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Frost formation in the cross-flow plate heat exchanger for energy recovery

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ABSTRACT

The paper is focuses on the numerical simulation and analysis of coupled heat and mass transfer under ice formation conditions in the cross-flow plate heat exchanger. The simulation is performed using the original mathematical model. The presented model was validated against experimental data. The obtained results showed satisfactory agreement with the data obtained from the experimental measurements. Numerical simulation reveals many unique features of considered heat exchanger connected with the heat and mass transfer occurring in the return air channel under ice formation conditions. The results of computer simulation showed that the efficiency gains are sensitive to various inlet conditions, and allow for estimation of the safe operating conditions for different inlet return airflow parameters, based not only on the exhaust air temperature but also on its relative humidity and different thermal efficiency of the exchanger. Several goals were achieved, including: establishing the most unfavorable operating conditions (from the standpoint of ice formation on the plate surface of the return air channels) for cross-flow plate heat exchanger, which correspond to the inlet value of the return airflow dew point temperature equaled to 0 °C, impact of the ice formation on temperature effectiveness, impact of inlet relative humidity on temperature effectiveness and safe operating conditions and safe operating conditions for variety of inlet exhaust air parameters.

1. Introduction

Heat recovery can be defined as the re-use of heat from any technical or physical process that would otherwise be irreversibly lost. Heat recovery can help to reduce the overall energy consumption, or provide useful heat for other purposes. Most of the newly designed buildings using energy for heating, cooling, ventilation or any sort of industrial process have the potential to benefit from the application of heat recovery devices [1].

Air-to-air energy recovery systems are applied in buildings to precondition the supply air by using the energy from the exhaust air to increase efficiency of the HVAC systems [2]. The increased energy consumption, environmental protection, and legal requirements resulted in the rational management of energy resources. Therefore, actions are used to improve the effectiveness of air conditioning and ventilation systems, the major consumers of electricity and heat [3]. Heat exchangers have been used extensively and play an important role in the capital cost, energy efficiency and physical size of air conditioning and ventilation systems [4].

There are a lot of types of heat recovery systems. Thermal wheel technology offers the greatest percentage of heat recovery within an air system, and therefore the greatest reduction in energy. However, there are limitations due to the physical size of the unit as well potential for cross contamination of the air streams. A ventilation heat pump heat recovery system is built for efficient energy transfer from one air stream to another where the two systems are physically independent from each other. Heat pumps can provide either heating or cooling energy to the coil located within the supply air stream. This system can be added retrospectively within existing and separate air handling units [1].

From the literature it can be observed, that plate heat recovery exchangers have been studied by many researchers and the interest in the heat recovery technologies used for air-conditioning systems is constantly growing. In brief, the improvement of the plate heat recovery techniques and designs relies on the following principles:

- Application of multistage heat recovery process within the confines of one unit;
- using plastic plates as a structural material for the heat transfer matrix.

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Nomenclature

c_p	specific heat capacity of moist air, J/(kg K)
F	heat or heat and mass transfer surface area, m^2
G	moist air mass flow rate, kg/s
H	height of heat exchanger channel, m
$Le = \alpha/(\beta c_p)$	Lewis factor, dimensionless
L_X	length of heat exchanger in X direction, m
L_Y	length of heat exchanger in Y direction, m
M	water vapor mass transfer rate, kg/s
$NTU = \alpha F/(Gc_p)$	Number of transfer units, dimensionless
q_{ice}	heat of fusion of ice, $q_{ice} \approx 330$ kJ/kg
q	heat flux, W/m^2
Q	rate of heat transfer, W
r	latent heat of the liquid–gas transformation, kJ/kg
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	Cartesian coordinate in X direction (along outdoor air flow direction), m
$\bar{X} = X/L_X$	relative X coordinate, dimensionless
Y	Cartesian coordinate in Y direction, m (along return air flow direction)
$\bar{Y} = Y/L_Y$	relative Y coordinate, dimensionless
Z	Cartesian coordinate in Z direction, m
$\bar{Z} = Z/H$	relative Z coordinate, dimensionless
α	convective heat transfer coefficient, W/(m^2 K)
β	mass transfer coefficient, kg/(m^2 s)
δ	thickness, m ($\delta_{ice2} \approx 1.0 \cdot 10^{-3}$ m)
ε	thermal effectiveness, dimensionless
RH	relative humidity,%
λ	thermal conductivity, W/(m K), $\lambda_{ice} = 0.15$ W/(m K), $\lambda_w = 0.60$ W/(m K), $\lambda_{plt} = 200$ W/(m K)
τ	time, s
σ	surface wettability factor (0.0...1.0), dimensionless.

Subscripts:

●	referenced to the elementary plate surface,
′	condition at the air-plate interface temperature
1	outdoor air flow
2	return air flow
b	barometric pressure
cond	heat transfer by thermal conduction
const	constant
DP	referenced to dew point temperature
EA	exhaust air parameters measured on the test bench
i	inlet
ice	ice layer
L	latent heat flow
max	maximum value
min	minimum value
o	outlet
p	plate surface
plt	channel plate
OA	outdoor air parameters measured on the test bench
RA	return air parameters measured on the test bench
S	sensible heat flow
sat	saturation state
SA	supply air parameters measured on the test bench
trshld	threshold value
w	water film.

- Implementation of the combined air-flows arrangement, allowing to rise heat recovery effectiveness under safe operating conditions.
- Searching for optimum operating conditions and suitable climatic zones for the coolers on the basis of using the modern methods of optimization.

In this regard, it should be mentioned that there are some novel trends in heat recovery. One of the most important trends is total heat recovery with the membrane-based exchangers. According to the literature there were many studies connected with this subject in recent years. Liu et al. [5] presented analysis of Poly (vinyl chloride)/montmorillonite hybrid membranes for total-heat recovery. It was established that hybrid membranes have large roughness, good thermal stability, high water vapor transmission and a good temperature and enthalpy exchange effectiveness. Zhang et al. [6] presented an one-step fabrication and analysis of an asymmetric cellulose acetate membrane for heat and moisture recovery. It was established that the optimum solution compositions for casting membranes are: acetic acid to deionized water ratio 70:30. The authors claim to provide an environmental friendly yet economical solution for preparing membranes. Another interesting methods for heat recovery system is heating and humidifying using the Coolerado technology through the M-Cycle [7], which was proposed by Professor Valeriy Maisotenko as the new approach of meeting above mentioned principles. According to the producer (Coolerado Corporation). The proposed method is an alternative to the conventional energy-saving heating systems and allows a substantial economy of energy consumption (about 3 times) compared to the known systems, via the unique humidifying air recuperator [8]. This device allows for heat recovery and humidification of the air stream within one unit (Fig. 1). The exchanger is equipped with a membrane separating outside and return air channel. The water condenses on membrane from the return air and it is transferred to the outside air channel in order to humidify the supply air stream. Owning to a high efficiency of the M-Cycle the sensible and latent heat recovery process occurs very effectively. This device however is still on the testing level.

The most important feature of the heat exchanger is the cost of investment, servicing and operation with unmixed fluids. For these reasons, systems using cross-flow plate heat exchangers are very popular in Northern Europe (Fig. 2) [3].

A cross-flow plate heat exchanger (or recuperator) transfers heat between the supply and the exhaust streams of an air handing unit (Fig. 3). It recovers energy from returned air that would otherwise be lost to the atmosphere and uses it to pre-heat (or pre-cool) the incoming outdoor air. A plate heat exchanger is typically comprised of a series of parallel plates of aluminum, plastic, stainless steel or synthetic fiber, which direct the outdoor (supply) air and return (exhaust) air. Cross-flow heat exchanger has no movement parts, therefore it is more reliable and has long service life [9]. Manufacturers claim that the total efficiency varies between 50% and 80% depending on the specification of the unit. In traditional plate heat exchangers, sensible heat (containing no moisture) will pass through the plates dividing the two air streams. However, in modern ventilation systems it cannot be stated that only sensible heat is recovered with the plate recuperators [10]. Most of the office and public buildings require humidifying of the supply air flow to obtain the thermal comfort in the apartments. The exhaust