Simplified Balance of Line for Milk Powder Production

VLP – Processing lines of food industry - Example

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Task – given data

A daily output of a milk powder is 20 t/d. Both dryer and evaporator work in a day cycle 20 h operation and 4 h chemical cleaning (CIP = cleaning in place). A milk heater is designed as a double heater. It is that one part operates as a heater / cooler and the second part is cleaned. In this way it is able to work 20 h like the evaporator.

Dry matter of incoming milk is 12 %, incl. fat content 4 %. In a separator is the fat separated, so that to the evaporator flows milk with the fat content c. 0 % (dry matter of skimmed milk is c. 8 %). In the fourth effect evaporator is the skimmed milk concentrated to 45 % DM and in the spray drier is dried to 97 % DM. Dry matter of cream from the separator is 40 %.

Milk specific heat is c. c_{PM} = 3,9 kJ/kgK and from reasons of simplification it is not taken into account its dependence on temperature and milk concentration.

We will calculate with a heat recuperation during milk heating and cooling (pasteurised hot milk will heat incoming cold milk in a regeneration section). Thus energy for milk heating and cooling is saved. Incoming milk temperature is 10 °C, pasteurisation temperature is 80 °C, outlet milk temperature is 10 °C. The separator is between regeneration and pasteurisation sections (lower amount of milk).

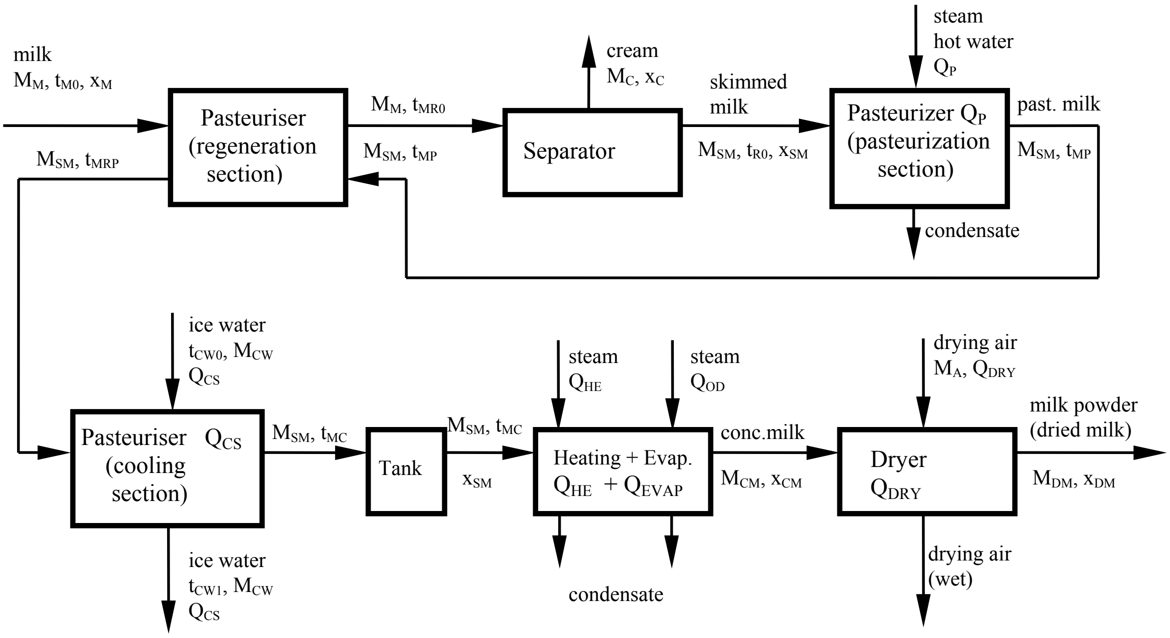
According evaporator technical specifications (TS) is a specific steam consumption d = 0,28 kg/kg E.W. (related to a total amount of evaporated water). Boiling temperature in a 1st effect is 70 °C, heating (condensing) steam temperature in the 1st effect is 80 °C. Heat in superheated milk (+) and heat losses (-) are neglected. According dryer technical specifications is heat consumption in such drier c. twice as a theoretical one (calculated from a balance of dried water in h – x diagram). For more detailed evaporator calculation see an example concerning a sugar juice evaporator.

Aims = To calculate, design and set:

1. A technological scheme of the line (flowsheet) with singe flow identifications
2. Daily amount of milk incoming to the line and amount of creme leaving separator. Specification of a line mass balance.
3. Consumption of energy of the line (thermal energy for heating or cooling, electric energy for pumps and fans).
4. Suggest a way of the line control (linkage and control elements draw in the flowsheet).
5. Check following possibilities of the line optimisation (here some possibilities are set)
    - Pasteurisation near the evaporator
    - Higher rate of regeneration in the milk heater
    - Installation of another one evaporator effect and a thermocompressor
    - Increase of milk concentration after the evaporator till 50 % DM

- Decrease of powder concentration 97 % to 95 % DM (the value is permitted by a Czech standard – better line operation control).

1. Flowsheet of the line for dried milk production



Note: - A regeneration section is usually divided into 2 sections. Between them are installed a separator (centrifuge) and a homogeniser (in a case of long-life drink milk production).
- Sections of regeneration, pasteurisation and cooling are in one apparatus (in1 stand).
- By reason of simplification is the milk heating before the evaporator drawn in 1 block with the evaporator (in reality there are several steps of the milk heating; step by step with vapours from the evaporator – see Example concerning the sugar juice evaporator).

2. Mass line balance

Given data:

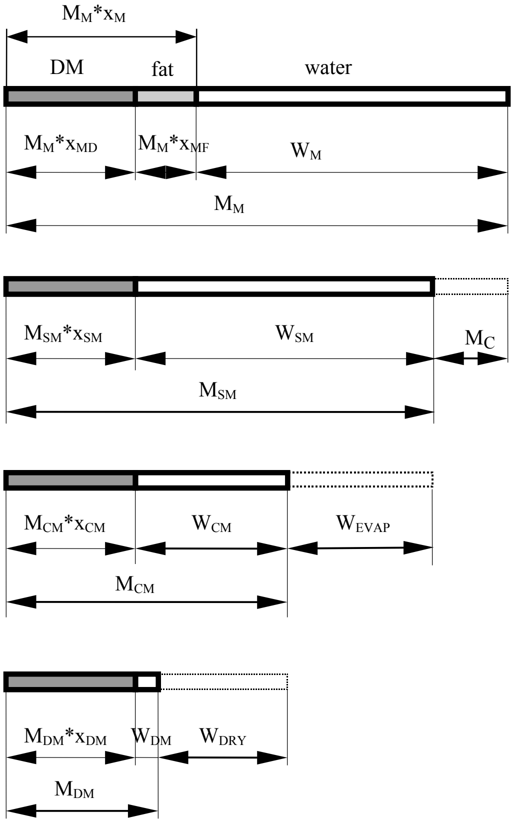
Amount of milk powder	M_{DM} = 20 t/d = 20 t/20 h = 1,0 t/h
Dry matter of inlet milk	x_M = 12 % DM
Dry matter of conc. milk	x_{CM} = 45 % DM
Dry matter of milk powder	x_{DM} = 97 % DM (moisture 3 %)
Dry matter of cream	x_C = 40 % DM (incl. fat) – mostly fat
Dry matter of skimmed milk	x_{SM} = 8 % DM

For our solution the conservation of mass law is used. It is that the amount of inlet mass has to be equal to the amount of outlet mass (in a line or apparatus or process). This is concerned of single components too (dry matter, water, fat etc.).

DM. of inlet milk = fat + milk sugar (lactose) + proteins (casein) + mineral matters

We suppose that all fat is separated (separation “sharpness” is c. 0,01 %) and that the amount of dry matter and water in the cream does not effect the skim milk dry matter too much. The simplification is done by reason of shortening of the long example.

We have to do the mass and dry matter balance of the line to calculate the amount of inlet milk. For the calculation we can use following figures.



fresh inlet milk
(x_{MD} = dry matter without fat)
($x_M = x_{MS} + x_{FM}$)

skim milk
(fat is separated - cream = M_C)

concentrated milk
(part of water is evaporated – W_{EVAP})

dried milk (milk powder)
(part of water is dried off – W_{DRY})

It follows from the figures that the amount of DM in milk is constant during processes of evaporating and drying. This makes possible to do the mass line balance. It is valid that:

$$M_{SM} * x_{SM} = M_{CM} * x_{CM} = M_{DM} * x_{DM} \qquad \text{amount of DM}$$

Amount of skim milk after the separator (= before the evaporator and in pasteurisation and cooling sections too).

$$M_{SM} = M_{DM} * x_{DM} / x_{SM} \approx 1{,}0 * 97 / 8 \approx 12{,}125 \text{ t/h}$$

Amount of concentrated milk

$$M_{CM} = M_{DM} * x_{DM} / x_{CM} \approx 1{,}0 * 97 / 45 \approx 2{,}156 \text{ t/h}$$

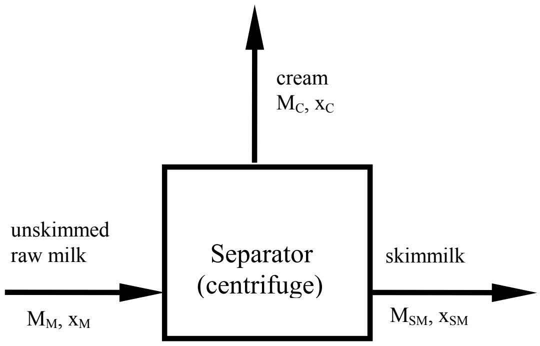
Amount of evaporated water in the evaporator

$W_{EVAP} = M_{SM} - M_{CM} = 12{,}125 - 2{,}156 = 9{,}969$ t/h

Amount of water dried off in the dryer

$W_{DRY} = M_{CM} - M_{DM} = 2{,}156 - 1{,}000 = 1{,}156$ t/h

Fat and milk balance in separator



Note: Fat is concerned as DM

$x_M = 12$ % DM	raw milk
$x_{SM} = 8$ % DM	skim milk
$x_C = 40$ % DM	cream
$M_{SM} = 12{,}125$ t/h	

$M_M = M_{SM} + M_C$ mass balance

$M_M * x_M = M_{SM} * x_{SM} + M_C * x_C$ DM balance

By substitution of given and calculated data in the 2 equations we specify amount of cream and amount of unskimmed raw milk incoming to the line.

$M_M = M_C + 12{,}125$

$M_M * 12 = M_C * 40 + 12{,}125 * 8 = M_C * 40 + 97{,}0$

$(M_C + 12{,}125) * 12 = M_C * 40 + 97{,}0$

$M_C = (12{,}125 * 12 - 97{,}0) / (40 - 12) = 1{,}732$ t/h amount of cream leaving the line

$M_M = M_{SM} + M_C = 12{,}125 + 1{,}732 = 13{,}857$ t/h amount of unskimmed milk entering the line

Daily milk consumption is then (20 h operation + 4 h chem. cleaning)

$M_{MD} = 13{,}857 * 20 = 277{,}1$ t/d

Dry mass balance checking

$13{,}857*0{,}12 = 1{,}663$ t/h DM inlet to separator
$1{,}732*0{,}40 + 12{,}125*0{,}08 = 1{,}663$ t/h DM outlet from separator

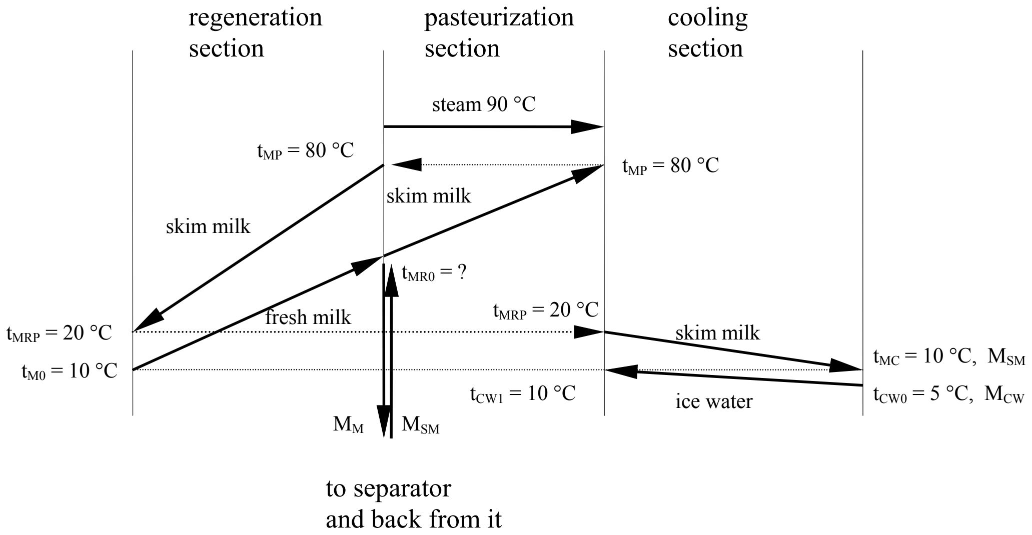
3. Energy consumption of line

For determination of an energy consumption of the line we have to do an energy balance of all parts of the line. We will use a principle of conservation of energy.

Thermal balance of pasteuriser

We suppose that the temperature difference between outlet temperature of cooled skimmilk and inlet temperature of inlet fresh milk is 10 °C. A temperature course in regeneration, pasteurisation and cooling sections is in the next figure.

Note: In following balances units frequently used in praxis are used (i.e. kg/h, t/h etc. instead of SI units).



Thermal balance of regeneration section

Firstly we have to specify a milk temperature after this section. Specifics heat of whole and skimmilk is c. 3,9 kJ/kgK (simplification – see above - for 15 °C and whole milk is 3,94 kJ/kgK, for skim milk is 3,96 kJ/kgK, for both milks with higher temperature slightly falls). Heat losses are neglected too. Than is:

$$Q_{REGheat} = Q_{REGcool}$$
$$M_M * c_M * (t_{MRO} - t_{M0}) = M_{SM} * c_M * (t_{MP} - t_{MRP})$$

$$13{,}857 * 3{,}9 * (t_{MRO} - 10) = 12{,}125 * 3{,}9 * (80 - 20)$$

$$t_{MRO} = (12{,}125 * 60 + 13{,}857 * 10) / 13{,}857 = 62{,}5\ °C$$ milk temperature after regen. preheating

Checking

$$Q_{REGheat} = 13857 * 3{,}9 * (62{,}5 - 10) / 3600 = 788{,}1\ kW$$
$$Q_{REGcool} = 12125 * 3{,}9 * (80 - 20) / 3600 = 788{,}1\ kW$$

For next calculation we specify a mean logarithmic temperature difference

$$\Delta t_{LREG} = ((80 - 62{,}5) - (20 - 10)) / \ln((80 - 62{,}5) / (20 - 10)) = 13{,}4\ °C$$

Note: It is a simplification for our example. In practice there are installed 2 regeneration sections. 1° heats milk to a temperature proper for fat separation alternatively for homogenisation, 2° heats milk to max. possible temperature before pasteurisation section (energy economy).

Heat needed for milk heating in pasteurisation section

Milk inlets to the section with the temperature of 62,5 °C and has to be heated to pasteurisation temperature 80 °C. With the temperature it flows to a holder (unheated tube or interplate channels), where it flows for a given time. Then it flows back to the regeneration section and heats fresh milk. Similar like in the previous we made the thermal balance.

$$Q_P = Q_{PAST} = M_{SM} * c_M * (t_{MP} - t_{MRO})$$
$$Q_P = 12125 * 3{,}9 * (80{,}0 - 62{,}5) / 3600 = 229{,}9\ kW$$
$$= 229{,}9*3600*20/10^6 = 16{,}55\ GJ/d$$

The past. section can be heated with condensing steam or recirculating hot water that is heated with steam injecting into water. If we neglect heat losses is the steam consumption for both cases the same. We suppose steam with pressure 100 kPa - abs. ($r_P = 2258$ kJ/kg). Then it is for milk pasteurisation necessary amount of steam:

$$M_{SP} = Q_P / r_P = 229{,}9 * 3600 / 2258 = 367\ kg/h$$

Heat taken away in cooling section from milk

$$Q_{CS} = M_{SM} * c_M * (t_{MRP} - t_{MC})$$
$$Q_{CS} = 12125 * 3{,}9 * (20 - 10) / 3600 = 131{,}4\ kW$$
$$= 131{,}4*3600*20/10^6 = 9{,}46\ GJ/d$$

Determination of heat regeneration ratio in pasteuriser - HRR

The ratio says us how many % of heat fed in the pasteuriser is reused for heating in the regeneration section. Formerly the ratio was above 85 %, nowadays is more than 95 %. the higher ratio the lower energy consumption (heat and cold) but at the expense of a greater heat transfer area (economical comparison of energy and material costs). For the same milk amount, specific heat and negligible heat losses it is possible to simplify the ratio to the following relation. It contains only known temperatures and it is possible to use it for approximate determination of HRR.

$$HRR = Q_{reused} / Q_{fed} \approx (t_{MP} - t_{MRP}) / (t_{MP} - t_{M0})$$
$$HRR \approx (80{,}0 - 20{,}0) / (80{,}0 - 10{,}0) * 100 = 85{,}7\ \%$$

Note: As it is said above the simplified relation is valid only for $M_M*c_M = M_{SM}*c_{SM}$.

Milk heating up before evaporator

According the task milk is heated up from 10 °C to a boiling temperature in the 1st evaporator effect, it is to 70 °C. Milk heating is done step by step with vapours leaving individual evaporator's effects. In the last step heating steam is used.

$$Q_{HE} = M_{SM} * c_M * (t_{EVAP1} - t_{SM})$$
$$Q_{HE} = 12125 * 3{,}9 * (70 - 10) / 3600 = 788{,}1 \text{ kW}$$
$$= 788{,}1*3600*20/10^6 = 56{,}75 \text{ GJ/d}$$

Heat fed as heating steam into the 1st evaporator's effect

Owing to the example simplification we do not calculate the evaporator exactly – various latent heats, heat losses, expansion of vapour from superheated milk or condensate etc. (see example "Calculation of sugar juice evaporator"). We take, for example, data from technical specifications, where the specific heating steam consumption **d** is given (see given data - **d** is related, for example, to steam at 0°C – r_{rel} = 2500 kJ/kg – this gives lower steam consumption, sometimes is d related to steam at 100 °C – r_{rel} = 2258 kJ/kg – this gives higher values, or to actual heating steam parameters → always it is necessary to check for what heating steam parameters is the specific heating steam consumption d given).

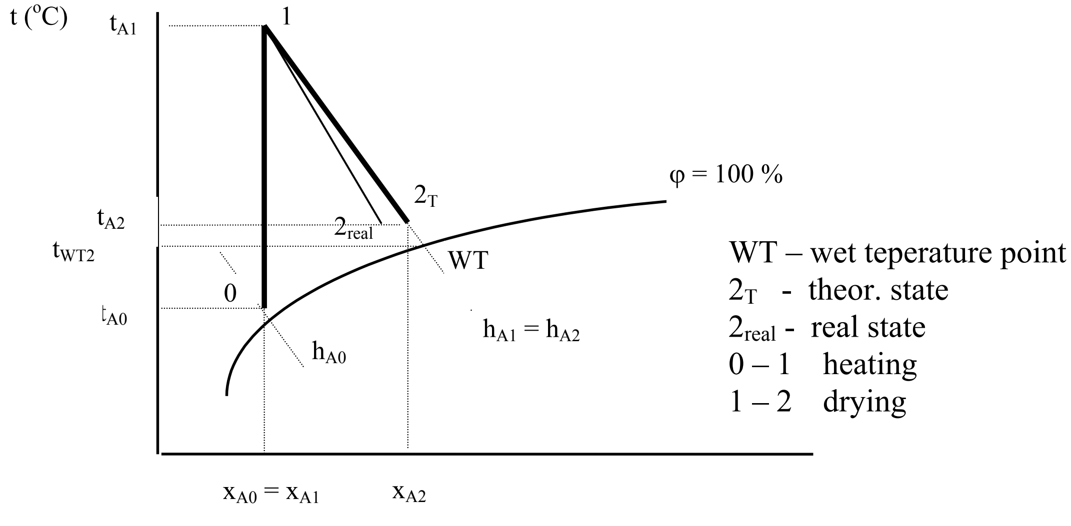
$$Q_{EVAP} = d * W_{EVAP} * r_{rel}$$
$$Q_{EVAP} = 0{,}28 * 9969 * 2500 / 3600 = 1938{,}4 \text{ kW}$$
$$= 1938{,}4*3600*20/10^6 = 139{,}56 \text{ GJ/d}$$

Amount of heating steam (pressure 100 kPa)

$$M_{HSEVAP} = Q_{EVAP} / r_{rel} = 1938{,}4 * 3600 / 2258 = 3090{,}5 \text{ kg/h}$$

Drying of concentrated milk in spray drier

For a dryer calculation we have to specify amount of drying air. Drying course is displayed in the Mollier's **h - s** diagram of wet air.



Parameters of drying air are usually given by requirements to a product quality and a dryer economy. The higher air temperature t_{A1} the higher dryer economy, the smaller dryer dimensions and the smaller amount of drying air (smaller fan and its electric energy consumption). On the other side high air temperature can deteriorate a product quality (digestibility, taste, colour, solubility etc.). Temperature of outlet air t_{A2} has to be so high so that in following equipment (piping, cyclone, filter, fan etc.) air temperature does not fall below temperature of wet thermometer (condensation of moisture from air). Therefore we set air temperature and relative humidity for 3 states of drying air (for the parameters we specify from the Mollier's diagram specific humidity **x** and enthalpy **h**):

Entering air before heating (sucked from a room where the dryer is installed - warm)
$t_{A0} = 30$ °C $\varphi_{A0} = 40$ % $h_{A0} = 55$ kJ/kg d.air $x_{A0} = 0{,}011$ kg hum./kg d.air.

Air after heater = inlet to dryer
$t_{A1} = 180$ °C $h_{A1} = 211$ kJ/kg d.air $x_{A1} = 0{,}011$ kg hum./kg d.air.

Air leaving dryer ($t_{WT} = 44$ °C)
$t_{A2} = 85$ °C $\varphi_{A2} = 13$ % $h_{A2} \approx 211$ kJ/kg d.air $x_{A2} = 0{,}047$ kg hum./kg d.air.

Amount of drying air is calculated on this premise. 1 kg of drying air with given temperatures is able to take away ($x_{A2} - x_{A1}$) of moisture from a dried material (milk). In the dryer it is necessary to take away $W_{DRY} = 1156$ kg/h of water. Than the theoretical amount of drying air is

$$M_A = W_{DRY} / (x_{A2} - x_{A1}) = 1156 / (0{,}047 - 0{,}011) = 32111 \text{ kg/h}$$

Theoretical amount of heat needed for taking away the amount of water W_{DRY} is (temperature of dried material is practically $t_{WT} = 44$ °C, for the temperature is the latent heat of evaporation $r = 2397$ kJ/kg)

$$Q_{DRYT} = W_{DRY} * r = 1156 * 2397 / 3600 = 769{,}7 \text{ kW}$$

Theoretical amount of heat needed for heating up of heating air in the dryer is given as a product of the amount of heating air and a difference of its enthalpies (after and before heating).

$$Q_{AT} = M_A * (h_{A1} - h_{A0}) = 32111 * (211 - 55) / 3600 = 1391{,}5 \text{ kW}$$

For heat losses in dryer c. 20 % is an real heat consumption in the dryer:

$$Q_{DRY} = 1{,}2 * Q_{AT} = 1{,}2 * 1391{,}5 = 1669{,}8 \text{ kW}$$
$$= 1669{,}8*3600*20/10^6 = 120{,}23 \text{ GJ/d}$$

Note: A higher drying air amount or higher drying air temperature t_{A1} (for example from 180 °C to 210 °C) or combinations compensate heat losses.

Checking of the dryer effectiveness (dryer heat consumption $\approx$ 2 x theoretical consumption)

$Q_{DRY} / Q_{DRYT} = 1669{,}8 / 769{,}7 = 2{,}17$ set temperatures are OK

Power requirements of drying air fans

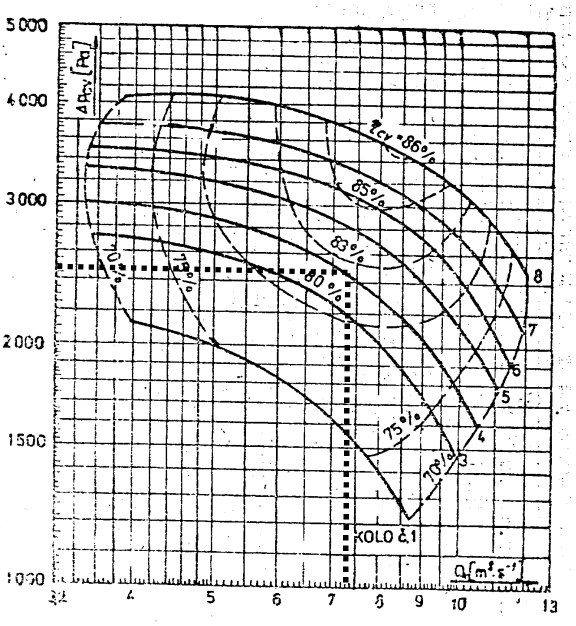
Such big dryer needs 2 fans, the first one (compressive) before the dryer, the second one (sucking) on the outlet after the dryer. A small underpressure has to be in the dryer (owing to a dusting to a dryer surroundings), so the sucking fan has to have a little higher discharge (performance) than the compressive one. We will consider both fans the same for our example. Total pressure losses in a dryer system (inlet air filter, heater, fan, piping, dryer, cyclones, outlet air filter, fan) are estimated to $\Delta p_{ZC} = 5000$ Pa (on the basis of a similar system measuring or a calculations. Than 1 fan (average) has to “give” pressure c. $\Delta p_{PL1} = 2500$ Pa. The 1 fan power requirement is then

$$P_{F1} = V_A * \Delta p_{PL1} / \eta_{TF}$$

$V_A = M_A / \rho_A = 32111 / (1{,}2 * 3600) = 7{,}43\ m^3/s$ amount of drying air

A fan efficiency is specified from a fan characteristic. The characteristic is available for every fan in a technical standard (see next fig.). The characteristic shows a dependence of total pressure on airflow (for various fan type, wheel diameter and speed). The efficiency is, for radial fans, c. from 75 to 86 %. For specified airflow and needed pressure we set $\eta_{CV} \approx 82$ %. Than is the power requirement of 1 fan (we consider 20 % of reserve – heat losses and from it resultant higher drying airflow)

$$P_{MF} = 1{,}2 * P_F = 1{,}2 * 7{,}43 * 2500 / 0{,}82 = 27183\ W \approx 27{,}2\ kW$$



Fan type is RVK 1250; n = 980 rpm, wheel No.4, motor 30 kW sucking and 25 kW compressing.

Note: Relations needed for a fan or pump power requirement calculation

$P_{TEOR} = M * \Delta p / \rho * \eta$ (W; kg/s, Pa, kg/m^3, -)

$P_{TEOR} = V * \Delta p / \eta$ (W; m^3/s, Pa, -)

$P_{TEOR} = M * \Delta H * g / \eta$ (W; kg/s, m, m/s^2, -)

$\Delta p_{PL} = H_{PL} * \rho * g$ (Pa = kg/ms^2; m, kg/m^3, m/s^2)

(W = kgm^2/s^3)

Milk pump (centrifugal) power requirement – before pasteuriser

For this specification we have to know pressure losses in the pasteuriser, piping, valves and fittings and a hydrostatic head. For it we have to keep at our disposal technical specifications of the pasteuriser and a topology of its installation (location of tank, pump, pasteuriser, piping length and topology, number and types of valves and fittings etc.). Usually it is necessary to calculate pressure loses in piping and fittings (valves or butterfly valves characteristics = dependence of pressure loss on % of opening and flow rate). For our example we consider following values:

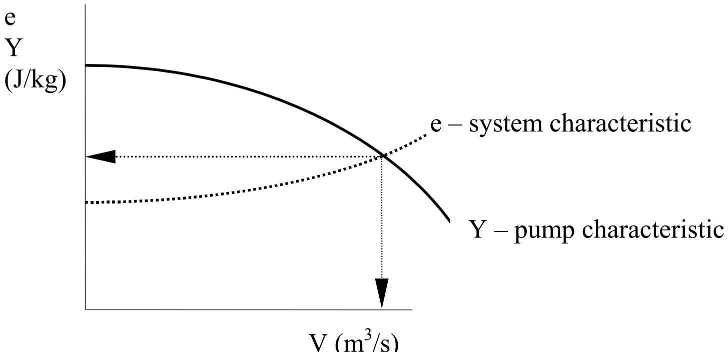
Pressure loss in system	$\Delta p_{PL} = 60$ kPa (N/m^2 = kg/m*s^2)
Hydrostatic head	$\Delta p_H = 100$ kPa (c. 10 m)
Milk flow rate	$M_M = 13857$ kg/h
Milk density	$\rho_M = 1030$ kg/m^3

<u>Specific energy given to milk in pump</u>

We use a working characteristic of the pump and system for needed calculations.

Y = specific energy given to pumped liquid by a pump in dependence on flow rate (a pump characteristic)

e = characteristic of the system = specific energy needed for a maintenance of the liquid flow rate (is specified from the system pressure loss)



Note: Needed flow rate in a system is set by a change of the system characteristic = for ex. by regulation valve.

$$e = \Delta p / \rho$$

Y = e ...... pump working point for a given system

(for $\rho = 1000$ kg/m^3, $e = Y \sim \Delta p_Z$, Y (J/kg) $\approx$ 10*H (m))

Considering of 20 % reserve is the pump power requirement

$$P_{MPP} = 1{,}2 * (\rho_M * V_M * Y) / \eta_P = 1{,}2 * M_M * Y / \eta_P \qquad [\text{kg/m}^3\text{*m}^3\text{/s*J/kg=J/s=W}]$$

Specific energy given to milk in the pump is:

$$e = \Delta p_{ZC} / \rho_M = (\Delta p_Z + \Delta p_H) / \rho_M = (60 + 100) * 10^3 / 1030 = 155{,}3 \text{ J/kg}$$

A pump efficiency varies, depending on pump types and pumping liquid, from 35 to 80 % (it is possible to set it from a pump characteristic for a selected pump). For our example is $\eta_P = 60\%$. Then is the pump power requirement:

$$P_{MPP} = (1{,}2 * 13857 * 155{,}3) / (3600 * 0{,}60) = 1196 \text{ W} \approx 1{,}2 \text{ kW}$$

Specification of the pump motor nominal input

$P_{MPPN} = R^* P_{MPP}$

Coefficient of reserve R is specified in dependence on the motor input in the next table:

P_{MP} (kW)	0,5 - 1,1	1,1 - 2,7	2,7 - 5,4	5,4 - 11	11 - 22	> 22
R (-)	2,0	1,5	1,4	1,3	1,2	1,1

Then is

$P_{MPPN} = 1{,}5 * 1{,}2 = 1{,}8$ kW

On the basis of pump's catalogues we specify a pump with a next higher motor input. In an actual plant for such flow rates and equipment pumps with 2,5 to 3 kW motor are installed (reserve for higher flow rate during chemical cleaning etc.).

Milk pump (centrifugal) power requirement – before evaporator

The pump is considered the same like before the pasteuriser. The pump pumps milk from a balance tank through 4 heaters to the 1st effect of evaporator (vacuum).

Concentrated milk pump power requirement – before dryer

Similar like in the previous we set:

Pressure lost in system	$\Delta p_{PL} = 20$ kPa ($N/m^2 = kg/m*s^2$)
Hydrostatic head	$\Delta p_H = 100$ kPa (c. 10 m)
Milk flow rate	$M_{CM} = 2156$ kg/h = 0,599 kg/s
Milk density	$\rho_M = 1100$ kg/m^3
Pump efficiency (< flow rate, > μ)	$\eta_P = 0{,}55$

$P_{MPD} = 1{,}2 * M_{CM} * \Delta p_{tot} / \rho_M * \eta_P$
$P_{MPD} = 1{,}2 * 0{,}599 * (20 + 100) / (1100 * 0{,}55) = 143$ W

$P_{MPDN} = R * P_{MPD} = 2{,}0 * 143 = 286$ W

In an actual plant for such flow rates and equipment pumps with 0,5 to 1 kW motor are installed.

Power requirement of spray disc motor

The calculation goes from these ideas. Concentrated milk has to be accelerated to a disc circumferential velocity and than has to get through holes in the disc. For simplification we take into account only a power input needed for the milk acceleration (bigger part).

$P_{SD} = M_{CM} * v_T^2 / 2 * \eta_{SD}$ [$kg/s * m^2/s^2 = kgm^2/s^3 = W$]

where $\eta_{SD} = 0{,}6$ až 0,7 is an effectiveness of the spray disc

$v_T = \pi * D_{SD} * n = 100$ to 300 m/s is a circumferential disc velocity
$v_T = 160$ m/s (Niro uses c. 150 to 180 m/s)

$$P_{SD} = 0{,}599 * 160^2 / 2 * 0{,}65 = 11794 \text{ W}$$

Theoretic motor input (gearbox efficiency 90 %, motor efficiency 95 % + reserve 20 %)

$$P_{SDM} = 1{,}2 * P_{SD} / \eta_{GB} * \eta_M)$$
$$P_{SDM} = 1{,}2 * 11794 / 0{,}90 * 0{,}95 = 16553 \text{ W} \approx 16{,}6 \text{ kW}$$

Nominal motor input

$$P_{SDMN} = R * P_{SDM} = 1{,}2 * 16{,}6 = 19{,}9 \text{ kW} \approx 20 \text{ kW}$$

Note: We did not consider a motor efficiency for pumps, as the inputs were too low and designed motors had sufficient reserves. But for the spray disc there are too high inputs and there is a gearbox (for example from c. 2800 to 15000 rpm) between the motor and disc.

Total energy balance of line

• Milk heating in pasteuriser (steam)	$Q_P = 229{,}9$ kW	= 16,55 GJ/d
• Heat taken away from milk in cooling section (c. 30 to 50 % of it is electric energy for compressors in cooling system)	$Q_{CS} = 131{,}4$ kW	= 9,46 GJ/d
• Milk heating before evaporator (steam, vapours)	$Q_{HE} = 788{,}1$ kW	= 56,75 GJ/d
• Self-cleaning separator (electric energy) (set from TS of separator)	$Q_{SEP} = 17$ kW	= 1,22 GJ/d
• Heat fed in heating steam into evaporator	$Q_{EVAP} = 1938{,}4$ kW	= 139,56 GJ/d
• Heat for heating air (steam)	$Q_{DRY} = 1670$ kW	= 120,23 GJ/d
• Input of compressing fan (electricity)	$P_{MFC} = 25{,}1$ kW	= 1,81 GJ/d
• Input of sucking fan (electricity)	$P_{MFS} = 30$ kW	= 2,16 GJ/d
• Input of pump before pasteuriser (electricity)	$P_{MPP} = 1{,}2$ kW	= 0,09 GJ/d
• Input of pump before evaporator (electricity)	$P_{MPE} = 1{,}2$ kW	= 0,09 GJ/d
• Input of pump before dryer (electricity)	$P_{MPD} = 0{,}5$ kW	= 0,04 GJ/d
• Input of spray disc motor (electricity)	$P_{MSD} = 20$ kW	= 1,44 GJ/d

Total daily energy consumption of the line is **$Q_{LCD} = 349{,}4$ GJ/d**

Note: From the table it is possible to see, what parts of the line are energetically demanding. We have to take into account different costs of electricity and steam too.

5. Design of the line control

Parameters important for proper line function

It is necessary to measure and file the parameters, as they are important for product quality, line economy and line function check-up. The parameters and their effects are shown in following sections.

Product quality:	pasteurisation temperature
	moisture of milk powder
	fat content in dried milk(skimmilk)
	quality of milk powder (burned particles, microorg., solubility etc.)
	fat content in cream etc.
Amount of products:	amount of milk powder
	amount of cream
	amount of fresh inlet milk
Line balance & economy:	temperatures in regeneration section
(+ quality too)	temperatures in cooling section
	temperatures and pressures in evaporator
	temperatures in dryer
	milk concentration in evaporator
	amount of heating steam to evaporator
	amount of steam for drying air heating
	heating steam pressures
	pressure losses (pasteuriser, dryer etc.)

Note: It is of advantage to specify requirements for the line control to experts for MaR (measuring and regulation = line control). These are for example: above mentioned parameters these are necessary to measure, control, and file etc. incl. mutual relationships, tolerance limits etc. MaR experts are not usually specialists in the branch of the PL.

Relationships between parameters necessary for line control – control circuits

The relationship we examine in simplification and generally. It means that in some lines some system is not used or is used other one. This is only an example what relationships are used not only in dairies. Once again we will examine these relationships from point of view individual important parameters together with a way of control.

<u>Line output and their basic parameters</u> (monitor dairy management and line workers):

- Amount of fresh milk input (capacity)
  Flowmeter ---> regul. valve (ev. butterfly valve) in pipe on milk inlet (control + account). Further see milk inlet control.

- Amount of milk powder (output)
  Scale in bagging (only account).

- Amount of cream (output)

Flowmeter for account, it is not possible to control (it is given by amount and fat content of fresh milk and separator setting)

<u>Parameters for line control and account </u>(monitor line workers and check management)

- Fat content of cream
  It is set for ex. in laboratory – it is affected by function of separator and inlet milk quality.

- Fat content in skimmilk (separating sharpness)
  Ditto – it is affected by separator design, revolutions, amount and milk quality ---> measure and adjust separator (balance of fat loss in skimmilk + ev. reclamation).

- Pasteurisation temperature (affects product quality)
  - Thermometer ---> account + control (cont. valve etc.).
  - According to past. temp. is controlled heating steam inlet to pasteurisation section or to hot water circuit.
  - For steam (hot water) temperature higher than a set value is pasteuriser set away and switched to cleaning mode (CIP) and the second part of double pasteuriser is switched in operation. Ev. the cleaning mode may be pre-set after the lapse of some time.

- Temperatures in regeneration section
  - temperatures are only measured and account for purpose of PL economy checking (they are indicated – in flow charts are mark TI).

- Cooled milk temperature
  - Maximal temperature is for ex. 10 or 5 °C (else quality deterioration), depends on technology, time of storage in tank (microorganisms breeding, acidity increase).
  - Thermometer ---> control valve (degree of opening is monitored)
  - Depending on cooled milk temperature is controlled ice water inlet to cooling section. Ice water temperature is usually constant and given by cooling system function.
  - When it is impossible to keep needed cooled milk temperature even when valve is fully open cooling section is switched to cleaning regime. (cooler is designed for the same cleaning intervals like pasteuriser or whole line see given data = 20 + 4 h).

- Milk inlet to evaporator (there are several relationships here – more complicated system see part “Evaporator”)
  - Level in tank (balance tank) before evaporator – for ex. float controls valve for milk inlet to evaporator.
  - Level in tank (balance tank) after evaporator - ditto but float controls valve for milk going to dryer.
  - DM of concentrated milk – owing to fouling goes down → control of heating steam temperature etc. – see below.
  - When all pre-set values are attained (temperatures, milk flow rate, DM) evaporator is switched to cleaning mode.

- Milk heating before evaporator (temperatures after heaters)
  - Milk heating with various vapours from evaporator is without any control as it is important to achieve maximal possible heating up with vapours as heat in vapours are cheaper than in heating steam.

- Milk temperature after last heater: thermometer ---> control valve on steam inlet to last heater
- Milk heating to boiling temperature in 1st effect is not economic as heat transfer coefficient for heating is lower than for boiling and additional heat to heating up is necessary. Result is lower performance of evaporator. That is why it is necessary to control good function of heaters.
- Heaters are designed for the same cleaning intervals like evaporator (20h+4h).

- **Evaporator**
  - Later had evaporator own control system. Nowadays it is controlled together with all line. Computers are used. Relations between parameters and control system are hereunder (in simplified form without equipment).
  - Milk inlet to evaporator (max. a minim. values – see above).
  - Concentration (DM) of concentrated milk (max. value = pumpable and good spraying → dryer function, optimal, minimal values → worse economy of dryer operation).
  - Heating steam temperature (pressure) in 1st evaporator (optimal and maximal values → milk quality deterioration.
  - Vapour temperature (vacuum) in the last effect (optimal and maximal values → it is given by parameters of vacuum pump and condenser = available vacuum).
  - Further are indicated and filed all temperatures and pressures in evaporator, milk levels in separators (or in effects), valves position, pumps function, condensate quality (probe for condensate conductivity control – higher conductivity → milk in condensate - according condensate quality it goes to boiler plant or to technology (for ex. cleaning etc.) or to drain and waste water treatment plant), ev. flow-rates of heating steam or condensate. Further line state is shown (milk, cleaning), amount of processed milk for day etc., piping system in operation etc.

  - **Practical way of evaporator control may be as it is shown below:**
    - Start-up – optimal milk flow-rate
      - Milk concentration is controlled with vacuum in the last effect (control valve in pipe for vapour exhaust to condenser or valve for control of cooling water flow-rate into condenser or small throttle valve for air inlet before vacuum pump (for over-designed vacuum pump) or combination).
        During operation fouling forms on heat transfer surface. From this follows that pressure in the last effect has to be lower. Higher $\Delta t_{EVAPtotal}$ compensates lower **k** values. This follows from equation $Q_{EVAP} = k_{EVAP\phi} * A_{EVAPtotal} * \Delta t_{EVAPtotal}$.
      - The way of control frequently is not used as condenser and vacuum pump operate without any reserve for regulation.
      - Densimeter → vacuum control valve.
    - Optimal milk flow-rate, limiting value of vacuum in the last effect is reached
      - Milk concentration is controlled with heating steam pressure in 1st effect (control valve in pipe for steam inlet to evaporator opens more).
      - Similar like above is further **k** value lowering compensated with further raising of $\Delta t_{EVAPtotal}$. This is way how keeps full evaporator performance.
      - Densimeter → heating steam control valve.

- Optimal milk flow-rate, limiting values of vacuum and heating steam are reached (max. acceptable temp. of heating steam and min. attainable temp. of the last vapour)
    - Milk concentration is controlled with milk flow-rate lowering. Milk flow-rate has lower limit too (min. "wetting" of heat transfer surface → fouling and α value and line economy).
    - Densimeter → inlet milk control valve.
- Minimal limit of milk flow-rate is reached and limiting temperatures in the 1st and last effects too.
    - In the situation it is not possible to control evaporator work. Only falls of milk concentration and dryer performance are monitored. When milk concentration falls to limit value is line operation uneconomical and line is stopped and switched to cleaning regime (CIP). Standard CIP program: rinsing with warm water (condensate), rinsing with boiling solution of soda lye (NaOH, rinsing with warm water (condensate), rinsing with boiling solution of nitric acid (HNO_3), rinsing with warm water (condensate) and finally rinsing with drinking water.

Note: Single control steps may be combined or omitted. There are mentioned only general survey of evaporator control in the example (and not only for evaporator in dairy).
There is common operational regime for evaporators in dairies.: 20 h operation + 4 h CIP, and it is re-run again and again. According line situation is sometimes evaporator opened, visually checked and ev. mechanically cleaned (spraying with hot high-pressure water).

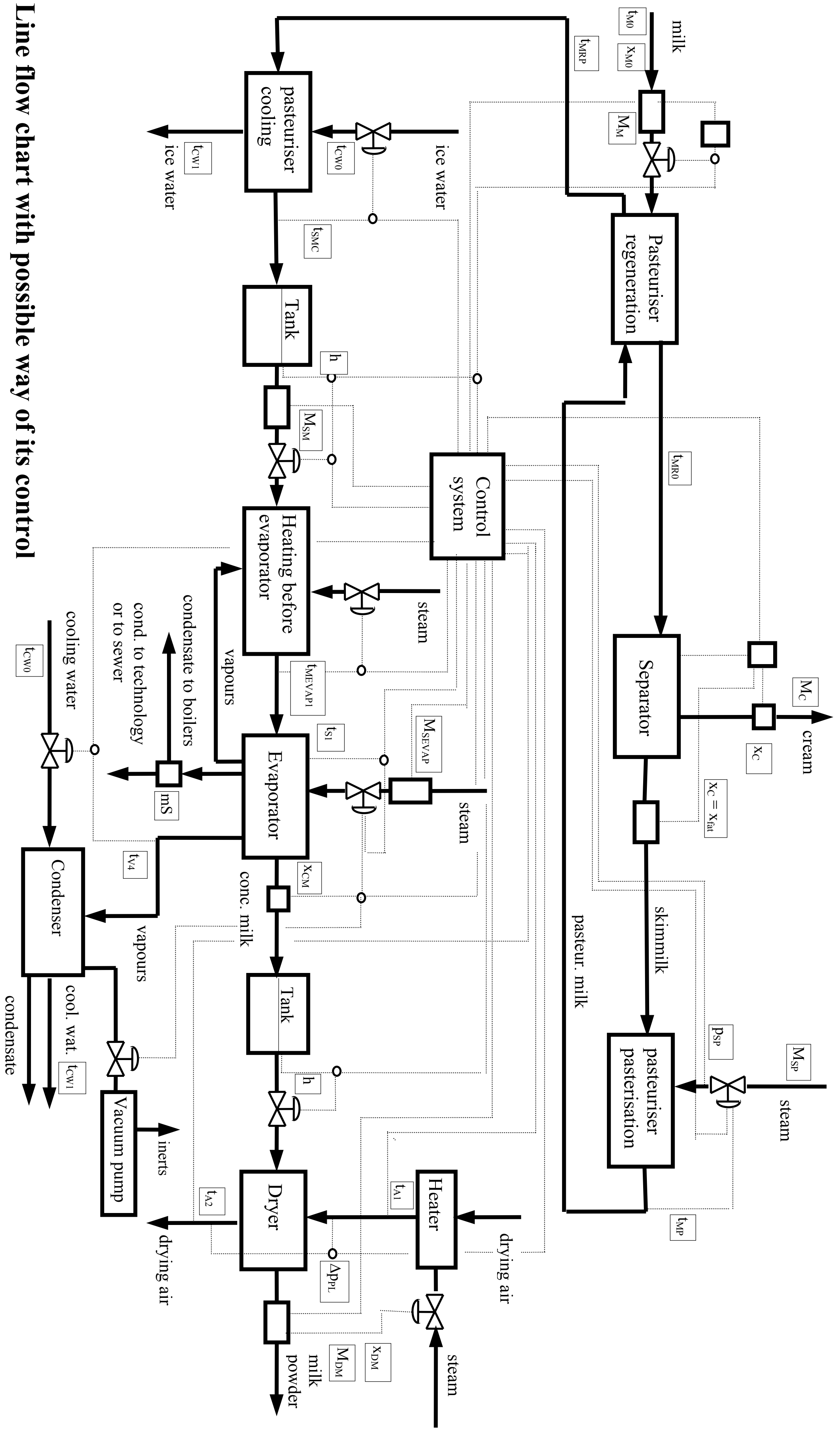
- **Dryer**
    - Similar like for evaporator there are described possible ways of control.
    - Inlet of concentrated milk depends on evaporator. Therefore it is not controlled.
    - There are limits for milk powder moisture – controlled with drying air temperature and ev. amount. Temperature is controlled with valve for heating steam coming to air heater. Powder moisture is set in laboratory (weighting, drying, and weighting more exact but last several hours) or moisture meter (quick but less exact).
    - Heating air temperature - maximal and minimal temperature – affects performance and economy of dryer (higher t. → higher effectivity), product quality (burned or too wet). Ditto = reg. valve for heating steam like above.
    - Amount of drying air maybe controlled by valves on fan outlet (ev. inlet). It is used in some cases. Else designed fan parameters and pressure losses in dryer system do it.
    - Pressure losses in air system are usually only monitored (U manometers with coloured water), sometimes are measured electronically and filed. They are used for checking of fans function, filters loading, air flow-rates in various parts of dryer etc.
    - Temperature of outlet heating air – affects dryer economy and product quality (lower t. → higher thermal effectivity, but danger of air moisture condensation in pipes after dryer → product dampness → microbial contamination).
    - Product quality ("burned" particles, coloured particles, microbial contamination, powder density, solubility, digestibility etc.).
According tests results technical regulations are done (dryer walls hammering,

stagnation zones elimination, cleaning process etc.).

- Possible way of dryer control:
  - Powder moisture is controlled by
    - Valve for heating flow-rate to air heater (heating air temperature)
    - Ev. flow-rate of heating air (in some cases when fans are over-designed) – valve in air pipe
    - Ev. flow-rate of dried liquid (for our line it is given by line performance see above); it may be used for separate dryer.
  - Pressure losses in dryer parts
    - We understand from it for requirement for filer regeneration or cleaning, lamellae in air heater cleaning, fan function etc.
  - Outlet heating air temperature is controlled by
    - Heating air inlet temperature (valve for heating steam before air heater).
    - Ev. flow-rate of dried liquid.
    - Ev. flow-rate of drying air (see above).

An example of one possible way of the line control is shown on the next page.

Line flow chart with possible way of its control



6. Possibility of the line optimisation

When we survey the flow chart of the designed line (see part 1), we find out that some given parameters are not optimal and there are possibilities to enhance its quality. These possibilities will be shown, calculated and set theirs effect in the chapter.

- If is the evaporator situated near the pasteuriser (double-pasteuriser) and performances of the pasteuriser, separator and evaporator are good synchronised it is not require to install the tank before the evaporator. In the case it is sufficient to install only a small tank (c. 100 l). Milk has not to be cooled till 10 °C. Hot pasteurised milk can flow straight away to the evaporator. We save milk the heating before the evaporator but the regeneration heat is not used.

- If the previous step is not feasible it is possible to improve the degree of regeneration in the pasteuriser. The measure has its effect for a line for drinking milk production (without any evaporator). The measure saves heat, but it is necessary to extend a heat transfer area.

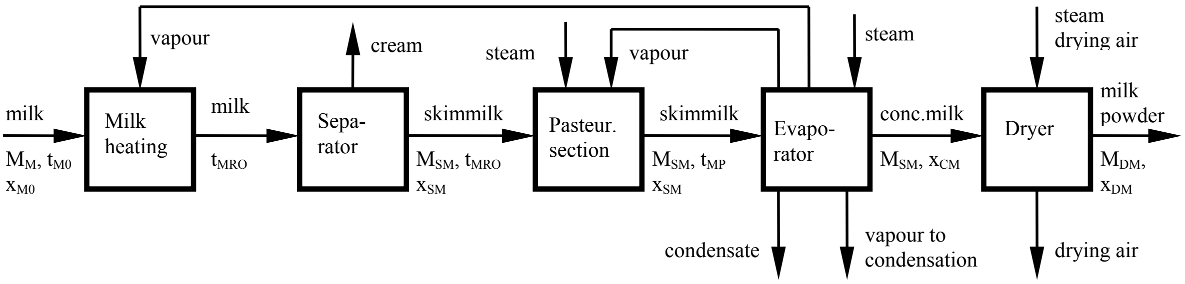
- Installation of an additional evaporator effect or thermocompressor (TK). An evaporator with more effects has lower steam consumption and higher outlet milk concentration and consequently lower steam consumption in the dryer.

Decrease of milk powder DM from given 97 % to standard 95 % ČSN standard). As there is a control quality of dryer insufficient in the dairy (DM varies c. +/- 2 %), it must be set to c. 97 % (actual values of DM varies from 99 to 95 %). The control quality improvement and more accurate staff can keep an average powder DM near the standard value 95 % (within the limits +/- 0,5 %). The measure saves heating steam and makes possible to produce of more products.

6.1. Hot pasteurised milk flows straight away to evaporator (label of var.‘)

Flow chart of the variant is in the next fig. (surge tank is not depicted).

Note: There is not milk cooling before the evaporator in the variant



The mass balance of the line is unchanged but the heat balance of the part of line before the evaporator is different (saving of milk cooling before a tank and re-heating before evaporator and milk heating before the separator will not be by hot milk but a vapour).

Note: We save only (100 - % of degree of regeneration) of heat and cold and a corresponding heat transfer area.

Heat needed for milk heating before separator

The calculation is similar like for the basic variant for given data. That is why a procedure of calculations will not be commented.

$Q'_{SMS} = M_M * c_M * (t_{MRO} - t_{MO})$
$Q'_{SMS} = 13857 * 3,9 * (62,5 - 10) / 3600 = 788,1$ kW
$= 56,75$ GJ/d

The heat is needed in addition compared to the basic variant.

Heat needed for milk heating in pasteurisation section

Either temperatures or flow-rates do not change so that the heat is the same.

$Q'_{PS} = 229,9$ kW $= 16,55$ GJ/d

Heat taken away in cooling section

Milk is not cooled ---> $Q'_{CS} = 0$ kW $= 0$ GJ/d

Milk heating before evaporator

Milk is not heated as the pasteurisation temperature $t_{MP} = 80$ °C is higher than the boiling temperature in the 1st effect is. In addition heat of superheated milk is utilised (expansion of superheated milk to temperature (pressure) in the 1st effect).

$Q'_{HE} = 0$ kW $= 0$ GJ/d

The effect we include in balance of milk heating and not in evaporator (we have not to have recalculate the evaporator).

$Q'_{SE} = M_{SM} * c_M * (t_{MP} - t_{B1°})$
$Q'_{SE} = 12125 * 3,9 * (80 - 70) / 3600 = 131,4$ kW
$= 9,46$ GJ/d

Total energy consumption of the part of the line

Heating

$Q'_{HEAT} = Q'_{SMS} + Q'_{PS} + Q'_{HE} - Q'_{SE}$
$Q'_{HEAT} = 788,1 + 229,9 + 0 - 131,4 = 886,6$ kW
$= 63,84$ GJ/d

Cooling

$Q'_{CS} = 0$

As all changes of heat consumption are included in the part of the line it is not necessary to recalculate the balances of the evaporator and dryer.

Original energy consumption of the line part

Heating

$$Q_{HEAT} = Q_{PS} + Q_{HE} = 229{,}9 + 788{,}1 = 1018{,}0\ \text{kW} = 73{,}30\ \text{GJ/d}$$

Cooling

$$Q_{CS} = 131{,}4\ \text{kW} = 9{,}46\ \text{GJ/d}$$

Effect of the variant

Heat saving in steam for milk heating

$$\Delta Q'_{HEAT} = Q_{HEAT} - Q'_{HEAT} = 1018{,}0 - 886{,}6 = 131{,}4\ \text{kW} = 73{,}30 - 63{,}84 = 9{,}46\ \text{GJ/d} \qquad \text{(decrease } 12{,}9\ \%)$$

We suppose a cost of 1 GJ of heat in steam C_S = 150,- Kč / GJ. In the cost are not included depreciation, wages and maintenance, only cost of fuel as we suppose that an existing source of energy will be used. In the case these costs will be approximately the same for all variants taken into consideration. Than the effect of the variant (total cost of steam per 1 day) is:

$$\Delta TCSteam' = \Delta Q'_{HEAT} * C_S = 9{,}46 * 150 = 1419{,}\text{- Kč/d}$$

For a cost of 1 GJ of cold in ice water C_{CW} = 230 Kč/GJ (there are not taken into account depreciation, wages and maintenance, but only electricity for compressors, pumps and fans; as we suppose that an existing cooling system is used for all considered variants). Then the effect in cost of cold (in a cooling system) per 1 day is:

$$\Delta CCSyst' = \Delta Q'_{CW} * C_{CW} = 9{,}46 * 230 = 2176{,}\text{- Kč/d}$$

Note: It is possible to reduce purchase costs (new line installation) as a boiler and cooling system with lower capacity can be installed. Lower depreciation is a result of it.

Further effect is a saving of the cooler and heaters before evaporator (lower purchase costs and consequently depreciation too.

Saving of heat transfer area - cooler

Heat transfer coefficient (HTC) in the cooler is estimated (or set by calculation Nu = f(Re, Pr)) to $k_{CS} = 3000\ \text{W/m}^2\text{K}$.

$$\Delta t_{LCS} = ((20 - 10) - (10 - 5)) / \ln((20 - 10) / (10 - 5)) = 7{,}2\ °\text{C}$$

$$\Delta Q'_{CS} = k_{CS} * \Delta A_{CS} * \Delta t_{LCS}$$

$\Delta A_{CS} = \Delta Q'_{CS} / k_{CS} * \Delta t_{LCS} = 131400 / 3000*7,2 = 6,1\ m^2$

Because heat exchangers (HE) are designed with c. 15 % of reserve, it is heat transfer area saving in the cooler c. $\Delta A_{CS} \approx 7,0\ m^2$. Cost of 1 m^2 of heat transfer area (stainless plates) is c. 6000,- Kč/m^2 (costs in 1997/98). Then is the effect in purchase cost of the cooler

ΔPCCool' = 7,0 * 6000 = 42000,- Kč

Saving of heat transfer area - milk heating before evaporator

A procedure is the same like in the previous item. By reason of simplification we assume HTC k = 3000 W/m^2K too. A milk heating in the basic variant was designed gradually, using 4th, 3rd, 2nd and 1st vapours from the evaporator (with temperatures c. 40 °, 50 °, 60 ° and 70 °C) and finally steam 80 °C. Milk was in the 5 HE heated with vapours from 10 °C to 22,5 °C, further to 35,0 °C, to 47,5 °C, to 60,0 °C and finally with steam to required 70 °C. Often it is useful to design a milk heating system in that way to be all heaters the same. The last HE, heated with steam, is over-designed as there is the maximal fouling forming. In addition there is a milk outlet temperature controlled. Mean logarithmic temperature difference is calculated for all HE c. 35 °C (average for all HE - owing to the example simplification).

Note: In practice an optimisation of system of liquid heating before an evaporator is done. See the example concerning to design and optimisation of sugar juice evaporator. In the example is this optimisation omitted. Evan after these simplifications is the example too large.

$\Delta t'_{L\phi HEAT} \approx ((50,0 - 22,5) - (50,0 - 35)) / \ln ((50,0 - 22,5) / (50,0 - 35)) = 20,3\ °C$

In all 5 HE is an heat transfer area saving

$\Delta A'_{HEAT} = \Delta Q'_{HEAT} / k_{HEAT} * \Delta t_L'_{HEAT} = 131400 / 3000*20,3 = 2,16\ m^2$

Considering the 15 % of reserve it is c. $\Delta A'_{HEAT} \approx 2,5\ m^2$. Considering the same cost of heat transfer area is the effect to the purchase cost of HE before evaporator

ΔPCHeat' = 2,5 * 6000 = 15000,- Kč

Note:
- We suppose that an area of heater before the separator (instead the regeneration section) is equal to the area of the regeneration section).
- The calculation is very simplified. When plate HE are used they are designed exactly based on requirements. Heat of vapours from "back" evaporator effects is used more. The measure improves an evaporator economy (see example about a sugar juice evaporator).
- Evaporators usually do not work with equal temperature differences in all effects as with a higher liquid concentration and lower boiling temperature is lower value of an overall heat transfer coefficient k. A solution of a real evaporator design has to be adapted.

Depreciation and maintenance saving per year

Let us assume depreciation rate of machinery 8,5 % (= 12 years of service life), maintenance costs c. 5,5 % from a purchase cost (in some cases they are comparable with depre ciation rate - in a real case it is necessary to use a realistic data). That are yearly costs c. 8,5 + 5,5 = 14 % of the purchase cost. Depreciation and maintenance saving is then

$$\Delta DM' = (\Delta PCCool' + \Delta PCHeat') * 0{,}14 = (42000 + 15000) * 0{,}14 = 7980\text{,- Kč/year}$$

Effect of the variant per year

Let us assume working time τ = 200 days per year and 20 hours per day. Than is an effect per year

$$YE' = \tau * (\Delta TCSt' + \Delta CCSyst') + \Delta DM'$$
$$YE' = 200 * (1419 + 2176) + 7980 = \underline{\textbf{726980,- Kč per year}}$$

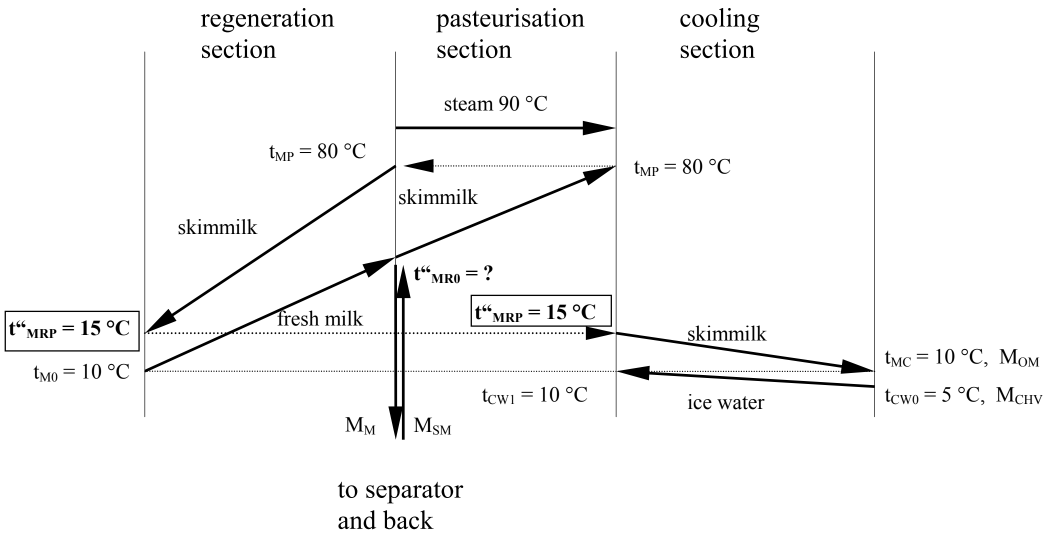
From these calculation follows that a saving of purchase costs (depreciation and maintenance) are insignificant in comparison with energy saving. A pay-off period is 0 as the variant does not need practically any purchase costs (POP = 0).

6.2 Degree of regeneration in pasteuriser (label of var.")

The variant is advantage for an existing line optimisation. As it is said above the variant is more advantageous for line for drinking milk production. For the line it is more advantageous the previous variant. Nevertheless we do following calculations to review its effect. The part of our example may be useful for solution of other lines.

An increase of number of plates, or using of plates with better characteristics (> k, $<\Delta p_Z$, < forming of fouling etc.), or substitution of an older type of HE for a new one, make it possible to lower a temperature difference in regeneration section from 10 °C to c. 5 °C

Because the difference is only 5 °C, it is possible to cool the pasteurised milk in regeneration section from 80 °C to 10 + 5 = 15 °C (inlet milk t. + t. dif.). Temperatures course in the pasteuriser is then (see following fig.):



Analogous to part 4. is

Thermal balance of regeneration section

First of all we have to set the temperature of milk after the regeneration section. as well as in the first part we consider the same heat capacity of milk and omit heat losses. Then is the thermal balance:

$Q''_{REGheat} = Q''_{REGcool}$ $(Q_{RSheat} = Q_{RScool})$
$M_M * c_M * (t''_{MRO} - t_{M0}) = M_{SM} * c_M * (t_{MP} - t''_{MRP})$

$13{,}857 * 3{,}9 * (t''_{MRO} - 10) = 12{,}125 * 3{,}9 * (80 - 15)$

$t''_{MRO} = (12{,}125 * 65 + 13{,}857 * 10) / 13{,}857 = 66{,}9$ °C milk temperature after the regeneration section

Check

$Q''_{REGheat} = 13857 * 3{,}9 * (66{,}9 - 10) / 3600 = 854$ kW
$Q''_{REGcool} = 12125 * 3{,}9 * (80 - 15) / 3600 = 854$ kW

Specification of degree of regeneration in pasteuriser

$DR'' = Q_{used} / Q_{delivered} \approx (t_{MP} - t''_{MRP}) / (t_{MP} - t_{M0})$
$DR'' \approx (80{,}0 - 15{,}0) / (80{,}0 - 10{,}0) * 100 = 92{,}9$ %

The degree of regeneration is higher (basic variant 85,7 %). It means that c. 92,9 % of delivered heat is used for milk preheating in the regeneration section (considering the same heat capacities of both flows).

Heat needed for milk heating in pasteurisation section

Milk inlet to the section with temperature 66,9 °C and there it must be heated up to pasteurisation temperature 80 °C. With the temperature flows to the holder and back to the regeneration section where is cooled with fresh cool milk. Similar as in previous the thermal balance is performed.

$Q''_{PS} = Q''_{PAST} = M_{SM} * c_M * (t_{MP} - t''_{MRO})$
$Q''_{PS} = 12125 * 3{,}9 * (80{,}0 - 66{,}9) / 3600 = 172{,}1$ kW
$= 172{,}1*3600*20/10^6 = 12{,}39$ GJ/d

Heat saving in pasteurisation section

$\Delta Q''_{PS} = Q_{PS} - Q''_{PS} = 229{,}9 - 172{,}1 = 57{,}8$ kW
$= 16{,}55 - 12{,}39 = 4{,}16$ GJ/d

Heat taken away from milk in cooling section

$Q''_{CS} = M_{SM} * c_M * (t''_{MRP} - t_{MC})$
$Q_{CS} = 12125 * 3{,}9 * (15 - 10) / 3600 = 65{,}7$ kW
$= 65{,}7*3600*20/10^6 = 4{,}73$ GJ/d

Cold saving in the cooling section

$$\Delta Q''_{CS} = Q_{CS} - Q''_{CS} = 131{,}4 - 65{,}7 = 65{,}7 \text{ kW}$$
$$= 9{,}46 - 4{,}73 = 4{,}73 \text{ GJ/d}$$

Effects of the variant

The process of the calculation is similar like in previous, so it is present without any comments.

A cost of steam saved per day is

$$\Delta TCSteam'' = \Delta Q''_{PS} * C_S = 4{,}16 * 150 = 624{,}\text{- Kč/d}$$

For cost of 1 GJ cold in ice water C_{CW} = 230 Kč/GJ (again without depreciation etc. , only electricity for compressors, pumps and fans - we assume an existing machinery utilisation) is a cost of cold saved per day (in a cooling system)

$$\Delta CCSyst'' = \Delta Q''_{CS} * C_{CW} = 4{,}73 * 230 = 1088{,}\text{- Kč/d}$$

An heat transfer area (HTA) in cooling and pasteurisation sections is lower, but a HTA in the regeneration section must be higher.

Saving of heat transfer area - cooling section

The value of HTC is estimated like in previous to k_{CS} = 3000 W/m^{2}K. Original was the log. temperature difference Δt_{LCS} = 7,2 °C. Now it is

$$\Delta t''_{LCS} = ((15 - 10) - (10 - 5)) / \ln((15 - 10) / (10 - 5)) = 5{,}0 \text{ °C}$$

$$\Delta A''_{CS} = A_{CS} - A''_{CS}$$

$$\Delta A''_{CS} = \Delta Q''_{CS} / k_{CS} * \Delta t''_{LCS} - \Delta Q_{CS} / k_{CS} * \Delta t_{LCS}$$
$$\Delta A''_{CS} = 131400 / 3000*7{,}2 - 65700 / 3000*5{,}0 = 1{,}7 \text{ m}^2$$

Because HE are designed with c. 15 % of reserve, is heat transfer area saving in the cooler c. $\Delta A''_{CS} \approx 2{,}0$ m^2. Cost of 1 m^2 of heat transfer area HTA (stainless plates) is c. 6000,- Kč/m^2. Then is the effect of cost of depreciation and maintenance for the cooler

$$\Delta DM''_{CS} = 0{,}14 * 2{,}0 * 6000 = 1680{,}\text{- Kč/r}$$

Saving of heat transfer area - pasteurisation section

Value of HTC is estimated like in previous to k_{PS} = 3000 W/m^{2}K. Original log. thermal difference (LTD) was Δt_{LPS} = 17,3 °C.

$$\Delta t''_{LPS} = ((90{,}0 - 66{,}9) - (90{,}0 - 80)) / \ln((90{,}0 - 66{,}9) / (90{,}0 - 80)) = 15{,}6 \text{ °C}$$

$\Delta A''_{PS} = A_{PS} - A''_{PS}$

$\Delta A''_{PS} = \Delta Q''_{PS} / k_{PS} * \Delta t''_{LPS} - \Delta Q_{PS} / k_{PS} * \Delta t_{LPS}$
$\Delta A''_{PS} = 229900 / 3000*17{,}3 - 172100 / 3000*15{,}6 = 0{,}75\ m^2$

Because HE are designed with c. 15 % of reserve, is the HTA saving in the past. section c. $\Delta A''_{PS} \approx 0{,}9\ m^2$. Cost of 1 m^2 of heat transfer area (stainless plates) is c. 6000,- Kč/m^2. Then is the effect of cost of depreciation and maintenance for the section.

$\Delta DM''_{PS} = 0{,}14 * 0{,}9 * 6000 = 756$,- Kč/r

Heat transfer area increase - regeneration section

Value of HTC is estimated like in previous to $k_{RS} = 3000\ W/m^2K$. Original log. thermal difference (LTD) was $\Delta t_{LRS} = 13{,}4$ °C. In the case a LTD is lower and amount of transferred heat is higher.

$\Delta t''_{LRS} = ((80{,}0 - 66{,}9) - (15 - 10)) / \ln ((80{,}0 - 66{,}9) / (15 - 10)) = 8{,}4$ °C

$\Delta A''_{RS} = A_{RS} - A''_{RS}$

$\Delta A''_{RS} = \Delta Q_{RS} / k_{RS} * \Delta t_{LRS} - \Delta Q''_{RS} / k_{RS} * \Delta t''_{LRS}$
$\Delta A''_{RS} = 788100 / 3000*13{,}4 - 853800 / 3000*8{,}4 = - 14{,}3\ m^2$

Because HE are designed with c. 15 % of reserve, is the HTA increasing in the reg. section c. $\Delta A''_{RS} \approx 16{,}4\ m^2$. Then is the effect of cost of depreciation and maintenance for the section.

$\Delta DM''_{RS} = 0{,}14 * (-16{,}4) * 6000 = - 13776$,- Kč/r cost increase !!

Note: For a real case is the calculation more complicated as with a temperature change HTC k changes too. For our illustration the method is sufficient.

Effect of the variant per year

Let us assume working time τ = 200 days per year and 20 hours per day. Than is an effect per year

$YE'' = \tau * (\Delta TCSteam''_{PS} + \Delta CCSyst''_{CS}) + \Delta DM''_{PS} + \Delta DM''_{CS} + \Delta DM''_{RS}$

YE" = 200 * (624 + 1088) + 756 + 1680 - 13776 = **331060,- Kč per year**

It follows from this that the effect of the variant is c. 50 % then for the previous variant. Nevertheless of it the pay-back period of the variant is short. We assume only purchase costs, depreciation and effects mentioned above, without "future cost of money" these are interests etc. = Cost - Benefit Analysis.

The pay-back period PBP is for purchase costs PC (HTA = additional plates; frames and stand are the same)

$PC'' = (\Delta A''_{RS} - \Delta A''_{CS} - \Delta A''_{PS}) * C_A = (16{,}4 - 2{,}0 - 0{,}9) * 6000 = 87000$ Kč

$PBP'' = PC'' / YE'' = 87000 / 331060 =$ **0,26 year ≈ 3 months**

$\Delta A''_{RS}$	increasing of HTA in reg. section	$\Delta A''_{PS}$	saving of HTA in pasteurising sec.
$\Delta A''_{CS}$	saving of HTA in cooling section	C_A	cost of 1 m^2 of HTA

6.3 Installation of an additional evaporator effect and thermocompressor TK (label of var.‘”)

Approximately it is possible to say that an installation of a TK has the same effect like an installation of another evaporator effect. Such the 5th effect’s evaporator with TK has a steam consumption practically the same like 6th effect’s evaporator without TK. An exact evaporator calculation is done in a course DHP (Dehydrating processes) and in the example about sugar juice evaporator. In this example a result of a balance is presented. The evaporator modification lowers the specific steam consumption for example to d’“ = 0,19 kg of steam / kg evap. water. Installation of the TK results in higher amount of water evaporated in the 1st effect and consequently requirements for higher heat transfer area in the effect (part of the 1st vapour flows to the TK and then back to the 1st effect – see fig. on next page). An installation of the 5th effect results in higher HTA too.

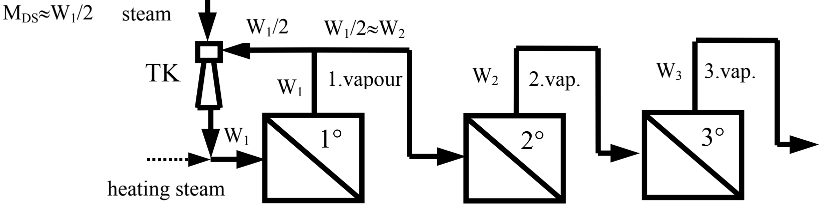
A total amount of evaporated water is divided into more effects (lower specific load of effects) but temperature differences in effects are lower too (the difference between heating steam t. and t. of vapour flowing to condenser is the same but now is divided by more effects). An effect of a boiling point elevation changes too and affects more effects. A result of it is that so-called usable temperature difference is lower

$(\Delta t_{usable} = t_{steam} - t_{boiling} = t_{steam} - (t_{vapour} + dt_{bpe}))$.

Like in previous we will calculate the evaporator. We suppose that 1 kg of steam evaporates 1 kg of vapour from milk, heat losses are omitted etc. Further we calculate with average value of evaporation heat $r_{iB\phi}$. Then is:

Heat fed as heating steam into the 1st evaporator’s effect

$$Q'''_{EVAP} = d''' * W_{EVAP} * r_{P\phi}$$
$$Q'''_{EVAP} = 0{,}19 * 9969 * 2500 / 3600 = 1315{,}4 \text{ kW}$$
$$= 1315{,}4*3600*20/10^6 = 94{,}71 \text{ GJ/d}$$



Steam and vapours pipe for 1° to 3° of evaporator

Heat transfer area increase in evaporator

An average boiling point elevation in evaporator effects is c. 0,5 °C (in 1° is lower (c.0,2 °C), in 5° is higher(c.0,8 °C)). The total amount of evaporated water is the same like for the basic variant (the same amount of milk and its concentrations). The basic simplified balance of the evaporator is:

$$W_{EVAP} = W_1 + W_2 + W_3 + W_4 \approx 4 * W_i \qquad (W_1 \approx W_2 \approx W_3 \approx W_4 \approx W_i)$$

For the variant is the balance

$$W_{EVAP} = W'''_1 + W'''_2 + W'''_3 + W'''_4 + W'''_5$$

Approximately (for our simplified example) it is possible to say that an amount of evaporated water in the 1st effect is double of other effects (amount of driving steam equals to amount of drawn vapour). More see in example about sugar juice evaporator.

$W'''_2 \approx W'''_3 \approx W'''_4 \approx W'''_5 \approx W'''_i$ amount of evap. water in an i- effect

$W'''_1 \approx 2 * W'''_i$ amount of evap. water in the 1st effect

The previous equations are transformed in form

$$W_{EVAP} = 6 * W'''_i = (n + 1) * W'''_i$$

An average value of HTC <u>k</u> is assumed the same like for the basic variant, an average evaporation heat too. As it is said above it is valid that $t_{P1} - t_{B4} = t'''_{P1} - t'''_{B5}$.

Balance of i- effect of evaporator and HTA estimation – basic variant

$A_i = Q_i / (k_i * \Delta t_i)$ $\qquad$ $Q_i = W_i * r_i = (W_{EVAP} / n) * r_i$

$\Delta t_i = (t_{P1} - t_{B4}) / n - \Delta_{i\phi}$ $\qquad$ $A_{EVAPT} = n * A_i$

$n = 4$ number of evaporator effects $\quad$ $\Delta_{i\phi} = \phi$ boiling point elevation in evaporator (properly it would be calculated for every effect)

$W_{EVAP} = 9969$ kg/h $\qquad$ $r_{i\phi} = 2370$ kJ/kg $\qquad$ $\Delta_{i\phi} = 0{,}5$ °C
$k_{i\phi} = 2000$ W/m²K $\qquad$ $t_{P1} = 80$ °C $\qquad$ $t_{B4} = 40$ °C

Pressure losses between effects are neglected (vapour temp. drop) as it are similar for both variants. Then it is:

$$Q_i = (9969 / 4) * (2370 / 3600) = 1640{,}7 \text{ kW}$$

$$\Delta t_i = (80 - 40) / 4 - 0{,}5 = 9{,}5 \text{ °C}$$

$$A_i = 1640700 / 2000 * 9{,}5 = 86{,}4 \text{ m}^2$$

$A_{EVAPT} = 4 * 86{,}4 = 345{,}6\ m^2$ total HTA of the evaporator for the basic variant

Balance of i- effect of evaporator and HTA estimation - variant “’ (i = 2 - 5)

$A'''_i = Q'''_i / (k_i * \Delta t'''_i)$ $Q'''_i = W'''_i * r_i = (W_{EVAP} / (n'''+1)) * r_i$

$\Delta t'''_i = (t_{P1} - t_{B5}) / n''' - \Delta_{i\phi}$ $A'''_{EVAPT} = (n'''-1) * A'''_i + A'''_1$

$n''' = 5$ number of evaporator effects

$W_{EVAP} = 9969$ kg/h $r_{i\phi} = 2370$ kJ/kg $\Delta_{i\phi} = 0{,}5$ °C
$k_{i\phi} = 2000\ W/m^2K$ $t_{P1} = 80$ °C $t_{B5} = 40$ °C

Like in the previous we neglect vapour temperature drop between effects (pressure losses in piping for vapour). An average boiling point elevation is assumed the same too. Then is:

For 2. to 5.° of evaporator

$W'''_i = W_{EVAP} / (n''' + 1) = 9969 / 6 = 1661{,}5$ kg/h

$Q'''_i = 1661{,}5 * (2370 / 3600) = 1093{,}8$ kW

$\Delta t'''_i = (80 - 40) / 5 - 0{,}5 = 7{,}5$ °C

$A'''_i = 1093800 / 2000 * 7{,}5 = 72{,}9\ m^2$

For 1° of evaporator

$W'''_1 \approx 2 * W'''_i \ \text{--->}\ Q'''_1 = 2 * Q'''_i \quad \Delta t'''_1 = \Delta t'''_i \quad k'''_1 = k'''_{i\phi}$

$A'''_1 = 2 * A'''_i = 2 * 72{,}9 = 145{,}8\ m^2$

A total HTA of the evaporator for the variant is

$A'''_{EVAPT} = A'''_1 + 4 * A'''_i = 145{,}8 + 4 * 72{,}9 = 437{,}4\ m^2$

Effect of the variant per year

A cost of HTA of the evaporator is c. $C_A = 5000$,- Kč/m^2 (only HTA, without costs of shells, frames, pumps, vapour/droplets separators etc. - these are considered approximately the same for both variants). The depreciation and maintenance cost are considered the same like in the previous chapter: 8,5 + 5,5 = 14 % of purchase costs. A cost of heat in heating steam is $C_P = 150$ Kč/GJ. An annual service time is $\tau = 200$ days/year.

Basic variant

Cost of steam per year

$$CS_{EVAP} = C_S * Q_{EVAP} * \tau$$
$$CS_{EVAP} = 150 * 139{,}56 * 200 = 4186800,\text{- Kč/r}$$

Depreciation and maintenance costs

$$CDM_{EVAP} = A_{EVAP} * C_A * DM = \underbrace{345{,}6 * 5000}_{= 1728000\,,\text{-}} * 0{,}14 = 241920,\text{- Kč/y}$$

= 1728000 ,- = cost of evaporator plates (without frames, pumps, separators, piping, control etc.)

Total annual costs

$$TAC_{EVAP} = CS_{EVAP} + CDM_{EVAP} = 4354500 + 241920 = 4596420,\text{- Kč/y}$$

Proposed variant

Cost of steam per year

$$CS'''_{EVAP} = C_S * Q'''_{EVAP} * \tau$$
$$CS'''_{EVAP} = 150 * 94{,}71 * 200 = 2841300,\text{- Kč/y}$$

Depreciation and maintenance costs

$$CDM'''_{EVAP} = A'''_{EVAPT} * C_A * DM''' = \underbrace{437{,}4 * 5000}_{= 2187000,\text{-}} * 0{,}14 = 306200,\text{- Kč/y}$$

= 2187000,- = cost of evaporator plates for the var.

Total annual costs

$$TAC'''_{EVAP} = CS'''_{EVAP} + CDM'''_{EVAP} = 2841300 + 306200 = 3147500,\text{- Kč/y}$$

Note: - There is a HTC in the 1st effect k_1 higher than in others effects (lower viscosity, higher temperature) in reality → A_1 will be lower → econ. effect will be more favourable
- Because the heating steam consumption in the evaporator was set from the specific steam consumption **d** (heat losses are included too), the steam consumption for both variants is higher than values $Q_S = Q_i$, set in the part.

The cost of HTA installed in addition was only considered in the preliminary calculations. The evaporator will be extended of another effect (frame, pump etc.) and thermocompressor. So an installation will need a piping, supporting structure (SS), control system, droplet/vapour separator, armatures including erection work. An estimation of these costs is in the following table.

Additional HTA (437,4 - 345,6) * 5000 =	459 000,- Kč
5th effect (without HTA), pump, separator, control system, piping, SS, armatures etc.	1 500 000,- Kč
TK incl. piping and control system	500 000,- Kč

Total cost of realisation of this var.‘‘‘ (investment cost) TIC’‘‘ = 2 459 000,- Kč

An actual cost is, compared to the previous calculation, higher of value c. (2459000 – - 459000) = 2000000,- Kč. Therefore the depreciation and maintenance have to be higher too for the variant - (0,14*2000000 = 280000). Than total costs are

TAC’“$_{EVAPreal}$ = 3147500 + 280000 = 3427500,- Kč/y

and the effect of the variant per year in comparison with the basic variant is

YE’“ = TAC$_{EVAP}$ - TAC’“$_{EVAPreal}$ = 4428720 - 3427500 = **1 001 200,- Kč / year**

The pay-back period PBP is for the total investment costs TIC’” (HTA = additional plates; frames and stand of the 5th effect, separator, TK, control system etc.)

PBP“ = TIC’“ / YE“ = 2459000 / 1001200 = **2,5 years**

6.4 Higher outlet milk concentration (label of var.““)

The increasing of HTA of the evaporator from the basic 4° to the recommended 5° evaporator with TK (var. 6.3.) makes possible to increase an outlet milk concentration from given 45 % to 50 % DM. A result of it is a higher amount of evaporated water and consequently a higher steam consumption in evaporator too (compared to var. 6.3.) but a steam consumption in the dryer will be much lower.

The increasing of HTA and other costs are assumed the same like for the variant 6.3. An average value of HTC $\mathbf{k}_{\phi}$ is assumed to be the same too in reality it will be a little lower – owing to a higher concentration). A more complicated control system is omitted too (variation of the outlet milk concentration has to be kept in narrower limits as a concentration > c. 52 to 55 % brings problems with milk pumping and spraying).

Steam consumption in evaporator

We go out from results of var. 6.3., it is 5° + TK (d’“ = 0,19 kg/kg). Original total amount of evaporated water for x_{CM} = 45 % was W_{EVAP} = 9969 kg e.w./h. For the higher milk concentration x““$_{CM}$ = 50 % is a new total amount of evaporated water

W““$_{EVAP}$ = M_{SM} * (1 – x_{SM} / x““$_{CM}$)
W““$_{EVAP}$ = 12125 * (1 - 8 / 50) = 10185 kg/h

Amount of concentrated milk flowing from the evaporator to the dryer is

M““$_{CM}$ = M_{SM} - W““$_{EVAP}$ = 12125 - 10185 = 1940 kg/h

Owing to a big extend of the example the evaporator is not re-calculated for these conditions. For needs of an approximate economic comparison of the variant it is sufficient to estimate a new HTA of the evaporator. The estimation is done using a change of total amounts of evaporated water. The new HTA of evaporator for this variant is calculated by using following equations:

$Q = k * A * \Delta t$ and $W \sim Q$

$A^{““‘}_{EVAPT} \approx A^{’“}_{EVAPT} * W^{““‘}_{EVAP} / W^{’“}_{EVAP} = 437{,}4 * 10185 / 9969 = 446{,}9\ m^2$

An increasing of a heating steam consumption in the evaporator is supposed to be proportional of total amount of evaporated water too. Compared the var. 6.3. are number of effect the same, as well as TK, operating principles of evaporator and vapours taking away for milk heaters. Than a heat consumption (heating steam) in the evaporator is

$Q^{““‘}_{EVAP} \approx Q^{’“}_{EVAP} * W^{““‘}_{EVAP} / W^{’“}_{EVAP} = 1315{,}4 * 10185 / 9969 = 1343{,}9$ kW
$Q^{““‘}_{EVAP} \approx d^{”’’} * W^{““‘}_{EVAP} * r_{\phi} = 0{,}19*10185*2500/3600 = 1343{,}9 = 96{,}76$ GJ/d

Heat consumption in dryer

A steam consumption for drying air heating will be lower as a lower amount of concentrated milk with higher concentration will be dried. A re-calculation is again done using the presumption that the steam consumption is proportional to the amount of dried off water. (we suppose that temperatures and moistures of drying air are the same, only its amount is lower).

Note: For an exact design of a dryer all approximate calculations have to be done once more exact (evaporator and dryer) for the selected optimal variation. But for the selection of an optimal variation it is possible to use such approximate calculations.

$W_{DRY} = 1156$ kg/d	basic total amount of dried off water in dryer
$W^{““‘}_{DRY} = M^{““‘}_{CM} - M_{DM} = 1940 - 1000 = 940$ kg/h	new total amount of dried off water in dryer
$Q_{DRY} = 1669{,}8$ kW $= 120{,}23$ GJ/d	basic heat consumption in dryer
$Q^{““‘}_{DRY} \approx Q_{DRY} * W^{““‘}_{DRY} / W_{DRY}$	
$Q^{““‘}_{DRY} \approx 1669{,}8 * 940 / 1156 = 1358{,}0$ kW	new heat consumption in dr.
$= 120{,}23*940/1156 = 97{,}76$ GJ/d	

Lower amount of heating air

$M^{““‘}_{A} = M_{A} * W^{““‘}_{DRY} / W_{DRY} = 32111 * 940 / 1156 = 26111$ kg/h

The lower amount of air the lower fan input. A lower fan input is (supposing the same pressure conditions – but for lower air flow are lower pressure loses too - → reserve to a side of higher security)

$P^{““‘}_{MF} = P_{MF} * M^{““‘}_{A} / M_{A} = 27{,}9 * 26111 / 32111 = 22{,}7$ kW

Effect of this variant per year

Supposing the same conditions like in previous variants the effect is related to var. 6.3. (“‘) it is 5 ° + TK. Ev. a dryer size reducing is omitted the (the simplification is again on the side of higher security).

Cost of steam for evaporator

$$CS''''_{EVAP} = C_S * Q''''_{EVAP} * \tau$$
$$CS''''_{EVAP} = 150 * 96{,}76 * 200 = 2902800{,}\text{- Kč/y}$$

Cost of steam for dryer

$$CS''''_{DRY} = C_P * Q''''_{DRY} * \tau$$
$$CS''''_{DRY} = 150 * 97{,}76 * 200 = 2932800{,}\text{- Kč/y}$$

Depreciation and maintenance of evaporator (for dryer is ≈ the same – the same dryer for both variants)

$$CDM''''_{EVAP} = A''''_{EVAPT} * C_A * DM$$
$$CDM''''_{EVAP} = 446{,}9 * 5000 * 0{,}14 = 312830{,}\text{- Kč/y}$$

Lower electric energy consumption for 2 motors of fans

$$\Delta CEE''''_{MF} = C_{EE} * \Delta P''''_{MF} * 2 * \tau \qquad C_{EE} \approx 4{,}00 \text{ Kč/kWh}$$
$$\Delta CEE''''_{MF} = 4 * (27{,}9 - 22{,}7) * 2 * 20 * 200 = 166400{,}\text{- Kč/y}$$

Total costs per year for var. 6.4 (only the changed parts of the line are assumed = evaporator and dryer – other costs are approximately the same)

$$TAC'''' = CS''''_{EVAP} + CS''''_{DRY} + CDM''''_{EVAP} - \Delta CEE''''_{MF}$$
$$TAC'''' = 2902800 + 2932800 + 312830 - 166400 = 5982000{,}\text{- Kč/y}$$

Costs of the compared variant 6.3 (only the changed parts of the line are assumed again = evaporator and dryer – other costs are approximately the same)

Total annual costs for evaporator incl. depreciation, maintenance etc.

$$TAC'''_{EVAP} = 3147500{,}\text{- Kč/y}$$

Total annual costs for dryer

$$TAC'''_{SDRY} = C_S * Q'''_{DRY} * \tau = 150 * 120{,}23 * 200 = 3606900{,}\text{- Kč/y}$$

Total costs per year for variant 6.3 (only for mentioned changed parts)

$$TAC''' = TAC'''_{EVAP} + TAC'''_{SDRY} = 3147500 + 3606900 = 6754400{,}\text{- Kč/y}$$

Effect of the variant per year

YE““ = TAC’“ - TAC““ = 6754400 - 5982000 = **772400,- Kč/y**

Because the variant does not need practically any purchase costs comparison with var. 6.3. (only better control system and more accurate staff) is a pay-back period = 0. If the effect is added to the effects of var. 6.3. (it is var. 6.3. + higher milk concentration) we can set a new pay-back period for a combination of var. 6.3. + 6.4.

PBP““ = PC’“ / (YE’” + YE““) = 2459000 / (1001200 + 772400) = **1,4 years**

(for the var. 6.3. was the pay-back period 2,3 y).

6.5. Increase of milk moisture from 3 % to 5 % (label of var. ^{V})

A Czech standard allows the moisture 5 %. Because there is a control quality of dryer insufficient in the dairy (DM varies c. +/- 2 %), it must be set to c. 97 % (actual values of DM varies from 99 to 95 %). The control quality improvement and more accurate staff can keep an average powder DM near the standard value 95 % (within the limits +/- 0,5 %) without a danger of stored milk powder deterioration (micro-organisms breeding etc. in a insufficiently dried batch of powder). The measure saves heating steam for the dryer and makes possible to produce more products (water in product is sold for a cost of milk powder).

Higher amount of product

$M^V_{DM} = M_{DM} * x_{DM} / x^V_{DM} = 1000 * 97 / 95 = 1021,0$ kg/h

A wholesale price of milk powder in bags was in 1997 $C_{DM} \approx 55$ Kč/kg (price in a real dairy where an energetic audit was done). Than is a profit from the production increase:

$\Delta C^V_{DM} = \Delta M^V_{DM} * C_{DM} * \tau$
$\Delta C^V_{DM} = (1021 - 1000) * 55 * 20 * 200 = 4620000$,- Kč/y

Amount of dried off water (related to var. 6.4.)

$W^V_{DRY} = M''''_{DM} - M^V_{DM} = 1940 - 1021 = 919$ kg/h
$W''''_{DRY} = 940$ kg/h

Accordingly to previous variant we determine a heat consumption in the dryer (re-calculation using proportion of amounts of dried off water)

$Q^V_{DRY} = Q''''_{DRY} * W^V_{DRY} / W''''_{DRY}$
$Q^V_{DRY} = 1358,0 * 919 / 940 = 1327,7$ kW
$= 97,76*919/940 = 95,58$ GJ/d

An effect of lower fan input is neglected for the variant (lower amount of drying air; the neglect is on a side of higher safety → reserve in the variant effect). Than savings of heat and cost of heating steam for the dryer are

$$\Delta Q^{V}_{DRY} = Q''''_{DRY} - Q^{V}_{DRY} = 97,76 - 95,58 = 2,18 \text{ GJ/d}$$

$$\Delta CS^{V}_{DRY} = C_S * \Delta Q^{V}_{DRY} * \tau = 150 * 2,18 * 200 = 65400,\text{- Kč/y}$$

Note: - Owing to the higher profit from milk production is this effect insignificant.
- Simplifications have to be done to a side of higher safety (conservatively)

Effect per year comparing with var. 6.4.

$$YE^{V} = \Delta C^{V}_{DM} + \Delta CS^{V}_{DRY} = 4620000 + 65400 = \mathbf{4\,685\,400,\text{- Kč/y}}$$

Purchasing costs for a realisation of the variant are estimated to c. 1000000,- Kč.- (a new control system, sensors, actuating appliance etc.). Than the pay-back period is

$$PBP^{V} = PC^{V} / YE^{V} = 1000000 / 4685400 \approx \mathbf{0,2 \text{ year}}$$

7. Conclusion - comparison of proposed variants of the line optimisation

Results of proposed variants are given in the following table.

Variant Description	Effect per year	Pay-back period of investment	Total effect per year for application of more variants	Note Variants applied
	RE (Kč/y)	PBP (y)	Σ RE (Kč/y)	(combination)
Basic variant - given data 4° evaporator	0	0	0	
Var. 6.1 - milk without cooling to evaporator	726 980	0	726 980	1
Var.6.2 - higher degree of regeneration in past.	331 060	0,3	331 060	2
Var. 6.3 - 5° + TK	1 001 200	2,5	1 728 180	1+3
Var.6.4 - higher milk concentration (50%)	772 400	1,4	2 384 780	1+3+4
Var.6.5 - higher moisture of milk powder	4 685 400	0,2	7 185 980	1+3+4+5

Results appreciation:

- An energy saving has usually higher effect comparing to purchase costs (depreciation).
- A production increase (higher yield, losses decrease etc.) has, for the same consumption of raw materials, usually much higher effect than energy savings.

Note: The example shows us possibilities of production lines design, calculation and optimisation incl. a basic economic appreciation. Simultaneously it shows effects of some optimisation steps.