Simulating Air Leakage in Walls and Roofs Using Indoor and Outdoor Boundary Conditions

Simon Pallin, PhD
Diana Hun, PhD
Philip Boudreaux

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Outline

• Why Reducing Air Leakage Through the Building Envelope?
  – Market Potential

• So What, and Why is Moisture Durability Complicated?
  – Moisture Accumulation

• How Can We Predict the Impact of Air Leakage?
  – Modelling Limitations
  – Simulation Approach
  – Assumptions

• So How Can We Account for Moisture Accumulation?
  – Empirical Formula
  – Example of Usage
Building Envelope Market Potential

U.S. Primary Energy Consumption
98 Quadrillion Btu

Transportation 28%
Industrial 31%
Buildings 41%

Buildings-Residential 23%
Buildings-Commercial 19%

Residential Buildings
- Space Heating 28%
- Space Cooling 15%
- Water Heating 13%
- Lighting 10%
- Electronics 8%
- Refrigeration 6%
- Wet Cleaning 5%
- Cooking 4%
- Computers 2%
- Other 9%

Commercial Buildings
- Lighting 20%
- Space Heating 16%
- Space Cooling 14%
- Ventilation 9%
- Refrigeration 7%
- Electronics 4%
- Water Heating 4%
- Computers 4%
- Cooking 1%
- Other 20%
Building Envelope Market Potential

Primary Energy Consumption in Residential Buildings Attributable to Fenestration and Building Envelope Components in 2010 (Quads)

Roofs: 2.85 Quads
Walls: 1.88 Quads
Foundation: 0.95 Quads
Infiltration: 0.48 Quads
Windows (conduction): 1.49 Quads
Windows (solar): 0.48 Quads

In total = 2.85 Quads (2.85 \times 10^{15} \text{ Btu})
Building Envelope Market Potential

Primary Energy Consumption Attributable to Fenestration and Building Envelope Components for Commercial Buildings in 2010 (Quads)

- Roofs: 0.93 Quads
- Walls: 1.45 Quads
- Foundation: 0.58 Quads
- Infiltration: 1.14 Quads
- Windows (conduction): 1.3 Quads
- Windows (solar): 0.41 Quads

In total = 5.81 Quads (5.81 x 10^15 Btu)

103 million tons of coal

~ 490 million barrels of oil
Moisture Accumulation
Moisture Accumulation

“Energy Leak”

“Moisture Leak”
Moisture Accumulation

![Graph showing moisture accumulation with relative humidity on the y-axis, air flow rate on the x-axis, and vapor pressure difference indicated by a condensation plane.](image)
Moisture Accumulation

- **Condition inside the air leakage path without any air flow**
- **Low airflow**
- **High airflow**
- **Condensation plane**
- **Inflowing air condition**
- **Point of steady state inside air leakage path depending on air flow**
- **Theoretical directions towards steady state conditions**
Modelling Limitations

Exact vs. Simplified Steady State Solutions for Heat Exchange in an Air Channel - Adaption of Step Change

Adaption of Temperature Step Change (\(-\))

CFM (Air Volume Flowing Through the Air Gap)

Out

In

WUFI

Exact Sol. (1 ft from air entrance)
Exact Sol. (2 ft from air entrance)
Exact Sol. (4 ft from air entrance)
Exact Sol. (6 ft from air entrance)
Exact Sol. (8 ft from air entrance)
Simplified
Simulation Approach

1D Solution

\[ T_{12}(I) = \frac{(T_1 + \frac{I}{K_1}) \cdot K_1 + T_2 \cdot K_2}{K_1 + K_2} \]

\[ I = \rho_{air} \cdot c_{air} \cdot (T_2 - T_{12}(I)) \cdot \dot{Q} \]

\[ T_1 \quad \text{K}_1 \quad T_{12} \quad \text{K}_2 \quad T_2 \]

2D Solution

\[ T(x) = T_1 + (T_2 - T_1) \cdot e^{\left(\frac{-x}{l_c}\right)} \]

\[ l_c = \frac{\rho_{air} \cdot c_{air} \cdot \dot{Q}}{L_{surf} \cdot K} \]
Simulation Approach

1D Solution

\[ T_{12}(I) = \left( \frac{T_1 + \frac{I}{K_1}}{K_1} \right) \cdot K_1 + T_2 \cdot K_2 \]

2D Solution

\[ T(x) = T_1 + (T_2 - T_1) \cdot e^{\left( -\frac{x}{l_c} \right)} \]

\[ \eta = \frac{T(x) \cdot K - T_2 \cdot K_2}{K_1} - T_1 \cdot K_1 \]

\[ \rho_{air} \cdot c_{air} \cdot (T_2 - T_{12}(I)) \cdot \dot{Q} \]

\[ ACH_\eta = \eta(x, \dot{Q}) \cdot ACH \]
Simulation Approach

Elevation of test wall

Cross-section

- Wall Cavity A
- Wall Cavity B

- Temperature
- Temperature and relative humidity
Simulation Approach

Calculated vs. measured steady-state temperatures at a leakage rate of 5.8 cfm (2.7 l/s).
Simulation Approach

- Where are these moisture leaks?
- Flow pattern?
Simulation Approach – Inward Flow

Airflow entry point — Potential airflow path
Simulation Approach – Outward Flow
Simulation Approach - Assumption

Out

CFM

Temperature

Adapting rate

CFM

Ratio of adaption

Vapor Pressure

Ratio of adaption

Temperature

Out In

Adapting rate

CFM

Simulation Approach - Assumption
Simulation Approach - Assumption

Air flow rates rarely exceed 1 cfm
Simulation Approach - Assumption

Air flow rates rarely exceed 1 cfm
A comparison between WUFI 2D and WUFI 1D reveals that the 1D tool is capable of simulating air leakage at any location inside the air leakage path.
Simulation Approach - Validation

Temperatures inside an air leakage channel at 20Pa pressure difference

- Measured
- Simulated with η-method
- Without air leakage

Temperature (F)
Length from point of air entrance (in)

Out
In

CFM
Simulation Approach - Validation

Temperatures inside an air leakage channel at 40 Pa pressure difference

- Measured
- Simulated with η-method
- Simulated without air leakage

CFM

Out

In

Temperature (F)

Length from point of air entrance (in)
Empirical Formula

Essential Inputs to account for Air leakage in the Assessment:

- Wind forces
- Wall air tightness
- $R$-value

Output:
- Air flow rate
Empirical Formula

Essential Inputs to account for Air leakage in the Assessment:

• Wind forces
Essential Inputs to account for Air leakage in the Assessment:

- Wall air tightness

Künzel, H. et.al. (2011). Vapour control design in wooden structures including moisture sources due air exfiltration.
Empirical Formula

Essential Inputs to account for Air leakage in the Assessment:

- Wall air tightness

  ACH50

  Energy leak  Moisture leak

  90%  10%
Empirical Formula

Essential Inputs to account for Air leakage in the Assessment:

- $R$-value

<table>
<thead>
<tr>
<th>CLIMATE ZONE</th>
<th>FENESTRATION $U$-FACTOR $^b$</th>
<th>SKYLIGHT $^c$ $U$-FACTOR</th>
<th>GLAZED FENESTRATION SHGC $^b$ $^c$</th>
<th>CEILING $R$-VALUE</th>
<th>WOOD FRAME WALL $R$-VALUE</th>
<th>MASS WALL $R$-VALUE</th>
<th>FLOOR $R$-VALUE</th>
<th>BASEMENT $R$-VALUE</th>
<th>SLAB $R$-VALUE &amp; DEPTH</th>
<th>CRAWL SPACE $R$-VALUE</th>
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<tbody>
<tr>
<td>1</td>
<td>NR</td>
<td>0.75</td>
<td>0.25</td>
<td>30</td>
<td>13</td>
<td>3/4</td>
<td>13</td>
<td>0</td>
<td>0</td>
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<tr>
<td>2</td>
<td>0.40</td>
<td>0.65</td>
<td>0.25</td>
<td>38</td>
<td>13</td>
<td>4/6</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>3</td>
<td>0.35</td>
<td>0.55</td>
<td>0.25</td>
<td>38</td>
<td>20 or 13+5$^h$</td>
<td>8/13</td>
<td>19</td>
<td>5/13$^f$</td>
<td>0</td>
<td>5/13$^f$</td>
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<tr>
<td>4 except Marine</td>
<td>0.35</td>
<td>0.55</td>
<td>0.40</td>
<td>49</td>
<td>20 or 13+5$^h$</td>
<td>8/13</td>
<td>19</td>
<td>10/13</td>
<td>10, 2 ft</td>
<td>10/13</td>
</tr>
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<td>5 and Marine 4</td>
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<td>13/17</td>
<td>30$^g$</td>
<td>15/19</td>
<td>10, 2 ft</td>
<td>15/19</td>
</tr>
<tr>
<td>6</td>
<td>0.32</td>
<td>0.55</td>
<td>NR</td>
<td>49</td>
<td>20+5 or 13+10$^h$</td>
<td>5/20</td>
<td>30$^g$</td>
<td>15/19</td>
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<td>NR</td>
<td>49</td>
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<td>9/21</td>
<td>38$^g$</td>
<td>15/19</td>
<td>10, 4 ft</td>
<td>15/19</td>
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</table>
Empirical Formula

Wind, $W$ (mph)

Wall air tightness, $P$ (cfm/ft$^2$)  \[ Q(W, P) \]

Air Flow, $Q$ (cfm)

Empirical Formula

\[ Q = A + B \cdot W + C \cdot P + D \cdot W^2 + E \cdot W \cdot P + F \cdot P^2 \] (cfm)
Example of Usage

\[ Q = A + B \cdot W + C \cdot P + D \cdot W^2 + E \cdot W \cdot P + F \cdot P^2 \quad (cfm) \]

Low Range \( \Rightarrow \) \( W \leq 5 \) mph

High Range \( \Rightarrow \) \( W > 5 \) mph
Example of Usage

\[ Q = A + B \cdot W + C \cdot P + D \cdot W^2 + E \cdot W \cdot P + F \cdot P^2 \quad (cfm) \]

<table>
<thead>
<tr>
<th></th>
<th>R-20</th>
<th>R-20 + 3.75</th>
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<th>R-20 + 11.25</th>
<th>R-20 + 15</th>
<th>R-13</th>
<th>R-20 + 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.0709</td>
<td>-0.0598</td>
<td>-0.0876</td>
<td>-0.0976</td>
<td>-0.1018</td>
<td>0.07215</td>
<td>-0.0661</td>
</tr>
<tr>
<td>B</td>
<td>-0.1142</td>
<td>0.01123</td>
<td>0.04161</td>
<td>0.05457</td>
<td>0.06122</td>
<td>-0.1153</td>
<td>0.01777</td>
</tr>
<tr>
<td>C</td>
<td>-0.2439</td>
<td>0.18237</td>
<td>0.2744</td>
<td>0.30936</td>
<td>0.32504</td>
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<td>0.20294</td>
</tr>
<tr>
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<td>0.02163</td>
<td>0.00329</td>
<td>-0.0015</td>
<td>-0.0037</td>
<td>-0.0049</td>
<td>0.02178</td>
<td>0.00227</td>
</tr>
<tr>
<td>E</td>
<td>0.44165</td>
<td>0.28122</td>
<td>0.21963</td>
<td>0.1871</td>
<td>0.1671</td>
<td>0.44241</td>
<td>0.26905</td>
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<tr>
<td>F</td>
<td>0.00751</td>
<td>-0.221</td>
<td>-0.2608</td>
<td>-0.2722</td>
<td>-0.2751</td>
<td>0.00983</td>
<td>-0.2306</td>
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Example of Usage

\[ Q = A + B \cdot W + C \cdot P + D \cdot W^2 + E \cdot W \cdot P + F \cdot P^2 \ (\text{cfm}) \]

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<td>-0.2599</td>
<td>-0.6423</td>
<td>-0.5036</td>
<td>-0.4064</td>
<td>-0.3419</td>
<td>-0.2534</td>
<td>-0.6214</td>
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<tr>
<td>B</td>
<td>0.01469</td>
<td>0.13171</td>
<td>0.1114</td>
<td>0.09502</td>
<td>0.08371</td>
<td>0.013</td>
<td>0.12917</td>
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<tr>
<td>C</td>
<td>0.17613</td>
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<td>1.73113</td>
<td>1.55883</td>
<td>1.42492</td>
<td>0.15629</td>
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<tr>
<td>D</td>
<td>0.00159</td>
<td>-0.0046</td>
<td>-0.0039</td>
<td>-0.0032</td>
<td>-0.0028</td>
<td>0.00167</td>
<td>-0.0045</td>
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<tr>
<td>E</td>
<td>0.50945</td>
<td>0.14144</td>
<td>0.08522</td>
<td>0.06698</td>
<td>0.05897</td>
<td>0.51235</td>
<td>0.12772</td>
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<tr>
<td>F</td>
<td>-0.6499</td>
<td>-1.2146</td>
<td>-1.0939</td>
<td>-0.9842</td>
<td>-0.9032</td>
<td>-0.6422</td>
<td>-1.201</td>
</tr>
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Example of Usage

IECC 2015
ACH50 = 3

ACH50 = 3

\[ P \approx 0.2 \text{ cfm/ft}^2 \]

R-20+5
Example of Usage

\[ Q = A + B \cdot W + C \cdot 0.2 + D \cdot W^2 + E \cdot W \cdot 0.2 + F \cdot 0.2^2 \]

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Example of Usage

\[ Q = A + B \cdot W + C \cdot 0.2 + D \cdot W^2 + E \cdot W \cdot 0.2 + F \cdot 0.2^2 \]

\[ Q = -0.0661 + 0.0177 \cdot W + 0.20294 \cdot 0.2 + 0.0023 \cdot W^2 + 0.2691 \cdot W \cdot 0.2 - 0.2603 \cdot 0.2^2 \]

\[ Q = -0.0347 + 0.0716 \cdot W + 0.0023 \cdot W^2 \]

Wind = 5 mph

\[ Q = 0.38 \, cfm \]
Example of Usage

<table>
<thead>
<tr>
<th>3 ACH50 &amp; R-20+5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind (mph)</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.3</td>
</tr>
<tr>
<td>0.4</td>
</tr>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>0.6</td>
</tr>
<tr>
<td>0.7</td>
</tr>
<tr>
<td>0.8</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

\[ Q = -0.0347 + 0.0716 \cdot W + 0.0023 \cdot W^2 \]
Discussion
Contact information

Simon Pallin, PhD
pallinsb@ornl.gov

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