Chapter 2
Meaning of Improved Heat Exchanger

Abstract The advances in heat transfer enhancement techniques in all its aspects have been dealt with.

Keywords Heat transfer enhancement techniques • Active technique • Passive technique • Combined techniques • Heat transfer coefficient and friction factor correlations • Performance evaluation criteria

The performance of heat exchanger is defined by its thermal performance (i.e. by improvement in convective heat transfer coefficient) and by its hydraulic performance (i.e. amount of power consumed in pumping the fluid). Hence the term thermohydraulic performance is used as an indicator to heat exchanger performance. By performance evaluation we mean the comparison of heat transfer and pressure drop characteristics of an enhancement device with a reference device which possesses the same basic dimensions except the part of enhancement structure. Different methods (active/passive/compound) are used for enhancing the heat transfer but the one which leads to larger heat transfer enhancement with relatively less increment in pumping power penalty will be an acceptable solution. Thus with the development of heat transfer enhancement techniques, the question of how to evaluate the effectiveness of enhancement technique also needs to be addressed. A qualitative comparison for enhanced heat transfer surface is an important issue in evaluating the performance improvement of the enhancement techniques. Broadly speaking, all the existing assessment methods, or criteria, can be classified into two categories. In one category of evaluation methods, the 2nd law of the thermodynamics is applied and either entropy or exergy generated is determined, while in the other category, discussion is only based on the 1st law of thermodynamics. Factors like ease of manufacturing, safety, reliability etc. also need to be incorporated in evaluation of the technique. But it seems intangible to propose a performance evaluation technique that will include all the said factors. Nevertheless, in the present scenario, the purpose of energy-saving of the heat transfer enhancement has received more attention of the international heat transfer community. Keeping energy saving as the prime purpose in mind the evaluation approach based on the comparison between enhanced and original (or reference) heat transfer surfaces (or structure) for identical flow rate, identical pressure drop and identical pumping power seems more logical. In this regard the performance evaluation plot of enhanced heat transfer

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techniques from energy saving point of view is important. The proposed plot should be capable of displaying

(i) Whether the enhancement technique under investigation can really save energy (pumping power).
(ii) Comparison of effectiveness of enhancement techniques from energy saving point of view
(iii) Which enhancement technique (among the available ones) will be more suitable in a prevailing situation (i.e. we can select the better heat transfer technology through corresponding performance evaluations).

Experimental and numerical investigations give the characteristics of heat transfer and pressure drop of an enhanced surface and those of the reference one. The correlations of friction factor and heat transfer for the reference surface and the enhanced surface help evaluate the performance comparison between the two surfaces.

2.1 Derivation of Basic Equations for Performance Evaluation and Performance Plot

Derivation of basic equations is done assuming that

1. The thermo-physical properties of fluid are constant.
2. Heat transfer area used for calculating the convective heat transfer coefficient of enhanced surface is the same as that of the reference one.
3. The cross-sectional area used for calculating the average velocity of fluid of enhanced surface is the same as that of the reference one.
4. The reference dimension used for calculating the dimensionless characteristic number of enhanced surface is the same as that of the reference one.

For the reference surface the average friction factors and Nusselt number can be fitted as

$$f_o(Re) = C_1 Re^{m_1} \tag{2.1}$$

$$Nu_o(Re) = C_2 Re^{m_2} \tag{2.2}$$

Ratio of friction factor of an enhanced surface over the reference surface at same Reynolds number (Re) will be

$$\frac{f_e(Re)}{f_o(Re)} = \left(\frac{f_e}{f_o}\right)_{at\ same\ Re} \tag{2.3}$$

Similarly, Ratio of Nusselt number of an enhanced surface over the reference surface at same Reynolds number (Re) will be

$$\frac{Nu_e(Re)}{Nu_o(Re)} = \left(\frac{Nu_e}{Nu_o}\right)_{at\ same\ Re} \tag{2.4}$$

Further, at different Reynolds numbers, the ratios of Nusselt number and friction factor of the enhanced heat transfer surface over the reference one is expressed by

$$\left(\frac{f_e}{f_o}\right)_{at\ different\ Re} = \frac{f_e(Re)}{f_o(Re_o)} \tag{2.5}$$

$$\frac{Nu_e(Re)}{Nu_o(Re_o)} = \left(\frac{Nu_e}{Nu_o}\right)_{at\ different\ Re} \tag{2.6}$$

From Eqs. (2.1) and (2.3) we get

$$f_e(Re) = C_1 Re^{m_1}\left(\frac{f_e}{f_o}\right)_{at\ same\ Re} \tag{2.7}$$

$$\text{But} \qquad f_o(Re_o) = C_1 Re_o^{\ m_1} \tag{2.8}$$

Now, substituting the values of $f_e(Re)$ and $f_o(Re_o)$ from Eqs. (2.7) and (2.8) in to the Eq. (2.5) we get an expression of friction factor ratio at different Reynolds numbers as

$$\left(\frac{f_e}{f_o}\right)_{at\ different\ Re} = \frac{f_e(Re)}{f_o(Re_o)} = \left(\frac{Re}{Re_o}\right)^{m_1}\left(\frac{f_e}{f_o}\right)_{at\ same\ Re} \tag{2.9}$$

Similarly, we can get the ratio of the Nusselt number at different Reynolds number:

$$\left(\frac{Nu_e}{Nu_o}\right)_{at\ different\ Re} = \frac{Nu_e(Re)}{Nu_o(Re_o)} = \left(\frac{Nu_e}{Nu_o}\right)_{at\ same\ Re}\left(\frac{Re}{Re_o}\right)^{m_2} \tag{2.10}$$

It is clear from Eqs. (2.9) and (2.10) that once the basic correlations of the reference surface and the ratios of friction factors (and Nusselt numbers) of enhanced and reference structures at the same Reynolds number are available, then the two ratios at different Reynolds number can be calculated.

In the performance evaluation of enhanced structure, the ratio of heat transfer rate is of great importance. Hence the ratio of heat transfer rate of the enhanced and reference surfaces can be presented form basic definition of rate of heat transfer as

$$\left(\frac{Q_e}{Q_o}\right) = \frac{(h.A.\Delta t)_e}{(h.A.\Delta t)_o} = \frac{\left(Nu.\dfrac{K_f}{D}.\ A.\ \Delta t\right)_e}{\left(Nu.\ \dfrac{K_f}{D}.\ A.\ \Delta t\right)_o} \tag{2.11}$$

But when the heat transfer rates of two surfaces are compared for surface evaluation, it is reasonable to assume the same temperature difference. Also, following the assumptions, we have

$$\frac{\left(\frac{K_f}{D}.\ A.\ \Delta t\right)_e}{\left(\frac{K_f}{D}.\ A.\ \Delta t\right)_o}=1 \tag{2.12}$$

Substituting Eq. (2.12) into Eq. (2.11), the ratio of heat transfer rate at different Reynolds no. becomes

$$\left(\frac{Q_e}{Q_o}\right)=\left(\frac{Nu_e}{Nu_o}\right) \tag{2.13}$$

Now, expressions of heat transfer ratio under the three constraints (i.e. for identical pumping power, identical pressure drop and for identical flow rate) are derived.

The ratio of power consumption of enhanced and reference surfaces can be presented as

$$\left(\frac{P_e}{P_o}\right)=\frac{\left(A_c.\ V.\ \Delta p\right)_e}{\left(A_c.\ V.\ \Delta p\right)_o}=\frac{\left(A_c.\ V.\ f.\ L.\ \rho.V^2/D\right)_e}{\left(A_c.\ V.\ f.\ L.\ \rho.V^2/D\right)_o} \tag{2.14}$$

But according to assumptions made,

$$\frac{\left(A_c.\ L.\ \rho/D\right)_e}{\left(A_c.\ L.\ \rho/D\right)_o}=1$$

Substituting this in Eq. (2.14) we get

$$\left(\frac{P_e}{P_o}\right)=\frac{\left(f.\ V^3\right)_e}{\left(f.\ V^3\right)_o}=\frac{f_e}{f_o}\frac{\left(Re^3\right)_e}{\left(Re^3\right)_o} \tag{2.15}$$

Now for same power consumption condition,

$$\left(\frac{P_e}{P_o}\right)=1$$

Substituting this in Eq. (2.15) we get

$$\frac{f_e}{f_o}=\left(\frac{Re}{Re_o}\right)^{-3} \tag{2.16}$$

Substituting Eq. (2.16) in Eq. (2.9) we get

$$\left(\frac{Re}{Re_o}\right)^{-3} = \left(\frac{Re}{Re_o}\right)^{m_1} \left(\frac{f_e}{f_o}\right)_{at\ same\ Re}$$

Simplifying we get,

$$\frac{Re}{Re_o} = 1 / \left(\frac{f_e}{f_o}\right)_{Re}^{\frac{1}{3+m_1}} \tag{2.17}$$

Substituting Eq. (2.17) in Eq. (2.10) we get heat transfer ratio under the **constraint of identical power consumption** as,

$$\left(\frac{Q_e}{Q_o}\right) = \left(\frac{Nu_e}{Nu_o}\right)_{at\ diff.\ Re} = \left(\frac{Nu_e}{Nu_o}\right)_{at\ same\ Re} / \left(\frac{f_e}{f_o}\right)_{Re}^{\frac{m_2}{3+m_1}} \tag{2.18}$$

Similar formulation for the heat transfer ratio can be derived for the constraint of identical pressure drop. The ratio of pressure drop of the enhanced and the reference surfaces is given by

$$\frac{\Delta p_e}{\Delta p_o} = \frac{\left(f.\ L.\ \rho.V^2 / D\right)_e}{\left(f.\ L.\ \rho.V^2 / D\right)_o} \tag{2.19}$$

But according to assumptions, we have

$$\frac{\left(A_c.\ L.\ \rho / D\right)_e}{\left(A_c.\ L.\ \rho / D\right)_o} = 1$$

Substituting in Eq. (2.19) we get,

$$\frac{\Delta p_e}{\Delta p_o} = \frac{\left(f.\ V^2\right)_e}{\left(f.\ V^2\right)_o} = \frac{f_e}{f_o}\left(\frac{Re}{Re_o}\right)^2 \tag{2.20}$$

Now, for identical pressure drop, $\frac{\Delta p_e}{\Delta p_o} = 1$

Substituting this in Eq. (2.20) we get

$$\frac{f_e}{f_o} = \left(\frac{Re}{Re_o}\right)^{-2} \tag{2.21}$$

Substituting Eq. (2.21) in Eq. (2.9) we get

$$\left(\frac{Re}{Re_o}\right)^{-2} = \left(\frac{Re}{Re_o}\right)^{m_1} \left(\frac{f_e}{f_o}\right)_{at\ same\ Re}$$

Simplifying we get,

$$\frac{Re}{Re_o} = 1 / \left(\frac{f_e}{f_o}\right)_{Re}^{\frac{1}{2+m_1}} \tag{2.22}$$

Substituting Eq. (2.22) in Eq. (2.10) we get heat transfer ratio under the **constraint of identical pressure drop** as,

$$\left(\frac{Q_e}{Q_o}\right) = \left(\frac{Nu_e}{Nu_o}\right)_{at\ diff.\ Re} = \left(\frac{Nu_e}{Nu_o}\right)_{at\ same\ Re} / \left(\frac{f_e}{f_o}\right)_{Re}^{\frac{m_2}{2+m_1}} \tag{2.23}$$

Finally, expression of heat transfer ratio **under the constraint of identical flow rate** can be found by substituting $\frac{Re}{Re_o} = 1$ (which is the condition of identical flow rate) in Eq. (2.10) we get

$$\left(\frac{Q_e}{Q_o}\right) = \left(\frac{Nu_e}{Nu_o}\right)_{at\ same\ Re} \tag{2.24}$$

Now, three equations can be collectively written as

$$C_i = \left(\frac{Nu_e}{Nu_o}\right)_{Re} / \left(\frac{f_e}{f_o}\right)_{Re}^{k_i} \quad (i = P, \Delta p, V) \tag{2.25}$$

Where P, Δp, V stand for identical pumping power, identical pressure drop and identical flow rate, respectively.

Taking logarithm

$$\ln\left(\frac{Nu_e}{Nu_o}\right)_{Re} = \ln C_i + K_i \ln\left(\frac{f_e}{f_o}\right)_{Re} \tag{2.26}$$

2.2 Plot Interpretation

Clearly, Eq. (2.26) represents equation of straight line in log–log coordinate system, where K_i is the slope and $\ln C_i$ is the intercept on y- axis. The physical interpretation of $\ln C_i$ and K_i are as follows.

The value of $\ln C_i$ is an indication of heat transfer enhancement under different constraint conditions. When $\ln C_i = 0$, the straight line crosses the point of coordinate (1,1) and this means that the enhanced and reference surfaces possess the same heat transfer rates under the corresponding constraint conditions. When $\ln C_i > 0$, the enhanced heat transfer surface can transfer a larger heat transfer rate than that of the reference one, and when $\ln C_i < 0$, the enhanced heat transfer surface transmits a lower heat transfer rate.

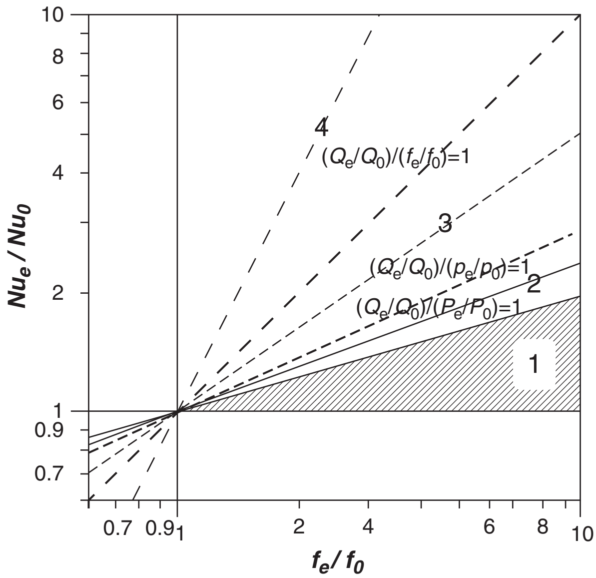

Fig. 2.1 A performance evaluation plot for enhancement technique

The performance plot as shown in Fig. 2.1 is divided into four regions. Region 1 is characterized by enhanced heat transfer without energy-saving, where the enhancement of heat transfer rate is less than the increase of power consumption. Region 2 is featured by enhanced heat transfer with the same pump power consumption, i.e., where the enhanced surface presents higher heat transfer rate than reference one under the same pumping power consumption. In Region 3 enhanced heat transfer can be obtained with the same pressure drop, i.e., where the enhanced surface presents higher heat transfer rate than the reference one under the identical pressure drop constraint. Region 4 is the most desirable one where the augmentation of heat transfer rate is more than the increase in friction coefficient under the same flow rate. Lines forming Regions are drawn using Eq. (2.25) under different constraint conditions and the values of variables m_1 and m_2 come from the relevant correlations.

2.3 How to Use the Proposed Performance Plot

In the proposed plot, the lines are representing the performance of some enhancing structure and are named as working lines. Any point on the working line is called a working point. There are three kinds of working lines corresponding to the three constraints. The shaded region is the case of enhanced heat transfer without energy-saving, i.e., when a working point of an enhancement technique is located in this region the consumption of unit pumping power leads to less heat transfer rate compared with that of the reference one. Thus for energy-saving purposes, the working point should be located outside the shaded region. Further, for energy-saving purposes, the larger the slope of the working line, the better the enhanced technique. As far as different points on the same working line are concerned, they have the same enhanced heat transfer ratio under corresponding friction loss constraint. Therefore, the working lines are the contours of the heat transfer enhancement ratio under different constraints.

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