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EXPERIMENTAL VERIFICATION OF THEORETICAL MODELS TO CALCULATE THE HEAT TRANSFER COEFFICIENT IN THE SHELL-AND-TUBE HEAT EXCHANGER

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Abstract: *This paper experimentally verifies the validity of theoretical models to calculate the heat transfer coefficient in shell-and-tube heat exchangers. Determination of the HTC is a complex problem, as a large deviation in the comparison of theoretical models and experiments commonly occurs. The methods by Kern, Bell-Delaware and Flow-stream analysis method for the evaluation of HTC in a vertical shell and tube condenser are compared with the results of measurements in the range of Reynolds number from 1200 to 6300. The HTC values by the Kern method reach the top boundary of the experimental results while the results of the Bell-Delaware method and the Stream-flow analysis method are at the bottom. Therefore, usage of the Bell-Delaware method and the Stream-flow analysis method is suitable in accordance with the design assurance.*

Keywords: Heat transfer coefficient, Shell-and-tube heat exchanger.

1. Introduction

The heat transfer coefficient (HTC) is an important parameter for the design of heat exchangers. Its value depends on the technical solution of the heat exchanger and the thermo-mechanical properties of the flowing fluid. This paper deals with shell and tube heat exchangers (Fig. 1). Methods commonly recommended for the calculation of shell-side coefficient values are the Kern method, the Bell-Delaware method and the Flow-stream analysis method (Hewitt et al., 1994). The Kern method, which has been the conventional method for a long time, is still used due to its simplicity, although its results are significantly higher in comparison with the other two methods (see Fig. 2). Determination of the HTC is a complex problem, as a large deviation in the comparison of theoretical models and experiments commonly occurs. Experimental values of the HTC for shell-and-tube heat exchanger may prove the difference between the theoretical methods and the real operation of the heat exchanger.

2. Experiment

Experiments are carried out on a vertical shell-and-tube heat exchanger (Fig. 1) in which the condensing water vapor flows downwards in vertical tubes and a cooling water countercurrent flows in the shell part. The vapor outlet is open to the atmosphere, thus the steam condenses at atmospheric pressure. The tube bundle is formed by 49 tubes with a length of 865 mm, an outside diameter of 28 mm and an inside diameter of 24 mm. The tubes are arranged in staggered arrays with a triangular tube pitch of 35 mm. The cross-section of the shell is rectangular in shape with a size of 223 mm by 270 mm. Seven segmental baffles (223x230mm) are used in the shell section, the tube-to-baffle diametral clearance is 1 mm and there is no shell-to-baffle diametral clearance. The material is stainless steel 1.4301 (AISI 304).

2.1. Measurements

Measured parameters are the outlet and inlet cooling water temperature, the cooling water flow, the inlet vapor pressure, the inlet vapor temperature and the amount of vapor condensate.

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Fig. 1: Vertical shell-and-tube condenser.

2.2. Determination of the heat transfer coefficient

The HTC is calculated from the heat balance of the exchanger. The total heat transfer rate of the heat exchanger is given by

$$Q = M_w \cdot c_w \cdot \left(t_{w,out} - t_{w,in}\right) \quad (1)$$

where M_w is the total cooling water mass flow, c_w is the specific heat capacity, $t_{w,out}$ is the outlet cooling water temperature and $t_{w,in}$ is the inlet cooling water temperature. The total heat flow rate of the heat exchanger is also given by

$$Q = U \cdot S \cdot \Delta t_{log} \quad (2)$$

where U is the overall heat transfer coefficient, S is the total area of the outside of the tubes and Δt_{log} is the logarithmic mean temperature difference. The shell-side HTC α_w is given from the following equation to calculate the overall heat transfer coefficient:

$$U = \frac{1/D_e}{\frac{1}{d_i \cdot \alpha_p} + \frac{1}{2k} ln\left(\frac{D_e}{d_i}\right) + \frac{1}{D_e \cdot \alpha_w}} \quad (3)$$

where d_i is the inside diameter of the tubes, α_p is the tube-side HTC (vapor condensation), k is thermal conductivity (material 1.4301), D_e is the outside diameter of the tubes. The heat transfer coefficient α_p is calculated according to the Nusselt model for filmwise condensation on vertical surfaces (Incropera & DeWitt, 1996 or Hewitt et al., 1994).

The value of the overall HTC primarily depends on the third term of the right side of Eq. (3), where the value of thermal resistance ($1/\alpha_w$, see Fig. 2) is significantly higher than the value of thermal resistance of the first and the second terms (approximately $1/10^4$ m^{2}K/W). Therefore, these terms do not significantly influence the result of Eq. (3) and it is possible to well determine the value α_w.

3. Theoretic Methods

Hewitt et al. (1994) represent the methods as follows. The first attempt to provide methods for calculating the shell-side heat transfer coefficient was the Kern method, which was an attempt to correlate data for standard exchangers by a simple equation analogous to equations for the flow in the tubes. Although the Kern method is not particularly accurate, it does allow a very simple and rapid calculation of shell-side coefficients to be carried out and is still successfully used.

In the Bell-Delaware method, correction factors for the specific configuration were introduced. Nevertheless, empirical correction factors are limited to the range of configuration for which the database was obtained.

A more generic method, covering the full range of possible arrangements, is the Flow-stream analysis method in which fluid streams were designed for each of the possible flow routes through the exchanger. The stream-analysis technique is particularly suitable for computer calculation. Therefore, a simplification for calculating it by hand has been developed.

Generally speaking, the Kern method offers the simplest route, the Bell-Delaware method offers the most widely accepted method and the Flow-stream analysis method offers the most realistic method.

3.1. Kern method

Based on data from industrial heat transfer operations and for a fixed baffle size (75 % of the shell diameter), the following equation was introduced:

$$\alpha_w = \frac{k}{D} \cdot 0.36 \cdot Re^{0.55} \cdot Pr^{0.33} \tag{4}$$

where k is fluid thermal conductivity, D is the relevant characteristic dimension. No change in viscosity from the bulk to the wall is assumed.

3.2. Bell-Delaware method

In this method, correction factors for the following elements were introduced:

1) Leakage through the gaps between the tubes and the baffles and the shell, respectively.
2) Bypassing of the flow around the gap between the tube bundle and the shell.
3) Effect of the baffle configuration (i.e., a recognition of the fact that only a fraction of the tubes are in pure cross-flow).
4) Effect of the adverse temperature gradient on heat transfer in laminar flow.

The ideal cross-flow heat transfer coefficient is given by

$$\alpha_c = \frac{k}{D} \cdot 0.273 \cdot Re^{0.653} \cdot Pr^{0.34} \tag{5}$$

then the shell side heat transfer coefficient is given by

$$\alpha_w = \alpha_c \cdot J_C \cdot J_L \cdot J_B \tag{6}$$

where J_C is the correction for the baffle configuration, J_L is the correction factor for leakage, J_B is the correction factor for bypass in the bundle-shell gap.

3.3. Flow-stream analysis (Wills and Johnson) method

This method analyses in detail the flow in a heat exchanger. The fluid flows from place A to place B via various routes. Leakage flows occur between the tubes and the baffle and between the baffle and the shell. Part of the flow passes over the tubes in cross-flow and part bypasses the bundle. The cross-flow and bypass streams combine to form a further stream that passes through the window zone. A correction factor F_{cr}, which adjusts the mass flow calculation (the Reynolds number), takes these effects into account. Then the shell-side heat transfer coefficient is given by

$$\alpha_w = \frac{k}{D} \cdot 0.273 \cdot Re_{cr}^{0.653} \cdot Pr^{0.34} \tag{7}$$

where

$$Re_{cr} = F_{cr} \cdot Re \tag{8}$$

4. Results

The experiments are carried out in the range of heat exchanger thermal power from 20 to 60 kW, with a logarithmic mean temperature difference from 6 to 28 °C and the Reynolds number from 1200 to 6300

(76 measured states). The comparison of the experimental results with the results of the theoretical methods is shown in Fig. 2. The deviation of the measurements ranges from 4 % up to 7 % in the dependence on operation parameters.

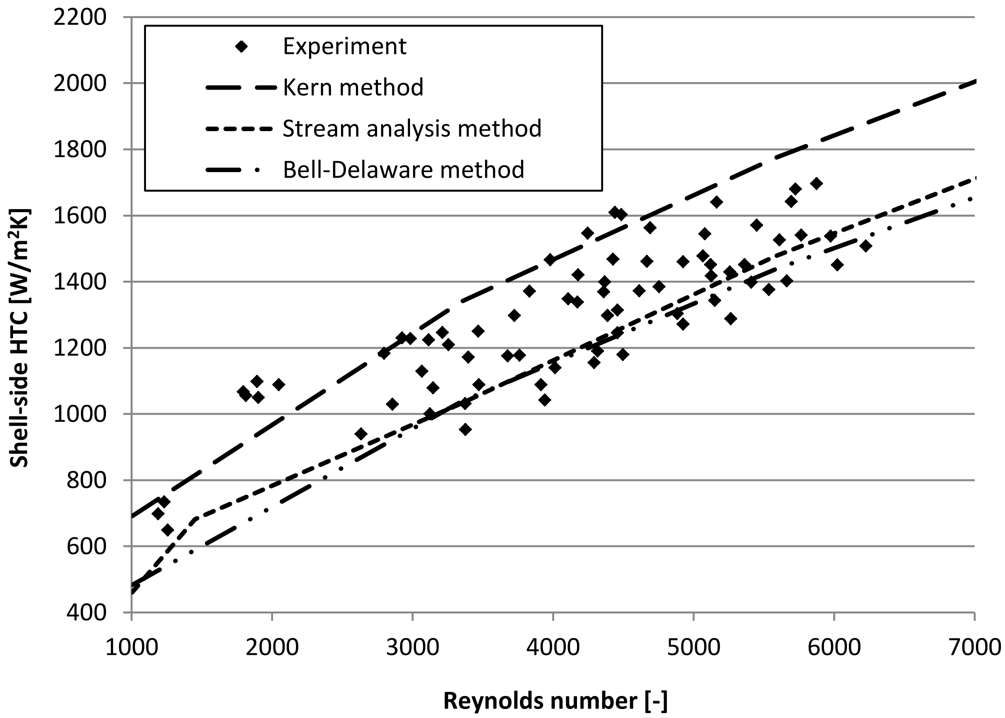

Fig. 2: Comparison of experimental and theoretical results.

The total variance in the experimental results is assumed concerning the complexity of the heat transfer process and various operation parameters.

5. Conclusions

This paper experimentally verifies the validity of theoretical models to calculate the HTC in shell and tube heat exchangers. The Kern, Bell-Delaware and Stream-flow analysis methods for evaluation of HTC in a vertical shell and tube condenser are compared with the results of experimental measurements in the range of the Reynolds number from 1200 to 6300.

The HTC values by the Kern method reach the top boundary of the experimental results while the results of the Bell-Delaware method and the Stream-flow analysis method are at the bottom. Therefore, usage of the Bell-Delaware method and the Stream-flow analysis method is suitable in accordance with the design assurance.

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