Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 121 (2015) 293 – 299
Procedia Engineering
www.elsevier.com/locate/procedia

9th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC) and the 3rd International Conference on Building Energy and Environment (COBEE)

Study on the Heat Transfer Characteristic of Compact Heat Exchanger Based on Experimental Data

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Abstract

Compact air - air heat exchanger (CAAHX) is a key component of the airborne environmental control system (ECS) for commercial airliners. In order to predict the performance of the ECS during the flight conditions, a computational model to descript the performance of CAAHX is needed. This study presents a common heat transfer model for engineering applications based on the η-NTU relationship and the structural parameters of CAAHX. Based on experiments, the common heat transfer models of two CAAHXs are established. Two kinds of values of the CAAHX's outlet temperature which calculated by the heat transfer model and measured in the test are used to verify the accuracy of the models. Results show that the proposed model can get the CAAHXs' characteristics in full working conditions by using only a small amount of experimental data, which can greatly improve the efficiency of the system design and optimization. The model can also provide a theoretical guidance in the related research fields.

Peer-review under responsibility of the organizing committee of ISHVAC-COBEE 2015

Keywords: Compact heat exchanger; Heat transfer characteristic; Experimental data

Nomenclature

c_p	specific heat, J/(kg·K)
G	mass flow, (kg/h)

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Peer-review under responsibility of the organizing committee of ISHVAC-COBEE 2015
doi:10.1016/j.proeng.2015.08.1071

C^*	$C^*=(Gc_p)_{min}/(Gc_p)_{max}$
η	heat exchanger's efficiency
Nu	Nusselt number
A	heat transfer area
λ	thermal conductivity, W/(mK)
δ	wall thickness, m
T	temperature, K
P	pressure, kPa
ε	error
Pr	Prandtl number
h	hot side
c	cold side
i	inlet
o	outlet
cal	calculated
ex	experimental
max	maximum
min	minimum

1. Introduction

CAAHX is a key component of the aircraft's ECS, and its efficiency has a significant impact on the performance of the entire system. CAAHXs' performance parameters are needed to analyze the ECS at different flight conditions, where the working conditions and efficiencies of the CAAHX are in a wide range of variation. So the CAAHXs' heat transfer characteristics play important roles in predicting and simulating the performance of aircraft's ECS for the whole flight envelope. Published research works about heat exchangers are as follows: N.A.Khan established a theoretical model for the coil heat exchanger [1]. The relative error between the model calculations and experimental values did not exceed 10%, but the heat transfer process had a lot of assumptions. Basing on the FLUNET, Kumar did the numerical simulations of different types of nanofluids flowing in a plate heat exchanger and obtained the particle diameters corresponding to the maximum heat transfer coefficient [2]. Gulenoglu compared three kinds of plate heat exchangers in his experiment and pointed out that reducing the size can improve the heat transfer coefficient [3]. Faizal and M.R. Amhed tested the performance of the CAAHX in small temperature difference [4]. Bejan made a theoretical analysis on the heat transfer characteristics in the form of small-scale cross flow and large-scale counter flow [5]. Zhang used the three-dimensional distribution model to optimize the heat exchanger with a target of minimum entropy production [6, 7].

In summary, the present study of heat exchanger mainly focused on theoretical analysis, CFD numerical simulation, and experiments. Theoretical analysis such as mean temperature difference method and η-NTU method needs iterative calculations to get the efficiency of the heat exchanger, and theoretical model needs strong assumptions which limit its application. The numerical simulation will simplify the actual situation which is harmful for the accuracy. Also, it will carry a heavy workload when there is a large amount working conditions to be calculated. Furthermore, obtain the full height heat transfer characteristics of the CAAHX by the experiment method entirely needs a long experiment cycle, which would bring uncontrollable cost and time pressure [8].

To cover the shortage of the current research methods, this paper presents a common heat transfer model for CAAHXs. The model based on the η- NTU method establishes a function of efficiency with the thermodynamic and structural parameters of CAAHX. Considering our research group has measured the inlet and outlet thermodynamic parameters, so the efficiency and the structure parameters can be calculated. For a certain heat exchanger, its structure parameters are constant. So in the other conditions, the inlet and structure parameters have already known. The heat transfer efficiency of the CAAHX can be calculated by the model established in this paper. The validity of the common heat transfer model can be verified by comparing the outlet temperature value calculated by the model and measured in the experiment.

2. Methods

2.1. Common heat transfer model

The structure and unit transfer area of a CAAHX are shown in Figure1.

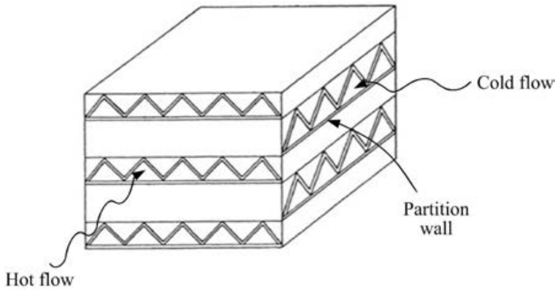


Fig. 1. Structure of CAAHX's core

The NTU is defined as [9]:

$$NTU = \frac{K \cdot A}{\left(G \cdot c_p\right)_{\min}} \tag{1}$$

The overall heat transfer coefficient K maybe expressed as [10]:

$$K = \left(\frac{1}{h_h} + \frac{\delta}{\lambda} + \frac{1}{h_c}\right)^{-1} \tag{2}$$

Because of the high heat conductivity and the small thickness of the wall, the item δ/λ can be ignored compared with the other two items.

The criterion of heat convection is shown in equation (3), wherein c, m, and n are constant, herein, m equals 0.8 and n equals 0.3[11]. The characteristic temperature is the inlet temperature of the heat exchanger.

$$Nu = c\,\mathrm{Re}^m\,\mathrm{Pr}^n \tag{3}$$

Combined the equations (1)~(3) and the definition of the criterion numbers, the common express of NTU is shown in equation(4), where k_1 and k_2 are constant only related to the structure parameters of the CAAHX. With the certain flow pattern, the heat transfer efficiency is the function of the NTU and the heat capacity ratio of the two fluids in the heat exchanger [12]. Particularly, the efficiency of the single-pass with cross-flow heat exchanger which used in the airborne ECS is wildly expressed in equation (5).

$$NTU = \frac{\dfrac{1}{\left(G \cdot c_p\right)_{\min}}}{k_1 \cdot \mathrm{Pr}_h^{0.5} \cdot [\dfrac{1}{\left(G \cdot c_p\right)_h}]^{0.8} + k_2 \cdot \mathrm{Pr}_c^{0.5} \cdot [\dfrac{1}{\left(G \cdot c_p\right)_c}]^{0.8}} \tag{4}$$

$$\eta_{\text{cal}} = 1 - \exp\{NTU^{0.22} \cdot [\exp(-C^{*} \cdot NTU^{0.78}) - 1] \cdot C^{*-1}\} \tag{5}$$

Equation (4) and (5) are the common heat transfer model. Where k_1 and k_2 are the coefficients to be determined, and the other parameters can be got from the working condition.

The efficiency of the CAAHX is also defined as:

$$\eta_{\text{ex}} = \frac{\left(G \cdot c_p\right)_h \left(t_{h,i} - t_{h,o}\right)}{\left(G \cdot c_p\right)\left(t_{h,i} - t_{c,i}\right)} \tag{6}$$

An objective function is shown as the following.

$$f = \left|\eta_{\text{cal}} - \eta_{ex}\right| \tag{7}$$

The smaller the value of the function f, the closer between η_{cal} and η_{ex} . It means that k_1 and k_2 are close to the real structure of the heat exchanger. So the undetermined parameters k_1 and k_2 can be found out with the MATLAB Software. As it is shown in equation (8), fminsearch is a function to optimize the objective function for minimum value, x_1 and x_2 are the initial value of k_1 and k_2 for iteration.

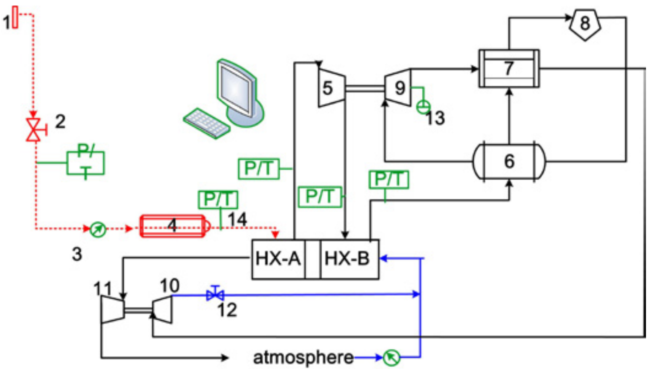
$$\left(k_1, k_2\right) = \text{fminsearch}\left(\text{f}, \left[\text{x}_1, \text{x}_2\right]\right) \tag{8}$$

2.2. Experimental method for heat exchanger

Two types of CAAHXs (HX-A and HX-B) are analyzed. They are tested on the test-bed which is established by our research group to test the ground performance of ECS. The schematic diagram of the experiment is shown in Figure 2, and it is composed of four subsystems: the engine bleed air simulation system (red lines), ram air simulation system (blue lines), cooling system (black lines), and measurement / control system (green lines).

Engine bleed air simulation system is composed of a high-pressure gas source, an electric furnace and a flow control valve. It is to simulate the temperature, pressure and mass flow rate of the engine bleed air in different working conditions; The function of the ram air simulation system is to provide the air with different temperature and mass flow rate for the heat exchangers' cold side; In the cooling system, the air from the bleed air simulation system with high temperature and high pressure flows into the HX-A for cooling and enters the compressor to rise its temperature, and then flows into the HX-B for cooling again. After that, the air in turn enters the hot side of regenerator, hot side of condenser, water-separator, cold side of re-heater, and finally is introduced to the turbine for expansion, the air with low temperature is ducted to the cold side of condenser, the outlet of condenser is used as the ram air; the measurement/control system is developed on the Labview and KLN4118 data acquisition equipment. The measurement accuracy is 0.5% for temperature, 0.5% for pressure, and 1% for mass flow rate. Figure 3 is the picture of the test rig.

Fig. 2. Pictures of the experiment system



1-air source;2-flow control valve;3-flowmeter ;4-electric heater; 5-compressor ;6-condenser; 7-regenerator; 8-water separator;9-primary turbine; 10-secondry turbine; 11-fan; 12-pneumatic valve;13-rotate speed instrument ; 14-temperature/ pressure sensor.

Fig. 3. Schematic diagram of the test rig

The cooling system inlet parameters such as temperature, pressure, and mass flow rate can be adjusted through the flow control valve and the electric heater, the outlet parameters can be tested. It means that both hot and cold side of the heat exchangers can be tested in different conditions.

3. Results

The balance between the heat flux of the cold side and the hot side is the basis to analyze the performance of heat exchanger. So the thermal equilibrium rate θ [Eq.(9)] of the data are tested. Figure 4 shows the test results of the two CAAHXs. The data with θ in 0.8~1.2 are selected as the valid data, herein, 49 test data for HX-A and 24 test data for HX-B. For the data, the inlet temperatures of the hot side are in the range from 373~443K for HX-A while 328~372K for HX-B; the inlet pressures of the hot side are in the range from 250~670kPa for HX-A and 272~752kPa for HX-B; the mass flow is from 201~625kg/h for both CAAHXs.

$$\theta = \left(G \cdot c_p \cdot (t_i - t_o)\right)_c / \left(G \cdot c_p \cdot (t_o - t_i)\right)_h \quad (9)$$

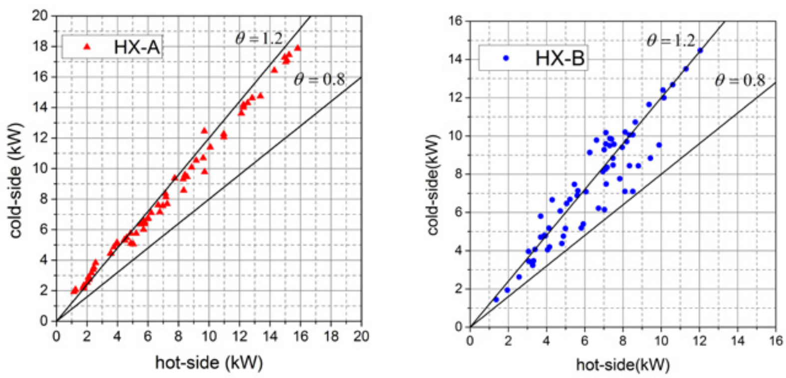


Fig. 4. Thermal balance between hot and cold side

In order to illustrate the model in this paper, four data sets of HX-A and three data sets of HX-B (Table 1) are selected to calculate the undetermined parameters k_1 and k_2 in the common heat transfer models [Eq.(4) and Eq.(5)] to complete the models. The calculation results are k_1=0.10035, k_2=0.1397 for HX-A and k_1=0.33953, k_2=0.0640 for HX-B.

Table 1. Calculation data

Case		G_h	$T_{h,j}$	$T_{h,o}$	P_j	G_c	$T_{c,j}$	$T_{c,o}$	P_c
HX-A	1	201.3	372.8	310.1	251.8	369.5	298.9	342.1	98.1
	2	357.1	383.8	317.4	395.9	601.8	300.9	346.5	96.1
	3	613.5	435.7	379.8	704.1	613.5	338.7	395.9	89.5
	4	627.5	363.9	336.5	707.3	627.5	312.6	345.1	89.7
HX-B	1	201.3	328.1	303.8	272.3	369.5	284.9	298.9	97.7
	2	570.8	369.21	314.2.7	650.6	850.5	277.8	313.5	93.1
	3	585.3	357.2	311.3	693.9	853.9	273.1	305.7	95.2

The other test data are used to verify the accuracy of the model in different conditions. According to the inlet measured parameters, the outlet parameters can be calculated by the heat transfer model. Comparing the outlet temperature calculated and measured, the difference is shown in Fig.5. The relative error Ɛ between the calculated and measured value and the average relative error for all cases are defined in Eq.(10) and Eq.(11). The maximum relative error is 9.38% for HX-A while 12.2% for HX-B; and the average relative errors are 5.42% for HX-A while 5.39% for HX-B.

$$\varepsilon = \left| \frac{T_{o,ex} - T_{o,cal}}{T_{i,ex} - T_{o,ex}} \right| \tag{10}$$

$$\varepsilon_{ave} = \frac{1}{N} \sum_{i=1}^{N} \varepsilon_i \tag{11}$$

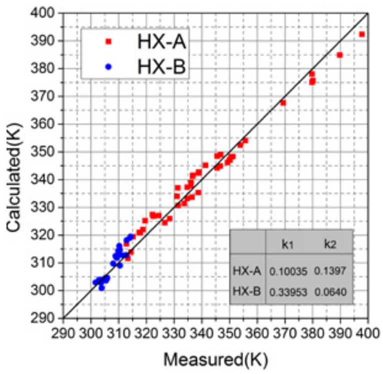


Fig. 5. Calculated and measured values

The test data are used to verify the heat transfer model. The results show that the relative errors between calculated and measured values are almost less than 10%. It means the common heat transfer model can achieve the engineering requirement when the working conditions of HX-A and HX-B change in a wild range.

4. Conclusions

This study presents a common heat transfer model for CAAHXs. With the help of airborne ECS ground simulation test-bed, the CAAHXs were tested and the results show that the common heat transfer model can be used to analyze the heat transfer characteristic of CAAHXs in different thermodynamic parameters, and it has a good accuracy in a wild range of working conditions.

On the parts concerned, just a small amount of data are needed to fit the undetermined parameters and then the heat transfer characteristic in different working conditions can be got quickly by the common heat transfer model. It is convenient being used to do the simulation for CAAHXs and will save the cost a lot for experiment. On the system concerned, the CAAHX can be simplified to a point model by the common heat transfer model. It will greatly improve the efficiency for system design and optimization.

The undetermined parameters k_1 and k_2 in the model are different for different CAAHXs and they need to be worked out with the data that are already known. The present work can be applied in the steady and dry air condition. The heat transfer characteristic in moisture conditions and the dynamic performance of the CAAHXs will be developed in the further research work.

Acknowledgements

The research present in this paper was supported financially by the National Basic Research Program of China (the 973 Program) through Grant No.2012CB720100.

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