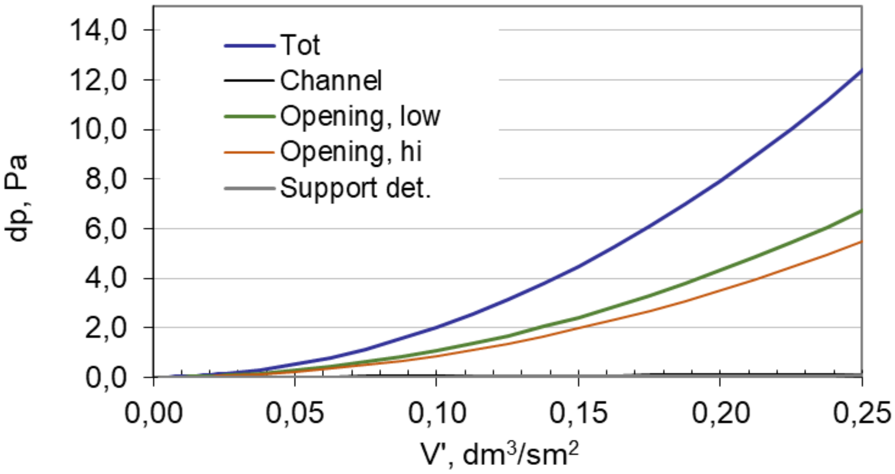
RESEARCH REPORT

VTT-R-01215-20



Ventilated façade concept for Paroc - Principle design guidelines

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Summary

Numerical studies were carried out to present guidelines for Paroc thermal insulation products when applied in ventilated walls of new multi-storey apartment buildings. These walls can be build using concrete, aerated concrete blocks, brick, wood frame or CLT as the load bearing structure. The ventilation cavity is between the thermal insulation layer and the façade element (typical materials are timber, brick, cement board). The guidelines were meant to show what ventilation opening areas are need to have adequate yearly average wall ventilation air flow rate for drying the additional moisture out of the structure, and to set the requirements for the air permeability of the thermal insulation product or define the possible need for additional wind barrier to avoid notable increase of yearly heat losses due to convection.

Some main findings: In a case where the wall ventilation air flows relatively freely in the direction of the cavity the maximum recommended air permeability of the thermal insulation is 50 ·10-6 m^3/m·s·Pa. If the ventilation openings allow local significant dynamic pressure conditions on the thermal insulation surface, a separate wind barrier layer is recommended locally. Wind barrier is recommended also in cases having fire breaks in the ventilation cavity.

These guidelines are determined using numerical simulations. They are mostly based on yearly average moisture load and wind conditions. Several boundaries were set based on expert opinion in order to study the defined cases of wall ventilation taking into account the project plan and scale. The results can not be considered as exact limit values, but they give good approximations on how to realize wall ventilation having adequate moisture drying efficiency with reasonable convection effects on thermal performance.
Adequate wall ventilation air flow rates are needed for good moisture performance of ventilated walls. This alone doesn't guarantee the safe performance.

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Contents

1. Introduction and objectives

Façade ventilation is needed to dry out the additional moisture from the structure. The typical moisture sources are: Initial building moisture, moisture loads from indoor and outdoor (ventilation) air and the wetting of the façade due to driving rain. The challenge is to provide sufficient ventilation for walls under different climates causing varying loads and wind pressures. The ventilation route may have variations depending on the cavity dimensions, structural details and the possible fire breaks in the cavity that can have a strong effect on the possible air flow rates under the dominant wind conditions.

The objective of this work was to present guidelines for Paroc thermal insulation products when applied in ventilated walls of new multi-storey apartment buildings. These walls can be build using concrete, aerated concrete blocks, brick, wood frame or CLT as the load bearing structure. The ventilation cavity is between the thermal insulation layer and the façade element made of timber, brick or cement board. The guidelines are meant to aswer the question: What Paroc thermal insulation can be used in different cases of wall ventilation to avoid reduction of U-value due to convection: What are the requirements for the air permeability of the product and is there a need for additional wind barrier or weather protection layer.

These design guidelines are aimed to give a general idea of the applicability of the Paroc thermal insulation products in the presented ventilated wall cases under typical European climates. Three locations were used in the studies:

1) Northern: Vantaa, Finland
2) Coastal mild: Bergen, Norway
3) Central European: Holzkirchen, Germany.

These guidelines were determined using numerical simulations. They are mostly based on yearly average moisture load and wind conditions. Several boundaries were set based on expert opinion in order to study the defined cases of wall ventilation taking into account the project plan and scale. The results can not be considered as exact limit values, but they give good approximations on how to realize wall ventilation having adequate moisture drying efficiency with reasonable convection effects on thermal performance.

Adequate wall ventilation air flow rates are needed for good moisture performance of ventilated walls. This alone doesn’t guarantee the safe performance. Several other factors (diffusion resistances of the material layers, climate loads, air leakages, etc.) may affect the moisture performance that has to be ensured separately.

2. Methods used in the analysis

The study was based on numerical methods. WUFI 6.1 /1/ software was used to study the moisture loads into the ventilation air cavity (having high air change rate) under different climates and with different structures. The results showed how much moisture has to be dried out by wall ventilation during the first year (including initial building moisture) and after that when about stationary in/outdoor moisture load conditions have been reached. In these studies the solar radiation was omitted, which increases the safety of the results. The results are presented as yearly average moisture loads per structure area.

When the moisture mass required to be ventilated was determined, the needed ventilation flow rates could be solved. The WUFI -solutions give approximation for the average increase of outdoor air temperature in the ventilation cavity. These temperature levels were used to study the safe increase of humidity of the ventilation air. The required amount of moisture to be ventilated and the average increase of ventilation air moisture content were used to solve the needed ventilation air flow rate (solved per structure area).

Average pressure differences for the different building heights were evaluated based on the climate data for the studied locations. These pressure differences were used as driving forces for the ventilation. Natural convection induced by temperature difference was also taken into account when necessary.

A simple air flow resistance model for the ventilation channel components was created. This was used to study the different cases of structures under different average pressure differences (building heights and climates). This performance assessment gave answers to the following questions:

- Can the required ventilation air flow rate be achieved under the set conditons, and
- What size openings between the ventilation cavity and outdoor air are needed to limit the average air flow rate to suitable levels.

The assumption was that when the air flow rate exceeds the needed level, the only way to adjust it to required level is to increase the air flow resistance of the air in/outlet openings by decreasing the opening area.

The methodology used in this study is shown in Figure 1.

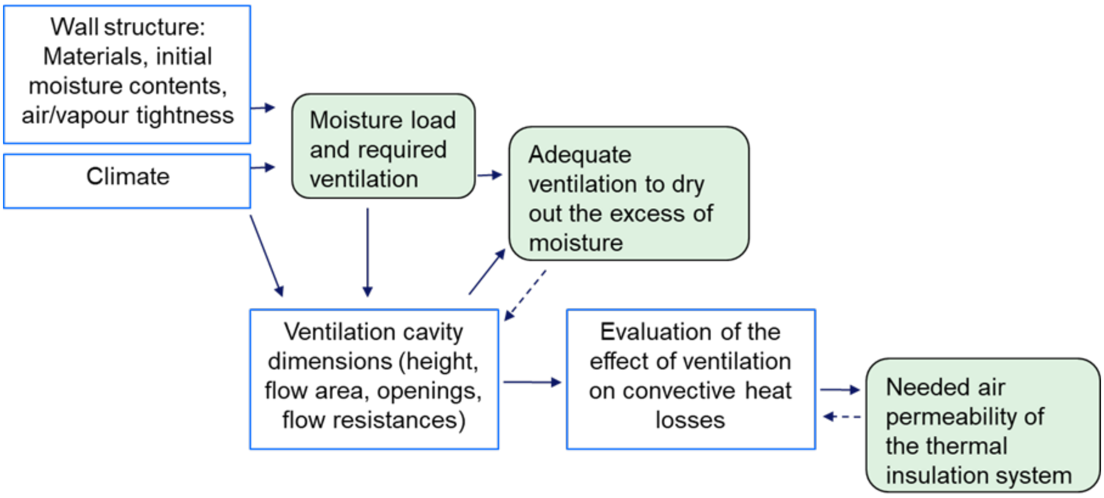

Figure 1. Methodology used in the study.

3. Assumptions

The analysis was based on simplified numerical studies using mainly average conditions.

Yearly average values were used for the moisture loads, wind velocities and needed ventilation air flow rates for different structural cases under different climate conditions.

The material data and climate information given in WUFI /1/ data base were used. The moisture load in the indoor climate was assumed to correspond typical apartment or office buildings.

The structures were assumed ideally built without any defects like water or air leakages.

The objective was to study realistic worst case scenarios. In the studied cases the solar radiation to the wall surface was omitted and the thermal insulation levels were set high, which meant low moisture uptake potential for the wall ventilation air. Also, initial additional moisture contents were used in relevant cases to study the drying phase of the structures. The studies carried out contain safety.

The air flow fields in the ventilation cavity and thermal insulation system are analysed using simplified models with set assumptions and mainly using average conditions.

4. Evaluation of the amount of moisture to be ventilated

Numerical simulations using WUFI© 6.1 -model /1/ were applied to a large set of following combinations of structural elements:

- Load bearing materials: concrete, aerated concrete, brick, wood frame or CLT
- Façade materials: Timber, brick, cement board
- Thermal insulation: Stone wool having thicknesses 200 mm, 250mm or 300 mm depending on the actual wall material and its dimensions
- Initial moisture content of the wall material (concrete, aerated concrete, brick).

Three to five year simulation periods were used in the analysis depending on how fast the initial moisture could be dried out. The outdoor climate was that from WUFI model library and the indoor climate had +20 °C temperature with level 2 moisture loads (maximum +4 g/m^3 increase of moisture compared to outdoor air). Only in wood frame structure there was a vapour barrier (S_d = 50 m).

4.1 Climate conditions

The simulations were carried out using the climate data presented in WUFI for the three locations (Table 1). For example the yearly average wind velocities can have different levels depending on the source, but in this study they were used as given in the WUFI climate library.

Table 1. Climate data from WUFI climate data base.

	Vantaa, Finland	Bergen, Norway	Holzkirchen, Germany
T,av (°C)	6,5	8,1	6,6
T,min (°C)	-24,8	-9,7	-20,1
v,wind,av (m/s)	4,4	3,4	2,3
Precipitation, yearly (mm)	756	2421	1185

The driving rain was taken into account in the simulations. The wall stuctures were facing the highest driving rain direction, typically south or south-west. The studied part of the wall was the top section of a high (> 25 m) building that has the highest driving rain loads. Solar radiation was omitted in the simulations and the analysis includes safety.

4.2 Studied structures

The main studied structure cases are presented in Table 2.

The thicknesses were set to be high to have the worst case scenario for the moisture performance: High moisture capacity and low temperature differences between ventilation and outdoor air. The initial moisture contents of the materials typically corresponded to that of 80 % RH equilibrium. In concrete wall case the concrete was assumed wet (95 % RH) due to the long drying time of the fresh concrete core. The moisture content of the CLT was set to 12 % (by weight) (= 67 % RH) that corresponds to the typical moisture after production. The brick and aerated concrete walls were set to have slightly increased moisture level, 85 % RH.

The façade materials showed about similar performance with similar internal moisture loads, and only some selected cases were needed to study in order to evaluate their effect on the need for ventilation.

Table 2. Numerically studied cases. Code number 1 refers to cement fibre board façade, 2 to timber and 3 to brick façade.

Code	Inner wall, mm	Initial moisture content, % RH	Stone wool, mm	Facade
C1	Concrete 150 mm	95	300	Cement f.board 8 mm
CLT2	CLT 120 mm	67	300	Timber facade 28 mm
T1	Timber frame + vapour barrier	80	300	Cement f.board 8 mm
T2	Timber frame + vapour barrier	80	300	Timber facade 28 mm
T3	Timber frame + vapour barrier	80	300	Brick facade 130 mm
AC1	Aerated concrete 300 mm	85	200	Cement f.board 8 mm
Br1	Brick wall 270 mm	85	250	Cement f.board 8 mm
Br3	Brick wall 270 mm	85	250	Brick facade 130 mm

4.3 Simulation results

Three to five year simulations were carried out for the presented structure combinations under the three climate conditions (Vantaa in Finland, Bergen in Norway and Holzkirchen in Germany). The net moisture mass flow rates from the inner structure and from the façade into the ventilation space were studied. In these studies the ventilation air space had air change rate 25 1/h corresponding to relatively high ventilation. The high level of wall ventilation was chosen to give the upper estimation for the moisture flow from the structure and façade into the ventilation cavity. These moisture flow rates were used to study the needed wall ventilation.

The sum of the net moisture mass flow rates into the ventilation space represent the moisture load that has to be ventilated during the studied time period.

The moisture loads are presented for the first year (including the drying of the initial moisture) and for the last year of the simulation period representing the stationary yearly moisture loads from indoor and outdoor.

The average moisture load from one year period was chosen for the evaluation. The moisture loads depend strongly on the climate conditions and the season, so the selected one year period gives a general approach for the load conditions undepending on the date when the building is finished.

Other assumptions, like omitting solar radiation, make the evaluation more general and increase the safety. Warming up of the ventilation cavity due to solar radiation would improve the drying efficiency of ventilation.

The results are presented for Vantaa, Finland in Table 3, for Bergen, Norway in Table 4, and for Holzkirchen, Germany in Table 5. The unit for the nominal moisture loads (g/m^2 d) was chosen to have simple figures that would be easy to compare.

The differences between the moisture loads with similar structures under different climates were relatively small. In cases with high initial moisture contents the load for the first year was significantly higher than that in stationary load conditions when the additional initial moisture had been dried out. Exceptions for this are the walls with brick façade.

The highest moisture loads into ventilation space were detected when using a 130 mm thick brick façade. The load with brick façade was not dependant on the inner wall structure. There was no surface coating preventing the brick from wetting due to driving rain.

Table 3. Vantaa, Finland (V initial). Yearly average moisture loads to be ventilated from the structures presented as daily average loads (g/m^2 d) for the first year and the last year of simulations (Stat. conditions).

Code	Inner wall	Initial moisture content	Facade	Moisture load to be ventilated	
		% RH		1st year	Stat.conditions
VC1	Concrete	95	Cement f.board	6,3	1,2
VCLT2	CLT	67	Timber	4,6	2,4
VT1	Timber frame	80	Cement f.board	2,0	0,5
VT2	Timber frame	80	Timber	2,2	0,8
VT3	Timber frame	80	Brick	27,3	25,8
VAC1	Aerated concrete	85	Cement f.board	6,4	2,0
VBr1	Brick wall	85	Cement f.board	6,5	1,7
VBr3	Brick wall	85	Brick	27,5	26,0

Table 4. Bergen, Norway (B initial). Yearly average moisture loads to be ventilated from the structures presented as daily average loads (g/m^2 d) for the first year and the last year of simulations (Stat. conditions).

Code	Inner wall	Initial moisture content	Facade	Moisture load to be ventilated	
		% RH		1st year	Stat.conditions
BC1	Concrete	95	Cement f.board	6,5	1,3
BCLT2	CLT	67	Timber	4,3	2,2
BT1	Timber frame	80	Cement f.board	2,1	0,6
BT2	Timber frame	80	Timber	2,2	0,7
BT3	Timber frame	80	Brick	24,1	22,4
BAC1	Aerated concrete	85	Cement f.board	6,6	2,2
BBr1	Brick wall	85	Cement f.board	6,8	1,9
BBr3	Brick wall	85	Brick	24,4	22,7

Table 5. Holzkirchen, Germany (H initial). Yearly average moisture loads to be ventilated from the structures presented as daily average loads (g/m^2 d) for the first year and the last year of simulations (Stat. conditions).

Code	Inner wall	Initial moisture content	Facade	Moisture load to be ventilated	
		% RH		1st year	Stat.conditions
HC1	Concrete	95	Cement f.board	6,4	1,2
HCLT2	CLT	67	Timber	4,5	2,2
HT1	Timber frame	80	Cement f.board	2,0	0,6
HT2	Timber frame	80	Timber	2,2	0,7
HT3	Timber frame	80	Brick	22,3	21,9
HAC1	Aerated concrete	85	Cement f.board	6,4	2,2
HBr1	Brick wall	85	Cement f.board	6,4	1,9
HBr3	Brick wall	85	Brick	23,0	22,1

5. Evaluation of the needed ventilation air flow rates

Based on the defined moisture loads, the needed ventilation air flow rates could be determined when the average moisture increase of the ventilation air is known. The assumption was that the outdoor air flows into the ventilation cavity where it warms up due to the heat losses through the wall. The warming up depends on the U-value of the structure and also on the moisture performance of the façade. High moisture content of the façade decreases the thermal resistance and the evaporating moisture decreases the temperature. Due to the high thermal insulation thickness, the warming up of the ventilation air was quite low. Typically the yearly average temperature difference of the ventilation air solved using WUFI and that of the outdoor air was in the range of 0,2 - 0,6 °C.

5.1 Criteria for the wall ventilation air

The air flow rates were solved using hourly simulation data. The air leaving the ventilation cavity was assumed to have the maximum relative humidity that has no risk for mould growth. The risk for mould growth was studied according to the equations used in the VTT mould model /2 - 4/. The VTT mold model has been applied as a moisture performance criteria, for example, in ANSI/ASHRAE Standard 160-2016 /5/.

For timber facades the assumption of *'sensitive'* material was used, for the other cases the assumption for materials adjacent to ventilation cavity was '*medium resistant'* /3, 4/. The leaving air had at least the same moisture content as that of the outdoor air, and the highest humidity level was set to be 95 % RH (no condensation allowed). The critical relative humidity levels for mould growth with different temperatures are presented in Figure 2.

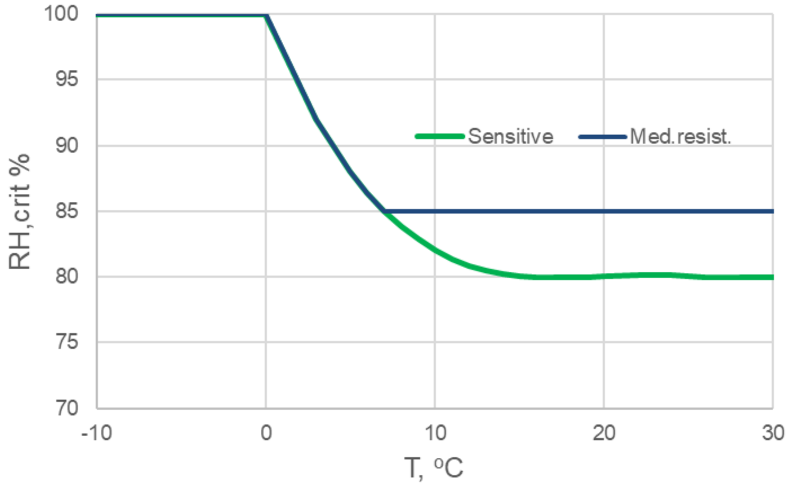

Figure 2. Critical relative humidity values as a function of temperature for sensitive (wood based materials) and medium resistant materials based on VTT mould model /2-4/.

The set condition for the ventilation air flowing out of the wall results in maximum relative humidities between 80 - 95 % RH (wood façade) and 85 - 95 % RH in other wall structures. This limit level could be higher than allowed in some countries. For example, in Sweden the critical upper limit for the relative humidity of load bearing structures is 75 % RH. This could make a difference in cases where the wooden load bearing structure is close to ventilation cavity. Recommendation to have continuous thermal insulation layer on the exterior side of the wooden stud structure is justified in all Nordic countries.

The use of this (lower limit for mold growth) or any other criteria does not mean that the wall ventilation air would stay below these maximum levels in practice. The selected RH-levels were used to define the moisture binding potential of the ventilation air assuming that the hourly RH-values in ventilation cavity do not exceed the set critical conditions. These limits also depend strongly on the temperature level (warming up) of the ventilation air. Finally, the moisture binding capacity is used to define the needed yearly average air flow rates for sufficient ventilation.

Also, even if the wall ventilation air flow rates are solved using the 'mold safe' -criteria for the ventilation air, it does not give any quarantee about the moisture performance of the actual structure. The analysis was carried out merely for the wall ventilation with the set assumptions for the structures.

5.2 Required air flow rates

Using this approach with the hourly climate data and the simulated temperature of the leaving ventilation air, the hourly moisture increase of the ventilation air could be solved. When the yearly moisture loads (g/m^2 d) and the (yearly average) moisture increase of the ventilation air were known, the needed average ventilation air flow rates (dm^3/s m^2) could be solved.

The solved average ventilation air flow rates are presented for Vantaa, Finland in Table 6, for Bergen, Norway in Table 7, and for Holzkirchen, Germany in Table 8. The results are presented for the first year moisture load values that include the drying of the set initial moisture content of the structures.

Table 6. Vantaa, Finland (V initial). Yearly average ventilation air flow rates needed to dry out the yearly moisture loads from the structures.

Code	Inner wall	Initial moisture content	Facade	Required average air flow rate for the wall ventilation, 1st year
		% RH		dm^3/s m^2
VC1	Concrete	95	Cement f.board	0,055
VCLT2	CLT	67	Timber	0,045
VT1	Timber frame	80	Cement f.board	0,020
VT2	Timber frame	80	Timber	0,022
VT3	Timber frame	80	Brick	0,33
VAC1	Aerated concrete	85	Cement f.board	0,056
VBr1	Brick wall	85	Cement f.board	0,056
VBr3	Brick wall	85	Brick	0,28

Table 7. Bergen, Norway (B initial). Yearly average ventilation air flow rates needed to dry out the yearly moisture loads from the structures.

Code	Inner wall	Initial moisture content	Facade	Required average air flow rate for the wall ventilation, 1st year
		% RH		dm^3/s m^2
BC1	Concrete	95	Cement f.board	0,075
BCLT2	CLT	67	Timber	0,057
BT1	Timber frame	80	Cement f.board	0,025
BT2	Timber frame	80	Timber	0,028
BT3	Timber frame	80	Brick	0,44
BAC1	Aerated concrete	85	Cement f.board	0,076
BBr1	Brick wall	85	Cement f.board	0,078
BBr3	Brick wall	85	Brick	0,39

Table 8. Holzkirchen, Germany (H initial). Yearly average ventilation air flow rates needed to dry out the yearly moisture loads from the structures.

Code	Inner wall	Initial moisture content	Facade	Required average air flow rate for the wall ventilation, 1st year
		% RH		$dm^3/s\ m^2$
HC1	Concrete	95	Cement f.board	0,060
HCLT2	CLT	67	Timber	0,037
HT1	Timber frame	80	Cement f.board	0,022
HT2	Timber frame	80	Timber	0,025
HT3	Timber frame	80	Brick	0,34
HAC1	Aerated concrete	85	Cement f.board	0,061
HBr1	Brick wall	85	Cement f.board	0,062
HBr3	Brick wall	85	Brick	0,34

The required wall ventilation air flow rates could be divided into different categories in each climate zone.

- The lowest air flow rates were with timber frame walls (generally walls having low moisture capacity and a vapour barrier

- The next lowest ventilation requirement was with CLT walls.

- Walls having cement fibre board façade with initially wet (95 % RH) concrete wall or 85 % RH aerated concrete or brick walls have quite similar ventilation requirement

- Walls with thick (130 mm) brick façade require very high ventilation compared to other cases to keep the ventilation air space in safe humidity levels

- Differences between brick facades in timber frame and brick wall cases depend on the slightly higher thermal insulation thickness in the timber frame case which reduces the temperature level of the ventilation cavity compared to the brick wall case. The lower brick wall case values can be considered suitable for the both cases.

- Timber façade requires about 10 - 15 % more ventilation than the cement fibre board. These cases can be considered to have same ventilation (defined for timber façade).

- The cement fibre board was relatively inert for the driving rain loads and these results are valid for other inert materials like stone, glass façade, etc.

6. Setting the average pressure difference levels

The driving force for the ventilation is the pressure difference over the ventilation channel. This is caused by the wind and temperature difference. The available pressure difference depends on the local climate, height of the structure, wall orientation, geometry of the building and structures, adjacent buildings and terrain, etc. Due to these several variables it is not possible to set exact and general pressure difference levels. The objective was to set practical levels for the average pressure differences for different cases and climates.

The yearly available average pressure differences were set using the pressure difference caused by the average wind velocity and assuming a propability factor for the wind direction and effect on the building. This factor was set to be 0.5 because wind has always some effect on the ventilation undepending on the direction and the studied direction was that with the highest driving rain and wind. Temperature caused pressure gradient was added to the wind pressure. The assumption was 1.5 ^{o}C higher temperature in the ventilation cavity, which takes into account a slightly higher increase of temperature than those solved for structural cases having relatively high thermal insulation thicknesses without solar radiation. With these assumptions the solved pressure differences are most likely still on the safe side, representing lower levels than could be typical in practice.

The average pressure differences for different climates and heights of the building are presented in Table 9. With the low (h = max. 7 m) structure a 0.8 correction factor was used for the wind pressure.

Table 9. Set yearly average pressure difference levels for different climates and building heights.

Building height category, (h used in the solution, m)	Vantaa, Finland ($v_{,wind,av}$ = 4,4 m/s) Pa	Bergen, Norway ($v_{,wind,av}$ = 3,4 m/s) Pa	Holzkirchen, Germany ($v_{,wind,av}$ = 2,3 m/s) Pa
≤ 7m (7)	5	3,5	2
≤ 14-18m (18)	7	5	3
≤ 28-32m (32)	8	6	4
≥ 56m (56)	10	7	5,5

7. Analysis of the wall ventilation system

Analysis of the ventilation system was based on the required average ventilation flow rates and the average available pressure differences. The analysis was carried out using a simple air flow resistance model for the channel components. This performance assessment was done to answer two questions:

1) Can the required ventilation rates be achieved with the available pressure differences
2) What dimensions of the openings (mm^2/m) to ventilation cavity are needed to reach the needed air flow rate with the available pressure differences

Two ventilation cavity dimensions were studied: 45 mm that corresponds to very open cavity and 25 mm corresponding to more typical cavity depth. The cavities were assumed to have openings to outdoor air on the top and bottom part of the building. Two different ventilation route schemes were used in the analysis:

1) Totally open cavity having small resistances on every floor with locally 50 % reduced free area in the cavity, and
2) A case with fire breaks in every floor having 5 % open area on both plates of the break (Figure 3). The fire break case is typically valid only in the case with timber façade in a high buildings.

Both ventilation cases had additional resistances in the openings on the top and bottom of the ventilation cavity. The sizing of these openings allowed matching the available pressure difference with the needed air flow rate in cases where the air flow should have additional resistances.

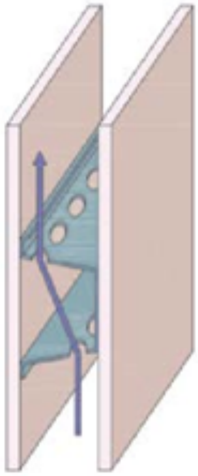

Figure 3. Fire breaks in the ventilation cavity. One breaks for each floor (3,3 m distance) and each break has two plates with 5 % open area compared to the cross section of the ventilation cavity.

7.1 Wall ventilation in different cases

The analysed wall ventilation is presented in different structural cases under different climate conditions. Typical pressure differences as function of air flow rates are presented in Figure 4 for the open ventilation cavity and in Figure 5 for the case with fire breaks resisting the air flow. When the height of the structure increases, the needed air flow rate increases and the required pressure difference to support the air flow rate increases exponentially.

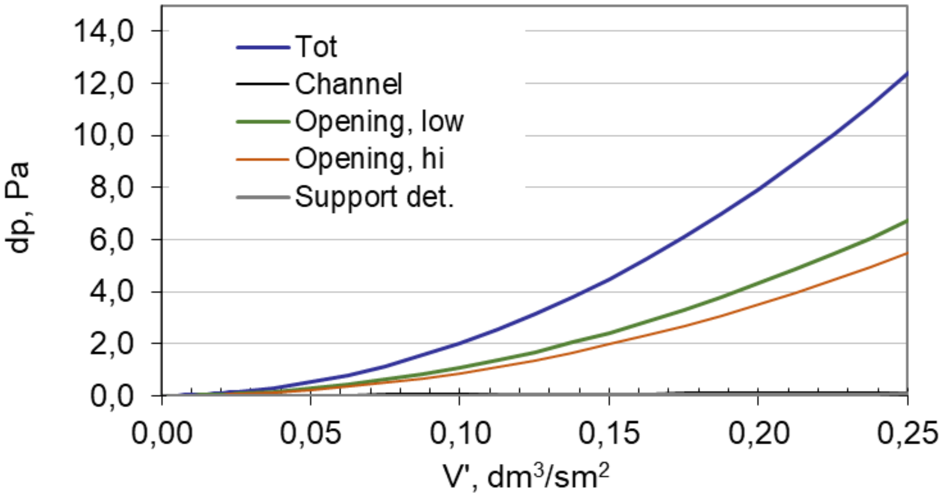

Figure 4. Typical pressure losses in an open ventilation cavity.

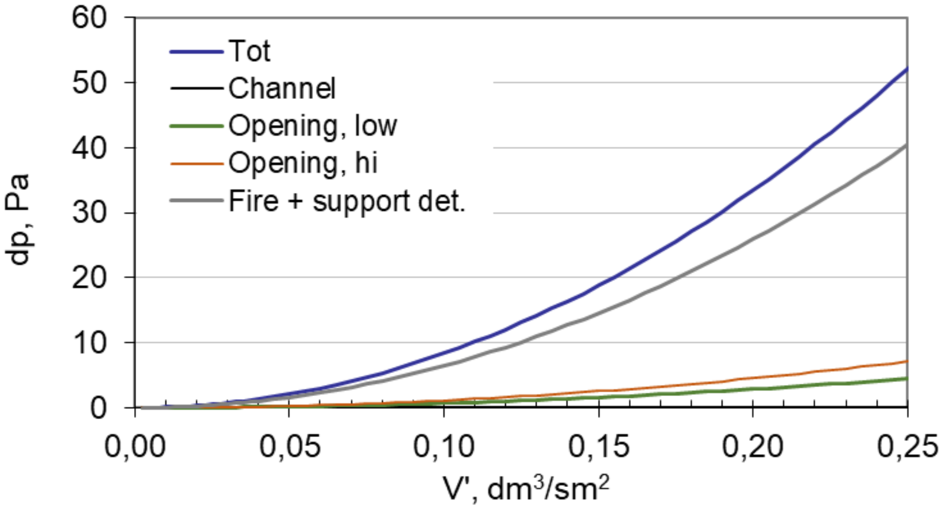

Figure 5. Typical pressure losses in a ventilation cavity having fire breaks in each floor.

The areas of the air inlet and outlet openings are presented in the following in mm^2. This corresponds to the area of one opening per the width of the structure (actually mm^2/m). The both openings were assumed to have the same area and the total opening area is two times higher than what is presented in the following.

The effect of ventilation gap width (45 mm / 25 mm) was quite low in cases with open ventilation cavity, but when there were fire breaks in the cavity, the effect was significant (Figure 6). The difference is due to the fact that fire breaks were solved assuming 5 % open area of the cross-section of the cavity. In the case with 45 mm gap width the fire breaks have 80 % higher open area than in the 25 mm case, which has a considerable effect on the air flow resistance of the breaks.

In the following the minimum area of the ventilation openings are solved assuming similar opening on both ends of the ventilation cavity. The total opening is two times higher than that solved for the single opening.

If the ventilation has only one opening that can be adjusted and the other end is fully open, the presented opening areas can be applied, even if it results to too high ventilation of the wall.

If there more openings in the wall ventilation route, the maximum height of the ventilation route from opening to next opening can be considered as the design height. In this case the minimum opening area for each opening is set by this design height. For example, a 28 m high building has ventilation openings at 7 m distance. The design height for the ventilation openings is 7 m and there are five about similar openings in the ventilation route. This approach can be applied also to window openings. The total opening area should be fulfilled and each opening should be at least 50 % of the total area devided equally for each opening.

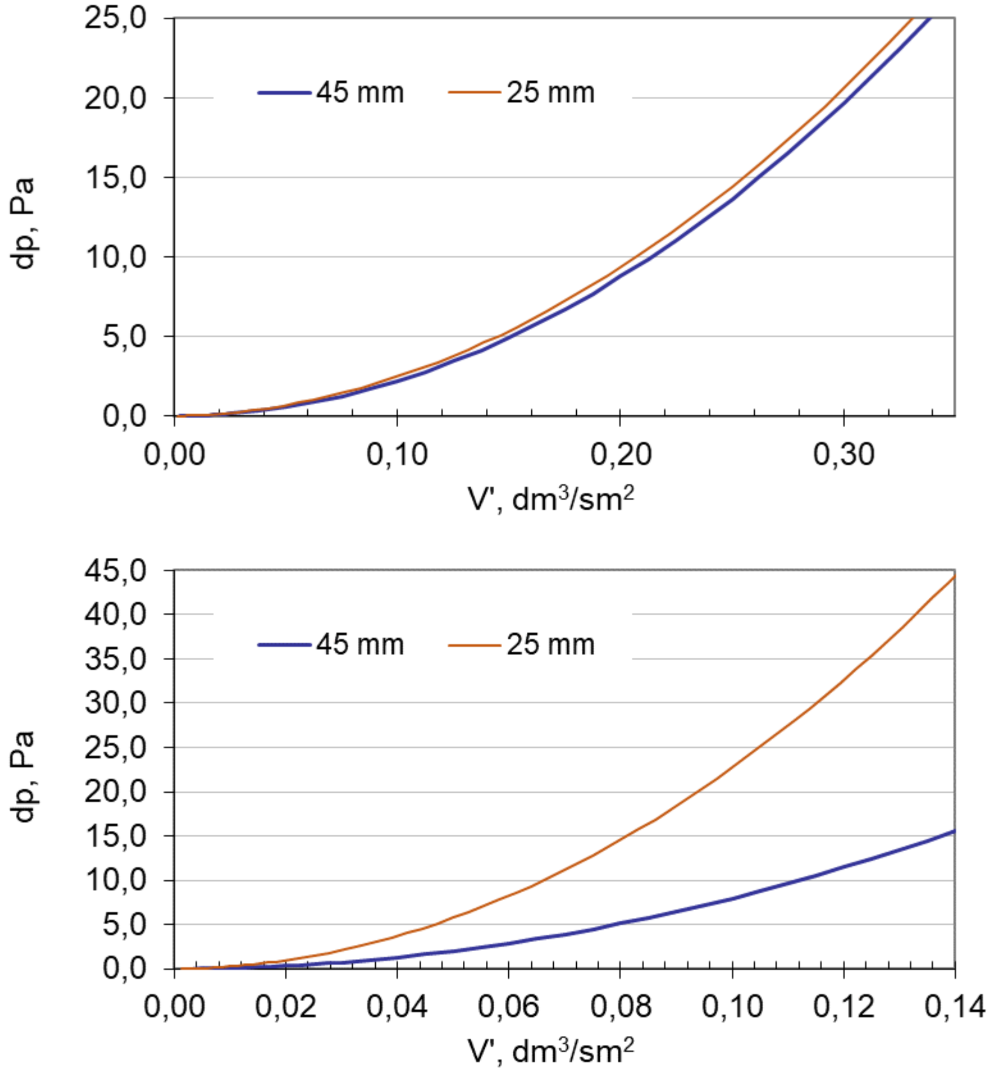

Figure 6. Example of the effect of ventilation gap width (45 mm or 25 mm) on the pressure difference of the ventilation cavity as a function of the air flow rate. Above open cavity and below a cavity with fire breaks.

7.1.1 Structures with brick facade

Brick facades were analysed using one wall ventilation air flow rate for each climate. Table 10 presents the solved opening areas for the air inlet and outlet openings for the walls with brick facades. In some of the cases the available pressure difference was not sufficient to support the need for ventilation and these cases are marked with “-“. The results for Vantaa and Holzkirchen are compared in Figure 7.

Table 10. Brick facades. Required minimum opening area(mm^2) of both the air inflow/outflow openings for different building heights under different climate conditions. The total opening area is two times higher.

	Vantaa Minimum opening area for one opening, mm^2		Bergen Minimum opening area for one opening, mm^2		Holzkirchen Minimum opening area for one opening, mm^2	
h, m	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm
7	1450	1500	5500	-	2500	2650
18	2800	3000	-	-	5500	7400
32	4600	5900	-	-	9600	-
56	8600	-	-	-	-	-

Only in Vantaa, Finland climate the air flow rate can reach the required level with the 56 m high building (d = 45 mm) when the average pressure difference is as it is presented in Table 9 (10 Pa). In Bergen only the 7 m wall (with ventilation cavity 45 mm) can have enough ventilation to dry out the constantly wetting brick façade due to driving rain. In Holzkirchen the needed ventilation can be achieved for a maximum 32 m high building having 45 mm cavity and 18 m high building with 25 mm cavity dimension.

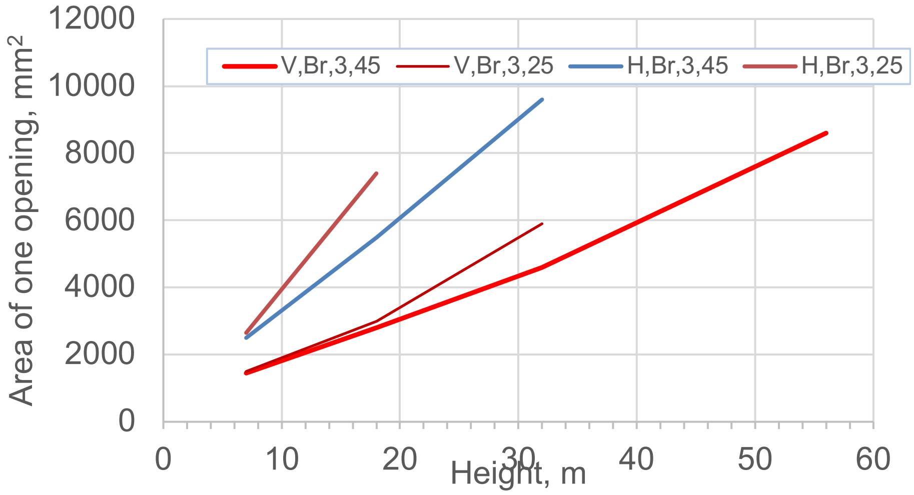

Figure 7. Required minimum opening area(mm^2/m) (solved per the width of the wall) of both the air inflow/outflow openings for different building heights under Vantaa and Holzkirchen climate conditions.

7.1.2 Wooden façades with fire breaks

Wooden facades with fire breaks in each floor are more sensitive to building height than brick façade walls with open ventilation cavities. In the presented cases the wall structure was CLT, but the results are accurate enough for concrete and aerated concrete block walls. Due to the fire breaks on each floor, the air flow resistance increases strongly when the building height increases and the available pressure differences do not support sufficient ventilation air flow rate in cases with higher buildings.

The results (Table 11) with the set conditions show that with fire breaks the 56 m high structure can not have sufficient ventilation under any of the studied locations. With 32 m high buildings, adequate ventilation can be reached only with 45 mm ventilation cavity under Vantaa, Finland conditions. In all the cases the highest building category having adequate ventilation is limited to 18 m.

To achieve adequate wall ventilation air flow rate in structures with fire breaks, there should be additional ventilation openings in the walls of high buildings. According to the results the maximum distance between ventilation openings is generally 18 m.

If there more frequent fire breaks (or similar air flow obstruction in the ventilation channel) than assumed here (one per each floor at 3,3 m distance), the results change drastically and it would be even more difficult to achieve the desired wall ventilation air flow rate.

Table 11. Case having timber façade with fire breaks. Required minimum opening area (mm^2) of both the air inflow/outflow openings for different building heights under different climate conditions. The total opening area is two times higher.

	Vantaa Minimum opening area for one opening, mm^2		Bergen Minimum opening area for one opening, mm^2		Holzkirchen Minimum opening area for one opening, mm^2	
h, m	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm
7	210	220	320	330	280	280
18	500	720	900	10000	680	10000
32	1850	-	-	-	-	-
56	-	-	-	-	-	-

7.1.3 Concrete, aerated concrete block and brick walls

Walls having cement fibre board façade with initially wet (95 % RH) concrete wall or aerated concrete block wall or brick walls having initial moisture content corresponding to 85 % RH have quite similar ventilation requirement. Timber façade requires about 10 - 15 % more ventilation than the cement fibre board, and these cases can be considered to have same ventilation requirement, when some safety is added in the results for practical recommendations.

Table 12 and Figure 8 present the solved opening areas for the air inlet and outlet openings for these walls with cement fibre board façade. The total opening area is two times higher.

Table 12. Concrete, aerated concrete block or brick walls having cement fibre board façade. The maximum initial moisture content for the concrete wall is 95 % RH, for the aerated concrete and brick 85 % RH. Required minimum opening area(mm^2) of both the air inflow/outflow openings for different building heights under different climate conditions. The total opening area is two times higher.

	Vantaa Minimum opening area for one opening, mm^2		Bergen Minimum opening area for one opening, mm^2		Holzkirchen Minimum opening area for one opening, mm^2	
h, m	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm
7	250	260	420	420	340	350
18	550	560	900	920	710	720
32	920	950	1460	1550	1100	1150
56	1460	1600	2420	2970	1660	1900

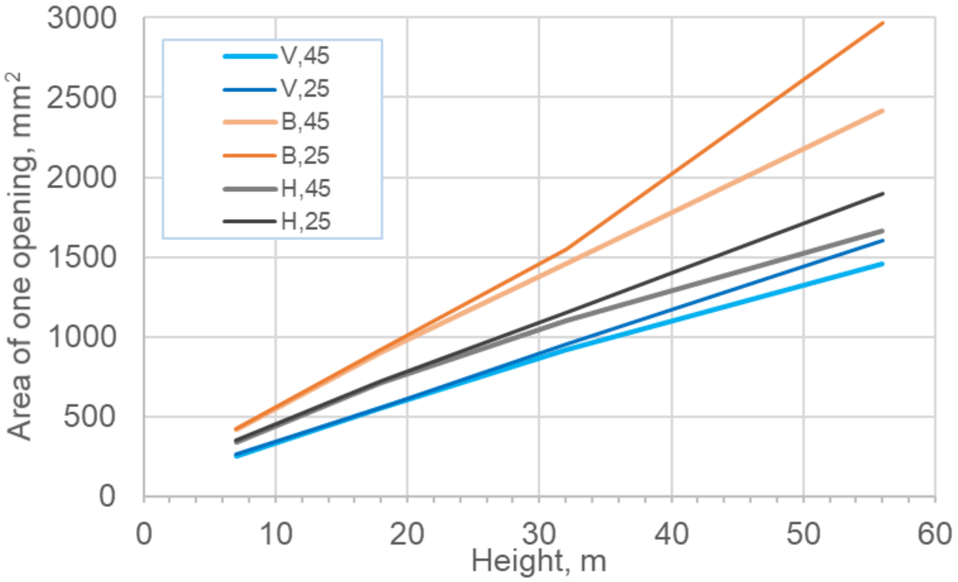

Figure 8. Required minimum opening area (mm^2) of both the air inflow/outflow openings for different building heights under Vantaa (V), Bergen (B) and Holzkirchen (H) climate conditions. Concrete, aerated concrete block and brick walls with cement fibre board façade. Two ventilation cavity dimensions, d = 45 mm (45) and 25 mm (25).

7.1.4 Timber frame and CLT walls

Results for CLT walls having timber façade are presented in Table 13 and the results for timber frame walls with inside vapour barrier and timber façade in Table 14. The CLT had initial moisture content corresponding to 67 % RH and the wooden layers of timber frame walls had 80 % RH initial conditions.

Table 13. CLT walls with timber façade. Required minimum opening area(mm^2) of both the air inflow/outflow openings for different building heights under different climate conditions. The total opening area is two times higher.

	Vantaa Minimum opening area for one opening, mm^2		Bergen Minimum opening area for one opening, mm^2		Holzkirchen Minimum opening area for one opening, mm^2	
h, m	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm
7	180	180	270	270	240	240
18	400	410	590	600	500	500
32	660	670	950	990	770	800
56	1030	1100	1550	1740	1140	1240

Table 14. Timber frame walls with inside vapour barrier and timber façade. Required minimum opening area(mm^2) of both the air inflow/outflow openings for different building heights under different climate conditions. The total opening area is two times higher.

	Vantaa Minimum opening area for one opening, mm^2		Bergen Minimum opening area for one opening, mm^2		Holzkirchen Minimum opening area for one opening, mm^2	
h, m	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm
7	110	100	160	160	170	190
18	220	230	350	350	380	390
32	370	380	560	570	600	620
56	580	600	910	970	890	940

7.2 Building height and ventilation

7.2.1 Setting opening area categories

In practice it would be useful to have exact cartegories set for the area of the openings. These should be functions of building height and depend on location (climate).

These opening areas presented in here mean the actual free open areas of the openings, taking into account, for example, the protection nets against animals or other similar structures reducing the actual open area.

In EN ISO 6946-2017 / 6 / the openings have different categories:

<u>Slightly ventilated</u> having openings of area > 500 mm^2 but < 1500 mm^2. This case gives some benefit when solving the thermal resistance of the air layer in U-value determination.

Well-ventilated air layer having openings of area equal to or exceed 1500 mm^2 per meter of length (in the horizontal direction) for vertical air layers.

These two opening area categories (> 500 mm^2 but < 1500 mm^2 and > 1500 mm^2 are applied to the solved results in the lower part of the opening area. The minimum open area is thus 500 mm^2.

In addition, some higher opening categories are presented: 3000 mm^2, 6000 mm^2 and 12000 mm^2. These opening areas reperesent the total opening area for the ventilation cavity and the area for one opening is 50 % of the total area. Thus the opening areas for one opening are: 1500 mm^2, 3000 mm^2 and 6000 mm^2.

When no additional resistance is needed, a fully open case is presented. In this case the opening to ventilation cavity is so wide that it does not have significant resistance for the air flow. Value presented for this is the same as the free open area of ventilation cavity. This means that the area for both the upper and lower opening is 50 % or higher of the cross-section area of the ventilation cavity. For example, with 25 mm wide ventilation cavity (25000 mm^2), both the openings could be (minimum) 500 mm x 25 mm (12500 mm^2) per meter of length (in the horizontal direction).

In the following the recommended opening area for the wall ventilation openings are presented as the maximum height of the ventilated cavity that can be ventilated with the different opening area categories. The results are presented for 25 mm and 45 mm wide ventilation cavities and for different climates. The ventilation opening area categories (mm^2) correspond the opening area per meter of length in the horizontal direction.

The presented maximum ventilation cavity heights are approximations based on the solved series of results.The maximum studied height of the ventilated wall was 56 m. Values above this level has not been presented.

7.2.2 Recommendations for brick façade walls

The recommended opening area for the wall ventilation openings of brick façade walls are presented for different opening categories, building heights and for different climates in Table 15.

The results could differ significantly from the presented if the façade brick layer was thinner having lower moisture capacity, or if the façade was protected against wetting by (hydrophobic) treatment.

Due to the heavy moisture load from the wetting brick façade, the wall ventilation could not reach needed air flow rate in several cases. For example, in Bergen the maximum height of a ventilated brick façade with 25 mm wide ventilation cavity is only 7 m and with 45 mm wide cavity about 14 m when the set assumptions were used in the solution.

This simplified simulation approach shows that there is clearly need for very high wall ventilation in the cases with thick and untreated brick facades. This study includes a lot of safety and the reality may not always be that bad: the moisture ventilation out of the wall can be higher due to solar radiation and lower thermal insulation levels, also the driving rain load depends on location and facade, and there can be possible additional air leakages through brick work enhancing the vwall ventilation. Based on the presented result the recommendation is to avoid high ventilated cavities with brick façade and to pay special attention to the wall ventilation, mayby have some more openings to reduce the cavity length. Also thinner or treated water repellant façade treatment can improve the moisture performance.

Table 15. Brick facades. Maximum height of a ventilation cavity (building façade) to reach required ventilation air flow rate under different climates and with 25 mm and 45 mm wide ventilation cavity and with different ventilation opening area categories (opening area mm^2 of both the air inflow/outflow openings).

Total area of both openings	Area of one opening	Vantaa Maximum height, m		Bergen Maximum height, m		Holzkirchen Maximum height, m	
mm^2	mm^2	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm
1500	750	-	-	-	-	-	-
3000	1500	7	7	-	-	-	-
6000	3000	18	18	-	-	7	7
12000	6000	40	32	7	-	18	14
Open	50 % of cavity cross-section	56	-	14	7	36	22

7.2.3 Recommendations for timber frame walls with fire breaks

The recommended opening area for the wall ventilation openings of timber façade walls having fire breaks are presented for different opening categories, building heights and for different climates in Table 16.

Table 16. Timber façades with fire breaks in each floor. Maximum height of a ventilation cavity (building façade) to reach required ventilation air flow rate under different climates and with 25 mm and 45 mm wide ventilation cavity and with different ventilation opening area categories (opening area mm^2 of both the air inflow/outflow openings).

Total area of openings	Area of one opening	Vantaa Maximum height, m		Bergen Maximum height, m		Holzkirchen Maximum height, m	
mm^2	mm^2	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm
1500	750	18		10	8	14	13
3000	1500	23	7	17		21	
6000	3000						
12000	6000						
Open	50 % of cavity cross-section	28	25	23	14	25	16

7.2.4 Recommendation for concrete, aerated concrete block and brick walls

These walls have cement fibre board façade with initially wet (95 % RH) concrete wall or aerated concrete block wall or brick walls having initial moisture content corresponding to 85 % RH. All of them have quite similar ventilation requirement, but the performance and opening requirement depends on the climate. Table 17 presents the results for these walls.

Table 17. Walls with cement fibre board or open timber façade having open ventilation cavity. Maximum height of a ventilation cavity (building façade) to reach required ventilation air flow rate under different climates and with 25 mm and 45 mm wide ventilation openings. Minimum opening area(mm^2) of both the air inflow/outflow openings for different building heights under different climate conditions. The total opening area is two times higher.

Total area of openings	Area of one opening	Vantaa Maximum height, m		Bergen Maximum height, m		Holzkirchen Maximum height, m	
mm^2	mm^2	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm
500	250						
1500	750	24	24	14	14	18	18
3000	1500	56	52	32	30	48	43
6000	3000		56	56	56	56	56
12000	6000						
Open	50 % of cavity cross-section						

7.2.5 Recommendation for timber frame and CLT walls

Table 18 presents the results for CLT walls and Table 19 for timber frame walls having both timber facades. Table present the maximum height of the ventilation channel that can be ventilated using different opening area categories.

Table 18. CLT -walls with timber façade having open ventilation cavity. Maximum height of a ventilation cavity (building façade) to reach required ventilation air flow rate under different climates and with 25 mm and 45 mm wide ventilation openings.Minimum opening area(mm^2) of both the air inflow/outflow openings for different building heights under different climate conditions. The total opening area is two times higher.

Total area of openings	Area of one opening	Vantaa Maximum height, m		Bergen Maximum height, m		Holzkirchen Maximum height, m	
mm^2	mm^2	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm
500	250	10	10	6	6	7	7
1500	750	33	33	21	21	30	30
3000	1500	56	56	35	34	56	56
6000	3000			56	56		
12000	6000						
Open	50 % of cavity cross-section						

Table 19. Timber frame walls with timber façade having open ventilation cavity. Maximum height of a ventilation cavity (building façade) to reach required ventilation air flow rate under different climates and with 25 mm and 45 mm wide ventilation openings.Minimum opening area(mm^2) of both the air inflow/outflow openings for different building heights under different climate conditions. The total opening area is two times higher.

Total area of openings	Area of one opening	Vantaa Maximum height, m		Bergen Maximum height, m		Holzkirchen Maximum height, m	
mm^2	mm^2	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm	d = 45 mm	d = 25 mm
500	250	18	18	11	11	11	10
1500	750	56	56	35	35	34	33
3000	1500			56	56	56	56
6000	3000						
12000	6000						
Open	50 % of cavity cross-section						

8. Recommended air permeability for the thermal insulation system

The aim was to evaluate the effect of wall ventilation on the convection heat losses through the wall and what requirements the air permeability of the thermal insulation system should have to maintain the average convective heat losses in suitable level.

The evaluation in this work is based only on the air permeability of the thermal insulation system (insulation and possible surface coatings) corresponding to ideal assembly of the insulation.

There are at least three different occasions in wall ventilation that have different effect on convective air flow in the thermal insulation layer:

1) The pressure gradient in the ventilation cavity in the direction of the cavity. Air flows in the cavity by the side of the thermal insulation. When the cavity is relatively open most of the air flows in the cavity, not through the insulation layer having significantly higher air flow resistance than the cavity. Temperature differences between the thermal insulation and ventilation air can increase natural convection inside the insulation layer. This may increase the convection and affect the heat losses more than the wind caused pressure difference over the cavity length.
2) Air flow through the ventilation openings. Wind causes dynamic pressure fields in the openings, and depending on the opening area, the air flow velocity levels through the opening can be high. When this air flow hits the thermal insulation surface, in some cases perpendicularly, it can cause high pressure differences and strong local convection in the thermal insulation.
3) Pressure differences over the structural details in the ventilation cavity. When the ventilation cavity has some structural details that cause strong resistance for the flow, the air flow tends to bypass this obstruction by flowing through the thermal insulation system. Especially these local pressure differences can be detected in cases with fire breaks that cause significant resistance for the ventilation air flow.

8.1 Criteria for the increase of heat losses

In this analysis the numerically approximated increase of heat losses under yealy average conditions was set for maximum 5 % of the conductive heat losses solved using the U-value of the wall. The result depends on the U-value of the wall, but in this analysis only one selected case was studied having the U-value 0,17 W/m^{2}K.

In some cases the use of more severe conditions as criteria can be justified and the results using the approximated yearly maximum 10 % occurrence wind velocities and design temperature conditions are presented.

8.2 Effect of the pressure gradient

In this analysis the assumption is that the wind caused pressure in the ventilation cavity is reduced by the properly set areas of the ventilation openings to reasonable levels so that the effect forced convection on the thermal insulation by the side of open ventilation cavity is relatively low. Therefore only the effect of natural convection was studied. The simplified study was based on the use of average temperatures. The pressure gradient inside the thermal insulation is caused by the temperature difference between the yearly average outdoor air and the (yearly and local) average temperature of the thermal insulation layer. This gives yearly average pressure gradient inside the thermal insulation.

The heat losses are solved using the yearly average temperatures and the set U-value 0,17 W/m^{2}K. The allowed 5 % of this gives the maximum effect of the convection heat losses. The maximum air flow rate and the allowed air permeability of the thermal insulation could be solved assuming that the convective air is warmed up to the average temperature of the thermal insulation cavity.

The solution is robust and includes several uncertainties. For example, when the warmed up air from the thermal insulation layer flows into the ventilation cavity, the cavity temperature increases, which decreases the temperature difference and convection. Also, due to heat exchange effect, the outflowing air gives out heat to the thermal insulation and the air of the convection air reduces. Due to this factor, the solved convective heat losses are in most cases too high and the solution includes safety. The direction of the error caused by the used estimation is known, but the exact magnitude remains unknown, and it depends strongly on each case.

On the other hand, natural convection takes place mainly in the direction of the stone wool fibers. In this direction the air permeability is typically higher than when the flow is perpendicular to the thermal insulation layer and the main fiber direction.

Table 20 presents the solved requirements for the air permeability of the thermal insulation under three locations using the yearly average and minimum temperatures. The yearly average temperature results are used as critical values. The minimum (design) temperature results only show the sensitivity of the permeability to the temperature conditions.

Table 20. Solved requirement for the maximum air permeability of the thermal insulation to reduce the effect of natural convection under 5 % of the conductive heat losses.

	Vantaa		Bergen		Holzkirchen	
	T °C	Air permeability m^3/msPa	T °C	Air permeability m^3/msPa	T °C	Air permeability m^3/msPa
$T_{,out,av}$	6,5	52E-06	8,1	61E-06	6,6	53E-06
$T_{,out,min}$	-25	12E-06	-10	20E-06	-20	14E-06

The recommendation derived from these results is to have thermal insulation with air permeability 50·10^{-6} m^3/msPa (or lower) in Vantaa, Finland and Holzkirchen, Germany climates. In Bergen, Norway the recommended air permeability is 60·10^{-6} m^3/msPa or lower.

In one published work /7/ based on laboratory measurements for lower structures, the air permeability of stone wool products were devided into three levels. In the lowest air permeability level there are products whose air permeability is not higher than 70·10^{-6} m^3/m·s·Pa. It was stated that the increase of the heat transfer caused by convection in the wall insulated with these products is very small when there is no forced ventilation near these layers and therefore, they do not need any protection against wind.

8.3 Ventilation openings

The effect of ventilation openings were studied using the air velocities through the opening and hitting perpendicular the thermal insulation surface causing a pressure difference over the insulation. The velocities were those solved with concrete wall structures and cement fibre board façade, corresponding to typical case of wall ventilation.

Two cases were studied: the yearly average wind speed with yearly average temperature differences and cases with the approximated yearly maximum 10 % occurrence wind velocities under design outdoor temperature conditions.

The air flow velocities through the ventilation openings were solved under these conditions. These air velocities caused local pressure conditions on the thermal insulation surface. Due to the local nature of the pressure gradient close to the ventilation opening, the results are valid only locally close to the opening area. The solution of the air permeability was the same as in the pressure gradient case including the same estimations and error sources. The assumption was that the pressure difference causes convection through the whole length of the thermal insulation system.

Base on the presented asumptions, the solved requirements for the air permeability levels of the thermal insulation are presented in Table 21. The average conditions (aver.) correspond to average wind velocities under yearly average temperatures and the maximum conditions (max.) correspond to 10 % maximum wind velocity under design outdoor temperature conditions. The highest effects could be detected in low buildings.

Wind caused pressure differences close to the ventilation openings can cause high convection flow into the thermal insulation especially close to the opening on the bottom of the ventilation cavity where natural convection enhances the colder outdoor air flow into the structure. This can result in significant changes in local temperature conditions, which affect the heat losses and even the thermal comfort locally. It is justified to use the maximum conditions as a criteria for the requirement of the air permeability of the thermal insulation system around ventilation openings. The results are valid for all façade materials.

Table 21. Solved requirement for the maximum air permeability of the thermal insulation to reduce the effect of convection under 5 % of the conductive heat losses when the air flow pressure through the ventilation openings and the effect of natural convection is considered. Wind barrier layer is recommended in each floor having ventilation openings.

	Vantaa		**Bergen**		**Holzkirchen**	
Height, m	$v_{,wind,}$ $+\Delta T$	Air permeability $m^3/msPa$	$v_{,wind,}$ $+\Delta T$	Air permeability $m^3/msPa$	$v_{,wind,}$ $+\Delta T$	Air permeability $m^3/msPa$
7	aver.	31E-06	aver.	43E-06	aver.	41E-06
7	max.	4,2E-06	max.	6,2E-06	max.	6,2E-06
18	aver.	39E-06	aver.	44E-06	aver.	44E-06
18	max.	7,1E-06	max.	11E-06	max.	10E-06
32	aver.	42E-06	aver.	49E-06	aver.	47E-06
32	max.	8,9E-06	max.	14E-06	max.	12E-06
56	aver.	44E-06	aver.	53E-06	aver.	48E-06
56	max.	10E-06	max.	16E-06	max.	13E-06

These conditions were solved assuming air flow perpendicular to the thermal insulation surface. In these cases the air flowing into the ventilation cavity may cause high dynamic pressure variations near the openings. The effect of these high dynamic pressure effects near the ventilation openings remain local. After some turbulent region the air flow settles to more stabile flow along the ventilation cavity. It is likely that these dynamic pressures are highest by the openings, not equally distributed along the ventilation cavity.

The recommendation is to have a wind barrier layer on the thermal insulation installed on each floor where there are ventilation openings that allow air flow to hit the thermal insulation layer causing considerable additional convection flow in the insulation layer. The aim is to shelter the thermal insulation from these local high dynamic pressure gradients and to guide the air flow in the direction of ventilation cavity.

The practical length (height) for the area covered with the additional wind barrier is one floor. The width depends on the case, for example, the distribution of the openings. The main principle is to protect the insulation against dynamic pressures to the surface and to guide the air flow in the direction of the ventilation cavity.

The recommended maximum air permeance of the wind barrier layer is $10 \cdot 10^{-6}$ m^3/sm^2Pa.

On those floors, were there are no such ventilation openings, the air permeability can be set according to the results presented in the pressure gradient chapter.

8.4 Ventilation cavity with fire breaks

When there are fire breaks in the ventilation cavity, they form the main resistance for the wall ventilation air flow route. In this evaluation the available pressure difference was equally divided for the fire breaks in each floor. They form pressure difference over the cavity parts separated by the breaks. In addition to wind caused pressure difference also the effect of natural convection was taken into account. The sum of these pressure drops were used to solve the possible air flow through the thermal insulation between the separated cavity parts.

The heat losses were solved using the yearly average temperatures and the set U-value 0,17 W/m^2K. The allowed 5 % increase of this gives the maximum allowed effect of the convection heat losses. Assuming that the convective air is warmed up to the average temperature of the thermal insulation cavity, the maximum air flow and allowed air permeability of the thermal insulation can be solved. This approach includes the same error sources as the stated in the previous chapters, and the results includes safety. Table 22 presents the solved requirements for the air permeability of the thermal insulation under three locations using the yearly average pressure conditions (aver. = average wind speed and outdoor temperature) and the maximum level pressure conditions (max. = 10 % maximum wind velocity values and design outdoor temperatures). The results are valid for all façade materials.

The highest convection effects are found in the cases with low buildings, where the pressure difference over a single fire break is relatively high. Table 11 showed the maximum height of the ventilation cavity with fire breaks that would allow sufficient ventilation for the wall with the set assumptions. In all the climate conditions the maximum height was below 32 m. Therefore the values solved for 7 m and 18 m high cases are valid in practice.

Due to the dynamic behaviour of the pressure fields, it is likely that the local pressure differences are highest close to the ventilation openings and may often exceed the average levels. The high wind velocities strongly enhance the convection in the thermal insulation for the air flow to pass the fire breaks. Therefore it is recommended to have a separate wind barrier in all the structures having ventilation cavity with fire breaks or similar flow resistances that can strongly enhance air flow through the thermal insulation layer. The wind barrier should cover the whole area of each section separated from each other by the fire breaks.

Table 22. Fire breaks in the ventilation cavity. Solved requirement for the maximum air permeability of the thermal insulation to reduce the effect of convection under 5 % of the conductive heat losses under yearly average conditions. The pressure difference is assumed to be equally divided over each fire break.

	Vantaa		Bergen		Holzkirchen	
Height, m	$v_{,wind,}$ $+\Delta T$	Air permeability $m^3/msPa$	$v_{,wind,}$ $+\Delta T$	Air permeability $m^3/msPa$	$v_{,wind,}$ $+\Delta T$	Air permeability $m^3/msPa$
7	aver.	15E-06	aver.	19E-06	aver.	19E-06
7	max.	1,6E-06	max.	2,0E-06	max.	2,5E-06
18	aver.	21E-06	aver.	27E-06	aver.	26E-06
18	max.	3,4E-06	max.	4,5E-06	max.	5,0E-06
32	aver.	27E-06	aver.	33E-06	aver.	31E-06
32	max.	5,0E-06	max.	7,3E-06	max.	7,1E-06
56	aver.	32E-06	aver.	39E-06	aver.	36E-06
56	max.	7,0E-06	max.	9,8E-06	max.	9,3E-06

9. Risk assessment

The analysis was based on simplified numerical studies using mainly average conditions. While the aim was to form general guidelines, these simplifications are justified. Some of the uncertainties are presented in the following.

The use of yearly average values for the moisture load and needed ventilation air flow studies do not take into account the seasonal deviations in the moisture performance.

The available and possible maximum level of wind loads for the wall are always relatively vague. They depend on the local climate, local topographic conditions, wall directions, structural details, etc. These conditons may vary strongly in practice. The levels of the solved average and approximated maximum levels of pressure differences differ significantly. The wall ventilation and convection in the thermal insulation depend strongly on the set criteria.

The set categories for the area of the ventilation openings means that the ventilation air flow rates and pressure conditons in the cavity have some differences between the solved case and the practical solution even in the average conditions.

Exact convection air flow fields were not studied. The air flow fields in the ventilation cavity and thermal insulation system were analysed using simplified models with set assumptions and mainly using average conditions. Due to the simplified approach also the solved air permeability levels for the thermal insulation materials or systems are relatively rough approximations.

The approximation of the convective heat losses was based on the assumption that the temperature of the out-flowing air is the same as the average temperature of the thermal insulation cavity. Due to heat exchange effect, the outflowing air gives out heat to the thermal insulation and the air of the convection air is reduced. Due to this factor, the solved convective heat losses are in most cases too high and the solution includes safety. The direction of the error caused by the used estimation is known, but the exact magnitude remains unknown and better general approximations couldn't be justified.

The solar radiation on the walls was omitted, which increases the safety of the analysed moisture performance. In practice, the drying potential of the wall ventilation can be higher than predicted in this approach.

10. Summary and conclusions

Numerical studies were carried out to present guidelines for Paroc thermal insulation products when applied in ventilated walls of new multi-storey apartment buildings. These walls can be build using concrete, aerated concrete blocks, brick, wood frame or CLT as the load bearing structure. The ventilation cavity is between the thermal insulation layer and the façade element (typical materials are timber, brick, cement board). The guidelines were meant to show what ventilation opening areas are need to have adequate wall ventilation air flow rate for drying the additional moisture out of the structure, and to set the requirements for the air permeability of the thermal insulation product or define the possible need for additional wind barrier to avoid notable increase of yearly heat losses due to convection.

These guidelines are determined using numerical simulations. They are mostly based on yearly average moisture load and wind conditions. Several boundaries were set based on expert opinion in order to study the defined cases of wall ventilation taking into account the project plan and scale. The results can not be considered as exact limit values, but they give good approximations on how to realize wall ventilation having adequate moisture drying efficiency with reasonable convection effects on thermal performance.

Adequate wall ventilation air flow rates are needed for good moisture performance of ventilated walls. This alone doesn't guarantee the safe performance. Several other factors (diffusion resistances of the material layers, climate loads, air leakages, etc.) may affect the moisture performance that has to be ensured separately.

The yearly average moisture flow rates from the structures and the required yearly average air flow rates to carry out these additional moisture loads were defined.

The opening area for different cases of structures and climates were presented to have suitable wall ventilation air flow rate with the available pressure difference in the studied climate.

The recommendations for the permeability of the thermal insulation systems were studied and presented for different structural cases aiming to avoid notable effect of convection on heat losses under different climate conditions.

These guidelines give an overview on the different factors having effect on the wall ventilation and on the risks for convection in thermal insulation. The recommendations for the air permeability of the thermal insulation are given for different cases

The summarized main guidelines are:

- The ventilation openings can be designed (using set categories of the opening area) to set the yearly average pressure differences over the ventilation cavity to match with the needed yearly average wall ventilation air flow rates
- If the ventilation openings allow local significant dynamic pressure conditions on the thermal insulation surface, a wind barrier layer should be installed on the thermal

insulation on each floor where there are ventilation openings in order to shelter the thermal insulation from local high dynamic pressure gradients and to guide the wall ventilation air flow in the direction of ventilation cavity

- In ventilation opening cases where additional wind barrier is recommended, the practical length (height) for the area covered with the additional wind barrier is one floor. The protection width depends on the case, the main principle is to protect the insulation against dynamic pressures to the surface and to guide the air flow in the direction of the ventilation cavity.

- In ventilation cavities where the air flows relatively freely in the direction of the cavity the maximum recommended air permeability of the thermal insulation is $50 \cdot 10^{-6}$ $m^3/m \cdot s \cdot Pa$

- Ventilation cavities with fire breaks are typically applied with timber facades. The fire breaks cause significant air flow resistances reducing the maximum practical height of the ventilation cavity and they also tend to cause strong convection flow into thermal insulation. A separate wind barrier is recommended in all structures having fire breaks in the ventilation cavity. The recommended maximum air permeance of the wind barrier layer is $10 \cdot 10^{-6}$ m^3/sm^2Pa.

The wind barrier layer should also perform as a weather protecting layer against the possible fine droplets of rain or snow entering the cavity by wall ventilation. The air permeance of the thermal insulation system depends not only on the product properties of the insulation and wind barrier, but also on the installation details and workmanship. The implementation should take into account both the sustainable protection against wind loads and the safe moisture performance taking into account the protection of the structure against moisture loads in water or vapour phase.

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