Effect of Flow Arrangement On Energy Efficiency Index

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Abstract. An energy efficiency index (EEI=k/▽p) was proposed by Zhang et al 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. However, whether EEI as an ideal index is correlated with the structure such as the flow arrangement or not was important and remained to be confirmed by the theoretical or experimental result. The present work was to analyze EEI for 5 heat exchangers with different flow arrangement: parallel flow, counter flow and combined flow by theoretical method. They all were composed of the same 37 pieces of BP type plate with Nu=0.091Re^{0.73}Pr, Eu=42400Re^{-0.545}. Their inlet velocities between plates and the inlet temperatures for hot and cold fluid were the same and 5 mathematical models were developed. The EEI took into consideration and weighted quantitatively the heat transferred as well as the pressure drop. The comparison verified that the proposed EEI for 5 heat exchangers were different with each other, but 5 heat exchangers with similar flow arrangement were close to each other, less than 5%.

1. Introduction
The heat transfer and flow pressure drop are two different aspects of heat exchanger, and how to review their influences is of great importance on designing and application of heat exchangers. So far there has been several energy efficiency rating indexes such as effectiveness-NTU[1], exergy[2], entropy production[3] and entransy dissipation[4,5,6] on the basis of different thermodynamic conceptions, 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/▽p) was proposed last year by Zhang et al[7] 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. However, whether EEI as an ideal efficiency index is correlated with the structure such as the flow arrangement or not was important and remained to be confirmed by the theoretical or experimental result. The present work was to analyze EEI for 3 plate heat exchangers with different flow arrangement: parallel flow, counter flow and combined flow at the same inlet temperature and velocity by theoretical method.

2. Configuration and boundary conditions
To review the effect of flow arrangement on EEI, 5 plat heat exchangers are composed with the same 37 sheets and operated at the same inlet temperature and fluid velocity. 3 different flow arrangements include 2 parallel flow heat exchangers shown in Figure 1 A, 2 counter flow heat exchangers Figure 1
B and 1 combined flow heat exchanger. Figure 1C. Both parallel flow and counter flow heat exchangers have two configurations: 37 plates in 1 shell pass and 1 tube pass and in 18 shell passes and 18 tube passes. The combined flow plate heat exchanger is composed of 3 shell passes in the hot water side and 6 tube passes in the cold water side.

The heat exchanger is water-water heat transfer process without phase-change. The inlet temperature for hot water is 110°C and 35°C for the cold water. The outlet temperature and pressure drop changes differently when the water velocity between plates increases from 0.05 m/s to 1.0 m/s.

3. Heat transfer and pressure drop model

The heat transfer and pressure drop fitting correlations by experimental data for BP type steel plate are written as:

\[
\text{Nu} = 0.091 \text{Re}^{0.73} \text{Pr}^n \quad (1)
\]

\[
\text{Eu} = 42400 \text{Re}^{0.545} \quad (2)
\]

The effectiveness for heat exchanger of parallel flow is written as follows:

\[
\varepsilon = \frac{1 - \exp\left[\frac{-\text{UA}}{\text{c}_{\min}} \left(1 + \frac{\text{c}_{\min}}{\text{c}_{\max}}\right)\right]}{1 + \frac{\text{c}_{\min}}{\text{c}_{\max}}} \quad (3)
\]

The effectiveness for heat exchanger of counter flow is written as follows:

\[
\varepsilon = \frac{1 - \exp\left[-\frac{\text{UA}}{\text{c}_{\min}} \left(1 + \frac{\text{c}_{\min}}{\text{c}_{\max}}\right)\right]}{1 - \frac{\text{c}_{\min}}{\text{c}_{\max}} \exp\left[-\frac{\text{UA}}{\text{c}_{\min}} \left(1 + \frac{\text{c}_{\min}}{\text{c}_{\max}}\right)\right]} \quad (4)
\]

The effectiveness for multiple shell passes is rather complicated. The plate heat exchanger with multiple passes is mathematically processed like a shell and tube heat exchanger: n shell passes and 2n tube passes. The configuration of 3 shell passes and 6 tube passes is divided into two steps: first, for 1 shell pass and 2 tube passes; second, for 3 shell passes and 6 tube passes. The effectiveness for heat exchanger of combined flow is written as follows:
The definition of energy efficiency index for plate heat exchanger is as follows:

\[ EEI = k / \sqrt{\eta}^{1/3} \] (7)

4. NUMERICAL RESULT

The cold fluid velocity between plates increases from 0.05 m/s to 1.0 m/s simultaneously with the hot water velocity, 5 plate heat exchangers have different variations.

Figure 2 gives EEI distribution under the same operating conditions, obviously EEI for 5 plate heat exchangers are near each other, EEI for the counter flow of 18 shell passes and 18 tube passes is the maximum and that for the combined flow heat exchanger is the minimum, and the former is 4.26% in average greater than the latter. Furthermore, EEI for the counter flow is slightly greater than that for the parallel flow with the same 18 shell passes and 18 tube passes, and so are the configurations with the same 1 shell pass and 1 tube pass. So it can be concluded from the given 5 heat exchangers that the flow arrangement makes little effect on EEI.

In other way, EEI increases with fluid velocity between plates, and approaches the maximum when the fluid velocity is in the range of 0.65 m/s to 0.95 m/s.

Figure 2. EEI of 5 heat exchangers

Figure 3. Effectiveness of 5 heat exchangers

Figure 3 gives the effectiveness distribution for 5 plate heat exchangers. The effectiveness for the combined flow is close to the counter flow of 18 shell passes and 18 tube passes.
From Figure 4, the heat exchangers with 1 shell pass and 1 tube pass are greater in the heat capacity than those with 18 shell passes and 18 tube passes, and the heat exchanger with 3 shell passes and 6 tube passes is between the former two. The heat capacity for the counter flow is slightly greater than that for the parallel flow with the same 1 shell pass and 1 tube pass, and so are the configurations with the same 18 shell passes and 18 tube passes.

Figure 5, Figure 6 gives out the hot side and cold side pressure drop distribution for 5 plate heat exchangers. The heat exchangers with 18 shell passes and 18 tube passes pass are greater in the pressure drop than those with 1 shell pass and 1 tube, and the heat exchanger with 3 shell passes and 6 tube passes is between the former two.

5. CONCLUSION

The EEI takes into consideration and weighted quantitatively the heat transferred as well as the pressure drop. EEI for 5 plate heat exchangers are near each other, EEI for the counter flow of 18 shell passes and 18 tube passes is the maximum and that for the combined flow heat exchanger is the minimum, and the former is 4.26% in average greater than the latter. Furthermore, EEI for the counter flow is slightly greater than that for the parallel flow with the same 18 shell passes and 18 tube passes, and so are the configurations with the same 1 shell pass and 1 tube pass. So it can be concluded from the given 5 heat exchangers that the flow arrangement makes little effect on EEI. In other way, EEI increases with fluid velocity between plates, and approaches the maximum when the fluid velocity is near 0.7 m/s to 0.8 m/s.

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