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Research Paper

Critical heat balance error for heat exchanger experiment based on entropy generation method

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HIGHLIGHTS

- Proposed a new method – critical heat balance error method for heat exchanger design, evaluation, and experiment.
- Analytically expressed the critical heat balance error to filter the invalid entropy generation cases.
- Obtained simplified expression of critical heat balance error criterion for engineering use.
- Experimentally validated the critical heat balance error criterion for counter-flow heat exchanger.

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ABSTRACT

This research is inspired by one interesting question: whether entropy generation measured (indirected measurement) in a heat exchanger experiment is always positive, and what criterion is needed to keep a positive entropy generation measurement. As is well-known, the entropy generation method is a second-law method in heat exchanger design and evaluation. However, according to authors' knowledge, most design and evaluation ignores the influence of error. In this paper, the relation of the entropy generation number and heat balance error is investigated through both analytical and experimental methods. Based on this relation, the concept of critical heat balance error is proposed. Being zero entropy generation in the experiment, the critical heat balance error is a perfect criterion to filter the invalid negative entropy generation in the heat exchanger experiment. The analytical form of critical heat balance error is expressed as: $-(1-\tau)(1-\varepsilon)$, where ε and τ are heat exchanger efficiency and inlet temperature ratio, respectively. In following experiment section, out of 975 experimental cases, 39 invalid cases are found. After verification of analytical relations, the filtration efficiency of the analytical criterion is reported to be as high as 82%. The present paper proposed a new definition called critical heat balance error and provided its application on heat exchanger experiment.

1. Introduction

Applying the second law of thermodynamics to heat exchanger design and evaluation enables the consideration of energy quality [1,2] by either exergy or entropy. The entropy generation method (EGM) is among the methods used to apply the second law of thermodynamics. It uses the non-dimensional form of entropy generation.

The entropy generation method proposed by Bejan (non-dimensionalized by dividing heat capacity) [1,3–6] is well-known because it is simple and easy to use. Numerous trials using Bejan's method have been conducted on the design and evaluation of heat exchangers and other thermal devices [7].

Experimental studies of entropy generation provide valuable data for phototype design and optimization. Experimental research covers multi-size level thermal-fluid systems from industrial size to micro [8] or even nano [9] size. For heat exchanger applications, heat exchanger efficiency–entropy generation relation (ε-NS) or Reynold number-entropy generation number (Re-NS) relations are widely used in design and evaluation of cross-flow heat exchangers [10], heat exchangers with helical baffles [11], pin fins [12] or porous media [13]. In these experiments, entropy generation is an indirect measured parameter, which means it has to be calculated by other parameters. These parameters commonly include the four inlet/outlet temperatures and heat capacity of heat exchanger.

These indirect measurements can be inaccurate due to measurement error and operational error. To evaluate the error of indirect measurement, one parameter called heat balance error (or heat exchanger balance error) is most commonly used. It is a comprehensive parameter and includes all the error sources like overall heat duty

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error, heat leakage, and the measurement error. It is zero for theoretical heat balance cases and a no-error measurement. Commonly, the heat balance errors are controlled within the ±5% criterion [14] for most heat transfer experiments.

For the entropy generation experiments, an interesting question is whether the entropy generation in the experiment is always positive within the commonly used heat balance error criterion. Another meaningful question is as follows: "What criterion should we use in the experiment to make sure that the entropy generation measured is positive?" Theoretically, due to irreversibility, no negative entropy generation is allowed for an isolated system.

Similarly, for a reliable experiment, entropy generation measured should also be positive. The second law of thermodynamics requires positive entropy generation for any process in an isolated system. Naturally, positive entropy generation measurements become our reasonable expectation. Thus, it is a priority to make the measurement values obey the second-law of thermodynamics. The positive entropy generation rate is a potential indicator for high quality heat transfer measurement experiments.

As researcher have noticed, uncertainty is magnified in entropy generation analysis [15]. Usually, the heat balance error is selected as a parameter of experiment quality. The necessity for positive entropy generation measurement inspired our further research on the development of a new criterion.

In this study, we redefine the experimental reliability by a positive entropy generation measurement. We study the influence of the heat balance error on the experimental entropy generation number of the counter-flow heat exchanger. Based on positive entropy generation requirements, we propose an analytical critical heat balance error which serves as the new heat balance error criterion. In the subsequent/resulting analytical work, we use the second-order Taylor's expansion method to help understand the influence of the heat balance error on the final entropy generation number measured. Additionally, a second law-satisfying criterion is developed to help improve future experiment reliability. The following heat transfer experiments were conduct to verify the new heat balance error criterion for the counter-flow heat exchanger. This paper has great potential to improve applications of the entropy generation method and heat exchanger thermal management.

2. Theoretical background

The present research uses a counter-flow heat exchanger with identical heat capacity in four hot and cold inlets and outlets. The schematic of control volume model is illustrated in Fig. 1. Four temperatures of hot/cold inlet/outlet are marked on Fig. 1.

2.1. Entropy generation number

Assuming both sides of the heat exchanger are adiabatic, no heat is exchanged between the outer wall and the surrounding environment. The entropy generation analysis for a counter-flow heat exchanger neglecting the pressure drop is [7],

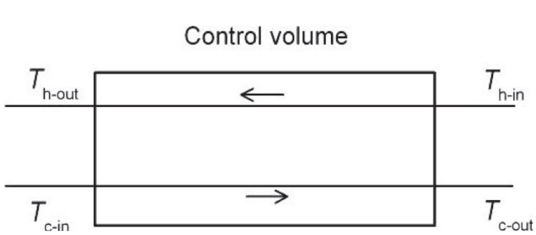

Fig. 1. Schematic drawing for counter-flow heat exchanger.

$$\dot{S}_{gen} = \sum_{out} \dot{m}s - \sum_{in} \dot{m}s \approx \dot{S}_{gen-T} = (\dot{m}c)_h \ln\frac{T_{h-out}}{T_{h-in}} + (\dot{m}c)_c \ln\frac{T_{c-out}}{T_{c-in}} \quad (1)$$

Where $\dot{S}_{gen}$ is the total entropy generation in the heat exchanger unit; $\dot{S}_{gen-T}$ is the temperature entropy generation in the heat exchanger unit; $\dot{m}c$ is the heat capacity of either side; $T_{\text{h-in}}$ is the hot side inlet temperature; $T_{\text{h-out}}$ is the hot side outlet temperature; $T_{\text{c-out}}$ is the cold side outlet temperature; and $T_{\text{c-in}}$ is cold side inlet temperature.

By non-dimensionalization, the entropy generation number [7] is defined as,

$$N_S = \dot{S}_{\text{gen}} / (\dot{m}c)_{\min} \quad (2)$$

$(\dot{m}c)_{\min}$ is the smaller value of cold and hot side heat capacity between the cold and hot sides. Since the heat exchanger with $(\dot{m}c)_c = (\dot{m}c)_h$ dominates the design and market, the rest of the paper is to show these heat exchangers.

2.2. Heat balance error

The experimental entropy generation is defined as the entropy generation value calculated by the direct measurement parameters (most importantly the cold and hot inlet and outlet temperatures). One of the most important parameters to control the experiment quality is the heat balance error. The heat balance error is calculated by the following expression,

$$Error\,(B) = \frac{(Q_c)_m + (Q_h)_m}{Q'_{ave}} \quad (3)$$

The heat transfer rate for the cold and hot side can be calculated by these two equations, $Q_c = (\dot{m}c)_c (T_{c-out} - T_{c-in})$ and $Q_h = (\dot{m}c)_h (T_{h-out} - T_{h-in})$. Here, $(Q_c)_m > 0$ and $(Q_h)_m < 0$. The average heat duty is given by Eq. (4), viz,

$$Q_{ave} = \left| \frac{(Q_c)_m - (Q_h)_m}{2} \right| \quad (4)$$

2.3. Error source analysis

For ease of analytical solution, we assume the error source is from one side or the other, for example take the cold side as error source. The heat transfer rate is measured to be, $(Q_c)_m = Q_c + \delta Q_c$, δQ_c is the result of error source. With this expression, the heat balance error could be reduced into this equation,

$$Error\,(B) = \frac{\delta Q_c}{Q_{ave} + \delta Q_c / 2} \quad (5)$$

Considering the relation, Q_{ave} and $\delta Q_c/2$ with Q_{ave} being much greater than $\delta Q_c/2$, the linear approximation can be obtained: $\delta Q_c = Q_c \times Error(B)$. By dividing $\dot{m}c$ on both sides, we can obtain the temperature–heat balance error relation,

$$\delta(\Delta T_c) = \Delta T_c \times Error\,(B) \quad (6)$$

Where, $\Delta T_c = T_{c-out} - T_{c-in}$.

3. Analytical results

3.1. Taylor expansion of entropy generation number

The relation between the entropy generation number measured and heat balance error can be illustrated by the second order