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Experimental methods for detecting frosting in cross-flow air-to-air energy exchangers

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ABSTRACT

Frost formation in air-to-air heat/energy exchangers is a challenging problem in regions with very cold weather conditions, when energy recovery is most needed. Membrane-based energy exchangers may assist in overcoming frosting. In this paper, an experimental facility was developed to enable researchers to test air-to-air exchangers under frosting conditions. The test setup, sensors and data acquisition system, uncertainty bounds for major parameters, and experimental procedure are described. Two geometrically identical plate exchangers: one with a water vapor permeable membrane (energy exchanger), and one with an impermeable plate (heat exchanger) were tested under frosting conditions. The first step in frosting experiments is to find a reliable and cost-efficient method to detect frosting in the exchangers. Four methods were used to determine the onset of frost growth: visual inspection, change in the effectiveness ($\Delta\varepsilon$), change in the pressure drop across the exchanger (Δp), and change in the outlet temperature (ΔT). The main contributions of the paper are the detailed comparison of these methods and the introduction of a new frost detection method based on temperature measurements only (ΔT method).

It is concluded that the Δp and ΔT methods were more reliable and practical than the other methods for both heat and energy exchangers. The ΔT method detected frosting sooner and with lower uncertainties than the other methods. Furthermore, the ΔT method was least affected by the operating conditions. On the other hand, the ΔP method gave a better indication of the severity of frosting in the exchanger as more frost resulted in a higher pressure drop across the exchanger.

1. Introduction

Air-to-air energy/heat exchangers are used in heating, ventilation and air-conditioning (HVAC) systems to reduce the energy used to condition the buildings. In these HVAC systems, fresh outdoor air (supply air) and the stale indoor air (exhaust air) pass through channels in the exchanger. Depending on the exchanger design, sensible energy (heat), or sensible and latent energy (heat + moisture) are transferred between the two air streams [1–3]. The energy transfer rate depends on the exchanger design and operating conditions [4,5]. However, in cold outdoor weather, frosting inside the exchanger negatively impacts the performance of the exchanger [6,7]. Frosting in exchangers can reduce the energy recovery by reducing the air flow, increasing the power consumption of fans, decreasing effectiveness, or deflecting the exchanger plates (creating flow maldistribution and possible physical damage). Protecting heat and energy exchangers from frosting has remained a challenge for decades [6]. This problem is more critical for the regions with arctic weather conditions such as Canada and Northern Europe, especially during the winter when the need and potential to recover energy from the indoor air is at its maximum.

Despite a large number of publications on frosting in energy exchangers, frost properties and models are limited to some specific surface geometries and temperatures [8–10]. There is a gap to understand the functional dependency of the frost-air interface temperature, which plays an important role in heat transfer analysis, makes it difficult to theoretically predict the behavior of an exchanger under frosting [11–16]. As a result, an experimental approach is necessary to study frosting in exchangers.

During frosting, warm and humid air (indoor air) that is flowing through the exchanger is cooled below the dew point temperature and the dew point temperature must below freezing. The conditions at which frost begins to grow in an exchanger is called the frosting limit. In this paper frosting limit is defined as the

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Nomenclature

Acronym

AHRI	air-conditioning, heating and refrigeration institute
ASHRAE	american society of heating, refrigerating, and air-conditioning engineers
ASME	american society of mechanical engineers
DAQ	data acquisition system
ERV	energy recovery ventilator
HRV	heat recovery ventilator
HVAC	heating, ventilation, and air conditioning
NSERC	natural sciences and engineering research council of Canada
SNEBRN	smart net-zero energy building strategic research network

English symbols

A	total heat or mass transfer surface area, m^2
a	half duct channel height in exchanger, mm
B	bias uncertainty
b	half duct channel width in exchanger, mm
C	$\dot{m}c_p$ for sensible, $\dot{m}h_{fg}$ for latent or $\dot{m}$ for total effectiveness
c_P	specific heat capacity of air, kJ/kg K
D_h	hydrodynamic diameter of an air channel, mm
D_{wp}	membrane water vapor diffusivity, m^2/s
EI	exhaust air inlet
EO	exhaust air outlet
H	exchanger height, mm
h	enthalpy, kJ/kg
h	convective heat transfer coefficient, $W/(m^2\ K)$
h_{fg}	heat of vaporization of water, kJ/kg
h_m	convective mass transfer coefficient, m/s
h_{sf}	heat of fusion (melting), kJ/kg
k	thermal conductivity, W/(m K)
L	exchanger depth/air channel length, mm
$\dot{m}$	mass accumulation rate of condensed water or frost, g/min
n	number of air channels in an exchanger
NTU	number of transfer unit, –
p	pressure, Pa
P	precision uncertainty
Q	volumetric flow rate, L/s
q	sensible, latent, or total transfer
Re	Reynolds number, –
RH	relative humidity, %
SI	supply air inlet
SO	supply air outlet
T	temperature, °C
t	time, min
t_f	time duration it takes to detect frosting, min
U_R	uncertainty of function R
U	overall heat transfer coefficient
u	velocity of air in channels
w	humidity ratio, g_{water}/g_{air}
X	exchanger width, mm

Greek symbols

ε	effectiveness, %
Δ	algebraic difference
α	apex angle for fin, °
δ	thickness (membrane, plate, frost), μm
φ	measured parameters such as T, RH, w
∂/∂	partial derivative

Subscript

a	dry air properties
avg	average value
E	exhaust
EI	exhaust inlet/indoor
f	fin
F or f	frosting
f/s	related to liquid or solid state of water
j	numeric indicator
l	latent heat
max	maximum
min	minimum
mix	fully mixed air properties
s	sensible heat
S or sup	supply
sf	solid to liquid
sg	solid to gas phase
SI	supply inlet/outdoor
tot	total
0	initial value
ΔT	related to ΔT method

combination of outdoor air temperature and indoor air relative humidity. There are only a few works in the literature which determined the frosting limit in air-to-air exchangers. Kragh et al. [17] measured frosting limit of −5 °C for typical counter-flow heat exchangers when the relative humidity was 42%. Fisk et al. [18] compared different cross-flow and counter-flow exchangers experimentally and concluded that a paper based cross-flow energy exchanger has a lower frosting limit temperature than the counter-flow and cross-flow heat exchangers. In another study, Holmberg [19] found that the frosting limit is approximately 5 to 10 °C lower in desiccant coated energy wheels than in heat wheels. Gazi [20] reported the frosting limit for an energy wheel between −20 °C and −25 °C through experiments. In general, energy wheels are more frost resistant than plate exchangers, however, the carryover of air from one stream to the other in wheels is undesirable in some applications. In contrast, carryover is insignificant in membrane energy exchangers compared to wheels.

In recent years, employing water vapor permeable membranes in the design of plate exchangers (called energy exchangers) has extended application of membranes [5,21]. In these exchangers, heat and moisture are transferred between two air streams simultaneously. The exchange of water vapor between the supply and exhaust air reduces the exhaust air dew point as it flows though the exchanger and as a result less frost is formed in the membrane-based exchangers [7]. Through a field test for a house in Ontario, Canada, Zhang et al. [22] found that the performance of an energy exchanger did not change until the supply temperature reached −16 °C. They also showed that defrosting cycle is needed 3.5 times more for a heat exchanger than for an energy exchanger [23]. In another field test [24], eight different energy exchangers were monitored during the winter, in Alaska, USA, without one frosting failure. However, the average outdoor temperature during monitoring time did not go below −16 °C and in some cases the exchangers were in defrosting cycle for 80% of their