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Research Paper

Simplified model of finned-tube heat exchangers based on the effectiveness method and calibrated with manufacturer and experimental data

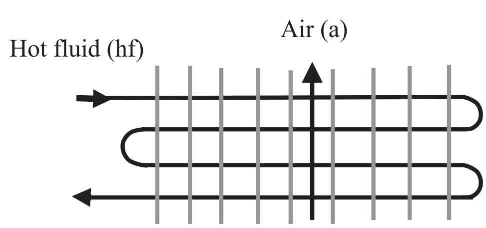
Celestino R. Ruivo [a,b,*], Fernando Dominguez-Muñoz [c], José J. Costa [b]

[a] Department of Mechanical Engineering, Institute of Engineering, University of Algarve, Campus da Penha, 8005-139 Faro, Portugal
[b] ADAI-LAETA, Department of Mechanical Engineering, University of Coimbra, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal
[c] Energy Research Group, ETSII-University of Málaga, C/Doctor Pedro Ortiz Ramos s/n, 29071 Málaga, Spain

HIGHLIGHTS

- Simplified model of finned-heat exchangers is presented.
- Model is based on the effectiveness method.
- Calibration parameters of the thermal resistances expressions are determined.
- Versions of a heating coil model is tested against catalogue data.
- Versions of an automotive radiator model is tested against experimental data.

GRAPHICAL ABSTRACT



$$\dot{Q} = \varepsilon C_{\min} (T_{\mathrm{hf,in}} - T_{\mathrm{a,in}}) \qquad R_{\varphi} = R_{\varphi,\mathrm{ref}} \left(\frac{\dot{m}_{\varphi,\mathrm{ref}}}{\dot{m}_{\varphi}} \right)^{n_{\varphi}} \chi_{\varphi}$$

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ABSTRACT

A simplified model for predicting the overall thermal performance of finned-tube heat exchangers considering water and air as hot and cold fluids, respectively, is investigated. The model is based on the classical ε-NTU method and the thermal convective resistance in each fluid is estimated after conventional-type (Nusselt number) empirical correlations. The model is calibrated with catalogue data of a heating coil. Calibrations of six families of model versions are performed by using different numbers of operating cases ranging from 2 to 320, some of them taking into account the influence of varying properties. The calibrated versions are tested for operating cases listed in the catalogue and the best performing versions are identified, such as the one calibrated with 24 cases and taking into account the effect of the fluid properties, which provided better accuracy than the versions calibrated in previous works. A test of the method robustness is conducted regarding the influence of the initial guessed values of the thermal resistances on the calibration procedure.

The validity of the component model is further investigated by using a set of published experimental data for an automotive radiator covering ranges of practical interest of the mass flow rates of both air and water streams, and some versions providing excellent results are identified.

The model based on a suitable version previously calibrated and tested is a promising procedure for the modular component simulation of finned-tube heat exchangers, when used as air conditioning heating coils or in other particular applications.

* Corresponding author at: Department of Mechanical Engineering, Institute of Engineering, University of Algarve, Campus da Penha, 8005-139 Faro, Portugal.
E-mail address: cruivo@ualg.pt (C.R. Ruivo).

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Nomenclature

a_φ	specific transfer area (m^{-1})
C	heat capacity rate ($J\ s^{-1}\ °C^{-1}$)
CR	ratio of heat capacity rates
c_p	specific heat ($J\ kg^{-1}\ °C^{-1}$)
c_φ	exponent in power law correlation for Nusselt number
D	internal hydraulic diameter of tubes (m)
h_φ	heat transfer coefficient ($W\ m^{-2}\ °C^{-1}$)
H	height of a cuboid finned-tube heat exchanger (m)
L	length of a cuboid finned-tube heat exchanger (m)
$\dot{m}_\varphi$	mass flow rate ($kg\ s^{-1}$)
n_φ	exponent in power law correlation for Nusselt number
N_{cir}	number of circuits for the hot fluid
NTU	number of transfer units
Nu_φ	Nusselt number
Pr	Prandtl number
$\dot{Q}$	heat transfer rate (W)
R	overall thermal resistance ($°C\ W^{-1}$)
Re	Reynolds number
R_φ	thermal resistance ($°C\ W^{-1}$)
T	temperature (°C)
$\dot{V}_\varphi$	volume flow rate ($m^3\ s^{-1}$)
V_{HE}	volume of a cuboid finned-tube heat exchanger (m^3)
W	with of a cuboid finned-tube heat exchanger (m)

Greek symbols

α_i^*	calibration parameter used in Eq. (7) (i = 3–5)
$\alpha_i'^*$	calibration parameter used in Eq. (7) (i = 1–2)
χ_φ	correction factor of properties
$\Delta\dot{Q}$	root mean square deviation of $\delta\dot{Q}$
$\Delta\dot{Q}_{max}$	maximum absolute value of error indicator $\delta\dot{Q}$
$\delta\dot{Q}$	error indicator
ε	effectiveness
γ	auxiliary parameter ($m\ s\ kg^{-1}$)
λ_φ	thermal conductivity ($W\ m^{-1}\ °C^{-1}$)
μ_φ	dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
ρ_φ	density ($kg\ m^{-3}$)
ψ^*	auxiliary parameter ($kg\ s^{-1}\ m^{-1}$)

Subscripts

a	air
hf	hot fluid (water)
HE	heat exchanger
in	inlet
min	minimum value
max	maximum value
out	outlet
ref	reference condition
φ	generic subscript regarding fluid identification (a: air; hf: hot fluid)

Superscripts

*	value estimated by the simplified approach or parameter of correlation derived from Gnielinski correlation to be calibrated

Abbreviations

ε-NTU	effectiveness method
Vi,j,k	approach version neglecting the effect of varying properties
V$^{p}i,j,k$	approach version taking into account the effect of varying properties

1. Introduction

Finned-tube heat exchangers are largely used in several air conditioning devices, such as air handling units, fan coil units and split systems, as well as in many other devices of industrial applications. Simulation of heat transfer phenomena occurring in such equipment is an important task to be addressed for the performance comparison of different solutions and also for optimization purposes.

Manufacturers of air conditioning equipment usually provide selection software to be used at system design stage by engineers, but they do not usually provide a program code to be used as a component model for the modular component simulation in TRNSYS, EnergyPlus or other dynamic simulation software, which would represent a useful tool for the engineering teams. The manufacturer catalogue and selection software should provide a list of parameters to be used as input data for the equipment component modelling.

Numerical models of heat exchangers based on the detailed computational fluid dynamics approach are very powerful but rather complex due to the need of solving the differential governing conservation equations. They are not intended to be used in practice as a component model in the most common dynamic simulation tools but they provide important guidelines to be considered in product optimization by the manufacturers as well as on the investigation of correlations for predicting both the friction factor and the convection heat transfer coefficient [1–6].

The simplified simulation of a finned-tube heat exchanger can be addressed by two well-known common methods: the LMTD (Logarithm Mean Temperature Difference) and ε-NTU methods [7]. When applying these methods, the dependence of the convective thermal resistances on the velocity and properties of the fluids must be taken into account in the estimation of overall thermal resistance. When using the effectiveness method for the simulation of systems operating with variable flow rates, the accuracy of the results becomes questionable when a constant effectiveness value is assigned, as done by Cejudo-Lopéz et al. [8].

The Wilson plot method is a remarkable procedure enabling the determination of parameters of appropriate expressions usually used for the calculation of thermal resistances in heat exchangers. It is based on the linear regression analysis supported imperatively by a set of accurate data obtained experimentally [9,10]. The original method requires that, when evaluating those parameters for the fluid circulating inside the tubes, the thermal resistance of the other fluid must be kept constant [9,10]. An interesting alternative to the direct use of experimental data is the detailed numerical modelling approach based on CFD. However, the dependence of the fin efficiency on the convection heat transfer coefficient will turn the application of the Wilson method more complex, which can be seen as a disadvantage of the method when dealing with finned heat exchangers [11,12]. Moreover, the application of the method is intended to deal with power-law expressions for the convective thermal resistances that can involve the use of dimensionless parameters for taking into account the effect of variable fluid properties [9].

Based on experimental data and using a non-linear regression method, Taler [12] determined the parameters for the air-side and water-side Nusselt number correlations applicable to cross-flow heat exchangers with extended surfaces. The addressed example was for an automotive radiator and seven pairs of correlations were investigated. Two sets of these correlations were used more recently by the same author in a new method for the numer-