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Calculus of heat transfer area necessary for a single-stage heat transformer

Cálculo del área de transferencia de calor necesaria para un transformador de calor de una etapa

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Abstract

A heat transformer is proposed in the literature by Colorado [3], with the aim of being in the desalination process. However, in that study, the heat transfer area of the main components in the system has not been calculated. The present investigation provides the proposal to calculate the area of each pieces of equipment to obtain the total transfer area and contributes the construction of the entire system. A lithium bromide solution and water are proposed as an absorbent and as a refrigerant, respectively for the system. A heat transformer is estimated based on calculations of energy analysis: coefficient of performance of 0.4049, the heat load in the evaporator is 2 kW and the heat load of the generator is 1.37105 kW. Four heat exchangers assuming the tubes and shell design are proposed in this research. The surface required for each heat exchanger to transfer those heat loads is calculated through a logarithmic temperature difference method using an appropriate global heat transfer, incrustation factors and local heat transfer, according to the proposal of Jain and Sachdeva [9].

Absorption, Design, Heat exchanger

Resumen

Un transformador de calor es propuesto en la literatura por Colorado [3], con la finalidad de ser implementado en etapas de precalentamiento en procesos de desalinización. Sin embargo, en dicho estudio, no se ha calculado el área de transferencia de calor de los principales componentes del sistema. El objetivo de la presente investigación propone calcular el área de cada componente que conforma el transformador de calor para obtener el área de transferencia total y contribuir a la futura construcción del sistema. Una solución de bromuro de litio como absorbente, y agua como el componente refrigerante son propuestas para el sistema. Basado en los cálculos del análisis energético se dimensiona un transformador de calor considerando: Coeficiente de desempeño de 0.4049, potencia en el evaporador de 2 kW y potencia en el generador de 1.3715 kW. Para el cálculo del área son propuestos cuatro intercambiadores de calor de tipo tubo y coraza. La superficie requerida para que cada intercambiador de calor transfiera dichas cargas de calor es calculada mediante un método que utiliza un coeficiente global de transferencia de calor apropiado, factores de incrustación y coeficientes de transferencia de calor locales de acuerdo con la propuesta de Jain y Sachdeva [9].

Absorción, Diseño, Intercambiador de calor

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Introduction

The present investigation is dedicated to the calculation of the convective coefficients and the total transfer area of a heat transformer by vapor absorption of simple effect, which will allow to obtain the preliminary design of the equipment and thus contribute to its future construction.

Thermal pollution is a consequence of the modification of bodies of water in a harmful way. Currently various industries emit waste heat to the environment and if that heat is not recovered immediately, it can cause local thermal pollution. On the other hand, most of the energy produced by various appliances and large industrial processes is wasted in the form of heat, normally that heat has a temperature lower than 100 ° C and is known as "low quality waste heat". One of the benefits of heat recovery has been to decrease energy costs per product by reducing the amount of fuel needed to generate heat and size requirements. The largest amount of waste heat is generated by different industries, usually by the food and tobacco industry, paper, basic metals, chemical industry and non-metallic minerals. "Some low-temperature processes may not be useful sources directly from industrial waste heat, however, the heat may be improved" [2].

To take advantage of this industrial waste heat there are different technologies available such as: Rankine cycle machines that work by the principle of heat recovery whose disparity lies in the use of an organic and specific working fluid in substitution of water, compression pumps of steam and the heat transformer by steam absorption.

The system with which we work has a great purpose which is the recovery and improvement of residual heat; and several advantages are known in comparison with the other technologies, for example, being able to work with sources of residual heat including renewable sources, requires less electric power compared to a heat pump by vapor compression and has a longer useful life, affirm Smölen and Budnik [14].

There is a lot of information about the equipment in question in the open literature, a clear example is the advanced exergy analysis applied to a single-effect steam absorption heat transformer proposed by Colorado [3].

In this work the energy analysis, classical exergy and advanced exergy is performed starting from a power of 2kW in the evaporator and obtaining a coefficient of performance of 0.4049, all this provides the flow diagram of the process, basic physical processes and the efficiency of the system , however, in the work of Colorado [3] some aspects such as:

- The area of heat transfer for each component.
- Its dimension
- Geometry
- Type of exchangers.
- Construction materials.

The present investigation allows to know these characteristics when calculating the heat transfer area of each of the main components and finally find the global transfer area necessary for the system and thus contribute to a future construction. We start from the balance of matter and energy, the operating conditions are considered to carry out the methodology for the calculation of the convective coefficients and the transfer area. Finally, the results that indicate the configurations of each team were tabulated. The four main components of the transformer are proposed as shell and tube heat exchangers. Considering with base in the fluids with which it works, that the material of its elaboration is the copper; two fluids are required: the absorbent and the refrigerant, and for the calculation of the area of each component the fouling factors are known following the suggestion of Jain [9].

Description of the system

Figure 1 outlines how the process is carried out. The single-effect heat transformer consists of an evaporator, an absorber, a generator and a condenser, as main elements. The residual heat possibly coming from a renewable source is added to the evaporator and the generator. In the evaporator, water vapor is generated and directed to the absorber. In the generator, the LiBr-water solution is placed at a lower concentration of absorbent, which is heated causing the refrigerant to evaporate. The absorbent solution is concentrated and sent to the absorber. In the absorber, the water vapor is brought into contact, causing the solution to be diluted, absorbing the vapors of the refrigerant and generating an exothermic reaction.

For this proposal, the heat obtained in the absorber is used for possible desalination applications. In the absorption-desorption circuit, carried out in the absorber and generator, a solution heat exchanger is placed in order to take advantage of the sensible heat transfer. In the generator, the refrigerant vapor flows from the generator to the condenser, passing to the liquid state, the pressure level is increased through a pump and continues to the evaporator. It is at this point where the cycle begins again. As it is possible to observe, the mass transfer only occurs in the absorber and generator, and the refrigerant flows on the external side of the tubes. For the calculation of the convective coefficients and the area of transfer, the present work assumes the hypotheses raised by Colorado [3].

The following are emphasized:

- Pressure drops in all components are neglected
- The solution left by the generator and the absorber is in saturation conditions, plus the refrigerant that comes out of the condenser and the evaporator.

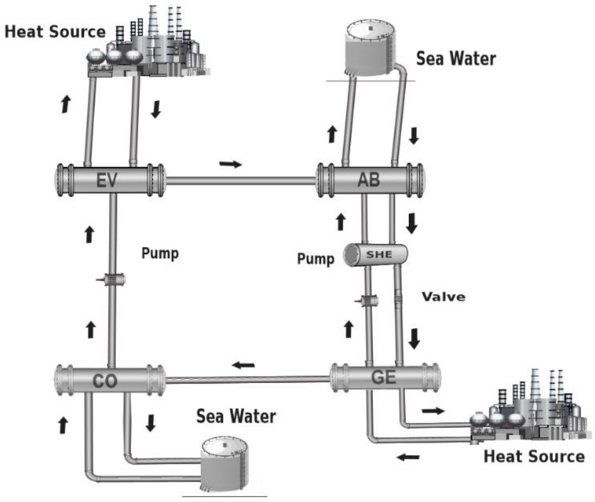

Figure 1 System diagram
Source: Own elaboration

Methodology

For the design of each of the components of the previously described cycle, the thermo-physical properties of the water and the lithium bromide solution are: density, specific heat, thermal conductivity and viscosity were calculated from various correlations proposed by Pátek and Klomfar [11], XSteam [8] and, Sharqawy and others [13].

The thermal conductivity of the construction material is fixed according to Holman [7]. For this work the geometry of "tube and shell" was selected for the main components. This type of design is commonly used in the industrial sector and because of the nature of the fluids.

The sizing parameters were tabulated following the recommendations of TEMA (Tubular Exchanger Manufacturers Association). The calculation of the area of each one of the components of the system is done by means of "the integrated form of the Fourier equation for the stable state" [10]:

$$\dot{Q}_k = A_k LMTD_k\, U_k \tag{1}$$

In this equation the LMTD refers to the logarithmic average temperature difference (for its acronym in English) and is obtained as shown below:

$$LMTD_k = \frac{\Delta T_k^2 - \Delta T_k^1}{ln\frac{\Delta T_k^2}{\Delta T_k^1}} \tag{2}$$

The overall heat transfer coefficient is obtained based on the outer surface of the tubes:

$$U_k = \frac{1}{\left(\frac{D_o}{D_i}\right)\left(\frac{1}{h_i}\right)+\left(\frac{D_o}{D_i}\right)F_i+\left(\frac{D_o}{2k}\right)ln\frac{D_o}{D_i}+F_o+\frac{1}{h_o}} \tag{3}$$

For the calculation of the total area (A_{TOTAL}) the following equation is used:

$$A_{TOTAL} = A_{Ev} + A_{Co} + A_{Ab} + A_{Ge} \tag{4}$$

Where the subscripts: Ev refers to the evaporator, Co to the condenser, Ab to the absorber and Ge to the generator.

For purposes of comparison and analysis of results, this paper proposes:

$$\dot{Q} = U^{*} LMTD\, A^{*} \tag{5}$$

Calculating the overall coefficient as shown below:

$$U^{*} = \frac{1}{h_i} \tag{6}$$

In the case of the calculation of the film coefficients on the side of the tubes as for the shell side, specific equations were found for each team, taking as reference a series of data provided by Jain and Sachdeva [9], and which are shown in Table 1:

Component	Di	Do	L	N. Steps	Fi	Fo
Evaporator	13.84	15.87	6.096	4	0.09	0.09
Absorber	13.84	15.87	6.096	4	0.09	0.09
Generator	13.84	15.87	6.096	6	0.09	0.09
Condenser	13.84	15.87	6.096	6	0.09	0.09

Table 1 Parameters of geometrical sizing and fouling factors of heat exchangers
Source: (Jain & Sachdeva, 2017)

Where Di and Do are the internal and external diameters in millimeters, respectively, L is the length of the tube in meters, Fi and Fo are the internal and external fouling coefficients ($\frac{m^2{}^\circ C}{kW}$). The solution of equations (1-3) taking as reference the Q powers of each component, the average logarithmic temperature differences, the internal film coefficients (side of the tubes) and the side of the shell, provide us with the area of heat transfer A.

To find the overall coefficient of each component (equation 3) it is necessary to calculate the convective coefficients. Concerning the convectives inside the tubes, single-phase, the first thing to be carried out is the Reynolds number calculation, since, knowing the fluid regime, it is possible to decide which equation to use for the following parameters.

$$Re = \frac{\rho v d}{\mu} \tag{7}$$

The number of Prandtl is calculated, making it possible to obtain the number of Nusselt with equation 8, under certain conditions: Pr > 0.5 y 3000 < Re < $5x10^6$.

$$Nu = \frac{fr}{8}(Re - 1000)\left[\frac{Pr}{1+12.7\left(\frac{fr}{8}\right)^{0.5}\left(Pr^{\frac{2}{3}}-1\right)}\right]^3 \tag{8}$$

Finally, and counting on all the previous variables, the local internal convection coefficient is determined, according to Gnielinski [5]:

$$hi = \frac{Nuk}{d_i} \tag{9}$$

The measurement of the outer film coefficient differs for each of the components. Next, the different equations for the calculation of this coefficient are shown, being classified by the type of component.

1 Evaporator

For the shell side it is important to know the saturation temperature and the wall temperature. The saturation temperature in this case is the temperature at which the refrigerant vapor exits, while the wall or surface temperature was found by an iterative method in which the assumption of the ho is necessary.

The iterative method concludes when the assumed value of the coefficient is equal to that calculated in accordance with equation (10) proposed by Rohsenow, Hartnett and Cho [12].

$$h_o(T_s - T_{sat}) = \mu_l h_{fg}\left[\frac{g(\rho_l-\rho_{v)}}{\sigma}\right]^{0.5}\left[\frac{Cp_l(T_s-T_{sat})}{0.013h_{fg}P_r}\right]^3 \tag{10}$$

2 Condenser

Something similar to the evaporator occurs in the condenser, but in an inverse manner. Once the internal film coefficient is found, the next thing is to know the saturation temperature in the component.

As the equation necessary for the coefficient to be calculated is a function of the saturation temperature and the surface temperature, an iterative method very similar to that of the evaporator is used, the differences are the equations with which the temperature is calculated of surface in the condenser and the film coefficient according to equations (11) and (12) that is provided by Holman [7].

$$T_s = T_c + \frac{ho(Tsat-Tc)}{hio+ho} \tag{11}$$

$$h_o = 0.725\left[\frac{g\rho_l(\rho_l-\rho_v)k_l^3 h_{fg}}{\mu_l(T_{sat}-T_s)d}\right]^{0.25} \tag{12}$$

3 Generator

The coefficient in this element is a function of the mass flow per unit length of wet tube of the solution and is represented by the Greek letter Γ according to equation (13), which is a correlation product of the combination of the developed one by Bakhtiari [1] and the results of Wang [15].

$$h_o = 5554.3\,\Gamma^{0.236} \tag{13}$$

4 Absorber

The representative equation for this component is based on the viscosity and density of the solution, it is a particular equation for horizontal tube heat exchangers [6].

$$h_0 = 2000\left[\frac{\frac{\mu}{\rho}}{10^{-6}}\right]^{-1.7} \tag{14}$$

For all the above, Ts refers to the saturation temperature, Ta is the average temperature of the fluid and can be replaced, if necessary, by the heat temperature of the fluids. The properties that contain the subscript "l" are referred to the fluid in the liquid state.

Having found each of the film coefficients on both sides of the exchangers, the next step is the calculation of the global coefficient of heat transfer with equation (3). Knowing the average logarithmic difference, the power exchanged and the global coefficient of heat transfer, it is possible to calculate the area of the Fourier equation for each exchanger, and finally add the areas of the evaporator, generator, condenser and absorber to obtain the total transfer area.

Results

Table 2 and Table 3 summarize the calculations obtained with the application of the methodology proposed by Jain and Sachdeva [9], and applied to the Colorado design for a heat transformer.

Exchanger	**T [°C]**		**Convective coefficients**	
	Ti	To	ho	hi
Evaporator	29.02	65	0.0103	12.7389
generator	56.43	64	1228.5373	8.8439
Absorber	64.96	97.1	725.172	1.0431
Condenser	65	29	18.3884	15.0062

Table 2 Heat transfer coefficients of each component of the transformer
Source: Own elaboration

Exchanger	**Heat transfer coefficients**		**Areas**	
	U	U*	A	A*
Evaporator	0.0103	12.7389	15.213	1.9961
Generator	3.0621	0.1131	0.0864	2.3388
Absorber	0.7712	0.9587	0.1651	0.1328
Condenser	3.0595	0.0666	0.0417	1.9158
Total			15.5062	6.3835

Table 3 Global heat transfer coefficients and areas by component and totals
Source: Own elaboration

Table 3 presents the different global heat transfer coefficients and their respective areas, where the heat transfer area (A *) is calculated from the coefficient U *, and the other area is calculated with the Jain methodology [9]. The global heat transfer coefficients have the units of $(\frac{kW}{m^2 °C})$, therefore, the calculated heat transfer areas are in m^2. According to the literature, the convective coefficients of a biphasic flow, evaporation and condensation, are larger than those determined for a single phase flow.

This is not observed in all our calculations, since there are higher convective coefficients on the shell side, with the exception of the evaporator.

When the values of the area of heat transfer (A) are compared with the area (A *) calculated with the global coefficient of different methodology (U *), it is possible to realize that there are true differences between the values. An A * = $6.383m^2$ and an area were obtained A = $15.5062m^2$.

Conclusions

This study presents the calculation of the total heat transfer area of a single-effect transformer, from the calculation of the convective coefficients, the global heat transfer coefficient and the average logarithmic temperature difference of each element of the system.

The total heat transfer area of the calculated heat transformer is 15.5062 m2. We observe that the greatest influence in the calculation of transfer area is due to the heat transfer coefficients where evaporation or mass transfer occurs.

Consequently, the occupied correlations have certain limits of application, mainly in the mass flow, proposed by Colorado [3] do not comply with these ranges. Therefore, a search for appropriate convective coefficients for the system is necessary.

References

[1] Bakhtiari, B., Fradette, L., Legros, R., & Paris, J. (2011). A model for analysis and design of H2O-LiBr absorption heat pumps. Energy Convers Manage, 1439–48.

[2] Bruckner, S., Liu, S., Miró, L., Radspieler, M., Cabeza, L., & Lävemann, E. (2015). Industrial waste heat recovery technologies: An economic analysis of heat transformation technologies. Applied energy.

[3] Colorado, D. (2017). Advanced exergy analysis applied to a single-stage heat transformer. Applied Thermal Engineering.

[4] Florides, G. A., Kalogirou, S. A., T. S., & Wrobel, L. C. (2003). Design and construction of a LiBr-water absorption machine. Energy Conversion and Managament, 2483-2508.

[5] Gnielinski, V. (1976). New equations for heat and mass transfer in pipe and channel flow. International Chemical Engineering, 359-367.

[6] Hoffmann, L., Greiter, I., Wagner, A., Weiss, V., & Alefeld, G. (1996). Experimental investigation of heat transfer in a horizontal tube falling film absorber with aqueous solutions of LiBr with and without surfactants. International Journal of Refrigeration, 331–41.

[7] Holman, J. P. (2010). Heat Transformer. New York: McGraw-Hill.

[8] Holmgrem, M. (2007). X-steam function of matlab r2010a for water and steam thermodynamic properties based on iapws if97 standard.

[9] Jain, V., & Gulshan, S. (2017). Energy, exergy, economic 83E) analysis and multi-objective optimization of vapor absorption heat transformer using NSGA-II technique. Energy Conversion Management.

[10] Kern, D. (1999). Procesos de Transferencia de Calor. Ciudad de México: Compañía Editorial Continental.

[11] Pátek, J., & Klomfar, J. (2006). A computationally effective formulation of the thermodynamic properties of LiBr–H2O solutions from 273 to 500 K over. International Journal of Refrigeretion.

[12] Rohsenow, W., Hartnett, J., & Cho, Y. (1998). Handbook of heat transfer. New York: McGraw Hill.

[13] Sharqawy, M. H., Linedhard V., J. H., & Zubair, S. M. (2010). On exergy calculations of seawater with applications in desalination. International Journal og Thermal Science.

[14] Smölen, S., & Budnik-Rodz, M. (2006). Low rate energy use for heating and in industrial energy supply systems-Some technical and economical aspects. Energy.

[15] Wang, C., Lu, Z., & Yuchi, B. (1996). Heat and mass transfer of the falling film generator in. Proceedings, (págs. 556–561.). Shanghai, China.