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Simplified component model of heating and dry-cooling coils: Influence of altitude and of glycol concentration in the heat transfer fluid on the error prediction of the heat transfer rate

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ABSTRACT

An empirical model for predicting the thermal capacity of a coil operating in dry mode is investigated. It is based on the well-known ε-NTU method. Thermal resistances are estimated by empirical correlations calibrated with manufacturer data by using two operating cases. Large number of operating cases by ranging the inlet states, the flow rates of both fluids, the altitude and the propylene-glycol concentration is considered in tests. The validity of several approaches of the empirical model is investigated for heating and dry-cooling operating cases. When considering pure water as heat transfer fluid, acceptable results were achieved without any correction of properties.

Similar tests were conducted considering propylene-glycol aqueous solution as heat transfer fluid. The error indicators are significantly reduced when the variation of the fluid properties is taken into account. According to the large number of tests conducted, the approach considering the correction of properties of both fluids is a promising procedure for the simulation of the coil, operating either as a heater or as a dry cooler, in TRNSYS, EnergyPlus or other dynamic simulation tools.

The validity of the empirical component model is also investigated by using available experimental data published in the literature using aqueous solution of ethylene glycol as heat transfer fluid. Although the number of experiments used is not large and the accuracy of some measured cases is not as good as desirable, the tested approaches with and without correction of properties provide acceptable results.

1. Introduction

The development of equipments and systems for industry in general and for air-conditioning of buildings in particular is carried on by increasingly using numerical modelling techniques. Simulation is a useful design tool providing several advantages for the manufacturers: rapid prototyping, low development costs, fast switch from old to new versions of the products [1]. Regarding the air conditioning field, manufacturers usually provide selection software that engineers responsible for sizing the systems can use in their projects. In the dynamic simulation of the building thermal behaviour, the heat and mass transfer processes occurring in the different equipments is an important task to be addressed by the engineering team, namely for the comparison of different possible solutions and optimization purposes. Despite the late technological advances, manufacturers do not usually provide a component model, a programme code or even data to be used in a simplified simulation of some manufactured equipments, which would represent an easy and valuable tool for the engineers. Cooling and heating coils are examples of those devices used in several applications of air conditioning [2,3].

Regarding heating coils, the most common applications are related to air handling units [4–6], fan coil units [7,8] and split systems [9,10], providing the right amount of supply airflow in the appropriate conditions to guarantee indoor thermal comfort. Heating coils also make part of air handling units in applications where both temperature and humidity must be controlled such as, for example, administrative [11] and hotel buildings [12], indoor swimming pools [13,14] and drying processes [15–17]. Heating

Abbreviations: ε-NTU, effectiveness method; ASPG, aqueous solution of propylene glycol; ASEG, aqueous solution of ethylene glycol

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Nomenclature

a_0, a_1, a_2 Coefficients used in correlations of (Eqs. (16) and 17)
a_φ Coefficient in Eq. (4)
b_0, b_1, b_2 Coefficients used in correlations of (Eqs. (16) and 17)
C Heat capacity rate (J s^{-1} °C^{-1})
CR Ratio of heat capacity rates
c_p Specific heat (J kg^{-1} °C^{-1})
$\bar{c}_p$ Average specific heat in the temperature range from 0 °C to T (J kg^{-1} °C^{-1})
c_φ Exponent in (Eqs. (4) and 5)
$c_{1\varphi}$ Exponent in Eq. (7)
$c_{2\varphi}$ Exponent in Eqs. (9.a) and (9.b)
c_0, c_1, c_2 Coefficients used in correlations of (Eqs. (16) and 17)
FR Flow rate (kg s^{-1} or m^3 h^{-1})
H Height or altitude (m)
$\dot{m}$ Mass flow rate (kg s^{-1})
n_φ Exponent in (Eqs. (4) and 5)
$n_{1\varphi}$ Exponent in (Eqs. (6) and 7)
$n_{2\varphi}$ Exponent in Eqs. (8), (9.a) and (9.b)
NTU Number of transfer units
Nu Nusselt number
P Atmospheric pressure (Pa)
Pr Prandtl number
$\dot{Q}$ Heat transfer rate (W)
R Thermal resistance (°C W^{-1})
Re Reynolds number
T Temperature (°C)
w_v Water vapour content in moist air (kg kg^{-1} d.a.)
$\dot{V}$ Volume flow rate (m^3 s^{-1})

Greek symbols

χ Correction factor of fluid properties
$\chi_{\rho,a}$ Correction factor due to change in air density
$\Delta\dot{Q}$ 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_{wg} Generic property of aqueous solution of propylene glycol
λ Thermal conductivity (W m^{-1} °C^{-1})
μ Dynamic viscosity (kg m^{-1} s^{-1})
ν Kinematic viscosity (m^2 s^{-1})
ρ Density (kg m^{-3})
ψ_g Mass fraction of glycol in aqueous solution of propylene glycol (kg kg^{-1})
θ Dimensionless parameter in (Eqs. (16) and 17): $\theta = \sqrt{273.15/(273.15+T)}$

Subscripts

1 Approach based on mass flow rates (Eq. (6))
2 Approach based on volume flow rates (Eq. (7))
a Air
hf Heat transfer fluid
in Inlet
min Minimum value
max Maximum value
out Outlet
ref Reference condition
st Standard air condition
w Water
wg Aqueous solution of propylene glycol
φ Air (a), heat transfer fluid (hf), water (w) or aqueous solution of propylene glycol (wg)

Superscripts

* Value estimated by the simplified approach

coils have also application in dedicated outdoor air systems in order to provide, during cold days, fresh air to the several zones [18–20], usually at a temperature close to the indoor temperature of the zones. Heat recovery in dedicated outdoor air systems is also possible by combining a heating coil with a cooling coil in heat pipe devices or in run-around coils [21–23].

There are several air handling units with a desiccant wheel for dehumidification of the supply airflow that also integrate a heating coil for the continuous desiccant regeneration. Configurations of air handling units are available that can control only the temperature of the zone or both humidity and temperature, or operate as dedicated outdoor air system [24–27].

Heating coils have also important applications whenever a device needs to reject heat to the atmosphere during its operation, such as through the condenser of a vapour-compression refrigeration cycle [9,10,28–31]. Enhanced operation of wasting heat can be achieved by combining the heat exchanger with evaporative cooling [32–34] or by using nanofluids as heat transfer fluid [35,36].

The dynamic simulation of the overall performance of a heating coil, either just the coil of a fan coil unit or together with other devices of an air handling unit, can be addressed by both LMTD (Logarithm Mean Temperature Difference) and ε- NTU methods [37] under the assumption of considering negligible coil thermal capacitance. In both methods, the overall thermal resistance must be estimated considering the variation of the convective thermal resistances with the velocity and properties of the fluids.

The effectiveness-based model validated by Angrisani et al. [38] under the assumption of constant effectiveness was used in the dynamic simulation of a system operating with constant air volume [39]. This model seems to be feasible only if the convective thermal resistance on the hot side is very low. When extending its application to the simulation of systems with variable flow rates, as done by Cejudo-Lopéz et al. [24], highly inaccurate results can be obtained.

Several works have been addressed by evaluating each convective thermal resistance through an empirical correlation generally in the form of $R_\varphi = R_{\varphi,ref}(FR_{\varphi,ref}/FR_\varphi)^{n_\varphi}$, where FR represents the mass or volume flow rate [40–47], however neglecting the influence of the fluids' properties. The influence of the velocity of both flows on the overall thermal resistance must be taken into account when simulating a variable-airflow system; and even in constant airflow operation, because the heat transfer fluid flow rate can vary by the action of a two- or three-way control valve.

The authors have recently investigated the feasibility of several versions of the approach based on the effectiveness method [47]. These versions differ from each other mainly in the adopted effectiveness correlation, taken from the literature for several heat exchanger configurations: (*i*) cross-flow, both fluids unmixed and