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Helical-coil Heat Exchanger Application in Falling Film Evaporator for Energy Saving

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Abstract

Falling film evaporators is an essential equipment of dairy powder production facilities. Evaporation is one type of thermal separation processes which makes the evaporation plant fundamentally energy intensive. Hence, improvements to its operation can have a significant impact on the energy usage. The studied plant has a two-effect falling film evaporator. Based on the current setup of the studied evaporator, a helical heat exchanger is designed and installed in order to reduce the steam usage by recycling the heat from vapor. With the new heat exchanger, one extra heat exchange step is added for transferring heat from hot vapor to cold liquid product. The results demonstrate that the total usage of steam, cooling water and electricity have been reduced.

1. Introduction

The concept of evaporative cooling systems has an ample spectrum of industrial applications such as refrigeration, power plants, desalinization industries, and petroleum refining as reported by numerous researchers [1–3]. Falling film evaporation from horizontal tubes is a process of heat and mass transfer from liquid to steam. Prime modes of heat transfer are conduction and convection, while mass transfer is influenced by diffusion of molecules [4]. The characteristics, including heat transfer efficiency, flow rate, steam consumption of a falling film evaporator were studied and reported by researchers [5-11]. Falling film evaporators are widely used for the concentration of liquid foods, especially milk prior to spray drying or crystallization. Typically, milk with about 13% solids content enters at the top of the evaporator body and flows down the inside of vertical tubes which are heated by steam or vapor. Significant energy savings can be made by having several stages in series whereby the vapor produced by one stage is used to heat next stage which is operating at a lower temperature and lower pressure. Each of these stages with a different pressure is termed an "effect". The liquid is pumped from one effect to the next effect. After flowing through all the effects, typically the liquid will be concentrated up to about 50% solids [12].

In the diary plant which was studied, the pasteurized liquid product with 18% solids content is being processed by a 2-effects falling film evaporator. Due to the membrane filtration process prior to evaporation. The liquid product is pre-heated to 140 degrees Fahrenheit before being sent to evaporator. The designed boiling point for the first effect of this falling film evaporator is 173 degrees Fahrenheit. In order to maximize the efficiency of evaporation process, the liquid product needs to be heated to 168 degrees Fahrenheit prior to entering the evaporator body. Heat exchange with steam in a shell and tube heat exchanger is applied to heat the pre-heated liquid product. This process involves large amount of steam consumption.

Due to the fact that a falling film evaporator has to function with low pressure inside the equipment body to achieve low boiling temperature point, one shell and tube condenser was installed to cool down part of the vapor generated during the evaporation process. The vapor is turned into condensate water in the condenser. During this process, the deduction of total volume from gas to liquid decreases the pressure inside the sealed evaporator body. In order to cool down the vapor, cooling water is pumped through the tubes inside the condenser. A radiator with a fan exposed to atmosphere air is applied to cool down the water after heat exchange.

For not only diary plants, but all the industries, efficient use of energy has always been an issue. In many industrial processes, a large amount of low-grade thermal energy is directly dumped into environment [13]. For example, the radiator installed for cooling water system directly dumps the energy into atmosphere air. One of the remedies for reducing energy waste is to recover this low-grade thermal energy through heat exchangers and then use it as the heat source.

Based on the design of the specific falling film evaporator in the plant studied, part of the heat from the vapor can be utilized to pre-heat the cold liquid product that needs to be heated to 168 degrees. With this process, the amount of steam injected in next step can be reduced. One heat exchanger can be applied in this case to directly exchange heat between vapor and liquid product. Theoretically, this application will not only reduce the steam usage but also reduce the energy used to cool down the cooling water in the condenser. Moreover, the increased surface area in the new heat exchanger will also help in reducing the fouling which occurs in the shell and tube heat exchanger.

Among the different types of heat exchangers, the shell and tube heat exchanger would normally be used for many continuous systems having small to medium heat duties [14]. However, the helical-coil heat exchanger (HCHE) might be a better choice in some cases: 1. Where space is limited, so that not enough straight pipe can be laid. 2. Under conditions of laminar flow or low flowrates, where a shell and tube heat exchanger would become uneconomical because of the resulting low heat-transfer coefficients. 3. Self-cleaning effect, whereby fouled surfaces cause a localized increase in fluid velocity, thus increasing the fluid friction on the fouled surface, thus helping to dislodge the blockage and keep the heat exchanger clean.

The falling film evaporator in this plant was designed and built in 1980. In the past 36 years, various types of modifications and pipe installations occurred in the production area which result in very limited space for new equipment installation. Moreover, the solids content, especially calcium in the liquid product, can easily cause fouling during the heat exchange process. A helical-coil heat exchanger is more suitable in this case.

In this project, a helical-coil heat exchanger is designed, purchased and installed which performs the function to exchange the heat between hot vapor generated during the evaporation process and cold liquid product needed to be heated to boiling temperature point. This application is meant to: 1. Reduce the steam usage during the liquid product heating step. 2. Reduce the energy usage to cool down the cooling water from the condenser. 3. Increase the surface area to heat the liquid which reduce the fouling in the steam heat exchanger.

2. Methods

2.1 Data analysis of original equipment

This project first analyzed the thermodynamic data of the specific falling film evaporator in order to design the proper heat exchanger. The original design of the equipment is shown in figure 1.

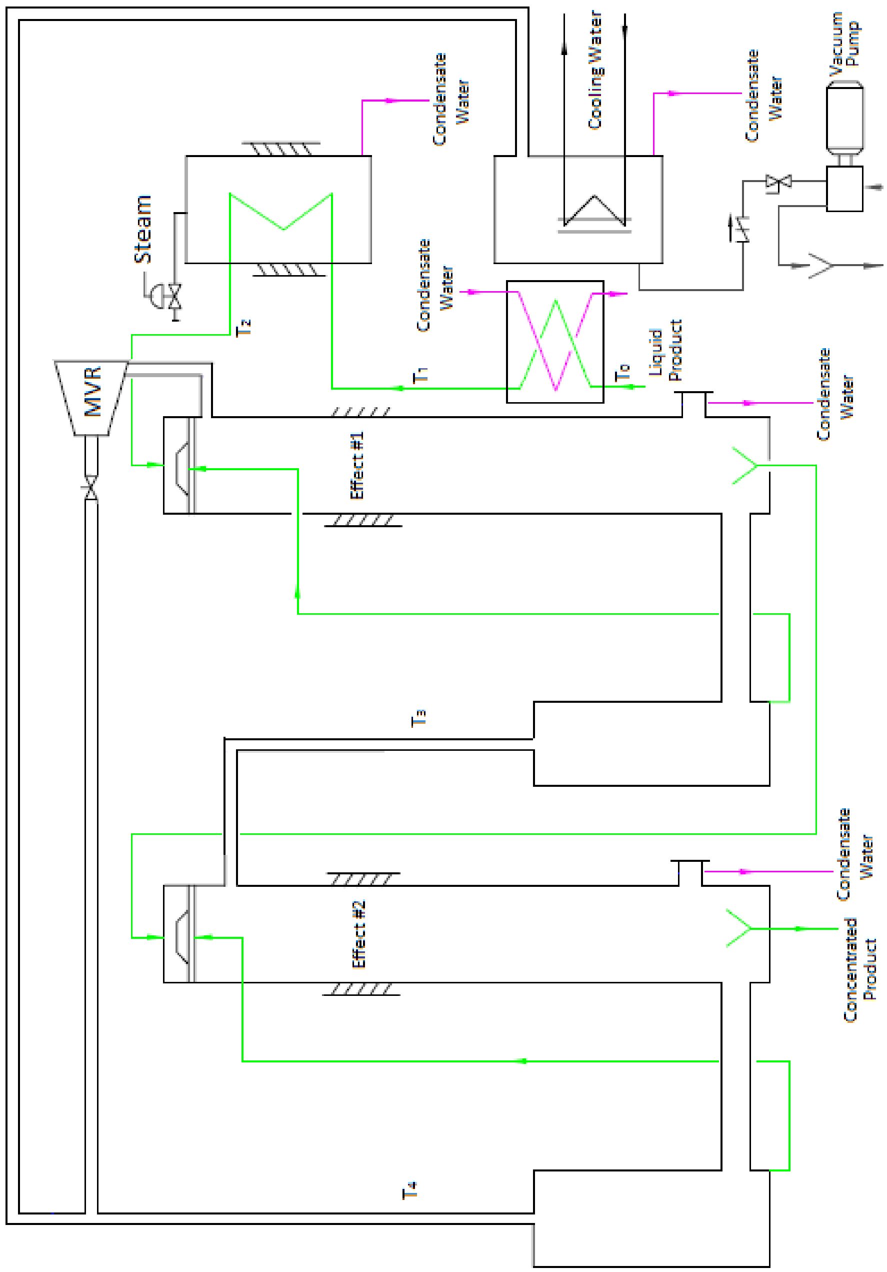

Figure 1. Schematic of original falling film evaporator setup. T_1 to T_6 are the temperature reading from installed RTD.

The product is pumped from a storage silo at 40 degree Fahrenheit (T_0 = 40°F) to a heat exchange plate to be heated by the condensate water discharged from the evaporator. The product which is heated to 140 degree Fahrenheit (T_1 = 140°F) enters the shell and tube heat exchanger. Controlled steam is injected into the shell-side to heat the product to reach at least 161 degree Fahrenheit. This temperature is required by the legal pasteurization temperature. In addition, the effect #1 is operated under 17 inch of Hg vacuum which changes the water boiling point to 173 degree Fahrenheit. In order to increase the efficiency of evaporation process in effect #1, the set point of target heated temperature is 168 degree Fahrenheit (T_2 = 168°F). The vapor generated from effect #1 becomes the heating source of effect #2 at 173 degree Fahrenheit (T_3 = 173°F). The operating pressure of effect #2 is under 20 inch of Hg vacuum which boils water at 160 degree Fahrenheit (T4 = 160°F). Part of the vapor generated in effect #2 is compressed by a mechanical vapor re-compression (MVR) to reach higher saturation temperature and recirculate back to the shell side of effect #1 as a heating source. The rest of the vapor is cooled down in the condenser to reduce volume in order to reduce the operating pressure. The cooling water is pumped from a storage silo through the condenser to a cooling radiator. The cooling water has a set point of 73 degree Fahrenheit, the cooling fan attached to the radiator turns on when cooling water temperature is higher than the set point.

During the production, the feed flow of liquid product from storage silo to steam heat exchanger is 59,000 lbs./hr. The energy needed to heat such amount of liquid from 40 to 168 degree Fahrenheit per hour is: (59,000) x (168 - 40) = 7.552×10^6 Btu/hr. The operating pressure of steam in the plant is 130 psi which gives 355.6 degree Fahrenheit saturation temperature. Assuming all the energy is utilized from the steam to heat the liquid product, the amount of steam can be calculated as: 7,552,000 / (199.7 + 970.3) = 6,454.7 lbs./hr. Due to every day's production schedule, the evaporator is on production mode for 14 hours. This result in 90,365 lbs. of steam consumed for the heating purpose.

2.2 Modified equipment design

As discussed in the previous section, the cold liquid product is pre-heated by the condensate water to 140 degree Fahrenheit, this process will decrease the temperature of condensate water from 160 to 153 degree Fahrenheit. Due to the application of condensate water in equipment cleaning process, the condensate water is stored and heated by steam to 160 degree Fahrenheit before being used. As a result, to maximize the energy saving in this case, the cold liquid product out of the storage silo needs to be heated by the vapor generated from effect #2 as hot as possible before entering the heat exchange plate. The modified schematic of the heat exchange system is showed in Figure 2.

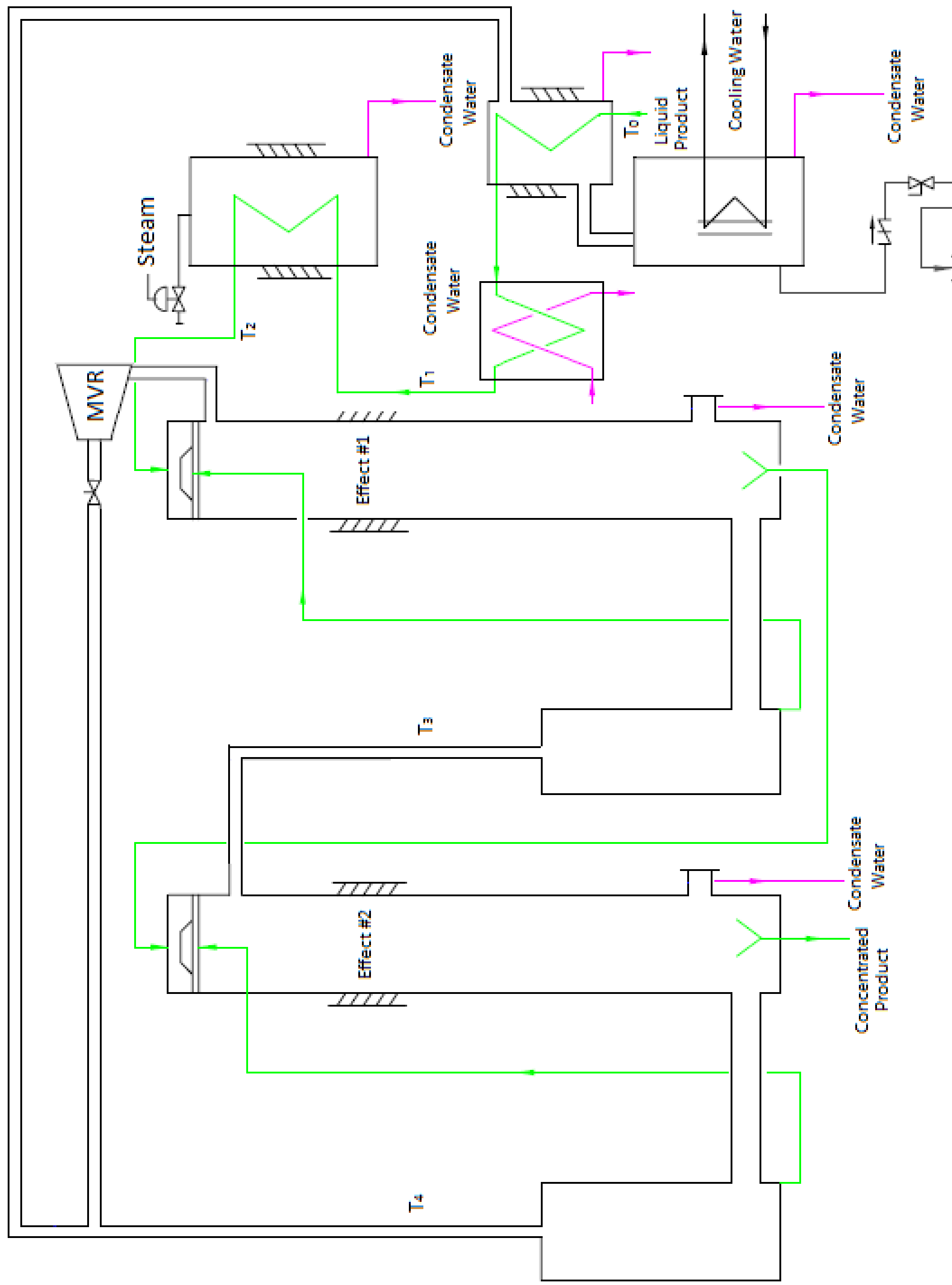

Figure 2. Schematic of modified falling film evaporator setup.
The new heat exchanger is installed prior to heat exchange plate.

The modified heat exchange system includes one heat exchanger installed prior to the heat exchange plate. The cold liquid product enters the new heat exchanger first to obtain heat from the vapor generated from effect #2. Moreover, the shell side of the new heat exchanger is connected to the original condenser in order to condense any over fed vapor.

2.3 Helical Heat Exchanger Installation

Due to the limited space for new pipes and equipment installation, the new heat exchanger has to be a helical heat exchanger and needs to be installed under the original condenser which is illustrate in Figure 3.

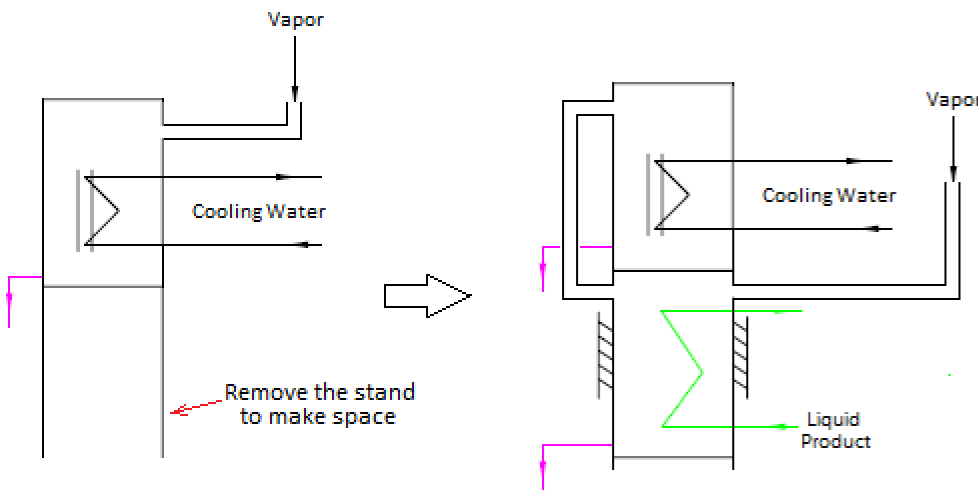

Figure 3. The schematic of the new heat exchanger installation.

2.4 Helical Heat Exchanger Design

The amount of vapor condensed in the original condenser can be calculated based on the cooling water flow rate and temperature change. The feed flow of cooling water during the production is 35,000 lbs./hr. The temperature of cooling water before entering the condenser is 73 degree Fahrenheit. The temperature of cooling water exiting condenser is 153 degree Fahrenheit. The btu exchanged inside the condenser is: (35,000) x (153 - 73) = 2,800,000 Btu/hr. According to the design of the evaporator, part of the vapor is essential for heating the effect #1. So the 2,800,000 Btu/hr heat exchange efficiency becomes the target of the new installed helical heat exchanger.

The collected data related for calculating overall heat transfer coefficient is shown in table 1.

	Liquid Product	Vapor
Mass flowrate (lbs./hr.)	59,000	N/A
Inlet temperature (°F)	40	160
Outlet temperature (°F)	120	N/A
Convective heat transfer coefficient (Btu/(hr ft^2 °F))	176	1057

Table 1. Physical properties of the liquid product and vapor entering the helical heat exchanger.

For a common safe and efficient pipe thickness in this application, it is usually design as 1.25 mm (0.049 inch) thick. For the feed flow rate of liquid product at 49,000 lbs./hr., 3 76.2 mm (3 inch) pipe diameter is used in this case. We need to calculate the proper helical heat exchanger effective heat exchange surface area based on collected data.

The overall heat transfer coefficient, U, is given by:

$1 / U = 1 / h_1 + l / k + 1 / h_2$

where

U = overall heat transfer coefficient

A = contact area for each fluid side

k = thermal conductivity of the material

h = individual convection heat transfer coefficient for each fluid

l = wall thickness

The U can be calculated as: $1/(1/176 + 0.0049/9.25 + 1/1057) = 139.7$ Btu/(ft^2 hr °F)

The required surface area can be calculated based on heat transfer rate q as:

$q = h_c A \ \Delta T$

where

q = heat transferred per unit time (Btu/hr)

A = heat transfer area of the surface (ft^2)

h_c = convective heat transfer coefficient of the process (Btu/(ft^2 hr °F))

ΔT = temperature difference between the surface and the bulk fluid (°F)

The surface area is $A = 2{,}800{,}000 / (139.7)(160 - 40) = 167$ ft^2

According to the data analyzed, the proper helical heat exchanger needs to have 167 ft^2 surface area on the coil to reach the theoretical maximum performance.

2.5 Characteristic of Purchased Helical Heat Exchanger

The company was able to find an already built helical heat exchanger with a design of multiple pass of coils. The helical heat exchanger parameter is shown in table 2.

Helical Heat Exchanger	
Coil tube diameter (inch)	1.57 x 0.049
Number of passes	3
Length per pass (inch)	1063

Table 2. The parameter of the built helical heat exchanger

To verify the application of this helical heat exchanger, the parameters are compared to the designed heat exchanger on several key factors.

The designed heat exchanger has the 3-inch coil for liquid product to flow through which is 7 in^2 area to let liquid pass. The built heat exchanger has 1.57-inch coil and 3 passes which is 6 in^2 area to let liquid pass. With the feed flow of 59,000 lbs./hr., the pass area is acceptable without creating much higher pressure.

The designed helical heat exchanger has a surface area of 167ft^2 to gain the target performance. The built heat exchanger has approximately $(1.57\pi)(1063)(3) = 109\ ft^2$. This means the efficiency of the heat transfer will be lowered by 35%. In this case, since the new helical heat exchanger will be an add-on in the system, the original condenser is still able to condense the over fed vapor into the new heat exchanger. Moreover, the limited space does not allow a full 167 ft^2 surface area heat exchanger to be installed. This built helical heat exchanger is determined to be applicable for this project.

3. Result

3.1 Installation of New Helical Heat Exchanger

The installation was performed on January 26th, 2017. A temporary stand was made to hold the original condenser while the new helical heat exchanger was installed under the condenser.

3.2 Evaluation of Helical Heat Exchanger Efficiency

The evaluation is based on the production data collected during the batch process time. Several key parameters are compared with the original production data. The key parameters are illustrated in Figure 4.

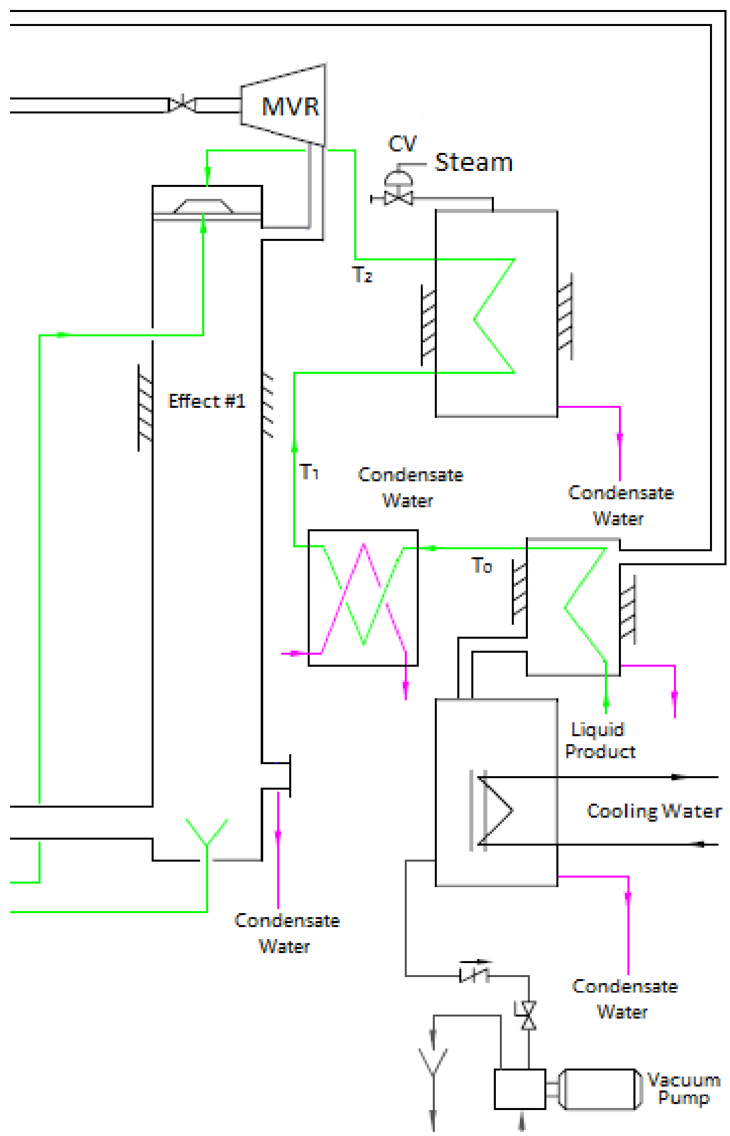

Figure 4. The data analyzed during the production batch is: 1. T_0, the discharge temperature of liquid product after the pre-heating step in new helical heat exchanger. 2. CV, the steam injection valve open percentage during the run. 3. Cooling water flow rate being sent into the condenser.

During the production process, all the set points for temperature control are maintained as the original parameters. To determine the actual steam deduction, the control valve of steam injection is monitored. Due to the fact the final temperature set point for liquid product to enter evaporator effect #1 is still 168 degrees Fahrenheit, this control valve reacts based on this final temperature. The heat obtained by the liquid product will cause the control valve to decrease flow for less steam injection. The flow rate of cooling water is monitored due to the function of liquid product as the other coolant to condense vapor. The flow rate of cooling water will automatically drop when less vapor is needed to be cooled down. Based on these two factors, the amount of steam deduction and cooling water usage can be calculated when comparing to the original data.

3.3 Data Analysis

The collected data comes from 3 batches finished before the helical heat exchanger was installed and 3 batches finished after the helical heat exchanger was installed. Each batch took 4 hours to process and the data is averaged from the reading every 30 minutes. The observed factor reading discussed in previous section is listed in Table 3.

	Original Equipment			With New Heat Exchanger		
Batch #	1	2	3	1	2	3
Average Steam Valve Opened (%)	28.7	29.4	27.6	13.4	12.9	13.2
Cooling Water Flow Rate (lbs/hr)	47.7	47.8	48.1	22.2	21.3	21.5
Temperature T_0 (°F)	43.1	41.2	44.3	108.4	109.3	108.2

Table 3. Collected data of key factor during different batches.

According to the data, obvious steam usage drop is observed. The steam usage ratio based on the data can be calculated 28.57:13.17 = 2.17. The original steam usage is 6,454.7 lbs./hr. and the steam usage after the application of helical heat exchanger is

2975.4 lbs./hr. Based on the 13 hours' total production process time. The calculated amount of steam saved is 45,230 lbs. per day.

Moreover, based on the cooling water feed flow rate, there is a 55% drop on the feed flow rate. This results in 55% operating time of cooling fan compared to original setup. The electricity usage due to the fan operating is cut by half.

4. Discussion

Due to shortage of energy resource and increasing demand on energy, efficient use of energy has already become an issue of great urgency for mankind. For the consideration of a manufacturing company, the saved energy with improved process directly decreases the cost and results in more profit. In this project, a simple helical heat exchanger helped the whole process to recycle back a large amount of low-grade thermal energy instead of dumping the heat back into the environment.

Under the limited conditions, the helical heat exchanger reflects several great advantages including high ratio of surface are to total volume, good heat exchange efficiency and capability of maintaining flow rate and in line pressure. In this case, the application deducts the steam usage by 67% and the cooling water usage by 55%. This also means the 45,230 lbs. water is saved from the boiler to supply steam. The saved energy and resource are valuable to both manufacture and environment.

Moreover, the surface area of pre-heating liquid product is increased by 66%. This is very useful in diary product evaporation processing. The less time to heat to reach the same high temperature, the lactose and calcium dissolved in the liquid precipitate out of the solution more easily. The precipitation can attach onto the wall of the coil pipe and result in fouling. Fouling is a major problem in the evaporation process since it reduces the area for product to pass through which reduce the batch time between each equipment wash. In addition, the precipitated product on the pipe is continuously heated by the heating source in the heat exchanger which will result in burnt product in the processed liquid. This can harm the quality of the product and reduce the yield as well. With the increased surface area and longer time for heating to reach desired temperature, both helical heat exchanger and condenser are able to maintain proper production flow and pressure longer.

It was observed that the installed helical heat exchanger does not function at 100% theoretical heat transfer coefficient. The reason could be the original condenser absorbed more vapor than it needed which reduces the vapor cooled down inside the new heat exchanger. A solution can be made later is to install a control valve between condenser and helical heat exchanger which can restrict the vapor flow and push more load onto the helical heat exchanger.

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