Frosting in HRVs/ERVs and its impact on energy recovery

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Test conditions

- -40°C to +40°C
- 20% to 90% RH
- 400 cfm (200 L/s)
Overview of air-to-air energy exchangers

- **Heat Exchange – Adjacent Duct**
  - Flat Plate Exchanger (paper or membrane)
  - Energy (Enthalpy) Wheel

- **Energy Exchange – Adjacent Duct**
  - Flat Plate Exchanger (aluminum or solid plastic)
  - Heat Pipe

- **Heat Exchange – Non-adjacent Duct**
  - Heat Wheel

- **Energy Exchange – Non-adjacent Duct**
  - Exhaust Exchanger
  - Glycol Run-Around System

- **Run-around, Membrane Energy Exchanger (RAMEE)**

Why do exchangers frost?

- Less condensation and frosting when exchanger has:
  - Lower effectiveness ($\varepsilon$)
  - Moisture transfer
Energy exchanger frosting

- Frost (rule-of-thumb)
  - when line joining indoor and outdoor states crosses saturation line
- Reduce/avoid frosting
  - Decrease $\varepsilon$ (bypass, speed control, …)
  - Preheat outdoor air
  - Increase moisture transfer?

$\varepsilon = 75\%$
NSERC Smart Net-zero Energy Buildings strategic Research Network (SNEBRN)

• 2011-2016
• 29 Professors
• 15 Universities
• 5 M$ from NSERC + 2 M$ from NRCan, industry, utilities
• VISION:
  – The vision of SNEBRN is to perform the research that will facilitate widespread adoption in key regions of Canada, by 2030, of optimized NZEB energy design and operation concepts suited to Canadian climatic conditions and construction practices
Other projects

- NSERC Engage project
  - Frosting of air-to-air membrane energy exchangers
  - Jan-June 2013
  - 25 k$ from NSERC, in-kind from dPoint Technologies
Frosting in exchangers may:
- Decrease effectiveness
- Reduce air flow
- Increase fans’ power consumption
- Deflect the plate or membrane
Literature Review

Distribution of the published work from 1980-2013 on frosting in heat/energy exchangers.

Distribution of the published work from 1980-2013 based on the type of heat/energy exchanger.

Project Overview

- HRV/ERV operating conditions without frosting?
- Suitable frost protection strategies?
- Energy impact of frosting?

Objectives

1. Develop a test facility to investigate frosting in exchangers
2. Quantify the frosting limit operating conditions through experiments
3. Quantify the energy impact of frosting-defrosting cycles in energy recovery
4. Develop a theoretical model to predict the frosting limit

Frosting Limit: Experimental Approach

Frosting-Defrosting and Required Defrosting Time

Energy Impact of Frosting
## Experimental Approach: Methodology

### Methods to detect frosting
- Visual method (endoscope)
- Pressure drop ($\Delta P$)
- Effectiveness ($\varepsilon$)

### Frosting limit
- Heat Exchanger
- Energy Exchanger
- Repeatability test

### Operating conditions
- $T_{SI} = 0^\circ C$ to $-30^\circ C$ (controlled)
- $T_{EI} = 22^\circ C$ (controlled)
- $RH_{EI} = 10\%$ to $50\%$ (Controlled)
- $RH_{SI} = 35\%$ to $50\%$ (uncontrolled)
- $Q = 40$ cfm ($18$ L/s)
- Test duration: $\sim 3$ hr for the main frosting test
Experimental Approach: Test Facility
Experimental Approach: Test Facility

- Downstream Fans
- Downstream
- Test section
- Test box
- Upstream
- Exchangers
- DAQ
- Air duct
- Endoscope
- Pitot-tube
- Thermocouples
- Energy Exchanger
- Heat Exchanger
Experimental Approach: Visual Method

Heat Exchanger

Condition: $T_{SI} = -20^\circ\text{C}$

$RH_{EI} = 20\%$
Experimental Approach: Visual Method

Energy Exchanger

Condition: $T_{SI} = -20^\circ C$

$RH_{EI} = 20\%$
Experimental Approach: $\Delta P$ Method

Conditions: $T_{SI} = -20^\circ C$
$RH_{EI} = 20\%$

- Increase in $\Delta P \rightarrow$ Frosting due to partial blockage
- No change in $\Delta p$ in supply $\rightarrow$ No frost in the supply side
- Energy exchanger has lower $\Delta p$ change
Experimental Approach: $\varepsilon$ Method

Conditions: $T_{SI} = -20^\circ\text{C}$
$RH_{EI} = 20\%$

- Reduction in effectiveness due to frosting,
- More effectiveness reduction in the heat exchanger,
- Relatively low rate of change in the effectiveness
- Small change in the latent effectiveness
## Experimental Approach: Methods comparison

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Visual | - Easy to use  
         - Quickly detects frosting  
         - Low uncertainty  
         - Inexpensive | - Does not show the amount of frost inside the exchanger  
                      - Not practical in frost protection systems because it is qualitative method  
                      - Frequent maintenance required |
| $\varepsilon$ | - Shows the effect of frosting on the energy recovery  
         - Quantitative method | - Not reliable in practical applications due to high uncertainty  
                      - Complex in terms of installation of different sensors and measurement |
| $\Delta p$ | - Easy to use  
         - Relatively quick response to the presence of frost  
         - Quantitative method | - Relatively expensive  
                      - Frequent calibration is needed  
                      - Sensitive to flow rate |
Experimental Approach: Frosting limit

- Energy Exchanger experiences frosting at almost 5 °C lower Supply temperature or 5%RH higher Exhaust relative humidity
Objectives

1. Develop a test facility to investigate frosting in exchangers
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4. Develop a theoretical model to predict the frosting limit

FROSTING LIMIT: EXPERIMENTAL APPROACH

FROSTING LIMIT: THEORETICAL MODEL

ENERGY IMPACT OF FROSTING

FROSTING-DEFROSTING AND REQUIRED DEFROSTING TIME
Theoretical model: Frosting limit

Methodology
- Heat & Mass transfer equations

Frosting conditions
- Subzero surface temperature
- Condensation on the cold surface

Assumptions
- Frosting initially forms in the first exhaust air channel
- The supply air temperature passing over the first channel is constant
- Negligible condensation heat release
- ...
Theoretical model: Exchanger properties

### Exchangers specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of channels for each flow, ( n )</td>
<td>31</td>
<td>Lab measurement</td>
</tr>
<tr>
<td>Half duct height, ( a )</td>
<td>( 1.52 \pm 0.07 \text{mm} )</td>
<td>Lab measurement</td>
</tr>
<tr>
<td>Half duct width, ( b )</td>
<td>( 3.61 \pm 0.07 \text{mm} )</td>
<td>Lab measurement</td>
</tr>
<tr>
<td>Apex angle, ( \alpha )</td>
<td>( 49° \pm 2° )</td>
<td>Lab measurement</td>
</tr>
<tr>
<td>Hydrodynamic diameter, ( D_h )</td>
<td>( 2.63 \pm 0.16 \text{mm} )</td>
<td>Lab measurement</td>
</tr>
<tr>
<td>Exchanger width ( X ), height ( H ), depth ( L )</td>
<td>( 165 \pm 2 \text{mm} )</td>
<td>Lab measurement</td>
</tr>
<tr>
<td>Membrane thickness, ( \delta )</td>
<td>( 100 \pm 0.02 \mu m )</td>
<td>Lab measurement</td>
</tr>
<tr>
<td>Membrane water vapor diffusivity, ( D_{wp} )</td>
<td>( 2.0 \times 10^{-6} \pm 3 \times 10^{-7} \text{m}^2/\text{s} )</td>
<td>Lab measurement</td>
</tr>
<tr>
<td>Thermal conductivity of membrane, ( k_p )</td>
<td>( 0.44 \text{W/(m K)} )</td>
<td>(L. Zhang, 2008)</td>
</tr>
<tr>
<td>Thermal conductivity of fin, ( k_f )</td>
<td>( 237 \text{W/(m K)} )</td>
<td>(L. Zhang, 2008)</td>
</tr>
<tr>
<td>Thermal conductivity of air, ( k_a )</td>
<td>( 0.0258 \text{W/(m K)} )</td>
<td>(ASHRAE, 2009)</td>
</tr>
<tr>
<td>Density of air, ( \rho_a )</td>
<td>( 1.12 \text{kg/m}^3 )</td>
<td>(ASHRAE, 2009)</td>
</tr>
<tr>
<td>Water vapor diffusivity in the air, ( D_{va} )</td>
<td>( 2.82 \times 10^{-5} \text{m}^2/\text{s} )</td>
<td>(L. Zhang, 2008)</td>
</tr>
<tr>
<td>Kinetic viscosity of air, ( \nu_a )</td>
<td>( 15.52 \times 10^{-6} \text{m}^2/\text{s} )</td>
<td>(ASHRAE, 2009)</td>
</tr>
<tr>
<td>Volumetric air flow rates, ( Q )</td>
<td>( 20.8 \pm 0.5 \text{L/s} )</td>
<td>Lab measurement</td>
</tr>
<tr>
<td>Face velocity, ( u_a )</td>
<td>( 1.5 + 0.1 \text{m/s} )</td>
<td>Lab measurement</td>
</tr>
<tr>
<td>Reynolds Number, ( Re )</td>
<td>( 228+22 )</td>
<td>Lab measurement</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exchanger type</th>
<th>( \varepsilon_s )</th>
<th>( \varepsilon_l )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoretical</td>
<td>Experimental</td>
</tr>
<tr>
<td>HRV</td>
<td>58% ± 3%</td>
<td>58% ± 2%</td>
</tr>
<tr>
<td>ERV</td>
<td>58% ± 3%</td>
<td>58% ± 2%</td>
</tr>
</tbody>
</table>
Theoretical model: validation

Energy Exchanger

Heat Exchanger
Theoretical model: Parametric Study

\[
\text{NTU}_h = \frac{(UA)_s}{\dot{m} c_p} \quad \text{NTU}_l = \frac{(UA)_l}{\dot{m}} \quad \epsilon_{s/l} = 1 - \exp \left[ \frac{\exp\left(-\text{NTU}_{s/l}^{0.78}\right) - 1}{\text{NTU}_{s/l}^{-0.22}} \right]
\]
Objectives

FROSTING LIMIT: EXPERIMENTAL APPROACH

Develop a test facility to investigate frosting in exchangers

Quantify the frosting limit operating conditions through experiments

FROSTING-DEFROSTING AND REQUIRED DEFROSTING TIME

Quantify the energy impact of frosting-defrosting modes in energy recovery

FROSTING LIMIT: THEORETICAL MODEL

Develop a theoretical model to predict the frosting limit

ENERGY IMPACT OF FROSTING
Defrosting of exchangers

- Bypass the supply air

- Partial blockage of the supply air

- Using PCM

- Auxiliary Exchanger
### Defrosting of Exchangers

<table>
<thead>
<tr>
<th>Technique</th>
<th>Control parameter</th>
<th>Capital Cost</th>
<th>Operating Cost</th>
<th>IAQ</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preheating the inlet air</td>
<td>Air temperature</td>
<td>↔</td>
<td>↑</td>
<td>↔</td>
<td>Simple; Can be used as frost prevention</td>
<td>Not economical in regions with long cold seasons</td>
</tr>
<tr>
<td>Reducing or closing the supply air side</td>
<td>Flow rate</td>
<td>↔</td>
<td>↔</td>
<td>↓</td>
<td>Simple</td>
<td>May decrease IAQ. Increases infiltration to building;</td>
</tr>
<tr>
<td>Recirculating warm exhaust air</td>
<td>Flow rate</td>
<td>↔</td>
<td>↓</td>
<td>↓</td>
<td>Simple; Melting process can be enhanced by increasing flow rate; suitable for extremely cold climates.</td>
<td>No outdoor ventilation air during defrosting</td>
</tr>
<tr>
<td>Bypassing the supply air partially or fully</td>
<td>Flow rate</td>
<td>↔</td>
<td>↑</td>
<td>↔</td>
<td>Simple</td>
<td>Reduced energy recovery during defrosting</td>
</tr>
<tr>
<td>Reducing the effectiveness of energy wheel, Tilting</td>
<td>Rotational speed of energy wheel, Tilting angles in heat pipes</td>
<td>↔</td>
<td>↑</td>
<td>↔</td>
<td>Simple; Can be used as frost prevention</td>
<td>Longer defrosting time than other techniques; not applicable in plate heat/energy exchangers; reduced energy recovery during defrosting</td>
</tr>
<tr>
<td>Auxiliary exchanger or double core heat exchanger</td>
<td>Flow rate</td>
<td>↑</td>
<td>↔</td>
<td>↔</td>
<td>one exchanger provides energy recovery while other exchanger is defrosted</td>
<td>Increased capital cost for large or redundant exchanger; not enough experimental results are available under very cold temperature</td>
</tr>
<tr>
<td>Changing surface properties</td>
<td>Coating type and thickness, membrane permeability</td>
<td>↑</td>
<td>↔</td>
<td>↔</td>
<td>appropriate materials may significantly reduce the frosting limit</td>
<td>Depend on many parameters each design is different; uncertainty in material long-term performance and durability</td>
</tr>
<tr>
<td>Use of phase-change materials</td>
<td>Surface temperature</td>
<td>↑</td>
<td>↔</td>
<td>↔</td>
<td>Continues high performance running</td>
<td>Not enough experimental results are available under very cold temperature; difficult design and control system</td>
</tr>
<tr>
<td>Partial blockage of supply inlet</td>
<td>Flow rate</td>
<td>↔</td>
<td>↔</td>
<td>↔</td>
<td>Continues high performance running</td>
<td>The amount of the blockage or moving speed of belt and roller depend on operating conditions.</td>
</tr>
</tbody>
</table>

↔: No considerable change; ↑: Increase; ↓: Decrease.

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Frost accumulation rate

- Frost accumulation rate is almost constant
- Frost accumulation rate in the heat exchanger is 3 times of the energy exchanger
Frost removal rate

- Frost removal rate decreases with time.

- Energy exchanger has a higher frost removal rate and much shorter defrosting time.

- The trend in the heat exchanger is independent of the amount of frost accumulated.

Normalized defrosting time

\[ t_{df}^* = \frac{\text{Defrosting time}}{\text{Frosting duration}} \]

Defrosting time is from when the defrosting phase starts.
Defrosting time requirement

- DTR can be very different depending on the operating conditions and exchanger type
- The methodology can be applied for commercial HRVs/ERVs

Required defrosting time ratio

\[ DTR = \frac{\text{Defrosting duration}}{\text{Frosting duration}} \]
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Energy Impact of Frosting

Frosting Limit: Experimental Approach

Frosting Limit: Theoretical Model

Frosting-Defrosting and Required Defrosting Time
Energy impact of frosting-calculation method

\[ \varepsilon_{\text{average}} = \varepsilon_0 \cdot \frac{(t_f)}{t_{\text{tot}}} \]
Energy impact of frosting-calculation method

- **$T_{EI} = 22 \, ^\circ C$**
- **$T_{Sup} = 20 \, ^\circ C$**
- **$T_{SI} = f(t)$**

**Total sensible heat required**

**Recovered sensible heat by exchanger**
Energy impact of frosting: calculation method

- Total energy required
- Total energy recovered by exchanger

Graph showing energy impact with axes for $T_{\text{outdoor}}$ (°C) and $h$ (kJ/kg). Lines $h_{EI}$ (22°C, 40%RH) and $h_{SO}$ (20°C, 35%RH) illustrate the energy impact at different outdoor temperatures.
Energy impact of frosting

Energy loss due to frosting depends on:

1) Climate (higher in cold climate)
2) Exchanger (lower with ERV)
3) Frost control method (lower with frost prevention)
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FROSTING LIMIT: THEORETICAL MODEL

ENERGY IMPACT OF FROSTING

FROSTING-DEFROSTING AND REQUIRED DEFROSTING TIME
Future research

- Energy analyses
  - Other climates
  - Other commercial HRVs/ERVs with actual frost-control schemes
  - “Real” indoor humidity conditions

- Verify model and lab data with field data

- Frost-free exchangers
  - Design
  - Control
Collaboration towards low/zero energy buildings

- Test facilities
- Simulation tools
- Expertise
- HQP (students)

Solution

Innovation

Industry

University
Acknowledgement
Acknowledgement

• University of Saskatchewan

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• dPoint Technologies Inc.

• Norwegian University of Science and Technology

• NWT & Nunavut Construction Association
THANK YOU FOR YOUR ATTENTION