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A general correlation for determining optimum baffle spacing for all types of shell and tube exchangers

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Abstract—A general procedure for heat exchanger design has been presented in the *Heat Exchanger Design Handbook* (HEDH), but no precise criterion for determining the baffle spacing has been offered, and the emphasis is only on its permissible range of application. In this paper, an optimization program has been used to calculate the optimum baffle spacing and the number of sealing strips for all types of shell and tube heat exchangers, using the procedure in HEDH. A set of correlation is presented for determining the optimum baffle spacing. This could be considered as complementary to the HEDH recommendations.

1. INTRODUCTION

The baffles are primarily used in shell and tube heat exchangers for inducing cross flow over the tubes, and as a result, improving heat transfer performance. In practice this objective is not quite achieved due to departure from cross flow, and due to several leakages and bypass streams through clearance required for the construction of the exchanger.

An early method of calculation assumed that the total stream, without leakage, flowed through the minimum cross flow area for calculating the heat transfer coefficient; then, a correction factor was used to account for leakage and bypassing.

Tinker [1] recognized and defined various leakages and bypass stream, and developed a stream analysis method. Later, the extensive research work at the University of Delaware summarized by Bell [2] lead to a procedure for predicting shell-side heat transfer and pressure drop. Then Heat Transfer Research Inc. [3] supplemented these data from the University of Delaware taken on small units with data on industrial-sized heat exchangers and developed a computer-based stream analysis method. Finally, Taborek [4] in the *Heat Exchanger Design Handbook* updated the work from the University of Delaware and published an extended method for the thermal design of shell and tube heat exchangers. This method has several attractive features: one feature of the HEDH method for calculating shell-side heat transfer and pressure drop is its completeness, because all of the necessary equations and correction factors are presented. Secondly, it provides several correction functions to account for some of the behavior noticed in the Delaware project, in terms of the different leakage streams present in the heat exchanger. Several attempts have been made for validating and determining the limitations of the HEDH method by means of comparing the predicted HEDH results with the measured data. As a result, new recommendations have sometimes been proposed [5, 6].

The aim of the heat exchanger optimization is to minimize the costs of owning and operating the exchanger. One feature of shell and tube heat exchanger optimization is to select the optimum inter-baffle spacing. Taborek [4] suggested that the space between the baffles could vary between a minimum of 20% of shell diameter and a maximum equal to the shell diameter. Saffar-Avval *et al.* [7] have studied the effect of baffle spacing on heat transfer area and pressure drop, and conclude that the baffle spacing has a decisive effect on pumping power and noticeable effect on required heat transfer area, where a guideline has been also developed to calculate the optimum baffle spacing for single phase E-type shell and tube heat exchanger.

In this paper, the same optimization procedure has been used, correlations for calculating the baffle spacing for all types of heat exchangers (E-type, U-tube and floating heat) are found as a part of the guideline by which the optimal design is made.

2. THERMO-HYDRAULIC PERFORMANCE

The task of analysis is to predict the heat transfer rate between two streams of the exchanger and the pressure drop of each one. To do that, the mean temperature difference, the heat transfer coefficient, and pressure drop of the two streams must be established first.

The mean temperature difference is calculated based on LMTD and F-factor according to HEDH recommendations. The heat transfer coefficient and

NOMENCLATURE

A	area [m^2]
a_1	annual heat transfer surface cost [m^{-2}]
a_2	annual cost of pumping power [kW^{-1}]
a_3	annual cost of heating and cooling effect [kW^{-1}]
D	diameter
D_{ctl}	diameter of circle through the centers of outermost tubes
D_r	reference diameter [25.4 mm]
F	objective function
H	rate of heat transfer by the exchanger [kW]
L_{bb}	inside shell diameter to bundle clearance
L_{bc}	baffle spacing
L_{tp}	tube pitch
$\dot{M}$	mass flow rate
N_{ss}	number of sealing strips
N_{tp}	number of tube passes
Pr	Prandtl number
Re	Reynolds number
Sm	cross flow area
$\dot{W}$	power [kW]
W_1	heat transfer area weight factor
W_2	pumping power weight factor.

Greek symbols

ΔP	pressure drop
μ	dynamics viscosity
ρ	density.

Subscripts

s	shell
t	tube.

the pressure drop for the tube-side is well known in the literature. The Sieder and Tate [4] relation is used for heat transfer coefficient. The pressure drop in non-dimensional form is taken from the Moody diagram.

The recommended method of HEDH is used for the shell-side calculation. This method, known as the Bell-Delaware method, has been summarized by Shah [8] and Mueller [9].

Based on the above method a computer program has been developed for sizing and rating of E-type shell and tube exchangers. The effects of baffle spacing, in the range of HEDH recommendation (0.2 D_s to D_s), and number of sealing strips have been studied. The results are shown in Figs. 1 and 2 where the normalized heat transfer area and normalized power consumption is figured as a function of dimensionless baffle spacing.

Referring to these figures the number of sealing strips, as it is expected for E-type exchanger, has a minor effect on the design. It is seen in contrast that the baffle spacing has a decisive effect on power consumption and a noticeable effect on required heat transfer area. Therefore, any hint on optimum selection of baffle spacing would provide a helpful device for designer.

3. OPTIMUM DESIGN

The cost of owning and operating a heat exchanger is the sum of [10]:

(i) C_s, the cost of providing the heat transfer surface;
(ii) C_p, the costs of maintaining the flow through it; and
(iii) C_h, the cost of heating or cooling effect supplied to the exchanger.

The first cost is taken as proportional to heat transfer area, $a_1 A$. The second one is assumed as proportional to the pumping power, $a_2 \dot{W}$. Finally, the third one is represented by an amount in proportion to the heat duty of the exchanger, $a_3 H$.

An optimum design would be defined as an exchanger which has the maximum ratio of the heat duty to the cost, J:

$$J = H/(C_s + C_p + C_h) \tag{1}$$

or,

$$J = 1/(C + a_3) \tag{2}$$

where

$$C = (a_1 A + a_2 \dot{W})/H \tag{3}$$

and

$$\dot{W} = (\dot{M}_t \Delta P_t)/\rho_t + (\dot{M}_s \Delta P_s)/\rho_s. \tag{4}$$

Clearly, the maximum value of J coincides with the minimum value of C, irrespective of energy cost, a_3.

Normalizing C by a reference function as:

$$Cr = [a_1(1\,\mathrm{m}^2) + a_2(1\,\mathrm{kW})]/H. \tag{5}$$

The result F is taken as the objective function of optimization program:

$$F = C/Cr \tag{6}$$

or

$$F = W_1 A + W_2 \dot{W}. \tag{7}$$

When the value of F is minimized, the function J reaches its maximum value and the optimum design will be obtained.

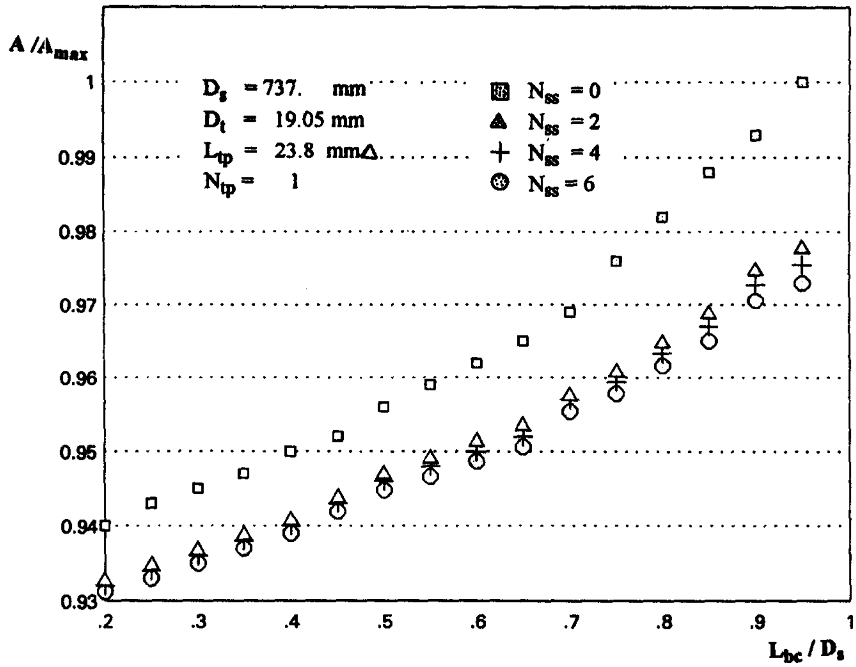

Fig. 1. Normalized required heat transfer area vs dimensionless baffle spacing for four different pairs of sealing strips.

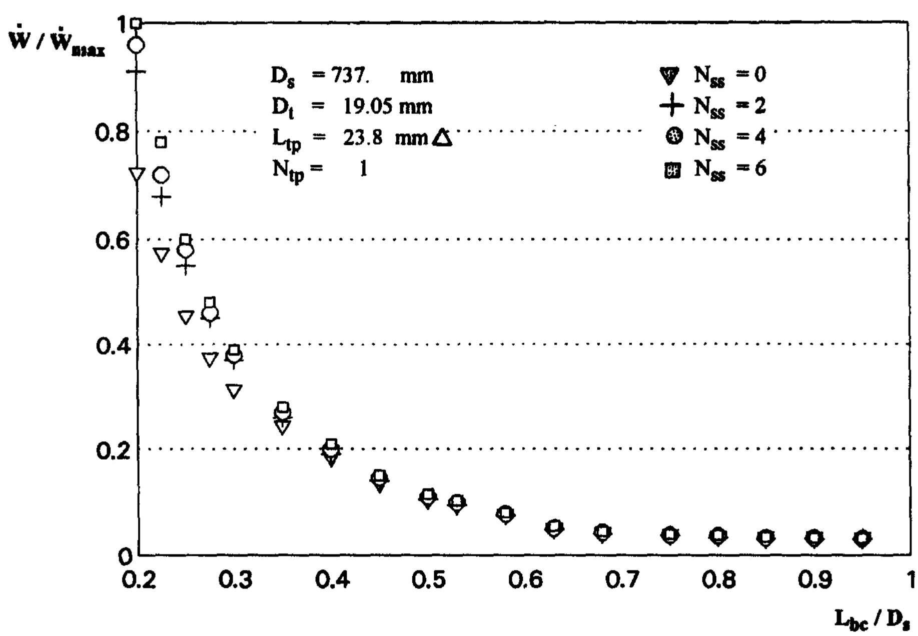

Fig. 2. Normalized pumps power consumption vs dimensionless baffle spacing for four different pairs of sealing strips.

W_1 and W_2 are the weight factors: the sum of them equals unity.

$$W_1 = a_1/(a_1+a_2) \tag{8}$$

$$W_2 = a_2/(a_1+a_2). \tag{9}$$

The values of a_1 and a_2 depend on the current manufacturing costs and electrical energy price. When a decision upon the values of a_1 and a_2 is made, suitable weight factors for the objective function would be provided.

The procedure of the optimization method is a combination of the Lattice and Univariate search method [7]. A computer program has been developed to carry out the optimization procedure, the thermal performance evaluation of this program is based on HEDH, Section 3.3 [4].

4. RESULTS AND APPLICATION

A parameter study of the optimum design has been made for all types of single phase shell and tube heat exchangers (fixed tube sheet, floating head and U-tube) in a wide range of normal operation. Tube and shell diameter, tube pitch, number of tube passes, tube arrangement, baffle spacing and number of sealing strips have been varied for all recommended values of HEDH. The heat duty and viscosity coefficient of both streams have been also varied extensively.

Similar to E-type exchangers, it is found that the number of sealing strips has a negligible effect on the optimum heat transfer area and pumping power, while the baffle spacing has a noticeable effect on these parameters. Therefore L_{bc} represents itself as the optimization variable.

By using the results of optimization program, it is concluded that the non-dimensional value of $Re_s \cdot Pr_s \cdot \exp(D_r/D_t)$ for each optimum design is well correlated with heat transfer area weight factor, W_1. These results for each type of exchanger are presented as follows:

(1) E-type: the total run of optimization program in the previous mentioned range of design parameters, are 450. The results are shown in Fig. 3 and seen the correlation as a distinct band of $Re_s \cdot Pr_s \cdot \exp(D_r/D_t)$ as a function of W_1. This correlation was fitted by a least square continuous curve with the following equation:

$$Re_s \cdot Pr_s \cdot \exp(D_r/D_t) = 8.89756 + 12.23475\, W_1 + 6.24858\, W_1^2 \quad (10)$$

where the shell-side Reynolds number is

$$Re_s = (\dot{M}_s D_t)/(\mu_s Sm). \quad (11)$$

(2) Floating head: the same procedure has been applied and the respective correlation is found to be:

$$Re_s \cdot Pr_s \cdot \exp(D_r/D_t) = 6.48571 + 23.67138\, W_1 - 6.08711\, W_1^2 \quad (12)$$

the total number of runs was 490.

(3) U-tube; similarly the correlation in this case is found:

$$Re_s \cdot Pr_s \cdot \exp(D_r/D_t) = 5.98419 + 28.88928\, W_1 - 14.13602\, W_1^2 \quad (13)$$

and the total runs were 290.

These correlation are shown in Fig. 4. It is seen that the three curves coincide together for middle values of W_1 while diverging for extreme values.

Therefore for middle values of W_1 (0.2 to 0.8) a single general correlation for all types of shell and tube exchangers could be found by similar procedure as

$$Re_s \cdot Pr_s \cdot \exp(D_r/D_t) = 7.44796 + 19.92351\, W_1 - 3.52039\, W_1^2. \quad (14)$$

This range of W_1 is the most probable value in design project.

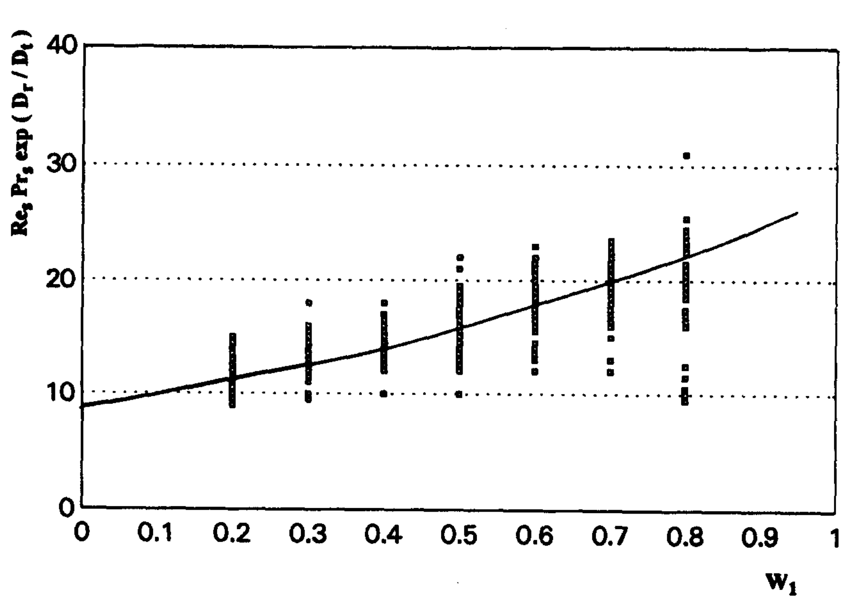

Fig. 3. Optimum shell-side $Re_s \cdot Pr_s \cdot \exp(D_r/D_t)$ vs W_1.

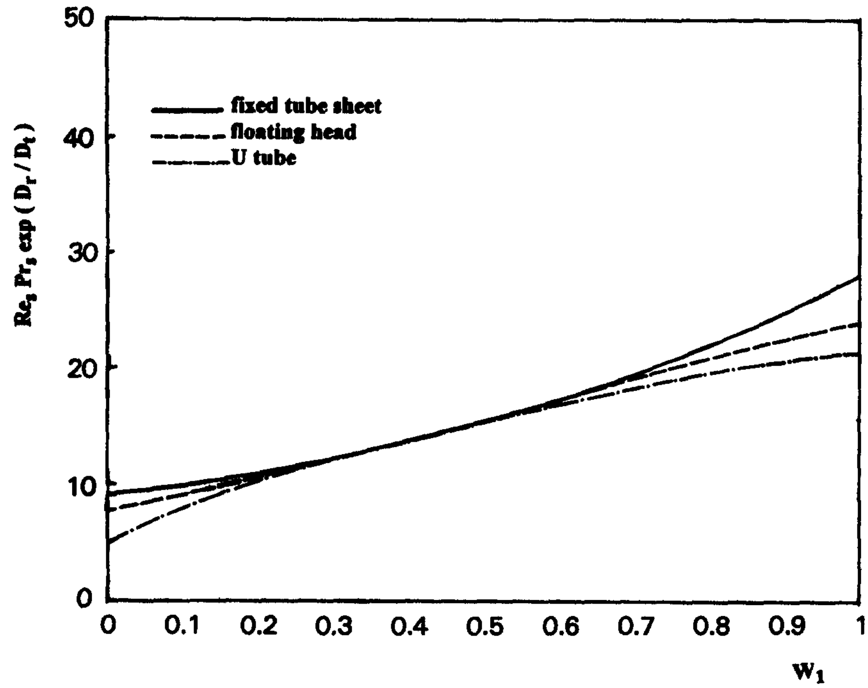

Fig. 4. Comparison of the correlation.

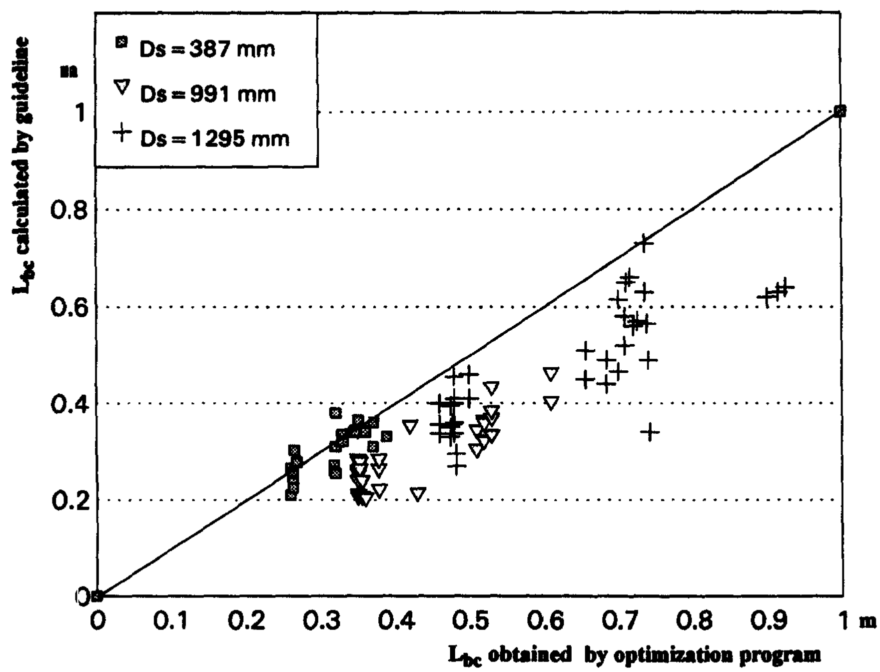

Fig. 5. Comparison of L_{bc} calculated by E-type correlation and L_{bc} obtained by optimization program for fixed tube sheet.

4.1. *The guideline*

The guideline is summarized in five following steps:

(1) Specify D_s, D_t, L_{tp}, L_{bb} from design specifications and recommendations of HEDH.

(2) Decide on the values of a_1 and a_2 according to manufacturing cost, energy price and engineering judgment for providing the suitable weight factor.

(3) Find the optimum values of $Re_s \cdot Pr_s \cdot \exp(D_r/D_t)$ by using the correlation.

(4) Calculate *Sm* by using equation (11).

(5) Finally, calculate optimum baffle spacing, L_{bc},

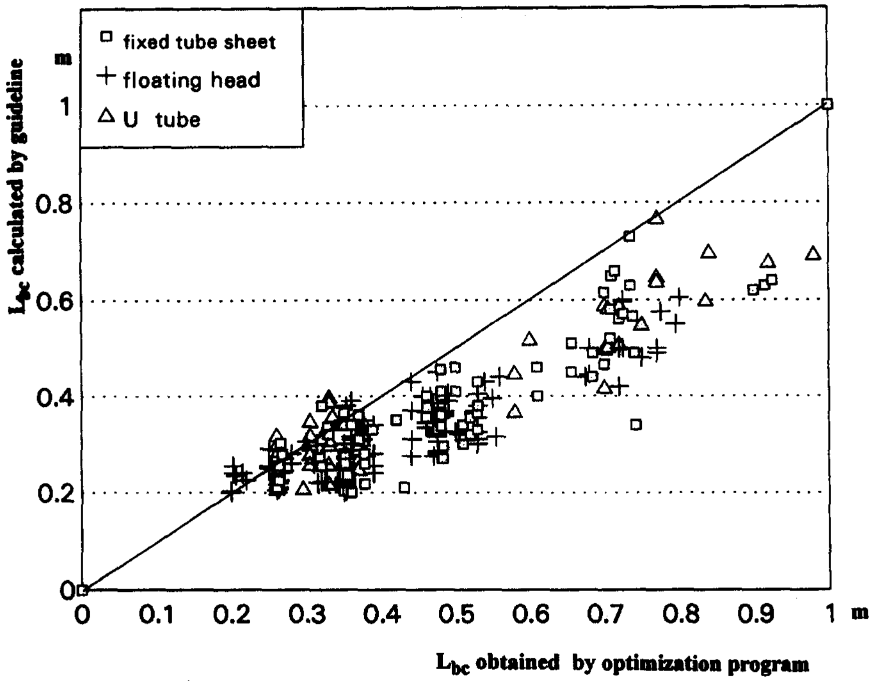

Fig. 6. Comparison of L_{bc} calculated by general correlation and L_{bc} obtained by optimization program for all types of shell and tude exchangers.

from:

$$L_{bc} = Sm/[L_{bb}+D_{ctl}(1-D_t/L_{tp})] \tag{15}$$

where

$$D_{ctl} = D_s+L_{bb}+D_t. \tag{16}$$

4.2. *Numerical application and comparisons*

Extensive numerical applications of the guideline for fixed tube sheet exchangers have been provided for a wide range of design input data according to HEDH recommendations.

These results are compared with baffle spacing obtained by the optimization program in Fig. 5. Good agreement between the results calculated by the guideline and the results obtained by the program can be observed. Similar agreement between the results can be shown for U-type and floating head type heat exchangers. Therefore, this simple guideline is a quick and efficient alternative method to obtain the optimum baffle spacing for all types of single phase shell and tube exchangers.

The validity of the general correlation is also studied by extensive numerical applications. The results of the guideline in comparison with the results of optimization program are illustrated in Fig. 6.

5. CONCLUSION

A wide range of design input specification data are considered for all types of shell and tube exchangers, and their optimum exchangers for different values of W_l are evaluated. This evaluation leads to correlations for determining the optimum baffle spacing. The steps of guideline are included, and the usefulness is studied.

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