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Frost formation and freeze protection with bypass for counter-flow recuperators

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ABSTRACT

An accurate and efficient model based on the modified ε-NTU method was developed for numerical simulations and analysis of coupled heat and mass transfer inside the counter-flow plate heat exchanger under frosting operating conditions. The proposed model was validated with experimental data. The successful comparison between simulated and experimental data indicates that the developed model is capable to predict adequately operating performance of the counter-flow plate heat exchanger under sub-zero outdoor air temperature conditions. Three active heat and mass transfer areas were established in a counter-flow plate heat exchanger equipped with bypass damper and face and bypass dampers. The detail analysis of these particular heat and mass transfer zones creation revealed the most probable variants of year-round operating conditions of the counter-flow heat exchanger. The implementation of the particular variant of heat and mass transfer depends upon the relations of the temperatures in two decisive zones on the return air channel surface (in the "*cold*" and "*hot*" *zone*) and the value of the inlet return airflow dew point temperature. It was established, that the most unfavourable operating conditions at sub-zero outdoor air temperature occur at the value of inlet return air dew point temperature equalled to 0 °C. Unfortunately, such value of dew point temperature corresponds to the normal indoor air conditions in winter season. The values of critical outdoor temperatures were determined on the base of parametric frosting limits analysis conducted under different inlet return airflow conditions for different values of heat recovery efficiency of the counter-flow plate heat exchanger at different opening levels of face and bypass dampers. It was established, that the frost tends to take place with increasing temperature effectiveness of the heat exchanger. It was established, that the fully open bypass technique does not provide complete frost protection under sub-zero outdoor air temperature operating conditions.

1. Introduction

Increasing global energy consumption, environmental protection and legal requirements forced the rational exploitation and management of the energy resources. In that context, researchers are constantly working on improving the existing or newly designed ventilation systems, known as the dominant consumers of electricity and heat [1]. The commercial and residential buildings use energy for heating, cooling and ventilation, therefore there is a high potential to reduce their energy consumption by using effective heat recovery devices.

Heat recovery can be potentially applied to any HVAC system which supplies and exhausts air from buildings. It's worth noting that nowadays, ventilation in new buildings is obligated to contain some form of heat recovery, due to the current regulations [2].

Based on the literature review, it was found, that a behaviour and performance of heat exchangers has been extensively studied. Alonso et al. [3] focused on energy recovery systems used in air handling units designed for apartment buildings located in cold climates countries. The authors compared the heat exchanger recovering only sensible heat with energy exchangers recovering both sensible and latent heat. Mardiana-Idayu and Riffat [4] presented the review of heat and energy recovery technologies for building applications. They described the classification of heat/energy recovery systems based on different airflow arrangements. Jung and Jeong [5] evaluated analytically the flow mal-distribution effect on effective NTU in a single body multi-channel counter-flow heat exchanger. Ghosh et al. [6] developed a novel algorithm for the analysis of multistream heat exchangers. Rao et al. [7] analysed the effect of the airflow distribution to the channels on the

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Nomenclature

c specific heat capacity, J/(kg·K)
D_H hydraulic diameter of the plate channel, m
F heat or heat and mass transfer surface area, m^2
F_o total surface area, m^2
$\bar{F} = (F/F_o) \cdot 100\%$ heat or heat and mass transfer surface area relates to total surface area, %
G moist air mass flow rate, kg/s
H height of heat exchanger channel, m
$\mathrm{Le} = \alpha/(\beta c_p)$ Lewis factor, dimensionless
L_{X_1} channel of heat exchanger in X_1 direction, m
L_{X_2} channel length of heat exchanger in X_2 direction, m
L_Y channel width of heat exchanger, m
M water vapour mass transfer rate, kg/s
p_g^{sat} water vapour saturation pressure, Pa
$p_{g,fr}$ water vapour pressure at the air/frost interface, Pa
$p_{g,fr}^{sat}$ water vapour saturation pressure, Pa
Pr Prandtl number, dimensionless
q_{fr}^o heat of fusion of frost, $q_{fr}^o \approx 330$ kJ/kg
q heat flux, W/m^2
Q heat transfer rate, W
r^o specific latent heat of the liquid-gas transformation for water at 0 °C, $r^o \approx 2500$ kJ/kg, kJ/kg
S supersaturation degree, dimensionless
Re Reynolds number, dimensionless
t temperature, °C
$\bar{t}$ average temperature, °C
V air volumetric flow rate, m^3/s
w airflow velocity, m/s
W heat capacity rate of fluid, W/K
x humidity ratio, kg/kg
$\bar{x}$ average moisture content, kg/kg
X or X_1 Cartesian coordinate in X direction (along outdoor airflow direction), m
$\bar{X}_1 = X_1/L_{X_1}$ relative X coordinate, dimensionless
X_2 Cartesian coordinate in opposite to X direction, m (along return airflow direction)
$\bar{X}_2 = X_2/L_{X_2}$ opposite X coordinate, dimensionless
Y Cartesian coordinate in Y direction, m
α convective heat transfer coefficient, $W/(m^2 \cdot K)$
β convective mass transfer coefficient, $kg/(m^2 \cdot s)$
δ thickness, m
ε temperature effectiveness of heat exchanger, dimensionless
η heat recovery efficiency, dimensionless
λ thermal conductivity, W/(m·K)
λ_{fr}^{eff} frost effective thermal conductivity, W/(m·K)
τ time, s
$\tau_o = w_2/L_Y$ time of the return airflow contact with the plate surface in the return airflow channel, s
$\bar{\tau} = \tau/\tau_o$ relative time of the return airflow contact with the plate surface in the return airflow channel, dimensionless
σ surface wettability factor (0.0...1.0), dimensionless

Subscripts
• referenced to the elementary plate surface
' condition at the airflow/water film or airflow/frost layer interface temperature
1 outdoor airflow
2 return airflow
avg average value
b barometric pressure
cond heat transfer by thermal conduction
const constant
BP bypass
D_H referenced to the hydraulic diameter of the plate channel
DP referenced to dew point temperature
EA exhaust air parameters measured on the test bench
g water vapour
eff effective
H referenced to the plate channel height
HE heat exchanger
i inlet
fr frost layer
L latent heat flow
max maximum value
min minimum value
o outlet
OA outdoor air parameters measured on the test bench
p plate surface/under constant pressure conditions
plt channel plate
RA return air parameters measured on the test bench
S sensible heat flow
SA supply air parameters measured on the test bench
sat saturation state
sub water vapour sublimation
trshld threshold value of outdoor air temperature
$\tau = 0$ referenced to initial time of frost formation
w water film

Acronyms
AHU Air Handling Unit
$\mathrm{NTU} = \alpha F/(G c_p)$ Number of Transfer Units
RH Relative Humidity

thermal performance of a plate heat exchanger. Liu et al. [8] analysed a novel quasi-counter-flow membrane energy exchanger and developed an analytical model to predict heat and moisture transfer in the heat exchanger core under low operating temperatures conditions. They concluded that the sensible and latent heat effectiveness are not sensitive to outdoor airflow temperature when there is no condensation and frost formation on the plate surface. Rose et al. [9] described a quasi-steady-state model of a counter-flow air-to-air heat-exchanger that takes into account the effects of condensation and frost formation. The model was developed using an Excel spreadsheet. The authors used this model to analyse control strategies for a particular heat exchanger design under different climatic conditions. Zhang [10] described a quasi-counter flow total heat exchanger and analysed coupled heat and mass transfer in membrane-formed parallel-plates channels. Bell et al. [11] presented a novel algorithm which can be used to determine the steady state thermal heat transfer rate for counter-flow heat exchangers under different phase change conditions. Vali et al. [12] studied the performance of the counter-cross-flow liquid-to-air membrane energy exchanger. The authors developed a numerical model for investigate the fluid flow and heat and mass transfer in the energy exchanger. Moreover, they compared the counter-cross-flow LAMEE effectiveness with the effectiveness of pure counter-flow and pure cross-flow liquid-to-air membrane energy exchanger. The authors found that the effectiveness of the counter-cross-flow LAMEE is lower than a counter-flow but higher than a cross-flow LAMEE with the same geometry parameters and operating specifications. Saha and Baelmans [13] described one-