Simplified Calculation of Energy Efficiency Index for Plate Heat Exchanger

Hongliang Lu1,2*, Bin Ren1,2, Zhe Pu1, Jun Si1, Facai Ren1, Yannan Du1

1 Shanghai Institute of Special Equipment Inspection and Technical Research, Shanghai, 200062, China
2 National Heat Exchanger Product Quality Inspection Center, Jinshan District, Shanghai, 201518, China

*Corresponding author’s e-mail: liholu@163.com

Abstract. Based on GB/T 27698.3-2011 heat exchanger and heat transfer element performance test method Part 3: Plate heat exchanger, a simplified method for the calculation of energy efficiency index is proposed other than just experimental data required by NB/T 47004.1-2017 plate heat exchangers-part 1: plate-and-frame heat exchangers. The new equation of EEI in term of 12 parameters \( \delta_p, \lambda_p, l_p, l_c, d_p, d_c, C_p, C_c, a_p, b_p, a_c, b_c \) incorporates both fitted correlations of experimental result and parameters for fluid physical properties and working conditions. Therefore, the method omits the intermediate processes such as total heat transfer coefficient \( k \) and pressure drops for both sides. It also solves the accuracy problem that deviates from the standard working conditions and is difficult to realize practically. The new test of high cost is unnecessary to obtain the energy efficiency index for old plate heat exchangers with part experimental data or correlations.

1. Introduction

There are many types of heat exchangers and ever-changing operating parameters. The energy efficiency rating indexes such as effectiveness-NTU \([1]\), exergy \([2]\), entropy production \([3]\) and entransy dissipation \([4,5,6]\) were proposed according to the different thermodynamic conceptions in the past. However they are not used presently due to their inherent shortcomings, for example, their magnitude difference by pressure drop is 2 orders of magnitude less than that by heat transfer. An energy efficiency index (EEI=\( k/\sqrt{\Delta p} \)) was proposed by Zhang et al\([7]\) and Patent CN 104036115B\([8]\) to rate the energy saving performance of plate heat exchanger, it was also considered to be independent on the heat transfer area and weakly correlated or not correlated with the flow velocity.

The quantitative evaluation method for EEI provides a scientific realization for determining the energy efficiency and grade of the heat exchanger adopted by the standard NB/T 47004.1-2017 Plate heat exchanger Part 1: Removable plate heat exchanger\([9]\). However, this method shown in figure 1 directly uses the total heat transfer coefficient \( k \) and cold and hot fluid flow pressure drops \( \Delta p_c \) and \( \Delta p_h \) obtained under standard operating conditions to calculate the energy efficiency evaluation index EEI. This paper refers to the standard operating condition test data to directly solve the energy efficiency evaluation indicator EEI. The method and device involve heat source, cold source, test instrument, test and data processing equipment, etc. Solving the calculation of energy efficiency evaluation index EEI requires fluid temperature, pressure, flow rate and other working condition parameters such as fluid density, thermal conductivity and other physical parameters. And the heat
exchanger structure parameters and heat transfer flow fitting coefficients, etc., and need to solve the intermediate process such as heat transfer Q and total heat transfer coefficient k. It can be seen that the above solution process is complex, with many steps, high cost, and long period. In addition, there are still the following three problems in directly solving the energy efficiency evaluation index EEI through this standard working condition test data:

Figure 1 Simplified method VS specific operating condition

a) The accuracy requirements of sensors and adjustment devices are too harsh, which makes it difficult to meet the test standard working conditions. The temperature of hot fluid at inlet is required to be 60±1℃ and that of cold fluid is required to be 30±1℃ in TSG R0010—2019 Energy Efficiency Test and Evaluation Regulation for Heat Exchanger\[10\]. Furthermore, The standard operating condition means that the qualitative temperature of the hot fluid is 50 ℃, the qualitative temperature of the cold fluid is 30 ℃, and the flow velocity between the cold fluid and the hot fluid plates is 0.5m/s. Due to the accuracy of the test equipment and the dynamic balance process of flow heat transfer, the actual test results can only be close to the standard working conditions and are difficult to achieve completely, which reduces the accuracy and credibility of the energy efficiency index (EEI) of the plate heat exchanger.

b) The old plate heat exchanger has only the test data of the total heat transfer coefficient k and the cold and hot fluid flow pressure drops Δp_c and Δp_h under the design conditions or use conditions, but there is no total heat transfer coefficient k and the standard conditions. Test data of pressure drop Δp_c and Δp_h for cold and hot fluid flow are unavailable.

c) Some old plate-type plate heat exchangers have only the correlation of the total heat transfer coefficient k and the correlation of the pressure drop of cold and hot fluid flow Δp_c, Δp_h. There is no design or operating conditions and standard conditions, including the test data such as temperature, pressure and flow rate.

In the present work, a new equation of EEI was proposed to incorporate both fitted correlations of experimental result and parameters for fluid physical properties and working conditions. Finally, an old type of plate heat exchanger was taken as an example to show the process of solving EEI.

2. Theoretical derivation

The definition of energy efficiency index (EEI) is given in equation (1).

\[
EEI = \frac{k}{\left(\frac{\omega_h \Delta p_h}{l_h} + \frac{\omega_c \Delta p_c}{l_c}\right)^{\frac{1}{\text{EST}}}}
\]

Where:

- k is the total heat transfer coefficient,
- \(\omega_h\) is the weight coefficient of the thermal fluid pressure gradient,
- \(\Delta p_h\) is the pressure drop of the hot fluid flow,
- \(l_h\) is the length of the hot fluid working fluid,
- \(\omega_c\) is the weight coefficient of the cold fluid pressure gradient,
- \(\Delta p_c\) is cold fluid flow pressure drop,
- \(l_c\) is the cold fluid working fluid flow length.

Meanwhile, the total heat transfer coefficient k is given in equation (2).

\[
k = \frac{1}{\frac{1}{l_h} \frac{\Delta p_h}{h} + \frac{1}{l_c} \frac{\Delta p_c}{h}}
\]

The convective coefficient h and the pressure drop Δp can be obtained by experimental correlation. For a given heat exchanger, the correlations of heat transfer are given in equation (3) and the correlations of pressure drop are given in equation (4) according to the test standard\[11\].
\[ N_u = C_h R_e^{n_h} P_r^{0.3} \]
\[ N_u = C_c R_e^{n_c} P_r^{0.4} \]
\[ \Delta p_h = a_h R_e^{b_h} \rho_h u_h^2 \]
\[ \Delta p_c = a_c R_e^{b_c} \rho_c u_c^2 \]
\[ \text{Then, the standard test condition GB/T 27698.3-2011 means that the qualitative temperature of the hot fluid is 50 °C, the qualitative temperature of the cold fluid is 30 °C, and the flow velocity between the cold fluid and the hot fluid plates is 0.5m/s. The water is usually used for test. The viscosity coefficients for the hot water, cold water are } \mu_h = 5.4654 \times 10^{-6} \text{Pa} \cdot \text{s}, \mu_c = 7.9722 \times 10^{-6} \text{Pa} \cdot \text{s}, \text{respectively. The above are incorporated into the Reynold number given in equation (5).} \]
\[ \text{Similarly, Prandtl number and thermal conductivity for water are provided: } \Pr = 3.54, \lambda_h = 0.648 \text{W/m} \cdot \text{K}, \lambda_c = 0.618 \text{W/m} \cdot \text{K}. \text{Thus, the convective coefficient } h \text{ can be expressed in equation (6). The equation (3), (4), (5), (6) and the other are substituted into equation (2), the total heat transfer coefficient } k \text{ is expressed in equation (7).} \]
\[ k = \frac{\frac{\Delta p_h}{\rho_h u_h^2 d_h} + \frac{\Delta p_c}{\rho_c u_c^2 d_c}}{1 + \frac{\omega_h \Delta p_h}{\rho_h u_h^2 d_h} + \frac{\omega_c \Delta p_c}{\rho_c u_c^2 d_c}} \]
\[ \text{The pressure drop is given as equation (8) in terms of } R_e. \]
\[ \text{Generally speaking for plate heat exchanger, the structure of the hot fluid is the same with that of the cold fluid, and the counter flow is employed. So there is } \omega_h = \omega_c = 0.5, \lambda_p = 0.5, l_h = l_c, d_h = d_c. \text{At last, all the variables involved in the definition of energy efficiency index are replaced by the previous given values except 12 parameters } \delta_p, \lambda_p, l_h, l_c, d_h, d_c, C_h, C_c, a_h, b_h, a_c, b_c, \text{ that is the new expressiono of EEI in equation (9).} \]
\[ \text{EEI is easy to be worked out by the new expression if 12 parameters are known, two parameters of plate material: } \delta_p, \lambda_p; \text{ four parameters of plate heat exchanger: } l_h, l_c, d_h, d_c; \text{ and six correlated coefficients: } C_h, C_c, a_h, b_h, a_c, b_c. \text{Furthermore, this method is especially convenient and direct for designing and optimizing a plate heat exchanger when the correlations for the particular plate structure and type are available.} \]

3. Case study

An old type of plate heat exchanger was taken as an example here to show the process of solving EEI. It adopted counter flow and the plate is stainless steel, \( \omega_h = \omega_c = 0.5 \), \( l_h = l_c = 1.237 \text{m} \), \( d_h = d_c = 0.00055 \text{ m} \), \( \lambda_p = 14.4 \text{ W} / (\text{m} \cdot \text{°C}) \), \( \delta_p = 0.0005 \text{ mm} \). The correlations of heat transfer and pressure drop are given in equation (10), (11).
So the correlated coefficients were obtained: $C_h = 0.2318, n_h = 0.7296, a_h = 1262.93, b_h = 1262.93, C_c = 0.2318, n_c = 0.7296, a_c = 35641.53, b_c = -0.56$.

Finally, EEI was worked out to be 231 in equation (12) according to equation (9) when all the variables were substituted by the 12 values given in the above.

$$EEI = \left[ \frac{123.81 \times (903940 \times 0.00055)^{0.166} + 124.46 \times 35641.53 \times (622476 \times 0.00055)^{0.166}}{0.941 \times 0.2318 \times (903940 \times 0.00055)^{0.7004} + 0.0005 \times 14.4 + 1.237 \times 0.00055} \right]^{-0.31} = 231 \quad (12)$$

The value of EEI is greater than 227 that is the lower limit value of level 1 given in the reference [9, 10]. Therefore, the energy efficiency grade is level 1 for the given plate heat exchanger.

### 4. Conclusion

A simplified method for the calculation of energy efficiency index is proposed other than just experimental data. EEI is easy to be worked out by the new expression if 12 parameters are known, two parameters of plate material: $\delta_p, \lambda_p$, four parameters of plate heat exchanger: $l_h, l_c, d_h, d_c$, and six correlated coefficients: $C_h, C_c, a_h, b_h, a_c, b_c$. Furthermore, this method is especially convenient and direct for designing and optimizing a plate heat exchanger when the correlations for the particular plate structure and type are available. An old type of plate heat exchanger was taken as an example to show the solution process of EEI.

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