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Dimensioning of a hybrid system boiler - solar collector of evacuated tubes, for the defrosting of fish

Dimensionamiento de un sistema híbrido caldera - colector solar de tubos evacuados, para el descongelamiento de pescado

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Abstract

The fishing sector, better known as the fishing industry, is part of the primary sector, which is why it is an important economic activity in the world, as it is part of the human diet and industrial processes. The processing of fish in industries requires defrosting, this is achieved by superheated steam produced in a boiler which uses fuel oil as primary energy, this increases production costs. This work aims to design a hybrid defrost system that is efficient, reduces costs and takes advantage of solar energy for water preheating. The purpose of the system is to reduce fuel oil consumption by taking advantage of solar thermal energy through evacuated tubes, for which the system is analyzed using the first law of thermodynamics. From the reduction of fuel oil consumption, the amount of CO_2 emitted into the environment will decrease, as well as production costs.

Fish, Hybrid, Thermodynamic

Resumen

El sector pesquero, más conocido como industria pesquera, forma parte del sector primario, por lo que es una actividad económica importante en el mundo, al ser parte de la dieta del ser humano y de procesos industriales. El procesamiento del pescado en las industrias requiere descongelarlo, esto se logra por medio de vapor sobrecalentado que se produce en una caldera la cual utiliza combustóleo como energía primaria, esto hace que aumente los costos de producción. Este trabajo tiene la finalidad de diseñar un sistema de descongelamiento híbrido que sea eficiente, que reduzca los costos y aproveche la energía solar para el precalentamiento del agua. La finalidad del sistema es reducir el consumo de combustóleo aprovechando la energía térmica solar mediante tubos evacuados, para ello se analiza el sistema mediante la primera ley de la termodinámica. A partir de la reducción de consumo de combustóleo disminuirá la cantidad de CO_2 emitida al medio y a su vez los costos de producción.

Pescado, Híbrido, Termodinámica

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Introduction

For many years, food freezing has been used as part of the preservation process that industries have opted for to guarantee the regular and standardized supply of fish, more specifically the quality and quantity of the product, as well as the economic value.

Freezing is an excellent procedure for food preservation and only generates minimal changes in the qualitative and organoleptic properties of seafood products. However, during thawing, abundant exudation occurs, which can be detrimental to food quality (Fabre, Perlo, Bonato and Teira, 2022).

Thawing has become a real challenge for organizations and companies, so that in the industry there are several alternatives for thawing the product such as water immersion, climatic chamber, radiofrequency, microwave, and even combinations of some of these processes mentioned (Xargayó et al, 2021). A popular alternative is the use of boilers, so that the energy contained in the fuel oil is transformed into thermal energy to defrost the product; however, this implies a considerable impact on the environment due to the exhaust gases, which are the product of combustion.

In view of this, a hybrid system with solar energy is an option to reduce the impact on the environment. Its operation consists of preheating the water to be used by the boiler with solar thermal energy and thus reducing the amount of fuel oil burned.

1. Problem statement

The industrial fish thawing process is a challenge for companies and organizations because the product requires a large amount of thermal energy at low temperatures. The operating costs and energy consumption of fish processing are very high due to the energy used for preservation/freezing, thawing, washing and other processes. In addition, carbon emissions from the fishing industry are increasing due to the continuous use of fossil fuels, which continues to be an environmental problem, so organizations have established air quality and energy consumption reduction as a priority in their policies.

A viable option is the use of renewable energies and it has been found that solar thermal energy is used in different countries in the industrial fishing sector in applications of drying processes and water heating, using different types of solar collectors depending on the thermal power capacity and temperature range.
In Mexico, the fishing industry is of great importance, therefore, this work proposes the performance analysis of a hybrid solar thermal system to optimize the continuous supply of hot water that is integrated to the defrosting process, in order to enhance energy savings in the freezing-thawing processes.

2. Calculation of the thermal load

It is necessary to calculate the amount of heat for defrosting, according to the transformation of the product when it is defrosted. For this case we have 20 tons of fish for 24 hours for thawing, with an inlet temperature of -20 °C and an outlet temperature of 5 °C. The fish has three processes during thawing, first the thawing below the freezing point in this case the freezing point of the fish is -2.2 °C, then there is a phase change in the thawing that considers the latent heat of vaporization and finally there is the heat generated above the thawing point.

By applying Equation 1, the amount of heat in the three fish processes is calculated, considering the specific heats above (Cp↑) and below (Cp↓) the freezing point, as well as the latent heat of vaporization hfg.

Cp↑= 1.776 kJ/kg K
Cp↓= 0.953 kJ/kg K
hfg = 234.92 kJ/kg

With these data, the amount of heat required is determined using Equation 1 (Çengel and Ghajar, 2011) for the thawing process as shown in Table 1.

$$Q = m\, C_p\, \Delta T \qquad (1)$$

Q_1	256454.4 kJ
Q_2	33888.8 kJ
Q_3	4698400 kJ

Table 1 Amount of heat in the fish processes Prepared by the company

Applying equation 2, the total heat of the 20 tons of fish to be thawed is calculated.

ISSN 2523-2881

$$Q_{total} = Q_1 + Q_2 + Q_3 \qquad (2)$$

$$Q_{total} = \frac{256454.4\ kJ + 338886.8\ kJ + 4698400\ kJ}{24\ h}$$

$$Q_{total} = 220{,}572.55\ \text{kJ/h}$$

Therefore, 220,572.55 kJ/h of heat is required to thaw the fish and have the proper conditions.

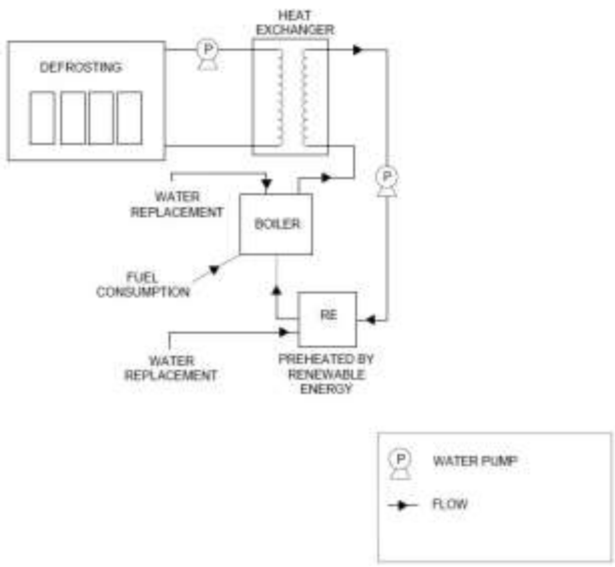

Figure 1 Components in the thawing process
Ovando, Huchin, Castillo and Estrada, 2016

Figure 1 graphically represents the components involved in the thawing process. The thawing room contains the frozen product, which is sprayed with hot water through sprinklers that conduct water at 30 °C. The water returns to the tank by decanting at a temperature of 10 °C and is then reheated in the heat exchanger through contact with steam pipes coming from the boiler.

The heat exchanger serves as a support to maintain the water flow and to have the correct defrosting temperatures, so that the water temperature at the outlet is 30 °C, is sent to the frozen fish and returns to the heat exchanger tank at 10 °C.

Reheating the water requires a steam flow from the boiler at 250 °C as superheated steam and will have an outlet of 40 °C as saturated steam.

3. Heat exchanger design

The thermodynamic analysis of the heat exchanger is shown below.

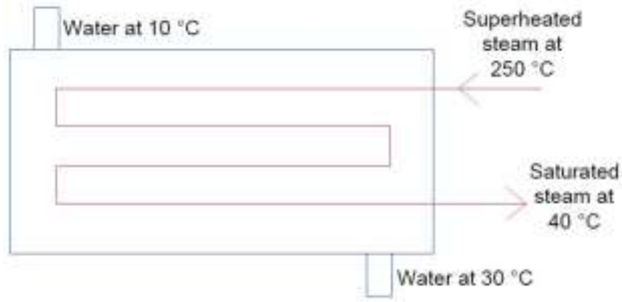

Figure 2 Heat exchanger
Prepared by the author

The heat exchanger is of the open type. The tubes are immersed in water to heat it with the steam coming from the boiler. The design of the heat exchanger was made from equations 3, 4 and 5.

Equation 3, 4 and 5 are used to calculate the Reynolds number (Re), Nusselt number (Nu) and convective coefficient (h_o) respectively for the outer side of the tank, so the convective coefficient of the air over the flat area surface is calculated.

ρ	1.225 kg/m^3
v	10800 m/hr
μ	6.26E-2 kg/m*hr
k	0.072 kJ/hr*m*K
Pr	0.7

Table 2 Properties of air Coopeland, G. n.d..

$$Re = \frac{\rho * v * L}{\mu} = 2.11x10^6 \qquad (3)$$

$$Nu = 0.664 * Re^{\frac{1}{2}} * Pr^{\frac{1}{3}} = 856.82 \qquad (4)$$

$$h_o = \frac{Nu * k}{L} = 6.169\ \frac{kJ}{hr * m^2 * K} \qquad (5)$$

To calculate the convective coefficient of water, the Reynolds number (Re), Prandtl number (Pr) and Nusselt number (Nu) are determined using equations 6, 7 and 8, respectively, using the data in Table 3. The result is shown in equation 9.

ρ	997 kg/m^3
v	18000 m/hr
μ	3.6172 kg/m*hr
k	2.1528 kJ/hr*m*K
Cp	4.182 kJ/kg*k

Table 3 Properties of water Coopeland, G. n.d.

$$Re = \frac{\rho * v * L}{\mu} = 49750499 \quad (6)$$

$$Pr = \frac{C_p * \mu}{k} = 7.007 \quad (7)$$

$$Nu = 0.0296 * Re^{\frac{4}{5}} * Pr^{\frac{1}{3}} = 81391.650 \quad (8)$$

$$h_i = \frac{Nu * k}{L} = 17522 \ \frac{kJ}{hr * m^2 * k} \quad (9)$$

The purpose of determining the convective coefficients of air and water is to calculate the overall heat transfer coefficient U (Equation 11) and from Equation 10 determine the resistance per flat plate area (thickness=0.3048 m, k=5.04 kJ/m*K).

$$R_T = \frac{1}{h_o} + \frac{x}{k} + \frac{1}{h_i} = 0.223 \ \frac{hr * m^2 * K}{kJ} \quad (10)$$

$$U = \frac{1}{R_T} = 4.492 \ \frac{kJ}{hr * m^2 * K} \quad (11)$$

Considering a U-tube heat exchanger, for steam at 250 °C with a latent heat of steam h_{fg} =1716.2 kJ/kg, the mass of steam will be (equation 12):

$$m = \frac{Q_{total}}{hfg} = 128.524 \ \frac{kg}{hr} \quad (12)$$

From equation 13 we calculate the steam quantity as a function of the mass flow rate (V_{esp}=0.2327 m^3/kg)

$$\dot{m} = m * Vol_{esp} = 29.9 \ \frac{m^3}{hr} \quad (13)$$

The flow velocity is calculated from equation 14. (D_{int}=0.0254 m)

$$v = \frac{\dot{m}}{A} = \frac{\dot{m}}{\pi \frac{d^2}{4}} = 59023.046 \ \frac{m}{hr} \quad (14)$$

The convective coefficient (*hl*) for steam at 250 °C is determined with equations 15,16,17,18 and 19 from the data in Table 4.

ρ	4.2966 kg/m³
V_{esp}	0.2327 m³/kg
μ	6.50E-2 kg/m*hr
k	0.108 kJ/hr*m*K
Cp	1.98 kJ/kg*K

Table 4 Properties of steam 250 °C Coopeland, G. n.d.

$$Re = \frac{\rho * v * d}{\mu} = 9.92x10^4 \quad (15)$$

$$Pr = \frac{\mu * C_p}{k} = 1.191 \quad (16)$$

$$Jh = \frac{0.491}{Re^{0.49}} = 0.001749 \quad (17)$$

$$Gr = \frac{Re * \mu}{d} == 253598.42 \ \frac{kg}{hr} \quad (18)$$

$$hl = \frac{Jh * Cp * Gr}{Pr^{\frac{2}{3}} * (\mu/\mu m)^{0.14}} = 781.792 \ \frac{kJ}{hr * K} \quad (19)$$

The convective coefficient for steam at 40 °C is determined by equations 20,21,22,23 and 24.

ρ	0.08314 kg/m³
V_{esp}	12.027 m³/kg
μ	3.58E-2 kg/m*hr
k	0.072 kJ/hr*m*K
Cp	1.94 kJ/kg*K

Table 5 Properties of steam at 40 °C Coopeland, G. n.d.

$$Re = \frac{\rho * v * d}{\mu} = 3.27x10^3 \quad (20)$$

$$Pr = \frac{\mu * C_p}{k} = 1.0282 \quad (21)$$

$$Jh = \frac{0.027}{Re^{0.2}} = 0.005352 \quad (22)$$

$$Gr = \frac{Re * \mu}{d} = 4907.176 \ \frac{kg}{hr} \quad (23)$$

$$hl = \frac{Jh * Cp * Gr}{Pr^{\frac{2}{3}} * (\mu/\mu m)^{0.14}} = 50.019 \ \frac{kJ}{hr * K} \quad (24)$$

With the results of Equation 19 and 24, the total interior coefficient is determined by Equation 25

$$hit = \frac{2}{3}(h_{40°C}) + \frac{1}{3}(h_{250°C}) = 293.943 \ \frac{kJ}{hr * K} \quad (25)$$

The overall heat transfer coefficient is determined (equation 29).

$$Nu = 0.036(Re^{0.8} * Pr^{0.43} - 17400) + 297 * Pr^{\frac{2}{3}} = 119949.968 \quad (26)$$

$$h_{sal} = \frac{Nu * k}{l} = 25822.829 \ \frac{kJ}{hr * K} \quad (27)$$

$$R = \frac{1}{hit} + \frac{x}{k} + \frac{1}{h_{sal}} = 0.003 \ \frac{hr * m^2 * k}{kJ} \quad (28)$$

$$U = \frac{1}{R} = 2878.282 \ \frac{kJ}{hr * m^2 * K} \quad (29)$$

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The logarithmic mean temperature LMTD is determined:

$$LMTD = \frac{\Delta T1 - \Delta T2}{Ln(\frac{\Delta T1}{\Delta T2})} = 95.361\,°C \quad (30)$$

The heat transfer area will be (equation 31):

$$A = \frac{Q}{U*LMTD} = 8.0235\,m^2 \quad (31)$$

The length of the exchanger tubes is determined from equation 32:

$$L = \frac{A}{\pi * d} = 100.60\,m \quad (32)$$

The pressure drop is determined using equation 34:

$$jf = \frac{0.05573}{Re^{0.261}} = 6.74x10^{-3} \quad (33)$$

$$\Delta P = 8 * jf * (\frac{\mu}{\mu m})^{0.14}\left(\frac{L}{d}\right)\left(\frac{\rho * V^2}{2}\right) = 2387.78\,\frac{kg}{m*s^2} \quad (34)$$

4. Fuel consumption calculation

In this analysis, the amount of fuel required to defrost 20 tons of product is determined in order to compare what will be saved if heat production with renewable energies is implemented. For this purpose, the data in Table 6 applied to Equations 35, 36, 37, 38, 39 and 40 will be used.

T_{ent}	40 °C
T_{sal}	250 °C
Efficiency	90 %
ρ fuel oil	920 kg/m^3
Calorific Power (LHV)	40,1664 kJ/kg
P_{ent}	120 kPa
P_{sal}	1176 kPa
h_1	2573.5 kJ/kg
h_2	2935 kJ/kg

Table 6 Boiler steam and fuel characteristics. Coopeland, G. n.d.

Calculation of steam mass and heat

$$m_{vapor} = 128.524\,kg/hr \quad (35)$$

$$Q_{vapor} = m_{vapor}\,(h_2 - h_1) = 46461.35\,\frac{kJ}{hr} \quad (36)$$

Calculation of fuel mass

$$m_{fuel} = \frac{Q_{vapor}}{\text{Efficiency} * LHV} = 1285.25\,\frac{kg}{hr} \quad (37)$$

$$\dot{m}_{fuel} = \frac{m_{fuel}}{\rho_{fuel}} * 1000 = 1397\,\frac{liters}{hr} \quad (38)$$

Considering a fuel cost of $13 MNX and a 12-hour production, the cost can be determined from equation 39 and 40.

$$Cost = \dot{m}_{fuel} * fuel\ cost = 18161.09\,\frac{MXN}{hr} \quad (39)$$

$$Cost_{daily} = Cost * production = 217{,}933.11\,\frac{MXN}{day} \quad (40)$$

5. Sizing of the system

The city of Tapachula is located at a latitude of 14.9 °N and a longitude of 92.3 °E, at an average altitude of 171 meters above sea level. It has a minimum irradiation level of 5.46 kWh/m2 day in the month of September and a maximum of 7.21 kWh/m^2 day in the month of March (INEGI,2017).

Design parameters	Values
Desired water temperature	30 °C
Ambient temperature	29.2 °C
Relative humidity	66 %
Wind speed	4.7 m/s
Water to be heated	18 m^3

Table 7 Design parameters of the solar collector
Prepared by the authors

The solar collector used is model SCSPV-15, its characteristics are shown in Table 8.

Solar collector	
Nominal size (cm)	181x210
No. of tubes	15
Integral system	
Empty weight (kg)	61.5
Full weight (kg)	211.2
Actual collection area (m^2)	2

Table 8 Solar collector characteristics
Own Elaboration with data from technical data sheet

The sizing of the system requires estimating the average energy that each collector can provide in the critical month based on the catchment area (Ovando, Huchin, Castillo and Estrada, 2016), for this case an average efficiency for evacuated tubes of 89% was considered (Albizzati, 2016)

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Although other parameters such as optical efficiency and removal factor must be taken into account (Venegas, Jaramillo, Rodríguez, Sosa and Domínguez, 2015), in addition to the minimum irradiation value of 5. 46 kWh/m^2 day (19656 kJ/m^2 day) so the average energy delivered by each equipment will be:

$$E = 19656 \text{ kJ/m2} * 2\, m^2 * 0.89 = 34{,}988\, kJ \quad (42)$$

Therefore, the total number of collectors that will make up the system must consider the energy requirement so that:

$$m^2 = \frac{Necesidad\ energetica}{Energia\ de\ colector} = \frac{4{,}988{,}742\ kJ}{34{,}988\ kJ} \quad (43)$$

This gives us a total of 143 evacuated tube solar collectors to meet the energy requirement.

We use a procedure for the minimum number of collectors needed to meet the energy requirement.

Collector unit price	$ 9,335.00
Cost of 143 collectors	$ 1,334,905.00
Pumping equipment	$ 187,645.00
Piping and fittings	$ 90,000.00
Estimated installation cost	$ 258.967.00
Project cost	$ 1,796,837.00

Table 9 Capital required
Own Elaboration

6. Acknowledgements

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7. Conclusions

Fish thawing is still using a traditional steam boiler system that uses fuel oil and in turn affects the environment, so that operating costs are high. In view of this, a viable option is the use of renewable energies such as solar-hybrid thermal energy to reduce the operating costs of the system, reduce the burning of fossil fuels, mitigate greenhouse gases and whose payback period is no more than 7 years.

It is of great importance that organizations begin to implement renewable energies such as photothermal and be aware that although the return on investment is not favorable, it favors the environment due to a lower production of CO_2.

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