/h}$, a heat transfer area of the 1st effect has to be increased too. To the original amount of W_1 corresponds the theoretical HTA $A_{IT} = 1428 \text{ m}^2$, the real was $A_1 = 1600 \text{ m}^2$. A HTA necessary for the last variant with the TC is estimated to

$$A'''_1 \approx A_{IT} * W'''_1 / W_1 = 1428 * 57,7 / 45,5 = 1810 \text{ m}^2 \quad (+ 382 \text{ m}^2)$$

$$A'''_1 \approx A_1 * W'''_1 / W_1 = 1600 * 57,7 / 45,5 = 2030 \text{ m}^2 \quad (+ 430 \text{ m}^2)$$

For this HTA of the 1st effect will be temperatures in the evaporator practically the same like for previous calculations.

3. Comparison of results for simplified and exact calculations

This exact calculation is done for the same given data and type of effects (1st and 2nd effects - Robert type, 3rd and 4th effects falling film type). Various latent heat of evaporation, heat losses 3 % of transported heat, pressure losses at vapour flow between effect, utilisation of heat of vapour from expanded condensate (marked Eij), condensate from technology return to receivers (KOi) and condensate withdrawals from receivers for technology purposes (Kti) are taken into account.

Comparisons of results of both calculations are introduced in the next table. SC = simplified calculation, EC = exact calculation from a computer.

Parameter	M_{J0} (t/h)	M_{J4} (t/h)	S_{J0} (%)	S_1 (%)	S_2 (%)	S_3 (%)	S_4 (%)
SC	120	26,5	15,0	24,2	40,0	57,5	68,0
EC	120	26,5	15,0	24,2	39,9	56,6	68,0

Parameter	ts_1 (°C)	tv_1 (°C)	tv_2 (°C)	tv_3 (°C)	tv_4 (°C)
SC	135,0	126,6	115,4	102,0	86,0
EC	135,0	126,6	115,8	101,3	81,9
Difference (%)	0,0	0,0	-0,3	0,7	5,0

Parameter	W_1 (t/h)	W_2 (t/h)	W_3 (t/h)	W_4 (t/h)	x (t/h)	y (t/h)	M_{SEVAP} (t/h)
SC	45,5	29,5	13,7	4,8	1,7	0,0	45,5
EC	45,6	29,0	13,2	5,7	5,4	0,0	47,5

Difference (%)	-0,2	1,7	3,8	-15,8	-68,5	0,0	4,2
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How it results from these comparisons differences between juice saccharisations (concentration) are small. Owing to heat losses in effects and actual latent heat of evaporation is for the exact calculation a higher heating steam consumption. Heat losses are assumed 3 % of transferred heat in effects. Latent heat of condensing steam/vapour is lower than latent heat of evaporating vapour in the same effect, it is that in every effect has to condense more steam/vapour than an amount of evaporated vapour from juice is.

Utilisation of vapour expanded from condensate reduces steam consumption, in our case about c. 2 t/h (without this it would be c. 49,5 t/h). Another effect of this is that the vapour loss to condensation is higher ($x = 1,7 \dots x = 5,4$ t/h) - see equations (3), (3''), (14) and (15). It is due to that expanded vapour from condensate flows to a vapour pipe and acts as a "negative withdrawal". From balance equation (3) results that for lower withdrawals and for keeping the same total amount of evaporated water has to be higher x value.

Differences between temperatures are for the all evaporator's effects max. 5 % (average 1,5 %). It is very good conformity for service. Only the difference for the 4th vapour (c. 4 °C) may brings problems with its utilisation for juice heating. Differences between amounts of evaporated water correspond for the 1st, 2nd and 3rd effects. For the 4th effect and vapour loss to condensation x are differences too high. The problem was sooner solved by this way. A last effect was designed to a vapour loss to condensation c. 4 - 5 % b. (to treated beet). For our case a corresponding value is $x = 4,2 - 5,2$ t/h. This corresponds to a calculated value. Last effects (concentrators) are usually over-designed as a thick juice concentration is controlled there (control using less or more open a control valve in a vapour pipe between the last effect and a condenser (see an example concerning a line for a powder milk production).

4. Conclusion

During a similar line optimisation we have to take into account other factors too. For example disposition of machinery, free available space, transport distance, control possibility, available sources of energy and variation of their supply. Parameters of a life steam (driving steam) have effect for example for a TC installation.

TC needs a constant pressure of a driving steam. If it fluctuates the TC works worse (for example it sucks in less 1st vapour - y). As a result of it is higher heating steam consumption. When a driving steam pressure is lower than c. 50 - 60 % of designed pressure a TC function goes out (such TC works like a T-fitting). A result of it is that the driving steam together with a part of heating steam from a 1st effect calandria flow directly to the 1st vapour. The 1st effect stops its boiling process. A concentration of thick juice is very low.

Lower pressure of the driving steam brings another risk too. A flow of mixture of the driving steam and the 1st vapour comes off and on a diffuser's wall from time to time. Rising pulsation causes fatigue loading and possible destruction. But the flow pulsation can destroy tubes in the 1st effect too (in front of heating steam inlet).

A simplified process of a sugar evaporator calculation and design is shown in the example. The process may be used for any evaporator with vapour withdrawals (for technological purposes). Ways of an optimisation of such evaporator and their effects to steam consumption etc. are shown too.

