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A distributed parameter model and its application in optimizing the plate-fin heat exchanger based on the minimum entropy generation

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ABSTRACT

A general three-dimensional distributed parameter model (DPM) was developed for designing the plate-fin heat exchanger (PFHE). The proposed model, which allows for the varying local fluid thermophysical properties inside the flow path, can be applied for both dry and wet working conditions by using the uniform enthalpy equations. The grids in the DPM were generated to match closely the flow passage of the heat exchanger. The classical correlations of the heat transfer and the flow friction were adopted to avoid solving the differential equations. Consequently, the computation burden of DPM becomes significantly less than that of the Computational Fluid Dynamics method. The optimal design of a PFHE based on the DPM was performed with the entropy generation minimization taken into consideration. The genetic algorithm was employed to conduct the optimization due to its robustness in dealing with complicated problems. The fin type and fin geometry were selected optimally from a customized fin database. The PFHE included in an environmental control system was designed by using the proposed approach in this study. The cooling performance of the optimal PFHE under both dry and wet conditions was then evaluated.

1. Introduction

The plate-fin heat exchanger (PFHE), one type of high-efficiency compact heat exchangers, has been extensively employed in many fields [1], such as the aerospace, chemical engineering, and energy system etc. Performance prediction and optimal design of PFHE are two key issues nowadays for the purpose of saving energy and reducing operational cost. There are several challenges regarding these two issues.

Firstly, the temperature difference between the inlet and outlet fluids is considerably large as the result of the high compactness (usually 700–2500 m^2/m^3) of PFHE. Some thermophysical properties of the fluids vary drastically with the changes in the temperature (Table 1) [2]. For example, the kinematical viscosity ν, and the Prandtl number of the oil reduce by 68 times and 58 times respectively when the fluid temperature increases from 0 °C to 80 °C. Hence, considering the property variation is crucial to evaluate precisely the performance of PFHE. Additionally, the phase change of the fluid also has evident influence on thermophysical properties. In a typical environmental control system (ECS) embedded in the aircraft (Fig. 1), there are four main heat exchangers (A, B, E, and G in Fig. 1), which occupy around 2/3 weight and volume of the entire ECS and affect the performance of the ECS significantly. The working conditions for these heat exchangers are always extremely complex. Specifically, the water condensation, even freeze, may take place inside the passage of the condenser 'E'. Such unwanted condensation or freeze likely results in blocking the passages and thus reducing the reliability of ECS. Further, water collected by the water separator 'F' is usually sprayed into the ram air flowing through the secondary and primary heat exchangers, where the water aerosol evaporates gradually. In such cases, the fluid properties substantially alternate during the heat and mass transfer processes.

Though integrated parameter model (IPM) has been widely used in designing the heat exchanger, it has inherent difficulty to characterize the different thermophysical properties of every point in the exchanger. Kays and London [1] developed the methods to correct the variance of the fluid properties resulted from the temperature change on the flow section and along the flow direction when the temperature varies pronouncedly large. Nevertheless, the correction method is not practical to use in modeling the cross-flow heat exchanger, because the fluid in each flow passage behaves differently.

To overcome such deficiencies of the IPM, the Computational Fluid Dynamics (CFD)-based methods have been broadly utilized in recent years. The CFD-based approaches are able to yield accurate

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Nomenclature

A_c	free flow area (m^2)
b	fin height (m)
c_p	specific heat capacity at constant pressure (J kg^{-1} K^{-1})
d	humidity ratio (kg kg^{-1} air)
D_h	hydraulic diameter of passage (m)
f	friction factor
F	heat transfer area (m^2)
h	convection heat transfer coefficient (W m^{-2} K^{-1})
h_m	mass transfer coefficient (m s^{-1})
H	exchanger height (m)
i	specific enthalpy (J kg^{-1})
i_{fg}	latent heat of vapor (J kg^{-1})
j	Colburn factor
l	element length (m)
L	exchanger length (m)
Le	Lewis Number
m	mass flow rate (kg s^{-1})
M_X, M_Y, M_Z	grid numbers in the direction of exchanger length, width and height, respectively
N_{fin}	index number of fin
P	pressure (Pa)
P_f	fin pitch (m)
ΔP	overall pressure drop of fluid (Pa)
$\Delta p_{\max}$	acceptable pressure drop of fluid (Pa)
Pr	Prandtl number
Q	heat duty (kW)
R	gas constant (J kg^{-1} K^{-1})
Re	Reynolds number
S_{gen}	entropy generation (J kg^{-1} K^{-1})
Sc	Schmidt number
t	time (s)
T	temperature (°C, K)
$\overline{T}_{ex}$	average outlet temperature of exchanger (°C)
u	velocity (m s^{-1})
W	exchanger width (m)
$\mathbf{X}$	vector of optimization variables

Greek symbols

β	Total areas per unit volumes (m^2 m^{-3})
δ	characteristic length of element (m)
ϕ	fin areas/total areas
η	effectiveness of heat exchanger
η_d	mass transfer effectiveness
η_{fin}	fin efficiency
λ	heat conductivity (W m^{-1} K^{-1})
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})

Subscripts

a	air
c	cold fluid
ex	outlet parameter
E	current element
f	fluid
fin	fin
h	hot fluid
in	inlet parameter
l	liquid
max	maximum value
min	minimum value
sat	saturation condition
v	vapor
w	wall

results through solving Navier–Stokes equation when selecting proper flow models, such as wall function, viscosity model and turbulence model, etc. Many investigators obtained the performance of the fins through CFD method and the numerical results were well validated by the experimental data [3–5]. However, CFD requires massive computational burden, mainly because of the complexity of generating the computational grids and the difficulty of solving the partial differential equations. For instance, the model in Ref. [6] contained approximately 1,000,000 elements and it took 5 h to simulate one operational condition of the compact heat exchanger. Nowadays, CFD method was also applied to simulate the performance of the plate heat exchanger [7] and the influence of the flow maldistribution on the whole heat exchanger [8]. But the huge computational cost of the CFD-based method was prohibitive to design or optimize heat exchanger, especially for the complex PFHE.

The primary purpose of the present study was, therefore, to establish a feasible three-dimensional (3D) distributed parameter model (DPM). The proposed approach can rapidly perform the PFHE simulation due to its higher computational efficiency in comparison with the traditional CFD methods, and its stronger ability in characterizing the varying fluid thermophysical

Table 1
Fluid thermophysical properties variations with the change in the temperature [2].

	T (°C)	ρ (kg/m^3)	c_p (J/(kg K))	λ (W/(m K))	$\nu \times 10^6$ (m^2/s)	Pr
Air	0	1.293	1.005	0.0244	13.28	0.707
	80	1.000	1.009	0.0305	21.09	0.692
	Variation	22.66%	0.40%	25.00%	58.81%	2.12%
Water	0	999.9	4.212	0.551	1.789	13.67
	80	971.8	4.195	0.674	0.365	2.21
	Variation	2.81%	0.40%	22.32%	79.60%	83.83%
R134a	−30	1385.9	1.260	0.1073	0.3106	5.054
	50	1102.0	1.569	0.0704	0.1431	3.515
	Variation	20.48%	24.52%	34.40%	53.93%	30.45%
Engine oil	0	905.0	1.834	0.1449	1336	15,310
	80	857.4	2.148	0.1379	19.7	263
	Variation	5.26%	17.12%	4.83%	98.53%	98.28%