CZECH TECHNICAL UNIVERSITY PRAGUE

FACULTY OF MECHANICAL ENGINEERING

Department of Process Engineering

Master Thesis

Energy analysis of milk powder production line

2020 Sumit Upadhyay

MASTER'S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Upadhyay Sumit** Personal ID number: **473394**

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II. Master's thesis details

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Energy analysis of milk powder production line

Master's thesis title in Czech:

Energetická analýza výrobní linky sušeného mléka

Guidelines:

Prepare literature review focused on the issues of milk powder production, used equipment, procedures and its energetic efficiency improvement.
Analyze the current state of the milk powder processing line (including PFD scheme, balances and its energy efficiency) and develop the modification of the processing line leading to the improvement of the energy efficiency of the production line (in form of techno-economical study).

Bibliography / sources:

According to the recommendation of the supervisor.

Name and workplace of master's thesis supervisor:

Ing. Jaromír Štancl, Ph.D., Department of Process Engineering, FME

Name and workplace of second master's thesis supervisor or consultant:

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Ing. Jaromír Štancl, Ph.D.	prof. Ing. Tomáš Jirout, Ph.D.	prof. Ing. Michael Valášek, DrSc.
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III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

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Annotation sheet

Name: Sumit

Surname: Upadhyay

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Supervisor: Ing. Jaromir Štancl Ph.D.

Submitter: Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Process Engineering

Annotation - Czech: Připravit přehled literatury zaměřený na problematiku výroby sušeného mléka, použitého zařízení, postupů a jeho energetické zvýšení účinnosti. Analýza současného stavu linky na zpracování sušeného mléka (včetně schématu PFD, rovnováhy a jeho energetické účinnosti) a vyvinout úpravu výrobní linky vedoucí ke zlepšení energetické účinnosti výroby linka (ve formě techno-ekonomické studie).

Annotation - English: Prepare literature review focused on the issues of milk powder production, used equipment, procedures and its energetic efficiency improvement. Analyze the current state of the milk powder processing line (including PFD scheme, balances and its energy efficiency) and develop the modification of the processing line leading to the improvement of the energy efficiency of the production line (in form of techno-economical study).

Keywords: Mass, Enthalpy, Six sigma, Efficiency, PFD, Strategy, Improvement, Production

Utilization: For Department of Process Engineering, Czech Technical University in Prague

Declaration

Supervisor: Ing. Jaromir Štancl Ph.D.

I declare that I have produced the submitted work independently and that I have provided all the information sources used in accordance with the Methodological Guideline on Ethical Principles in the Preparation of Graduate Final Theses.

In Prague on ....

Sumit Upadhyay

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Preface

This thesis work is a case study on local dairy industry called Company A dairy located in České Budějovice, a city of Czech Republic. The entire work is divided into seven chapters.

The first chapter introduces the thesis to the readers in terms of motivation behind the project, followed by a brief background of the dairy with which the collaboration of this project has been carried out. The second chapter gives a brief literature review of energy analysis. It also gives a detailed description of the process production of milk powder along with its energy efficiency studies. A brief description of methodology followed in the present work to perform the energy study of the milk dairy is presented in the third chapter followed by description of the current state of base scheme. The fourth chapter provides a detailed picture of the modeling and simulation of the milk powder plant followed by its mass and enthalpy analysis. In the analysis, different sections of the plant are located which showed us where we can do improvisation. Thus, to improve this aspect of the plant, a few strategies are devised and discussed in the last part of this section in order to make the overall plant more energy efficient. Chapter five include six sigma methodology with the help of which we can improve the quality and also optimize the efficiency of plant. Chapter six state the economic study for the work and comparison of base and final scheme in term of capital and profit. The final chapter summarizes the entire thesis work and provides suggestion on future scopes of the project.

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Nomenclature

Symbol	*Description*	*Units*
C_p	Specific heat capacity at constant pressure	$kJ\ kg^{-1}\ K^{-1}$
H	Specific enthalpy	$kJ\ kg^{-1}$
$\dot{m}$	Mass flow rate	$kg\ s^{-1}$
P	Pressure of a system	$kg\ m^{-1}\ s^{-2}$
$\dot{Q}$	Heat flow rate	$kJ\ s^{-1}$
R	universal gas constant (= 8.314)	$kJ\ kg^{-1}\ K^{-1}$
s	Specific entropy	$kJ\ kg^{-1}\ K^{-1}$
t	Time	s
T	Temperature of a system	K
$\dot{W}$	Power (or work per unit time)	$kJ\ s^{-1}$
W	Total amount of evaporated water	kg
M_{sm}	Flow rate of skimmed milk	$kg\ h^{-1}$
T_{sm}	Skimmed milk inlet temperature	°C
S_{sm}	Dry matter content of inlet milk	%
S_{cm}	Dry matter content of concentrated milk	%
M_m	Milk flow rate from respected evaporator	$kg\ h^{-1}$
dTB	Boiling point elevation for respective effect	°C

K	Over all heat transfer coefficient	$W\ m^{-2}\ K^{-1}$
A	heat transfer area of evaporator	m^2
RH_a	Ambient air relative humidity	%
A_{dc}	Surface of drying chamber	m^2
P_{bar}	Ambient air barometric pressure	Pa
Y_a	Absolute humidity of ambient air	kg/kg
C_a	Heat capacity of air	J/kg.°C
C_{va}	Heat capacity of water vapor	J/kg.°C
H_a	Specific enthalpy of ambient air	J/kg D.a.
M_{da}	Drying air flow rate	kg/h
Y_2	Exhaust air absolute humidity	kg/kg d.a.
$Rho_{air,T1}$	Inlet air density	kg/m^3
$V_{air,T1}$	Inlet air Volumetric flowrate	m^3/h
dP_{cf}	Pressure drop - compressing fan	Pa
dP_{dch}	Pressure drop over drying chamber	mm H2O
dp_{sf}	Pressure drop - sucking fan	Pa
eta_{fan}	Fan efficiency	%

Subscripts

Symbol	*Description*
0	Thermodynamic state with ambient conditions
1	Thermodynamic state
2	Thermodynamic state
A	Fluid
B	Fluid
C_v	Control volume
I	Initial
in	Inlet stream
f	Final
out	Outlet stream
p	Constant pressure
vap	Vaporization

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Chapter 1: Introduction

Production of milk powder is a process associated with high energy consumption and relatively low energy utilization. Consumption of fossil fuels results in the emission of greenhouse gases which can be significantly reduced by making the industrial sector more energy efficient [1]. Several scientific and engineering methods are being continuously developed for the identification of potential energy saving strategies for the large-scale industries. One such method is the basic energy analysis, the conventional approach to study various energy consumption processes [7]. The mass and enthalpy analysis are able to distinguish the different qualities of energy such as heat quality which is dependent on the heat source temperature [8]. Due to these benefits of mass and enthalpy analysis, which provides a much clearer picture of the process flow has proved to be a better tool to solve the purpose.

Czech Republic is now one of the largest producers of milk [3] Which is useful to vegetarian population around Europe and thus it is the largest consumer of its own dairy products such as butter, cheese, milk powder etc. as these are the only acceptable sources of animal protein for the vegetarians [5]. Substantial amounts of fresh water and energy are consumed during milk processing which in turns affects the sustainability of the plant. Thus, the motivation behind this work was to study the energy efficiency at milk processing plant followed by proposing retrofits to improve the plant's sustainability. So, we can optimize the plant by mass and enthalpy analysis and six sigma methodology.

In our work, we have made a case study on the fictive Company A Dairy, located in Czech Republic, as our fictive Company A is considered one of the largest food brands in Czech Republic with unparalleled production of milk and milk products over the past many years. It works on the basis of collection of milk from around villagers [5].

Chapter 2: Energy analysis

2.1 Literature review

All rational human activity is characterized by continuous striving for progress and development. The tendency to search for the best solution under defined circumstances are called optimization—in the broad sense of the word. In this sense, optimization has always been a property of rational human activity. However, in recent decades, the need for methods that lead to an improvement of the quality of industrial and practical processes has grown stronger, leading to the rapid development of a group of optimum-seeking mathematical methods, which are now collectively called methods of optimization. Clearly, what brought about the rapid development of these methods was progress in computer science, which made numerical solutions of many practical problems possible [9].

In mathematical terms, optimization is seeking the best solution within imposed constraints. Process engineering is an important area for application of optimization methods. Most technological processes are characterized by flexibility in the choice of some parameters; by changing these parameters, it is possible to correct process performance and development. There are also decisions that need to be made in designing a new process or new equipment. Thanks to these decisions (controls) some goals can be reached. For example, it may be possible to achieve a sufficiently high concentration of a valuable product at the end of a tubular reactor at minimum cost; or in another problem, to assure both a relatively low decrease of fuel value and a maximum amount of work delivered from an engine. How to accomplish a particular task is the problem of control in which some constraints are represented by transformations of the system's state and others by boundary conditions of the system. If this problem can be solved, then usually a number of solutions may be found to satisfy process constraints. Therefore, it is possible to go further and require that a defined objective function (process performance index) should be reached in the best way possible, for example, in the shortest time, with the least expenditure of valuable energy, minimum costs, and so on. [9].

In Thermodynamics with respect to Carnot engine, Energy analysis can be defined as

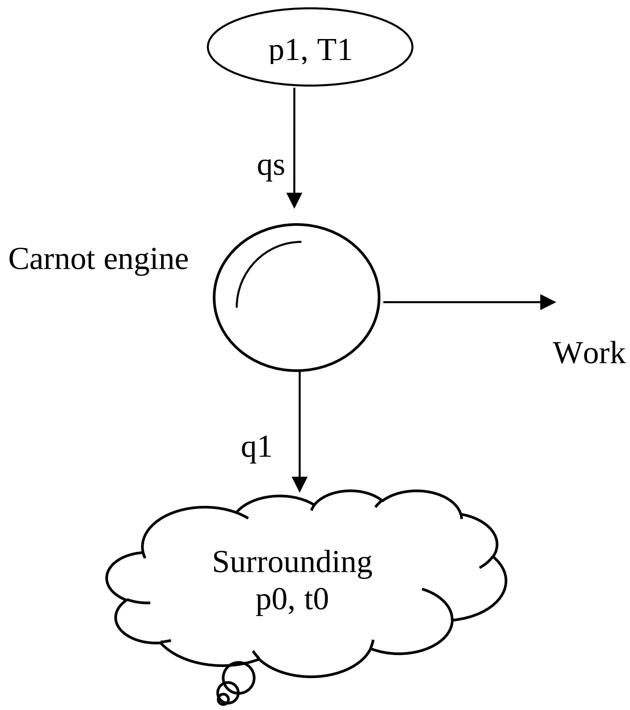


Figure 1- Carnot engine energy

We use Carnot engine because Carnot efficiency is the maximum efficiency that can be achieved by the 2nd law of Thermodynamics.

Efficiency of Carnot engine can be given by the equation: -

$$\eta = \left(1 - \frac{t0}{t1}\right) \tag{1}$$

Now efficiency can also be defined in general as the ration between work obtain and heat given, so we can rewrite equation 1 as,

$$\eta = \left(1 - \frac{t0}{t1}\right) = \frac{\text{work obtain}}{\text{Heat given}} \tag{2}$$

$$\left(1 - \frac{t0}{t1}\right) = \frac{W_{max}}{Q} \tag{3}$$

$$Q\left(1 - \frac{t0}{t1}\right) = W_{max} \tag{4}$$

So, from equation 4 we get maximum work W_{max} that is the energy.

2.2 Energy dependence on temperature

Now, in this section we will learn how energy depend on temperature. For that let us consider two system *S1* and *S2* at temperature *T1* and *T2* respectively and *T1* is greater than *T2*. Now we need to know in which system energy will be more [10].

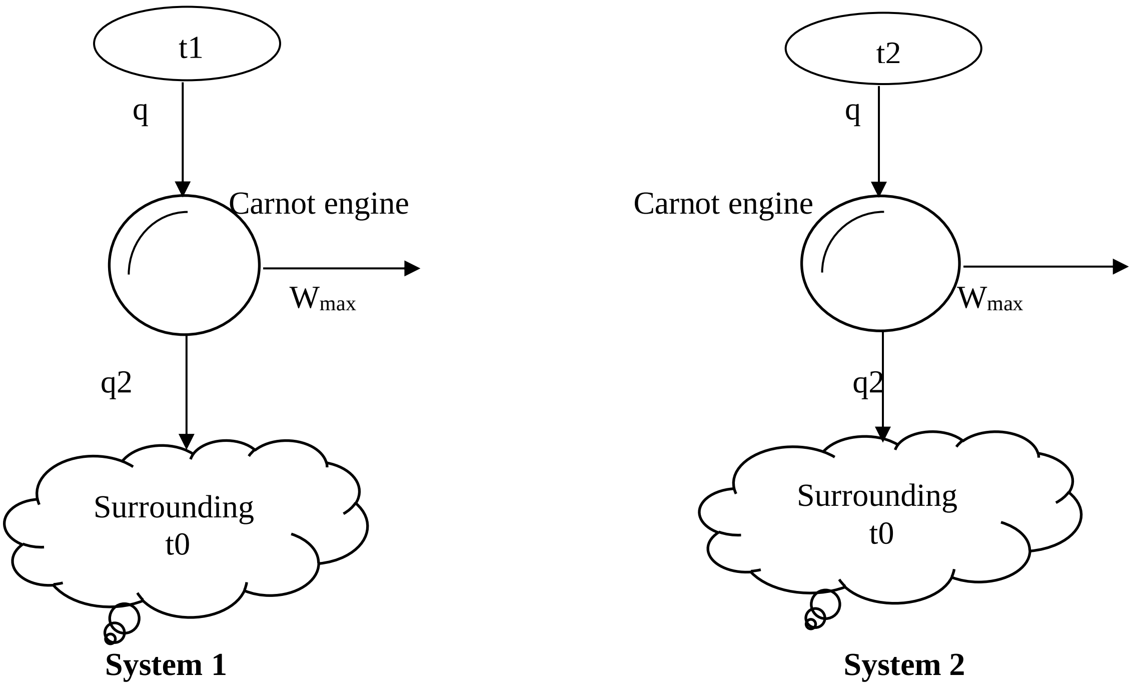


Figure 2 -Carnot engine energy comparison between different temperatures

We know that the maximum work which can be defined by equation 4 i.e. $q\left(1-\frac{t0}{t1}\right) = W_{max}$. Maximum work for system 1 and system 2 can be defined as

$$q\left(1-\frac{t0}{t1}\right) = \boldsymbol{System\ 1} \qquad\qquad q\left(1-\frac{t0}{t2}\right) = \boldsymbol{System\ 2}$$

Suppose the values for t0 = 100 K, t1 = 300K, t2 = 200K. now put there given values in system 1 and system 2.

$q\left(1 - \frac{100}{300}\right) = \boldsymbol{System\ 1}$ $\qquad\qquad$ $q\left(1 - \frac{100}{200}\right) = \boldsymbol{System\ 2}$

0.67q = system 1 = 67% $\qquad\qquad$ 0.5q = system 2 = 50%

So, from above calculation we get to know that system 1 has more potential then system 2, so mathematically we found that system has higher temperature has higher energy considering surrounding temperature same. This implies that energy at higher temperature levels can be better utilized to increase efficiency.

2.3 Milk powder production process

Milk drying is an energy-intensive process needing hot air as a heating medium helping contemporary heat and mass transfer between the milk and the drying air. For dairy products, the most popular tool for dehydration is spray drying after evaporation, reason actuality, and easy maintenance of food properties as they do not involve critical heat treatments and provide storage of powders at ambient temperature [12]. The modern drying operation usually takes place in three back to back stages: i) Spray chamber (first stage), where drying happens within a few seconds; ii) internal stationary fluid bed (second stage), at the conical base of the spray chamber equipped for better control of particle agglomeration and drying [13]; iii) external fluid bed (third stage), to bring the particles moisture content to the aspired level and to cool the outfeed product stream. The water molecules present in the milk escape as vapor when sufficient energy is imparted into milk by heating it at a certain temperature. The rate at which the vaporization takes place depends on a few factors such as, milk temperature, surrounding temperature, pressure above the surface of the milk and the heat transfer rate.

2.3.1 Process Description

Milk powder production requires the tender removal of water from milk at a minimum cost and following strict hygiene requirements while maintaining all the needed natural properties of the milk – appearance, taste, solubility, nutritional content [14]. During the process, water present in the milk is separated by boiling the milk under decreased pressure at low temperature in a process called evaporation. The resulting thick milk is then sprinkled in a small droplet into hot air to remove additional moisture through producing the powder.

Roughly, 9 kg of skim milk powder (SMP) or 13 kg of whole milk powder (WMP) can be prepared from 100 L of entire milk [14]. The traditional process for milk powder production begins with taking the raw milk collected at the dairy factory and pasteurizing and parting it into skim milk and cream employing a radial cream separator. If whole milk powder is to be produced, a part of the cream is added back to the skim milk to standardize the fat content as per requirement.

There are two divisions in milk powder production: First, it is the evaporation section and second the spray drying section. The milk at temperature 4-7 °C with about 9-12 % solids is drawn to the pasteurization unit in order to prevent the microbiological contamination. and then to multi effect evaporators, each followed with a feed preheater. Because of preheating a controlled denaturation of the whey proteins in the milk simultaneously with killing bacteria, inactivating yeasts and producing natural antioxidants thereby allowing heat stability [14]. The steam, which is supplied in the first stage is produced with the help of boiler. The pressure in the five stage ranges from about 28.5 kpa in 1st stage to around 9.5 kpa in the last stage with a variation of about (9.5) kpa between any two nearby stages. The vapor generated in the first and second effect is divided into two parts, one part is sent to preheater to preheat the incoming milk and the second part is sent to the next stage, (Figure 4). Condensate from the all three stages and from preheater, gets settled in the condensate tank. In first stage we get big amount as correlated to other stages, the rich milk leaving the evaporation section has a temperature of about 40-45 °C and solid content of round 49 % [12].

A part of the milk leaving the three stages evaporation process at temperature 42 °C and is supplied to the scraped surface heat exchanger where it is heated to 75°C before being provided to the spray dryer. In the spray dryer, atomization of the milk concentrate from the evaporator into minute droplets takes place. All this is done inside a comprehensive drying chamber in a flow of hot air at a temperature of 180-230 °C using either a series of high-pressure nozzles or a spinning disk atomizer. The milk droplets are moderated by evaporation before they touch the temperature of the air so they never touch the temperature of the air. The concentrated milk may be heated earlier to atomization to decrease its viscosity and to improve the energy possible for drying. The atomized particles come in touch with hot air and water in it gets evaporated leaving a fine powder of about 5 % moisture content with a mean particle size of < 0.2 mm diameter which is received in the cellar. Sometimes an additional drying takes place in a fluidized bed by which hot air is driven to remove some more water content to give a result with a moisture content of 2-5 %. Some quantity of dried output product may also get directed with the exhaust air which is then removed in a high-efficiency cyclone separator and transferred back to the chamber. The milk powder produced is then received at the base of the dryer in bags or cellar and sent for a storehouse.

2.4 Energy Utilization in Drying

Transforming a liquid into dry powder requires to remove of practically all water contained in the food product to be processed During the drying process, the product is undergoing significant changes of its physical properties (mainly its structure), starting with water like liquid and finishing as dry powder at the end of the process. Therefore, one method of water removal is not optimal through the whole process [21].

- Because the drying is extremely energy intensive operation, there are methods that can be used to minimize the energy consumption like [22]:
- Minimizing the water content of the feed before drying (concentrating the product to be dried)
- Maximizing the temperature of the drying gas and minimizing the outlet temperature of the drying gas on output from the dryer
- Using multi-stage drying process
- Utilizing the heat in the discharge drying gas to preheat incoming drying gas
- Utilizing direct heat wherever possible
- Reducing radiation and convection heat loss

2.4.1 Minimizing the water content of the feed before drying

Minimizing the water content of the dried food product before drying is the most important method to improve the energy utilization during drying [22]. While the steam consumption is approx. 0.10 - 0.20 kg/kg of evaporated water in the evaporator, it is 2.0 – 2.5 kg/ kg of evaporated water in conventional one-stage spray dryer – it is in other words 20 times higher comparing with the evaporator. This means that the evaporator is able to remove more water at low energy consumptions, so the solids content in the dried product should be increased before drying. On the other hand, the viscosity of the feed influences the atomization of the drying product in the spray dryer. The viscosity of concentrated milk increases with increased content of proteins, crystallized lactose and overall solid content. An increase in the solid content will require an increase in the outlet drying gas temperature because the evaporation becomes slower due to the smaller average diffusion coefficient – bigger temperature difference between the particle and drying gas will be necessary [21].

To concentrate the dried product before drying (increasing its solids content), the mechanical separation processes such as settling, centrifuging, filtration, reverse osmosis etc., or thermal processes such as evaporation can be selected. However, the mechanical separation processes are far more energy efficient than thermal processes, there are food products when mechanical separation is not possible (for example milk powder production) and evaporation should be considered [22].

2.4.2 Temperature and moisture content of the drying gas

Unlike evaporators where the latent heat of the evaporated water can be reused as heating medium for the next effect at lower pressure, the latent heat in evaporated water from the dryer is not easily reused apart from preheating applications. The vapor is carried in a drying gas stream, which reduces the thermal potential. Therefore, it is important to minimize the volume of inlet drying gas to input the heat and carry over the vapors that are generated during drying. If large quantities of drying gas exit the dryer, an equally large quantity of heat is lost. The higher the inlet drying gas temperature is, the lower the quantity of drying gas will be required which increase the efficiency of the dryer [22].

- The outlet temperature of the drying gas is determined by many factors, the most important are [21]:
- Moisture content in the final powder – the lower residual moisture content of the powder is wanted, the lower the relative humidity and higher outlet temperature of the drying gas will be achieved
- Temperature and moisture content of the drying gas – the higher amount of moisture in the inlet drying gas, the outlet temperature has to be increased to compensate the extra moisture
- Solids content in the concentrate (feed) – the higher solid content of the concentrate, the higher outlet temperature of the drying air
- Atomization – finer spray will result lower outlet temperature of the drying air

- Viscosity of the concentrate – influences the atomization

The overall drying efficiency can be expressed by the approximated by formula 5 [21] or [19]:

$$\boldsymbol{\eta = \frac{T_i - T_o}{T_i - T_a}} \quad (5)$$

where T_i is drying gas inlet temperature, T_o is drying gas outlet temperature and T_a is ambient temperature.

From formula 5 we can see, that the only possibility of increasing the efficiency of spray drying process is by increasing ambient temperature by preheating the drying air sucked by fan to the drying air heater or by increasing the inlet temperature or decreasing the outlet temperature [21, 19]. The overall drying efficiency (5) in case of classic spray dryers operated on skim milk (inlet/outlet temperature 200/90 °C) will be around 56 % and it can be as well the indicator of the dryer performance [21].

2.4.3 Using multi-stage drying process

From previous discussion in chapter 2.4.2, the particle temperature is given by the surrounding air temperature (outlet drying air temperature). As the last water is the most difficult to remove by the drying, the outlet drying air temperature has to be high enough to ensure driving force capable to remove the last moisture [21].

As mentioned in previous chapter, the residual moisture content in powder has a big effect on outlet drying air temperature. The lower the residual moisture content of the powder, the higher outlet drying air temperature and the lower overall drying efficiency.

To increase the overall drying efficiency, we can reduce the outlet drying air temperature. It may be appropriate to use two or more stages of drying. The first stage of drying would remove the bulk of the water and because the residual moisture of the powder would be higher, the outlet drying air temperature would be lower. To reach the wanted low residual moisture of the powder, a second and much smaller dryer would be used as the final stage [22]. On the other hand, the residual moisture of milk powder should not be lower than 8 – 10 %, because the powder would get sticky.

The calculations presented in literature shows that skim milk powder with 3.5% residual moisture requires 1595 Kcal/kg of the powder while for a powder with 6% residual moisture it is only 1250 Kcal/kg powder [21].

New installations for milk powder production are usually designed as two or three stage dryers where the spray dryer system is equipped with fluid bed conveyor dryer operating with much lower temperature of drying air or with fluid bed bottom of the drying chamber (two stage drying process). The spray dryer with fluid bed bottom can be completed with vibrio fluid bed conveyor (three stage drying process) – see Fig. 4. The advantage of the two-stage drying are [20]:

- higher capacity/kg drying air
- better economy
- better product quality (good solubility, high bulk density, low free fat)
- less powder emissions

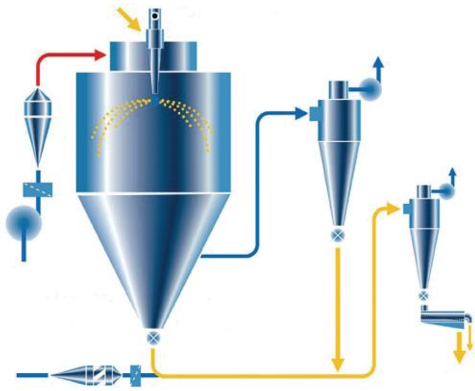


Figure 3 -*Single stage spray drying system – GEA Niro spray dryer with pneumatic conveying system [20]*

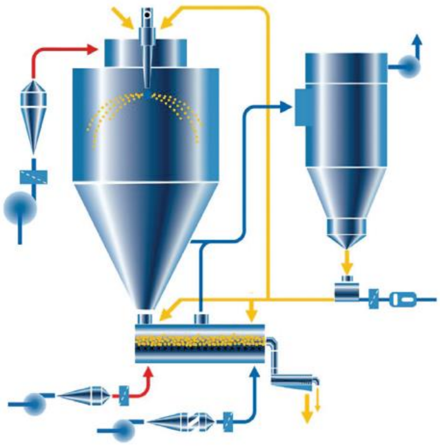


Figure 3(a) -Two-stage drying system: GEA Niro spray dryer with a VIBRO FLUIDIZER;

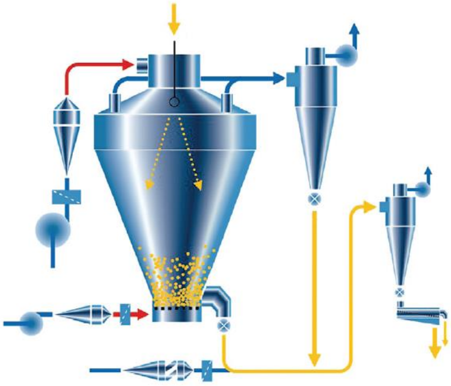


Figure 3(b) -Two-stage drying system: GEA Niro fluidized spray dryer with integrated fluid bed;

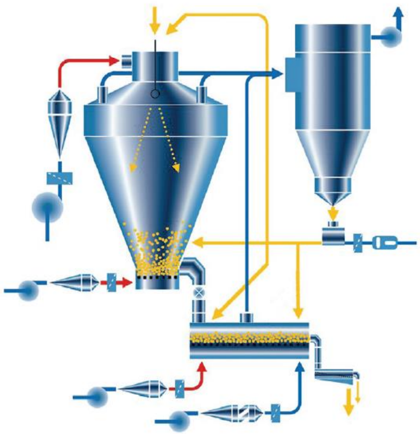


Figure 3(c) -Three-stage drying system: GEA Niro multi stage dryer [20]

2.4.4 Recuperative heating of inlet drying air

Heat can be saved by using outlet drying air and vapor from evaporated moisture mixture to preheat the inlet drying air [22]. It is also possible to use the recuperated heat to heat water for CIP or air for heating rooms [21]. Other option is using a heat pump to increase low potential energy from exhausted air to preheat water for CIP or inlet drying air [23].

There are 2 main different recuperating systems [21]:

- Air to air system
- Air – liquid – air system

In the air to air recuperator (Fig. 4), the drying air is preheated by means of the output air passing counter currently over the heat transfer surface of the recuperator. Because the temperature to which the air can be preheated depends upon the temperature of the output air from the dryer, this type of recuperator is most beneficial in one stage drying installations where the temperature of outgoing air is high [21].

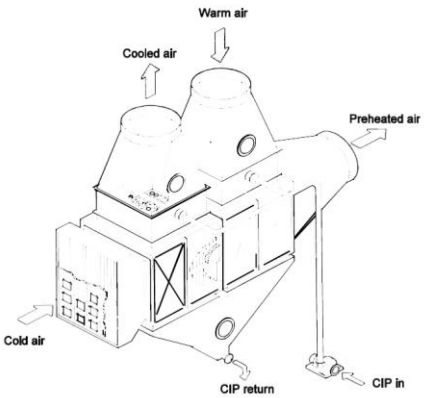


Figure 4 -Air to air heat recuperator [21]

Air – liquid – air heat recuperator (Fig. 5) is more flexible regarding the installation. This system is divided in two heat exchangers in between which a heat transfer liquid is circulated. Due to the higher heat transfer coefficient for air-liquid than for air-air, this system seems to be more efficient than the air to air heat recuperator despite the fact that two heat transfer surfaces are needed [21].

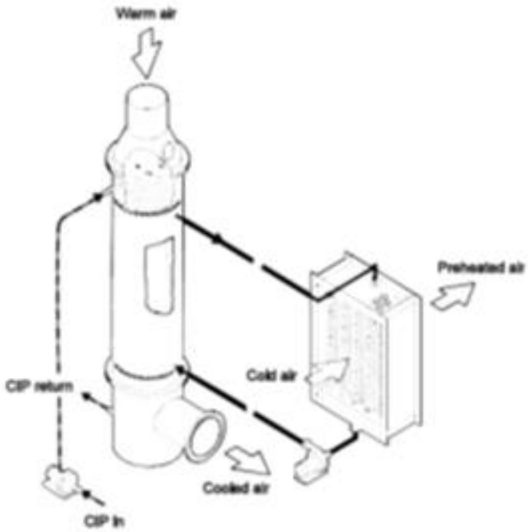


Figure 5 -Air liquid air heat recuperator [21]

Positive effect of heat recuperation on drying economy is confirmed by Walmsley et al. [28]. Their study indicates for air liquid air heat recuperator with finned tubes the IRR up to 71 %. The energy savings of Air to air heat recuperators depends on the drying air temperatures where the highest values (more than 50 %) were investigated at high drying air temperatures [24]. We can obtain more energy savings using not only the heat recuperator but the recirculation of exhaust air [25].

Another study presented that using heat recuperation we can significantly increase the overall efficiency of the dryer (up to 70 %) and the heat recuperator is able to preheat the cold air before heater about 30 – 35 °C [26].

As mentioned before the heat recuperation depends on the output temperature from the dryer and should be as high as possible [24]. Therefore, it is the best method for one stage drying system where the output air temperature is quite high. But there are the methods how to use heat recuperation for drying systems where the temperature of outgoing air is lower. One of this method is using heat pump. The output air from the dryer passing through the heat exchanger where the circulating liquid is heated up by the warm exhausted air. The circulating liquid flows through the evaporator of the heat pump and the inlet drying air is heated in condenser of the heat pump (Fig. 6) [23]. Another more academic method is using liquid sorption process [29].

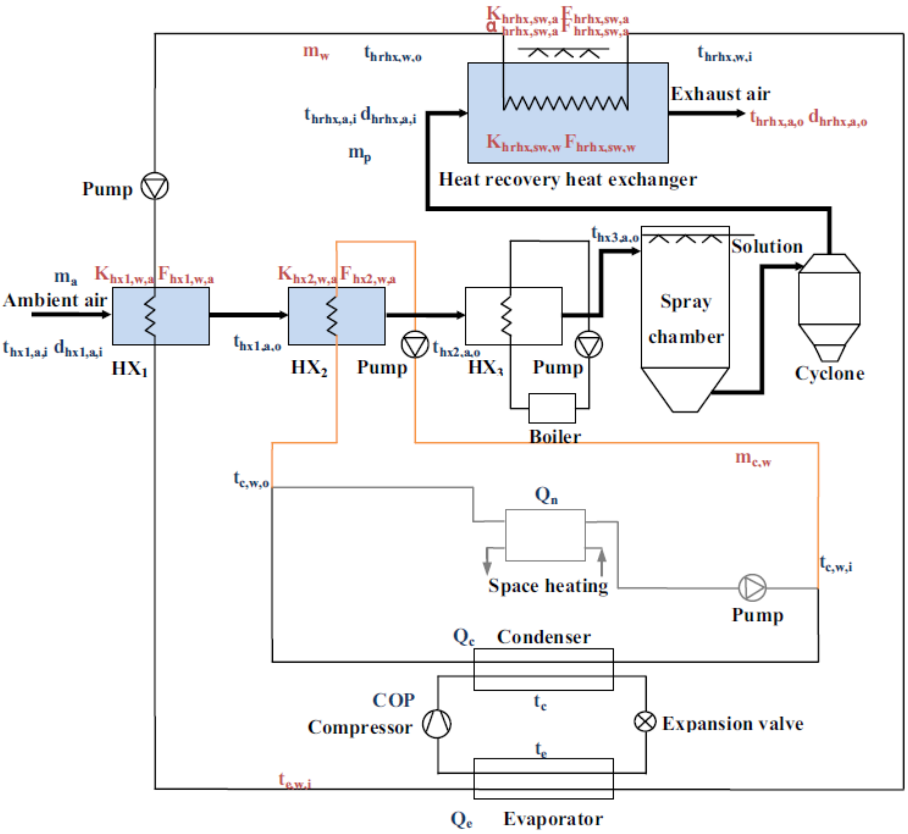


Figure 6 - Schematic diagram of the heat recovery system using heat pump [23]

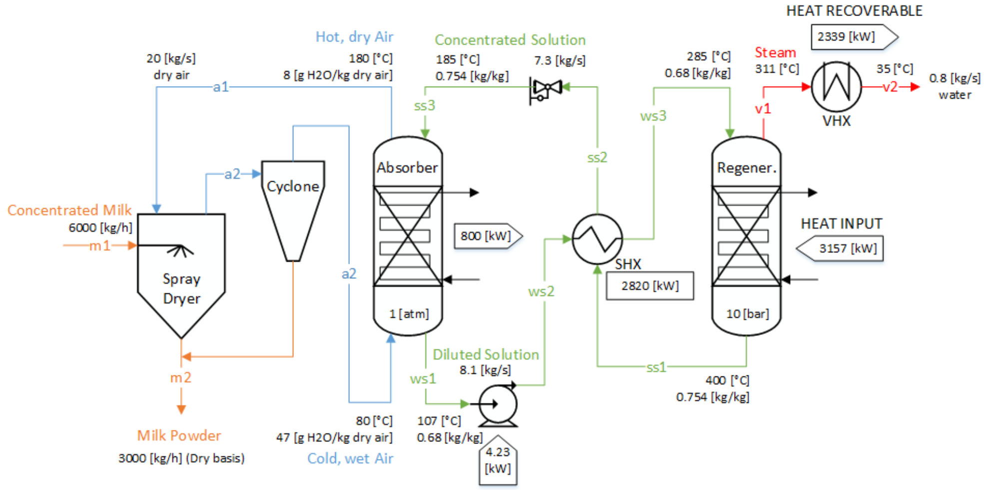


Figure 7 - *Schematic diagram of the heat recovery system using liquid sorption process [29]*

The efficiency of the heat recuperation system is significantly influenced by deposition of sticky milk dust on heat transfer surface [27]. To reduce the possibility of dust fouling on heat transfer surface of the heat recuperator, the filter (bag filter) should be installed prior to the heat recuperator. As the dust deposits cannot be completely avoided even the fine filters are installed prior the heat recuperator, it would be necessary to clean the heat recuperator surfaces. This can be done by means of built in CIP [21].

2.4.5 Direct heat utilization

It is suitable for drying system where the inlet drying air is heated directly by the combustion gases from the gas or oil burner [22]. This is not possible for milk powder production.

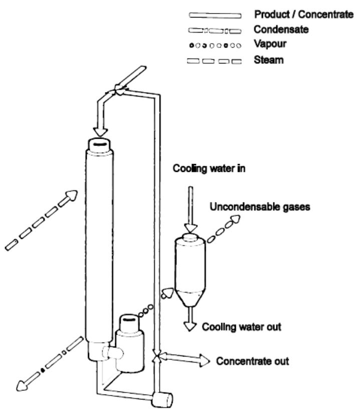
2.4.6 Thermal insulation

Drying equipment’s are large and operates at quite high temperatures. It is connected with a large potential for high heat loss from convection and radiation. Good insulation of the dryer is the way to ensure energy efficiency [22].

2.5 Energy Utilization in Evaporator

As mentioned in previous chapter, the milk should be concentrated before entering spray dryer to minimize water content in dried milk because the steam consumption per kg of evaporated water in evaporator is much lower than in the spray dryer. In case of milk powder manufacturing process, the thermal process of water evaporation on falling film evaporators is mostly used.

In falling film evaporator (Fig. 8), the milk will flow downwards through the boiling tube forming a thin film, from which the boiling/evaporation will take place because the heat applied by heating steam. Heating steam will condense and flow downwards on the outer surface of the boiling tubes. The concentrated liquid and vapors leave the boiling section (so called calandria) at the bottom part from the main proportion of concentrated liquid is discharged. The remains part enters tangentially the subsequent separator together with the vapors. The concentrate is discharged by the pump and the vapors leaves the separator from the top. The heating steam is collected as condensate at the bottom part of the boiling section [21].



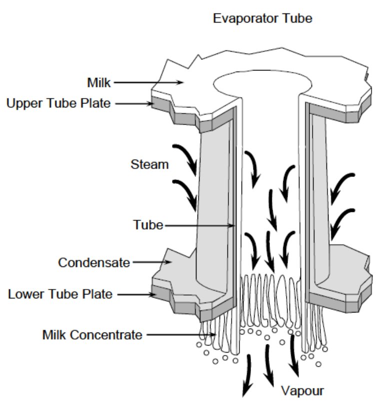


Figure 8 - – a) Falling film recirculation evaporator; b) evaporation in a falling film evaporator tube [21]

Because milk, due to the protein content, is a heat sensitive product, the boiling section is operated under vacuum – the boiling/evaporation takes place at lower temperature to keep the nutritional value of milk damaged by the heat as low as possible. The vacuum is created by vacuum pump and maintained by condensing the vapors by cooling water circuit. Vacuum pump is used to evacuate incondensable gases from milk [21].

2.5.1 Number of evaporator effects

As vapor from the evaporated milk contains almost all the applied energy by supplied by heating steam, it is obvious to utilize this vapor to evaporate more water by condensing the vapor in another added calandria to the evaporator (second effect). This second effect where the boiling temperature is lower works as condenser for vapors from the first effect so the energy in vapors is utilized as it condenses [21]. To obtain a temperature difference in the second effect between the product and vapors, the boiling section of the 2nd effect is operated under higher vacuum to lower the boiling temperature. 3rd effect or more can be added, but the amount of effects is limited by the lowest obtainable vacuum and is decided from amount and temperature of the cooling water condensing the vapors from the last effect. The practical limit (due to the viscosity and lactose crystallization) of boiling temperature for milk in the last effect is about 45 °C [20].

We can see (Fig. 9) that 1kg of heating steam is able to evaporate 2 kg of water using second effect and applying a third effect, 1 kg of heating steam is able to evaporate 3 kg of water [21]. The more effects of the evaporator the better is the utilization of the energy in heating steam.

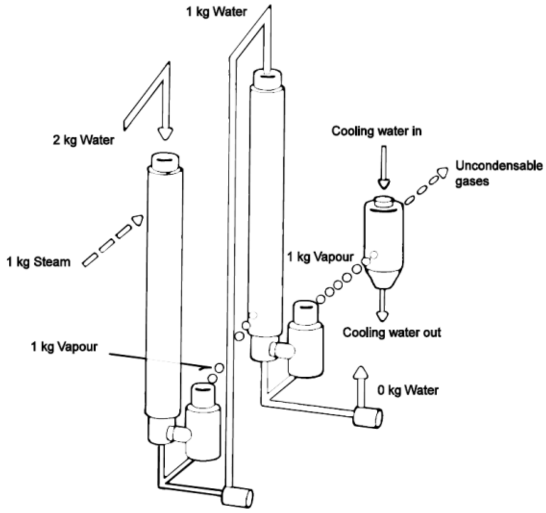


Figure 9 -Principle of multi effect evaporator [21]

By dividing given total temperature difference between the first and last effect in multi-effect evaporators requires an enormous heat transfer area of the calandrias and consequently an expensive installation. The total heat transfer area can be reduced only by increasing the temperature difference between heating medium and boiling temperature of the product. It can be done by increasing the temperature of the first effect heating section resulting higher boiling temperature which will increase the fouling formation on the tubes. So, it is not recommended using boiling temperature of the milk in first effect higher than 66 – 68°C in 20h operation [20].

Dividing the total temperature difference (from 66°C to 45°C = 21°C) between each effect means, that in a three-effect evaporator, each effect will have a big ΔT corresponding to a relatively small heat transfer area and low investment costs. By increased number of effects, however the heating steam consumption goes down, the available ΔT becomes smaller in each effect resulting that higher heat transfer area is required and investment costs go up [21]. We can see that the design of multi-effect evaporator is usually the task for optimization between investment costs, operational costs done by steam consumption and product quality because more added effects increases the residence time where the product is exposed to heat [21].

Nowadays in milk powder processing the 5th up to 7th effect evaporators are designed so the modern evaporator with 15m long tubes in calandria can work with quite low temperature difference between heating media and product (up to 5°C) but for better economy, the vapor recompression is used – in a 7-effect evaporator with mono thermal-compression, we can evaporate 9kg of water using only 1kg of heating steam [20].

2.5.2 Vapor recompression

Another way of saving energy during evaporation process is by using vapor recompression. Thermo-compressor or mechanical vapor compressor can be used.

Thermo compressor will increase the temperature and pressure level of the vapor – compress the vapor exiting the evaporator from a lower pressure to a higher pressure by using heating steam of higher pressure than that of the vapor. Thermo-compressor (TVR) operate at very high steam flow velocities and have no moving parts. The construction is simple, dimensions are small, and the investment cost is low. The principle of the thermo-compressor shows the figure 10. The best efficiency in the thermo-compressor (the best suction rate and thereby a good economy) is obtained when the temperature difference (pressure difference) between the boiling section and heating section of the evaporator is low. A thermo-compressor, which have been designed for a higher heating steam pressure, can draw a larger amount of vapor from the separator than one built for a lower pressure.

New designed thermo-compressors can operate with an efficiency of 1:3 [21].

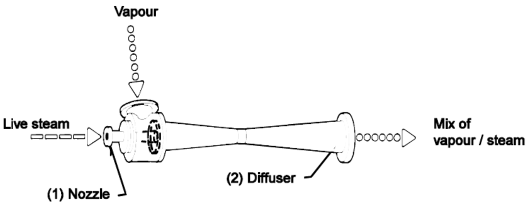


Figure 10 -Thermo-compressor [21]

As mentioned in previous chapter, by adding 2nd effect means that of 1kg heating steam can evaporate 2kg of water. Using thermo-compressor in two-effect evaporator (Fig. 11) by means of 1kg heating steam can evaporate 4kg of water, so the saving of steam is as great as that obtained by addition of two effects in multi-effect evaporation [21].

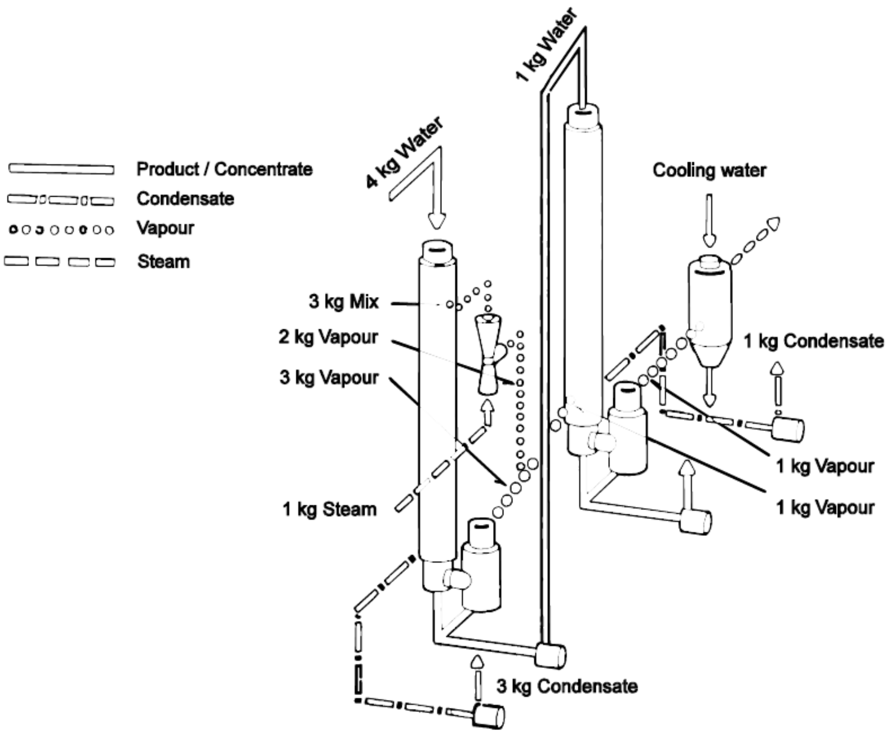


Figure 11 - Two-effect evaporator with thermo-compressor [21]

As an alternative to the TVR, the mechanical vapor compressor (MVR) has during the last 15 years found extensive use in evaporators in the dairy industry. The applied energy is usually electricity. The usage of MVR according to the TVR is profitable if the price of the electricity/kW < 3x (price/kg steam) [20, 21].

2.6 Energy Efficiency Studies

In a milk powder making plant, there are several streams of them some need cooling and some demand heating. The individual stream can have different start and end temperatures, different heat capacities and flow models. When a process stream needs to be heated over a certain temperature limit, it is brought in indirect contact with another process stream which requires to be cooled over a similar temperature interval using a heat exchanger. This is more beneficial than using chilled water to cool one stream and steam to heat the other [2]. A number of heat recovery issues are there which are specific to the building dairy industry. Heat exchangers occasionally signal leaks, and heat recovery might result in corruption between two streams. This is not pleasant in milk processing and the likely solution is to isolate by pressure differential double plate heat exchangers or intermediate circuits in those types of cases. Also, many waste streams might have the tendency to carry contaminants therefore concerning the heat recovery equipment by destroying their surfaces. In the recovery of gas from waste gas streams, there is also the chance of contaminants making a fire hazard. There is also a risk of condensation because of the presence of any moisture provided by waste gas streams on lowering temperature badly. Large heat exchangers use back pressure on boilers and spray dryers and hence the capacity of original equipment to resist this back pressure should be observed. In this situation, the use of condensate at an optimal level should help in the restoration of the condensate. It can lead to advantages such as preservations of the cost of water treatment, by replacing the lost condensate, heat, to pre-warm new boiler feed water, and wastewater, because due to less condensate the wastewater produced is likewise shorter [50].

Chapter 3: Description of the current state

In our thesis we are assuming fictive milk processing company which are producing typical dairy products as a pasteurized milk filled in plastic bottles, UHT processed milk packed in Tetrapacks, sweet cream, butter, cheese, yogurts and desserts. In the past, our company also produced milk powder.

Because the production of yogurt, cheese and some bottled milk has moved to a new location and demand for milk powder increased, the company decided to use new free capacity in production to resume production of skim milk powder for bigger food producers.

For this purpose, our company has an older 3 effect evaporator for increasing the concentration of the milk to by dried and older one stage spray dryer to produce milk powder. The company has also the necessary capacity in energies (mainly in steam) and due to the free capacity in production enough capacity in pasteurization station. Company has necessary warehouse capacity to store the milk powder and transport technology.

Because the technology for milk powder manufacturing in our company is quite old, the company will do the necessary reconstructions to be able to operate their milk powder technology. The company would like to know, if there exist some ways to reduce the energy consumption and what will be the effect on economy.

Our task is to find the ways to reduce energy consumption in current state of milk powder technology in our fictive company with minimum investment requirements to keep the expected capacity of the processed milk to be dried.

Expected capacity of the milk powder technology:	12,000 kg/h
Processed product:	skim milk
Dry matter content:	9%
Temperature of skim milk in daily storage tank:	5°C
Final moisture content in skim milk powder:	5 %
Operation:	20 h/day 5days/week
Cleaning and sanitation:	4 h/day
Available energy sources:	steam 16 bar
	Natural gas
	Electric energy

3.1 Description of the current state of milk powder technology

The layout of the current milk powder production line can be seen in the process flow diagram of the current state – see appendix 1.

Pasteurized skim milk is pumped from daily storage tank to the feed tank of the evaporator. From the feed tank, the milk is pumped through the milk preheaters PR03, PR02 and PR01 where the processed milk is preheated by condensing vapors from evaporator effects. Because the temperatures in these preheaters are ideal for bacteria to grow it is necessary the repasteurization of the processed skim milk before entering the first effect. For this purpose, a plate pasteurizer with holding section is installed prior the evaporator. Pasteurizer is heated by steam from boiler room.

From preheaters the milk is led through the steam heated plate pasteurizer PA01 and holding section directly to the first effect of the evaporator to be concentrated.

To minimize the water content in milk before drying, the 3-effect falling film evaporator which operates under vacuum conditions is installed. First effect of the evaporator (EF01) is heated by steam. Concentrated milk is pumped by the pump to the next effect. Vapors withdrawal from first effect are used to heat up second effect and milk preheater PR01. Condensate from the heating steam is mainly returned to the boiler room. Second effect (EF02) is heated by part of vapors from first effect. Concentrated milk from second effect is pumped to the last third effect. Vapors from second effect are used to heat up third effect and milk preheater PR02. Third effect (EF03) is heated by part of vapors from previous effects. Concentrate from third (last) effect is led to the feed storage tank of the spray dryer. Vapors from last effect are partly used to heat up milk preheater PR03 and the rest is condensed in vapor condenser CHE01. Condensates from second and third effect, from milk preheaters and from vapor condenser are collected in condensate tank to be drain. Vapor condenser creates necessary vacuum in heating sections of evaporator calandrias together with vacuum pump VP01. Incondensable vapors from boiling sections of calandrias are sucked by vacuum pump to create necessary low-pressure condition for milk boiling.

Vapor condenser is cooled by cooling water circuit equipped by cooling tower. Concentrate to be dried is stored in double feed tanks. From feed tanks, the concentrate is pumped and led through the concentrate preheater to the atomizing device of the spray dryer. Spray dryer is equipped with rotary atomizer driven by electric drive. Atomizing device is cooled by cooling air. Drying air is sucked through fine filter by fan blower and is led through the calorifier to the drying chamber of the spray dryer (SD01). Calorifier is used to heat up the drying air. Steam air heater is installed to heat up drying air. Milk powder is collected partly on bottom part of the drying chamber, the rest is separated from drying air on outlet by cyclone separate and bag filter.

Evaporator	
No of effects:	3
Type	Falling film – vacuum
Producer	GEA Niro
Calandria 1:	1st effect
Number of tubes	116
Diameter of the tubes	48 mm
Length of the tubes	5 m
Calandria 2:	2nd effect
Number of tubes	226
Diameter of the tubes	48 mm
Length of the tubes	5 m
Calandria 3:	3rd effect
Number of tubes	113
Diameter of the tubes	48 mm
Length of the tubes	5 m
Heating medium	Saturated steam
Cooling water inlet temperature	10-25 °C
Cooling water outlet temperature	Up to 43°C
Cooling water flowrate	Up to 250 m^3/h

Table 1. Technical parameters of the evaporator

Dryer	
No of stages:	1
Type	Spray dryer
Producer	GEA Niro
Atomizing device	Rotary atomizer
Rotary atomizer driven by	Electric drive
Fines recirculation	No
Amount of cooling air for atomizing device	
Dimensions of drying chamber	
Drying air heater	Steam heater
Heating medium	Steam 16 bar / 220 °C

Table 2. Technical parameters of the dryer

4.2 Mass and enthalpy balance of the current state technology

To study the opportunities to save the energy it is necessary deeply analyze the current state of the technology. For this purpose, mass and enthalpy balance model in excel was prepared.

Figure 12 shows simplified balancing scheme of the milk powder technology in the current state.

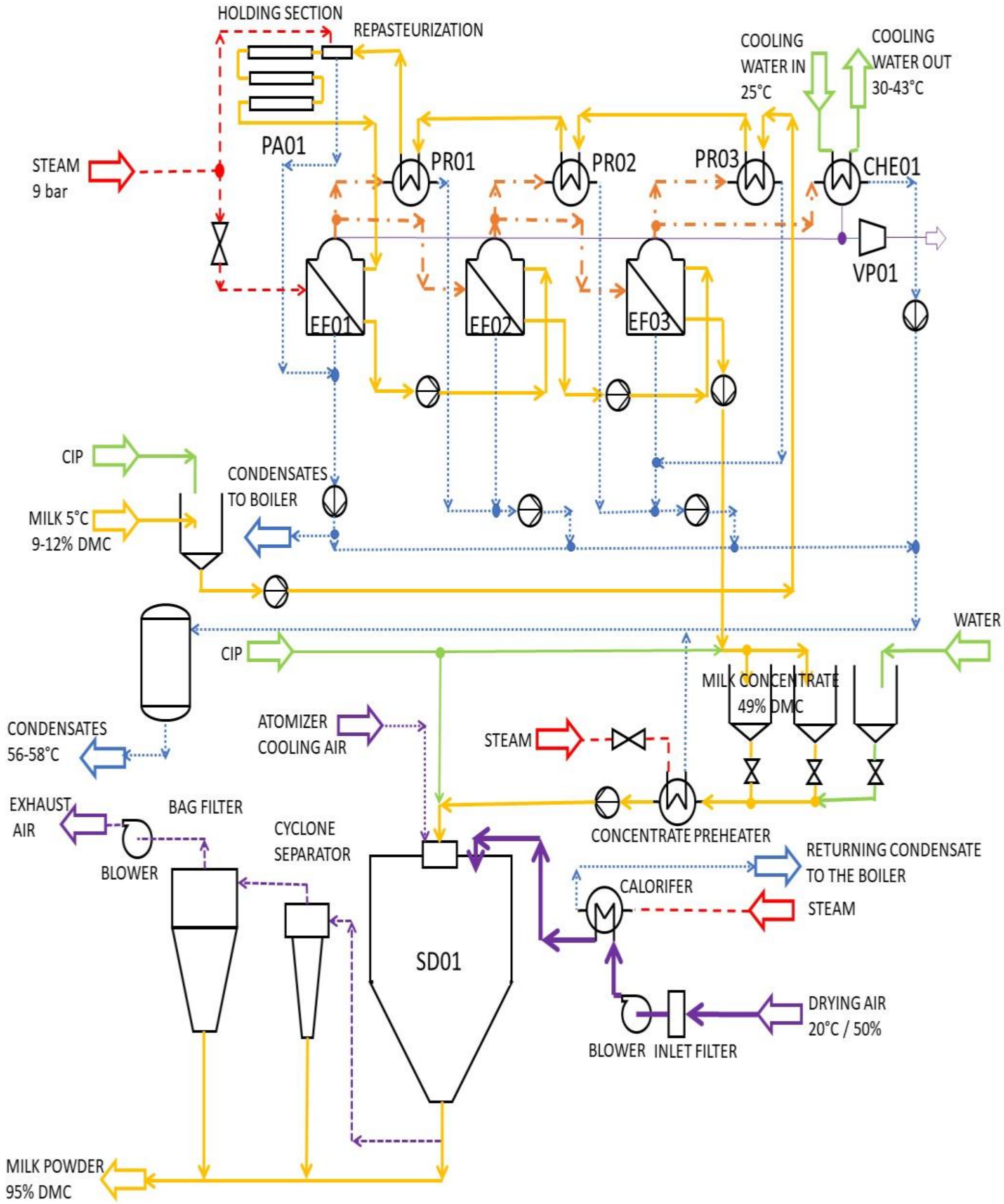


Figure 12 -Balancing scheme of the current state of milk powder technology

3.1 Evaporation mass and enthalpy balance – the methodology

In this section, the balance of mass and energy discussed, by taking the flowrate, inlet temperature and dry matter content of skimmed milk, followed by replacing the device with the different type of equipment which were studied in our work. The methodology was prepared with a help of some publications, mainly [32], [20] and [21].

Flow rate of skimmed milk (M_{sm}) kg/h (given parameter)

Skimmed milk inlet temperature (T_{sm}) °C (given parameter)

Dry matter content of inlet skimmed milk (S_{sm}) % (given parameter)

Concentrated dry matter content after evaporation section (S_{cm}) % (given parameter)

Total amount of evaporated water (W)

$$W = M_{sm} * \left(1 - \left(\frac{S_{sm}}{S_{cm}}\right)\right) Kg/h \tag{5}$$

Total amount of concentration (M_{cm})

$$M_{cm} = M_{sm} - W\ kg/h \tag{6}$$

Cooling water in ($T_{cool\ in}$) °C (given parameter)

Cooling water out ($T_{cool\ out}$) °C (given parameter)

Flowrate of cooling water (M_{cool}) m^3/h (given parameter)

Number of effects (N) (given parameter)

Vapor withdrawal for milk preheater from 1st effect (O_1) kg/h (optimized parameter)

Vapor withdrawal for milk preheater from 2nd effect (O_2) kg/h (optimized parameter)

Vapor withdrawal for milk preheater from 3rd effect (O_3) kg/h (optimized parameter)

With reference to our base scheme we do not have thermo-compressor in base scheme, so vapor from 2nd effect to thermo-compressor will be zero.

Vapor from 2nd effect to thermocompressor (Y) kg/h

Loss to condensation (X)

$$X = [(W - (3 * O3) - (2 * O2) - (1 * O1) - (2 * Y)] \frac{Kg}{h} \qquad (7)$$

Evaporated water 1st effect (W_1)

$$W_1 = (X + O_3 + O_2 + O_1 + Y)\ kg/h \qquad (8)$$

Evaporated water 2nd effect (W_2)

$$W_2 = (X + O_3 + O_2 + Y) \frac{kg}{h} \qquad (9)$$

Evaporated water 3rd effect (W_3)

$$W_3 = (X + O_3) \frac{Kg}{h} \qquad (10)$$

Total amount of Evaporated water (W)

$$W = (W_1 + W_2 + W_3) kg/h \qquad (11)$$

Flowrate concentration of milk from first effect (M_{m1})

$$M_{m1} = (M_{sm} - W_1)kg/h \tag{12}$$

Flowrate concentration of milk from second effect (M_{m2})

$$M_{m2} = (M_{m1} - W_2)kg/h \tag{13}$$

Flowrate concentration of milk from third effect (M_{m3})

$$M_{m3} = (M_{m2} - W_3)kg/h \tag{14}$$

Dry matter content after first effect (S_{m1})

$$S_{m1} = \left[\left(\frac{M_{sm}}{M_{m1}}\right) * S_{sm}\right] \% \tag{15}$$

Dry matter content after second effect (S_{m2})

$$S_{m2} = \left[\left(\frac{M_{sm}}{M_{m2}}\right) * S_{sm}\right] \% \tag{16}$$

Dry matter content after third effect (S_{m3})

$$S_{m3} = \left[\left(\frac{M_{sm}}{M_{m3}}\right) * S_{sm}\right] \% \tag{17}$$

It was predicted that the boiling point elevation, BPE, would present some significant effect on the film flow. The boiling point elevation was calculated based on typical dry basis of skim milk composition [11].

Figure 13 shows that the BPE increased up to about 1 K at about 43% total solids.

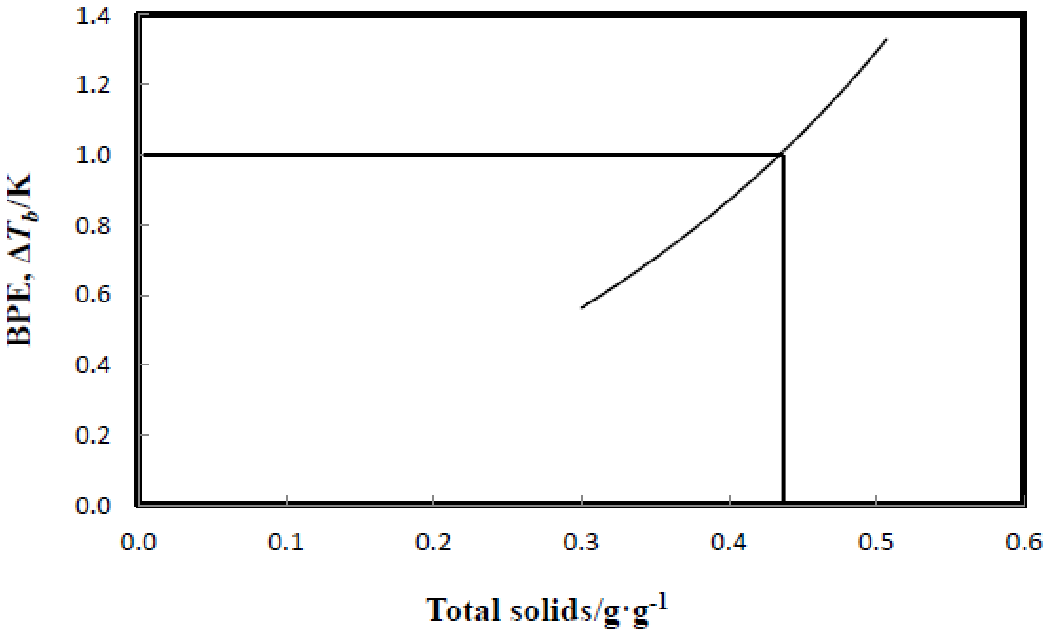


Figure 13 -The calculated boiling point elevation of milk.

Boiling point elevation for 1st effect (dTB_1) °C (calculated according dry matter content)

Boiling point elevation for 2nd effect (dTB_2) °C (calculated according dry matter content)

Boiling point elevation for 3rd effect (dTB_3) °C (Calculated according dry matter content)

Boiling temperature of milk in 1st effect (T_{m1}) °C

Boiling temperature of milk in 2nd effect (T_{m2})

$$T_{m2} = \left(T_{s2} - dT_{2effect}\right) °C \tag{18}$$

Boiling temperature of milk in 3rd effect (T_{m3})

$$T_{m3} = \left(T_{s3} - dT_{3effect}\right) °C \tag{19}$$

Vapor temperature of 1st effect (T_{v1})

$$T_{v1} = (T_{m1} - dTb\_1) °C \tag{20}$$

Vapor temperature of 2nd effect (T_{v2})

$$T_{v2} = (T_{m2} - dTb_2) °C \tag{21}$$

Vapor temperature of 3rd effect (T_{v3})

$$T_{v3} = (T_{m3} - dTb_3) °C \tag{22}$$

Overall temperature difference ($dT_{overall}$)

$$dT_{overall} = (T_{m1} - T_{m3}) \text{℃} \tag{23}$$

Temperature difference between 1st effect ($dT_{1effect}$) °C (optimized value)

Temperature difference between 2nd effect ($dT_{2effect}$) °C (optimized value)

Temperature difference between 3rd effect ($dT_{3effect}$) °C (optimized value)

Temperature drop between effects 1 and 2 ($dT_{1,2}$) °C (assuming 1°C)

Temperature drop between effects 2 and 3 ($dT_{2,3}$) °C (assuming 1°C)

Heating steam temperature of 1st effect (T_{s1})

$$T_{s1} = \left(T_{m1} + dT_{1effect}\right) \text{°C} \tag{24}$$

Heating vapor temperature of 2nd effect (T_{s2})

$$T_{s2} = \left(T_{v1} - dT_{1,2}\right) \text{°C} \tag{25}$$

Heating vapor temperature of 3rd effect (T_{s3})

$$T_{s3} = \left(T_{v2} - dT_{2,3}\right) \text{°C} \tag{26}$$

Latent heat for 1st effect r_1 = 2338.71 kJ/kg (from steam table: r_LG = h”-h’)

Latent heat for 2nd effect r_2 = 2363.28 kJ/kg

Latent heat for 3rd effect r_3 = 2394.55 kJ/kg

Heat power 1st effect (Q_{E1})

$$Q_{E1} = \left[\frac{r1*W1}{3600}\right] Kw \tag{27}$$

Heat power 2nd effect (Q_{E2})

$$Q_{E2} = \left[\frac{r2*W2}{3600}\right] Kw \tag{28}$$

Heat power 3rd effect (Q_{E3})

$$Q_{E3} = \left[\frac{(r3*W3)}{3600}\right] Kw \tag{29}$$

Overall heat transfer coefficient 1st K_1 2900 W/(m^{2}k)

Overall heat transfer coefficient 2nd K_2 1900 W/(m^{2}k)

Overall heat transfer coefficient 3rd K_3 1300 W/(m^{2}k)

Necessary heat transfer area A1 (*Calandria 2*)

$$A_1 = \left[\frac{Q_{E1}*1000}{K1*dT_{1effect}}\right] m^2 \tag{30}$$

Necessary heat transfer area A2 (*Calandria 1*)

$$A_2 = \left[\frac{Q\_E2*1000}{K2*dT_{2effect}}\right] m^2 \tag{31}$$

Necessary heat transfer area A3 (*Calandria 3*)

$$A_3 = \left[\frac{Q_{E3}*1000}{K3*dT_{3effect}}\right] m^2 \tag{32}$$

Necessary amount of heating steam for evaporators ($M_{steam\ ev}$)

$$M_{steam}, ev = (\boldsymbol{W_1} - \boldsymbol{Y})\boldsymbol{kg/h} \tag{33}$$

Necessary amount of heating steam for Pasteurization ($M_{steam\ pas.}$)

$$M_{steampas} = \left[\left(\frac{Q_{pas}}{r_{steam,past.}}\right) * 3600\right] \tag{34}$$

3.2 Dryer

In this section, the balance of mass and energy in dryer section will be discuss, by taking the flowrate, inlet temperature and dry matter content of concentrated milk coming from evaporation section. The methodology was prepared with a help of some publications, mainly [30], [31], [20] and [21].

Flow rate of concentrate from evaporator station – FEED (M_{cm})

Total solids of skim milk concentrate from evaporator (S_{cm}) %

Total solids of powder from spray dryer (S_{mpsd}) %

Flow rate of powder from spray dryer (M_{psd}) kg/h

$$M_{psd} = M_{cm} * \left(\frac{S_{cm}}{S_{mpsd}}\right)\frac{kg}{hr} \tag{35}$$

Amount of evaporated moisture from spray dryer (W_{sd}) kg/h

$$W_{sd} = \left(M_{cm} - M_{psd}\right)kg/h \tag{36}$$

Ambient air temperature - sucking air to the heater (T_a) °C (given value)

Ambient air relative humidity (RH_a) % (given value)

Inlet air temperature to the drying chamber (T_1) °C (given value)

Outlet air temperature from drying chamber (T_2) °C (calculated value)

Temperature of the milk concentrate - feed temperature (T_f) °C (given value)

Milk powder temperature at output from dryer (T_p) °C (assumed value)

Cooling air rate to cool atomizing device (ambient) (A_c) kg/h (given value from technical description of used atomizing device)

Total heat to remove moisture from feed (Q_{TE}) kW

$$Q_{TE} = [\left(\frac{W_{sd}}{3600}\right) * \left(r + \left(\frac{C_{v2}}{1000}\right) * \left(T_2 - T_f\right)\right] \tag{37}$$

Total heat in outcoming product (Q_{PR}) kW

$$Q_{pr} = \left[\left(\frac{M_{psd}}{3600}\right) * \left(T_p - T_f\right) * \left(\frac{C_{ps}}{1000}\right) * \left(\frac{S_{mpsd}}{100}\right) + \left(\frac{C_{pm}}{1000}\right) * \left(1 - \left(\frac{S_{mpsd}}{100}\right)\right)\right] \quad (38)$$

Heat loss of the drying chamber (Q_{loss}) kW

$$Q_{loss} = \frac{k * A_{dc} * (T_2 - T_a)}{1000} \ kW \quad (39)$$

Total necessary heat input (Q_{in}) kW

$$Q_{in} = \left(Q_{te} + Q_{pr} + Q_{co} + Q_{tr} + Q_{rf} + Q_{loss}\right) \quad (40)$$

Drying air flow rate (M_{da}) kg/h

$$M_{da} = [\frac{Q_{in}}{T_1 * \left(\frac{C_{a1}}{1000}\right)} * \left(T_2 * \left(\frac{C_{a2}}{1000}\right)\right) + (Y_a * ((T_1 * \left(\frac{C_{v1}}{1000}\right) - \left(T_2 * \left(\frac{C_{v2}}{1000}\right)\right) * 3600 \quad (41)$$

Exhaust air absolute humidity ($Y2$) kg/kg d.a

$$Y_2 = \frac{M_{va} - M_{vp}}{M_{dry}} \quad (42)$$

Calorifier heat duty (Q_{cal}) Kw

Amount of steam to heat the drying air (M_{Steam}) Kg/h

$$M_{steam} = \left(\frac{Q_{cal}}{2360}\right) * 3600 \qquad (39)$$

3.2.1 Results summary from balancing model – evaporator

Sl. No.	Condition	Value
01.	Incoming milk temperature	5 °C
02.	Incoming milk solid concentration	9 %
03.	Milk flow rate	12000 kg/h
04.	Concentrate dry matter content	49 %
05.	Cooling water in	25 °C
06.	Cooling water out	31.3 °C
07.	Cooling water flowrate	210 m^3/h
08.	Vapor withdrawal from 1st effect for preheater 1	193.8 kg/h
09.	Vapor withdrawal from 2nd effect for preheater 2	408.2 kg/h
10.	Vapor withdrawal from 3rd effect for preheater 3	633.0 kg/h

11.	Milk temperature after preheater 1	60.8 °C
12.	Milk temperature after preheater 2	51.4 °C
13.	Milk temperature after preheater 3	31.3 °C
14.	Milk temperature after pasteurizer	72 °C
15.	boiling point elevation 1^{st} effect	0.2 °C
16.	boiling point elevation 2^{nd} effect	0.4 °C
17.	boiling point elevation 3^{rd} effect	1.15 °C
18.	Milk boiling temperature in 1^{st} effect	71 °C
19.	Milk boiling temperature in 2^{nd} effect	61.8 °C
20.	Milk boiling temperature in 3^{rd} effect	42.4 °C
21.	Temperature difference 1st effect	12 °C
22.	Temperature difference 2nd effect	8 °C
23.	Temperature difference 3rd effect	15 °C
24	Overall heat transfer coefficient for 1^{st} effect	2900 W/m^2K
25..	Overall heat transfer coefficient for 2^{nd} effect	2100 W/m^2K
26.	Overall heat transfer coefficient 3^{rd} effect	900 W/m^2K

Table 3. Process requirements for milk powder production in evaporation section

Sl. No.	**Process condition**	**Value**
01.	Temperature of milk leaving the evaporators	42.4 °C
02.	Solid concentration of milk leaving the evaporators	49 %
03.	Total amount of evaporated water	9795.918 Kg/h
04.	Loss to condensation	2295.55 Kg/h
05.	Dry matter content after 1^{st} effect	12.75 %
06.	Dry matter content after 2^{nd} effect	21.04 %

07.	Dry matter content after 3rd effect	49 %
08.	Vapor temperature 1st effect	70.8 °C
09.	Vapor temperature 2nd effect	61.4 °C
10.	Vapor temperature 3rd effect	41.25 °C
11.	Heating steam temperature 1st effect	83 °C
12.	Heating vapor temperature 2nd effect	69.8 °C
13.	Heating vapor temperature 3rd effect	60.4 °C
14.	Necessary amount of heating steam for evaporators	3530.56 kg/h
15.	Necessary amount of heating steam for pasteurizer	237.57 kg/h
16.	Necessary amount of heating steam for CIP	1900 kg/h
17.	Pressure in Calandria 1	31 kPa
18.	Pressure in Calandria 2	21 kPa
19.	Pressure in Calandria 3	9.5 kPa
20.	Total power of installed pumps	12.7 kW
21.	Total power of vacuum pumps	2x5.5 kW = 11 kW

Table 4. Mass and energy balance of base scheme

Calandria			1	2	3
Length of tube	L	m	5	5	5
Diameter of tube	D	mm	48	48	48
Number of tubes	NT		226	116	113
Heat transfer area of one tube	A_1tb	m^2	0.75398	0.75398	0.75398
Total heat transfer area	A_eff	m^2	170.4	87.5	85.2
Reserve in heat transfer area	A_res	m^2	26.3	21.6	2.0
Heat transfer area check			OK	OK	OK

Table 5. Evaporators heat transfer areas

3.2.2 Results summary from balancing model – spray drying

Sl. No.	Condition	Value
01.	Total solids of powder from spray dryer	95 %
02.	Ambient air temperature - sucking air to the heater	20 ℃
03.	Ambient air relative humidity	50 %
04.	Inlet air temperature to the drying chamber	200 ℃
05.	Outlet temperature from drying chamber	94.6 ℃
06.	Temperature of the milk concentrate - feed temp.	60°C
07.	Milk powder temperature at output from dryer	80 °C
08.	Cooling air rate to cool atomizing device (ambient)	100 Kg/h
09.	Surface of drying chamber	230.04 m^2
10.	Drying air flowrate	27000 kg/h

Table 6. Process requirements for milk powder production in dryer section

Sl. No.	Process condition	Value
01.	Total Heat to remove moisture from feed	760.46 KW
02.	Total heat in outcoming product	8.86 KW
03.	Heat of atomizing device cooling air	2.11 KW
04.	Heat loss of the drying chamber	59.87 KW
05.	Total necessary heat input	831.30 KW
06.	Drying air flow rate	27000 kg/hr
07.	Theoretical amount of air	26898 kg/hr
08.	Exhaust air absolute humidity	0.04715 kg/kg d.a
09.	Theoretical heat duty to heat up drying air from ambient temperature	1395 kW
10	Calorifer efficiency	98 %
11.	Calorifer heat duty	1423.51 KW
12.	Overall drying efficiency	0.586 KW
13.	Amount of steam to heat the drying air	2171.45 kg/hr
14.	Specific steam consumption (classic spray dryer: 2.0 – 2.5 kg/kg)	2.03 kg steam/ kg evaporated moisture
15.	Specific air amount for drying (classic spray dryer: 15-30 m^3/kg powder)	24.84 m^3/kg of the powder
16.	Amount of steam to preheat the feed before dryer	76.5 kg/h
17.	Total power duty – electric energy (fans, pumps, atomizing device)	100 kW

Table 7. Mass and energy balance of dryer section

Energy balance of the current state is summarized in following table together with the costs for energies (cost of steam 500 CZK/GJ, cost of electric energy 2540 CZK/MWh).

		Current state			
Total Heat consumption		**kg/h**	**GJ/day**	**GJ/year**	**CZK/year**
	for evaporators:	3530,56	161,2	38684	19 342 095,10
	for pasteuriser:	237,57	10,8	2603	1 301 532,62
	for dryer:	2171,45	84,5	20288	10 144 152,57
	for dryer feed preheater:	76,50	3,0	715	357 396,31
	for CIP:	1900	17,3	4164	2 081 822,40
Total steam consumption:		**7916,09**	**276,9**	**66454**	**33 226 999,00**

Total Electric consumption		**kW**	**MWh/day**	**MWh/year**	**CZK/year**
	evaporator	23,7	0,57	136,5	346 740,48
	dryer	100	2,00	480,0	1 219 200,00
Total Electric energy consumption			**2,57**	**616,5**	**1 565 940,48**

Total energy costs CZK/year		**34 792 939,48**

Table 8. Energy and cost evaluation of the current state (base scheme)

Chapter 4: Improving energy efficiency by process integration

In this section, the simulation of the normal performance of the milk powder plant which was discussed in previous chapter by its mass and enthalpy analysis. With our analysis, first, we will analysis the area where the heat loss is relatively more will be determined which will be followed by improving strategies through the mass enthalpy balance to make the entire plant much more energy efficient.

4.1 Energy analysis of base Scheme

We need to find the amount of heat loss in each part of the plant, mass and energy analysis of the base Scheme was performed with the help of the equations that we have explained and the outcome are given in previous chapter. From our results, we can assume that we can propose some idea to make plat more efficient and optimize and then we can do the mass and enthalpy balance of the new scheme with the help of same equations and then compare the results of two schemes.

4.1.1 Energy Efficiency Opportunities

Various opportunities exist within the diary processing industry to reduce energy consumption while maintaining or enhancing production. As part of the dairy industry's aggressive move to reduce the carbon footprint and energy consumption of the industry as a whole, energy efficiency improvements to dairy processing facilities are key to attaining this goal.

The most effective method to improving energy efficiency in a dairy processing facility is to implement energy saving techniques across various levels of production. At the component and equipment level, energy efficiency can be improved by preventative maintenance, proper loading and operation, energy efficient choices for new equipment, and the replacement of older components and equipment with higher efficiency models when feasible.

At the process level, process control, optimization, and integration can ensure maximum efficiency. In addition, implementation of new or alternate process systems can improve efficiency and reduce operating costs.

On the facilities level, efficient lighting, heating, and cooling can reduce energy loads, and implementation of combined heat and power or process integration systems can improve efficiency.

Finally, on the organizational level, a strong company commitment to energy management, augmented by energy monitoring, target setting, employee involvement and continuous improvement, is essential to the long-term success of energy efficiency improvements and its associated cost benefits [17].

The following subchapters in this Energy Guide discuss some of the most pertinent energy efficiency measures applicable to the dairy processing industry. This guide focuses on measures that are proven, cost effective, and available for implementation today [17].

Based on the energy expenditure, we can primarily on the following major areas of opportunity for energy efficiency: steam systems, motor and pump systems, refrigeration systems, compressed air systems, building facilities, self-generation, pasteurization processes, evaporation processes, and drying processes. As such, the measures described that, collectively, account for over 90% of the energy used in the dairy processing industry [17].

We primarily on reducing energy usage, the dairy industry consumes significant amounts of energy in the form of stream and water in CIP and other systems. Given water's rising importance as a resource, as well as the energy use associated with heating and pumping water, this guide includes a chapter on basic water efficiency measures applicable to the dairy processing industry [17].

4.1.2 Strategies to improve energy efficiency

4.1.2.1 First strategy

To overcome the quantity of heat loss in the equipment and how to improve the energy efficiency of the plant, several strategies that have the potential to enhance the present condition were analyzed. It was recognized that use of steam can be compensate with the help of introducing TVR (Thermal Vapor Recompression) or MVR (Mechanical Vapor Recompression). It is considered as our first strategy.

4.1.2.2 Second strategy

As we already discussed in the previous chapter that dairy industry consumes significant amount of water in the form of CIP (Cleaning in Process). **Clean-in-place** (**CIP**) is a process of cleaning the interior surfaces of milk powder plant's pipes, vessels, process equipment, filters and associated fittings, without disassembling the plant. In our base scheme we use CIP from external first by heating the water and then mixed with CIP liquid. It was recognized that use of water from different source and heating it could be compensating by the heat available in part of condensates, which we received from all three effects and are not returned back to the boiler.

4.1.2.3 Third strategy

To overcome the quantity of heat loss in the dryer section and how to improve the efficiency of the dryer, some strategies that have potential to enhance the present condition were analyzed and it was recognized that we can regenerate the hot air, which is coming out of dryer (from cyclone separator and bag filter) and use its energy to heat up the incoming air and save our steam. Our company operates one stage drying where the output air temperature from the dryer is relatively high, so the heat regeneration system is possible.

Other opportunities are using the heat in condensates from evaporator to preheat the inlet air to the dryer or using part of vapors from the evaporator for the same thing. However, we are using the heat in condensates for CIP water preheating (strategy 2) so that it will be not enough heat for preheating the drying air. Similar with the vapors from evaporators. Great amount of vapors are used to preheat incoming milk before evaporation and we have practically no reserve to use the vapors to preheat the drying air.

Another problem is to substitute the steam drying air heater by indirect natural gas heater. But the efficiency of indirect gas heater is much lower and direct gas heater with greater efficiency is not possible in dairy industry. It will bring only the effect to reduce the maintain costs for high-pressure steam so this opportunity will not be further discussed.

4.2 Optimized process flow diagram

After implementing all three above mentioned strategies in our base scheme, we will optimize our base scheme and will be able reduce energy and this will lead to a certain percentage of reduction in direct operating cost which will be further explained in following economy section. The optimized process flow diagram (PFD) after implementing all three strategies is available in the appendix to this work.

4.2.1 Outcomes with first strategy

First strategy is about introducing of vapor recompressor so it could recompress the vapor and we will be able to save out steam, in order to serve this purpose, we will use TVR (thermal vapor recompression) instead of MVR (mechanical vapor recompression) because MVR is way too expensive as compare TVR and is better for new designed evaporators. Therefore, we will introduce TVR as shown in figure 14 as it will take the steam from second effect and recompress it and fed it to first effect (mono thermal vapor recompression). The details are shown in table 11 and by comparing table we can see that we are able to save sufficient amount of steam i.e. “1369 kg/h” with the help of TVR.

On the other side, using TVR in our evaporator will cause the decrease of temperatures of milk preheaters so the installed pasteurization unit will not have enough power to heat up the milk to necessary pasteurization temperature, which will increase the investment costs. To implement TVR, new reconnections of evaporator callandrias will be necessary. Due to the lower vacuum according to base scheme, new vacuum pumps will be purchased and installed.

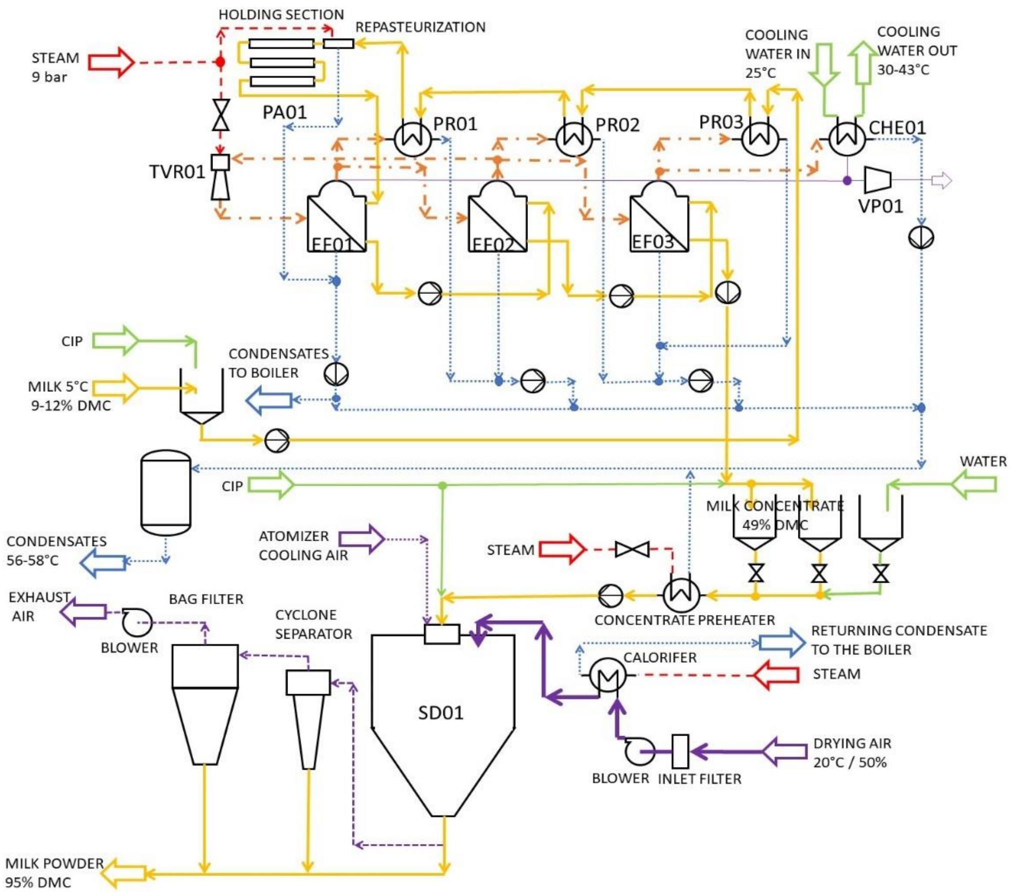


Figure 14 - Balancing scheme of the improved system according 1st strategy.

To select the proper TVR we will need information about necessary suction steam rate M_S, motive steam rate M_M, suction vapor pressure p_s and discharge vapor pressure p_d.

Suction vapor flow rate	M_S	[kg/h]	2022.057
Motive steam flow rate	M_M	[kg/h]	2161.439
Discharge vapor flow rate $M_D=M_S+M_M$	M_D	[kg/h]	4183.496
Entertainment ratio $R=M_S/M_M$	R	[-]	0.95
Suction vapor pressure	p_s	[bar]	1.18
Discharge vapor pressure	p_d	[bar]	1.285
Compression ratio $C=p_d/p_s$	C	[-]	1.1
Expansion ratio $E = p_m/p_s$	E	[-]	1.67
Motive steam pressure	p_m	[bar]	1.97
Selected type DN motive steam / DN suction nozzle / DN discharge nozzle	-	-	5“ DN80/ DN125/ DN125
TVR Efficiency			1:1.94

Table 9. Details about TVR (1st Scheme) [33].

Sl. No.	Condition	Value
01.	Incoming milk temperature	5 °C
02.	Incoming milk solid concentration	9 %
03.	Milk flow rate	12000 kg/h
04.	Concentrate dry matter content	49 %
05.	Cooling water in	25 °C
06.	Cooling water out	31.2 °C
07.	Cooling water flowrate	70 m^3/h
08.	Vapor withdrawal from 1^{st} effect for preheater 1	193.04 kg/h
09.	Vapor withdrawal from 2^{nd} effect for preheater 2	346.4 kg/h
10.	Vapor withdrawal from 3^{rd} effect for preheater 3	632.3 kg/h
11.	Milk temperature after preheater 1	52.8 °C
12.	Milk temperature after preheater 2	43.4 °C
13.	Milk temperature after preheater 3	26.3 °C
14.	Milk temperature after pasteurizer	72 °C
15.	boiling point elevation 1^{st} effect	0.2 °C
16.	boiling point elevation 2^{nd} effect	0.4 °C
17.	boiling point elevation 3^{rd} effect	1.15 °C
18.	Milk boiling temperature in 1^{st} effect	68 °C
19.	Milk boiling temperature in 2^{nd} effect	58.8 °C
20.	Milk boiling temperature in 3^{rd} effect	42.4 °C
21.	Temperature difference 1st effect	12 °C
22.	Temperature difference 2nd effect	8 °C
23.	Temperature difference 3rd effect	15 °C

24	Overall heat transfer coefficient for 1st effect	2900 W/m^2K
25..	Overall heat transfer coefficient for 2nd effect	2100 W/m^2K
26.	Overall heat transfer coefficient 3rd effect	900 W/m^2K

Table 10.Mass and energy balance of base scheme with TVR

Sl. No.	**Process condition**	**Value**
01.	Temperature of milk leaving the evaporators	42.4 °C
02.	Solid concentration of milk leaving the evaporators	49 %
03.	Total amount of evaporated water	9795.918 Kg/h
04.	Loss to condensation	989.7 Kg/h
05.	Dry matter content after 1st effect	13.8 %
06.	Dry matter content after 2nd effect	28.2 %
07.	Dry matter content after 3rd effect	49 %
08.	Vapor temperature 1st effect	67.8 °C
09.	Vapor temperature 2nd effect	58.4 °C
10.	Vapor temperature 3rd effect	41.25 °C
11.	Heating steam temperature 1st effect	80 °C
12.	Heating vapor temperature 2nd effect	66.8 °C
13.	Heating vapor temperature 3rd effect	57.4 °C
14.	Pressure in Calandria 1	28.5 kPa

15.	Pressure in Calandria 2	18 kPa
16.	Pressure in Calandria 3	9.5 kPa
17.	Necessary amount of heating steam for evaporators	2161.4 kg/h
18.	Necessary amount of heating steam for pasteurizer	406.5 kg/h
19.	Necessary amount of heating steam for CIP	1900 kg/h
20.	Total power of installed pumps	12.3 kW
21.	Total power of vacuum pumps	2x8 kW = 16 kW

Table 11.Mass and energy balance of strategy 1

Calandria			**1**	**2**	**3**
Length of tube	L	m	5	5	5
Diameter of tube	D	mm	48	48	48
Number of tubes	NT		116	226	113
Heat transfer area of one tube	A_1tb	m^2	0.75398	0.75398	0.75398
Total heat transfer area	A_eff	m^2	87.5	170.4	85.2
Reserve in heat transfer area	A_res	m^2	9.4	14.5	5.3
Heat transfer area check			OK	OK	OK

Table 12. Evaporators heat transfer areas

	Base				strategy 1 - installing thermo-compressor				Effect - savings			
Total Heat consumption	kg/h	GJ/day	GJ/year	CZK/year	kg/h	GJ/day	GJ/year	CZK/year	kg/h	GJ/day	GJ/year	CZK/year
for evaporators:	3530.56	161.2	38684	19,342,095.10 Kč	2161.4	98.7	23682.81	11,841,404.96 Kč	1369.12	62.51	15001	7,500,690.15 Kč
for pasteuriser:	237.57	10.8	2603	1,301,532.62 Kč	406.5	18.6	4464	2,232,000.00 Kč	-168.93	-7.75	-1861	- 930,467.38 Kč
for dryer:	2171.45	84.5	20288	10,144,152.57 Kč	2171.45	84.5	20288.31	10,144,152.57 Kč	0.00	0.00	0	- Kč
for dryer feed preheater:	76.50	3.0	715	357,396.31 Kč	76.50	3.0	714.7926	357,396.31 Kč	0.00	0.00	0	- Kč
for CIP:	1900	17.3	4164	2,081,822.40 Kč	1900.0	17.3	4163.645	2,081,822.40 Kč	0.00	0.00	0	- Kč
Total steam consumption:	**7916.09**	**276.9**	**66454**	**33,226,999.00 Kč**	**6715.9**	**222.1**	**53313.6**	**26,656,776.24 Kč**	**1200.19**	**54.75**	**13140**	**6,570,222.76 Kč**
Total Electric consumption	kW	MWh/day	MWh/yea	CZK/year	kW	MWh/day	MWh/yea	CZK/year	kW	MWh/day	MWh/year	CZK/year
evaporator	23.7	0.57	136.5	346,740.48 Kč	28.3	0.6792	163.008	414,040.32 Kč	-4.6	-0.1104	-26.496	- 67,299.84 Kč
dryer	100	2.00	480.0	1,219,200.00 Kč	100	2.00	480.0	1,219,200.00 Kč	0	0	0	- Kč
Total Electric energy consumption		**2.57**	**616.5**	**1,565,940.48 Kč**		**2.68**	**643.0**	**1,633,240.32 Kč**	**-4.6**	**-0.11**	**-26.5**	**- 67,299.84 Kč**
Total energy costs CZK/year				**34,792,939.48 Kč**				**28,290,016.56 Kč**				**6,502,922.92 Kč**
Total savings in heat	GJ/year	13140	CZK/year	6,570,222.76 Kč				Investments	CZK	9,077,420.00 Kč		
Total savings in electric	MWh/year	-26.5	CZK/year	- 67,299.84 Kč				Simple payback	year	1.40		
Total savings - energy			CZK/year	**6,502,922.92 Kč**								

Table 13.Total energy consumption balance of strategy 1

4.2.2 Outcomes with second strategy

Our second strategy is to save energy to heat up the water for CIP purpose and use heat in rest of condensates, which we are receiving from all three effects and collecting in condensate tank. Condensates from live heating steam are returned to the boiler. The total value of available condensates from all three effect is 9796 kg/hr. To heat the liquids for CIP 1900 kg/hr of life steam is needed. A plate heat exchanger will be installed to the condensate line to preheat the water for CIP purpose. The heated CIP water will be accumulated in new installed accumulation tank. Available amount of condensates and its temperature is not able to heat up the water for CIP to the needed temperature. But the preheating of CIP water can slightly reduce the live steam consumption from 1900 kg/hr. to 1422 kg/hr.

Flowrate of CIP water/liquids	[kg/hr]	12979
Flowrate of condensates	[kg/hr]	9795
Condensates - inlet temperature	[°C]	55
Condensates – outlet temperature	[°C]	30
CIP water inlet temperature	[°C]	10
CIP water outlet temperature	[°C]	28.8
CIP water required temperature	[°C]	85
Amount of steam needed for heating CIP water from 28.8 to 85°C	[kg/hr]	1422

Table 14. CIP preheater balance

The optimized process flow diagram after implementing first and second strategies as in figure 15. Evaluated energy consumption and energy cost savings are summarized in following table 15.

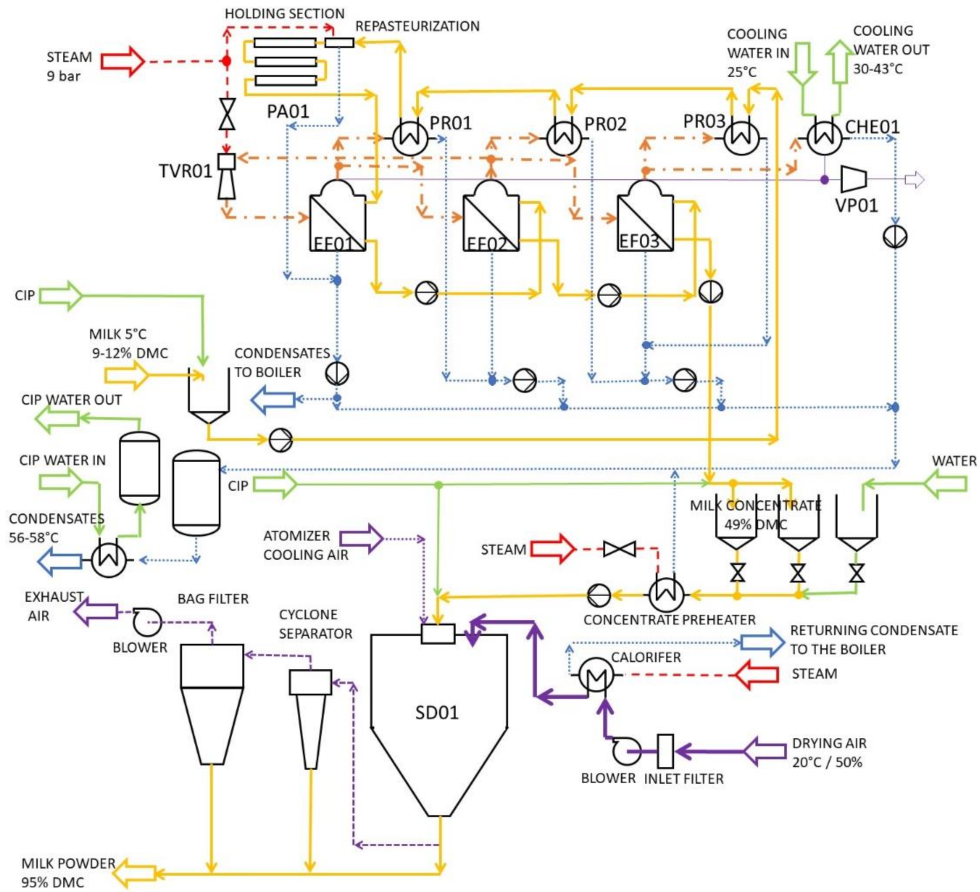


Figure 15 -Balancing scheme of the improved system according to 2nd strategy.

	Base				strategy 2 - installing CIP preheater				Effect - savings			
Total Heat consumption	kg/h	GJ/day	GJ/year	CZK/year	kg/h	GJ/day	GJ/year	CZK/year	kg/h	GJ/day	GJ/year	CZK/year
for evaporators:	3530.56	161.2	38684	19,342,095.10 Kč	3530.6	161.2	38684.19	19,342,095.10 Kč	0.00	0.00	0	- Kč
for pasteuriser:	237.57	10.8	2603	1,301,532.62 Kč	237.6	10.8	2603.065	1,301,532.62 Kč	0.00	0.00	0	- Kč
for dryer:	2171.45	84.5	20288	10,144,152.57 Kč	2171.45	84.5	20288.31	10,144,152.57 Kč	0.00	0.00	0	- Kč
for dryer feed preheater:	76.50	3.0	715	357,396.31 Kč	76.50	3.0	714.7926	357,396.31 Kč	0.00	0.00	0	- Kč
for CIP:	1900	17.3	4164	2,081,822.40 Kč	1422.1	13.0	3116.291	1,558,145.45 Kč	477.94	4.36	1047	523,676.95 Kč
Total steam consumption:	**7916.09**	**276.9**	**66454**	**33,226,999.00 Kč**	**7438.1**	**272.5**	**65406.6**	**32,703,322.05 Kč**	**477.94**	**4.36**	**1047**	**523,676.95 Kč**
Total Electric consumption	kW	MWh/day	MWh/yea	CZK/year	kW	MWh/day	MWh/yea	CZK/year	kW	MWh/day	MWh/year	CZK/year
evaporator	23.7	0.57	136.5	346,740.48 Kč	23.7	0.57	136.5	346,740.48 Kč	0	0	0	- Kč
dryer	100	2.00	480.0	1,219,200.00 Kč	100	2.00	480.0	1,219,200.00 Kč	0	0	0	- Kč
Total Electric energy consumption		**2.57**	**616.5**	**1,565,940.48 Kč**		**2.57**	**616.5**	**1,565,940.48 Kč**	**0**	**0.00**	**0.0**	**- Kč**
Total energy costs CZK/year				**34,792,939.48 Kč**				**34,269,262.53 Kč**				**523,676.95 Kč**
Total savings in heat	GJ/year	1047	CZK/year	523,676.95 Kč				Investments	CZK	1,815,484.00 Kč		
Total savings in electric	MWh/year	0.0	CZK/year	- Kč				Simple payback	year	3.47		
Total savings - energy			CZK/year	**523,676.95 Kč**								

Table 15. Total energy consumption balance of strategy 2

4.2.3 Outcomes with third strategy

In third and final strategy we plant to save energy in dryer section by regeneration. By using the energy of the hot air which is coming out from cyclone separator and bag filter to heat the incoming air in the dryer. Mass and energy balance of dryer section with regeneration is shown in table 7 and by comparing the result with table 5 we can see that we are able to save sufficient amount of steam i.e. “422.49 kg/h” with the help of regeneration.

In our study we are assuming using air to air regeneration where the outcoming drying air from bag filter will be connected to the recuperation unit. Incoming air will be sucked through the recuperation unit to be preheated by outcoming air and will be led through the steam calorifer to the drying chamber.

To use the new recuperation unit, complete reconstruction of air ducts will be necessary. Because the recuperation unit will significantly increase the pressure loss, we have to use new fans – it will significantly increase the electric consumption of both fans.

In our study we used simplified calculation of regeneration unit based on efficiency of recuperation according to the formula

$$\epsilon = \frac{T_{out} - T_a}{T_{in} - T_a}$$

where T_{out} is a temperature of preheated air leaving the recuperation unit, T_a is ambient air temperature and T_{in} is temperature of the outcoming air from bag filter entering the recuperation unit.

However typical dry efficiency of recuperation unit reported by manufacturers is 72 – 75 %, we are assuming for our calculation recuperation unit efficiency only 55 %. It is because the possibility of fouling creation by sticky dust particles contained in outcoming air. Our recuperation unit can preheat the incoming air to the dryer about 35°C (although this value is rather optimistic), which is consistent with the values published in literature [26]. Because the outcoming air from dryer goes through the cyclone separator and bag filter, we are assuming for our calculation that the air temperature will drop to the 85 °C. The balance of recuperation unit is summarized in the following table 15. Scheme of the technology which combines strategy 1, strategy 2 and heat recuperation (strategy 3) is in the figure 16.

Assuming efficiency of the recuperation ε	[%]	55
Ambient air temperature T_a	[°C]	20
Assuming temperature of outcoming air from bag filter entering the recuperation unit T_{in}	[°C]	85
Temperature of preheated drying air leaving the recuperation unit T_{out}	[°C]	55.75
Absolute humidity of preheated air	[Kg/kg]	0.0074
Specific enthalpy of preheated air at temp. T_{out}	[kJ/kg]	75.541
Drying air flowrate	[kg/h]	27000
Drying air temperature leaving steam heater	[°C]	200
Specific enthalpy of drying air leaving steam heater	[kJ/kg]	226.476
Theoretic Heat power of steam heater	[kW]	1123.6
Real heat power of steam heater	[kW]	1146.5
Amount of steam to heat up the drying air	[kg/h]	1748.96

Table 16. Balance of the recuperation unit

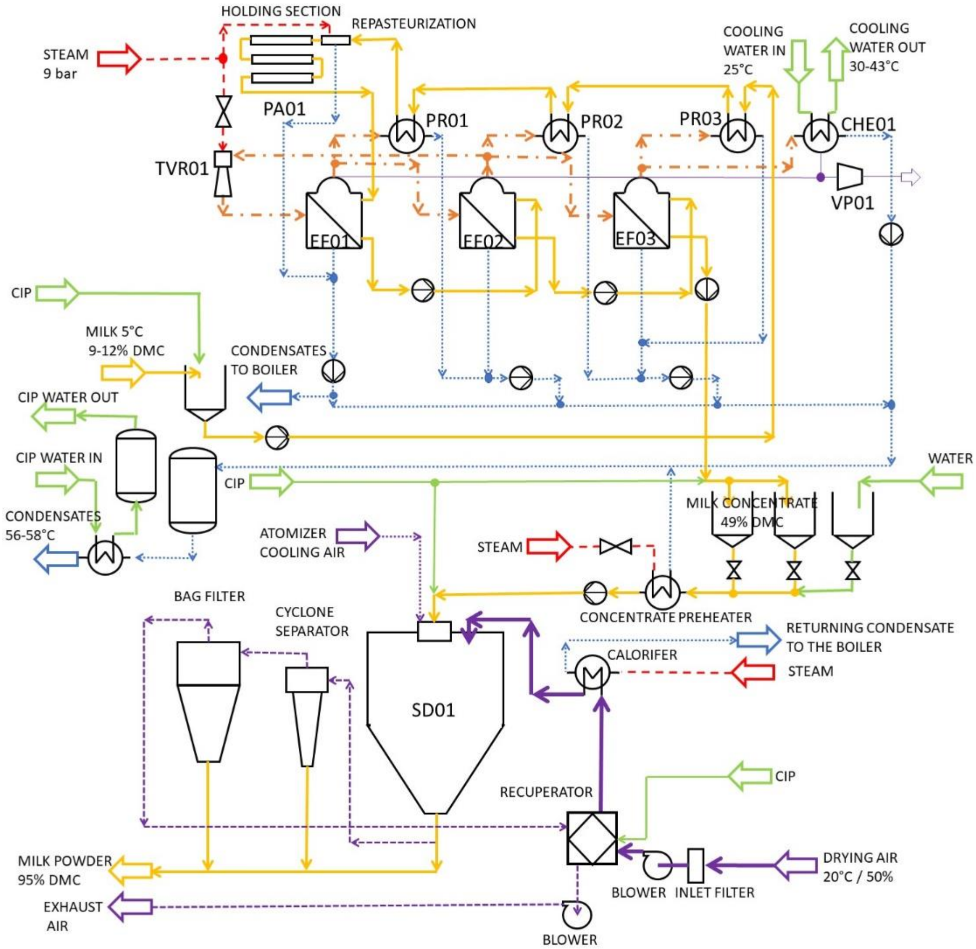


Figure 16 -Balancing scheme of the improved system according to 3rd strategy.

	Base				strategy 3 - installing recuperator				Effect - savings			
Total Heat consumption	kg/h	GJ/day	GJ/year	CZK/year	kg/h	GJ/day	GJ/year	CZK/year	kg/h	GJ/day	GJ/year	CZK/year
for evaporators:	3530.56	161.2	38684	19,342,095.10 Kč	3530.6	161.2	38684.19	19,342,095.10 Kč	0.00	0.00	0	- Kč
for pasteuriser:	237.57	10.8	2603	1,301,532.62 Kč	237.6	10.8	2603.065	1,301,532.62 Kč	0.00	0.00	0	- Kč
for dryer:	2171.45	84.5	20288	10,144,152.57 Kč	1748.96	68.1	16344	8,172,000.00 Kč	422.49	16.43	3944	1,972,152.57 Kč
for dryer feed preheater:	76.50	3.0	715	357,396.31 Kč	76.50	3.0	714.7926	357,396.31 Kč	0.00	0.00	0	- Kč
for CIP:	1900	17.3	4164	2,081,822.40 Kč	1900.0	17.3	4163.645	2,081,822.40 Kč	0.00	0.00	0	- Kč
Total steam consumption:	**7916.09**	**276.9**	**66454**	**33,226,999.00 Kč**	**7493.6**	**260.5**	**62509.7**	**31,254,846.43 Kč**	**422.49**	**16.43**	**3944**	**1,972,152.57 Kč**
Total Electric consumption	kW	MWh/day	MWh/yea	CZK/year	kW	MWh/day	MWh/yea	CZK/year	kW	MWh/day	MWh/year	CZK/year
evaporator	23.7	0.57	136.5	346,740.48 Kč	23.7	0.57	136.5	346,740.48 Kč	0	0	0	- Kč
dryer	100	2.00	480.0	1,219,200.00 Kč	154	3.08	739.2	1,877,568.00 Kč	-54	-1.08	-259.2	- 658,368.00 Kč
Total Electric energy consumption		**2.57**	**616.5**	**1,565,940.48 Kč**		**3.65**	**875.7**	**2,224,308.48 Kč**	**-54**	**-1.08**	**-259.2**	**- 658,368.00 Kč**
Total energy costs CZK/year				**34,792,939.48 Kč**				**33,479,154.91 Kč**				**1,313,784.57 Kč**
Total savings in heat	GJ/year	3944	CZK/year	1,972,152.57 Kč				Investments	CZK	5,097,730.00 Kč		
Total savings in electric	MWh/year	-259.2	CZK/year	- 658,368.00 Kč				Simple payback	year	3.88		
Total savings - energy			CZK/year	**1,313,784.57 Kč**								

Table 17. Total energy consumption balance of strategy 3

Evaluated energy consumption and energy cost savings for optimized scheme (Strategy 1+2+3) are summarized in following table 18.

	Base				Optimized - Strategy 1+2+3				Effect - savings			
Total Heat consumption	kg/h	GJ/day	GJ/year	CZK/year	kg/h	GJ/day	GJ/year	CZK/year	kg/h	GJ/day	GJ/year	CZK/year
for evaporators:	3530.56	161.2	38684	19,342,095.10 Kč	2161.4	98.7	23682.81	11,841,404.96 Kč	1369.12	62.51	15001	7,500,690.15 Kč
for pasteuriser:	237.57	10.8	2603	1,301,532.62 Kč	406.5	18.6	4464	2,232,000.00 Kč	-168.93	-7.75	-1861	- 930,467.38 Kč
for dryer:	2171.45	84.5	20288	10,144,152.57 Kč	1748.96	68.1	16344	8,172,000.00 Kč	422.49	16.43	3944	1,972,152.57 Kč
for dryer feed preheater:	76.50	3.0	715	357,396.31 Kč	76.50	3.0	714.7926	357,396.31 Kč	0.00	0.00	0	- Kč
for CIP:	1900	17.3	4164	2,081,822.40 Kč	1422.1	13.0	3116.291	1,558,145.45 Kč	477.94	4.36	1047	523,676.95 Kč
Total steam consumption:	**7916.09**	**276.9**	**66454**	**33,226,999.00 Kč**	**5815.5**	**201.3**	**48321.9**	**24,160,946.72 Kč**	**2100.62**	**75.55**	**18132**	**9,066,052.28 Kč**
Total Electric consumption	kW	MWh/day	MWh/yea	CZK/year	kW	MWh/day	MWh/yea	CZK/year	kW	MWh/day	MWh/year	CZK/year
evaporator	23.7	0.57	136.5	346,740.48 Kč	28.3	0.68	163.0	414,040.32 Kč	-4.6	-0.1104	-26.496	- 67,299.84 Kč
dryer	100	2.00	480.0	1,219,200.00 Kč	154	3.08	739.2	1,877,568.00 Kč	-54	-1.08	-259.2	- 658,368.00 Kč
Total Electric energy consumption		**2.57**	**616.5**	**1,565,940.48 Kč**		**3.76**	**902.2**	**2,291,608.32 Kč**	**-58.6**	**-1.19**	**-285.7**	**- 725,667.84 Kč**
Total energy costs CZK/year				**34,792,939.48 Kč**				**26,452,555.04 Kč**				**8,340,384.44 Kč**
Total savings in heat	GJ/year	18132	CZK/year	9,066,052.28 Kč				Investments	CZK	15,990,634.00 Kč		
Total savings in electric	MWh/year	-285.7	CZK/year	- 725,667.84 Kč				Simple payback	year	1.92		
Total savings - energy			CZK/year	**8,340,384.44 Kč**								

Table 18. Total energy consumption balance for strategy (1+2+3)

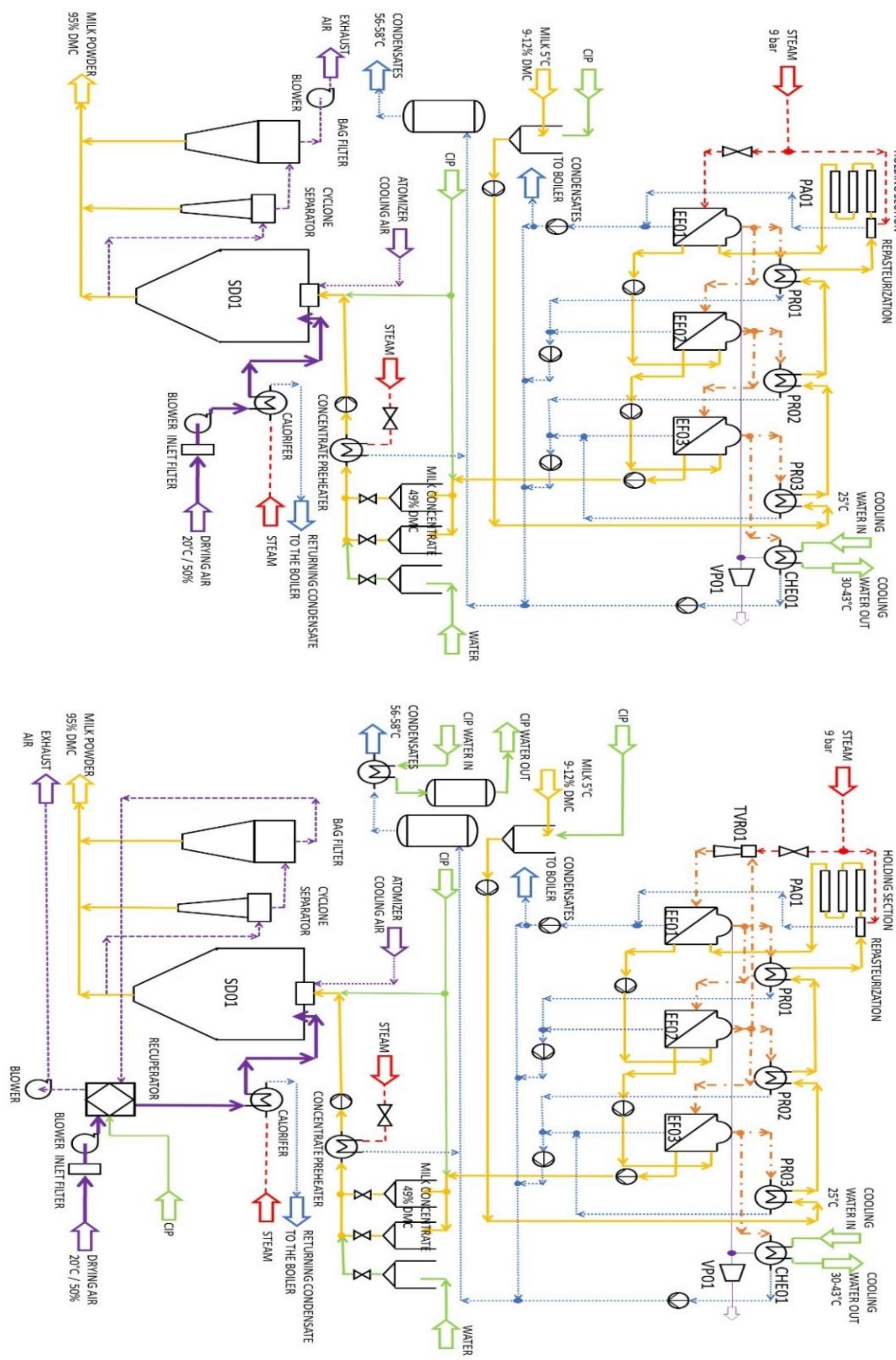


Figure 17 -. Comparison of base and final process flow diagram

Chapter 5: Other Consideration

Apart from energy analysis we could use consider other methodology for optimization of manufacturing plant, like Six Sigma.

Six Sigma-based structure using define-measure-analyze-improve control (DMAIC) the methodology is selected through the utilization of design of experiments tool to concentrate on customer's demands to improve the quality aspect of milk powder production process in milk powder manufacturing company [18].

The integrity of Six Sigma plays the best role for facilitating any dairy company to define the problem and minimize its goal through a well-organized procedure.

Six Sigma has been examined to be a well-organized, commanding system to continuously enhance the processes and produce new products by using efficient scientific and statistical tools and methods. So, after optimizing plant with mass and enthalpy analysis we can use a Six Sigma-based structure using DMAIC methodology to advance the quality aspect of the milk powder production process in the company.

We need to study to see the possible area in which Six Sigma DMAIC approach can help to improve the quality of milk powder production process. This case can assist managers of the company to apply the Six Sigma method to discuss complex problems in other processes, where problems individually are not clear.

Basically, in six sigma we focus on variation and defects, we can eliminate the defects but we cannot eliminate the variation but we can minimize the variation, for example in the production of milk powder we face problems regarding the Ph. of milk and milk powder is 6 to 7. Which we can explain in the following illustration below

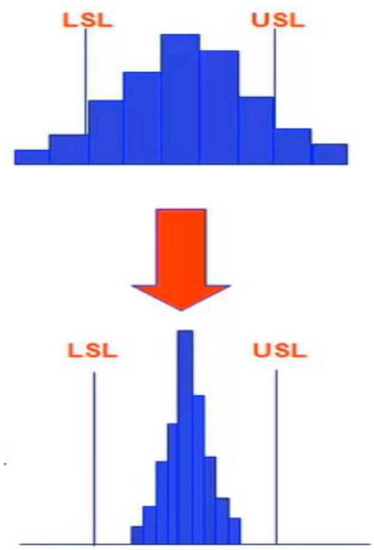


***Figure 18** -Explanation for LSL AND USL in histogram*

So, if we consider LSL (lower specific limit) as 6 and USL (upper specific limit) as 7. So, in first case we see we have lots of variation and some values are out of the limits. So, after using six sigma we can control variation (figure 11) within the limits and ideally try to eliminate them. It's one example to show how we can implement six sigma in the process to optimize and improve the process quality of the process and similarly we can use six sigma methodology in other problem in our process by Defining – Measuring – Analyzing –Improving and Controlling (DMAIC).

Chapter 6: Economy

In the previous chapter we have discussed some ways how to optimize the milk powder production line by making changes in process flow diagram. In this chapter, we will discuss economy aspect of our optimized process flow diagram and compare it with base scheme.

Because the current milk powder technology has been shut down for longer time, putting the technology back into operation will require some investments whose exact scope we cannot determine. For this reason, the economic evaluation of the proposed strategies will be carried out only from the perspective of necessary investments for proposed strategies accepting some amount of investments to repair the current evaporator.

6.1 Fixed capital investments

In this section, we will calculate fixed capital investments for each proposed strategy as a change of necessary total investment costs to put the current state into the operation and for proposed improvement.

6.1.1 Fix capital investments to install TVR

Fix capital investments for new proposed TVR installation to the evaporator are mainly connected with purchasing the thermo-compressor ant its cost for installation. As commented before, after application TVR, the outlet temperature from milk preheaters will be lower and current pasteurization unit for milk repasteurization will not have enough power to heat up the milk to required temperature. Therefore, the new pasteurization unit have to be purchased together with new vacuum pumps due to the slightly lower pressure in the effects. Finally, some amount of investments for evaporator renovation, reposition of the effects and its cleaning are considered too. Necessary investments are summarized in table 19.

Equipment	Pieces	CZK/piece	CZK total
Thermo-compressor	1	750 000,00 Kč	750 000,00 Kč
New pasteurizer	1	2 500 000,00 Kč	2 500 000,00 Kč
vacuum pump	2	85 000,00 Kč	170 000,00 Kč
Installations	1	600 000,00 Kč	600 000,00 Kč
Evaporator reposition, cleaning and assembly	1	2 800 000,00 Kč	2 800 000,00 Kč
subtotal			**6 820 000,00 Kč**
Project and engineering (10 %)			682 000,00 Kč
Total investment cost			**7 502 000,00 Kč**
Total investment cost including TAX			**9 077 420,00 Kč**

Table 19. Fix capital investments for TVR installation according strategy 1 scheme

6.1.2 Fix capital investments to utilize the heat in condensates to preheat CIP liquids

Assumed fix capital investments for utilization the heat in condensates from evaporator effects to preheat the water for CIP are summarized in table 20. Investments counting with purchasing new plate heat exchanger (with quite large heat transfer area), accumulation tanks for preheated CIP water accumulation, necessary pumps and costs for assembly and installation.

Equipment	Pieces	CZK/piece	CZK total
Heat exchanger	1	550 000,00 Kč	550 000,00 Kč
Warm water accumulator	4	120 000,00 Kč	480 000,00 Kč
Pumps	2	42 000,00 Kč	84 000,00 Kč
Installations	1	250 000,00 Kč	250 000,00 Kč
subtotal			1 364 000,00 Kč
Project and engineering (10%)			136 400,00 Kč
Total investment cost			**1 500 400,00 Kč**
Total investment cost including TAX			**1 815 484,00 Kč**

Table 20. Fix capital investments for utilization heat in condensates to preheat CIP liquids

6.1.3 Fix capital investments for drying air regeneration

Finally, the fix capital investments cost for drying air regeneration proposed as 3rd strategy are summarized in table 21. The investments counting with purchasing the cleanable air to air recuperation unit applicable in food processing industry together with necessary materials to rebuild air ducts. Because of higher pressure loses in air ducts, it is necessary to change the current fans with bigger one. The last part of the fix capital investments are the costs for assembly and installation of the recuperation unit, new air ducts and fans.

Equipment	Pieces	CZK/piece	CZK total
Heat recuperation unit	1	2 320 000,00 Kč	2 320 000,00 Kč
Air ducts and other materials	1	120 000,00 Kč	120 000,00 Kč
Fans	2	320 000,00 Kč	640 000,00 Kč
Installations	1	750 000,00 Kč	750 000,00 Kč
subtotal			3 830 000,00 Kč
Project and engineering (10%)			383 000,00 Kč
Total investment cost			**4 213 000,00 Kč**
Total investment cost including TAX			**5 097 730,00 Kč**

Table 21.Fix capital investments for drying air heat regeneration

6.2 Methodology of economical evaluation

The first step of our economical evaluation is the cash flow estimation. Cash flow means the balance of money (incomes and expenditures) on project account. Clear annual cash flow is annual incomes and expenditures excluding fix capital investments.

$$CF = \sum (Incomes - expenditures) - Investments$$

where *CF* express annual profit of the project (cash flow) and in our study it is the change of operational expenditures before and after project realization excluding investments.

Simple payback period *SPP* is one of the indicator of economic efficiency of the project but it does not include the effect of time value of money. This parameter is suitable indicator of project profitability only for very simple projects.

$$SPP = \frac{Capital\ Investments}{CF}$$

To reflect the time value of money (effect of inflation and effect of other possible investment opportunities) we are using discount factor to recalculate our project cash flow with respecting time value of the money. Discount rate *r* is usually set by company management and it is equal to the profitability of other investment opportunity. Using discount rate we are able to recalculate future cash flows of the project to the present time. Discount rate is usually set as minimal acceptable profitability of the invested capital.

The sum of annual project cash flow discounted by constant discount rate r to the present time represents the other economic indicator - Net Present Value *NPV:*

$$NPV = \sum_{t=1}^{t_L} \frac{CF_t}{(1+r)^t} - Capital\ Investments$$

where NPV is net present value, r is discount rate, CF_t is cash flow in year t and t_L is the lifetime of the project (evaluation time of the project).

NPV is the main indicator for the decision about project implementation. Only from the economical point of view, we should recommend the proposed strategy with the highest positive value of NPV.

Another indicator of project profitability is Real Payback Period *RPP*. It is similar indicator as *SPP* but with reflecting time value of money. RPP can be calculated from condition

$$\sum_{t=1}^{RPP} \frac{CF_t}{(1+r)^t} - Capital\ Investments = 0$$

The last evaluated indicator of economic profitability of the proposed project is Internal Rate of Return *IRR*, which can be calculated from:

$$\sum_{t=1}^{t_L} \frac{CF_t}{(1+IRR)^t} - capital\ investments = 0$$

where *IRR* is Internal Rate of Return, CF_t is cash flow in year t and t_L is the lifetime of the project (evaluation time of the project). In other words, it is the value of discount rate where the NPV is directly equal to zero. Next to the NPV, IRR is the second important parameter for decision about project implementation.

Our economy evaluation is carried out without considering the way of financing and does not reflect the annual increases in energy prices.

6.3 Project cash flow estimation

Our project cash flow represents the change of operating expenditures comparing the current state and state after proposed strategy to reduce energy consumption implementation together with depreciations of investment costs and income tax.

Depreciation of investments:

Duration:	10 years
Depreciation rate in 1st year:	5.5%
Depreciation rate in year 2-10:	10.5%
Income Tax rate:	19 %

Our cash flow is estimated by the save of money connected with savings of energy in steam and electric energy. But new equipment will require some annual maintenance, annual revisions and other costs, we are assuming this operating cost as 2% from investments.

6.4 Results of economical evaluation

In this chapter, the results of economical evaluation of all proposed strategies to reduce the energy consumption of milk powder technology will be presented and discussed according evaluated economic profitability indicators.

6.4.1 Economic evaluation of 1st strategy

Strategy 1 represents the evaporator optimization by installing thermal vapor recompression (TVR).

Parameter	**Unit**	**Value**
Capital Investments	CZK	9 077 420
Change of Incomes from selling the product	CZK/year	0
Change of costs on raw materials	CZK/year	0
Change of personal costs	CZK/year	0
Change of costs on energies	CZK/year	6 502 922.92
Change of other operational costs (maintenance and other costs)	CZK/year	-181 548.48
Total profit before TAX	CZK/year	6 321 374.52
Depreciations – year 1	CZK/year	499 258.10
Depreciations – year 2-10	CZK/year	953 129.10
Change of Income TAX – year 1	CZK/year	-1 106 202.12
Change of Income TAX – year 2-10	CZK/year	-1 019 966.63

Change of Income TAX – year 10-next	CZK/year	-1 201 061.16
Project lifetime t_L	years	15
Discount rate	%	8
Simple payback period SPP	years	1.44
Real Payback Period RPP	years	2
Net Present Value NPV	CZK	35 885 104.46
Internal Rate of Return IRR	%	58

Table 22. Economic evaluation of 1st strategy

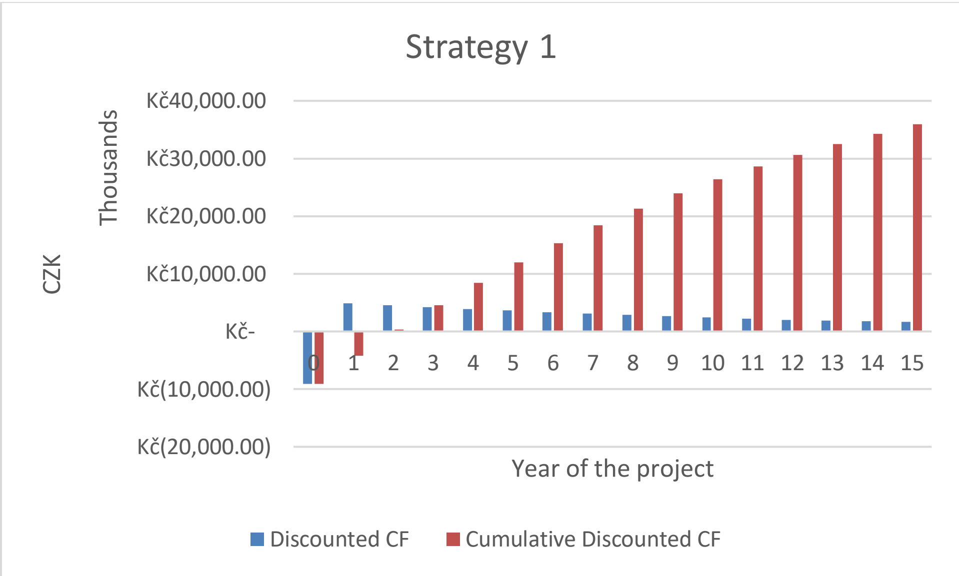


Figure 19 - Economic evaluation graph for 15 years after 1st strategy

6.4.2 Economic evaluation after (1^{st} + 2^{nd}) strategy

Strategy 2 represents the evaporator optimization by installing thermal vapor recompression (TVR) together with the utilization of heat in condensates to preheat the water for CIP.

Parameter	**Unit**	**Value**
Capital Investments	CZK	10 892 904
Change of Incomes from selling the product	CZK/year	0
Change of costs on raw materials	CZK/year	0
Change of personal costs	CZK/year	0
Change of costs on energies	CZK/year	7 026 599.87
Change of other operational costs (maintenance and other costs)	CZK/year	-217 858.08
Total profit before TAX	CZK/year	6 808 741.79
Depreciations – year 1	CZK/year	599 109.72
Depreciations – year 2-10	CZK/year	1 143 754.92
Change of Income TAX – year 1	CZK/year	-1 179 830.09
Change of Income TAX – year 2-10	CZK/year	-1 076 347.50
Change of Income TAX – year 10-next	CZK/year	-1 293 660.94
Project lifetime t_L	years	15
Discount rate	%	8
Simple payback period SPP	years	1.59
Real Payback Period RPP	years	3
Net Present Value NPV	CZK	37 675 686.61
Internal Rate of Return IRR	%	52

Table 23. Economic evaluation of 2^{nd} strategy

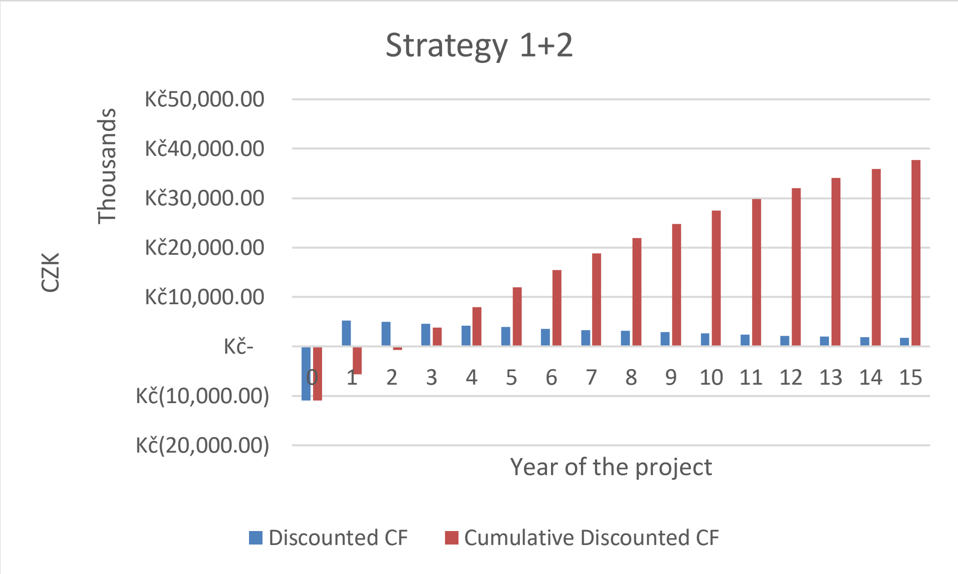


Figure 20 -Economic evaluation graph for 15 years after (1st + 2nd) strategy

6.4.2 Economic evaluation after (1st + 2nd +3rd) strategy

Strategy 3 represents the evaporator optimization by installing thermal vapor recompression (TVR) together with the utilization of heat in condensates to preheat the water for CIP and drying air regeneration.

Parameter	**Unit**	**Value**
Capital Investments	CZK	15 990 634
Change of Incomes from selling the product	CZK/year	0
Change of costs on raw materials	CZK/year	0
Change of personal costs	CZK/year	0
Change of costs on energies	CZK/year	8 340 384.44
Change of other operational costs (maintenance and other costs)	CZK/year	-319 812.68
Total profit before TAX	CZK/year	8 020 571.76
Depreciations – year 1	CZK/year	879 484.87
Depreciations – year 2-10	CZK/year	1 679 016.57
Change of Income TAX – year 1	CZK/year	-1 356 806.51

Change of Income TAX – year 2-10	CZK/year	-1 204 895.49
Change of Income TAX – year 10-next	CZK/year	-1 523 908.63
Project lifetime t_L	years	15
Discount rate	%	8
Simple payback period SPP	years	1.99
Real Payback Period RPP	years	3
Net Present Value NPV	CZK	41 617 361.38
Internal Rate of Return IRR	%	42

Table 24. Economic evaluation of 3rd strategy

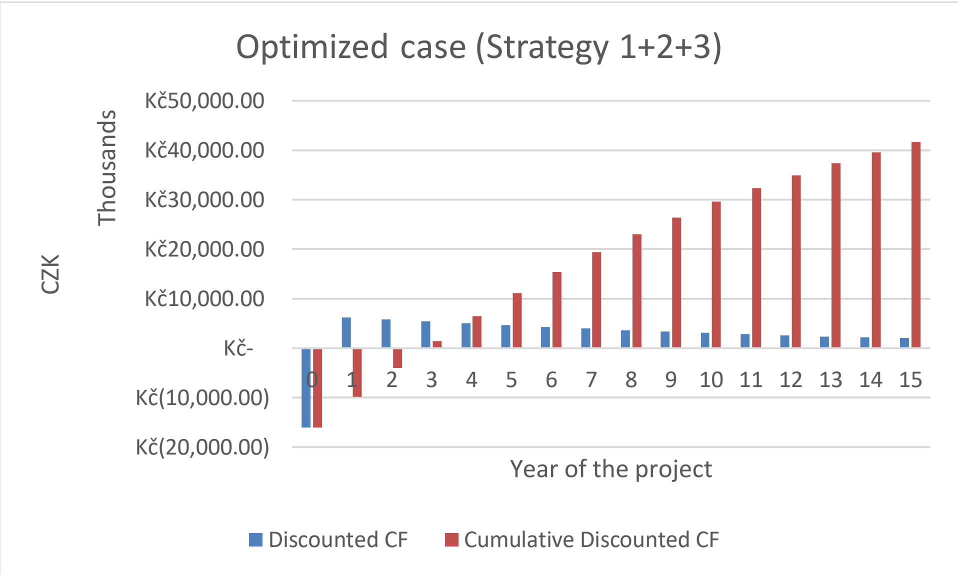


Figure 21 -Economic evaluation graph for 15 years after (1st + 2nd +3rd) strategy

6.5 What – If analysis

From the economical evaluation presented in previous chapter, we can see that all proposed strategies to optimize the energy consumption of the current state of milk powder technology, are profitable. Although it seems that the greatest profit brings strategy 1 (TVR), the highest value NPV was evaluated at strategy 3. Therefore, the strategy 3 is the optimal case for reducing energy consumption that brings the highest energy savings, money savings and has greatest NPV value.

To study the effect of capital investment costs, cash flow and discount rate on NPV, what-if analysis was done. What-if analysis should tell us if the optimal strategy will be profitable, if the investment costs will be higher than assumed or money savings lower than assumed etc.

A) Effect of discount rate on NPV for optimized strategy 3:

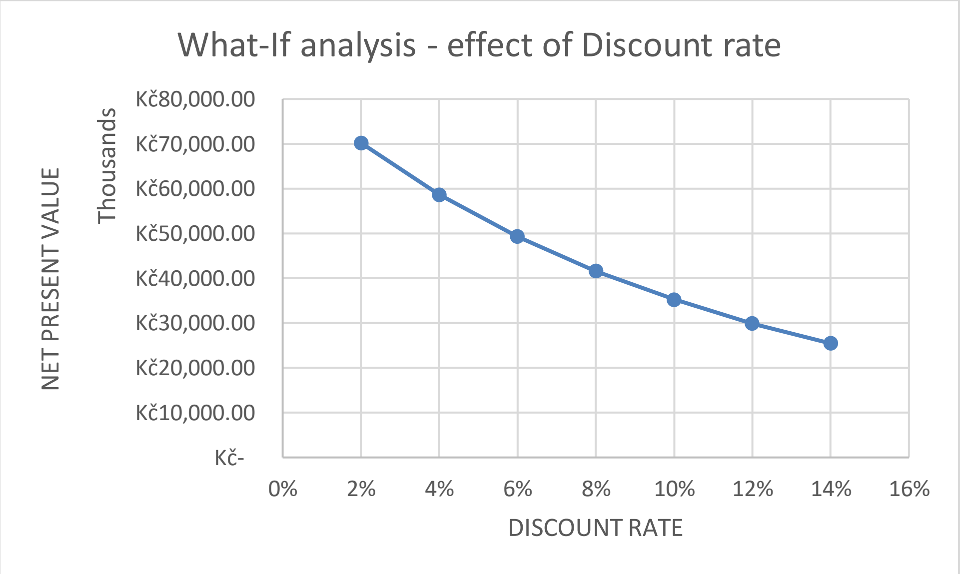


Figure 22 -Effect of discount rate on NPV for optimized strategy 3

B) Effect of amount of investment on NPV for optimized strategy 3:

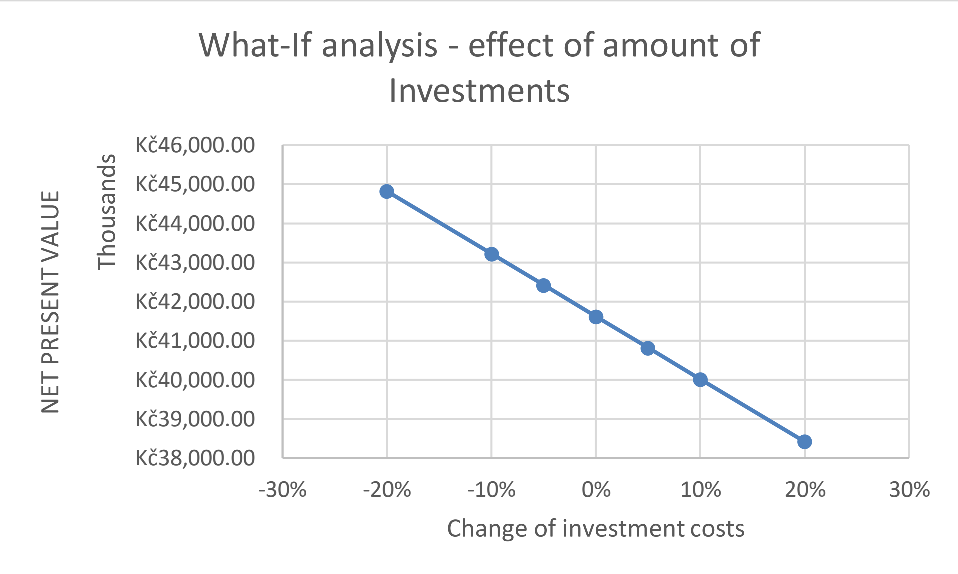


Figure 23 -Effect of amount of investment on NPV for optimized strategy 3

C) Effect of amount of cash-flow on NPV for optimized strategy 3:

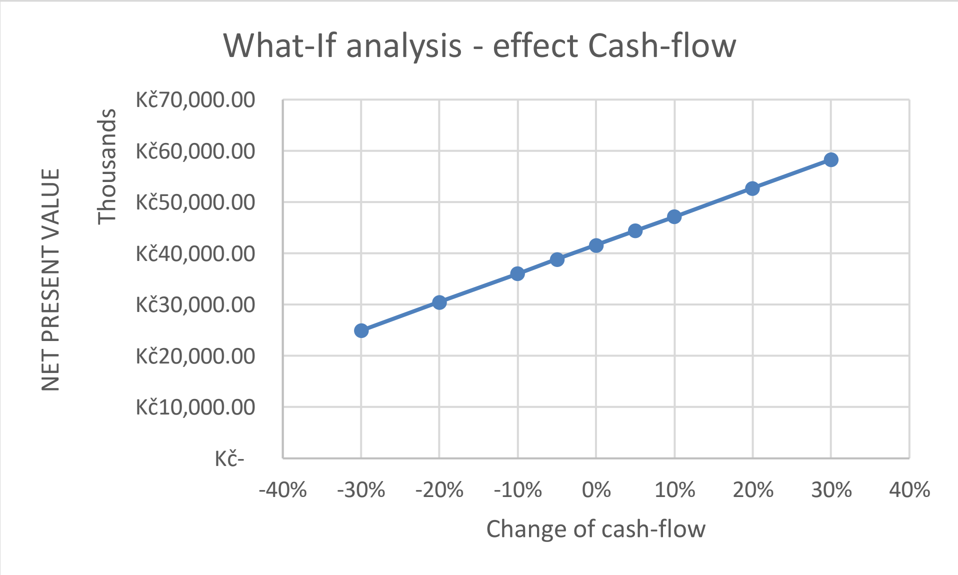


Figure 24 - Effect of amount of cash-flow on NPV for optimized strategy 3

Chapter 7: Summary

With this report we can improve or optimize the milk powder production plant or any other plant with the help of six sigma and energy analysis. Firstly we create a model of a milk powder plant of Company A and then after mass and enthalpy balance with the help of MS-excel software by which we get to know the performance of process flow diagram under normal operation, then we can examine where we can improve the efficiency of the plant in order to make overall efficiency of plant better. On the basis of values, we get by mass and enthalpy balance, we proposed three strategies and if we implement those strategies it can lead to important improvement in overall efficiency of the plant. Then we try to explain how we can implement six sigma methodology in food processing industry and benefits of six sigma which can improve the quality of the product.

The overall approach of improving energy efficiency and quality of the product can lead to huge profit to the company if company implement the recommended changes in process flow diagram for energy efficiency and six sigma for quality improvement rejection control also it is beneficial to the environment.

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APPENDICES

I. Process flow diagram of the base scheme
II. Process flow diagram of the final scheme