An Energy Efficiency Indicator and Grading of Shell-and-Tube Heat Exchangers

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Abstract. The shell-and-tube heat exchanger is the most commonly used heat exchange equipment in the industry. Whether shell-and-tube heat exchangers are energy-saving is of great significance for the efficient using of energy. Therefore, the corresponding evaluation system and index are needed for evaluating the heat transfer process in the shell-and-tube heat exchanger. In this paper, based on Kern method, the energy efficiency evaluation index of shell-and-tube heat exchanger suitable for oil-water working medium is derived. And the relevant database is used to obtain the overall energy efficiency distribution of the industry, which is subject to the normal distribution, finally according to the overall energy efficiency distribution, the energy efficiency of the shell-and-tube heat exchanger is graded.

1. Introduction
Heat exchangers are widely used in petrochemical, energy power, urban heating, mechanical light industry and other fields, accounts for 30%-40% of the total equipment investment usually. In some thermal power plants, they can even account for more than 70% of the total investment of the entire power plant[1]. Therefore, research on energy efficiency and energy-saving technologies in heat exchangers is of great significance for energy conservation and emission reduction.

The shell-and-tube heat exchanger is a partition wall heat exchanger which heat exchange surface is a heat exchange tube bundle enclosed in a shell. This kind of heat exchanger has the advantages of simple structure, easy manufacture, low cost, wide flow section and easy cleaning, but at the same time, the heat transfer coefficient is low relatively and the floor space is large. Shell-and-tube heat exchangers can be manufactured from a variety of structural materials (metal materials mainly) and can be operated under high temperature and high pressure conditions. They are the most widely used heat exchanger types and they play a vital role in industrial systems around the world nowadays.

There have been many studies on energy efficiency indicators for heat transfer processes. The heat transferred by the power of the unit fluid was proposed as the evaluation standard, that is, Q/N as the evaluation index[2]. Based on the work of the predecessors, R.L.Webb proposed a relatively complete set of PEC criteria[3]. Bejan proposed the number of entropy production units based on the second law of thermodynamics as an evaluation index, and demonstrated that Q/N could not fully reflect the rationality of energy utilization through model calculation[4].

There are also some researches on the energy efficiency index of heat exchangers. Zhang Yanfeng et al. theoretically deduced the energy efficiency index of plate heat exchangers, proposed a new energy efficiency index EEI, and obtained a normal distribution map of energy efficiency
However, there is no established energy efficiency level and related standards for shell-and-tube heat exchangers at home and abroad. There is no universally recognized energy efficiency evaluation method or indicator in academia and related industries. The commonly used indicators can only be used from one aspect of energy utilization and lack of rigorous theoretical derivation, it is difficult to compare shell-and-tube heat exchangers of different structures.

In this paper, from the theoretical point of view, the specific form of the energy efficiency index of the shell-and-tube heat exchanger applicable to the oil-water working medium is derived based on the Kern method, and the overall energy efficiency distribution of the industry is obtained by combining the performance data of the shell-and-tube heat exchanger.

2. Energy efficiency indicator of shell-and-tube heat exchanger

2.1 Theoretical derivation

Kern method for designing shell-and-tube heat exchangers was proposed in the 1950s[6]. The method focuses on the flow and heat transfer on the shell side, and the calculation error for the shell side convective heat transfer coefficient is small. The calculation of the drop is slightly not accurate compare with the experiment data. However, the qualitative analysis of the Kern method is accurate and basically covers the main structural parameters of the shell-and-tube heat exchanger (tube spacing, shell side inner diameter, number of baffles), the equation structure is easy to deduct and simplify, so the energy efficiency index of the shell-and-tube heat exchanger can be derived based on this method.

In shell-and-tube heat exchangers, since the thermal resistance of the tube side and the shell side is usually on the order of $10^{-5}$ magnitude, much less than the thermal resistance of the working medium during heat transfer, it is ignored in the derivation. The total heat transfer coefficient of the heat exchanger can be expressed by equation (1):

$$\frac{1}{k} = \frac{1}{h_i d_i} + \frac{d_o}{2\lambda_w} \ln \left( \frac{d_o}{d_i} \right) + \frac{1}{h_o}$$

Where $k$ is the total heat transfer coefficient of the heat exchanger, W m$^{-2}$ K$^{-1}$; $h_i$, $h_o$ are the convective heat transfer coefficients of the tube side and the shell side, respectively, W m$^{-2}$ K$^{-1}$; $d_i$, $d_o$ are the inner and outer diameters of the internal heat transfer tube, m; $\lambda_w$ is the thermal conductivity of the tube wall, W m$^{-1}$ K$^{-1}$.

If the convective heat transfer coefficient of the shell side of the shell-and-tube heat exchanger is much smaller than the convective heat transfer coefficient of the tube side, and the heat conduction resistance caused by the wall thickness is ignored, the main thermal resistance of the heat transfer process is reflected in shell side. It can be approximated:

$$k \approx h_o$$

Therefore, if the convective heat transfer coefficient of the shell side working fluid is much smaller than the convective heat transfer coefficient of the pipe side working fluid (such as cooling oil and water), the heat transfer of the shell side working fluid can be used to approximate the shell-and-tube heat exchanger’s overall heat transfer situation.

For the shell side of shell-and-tube heat exchangers, the experimental correlation of Nusselt number and pressure drop is:

$$Nu_{shell} = \frac{h_i D_o}{k} = 0.36 \text{Re}_{shell}^{0.55} Pr^{0.14} \left( \frac{\mu}{\mu_w} \right)^{0.14}$$

$$\Delta P_{shell} = 4 f_{shell} G^2 D_o (N_u + 1)$$

$$Re_{shell} = \frac{G D_o}{\mu}$$

$$\text{Pr} = \frac{C_p \mu}{\lambda_w}$$

$$\text{Re} = \frac{GD}{\mu}$$

$$\text{Pr} = \frac{C_p \mu}{\lambda_w}$$

$$Nu = \frac{h_i D_o}{k}$$
\[ f_{\text{shell}} = 0.25e^{0.576 - 0.19 \ln \text{Re}^{0.25}} \]  

(6)

Where \( N_{u,\text{shell}} \) is Nusselt number; \( \text{Re}_{\text{shell}} \) is Reynolds number for shell side flow; \( \text{Pr} \) is Prandtl number; \( \Delta \text{P}_{\text{shell}} \) is pressure drop of shell side, Pa; \( \mu, \mu_c \) are the dynamic viscosity coefficients of hot fluid and cold fluid respectively. \( N \cdot s / m^2 \); \( f_{\text{shell}} \) is Shell side friction factor; \( G_s \) is mass flow under the minimum flow area of the shell side, kg/m\(^2\)s; \( D_i \) is inner diameter of the shell, m; \( N_b \) is the number of baffles; \( \rho \) is shell side working medium density, kg/m\(^3\); The specific calculation method is as shown in the formula (7) (8):

\[
D_i = \frac{4(P_i - \frac{\pi d_o^2}{2})}{\pi d_o^2} \quad \text{(For square pitch)}
\]

(7)

\[
D_i = \frac{4(P_i - \frac{\pi d_o^2}{4})}{\pi d_o^2} \quad \text{(For triangular pitch)}
\]

(8)

Where \( P_i \) is the pipe center spacing, m.

The total heat transfer coefficient represents the benefit of the heat exchanger operation, which reflects the heat transfer characteristics of the heat exchanger as a whole; the pressure drop represents the energy consumption during the operation of the heat exchanger, which reflects the flow characteristics of the heat exchanger during operation. The physical meanings of the two are different, and the total amount of heat transfer and the pumping power, the heat loss and the helium loss of the flow, and the entropy increase are about one order of magnitude, so in order to reflect the \( k \) and \( \Delta \text{P} \)'s importance in energy efficiency, we introduce \( \frac{k}{\Delta \text{P}^n} \), combining equations (3)-(8) we can get:

\[
\frac{h_o}{\Delta \text{P}^n} = \frac{0.36 \frac{\lambda}{D_i} \left( \frac{D_i u_o}{\mu} \right)^{0.85} \text{Pr}^{0.5}}{(0.5e^{0.376} - \rho^{0.376} (N_b + 1)^{0.15} u_o^{1.81} D_i^{1.94})^n}
\]

(9)

Simplify:

\[
\frac{h_o}{\Delta \text{P}^n} = \frac{0.36 \lambda (N_b + 1)^{0.85} \text{Pr}^{0.5} \mu^{-0.55 - 0.19} \rho^{-0.55 - 0.81} D_i^{-1.94 n - 0.45} u_o^{0.55 - 1.81 n}}{0.8895}
\]

(10)

Where \( u_o \) is the shell side working fluid flow rate, m/s.

If the energy efficiency index is weakly correlated or not correlated with the working fluid flow rate, thereby reducing or even eliminating the influence of the working fluid flow rate on the energy efficiency index, the speed index term 0.55-0.81n needs to be near zero, so the value of n is:

\[ n = 0.304 \]

(11)

Substituting into (10), the energy efficiency indicator can be written as:

\[
\frac{h_o}{\Delta \text{P}^{0.304}} = \frac{0.373 \lambda^{0.303} \text{Pr}^{0.5} \mu^{0.303} D_i^{0.304}}{(N_b + 1)^{0.304} \rho^{0.608}}\]

(12)

2.1 Influencing factor

As can be seen from Equation 15, the energy efficiency indicator can be divided into two parts. The first part represents the influence of the shell-and-tube heat exchanger structure on energy efficiency indicators, structurally related parameters include the number of baffles and the equivalent diameter of the shell side, reflects the design and production level of shell-and-tube heat exchangers; The second part represents the influence of fluid thermal properties on energy efficiency indicators, including density, dynamic viscosity, Prandtl number and thermal conductivity. The energy efficiency index will
be affected by the type of fluid, even if the fluid type is constant, the change of fluid temperature will affect the thermal properties of the fluid, which in turn affects the energy efficiency index.

2.3 Shell-and-tube heat exchanger flow heat transfer performance database
After collecting and collating the articles on the shell-and-tube heat exchanger experiments in each database, a total of 68 liquid-liquid phase-change shell-and-tube heat exchangers were collected. The structure mainly includes a spiral baffle plate and a conventional bow plate, and the size of the heat exchanger is mostly a small heat exchanger for testing, and the detailed data for the industrial large-sized shell-and-tube heat exchanger is still to be perfected. For the shell-and-tube heat exchangers with oil-water working fluids, there are 38 groups, some of which lack geometric parameters or flow parameters. The size of the heat exchanger ranges from 0.5m to 5m, and some of the heat exchangers use enhanced heat transfer means such as new high-efficiency heat transfer tubes.

2.4 Distribution of energy efficiency indicators of shell-and-tube heat exchangers
Taking the energy efficiency index of the shell-and-tube heat exchanger with oil-water as the working fluid in the database as a sample, the overall energy efficiency distribution of the shell-and-tube heat exchanger industry can be estimated by mathematical statistics. The energy efficiency indexes of 38 sets of shell-and-tube heat exchangers with oil-water as working fluid under standard working conditions were calculated, and the distribution histogram was obtained as shown in Fig. 1. The probability density distribution of the overall energy efficiency index of the shell-and-tube heat exchanger satisfies the normal distribution function $f(x) = N(38.4, 7.97^2)$.

![Figure 1: Total energy efficiency indicator histogram and fitted normal distribution curve](image)

According to the probability energy function of the overall energy efficiency index of the shell-and-tube heat exchanger $f(x) = N(38.4, 7.97^2)$, the energy efficiency interval can be divided. For example, the energy efficiency of shell-and-tube heat exchangers is divided into three energy efficiency intervals: low energy efficiency, medium energy efficiency and high energy efficiency, and the proportions are 30%, 50%, 20%, respectively. When the energy efficiency index of the heat exchanger is less than 32.2 and the heat exchanger is at a low energy efficiency level, the heat exchanger should be phased out or updated; when the heat exchanger energy efficiency index is between 32.2 and 64.2, the heat exchanger is at a medium energy efficiency level, then the heat exchanger can continue to be used; when the energy efficiency index of the heat exchanger is greater than 64.2, the heat exchanger is at a high energy efficiency level, and the heat exchanger should be vigorously promoted.
3. Conclusion

From the theoretical point of view, based on the Kern formula, the energy efficiency index \( \frac{h_i}{\Delta p_{0.84}} \) of the traditional bow-baffle shell-and-tube heat exchanger based on oil-water working fluid is proposed. The indicator can be divided into two parts, which respectively reflect the influence of the structural parameters of the shell-and-tube heat exchanger and the thermal properties of the running medium on the flow and heat transfer of the heat exchanger. Combined with the flow and heat transfer performance database of shell-and-tube heat exchanger, the overall energy efficiency distribution of shell-and-tube heat exchanger \( f(x) = N(38.4, 7.97) \) is obtained. According to this, the quantitative energy efficiency evaluation and energy efficiency level division of the shell-and-tube heat exchanger are completed.

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