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Technical Note

Single-phase heat transfer correlation based on minimum variance

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ABSTRACT

Evaluation and prediction methods for heat exchangers have significantly developed over the years where the equal flow Reynolds number, equal flow velocity, and Wilson plot techniques are commonly used. However, equal flow *Re* and equal flow velocity techniques impose restrictions on the flow conditions and the flow passage configuration. Similarly, Wilson plot technique is applicable under a known exponent of *Re*. Using these techniques, it is difficult to obtain generalized correlations even for single passage because many unknowns are needed to be solved. Therefore, a simplified and handy method to develop heat transfer correlation is required to design new equipment or predict their performance. A general variance minimization method is presented to avoid the need for determination of various coefficients and exponents used in regression process. This method is validated by comparing its results with the experimental data.

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1. Introduction

Heat exchangers are widely used industrial equipment for heat transfer between two fluids. Their thermal performance depends on the design parameters and operating conditions. Actual performance of a newly designed heat exchanger is different from the designed performance, and experiments are necessary to verify its actual performance [1–4]. Heat flux, average temperature difference and overall heat transfer coefficient (HTC) etc. can be obtained from experiments. In order to get correct results under any operating conditions, it is necessary to develop separate correlations on the two flow passages [5–8].

Regression correlations to evaluate heat transfer in heat exchangers have been developed a great deal in the past century. Wilson plot is the original method and its further development is widely utilized effectively [7]. Taler presented a numerical method for determining a correlation to predict air-side HTC and friction factors as a function of Reynolds number (*Re*) [9]. Air-side HTC is calculated based on theoretical and measured outlet temperatures of cooling liquid. Ouyang presented a method for plate heat exchangers which depends on equal *Re* and further illustrated by comparing experimental and numerical methods [10]. The equal velocity method can be effective for the cases where the same fluid is flowing in two similar flow passages of heat exchanger, provided that the fluid properties are not temperature dependent [11]. Wilson plot method obtained correlations from experimental data with velocity being constant in one passage and with known HTC [12–15]; therefore, HTC for an experiment can be calculated from overall HTC and the known HTC. The coefficient, c and exponent, m in $Nu = cRe^{m}Pr^{n}$ can then be determined from experimental data. The equal velocity method does not require the conditions of Wilson plots; however it requires the two passages to be similar in heat exchanger. These requirements make it difficult to test some heat exchangers and cannot separate the individual HTC from overall HTC. In this regard, a lot of work has been done and documented previously. For example, Huang obtained a correlation of HTC for a Quench Front [16]. Gray did work on heat exchangers having continuous flat fins and used a multiple regression technique to correlate fin frictional data [17]. Kim investigated heat exchangers with plate fins in herringbone wave configuration and developed correlations to predict the air-side HTC and friction factor using a multiple regression technique [18]. Ghajar introduced heat transfer correlation using four sets of experimental conditions (a total of 255 data points) for a turbulent, gas–liquid flow in vertical pipes with different flow patterns and fluid combinations [19]. He also analyzed the problem using an artificial neural network to develop a more accurate correlation. Pacheco-Vega developed a data reduction technique to improve correlations obtained from heat exchanger measurements [20]. However, it neglects wall resistance if it is unknown, which cannot be ignored for heat exchangers with significant wall resistance. Pacheco-Vega's method is not accurate if wall resistance is not calculated correctly. Determination of wall resistance in some heat

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Nomenclature

A	heat transfer area, m^2
B	$Pr^n k/l$
c	coefficient in regressed correlations
c_p	specific heat capacity of fluid, J kg^{-1} K^{-1}
E^2	total general variance between U_c and U, W^2 m^{-4} K^{-2}
f	random fluctuate coefficient, W m^{-2} K^{-1}
h_v	surface HTC of variable velocity passage (VVP), W m^{-2} K^{-1}
h_c	surface HTC of constant velocity passage (CVP), W m^{-2} K^{-1}
$1/h_g$	sum of thermal resistance of CVP and wall, m^2 K W^{-1}
k	thermal conductivity of fluid, W m^{-1} K^{-1}
l	characteristic length of flow passage, m
M	mass flow rates, kg s^{-1}
m	exponent of Re in regressed correlations
n	exponent of Pr, and data points
Nu	Nusselt number
Pr	Prandtl number
Q	heat transfer rate, W
r	thermal resistance, m^2 K W^{-1}
Re	Reynolds number
T	temperature, °C
U	experimental overall HTC, W m^{-2} K^{-1}
U_c	calculated overall HTC, W m^{-2} K^{-1}
V	volumetric flow rates, m^3 h^{-1}

Subscripts

c	cold fluid
h	hot fluid
i	fluid inlet
out	fluid outlet
w	wall

Greek symbols

γ	relative error
ε	error between experimental data and correlation, W m^{-2} K^{-1}
ρ	density of fluid, kg m^{-3}
ΔT_m	mean temperature difference, °C

exchangers is both tedious and difficult. Rose described important topics regarding calculation methods and accuracy of heat transfer measurements [21]. He provided an accurate method which is better than traditional Wilson plot. He obtained correlations in the form $Nu = cRe^m Pr^n$ from experimental data with the exponent m as a known constant. The unknown parameters are c and HTC of the fixed passage. However, known constant m is impractical in testing some heat exchangers.

Previous methods are somewhat simplified in regression process and rely on some significant parameters to be known.

In the present paper, new generalized method is proposed to develop correlations, by introducing a procedure with nested loop to resolve three unknowns simultaneously. It is free from the necessary constraints used in equal velocity method, Wilson plot method, and the above referenced analyses. It needs a series of overall HTC with constant flow in one passage of the test heat exchanger and varied in the other.

2. Present analysis

Assuming that a heat exchanger consists of two flow passages, the HTC on variable velocity passage (VVP) is expressed as:

$$h_v = cRe^m Pr^n k/l \tag{1}$$

The thermal resistance on the VVP of heat exchanger with equal surface areas of two passages is:

$$\frac{1}{h_v} = \frac{1}{U} - \frac{1}{h_c} - r_w = \frac{l}{cRe^m Pr^n k} \tag{2}$$

where U is the overall HTC, h_c is the surface HTC on the constant velocity passage (CVP), and r_w is wall resistance. Defining B=$Pr^n k/l$, and $1/h_g = r_w + 1/h_c$, hence $h_g = h_c/(1 + r_w h_c)$. Combine above defining, Eq. (2) can be expressed as:

$$\frac{h_g \cdot U}{h_g - U} = cRe^m \cdot B \tag{3}$$

Here h_g is an unknown constant. The task in this research is to solve it along with unknown wall resistance. The left side of Eq. (3) can be obtained from experimental data, whereas the right side needs to be correlated. The error, ε, between experimental and correlated results is given by:

$$\varepsilon = \frac{h_g \cdot U}{h_g - U} - cRe^m \cdot B \tag{4}$$

The variance of Eq. (4) for all experimental data is defined as:

$$\varepsilon^2 = \sum_{i=1}^{n} \left(\frac{h_g \cdot U_i}{h_g - U_i} - cRe_i^m \cdot B \right)^2 \tag{5}$$

Differentiating Eq. (5) with respect to c and m, equating them to 0 gives.

$$\frac{d\varepsilon^2}{dm} = \sum_{i=1}^{n} 2 \cdot \left(\frac{h_g \cdot U_i}{h_g - U_i} - cRe_i^m \cdot B \right) \cdot cRe_i^m \cdot B \cdot \ln(Re_i) = 0 \tag{6}$$

$$\frac{d\varepsilon^2}{dc} = \sum_{i=1}^{n} 2 \cdot \left(\frac{h_g \cdot U_i}{h_g - U_i} - cRe_i^m \cdot B \right) \cdot Re_i^m \cdot B = 0 \tag{7}$$

c and m are determined by solving Eqs. (6) and (7), and they result in minimum variance defined by Eq. (5). The calculated overall HTC U_c is expressed as:

$$U_c = cRe^m Pr^n k \cdot h_g/(h_g \cdot l + cRe^m Pr^n k) \tag{8}$$

The variance between the calculated values of U_c in Eq. (8) and U obtained from experimental data is:

$$E^2 = \sum_{i=1}^{n} (U_{ci} - U_i)^2/n \tag{9}$$

Here, the accurate c and m are not calculated because h_g is unknown. A program shown in Fig. 1 is used to find out accurate c, m by assuming different h_g, and record them when E^2 reaches its minimum. Comparing to Pacheco-Vega et al. [20] and Rose [21], we propose a new method to resolve the three unknown parameters i.e. c, m and h_g simultaneously, and it gives accurate result without the precondition of known wall resistance and HTC on constant velocity side.

3. Validation of analysis

The correlation is validated by several sets of simulation data and two sets of experimental results.

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