Can adventitious ventilation negatively impact moisture performance of building envelopes in moderate climates?

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ABSTRACT

In moderate climates, adventitious ventilation helps in keeping the water vapor balance in a building under control. This does not hold in hot and humid climates, where the outside air is a moisture source. Adventitious ventilation should be avoided in such climates and intended ventilation flows must be dried before entering the space.

Anyhow, could adventitious ventilation also generate moisture problems in moderate climates? To get an answer, a reference case was analyzed with the air leakage distributed over facades and roof. The calculated results show adventitious ventilation may cause severe interstitial condensation in the envelope, if too air-leaky. Especially the roof is critical. Part of the vapor released inside could condense in the roof's section where it induces mold on laths and battens and may result in unpleasant dripping of. A confirmation was found in a practice case, where severe winter condensation was noted in the cathedralized ceilings of the sleeping rooms.

INTRODUCTION

In moderate climates, adventitious ventilation helps in keeping the vapor balance in a building under control (Annex 14, 1900) (Liddament, 1996). In winter, the outside air with its low vapor concentration dilutes the vapor produced inside, which in turn helps in controlling dust mite population, mold risk and the probability of severe surface condensation. In hot and humid climates instead, the outside air is a moisture source. In such climates adventitious air infiltration must be avoided and intended ventilation flows should be air-dried before entering the inhabited space (Moyer, 2001).

Hence, can adventitious flows also cause a deficient moisture performance in moderate climates? To answer that question, we did a simple steady state simulation of the air and vapor balance in the inside environment and the roof, using a terraced reference dwelling with the second floor cathedralized. Variables considered are: stack, wind, orientation, air leakage of the dwelling and the roof's air permeance. Then we looked to practice and found a clear example of what the simulations predict.

A REFERENCE CASE ANALYSED

Dwelling

Figure 1 shows the terraced reference. Volume: 288 m^3. Envelope surface (including roof and floor above grade): 287 m². Floor height: 2.7 m. Two roof pitches of 21,3 m² each with a 15° slope. Roof section (from inside to outside): (1) internal lining with a vapor diffusion thickness of 1.12 m, air permeance varying from poor to good, (2) 10 cm mineral fiber, (3) air space, (4) roof cover. The roof possesses no hygric inertia, giving an instantaneous moisture response especially when air in- or exfiltration intervenes. An open staircase connects the first to the second floor. The family of four, using the dwelling, releases 13.68 kg water vapor per day on the average. During daytime, sleeping and bath room stay open, which brings the dwelling close to a one-volume system. Ventilation is adventitious through leaks concentrated in and around the windows and at the roof level. Roof leakage is uniformly distributed over the inside lining. As the windows are equally distributed over the four façade parts (two facades with a first and second floor part), air leakage is also distributed that way, simplifying the dwelling to the 3-nodes hydraulic circuit of figure 2. Suppose the air-leakage of both the dwelling and the roof is fixed by a formula of the form (ASHRAE, 2001):

$$G_a = a\Delta P_a^{0.67} \quad (1)$$

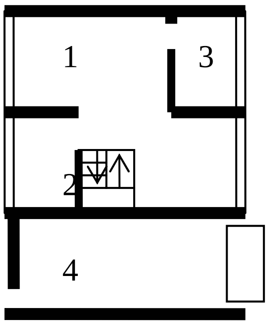

Figure 1 Reference dwelling, first and second floor (1: living room, 2 kitchen, 3 entrance, 4 garage, 5, 6, 8 sleeping rooms, 7 bathroom)

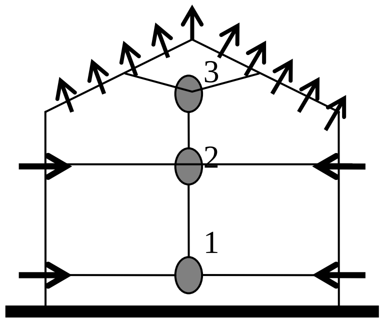

Figure 2 The dwelling as a leakage circuit

For the dwelling, the air-leakage coefficient (a) follows from a blower door test and is expressed in terms of a ventilation rate at 50 Pa for all leaks in parallel (n_{50}). The leakiest dwelling has n_{50}=12 h^{-1}, the most airtight one n_{50}=6 h^{-1}. Below 6 h^{-1}, a purpose designed ventilation system should be provided (Liddament, 1996). The highest permeance coefficient (a) for the roof is 4 10^{-4} kg/(m².s.$Pa^{0.67}$), the lowest 5 10^{-6} kg/(m².s.$Pa^{0.67}$). That interval of values was repeatedly measured for typical pitched roof solutions (figure 3) (Hens et al, 2003).

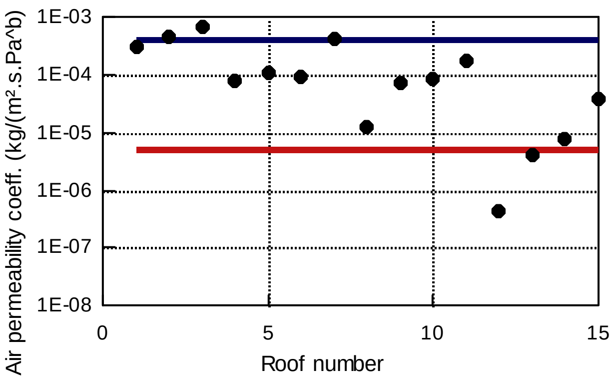

Figure 3 Measured air permeability coefficients for typical pitched roof solutions. The two lines show the upper and lower limit, used in the calculations

Simulations

In a first step, we kept n_{50} constant, independently of the roof's air-tightness. This means that a more airtight roof is compensated by higher air permeability of both facades and vice versa. Such hypothesis may seem strange. However, when measuring n_{50}, one never knows the correct location of the leaks, which means that any case between a more air-leaky roof and less air-leaky façades or a less air-leaky roof and more air-leaky facades is randomly probable.

Table 1, figure 4 and figure 5 shows some results in case thermal stack is the only driving force intervening. Outside temperature is 0°C, inside temperature 18°C, while the outside vapor pressure equals 580 Pa, i.e. values typical for a winter week in moderate climates. Table 1 underlines the clear relationship between n_{50} and the actual ventilation rate. Ratio between both: 25 to 28.6. The table also reminds of the commonly known fact in moderate climates that better ventilation results in lower vapor pressures inside. At the same time, however, more ventilation increases air exfiltration through the roof, although figure 4 shows that condensation deposit in it is much more governed by an increase in vapor pressure inside than by an increase in exfiltration. One even gets dramatic situations. When the roof's air permeance is high and the ventilation rate is low, nearly 89% of all vapor released inside condenses underneath the roof cover. Fortunately, that percentage decreases with increasing n_{50}-value and decreasing vapor pressure, to reach 42% for n_{50}=12 h^{-1}. Figure 4 in turn underlines that a better air-tightness of the roof anyhow offers a much more effective strategy in minimizing interstitial condensation than a higher overall air permeability. If a roof's permeance coefficient of 10^{-5} kg/(m².s.$Pa^{0.67}$) could be guaranteed, the percentages drop to 2.7% (n_{50}=12 h^{-1}), respectively 6% (n_{50}=6 h^{-1}). This hardly differs from the percentages which will be measured if the roof was perfectly airtight and diffusion only intervened (figure 5).

TABLE 1

Thermal stack only. 18°C inside, 0°C, 580 Pa outside. Ventilation flows, ventilation rate, inside vapor pressure

n_{50} h^{-1}	Air permeability roof a kg/(m².s,$Pa^{0.67}$)	Incoming ventilation First floor m³/h	Outgoing flow Second floor m³/h	Exfiltration through the roof m³/h	Ventilation rate h^{-1}	Inside Vapor pressure Pa
12	4 10^{-4}	138	63	75	0.48	1137
10	4 10^{-4}	114	43	71	0.40	1254
8.3	4 10^{-4}	93	25	68	0.32	1404
6	4 10^{-4}	62	2	60	0.21	1829

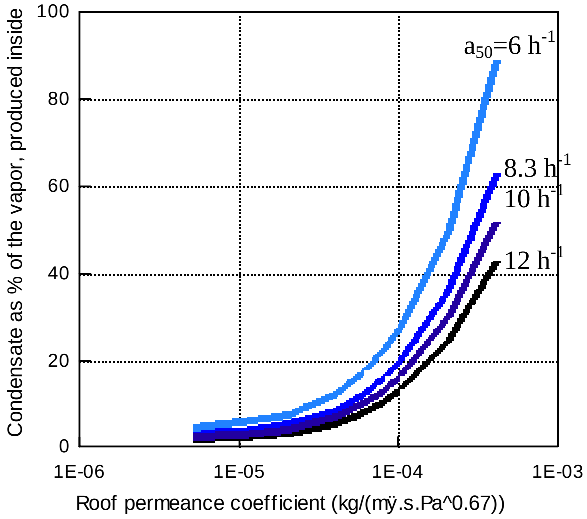

Figure 4 Stack only, 0°C outside, 18°C inside, percentage of the vapor released inside that condenses in the roof.

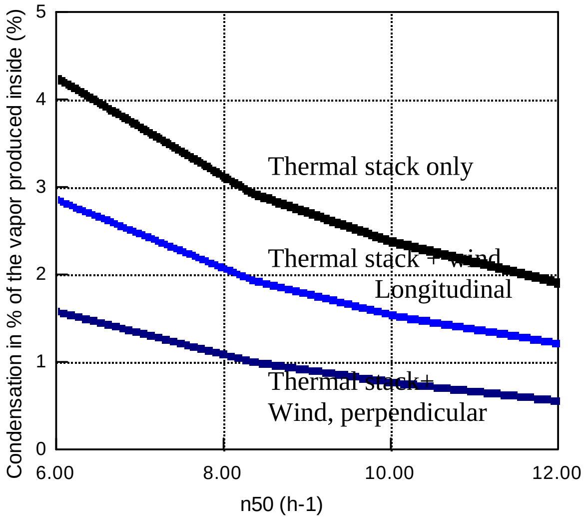

Figure 5. Airtight roof (diffusion only). Percentage of vapor released inside that condenses in the roof.

TABLE 2

Thermal stack and wind (4 m/s), wind direction perpendicular tot the facade. Temperatures: 18°C inside, 0°C outside, vapor pressure: 580 Pa outside. Ventilation flows, ventilation rate, inside vapor pressure

n_{50} h^{-1}	Air permeability roof a kg/(m².s,$Pa^{0.67}$)	Incoming flow. First and second floor m³/h	Outgoing flow First and second floor m³/h	Exfiltration through the roof m³/h	Ventilation rate h^{-1}	Inside Vapor pressure Pa
12	4 10^{-4}	315	143	182	1.09	824
10	4 10^{-4}	258	92	165	0.90	877
8.3	4 10^{-4}	224	64	159	0.78	923
6	4 10^{-4}	164	28	136	0.57	1044

TABLE 3
Thermal stack and wind (4 m/s), wind direction longitudinal to the facade. Temperatures: 18°C inside, 0°C outside, vapor pressure: 580 Pa outside. Ventilation flows, ventilation rate, inside vapor pressure

n_{50} h^{-1}	Air permeability roof a $kg/(m^2.s,Pa^{0.67})$	Incoming flow. First and second floor m^3/h	Outgoing flow First and second floor m^3/h	Exfiltration through the roof m^3/h	Ventilation rate h^{-1}	Inside Vapor pressure Pa
12	$4\ 10^{-4}$	192	92	100	0.67	978
10	$4\ 10^{-4}$	160	64	96	0.55	1062
8.3	$4\ 10^{-4}$	130	40	90	0.45	1170
6	$4\ 10^{-4}$	86	6	80	0.30	1473

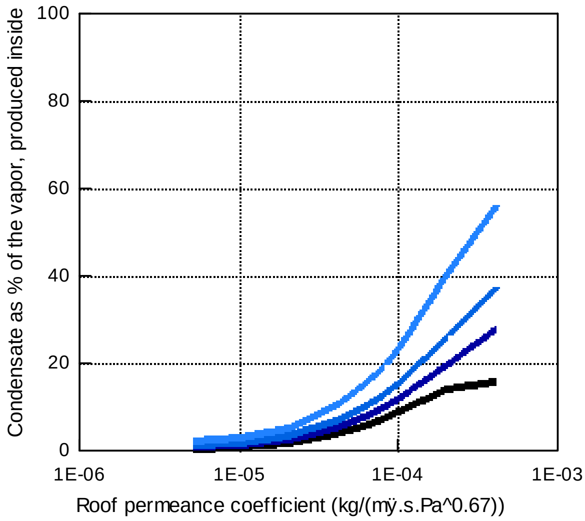

Figure 6 Stack and wind, 4 m/s, perpendicular to the facade. 0°C outside, 18°C inside. Percentage of the vapor released inside that condenses in the roof.

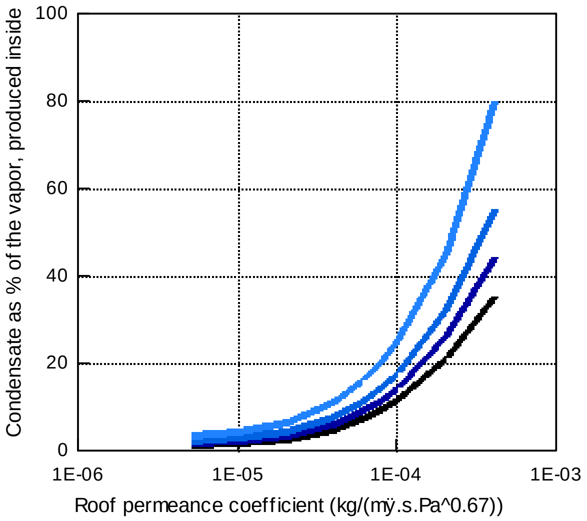

Figure 7 Stack and wind, longitudinal to the facade. O°C outside, 18°C inside. Percentage of the vapor released inside that condenses in the roof.

Is stack driven adventitious ventilation a worse case scenario? The answer is yes. Table 2, table 3, figure 6 and figure 7 summarize results calculated for a combination of stack and wind with an average velocity of 4 m/s at a height of 10 m (a mean value in many moderate climates). Wind direction is either perpendicular or longitudinal to the main façade. In both cases, the percentage of water vapor released inside that condenses beneath the roof cover stays lower than for stack only. Again, inside vapor pressure is dominant, while a low air permeance of the roof remains the best strategy to avoid abundant percentages of condensation deposit.

Suppose now a problem case has to be cured. Tracer gas measurements reveal that the pitched roof is quite air-leaky, air permeance at 1 Pa, $4\ 10^{-4}$ $kg/(m^2.s.Pa^b)$. A blower door test gives a whole dwelling n_{50}-value of 10 h^{-1}, i.e. high enough for adventitious ventilation to give acceptable air-flows. The solution proposed is air-tightening the roof to bring the air permeance down from $4\ 10^{-4}$ $kg/(m^2.s.Pa^b)$ to $5\ 10^{-6}$ $kg/(m^2.s.Pa^b)$. Results (0°C outside, 18°C inside, wind of 4 m/s, longitudinal to the façade): before, 44% of the water vapor released condensing in the roof, after, a deposit decreasing to 2.8%. Simultaneously however, the adventitious ventilation drops from $160 m^3/h$ to $116 m^3/h$, showing that, when adventitious infiltration is the only ventilation mode, one should evaluate the n_{50}-value after the necessary roof measures taken and, if necessary, combine air-tightening the roof with a purpose designed ventilation system.

PRACTICE CASE

The practice case concerns a low income estate of 48 two story dwellings with cathedralized ceiling (Anon. 1981) (figure 8). The only difference between dwellings is the orientation of the main façade: 24 NE-SW, 14 NW-SE, 6 W-E and 4 NNW-ESE. All dwellings have an open staircase, while the roof is composed of (1) gypsum boards with open joints, (2) 6 cm glass-fiber bats with a vapor retarder at the underside, (3) un-vented air space and (4) corrugated fiber cement plates as roof cover (figure 9). All dwellings are adventitiously ventilated with peak ventilation provided by opening windows. 85% show moisture spots on the roof's internal lining, while a large number of inhabitants complain of dripping moisture in the sleeping rooms after a cold spell. A detailed inspection of some roofs reveals poor installation of the glass-fiber bats, abundant traces of condensation on the backside of the corrugated fiber-cement cover, the rafters and the inside lining, and, mold spots on the rafters.

In a first step, a correlation was sought between the complaint's severity and the average number of inhabitants, well or no cooking hood in the kitchen, the average annual heating consumption and the orientation of the main façade. Heating consumption explained most of the difference: correlation coefficient r^2=0.27, F=0.34, 128 GJ/a on the average in the dwellings with severe damage, 164 GJ/a on the average in the dwellings with moderate damage. In the dwellings with less damage, people apparently heated better or/and ventilated more. The other three parameters had hardly any impact. Logic for the orientation, as all dwellings looked to dominant wind directions.

Figure 8 The estate, a view on a dwelling

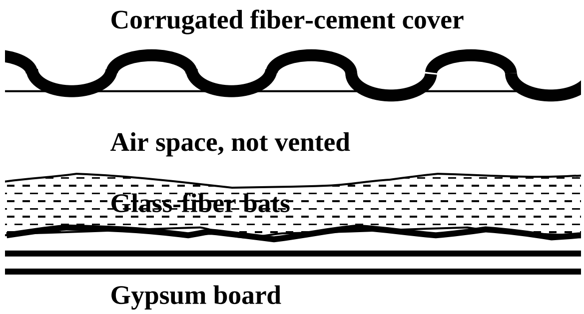

Figure 9 The roof section

In a second step two dwellings with severe (2 and 3) and one with moderate complaints (1), were followed during a whole winter. Beforehand, dwelling 2 got an airflow and vapor retarder mounted below the gypsum board lining, with all joints and overlaps carefully sealed. At the laboratory two roof models were constructed and tested in a hot box rig, one 'as built' and one seen as 'the solution' (from inside to outside: gypsum board, cavity, airflow and vapor retarder, 17 cm mineral fiber, vapor permeable underlay, battens, corrugated plates).

TABLE 4
Mean inside temperature and vapor pressure excess (Severe+: airflow and vapor retarder installed)

Dwelling	Parents sleeping room		Childrens sleeping room		Bathroom	
	Temperature °C	Inside vapor press. Excess Pa	Temperature °C	Inside vapor press. Excess Pa	Temperature °C	Inside vapor press. Excess Pa
Less	$13.6+0.42\theta_e$	$196-1.23\theta_e$	$14.1+0.42\theta_e$	$159-0.9\theta_e$		
Severe,+	$13.1+0.32\theta_e$	$373-14.7\theta_e$	$13.9+0.26\theta_e$	$237+2.5\theta_e$	$14.3+0.21\theta_e$	$457-17.7\theta_e$
Severe	$11.7+0.48\theta_e$	$324-10.8\theta_e$	$15.6+0.06\theta_e$	$411-34\theta_e$	$17.7+0.25\theta_e$	$395-19.4\theta_e$

Table 4 gives the inside vapor pressure excess measured in the sleeping rooms and bathroom of the three dwellings. In dwelling 2 and 3, the excess is higher while temperatures are lower than in dwelling 1. Previous paragraph showed that a higher excess, which means a higher indoor vapor pressure, is very negative in terms of condensation deposit. We then calculated the vapor diffusion thickness of poorly installed mineral fiber bats from a condensation test in the hot box rig on the roof 'as built' (40 days between 2.7°C, 557 Pa and 23.6°C, 2165 Pa). 0.23 m was measured instead of the wet cup's 5.2 m. Poor workmanship clearly kills vapor retarding qualities. Anyhow, even that could not explain the dripping. In fact, calculated cumulated deposit by diffusion did at any moment pass the 2 l/m² the corrugated fiber-cement could buffer. Adventitious ventilation with air exfiltration through the roof instead fully explained the case. An air permeance measurement on the test roof as built revealed a poor $3.3\ 10^{-4}\Delta P^{0.66}$, i.e. close to the worst case in previous paragraph. The PE airflow and vapor retarder in dwelling 2 also solved the problem. A particle board sample, glued against the corrugated fiber-cement, remained drier there than in dwelling 3. Also not a single complaint of moisture dripping on the retarder was noted. A roof control early February revealed a perfectly dry system. In the dwelling 3, instead, severe dripping happened after a cold spell in January while a roof control early February showed abundant moisture deposit at the backside of the corrugated fiber-cement. Also a hot box test on the better solution only showed condensation deposit after the vapor and airflow retarder was deliberately perforated and the air-tightness gone.

CONCLUSION

Can adventitious ventilation negatively impact the moisture performance of building envelopes in moderate climates? The answer is yes. For it to happen, three conditions should be fulfilled. First, the air-tightness of the envelope must be questionable. Secondly, part of the adventitious ventilation air should leave the building by exfiltration through the envelope. Thirdly, the ventilation flow should be moderate enough to create a larger vapor excess between inside and outside. The condensation deposit may be very high as was shown by the calculation on the reference case and proven by the field observation. The case described in the paper is only one of the many the laboratory has been confronted with. On paper, the solution looks very simple. Lower the air permeance of the roof, with as a safe threshold in moderate climates: $a<10^{-5}$ kg/(m².s.Pa^b). In practice, however, realizing that low permeance is not as simple. Not only an airflow retarder is needed but also a careful design of all overlaps and jointing and excellent workmanship are necessary.

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