Does heat, air, moisture modelling really help in solving hygrothermal problems

H. Hens

K.U.Leuven. Department of Civil Engineering, Laboratory of Building Physics
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Combined HAM modeling

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- Airflow?
- Not considering risk!

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Combined HAM modelling

Conservation of heat, mass and momentum

\[ \text{div(Flux of } X) + S(X) = -\frac{\partial X}{\partial t} \]

Flux equations: 2 types, diffusive and bulk

- Mass flux: \( q = -\lambda \text{grad}(T) \)
- Volume flux: \( g_v = -\partial \text{grad}(p) \)
- Water flux: \( g_w = -k_w \text{grad}(s) \)
- Water, saturated flux: \( g_w = -k_{w,\text{sat}} \text{grad}(P) \)
- Air flux: \( g_a = -k_a \text{grad}(P_a) \)

Storage (P: driving forces)

\[ \frac{\partial X}{\partial t} = \sum C_i \frac{\partial P}{\partial t} \text{ with } C_i = \frac{\partial X}{\partial P} \]
Combined HAM modelling

Equations of state

$p_{\text{sat}} = f(\theta, r_{eq})$

$h = c_p \theta + l_b$

Sorption isotherm

Geometry

Boundary, initial and contact conditions

Outside climate

Inside temperatures

Inside relative humidity

Air pressure distribution

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Mathematics

Materials assumed composed of equal REV’s

In principle, equations work with average values per REV

For REV’s infinitesimally small, a continuum approach applies

That results in PDE’s with variable coefficients

Solved numerically

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## Combined HAM modelling

### Basic material properties

<table>
<thead>
<tr>
<th></th>
<th>Storage</th>
<th>Transport</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General</strong></td>
<td>Density ($\rho$), porosity ($\Psi$)</td>
<td></td>
</tr>
<tr>
<td><strong>Heat</strong></td>
<td>Specific heat capacity ($c_p$)</td>
<td>Thermal conductivity ($\lambda$)</td>
</tr>
<tr>
<td><strong>Air</strong></td>
<td></td>
<td>Air permeability ($k_m$) or Air permeance coefficient ($a$) and flow exponent ($n$)</td>
</tr>
<tr>
<td><strong>Moisture</strong></td>
<td>Specific moisture content ($\xi$)</td>
<td>Vapor permeability ($\delta_v$) or vapor resistance factor ($\mu$)</td>
</tr>
<tr>
<td><strong>Liquid</strong></td>
<td></td>
<td>Moisture permeability ($k_m$)</td>
</tr>
</tbody>
</table>

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Weaknesses in actual modelling

Identical REV's?

Answer in a question format:

Very clear when mass related characteristics are considered.

General negative characteristics are considered.

Buffering and systems only accidental.

Porous systems only accidental.

REV's, i.e. homogeneous.

Flow characteristics typify.

Mass flows develop in the pores.

So: probability of getting identical.

Same material, same small amount of samples of equal material very small.

For same material showing characteristics showing.

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Weaknesses in actual modelling

Material properties

Example: water vapor resistance factor

Characterizes impact of porous system on water vapour flow by diffusion.

Defined as:

$$\mu = \frac{\delta_{v,a}}{\delta_v}$$

Straight pores with constant section perpendicular to the surface:

$$\mu = \frac{1}{\Psi_o}$$

Straight pores with constant section slope $\alpha$ with the surface:

$$\mu = \frac{1}{\Psi} \left( \frac{1}{\cos \alpha} \right)$$

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Water vapor resistance factor

Straight pores, angle $\alpha$, varying section

\[ \mu = \frac{1}{\Psi} \left\{ \frac{\Psi}{\cos \alpha} \sum_{i=1}^{n} \left[ \sum_{j=1}^{m} \left( \frac{d_j}{A_j} \right) \right] \right\} \]

In general: $\mu = \frac{1}{\Psi} \Psi_T$

with $\Psi_T$ tortuosity

$\Psi_T$ may vary substantially between samples of same material
Weaknesses in actual modelling

Water vapor resistance factor

Anyhow, $\mu$ expected constant for given sample
Not so for hygroscopic materials
Decreases with increasing relative humidity!
Also that relationship differs between samples.
Even function of temperature!

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Graphs showing vapor resistance factor vs. mean relative humidity for EPS and Sand-lime stone.
Weaknesses in actual modelling

Water vapor resistance factor

With n samples tested, how to calculate average $\mu$-value?

Not as: $\mu_m = \frac{\sum \mu}{n}$, but

If sample thickness equals material thickness:

$\mu_m = \frac{n}{\sum 1/\mu_i}$

Otherwise:

$\mu_m = \frac{1}{n_2} \sum_{j=1}^{n_2} \left( \frac{n_1}{\sum_{i=1}^{n_1} 1/\mu_i} \right)$
Weaknesses in actual modelling

Water vapor resistance factor

Complexity still grows when composite layers are considered.

Take veneer wall

Why such low values?
Cracks between blocks and head joints, voids in mortar joints

<table>
<thead>
<tr>
<th>Wall</th>
<th>Mean RH</th>
<th>Diffusion resistance factor blocks, $\mu$</th>
<th>Diffusion resistance factor veneer wall, $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>59</td>
<td>50</td>
<td>3.0</td>
</tr>
<tr>
<td>2</td>
<td>57</td>
<td>50</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Weaknesses in actual modelling

Contact resistances between layers

Almost never considered but reality

Different contacts:

Ideal (continuity holds)

Air layer (diffusion only, capillary transport blocked)

Real (pattern of voids and capillary contacts, contact layer different from bulk layers)

Problem: each situation different!

Contact resistances retard moisture transport between layers

Thin air layers, however, may promote air ingress, be capillary active and help gravity flow

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Cavity wall, as implemented in 1D models

Weaknesses in actual modelling

Geometry

Geometry used when applying models, always virtual picture. Reality very different. Where virtual picture is evaluated on HM transport, real part see HM plus air washing and gravity flow.
Weaknesses in actual modelling

Geometry
A simple one-dimensional roof section on paper
Turns out behaving in a three-dimensional way.

Why?
Vents
Weaknesses in actual modelling
Rain run-off

Rain impingement quite well predictable using CFD and droplet tracing
Learns that top corners and top zones see more wind driven rain than lower zones
Weaknesses in actual modelling

Rain run-off

Rain hitting a surface partially sucked partially evaporates partially runs of Sucked water no problem Run off main cause of rain leakage.

Run off mechanism and patterns difficult to predict. Water coming down may dilute or concentrate

\[ t_r = 0.62 \frac{A^2}{g_w} \]
Weaknesses in actual modelling

Wind pressure inducing moisture flow

Part of a main problem: accounting for pressure differences as cause of moisture flow

Wind pressures helps in pushing rain run-off to the cavity side through cracks between head joints and bricks

Experimental formula
(Vos, 1976)

\[ G_{sp} = 2.15 + 0.196G_{rv} + 0.0308\Delta P_a + 0.0017G_{rv}\Delta P_a \]
Weaknesses in actual modelling

Gravity effects

Gravity forces much stronger than wind
Induce analogous problems: leakages through joints, cracks, holes, voids, etc
Back to experimental formula for veneer leakage
Constant underlines importance of gravity

$$G_{\text{rsp}} = 2.15 + 0.196G_{\text{rv}} + 0.0308\Delta P_a + 0.0017G_{\text{rv}}\Delta P_a$$
Weaknesses in actual modelling

Air flow

Although well known as a phenomenon, correct simulation highly random.
Main reason: lack of knowledge on real geometry, included cracks, air layers, voids, etc.
Weaknesses in actual modelling

Not considering risk!

Risk: probability event will happen multiplied with severity of consequences
Randomness caused by uncertainty on influencing parameters
Future outside climate
Inside vapour release
Ventilation habit

Air pressure differences
Workmanship
Design weaknesses
Practice example

Large university building
Program demanded for underground parking, large lecture rooms, library, smaller seminar rooms and individual office rooms
Solved by lay-out which narrows from basement to top. Large lecture rooms below, library above, seminar rooms and offices on top
Result: building with oblique façade walls till the two highest floors
Cavity walls, oblique inside leaves in concrete
Problems faced

Severe cracking

Abundant traces of water penetrations under all windows, and in the middle of the walls.
Problems faced

View on oblique facade during rain shows run-off
Collects where the higher vertical facade touches the oblique part, provisional crack repair
Concentrated run of between oblique parts and window bays

Very intense... Run-off above the inconic hall
Problems faced

Intensive moss growth in the joints of the oblique veneer walls
Window sill wrongly detailed, drains water to the window frame, where no edge below is detailed that halts the water
Oblique veneer not bonded, favors buckling!
Analyzing the causes

Major cause: exposure to precipitation
Building form results in high wind-driven rain concentration on several surfaces
Oblique veneer walls even capture rain under windstill conditions
Water-repellant treatment increases water-load on mortar joints
Leaking water collects in the cavity, penetrates the insulation layer and humidifies the concrete inside leaf, where run-off bypass shrinkage cracks
Wall insulation facilitated veneer masonry cracking
Repairs

First proposal
Repacing oblique parts by stepwise retiring façade walls
May solve rain penetration problem
One bay finished
But
Veneer walls not raintight
Cavity leakage collects on concrete steps, could drain to the inside
Quite severe thermal bridging were concrete steps penetrate thermal insulation
Repairs

Second proposal
Demolishing oblique veneer walls
Standing seam zinc cover instead
Correct detailing very important, must solve whole bunch of problems without introducing new ones, such as reinforced thermal bridging, backside interstitial condensation, a.o.
Conclusion
How to become an expert in HAM?

Not by studying only

but additionally, by testing and gaining field experience