CHEMICAL ENGINEERING TRANSACTIONS

VOL. 114, 2024

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Min Zeng, Yee Van Fan, Xuechao Wang

ISBN 979-12-81206-12-0; **ISSN** 2283-9216

DOI: 10.3303/CET24114056

The Role of the K-loss Coefficients Applied to Finned Tube Heat Exchanger Design

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This article presents a modified method for designing finned tube heat exchangers based on calculating the K-loss coefficients on the side tube. Besides, a CFD simulation is set up to analyse pressure drop and flow distribution on the staggered tubes. The performance of finned tube heat exchangers depends on several factors, including the number of staggered tubes, tube length, fin pitch, tube pitch, and fin area. Finned tube heat exchangers improve thermal effectiveness, particularly when dealing with gas and liquid fluids. The staggered tube arrangement complicates the prediction of pressure drop on the tube side. Also, two head pipes configure the inlet and outlet flows. The equations for determining pressure drop assume uniform velocity and constant flow distribution throughout the equipment. These correlations do not include the frictional pressure drop caused by the 180° bends welded on the tubes. In addition, equations fail to include the fluid distribution in each parallel circuit of tubes. Considering heat exchanger components as hydraulic resistances in both series and parallel configurations, an equation was developed to sum the K-loss coefficients for the tube bundle, bends, inlet pipe, and outlet pipe. From the hydraulic design results and considering that all tubes distribute water at 93 °C, the next stage consists of the thermal heat exchanger design based on the NTU method to heat air at 50 – 60 ºC. The heat exchanger design is evaluated by comparing the results with an experimental case study. This includes water flow distribution, heat transfer area, hot and cold outlet fluid temperatures, pressure drop and CFD numerical results.

1. Introduction

Finned tube heat exchangers, Figure 1, are designed to transfer thermal energy, particularly when gas fluid is involved. They are equipment where an extra heat transfer area (fins) is added on the outside diameter and along the tube (Sung 2019). These devices are recommended when one of the fluids is gas because they have low thermal conductivities and heat capacities (García et al., 2019). Due to the crossflow configuration, empirical models have been developed to enhance heat transfer between the gas and liquid fluids (Webb 1980). Finned tube heat exchangers are designed with staggered tube configuration, Figure 2. The performance depends on the geometrical characteristics of these exchangers. It can vary depending on the type of tube arrangement, the number of tubes, the flow distribution in the tubes, the number of passages, and the inlet and outlet section flow. These variables define the hydraulic performance of the equipment. The correlations for the hydraulic design of this equipment do not consider the installation of 180º bends necessary to generate the hot fluid pass through the tubes (Hammock, 2011). The number of passes and the configuration of the tubes to promote heat transfer varies depending on the design methodology and the energy demand required. Some heat exchanger designs incorporate combinations of different tube arrangements to improve the efficient use of energy (Okbaz et al., 2020). Most design procedures use trial and error to achieve method convergence more efficiently. This can be enhanced by implementing programmed algorithms (Xie et al., 2008). Studies focused on improving fin-and-tube heat exchangers, and hydraulic and heat performance in HVAC systems, power generation, and process industries (Xu 2024). Besides, researchers use simulations on fin-and-tube heat exchangers to explore the

Paper Received: 13 May 2024; Revised: 20 July 2024; Accepted: 22 November 2024
Please cite this article as: Canizalez-Dávalos L., Murrieta-Luna E., Cruz-Delgado V.J., Valero-Luna C.Y., Bañuelos-Frías A., 2024, The Role of the K-loss Coefficients Applied to Finned Tube Heat Exchanger Design, Chemical Engineering Transactions, 114, 331-336 DOI:10.3303/CET24114056

impact of refrigerants on indoor residential (Saleem 2022). This work develops a design methodology since it is possible to analyse hydraulically finned tube heat exchangers by quantifying the K_i loss coefficients based on the friction losses, especially in the hot flow section (tube side).

Figure 1: Finned tubes

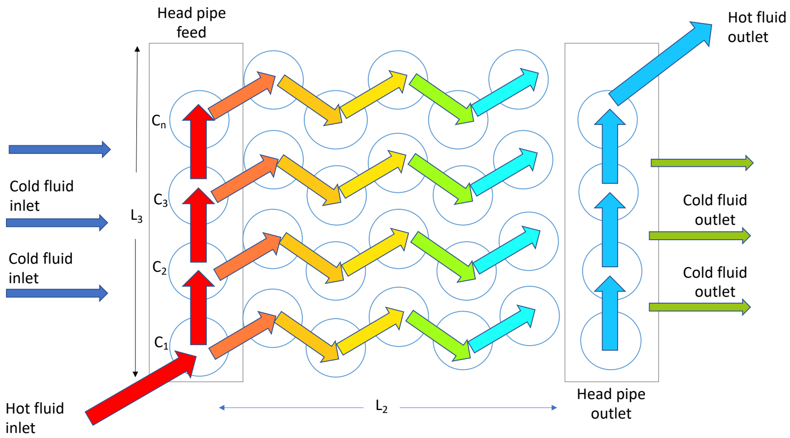


Figure 2: Staggered tube configuration

2. Methodology

The design methods start from an initial heat transfer area, if this geometrical configuration is sufficient to achieve the required outlet temperatures and pressure drops, the calculations are completed, and the design is finished. In this paper, the design of a finned tube heat exchanger is described in terms of the convergence of the dimensions L_1 (tube length), L_2 (heat exchanger depth) and L_3 (heat exchanger height or feed head length), Figure 2. First, the height of the heat exchanger is specified as L_3. The second specification consisted of the number of tubes connected (number of circuits) to L_3. The aim is to distribute the hot flow inside the heat exchanger. From this input data, the total flow (F_T) is divided by the number of circuits (Cn) to calculate the initial flow distribution (F_n), Eq(1).

$$F_n = \frac{F_T}{C_n} \tag{1}$$

Piping systems can be divided into major losses (straight pipes) and minor losses (fittings, valves, bends, elbows, pipes, etc.). The minor losses can be determined using the loss coefficient K. The heat exchanger consists of tubes, elbows, an inlet manifold, and an outlet manifold so the concept of the loss coefficient K was used for the hydraulic design (Granados et al., 2019). Tables for determining the k-values for different fittings can be found in the literature. The current bibliography shows four methods for calculating the losses: K-method (excess head), 2K-method, 3K-method, and equivalent length Eq(2). The K-method has been used in this work because it is more appropriate than other methods. The friction factor f defines K in terms of the Fanning equation, the length L and the diameter D are described in Eq(3).

$$K = f\frac{L_{eq}}{D} \tag{2}$$

To calculate the pressure drop in the pipes, Eq(3) was used.

$$\Delta P_{pipe} = 2f\rho\frac{L}{d_i}u^2 \tag{3}$$

Where d_i is the internal diameter in m, u is the velocity in m/s and ρ is the density in kg/m^3.
From Eq(3), the value of K was determined for a tube pipe, Eq(4):

$$K = 2f\rho \frac{L}{d_i} \tag{4}$$

Different velocities develop through the pipes, including at the inlets and outlets of the equipment as well as at the bends. To improve the convergence of the calculations, instead of using the fluid velocity in m/s in Eq(3), volumetric flow (F) in m3/s, was used Eq(5).

$$\Delta P_{pipe} = K\,F^2 \tag{5}$$

To evaluate the results of this work, the operating conditions of an existing finned tube heat exchanger in a solar drying plant in the city of Zacatecas Mexico were used (Garcia O., 2019), Figure 3. This device incorporates 125 copper tubes of 1.2 m and two headers for the inlet and outlet water with a length of 1.3 m. The tubes are fitted with 6 fins/cm, and the distance between the fins is 1.6 mm.


a) b)

Figure 3: a) Finned tube heat exchanger of the Solar Plant in Calera Zacatecas, Mexico, b) head pipes and bends

Table 1 shows the operating conditions of the solar plant heat exchanger.

Table 1: Operating data of the solar plant exchanger

Fluid	Air (Cold Fluid)	Water (Hot Fluid)
Mass Flow, (kg/s)	1.8	0.37
Inlet Temperature, (°C)	25	93
Outlet Temperature, (°C)	50 - 60	50 - 60
Density (kg/m3)	1.075	983.261
Heat Capacity (KJ/kgK)	1.004	4.5286
Thermal Conductivity (W/mK)	0.0281	0.64
Viscosity (cp, N m s/m2)	0.000018	0.5375

From the data reported in Table 1 and Eq(1) to Eq(5), the following algorithm (Eq(6) to Eq(10) was developed and solved (Hebert et al., 2019). The model was simultaneously simulated for each hydraulic section (pipes, elbows, and tubes) specifically on the tube side of the heat exchanger.

$$F_x = \frac{F}{A_s} \tag{6}$$

F_x is the flow velocity (m/s) and A_s is the area (m^2). Subsequently, the Reynolds number was calculated using Eq(7).

$$R_e = \frac{F_x D_i}{\mu} \tag{7}$$

The friction factor was determined during the calculation sequence.

$$f = 0.0035 + \frac{0.264}{{R_e}^{0.42}} \tag{8}$$

The pressure drop in each tube was calculated using Eq(9).

$$\Delta P = 2f\rho \left(\frac{L}{D_i}\right)({F_x}^2) \tag{9}$$

Eq(10) was applied to calculate the K loss coefficient.

$$K_x = \frac{\Delta P}{F^2} \tag{10}$$

The staggered arrangement of the heat exchanger tubes represents a network of pipes. In this system, the heat exchanger has tubes in parallel for flow distribution and tubes in series to configure the number of times the hot fluid passes through the staggered arrangement. To calculate the coefficient K for the total number of tubes (K_{tubes}), Eq(11) was used.

$$K_{tubes} = \frac{1}{\left[\left(\frac{1}{K_{x1}}\right)^{0.5}+\left(\frac{1}{K_{x2}}\right)^{0.5}+\cdots+\left(\frac{1}{K_{xn}}\right)^{0.5}\right]^2} \tag{11}$$

The pressure drop was determined with Eq(12) as a function of the resistance K of the complete system (heat exchanger).

$$\Delta P_{tubes} = \Delta P_{total}\left(\frac{K_{tubes}}{K_{sys}}\right) \tag{12}$$

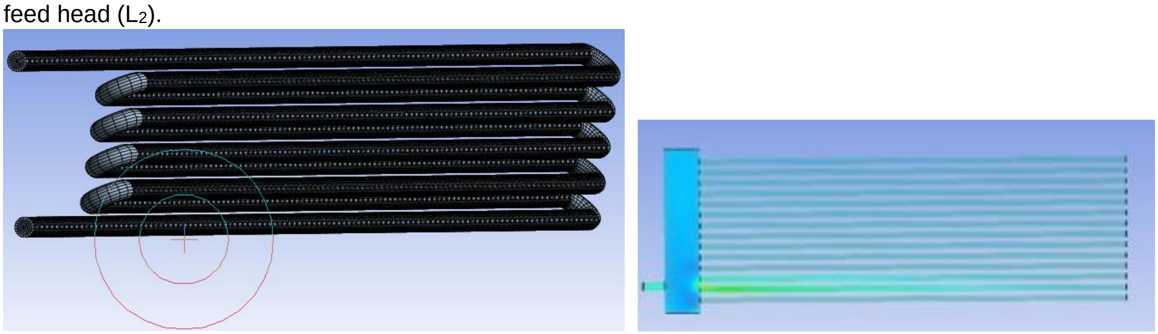
Eq(13) was used to calculate the flow through tubes (F_{tube}).

$$F_{tube} = \left(\frac{\Delta P_{tubes}}{K_x}\right)^{0.5} \tag{13}$$

The design reported by Lee Ho Sung (2010) calculates the heat transfer area, thermal effectiveness, heat transfer coefficients, and outlet temperatures.

The design procedure assumes the number of tubes connected to a feed head defined by the height L_3. These initial tubes represent the first pass of the hot fluid in the tubes. Next, the flow distribution through the pipes was estimated, pressure drops were calculated, and outlet temperatures were determined. If the temperature has not reached its target value, the same number of tubes are connected in series by 180° bends to set up the second pass through the tubes. The distance defined by these staggered tubes is the depth of the heat exchanger represented as L_2. Later, the pressure drop and the outlet temperatures are recalculated to determine whether the simulated area is sufficient to reach the required heat load. As the number of passes increased, the L2 distance also became longer. The design ended when the length L_2 calculated the number of staggered tubes reaching the desired temperatures, and the pressure drop was within the allowable range. The design algorithm was implemented using the Visual Basic programming module in Excel. The resulting design determined the hot flow distribution in the tubes, the total pressure drop, the heat transfer area and the fluid outlet temperatures.

The hydraulic results of the design method were compared with a computational fluid dynamics (CFD) simulation using Ansys Fluent software. Figure 4 shows the geometries used in the computational simulation. Figure 4a illustrates the number of passes of a single circuit of tubes (L_1). Figure 4b, shows the tubes connected to the feed head (L_2).



a) *b)*

Figure 4: a) Staggered tube, b) head pipe

3. Results

The results are reported in Table 1. The calculated heat transfer area was 15.17 m^2. The outlet temperatures were, for the air (cold fluid) 45.56 ºC, and the water (hot fluid) 55.83 ºC.

Table 2: Design results

Variable	Target value	Calculated value
Pressure Drop (Air), kPa	--	71.11
Pressure Drop (Water), kPa	--	125.02
Outlet Temperature (Air), ºC	50 - 60	45.56
Outlet Temperature (Water), ºC	50 - 60	55.83
Heat Transfer Area, m^2	--	15.17

Figure 5 plots the temperature profiles of the fluids as a function of distance L_2 (depth of the equipment). It is observed that the target temperatures are reached at a length (L_2) of 0.43 - 0.5 m.

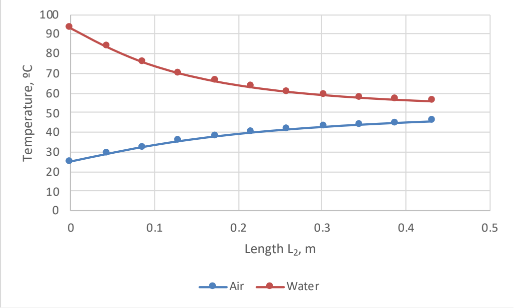
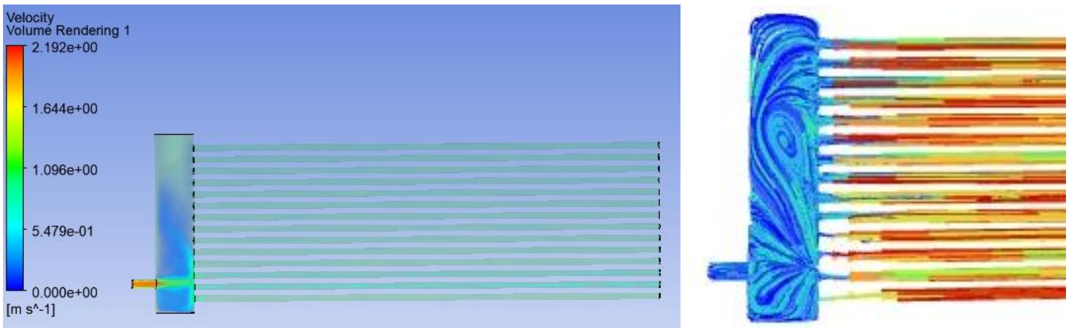


Figure 5: Fluid temperature profiles

Figure 6a shows the fluid velocity distribution contours. The velocities of the numerical simulation in the pipes have values from 0.5 m/s to 1.09 m/s. Figure 6b shows the velocity profile. According to the red colour in Figure 6b, the flow distribution is similar in all tubes.



a) b)

Figure 6: a) Velocity distribution and b) streamlines profile

The water flow distribution as a function of head height L_3 is presented in Figure 7. The total height of this pipe was 0.96 m. It was observed that the flow distribution in the 13 tubes installed in the header was uniform. In the bottom pipes, the highest flow rate was 0.174 L/min.

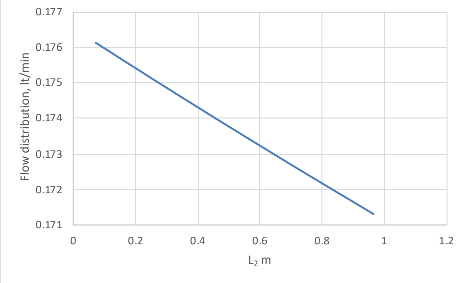


Figure 7: Flow distribution profile

Figure 8 shows the numerical pressure profiles for a tube circuit. The results are plotted at three points of the heat exchanger, entrance, tubes, and outlet. The inlet pressure was 656 kPa, and the outlet pressure was 26.6 kPa. The dynamic simulation pressure drop was 868 kPa. The method calculated the pressure drop of the water at the outlet of each pass through the pipes, as well as the pressure drop of the crossflow air. The algorithm calculated a pressure drop of 125 kPa.

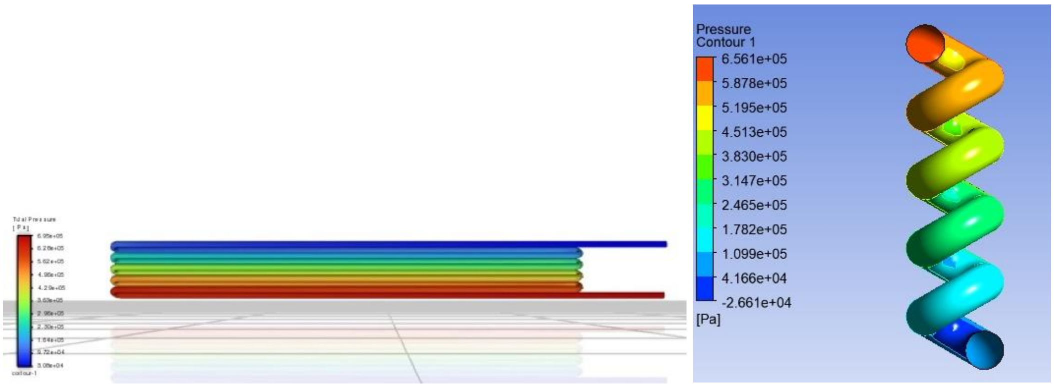


Figure 8: Pressure drop profile

4. Conclusions

This alternative design allows for sizing finned tube heat exchangers by solving simultaneously the coefficients of friction loss in the tubes, the loss coefficient in the elbows, and the coefficient at the inlet and outlet headers. Calculating the outlet temperatures of the fluids at each pass through the tubes was possible. At the solar plant, the heat exchanger reports air temperatures between 50-60 °C and water temperatures from 49-60 °C. The design algorithm determined outlet temperatures of 45.56 ºC for air and 55.83 ºC for water. The existing heat exchanger has 125 tubes installed; the proposed design methodology calculated 130 tubes. The numerical simulation of 13 tubes installed in the feed head performed a uniform flow distribution. However, if the number of tubes installed in the header increases, the flow distribution differs between the tubes. Therefore, the design variables that defined the sizing and performance of the heat exchanger were the number of tubes connected to the feed header, the length of the tubes, and the staggered arrangement. The results presented are approximate in comparison to experimental data. The correlations for predicting pressure drop in a staggered tube system present an alternative method to design finned tube heat exchangers. Besides, this method included equations for calculating flow distribution through heat exchanger tubes.

References

García V.O., Pilatowsky F.I., Ortiz R.N., Menchaca V.C., 2019, Solar Thermal Dehydrating Plant for Agricultural Products Installed in Zacatecas, México. Weentech Proceedings in Energy, 5, 1-19.

Hammock G.L. 2011, Cross-Flow, Staggered-tube Heat Exchanger Analysis for High Enthalpy Flows. MSc Dissertation, University of Tennessee, Knoxville, USA.

Lugo G.H., Canizalez D.L., Picón N.M, 2019, Incorporating the Use of Fouling Model in the Design and Operating of Cooling Networks. Chemical Engineering Transactions, 76, 43-48.

Okbaz A., Pinarbasi A., Bahadir O.A., 2020, Experimental Investigation of Effect of Different Tube Row-Numbers, Fin Pitches and Operating Conditions on Thermal and Hydraulic Performances of Louvered and Wavy Finned Heat Exchangers. International Journal of Thermal Science, 151, 1-14.

Saleem S., Bradshaw C.R., Bach C.K., 2022, Development of design guidelines for fin-and-tube heat exchangers with low-GWP refrigerants. International Journal of Refrigeration, 143, 166-181.

Sung L.H., (Ed) 2010. Thermal Design Heat Sinks, Thermoelectrics, Heat Pipes, Compact Heat exchangers, and Solar Cells. John Wiley & Sons, Inc., Hoboken, New Jersey, USA, DOI:10.1002/9780470949979.

Webb R.L., 1980, Air-Side Heat Transfer in Finned Tube Heat Exchangers. Heat Transfer Engineering, 1(3), 33–49.

Xie G., Wang Q., Sunden B, 2008, Application of a Genetic Algorithm for Thermal Design of Fin-and-Tube Heat Exchangers. Heat Transfer Engineering, 29(7), 597–607.

Xu L., Li J., Sun K., Xi L., Gao J., Li Y., 2024, Heat analysis and optimal design of fin-and-tube heat exchanger with X-truss vortex generators. International Communications in Heat and Mass Transfer, 152, 107248.