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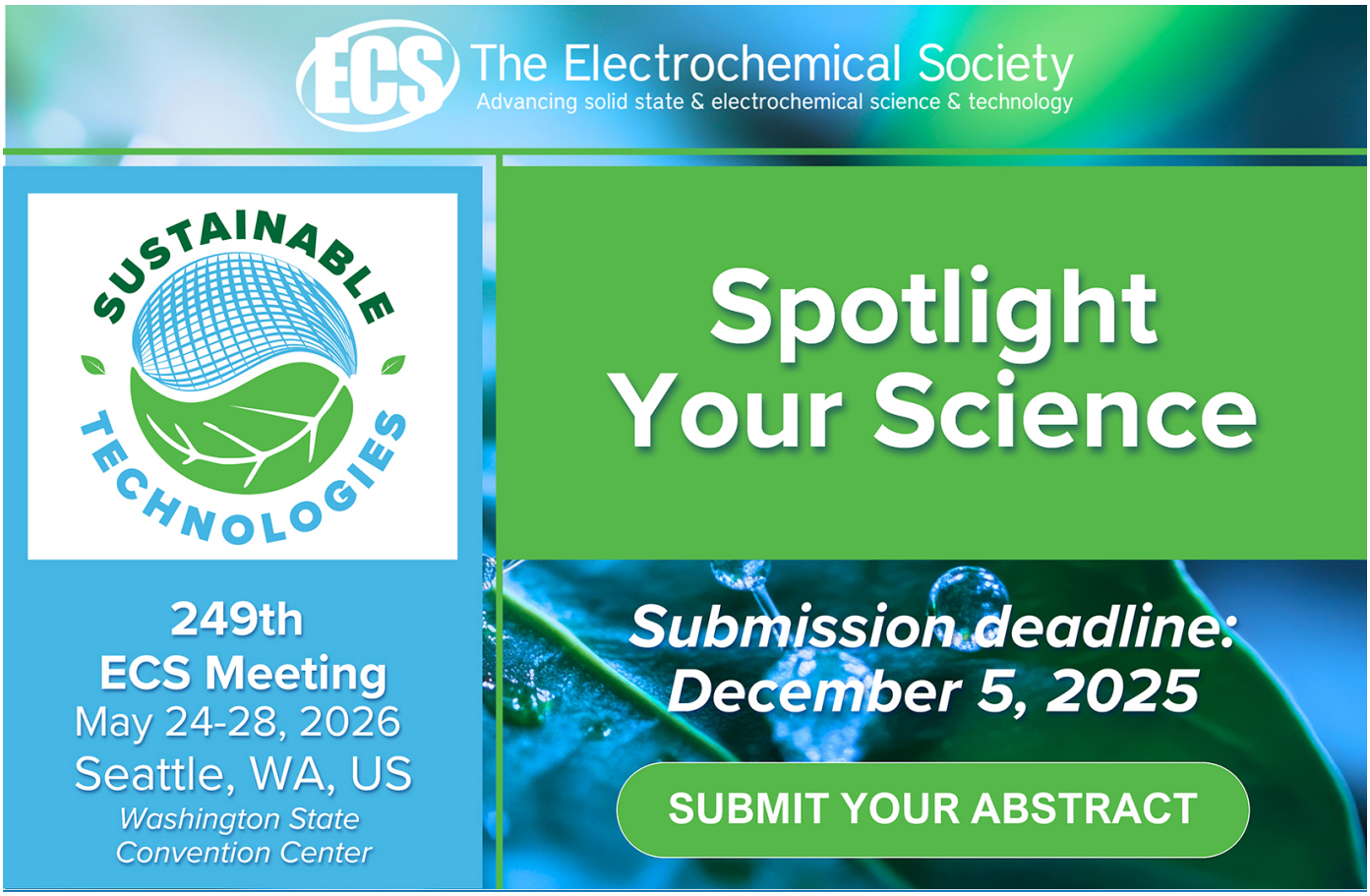
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To cite this article: E E Espinel-Blanco *et al* 2020 *J. Phys.: Conf. Ser.* **1708** 012010

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Energy evaluation of a refrigeration system by calculating the coefficient of performance

E E Espinel- Blanco[1], **E Flores-Solano**[2], **and J H Arévalo- Ruedas**[1]
[1] Grupo de Investigación en Tecnología y Desarrollo en Ingeniería (GITYD), Universidad Francisco de Paula Santander, Seccional Ocaña, Colombia
[2] Grupo de Investigación en Ingeniería Aplicada para la Innovación, Gestión y Desarrollo (INGAP), Universidad Francisco de Paula Santander, Seccional Ocaña, Colombia

E-mail: eeespinelb@ufpso.edu.co, enflorezs@ufpso.edu.co

Abstract. The calculation of the coefficient of performance for the refrigeration system in a dairy product processing plant is presented, with the objective of knowing the energy efficiency of the system based on the thermodynamic analysis of the refrigeration cycle. The operation of the cooling system is based on the physical principles related to the heat transfer between two flows, where the cooling fluid fulfills a closed thermodynamic cycle and the system needs to consume energy to extract certain amount of heat. The evaluation of the coefficient of performance was developed following an integrated methodology of three stages. Firstly, the amount of heat necessary to extract from the products to be cooled was determined to estimate the necessary energy consumption. Secondly, the heat gain in the cooling water pipe-lines was then calculated since this magnitude increases energy consumption. Finally, the operating coefficient was determined to evaluate the energy efficiency of the refrigeration cycle. It was verified that the capacity of the installed system is sufficient for the extraction of heat in the products to be cooled according to the operating conditions of the plant and the requirements to maintain the products. The analysis of heat transfer of the cooling water lines showed that the absorption of heat is caused by problems in the insulation of the pipe, which is necessary to inspect through maintenance activities to reduce energy consumption and maintain the thermodynamic efficiency of the cycle with values greater than 70%.

1. Introduction

In the field of refrigeration there are two topics that are currently under study: the reduction of energy consumption and the reduction of the emission of greenhouse gases [1]. Therefore, different and new alternatives to reduce energy use or achieve more efficient systems are important research areas in this field [2]. Industrial refrigeration, whatever its size and application, from domestic refrigerators to the largest industrial systems, uses vapor compression systems for the production of cold [3].

Refrigeration with ammonia is one of the most used methods in the cooling of products in the food industry, since ammonia is a gas with excellent thermodynamic properties in well-operated systems. Also, it substantially reduces pollution, energy consumption, and environmental impact [4]. An indicator of the energy consumption required to extract heat in a refrigeration system is the coefficient of performance (COP) of the thermodynamic cycle, which depends on the operating conditions and the losses of cold in the pipeline and in the facilities [5]. To determine the COP during a refrigeration process, it is necessary to know the amount of energy in the form of heat necessary to extract from the

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refrigerated space and the amount of energy lost due to heat absorption that implies an increase in energy consumption, that is, work in the system compressor [6].

It is proposed to determine the COP in the dairy products plant of "Freskaleche" Company located in the city of Bucaramanga in Colombia, to maintain the appropriate temperature of both raw milk and products in the different stages of the process. The plant uses anammonia refrigeration system to keep the cooling water between 0 °C and -2 °C [7]. The COP calculated based on the process variables will be an indicator of the efficiency of the refrigeration system operation and will allow decisions to be made in real time on its operation and maintenance to reduce energy consumption [8].

2. Materials and materials

The refrigeration system in the plant operates in a closed thermodynamic cycle shown in Figure 1. The cooling fluid completes the thermodynamic cycle from state 1 to 4. The heat of the refrigerated space, in this case the ice banks, is absorbed in the evaporator and transferred to the outside in the condenser, the compressor consumes energy for the operation of the system.

In Figure 2 the cooling scheme is presented, the heat is absorbed from the different stages of the process through the cold water that evaporates the ammonia in the ice banks.The working fluid enters the evaporator and absorbs the low temperature heat extracted from the refrigerated products.

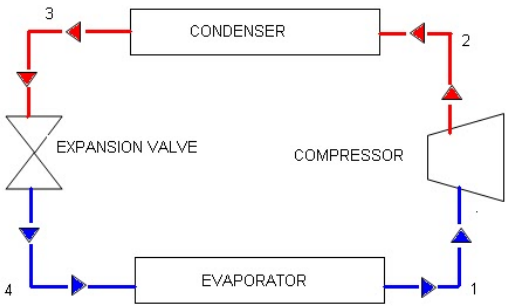


Figure 1. Thermodynamic refrigeration cycle.

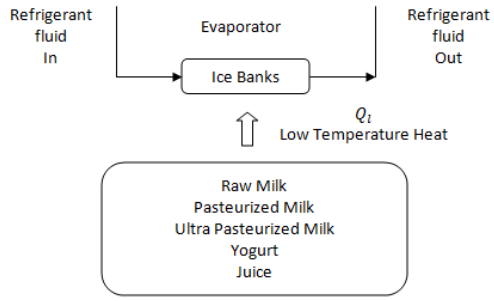


Figure 2. Product refrigeration scheme.

The energy evaluation of the refrigeration system was carried out according to the procedure shown in Figure 3. Initially, the amount of heat required to keep the product refrigerated was calculated, the loss of cold by heat absorption in the cold water lines was calculated and finally the COP was determined. The estimates were made based on the data recorded in the pressure gauges, thermometers, and flow meters installed in the plant.

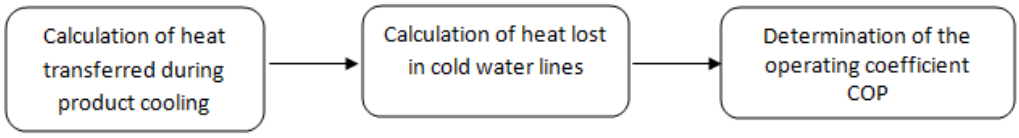


Figure 3. Thermodynamics analysis phases.

2.1. Heat transferred during the process

The extraction of the heat in the products is carried out in heat exchangers like the one shown in Figure 4, in which the data for the cooling of yogurt is shown as a reference. The product to be refrigerated enters at 25 °C and its temperature drops to 5 °C while the cooling water absorbs the heat and increases its temperature by 7 °C. The cold water that acts as a refrigerant in the exchangers comes from the ice banks of the refrigeration system. To determine the amount of heat that is necessary to extract in the different stages of the process in the plant, a thermodynamic analysis was carried out applying the conservation of energy to the process of heat exchange in flow and steady state ($\dot{Q}$) according to Equation (1), Equation (2), and Equation (3) [9].

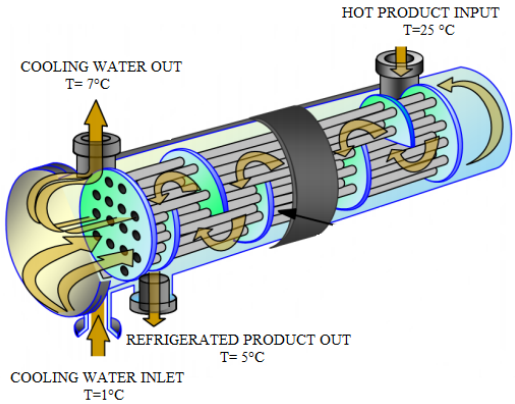


Figure 4. Heat exchanger products.

$$(\dot{Q}_P) = (\dot{Q}_r), \tag{1}$$

$$(\dot{m}_P)(C_{PP})(T_{1P} - T_{2P}) = (\dot{m}_r)(C_{Pr})(T_{2r} - T_{1r}), \tag{2}$$

$$(\dot{V}_P)(\rho_P)(C_{PP})(T_{1P} - T_{2P}) = (\dot{V}_r)(\rho_r)(C_{Pr})(T_{2r} - T_{1r}), \tag{3}$$

where, $\dot{m}_P$ = Hot product mass flow, $\dot{V}_P$ = volumetric flow of hot product, ρ_P= density of hot product, C_{PP}= Specific heat at constant pressure of the hot product, T_{1P}=Hot product inlet temperature, T_{2p}= Hot product outlet temperature, $\dot{m}_P$= Refrigerant mass flow, $\dot{V}_r$= Volumetric flow of the refrigerant fluid, ρ_r= Refrigerant density, C_{Pr}= Specific heat at constant pressure refrigerant, T_{1r} = Refrigerant inlet temperature, T_{2r} = Refrigerant outlet temperature.

Table 1 reports the values of the state variables (temperature, density and volumetric flow) registered in the heat exchangers for each of the product cooling processes.

Table1. State of flows in heat exchanger.

Product to refrigerate	Estate of product to be refrigerated						Cold water				
	T1 (°C)	T2 (°C)	ΔT (°C)	CP (kJ/kg*°C)	Density (Kg/l)	Volumetric fluid (l/h)	T1 (°C)	T2 (°C)	ΔT (°C)	CP (kJ/kg*°C)	Density (Kg/l)
Yogurth	25	5	20	3.800	1.05	4000	1	7	6	4.187	1
Juice	30	12	18	4.100	1.04	3000	1	5	4	4.187	1
Pasteurized milk	7	4	3	3.894	1.03	10000	1	7	6	4.187	1
Ultra-pasteurized milk	20	10	10	3.894	1.03	15000	1	8	7	4.187	1
Raw milk	7	4	3	3.894	1.03	18000	1	4	3	4.187	1

2.2. Heat lost in cold water lines

Heat losses in cold water pipelines were determined based on the analysis of heat transfer produced along the pipe in radial direction. It is necessary to know the dimensions per equivalent pipe path through which the cold water circulates and the corresponding type of insulation that is used, in order to carry out the heat transfer analysis [10]. Table 2 shows the diameter of the pipe, the length of the path, and the type of insulation used.

The calculation of the heat transfer (q) for each path was carried out by applying Equation (4), Equation (5), Equation (6), Equation (7), and Equation (8) [10], for a heat transfer process to the outside in the radial direction of flow in a pipe.

Table 2. Characteristics of the pipe.

Nominal diameter (in)	Type of Insulation	pipe length (m)
1	Fiberglass	95
1 1/2	Fiberglass	140
2	Fiberglass	50
3	Fiberglass	10

$$q = \frac{T_{ref}-T_{ext}}{\frac{E_{eq}}{k}+\frac{1}{h}}, \quad (4)$$

$$E_{eq} = r_2 \ln\frac{r_2}{r_1}, \quad (5)$$

$$h = h_r + h_c, \quad (6)$$

$$h_r = (0.9824x10^{-8})(\varepsilon)\left[\frac{T_{ext}^4-T_s^4}{T_{ext}-T_s}\right], \quad (7)$$

$$H_c = (2.7241)(C)(D_{ais})^{-0.2}\left[\frac{1.11}{(T_s+T_{ext}-510.44)}\right]^{0.181}[1.8(T_s-T_{ext})^{0.266}[1+(7.9366X10^{-4})(V_{air})]^{0.5}]. \quad (8)$$

To carry out the corresponding calculations, we have the values reported by the plant through measurements made in the heat exchangers and in the pipeline. The other data required for the calculation are presented in Table 3 and Table 4 considered as [11,12].

Table 3. Constants for heat transferred in pipes.

T_{ref} (°K)	T_{ext}(°K)	V_{air} (m/h)	ε	k
274.15	303.15	12000	0.7	0.04

Table 4. Variables for heat transferred in pipes.

Eeq	k	hc	hr	1/h
0.094	0.04	29.37	0.692	0.0333
0.085	0.04	28.76	0.692	0.0340
0.079	0.04	28.32	0.692	0.0345
0.071	0.04	27.41	0.692	0.0356

2.3. Determination of the coefficients of performance

Refrigeration systems have a performance, called coefficient of performance it is an expression of the efficiency of the cycle and is defined as the ratio of heat absorbed in the refrigerated space to the equivalent thermal energy of the energy supplied to the compressor.

This operating coefficient is applicable in the same way to both the ideal cycle and the real cycle in a refrigeration process. To determine the performance of the refrigeration system installed in the plant, each point of the refrigeration system is located based on the states described in Figure 1, to obtain the values of the state variables required for the COP calculation.

Table 5 presents the location of each point where the values of the state variables were recorded according to the thermodynamic refrigeration cycle. The determination of the coefficientof performance indicates the efficiency of the system. This,considers the energy consumption of the compressor (W_{in}) that is necessary to extract the amount of heat (Q_l) from the refrigerated products, this is calculated from Equation (9) according to the reference [9].

$$COP = \frac{Q_l}{W_{in}}, \quad (9)$$

where, Q_l is the amount of heat extracted by the system, and W_{in} is the work or energy consumption in the compressor necessary to extract (Q_l). According to the location of each state in the thermodynamic cycle, the variables of the refrigeration process, pressure, temperature, recorded from the measuring instruments are described in Table 6 and the enthalpy is determined as presented in the reference [13].

Table 5. location of state variables.

State	Location	Coolant status	Variable
1	Compressor suction	Superheated steam	Temperature, Pressure
2	Compressor discharge	Superheated gas	Temperature, Pressure
3	Condenser output	Superheated gas	Temperature, Pressure
4	Throttlevalveoutlet	Subcooled liquid	Temperature

Table 6. State variables.

State	Pressure (kPa)	Temperature (°C)	Enthalpy (kJ/kg)
1	245.2	7.2	1459.64
2	1010.0	98.4	1679.10
3	1010.0	30.0	1345.80
4	----	7.2	341.80

3. Results

With the data presented in Table 1 for the cooling processes, the Equation (1), Equation (2), and Equation (3) were used and the amount of heat required to extract for each product ($\dot{Q}_L$) and the corresponding mass flow rate of cooling water ($\dot{m}_r$) necessary for carry out the refrigeration of the products.

The results of these analyzes are presented in Table 7 and Table 8. It was evidenced that in the cooling process of the products made in the plant ($\dot{Q}_L$) 413.33 kW of heat are transferred to the cooling water and that to disperse this amount of energy is required a volumetric flow of cold water ($\dot{V}_r$) of 69012 l/h, which in turn loses temperature in the ice banks that are the evaporator of the refrigeration system according to the thermodynamic cycle described in Figure 1. To determine the efficiency of the refrigeration system, the coefficient of performance was initially determined by the work consumed by the compressor (w) using Equation (10) following the reference [9].

$$W_{in} = h_2 - h_1. \tag{10}$$

The heat transferred at high temperature (Q_h), in the condenser of the system was calculated based on Equation (11) following the reference [9].

$$Q_h = h_2 - h_3. \tag{11}$$

To calculate the heat extracted in the space cooled at low temperature (Q_l) in the evaporator in the ice banks, which absorbs the heat from the cooling water used in the lines to cool the products, Equation (12) was used following the reference [9].

$$Q_l = Q_h - W_{in}. \tag{12}$$

Results for net input work (W_{in}), heat released at high temperature (Q_h), heat gained at low Temperature (Q_l) and Coefficient of Performance of the cooling system COP are presented in Table 9 according to that reported by [9].

Table 7. Results of heat and mass flow calculations.

Cooling process	Product to be refrigerated			heat extracted	Cooling water		
	ΔT (°C)	Cpp (kJ/kg*°C)	$\dot{m}_p$ (kg/s)	$\dot{Q}_L$ (Kw)	ΔT (°C)	Cpr (kJ/kg*°C)	$\dot{m}_r$ (kg/s)
Yogurth	20	3.800	1.17	88.67	6	4.187	3.53
Juice	18	4.100	0.87	63.96	4	4.187	3.82
Pasateurized milk	3	3.894	2.86	33.42	6	4.187	1.33
Ultra-pasteurized milk	10	3.894	4.29	167.12	7	4.187	5.70
Raw milk	3	3.894	5.15	60.16	3	4.187	4.79
Total				413.33			19.17

Table 8. Results heat gained in the pipes.

Pipe length(m)	Nominal diameter of the pipe(in)	Insulation diameter(m)	Heat transfer area(m^2)	Heat transfer per unit area(W/m^2)	Net heat gained in pipes(W)
95	1	0.135	40.291	12.17	490.34
140	2	0.150	65.929	13.43	885.43
50	2	0.162	25.431	14.43	366.97
10	3	0.191	5.985	160.02	95.88
Total heat gained in the pipes					1838.62

Table 9. Refrigeration systems results.

W_{in} (kJ/kg)	Q_h (kJ/kg)	Q_l (kJ/kg)	COP
209.56	1337.30	1127.71	5.38

4. Conclusions

With the thermodynamic analysis carried out, it was estimated that it is necessary to extract 413.33 kW of energy in the form of heat to keep the products cooled to the operating conditions necessary for the process in the plant, this indicates that a cooling water flow of 19.17 is required kg / s equivalent to 69012 l/h. Additionally, the cold lost in the cooling water transport lines caused by the temperature gain due to thermal insulation problems shouldbe supplied, which correspond to 1838.2 W of energy.

The ice banks have sufficient capacity to absorb the heat of the cooling water in a way that guarantees the accumulation of cold required to supply both the heat extracted in the products and the losses due to transport of the cooling water in the supply lines. The operating coefficient is 5.83 equivalent to an efficiency of 75% of the thermodynamic cycle considered very good for the type of industrial installation.

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