

## **Air flow effects on hygrothermal performance of lightweight assembly walls**

### ***Project overview***

The effect of air exfiltration on hygrothermal performance of a lightweight wall construction is investigated. The first project (1Wall) is used to adjust the air permeabilities of the gap and mineral wool for a given pressure difference. The second project (6Walls) is a 6-in-1 simulation, i.e. 6 walls under different indoor-outdoor air pressure differences are simulated together in one project.

### ***Questions for this exercise***

The current implementation of the air mass balance in CHAMPS is a quasi-steady-state solution (air pressures that are updated in short time intervals). The air mass balance is solved first and then the coupled heat and moisture balances. The time steps are chosen by the CVODE time integrator according to convergence criteria and accuracy settings.

The air flow model implemented needs to be validated. Purpose of this exercise is to give you an idea about the lightweight construction we would like to use for validation of the model. The validation can be done in several steps.

1. What are realistic numbers for air permeabilities of materials being used in assemblies?
2. Does the CHAMPS software calculate expected results in terms of air flows?
3. Does the CHAMPS software calculate expected results in terms of humidity and temperature fields?
4. What about moisture accumulation and heat losses?

This exercise is just the beginning of a model validation. Next steps to be taken are described at the end of this exercise report.

## Problem description

This example introduces simulation of air leakage effects by example of a typical lightweight wall assembly consisting of spruce, mineral wool, gypsum board and OSB-board. This construction is widely used in North America. There is air exfiltration flux from bottom to top due to imperfection of the air barrier. The air exfiltrates through an inlet close to the wood bottom plate, then it flows upward in the mineral wool and leaves through an outlet at the wood top plate.

Inlet and outlet are modeled as air gaps of 3mm width with connection to the mineral wool insulation. Mineral wool is the only air permeable material in this assembly. The vinyl siding is assumed to be rain tight; it is omitted here as well as the rain and radiation boundary conditions outside.

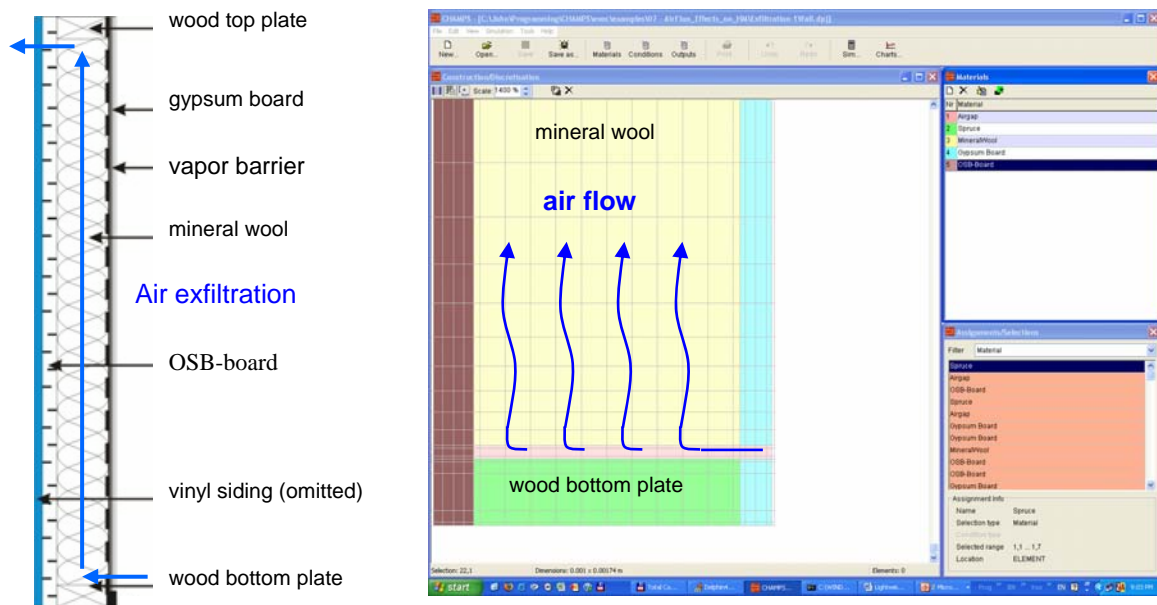


Fig. 1: Wall assembly and modeling of detail wood bottom plate in the CHAMPS program

Simulation of this example requires material properties of air. The air gap is treated as “special” material with hygrothermal properties, e.g. the sorption isotherm (moisture content versus relative humidity) is calculated from the ideal gas equation.

The air permeabilities of the mineral wool and the air gap are estimated from an integral air permeability of the wall assembly which is adjusted according to two simple approximations. The air exfiltration rate is calculated by the Sherman-Grimsrud model and the pressure difference indoor to outdoor is determined after Petzold. Both, the air exfiltration rate and the pressure difference are calculated as function of the average wind speed. Using numerical simulation, the specific air permeabilities can be adjusted such that the exfiltration rate is obtained at the given pressure difference.

With this information, six wall assemblies are studied in a second simulation run at different air pressure differences and the effects of air exfiltration on their hygrothermal performance are reported.

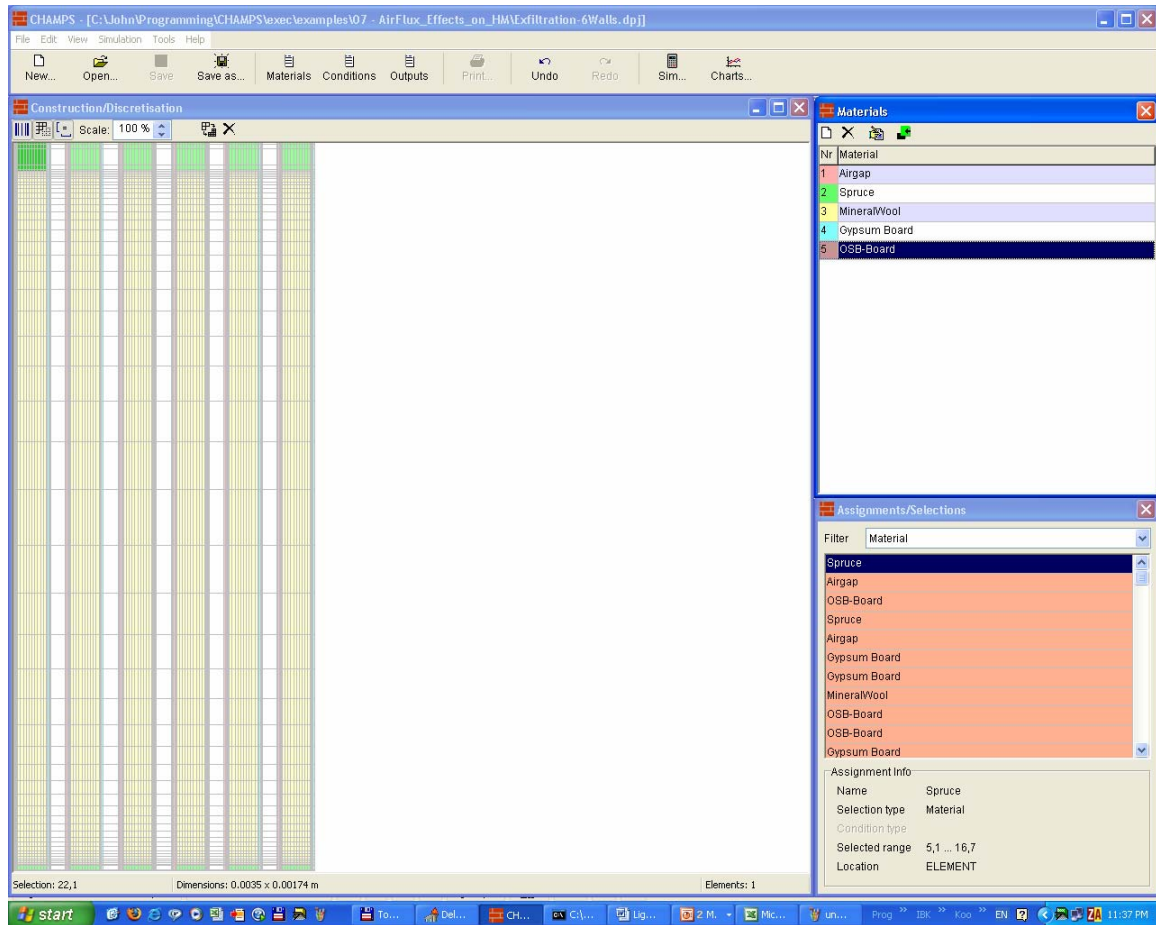


Fig. 2: Modeling of 6 assembly walls in one simulation setup

## **Boundary conditions**

The temperature and humidity boundary conditions are the same in both simulations (1 wall, 6 walls) and for each of the 6 assemblies in the second simulation.

*Tab. 1: Hygrothermal boundary conditions*

	Inside	Outside
Temperature	20 °C	10 °C
Relative Humidity	50 %	85 %

The air pressure boundary conditions are different for each of the 6 assemblies in the second simulation.

*Tab. 2: Air pressure boundary conditions of 1-wall simulation*

	Inside	Outside	Difference
Air pressure	101325 Pa	101317 Pa	8 Pa

*Tab. 3: Air pressure boundary conditions of 6-walls simulation*

	Inside	Outside	Difference
Air pressure assembly 1	101325 Pa	101325 Pa	0 Pa
Air pressure assembly 2	101325 Pa	101323 Pa	2 Pa
Air pressure assembly 3	101325 Pa	101321 Pa	4 Pa
Air pressure assembly 4	101325 Pa	101317 Pa	8 Pa
Air pressure assembly 5	101325 Pa	101309 Pa	16 Pa
Air pressure assembly 6	101325 Pa	101293 Pa	32 Pa

## **Initial conditions**

The initial conditions are set constant. Only temperature and relative humidity need to be specified. The air mass balance needs no initial air pressure since its stationary solution is calculated for each time interval.

*Tab. 4: Initial conditions*

	Initial value
Temperature	15 °C
Relative Humidity	65 %

## Estimation of air permeabilities

For estimation of the air flow rate, the Sherman-Grimsrud formula (Ref: ASHRAE Handbook of Fundamentals 1993, 23.19 equation 32) has been used.

$$Q_{air} = A_L \cdot \sqrt{c_s \cdot \Delta T + c_w \cdot U^2}$$

$Q_{air}$	Air flow rate in	[cfm]
$A_L$	Effective air leakage area	[in <sup>2</sup> ]
$c_s$	Stack coefficient	[cfm <sup>4</sup> / in <sup>4</sup> F]
$\Delta T$	Average indoor-outdoor temperature difference	[F]
$c_w$	Wind coefficient	[cfm <sup>4</sup> / in <sup>4</sup> mph <sup>2</sup> ]
$U$	Average wind speed	[mph]

The following tables show the calculation of the respective air flow rate using the input parameters from the simulation.

Tab. 5: Calculation sheet for air flow rate after Sherman-Grimsrud equation

Estimation of air flow rate after SHERMAN-GRIMSRUD					
Input parameters					
				m2	in2
Effective air leakage area	$A_L$		0.003	4.65	
				cfm2/(in4°F)	
Stack coefficient	$C_s$			0.03	
Temperature difference [indoor-outdoor]				°C	°F
		$T_i$	20	68	
		$T_e$	10	50	
		$\Delta T$	10	18	
				cfm4/(in4*mph2)	
Wind coefficient	$C_w$			0.0016	
				m/s	mph
Average wind speed	$U$		5	11.2	
				m3/h	cfm
Air flow rate (Sherman-Grimsrud)	$Q_{air}$		6.79	4.0	
Resulting air mass flux density	$j_{air}$		0.811	kg/m2s	

Tab. 6: Related information to Sherman-Grimsrud equation

Related information						
Estimation of effective air leakage area (accounts for all kind of leakage)						
$A_l = 0.133 \cdot A_{gross}$		$A_{gross}$	Wall gross surface area in ft <sup>2</sup>			
Stack coefficients in cfm <sup>2</sup> /(in <sup>4</sup> *F)						
1 Story		0.015				
2 Story		0.030				
3 Story		0.045				
Wind coefficients in cfm <sup>4</sup> /(in <sup>4</sup> *mph <sup>2</sup> )						
Shielding class		1	2	3	4	5
1 Story		0.01190	0.0092	0.0065	0.0039	0.0012
2 Story		0.01570	0.0121	0.0086	0.0051	0.0016
3 Story		0.00184	0.0143	0.0101	0.0060	0.0018

In a next step, the outdoor-indoor air pressure difference at luff and lee sides of a building is estimated. Petzold (Ref: Lehrbuch der Bauphysik, B.G. Teubner Stuttgart, ISBN 3-519-25014-4) gives following formula and drag coefficients.

$$\Delta p_{air} = c_d \cdot \frac{\rho_{air}}{2} \cdot U^2$$

$\Delta p_{air}$  Over- / under-pressure [Pa]

$c_d$  Drag coefficient [-]

$\rho_{air}$  Density of air [kg/m<sup>3</sup>]

$U$  Average wind speed [m/s]

Drag coefficients	min	max
Luff side (infiltration)	0.8	1.2
Lee side (exfiltration)	0.20	0.50

Tab. 7: Calculation sheet for air pressure difference estimation

Estimation of air pressure difference after PETZOLD					
Air density		$\rho_{air}$		1.29	kg/m <sup>3</sup>
Drag coefficient		$c_d$		0.50	---
Air pressure difference [indoor-outdoor] (assuming normal indoor air pressure)		$\Delta p_{air}$		8.06	Pa

Knowing the air flow rate and the pressure difference, one can set up a simulation and adjust the air permeabilities of the materials such that the program delivers the air flow rate at the given pressure difference.

In a first simulation, all permeable materials get the same (estimated) permeability (here  $K_{air,est} = 2.5e-2 s$ ). The resulting air mass flux density is taken to calculate an effective air flow path length. This characteristic length of the air flow path through the wall assembly is introduced since the pressure difference is known but the air permeability relates to an air pressure gradient.

$$l_{eff} = \frac{\Delta p_{air}}{j_{air,est}} \cdot K_{air,est}$$

$l_{eff}$       Effective flow path length      [m]

$K_{air,est}$       Estimated assembly air permeability      [s]

$j_{air,est}$       Air mass flux density using  $K_{air,est}$       [kg/m<sup>2</sup> s]

With the characteristic length of the air flow path the integral air permeability of the wall assembly can be calculated.

$$K_{air} = \frac{j_{air}}{\Delta p_{air}} \cdot l_{eff}$$

$K_{air}$       Assembly air permeability      [s]

$j_{air}$       Air mass flux density from Sherman-Grimsrud      [kg/m<sup>2</sup> s]

Tab. 8:      Calculation sheet for wall assembly's air permeability estimation

Estimation of air permeability of the wall assembly by simulation				
Estimated mean air permeability	$K_{air,est}$	2.50E-02	s	
(used in a first simulation - set all permeable materials to that value)				
Resulting air mass flux density	$j_{air,est}$	1.260	kg/m <sup>2</sup> s	
(resulting air mass flux density per effective leakage area)				
Effective flow path length	$l_{eff}$	0.160	m	
(the pressure difference is known but the permeability is related to a gradient)				
Air permeability of assembly	$K_{air}$	1.61E-02	s	
(the air mass flux divided by the pressure gradient using effective flow path length)				

With the determined  $K_{air}$ , the simulation program calculates the right  $j_{air}$ . In a final step, the air permeabilities of the air permeable materials can be differentiated. Here, we use  $K_{airgap} = 0.1 s$  and  $K_{minwool} = 0.0125 s$  which gives the same  $j_{air}$ .

## Simulation time and outputs

The total simulation time is 20 days. This time is needed to reach an almost stationary state. Slow moisture accumulation is still in progress at the end.

In this project setup, the field output definitions have been assigned to the whole range (all volume elements) causing the CHAMPS program to write field outputs of temperature, relative humidity and water content of all six assemblies together. This allows straight forward graphical comparison of the results for the different air flow rates.

In case of field outputs, the state variables of each cell are reported as function of time. This generates usually large data files. Therefore, it is recommended to set the BINARY output mode for a faster post processing. The figure below shows the fields of relative humidity and temperature at the end of simulation.

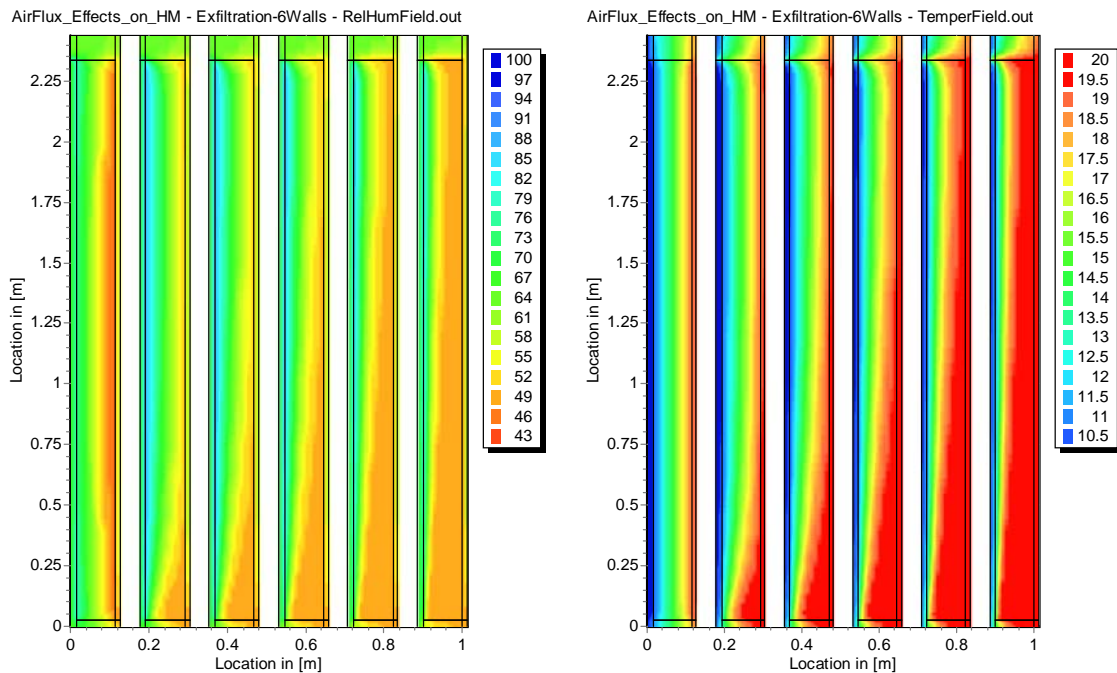


Fig. 3: Relative humidity field (left) and temperature field (right) at the end of simulation (after 20 days)

Further outputs of this project are the air mass flux densities, the heat flux densities and the integral water masses. Both flux densities are reported as averaged quantities over the internal surface (heat flux over the entire surface, air flux inlet surface only). The integral water mass is calculated for each assembly separately as volume-weighted sum of moisture mass densities over all volume elements. The moisture mass density ( $\text{kg/m}^3$ ) gets an absolute mass (kg) by multiplication with the volumes ( $\text{m}^3$ ).

The fluxes and integral outputs are numbered from 1 – 6 according to their assembly number they belong to (start numbering on left hand side with 1).

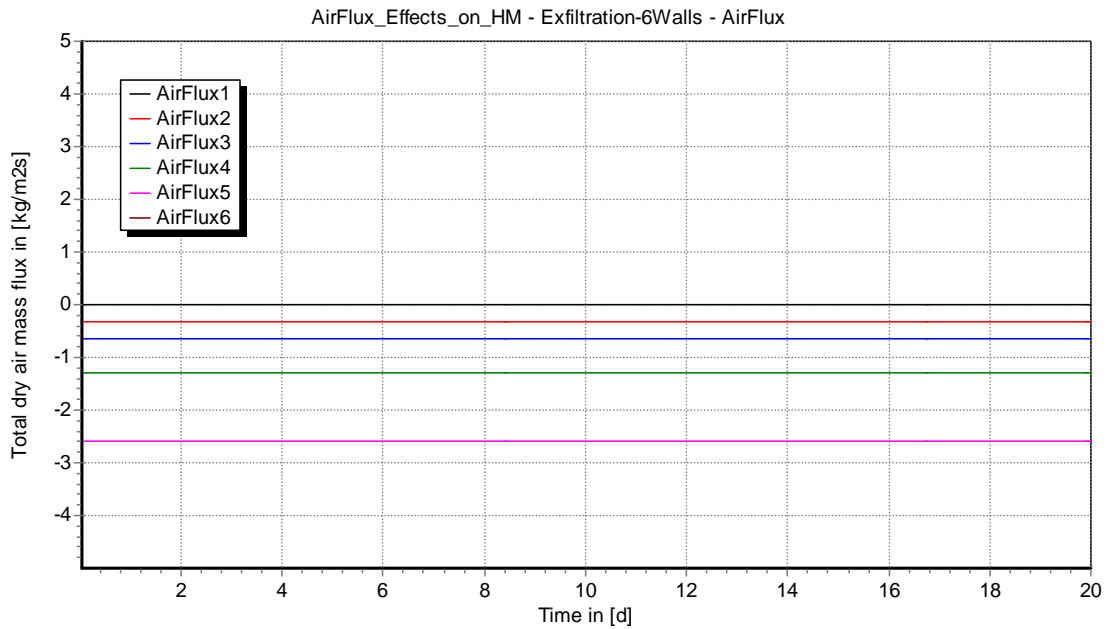


Fig. 4: Air mass flux densities reported by CHAMPS. The positive flux direction is defined from left to right. Here, exfiltration is a negative flux from right to left. The flux density increases with higher pressure difference.

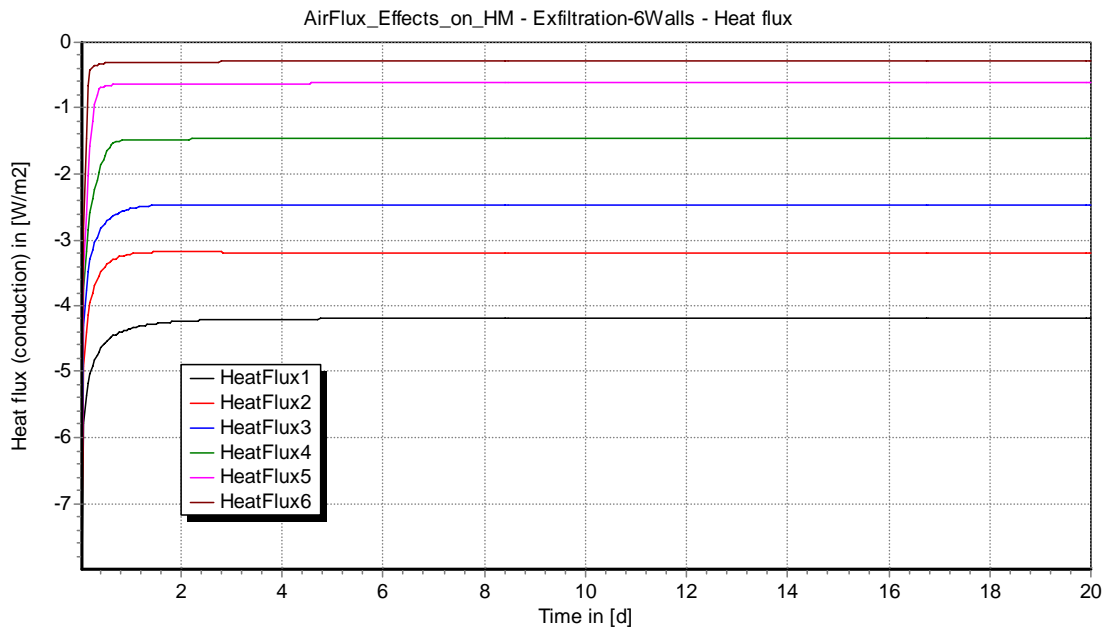


Fig. 5: Heat flux densities reported by CHAMPS (heat conduction only). More air flux warms the assembly up and reduces the heat loss by conduction. The advective heat loss is not included / reported here.

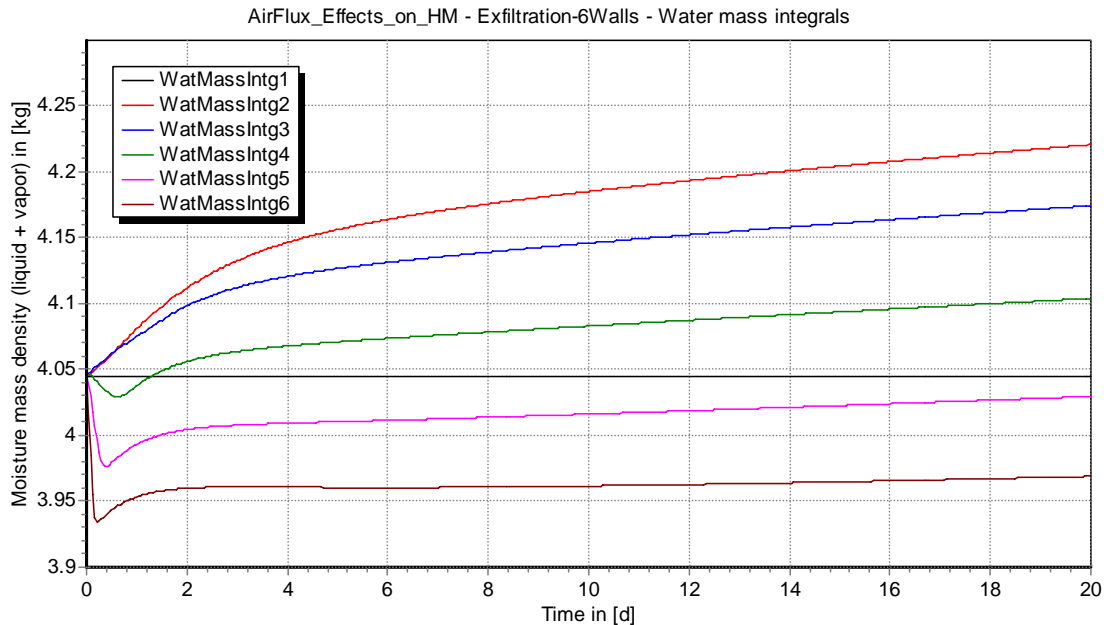


Fig. 6: The water mass integrals reported by CHAMPS. No air flux means no moisture accumulation since the construction is very tight. With air flux there is additional moisture introduced. Higher air fluxes reduce the moisture accumulation in the construction by the warming effect.

## Further questions and tasks

- Review simplified models to estimate the infiltration / exfiltration rates of air through lightweight envelope constructions;
- Review simplified models to estimate the air over / under pressure in dependence of wind speed at building luff and lee sides;
- Figure out "how much CFD-coupling" we need to model air flow effects on heat & moisture performance of lightweight building envelope systems as accurately as needed. Approach: Try to simulate just the air flows in this (or a similar) lightweight construction using CFD. CHAMPS can output the air flows and we can compare them with CFD-simulated ones. We can also do 3D simulations using CFD and use a 2D-subset of them as input to CHAMPS simulation and look at the differences in the HM-results (accumulation of condensation, thermal performance). The outcome could be a model-by-model validation in addition to an experimental validation.