Better Estimation of Cross-ventilation through Roof Windows in an Attic - Possible Improvement for EN 16798-7:2017

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ABSTRACT

EN 16798-7:2017 considers that windows on roofs that have a pitch below 60° are not included on the windward side whatever their orientation. It means that roof windows are accounted for, but only on the leeward side when using the existing standard for calculation of air flows, EN 16798-7.
Therefore, in the specific case of a room only equipped with roof windows (e.g. an attic) and aeraulically independent from the rest of the building, whatever the orientation of the roof windows, only the simplified "single-sided" calculation method of EN 16798-7:2017 is applicable.
However, literature (Liddament 1996) shows that roof windows can have in some cases a positive wind pressure coefficient (Cp), when the wind is attacking straight onto the windows.
This purpose of this note is to:

- develop a more precise calculation method adapted to roof windows to take into account cross-ventilation that may occur through them (even when there are no facade windows in the zone)
- compare results obtained using this "adapted" method and the existing single-sided method from EN 16798-7.

This study has shown that, for a building with low buildings surrounding it, the simplified single-sided method from EN 16798-7 was indeed underestimating the airflow rate by up to 77%.
More information on the calculation method proposed in EN 16798-7:2017, including the validation of simplified formula with a pressure code, can be found in (Leprince, Valérie; Carrié, François-Rémi, 2016) and (Larsen et al. 2018).

KEYWORDS

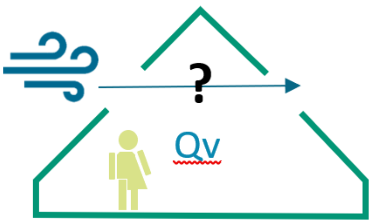
Cross-ventilation, roof window, attic, 16798-7, calculation method

NOMENCLATURE

Variable	Unit	Definition
$A_{ori;j}$	m²	Window area on the orientation "j"
$A_{w,i}$	m²	Area of window "i"
$A_{w,tot}$	m²	Zone total windows area
$A_{w,cross}$	m²	Window area considered for cross-ventilation
$C_{D;w}$	_	Discharge coefficient
Cp	_	Wind pressure coefficient
C_{st}	m/s/(m.K)	Coefficient taking into account stack effect in airing calculations
C_{wnd}	-	Coefficient taking into account wind speed in airing calculations
N_{ang}	-	Number of divisions of the horizontal plane (4 for facade windows, 6 for case 1, 15 for case 2)
N_w	-	Number of windows in the building
$h_{w;st}$	m	Useful height for stack effect for airing: height difference between the bottom and the top of the windows
$u_{10,site}$	m/s	Wind speed at 10 meter high

$\alpha_{w,i}$	°	Orientation of window "i"
$\beta_{w,i}$	°	Tilt angle of window "i"
ΔT	°C	Temperature difference between inside and outside
ρ_a	kg/m^3	Air density

1 INTRODUCTION



Attic independent from the rest of the building

The questions raised in this study are:

- What airflow rate, due to cross ventilation, may occur through 2 roof windows in an attic?
- Would it be relevant to develop a more precise method, than the one described in EN 16798:7:2017, for the specific case of cross-ventilation through roof windows?
- Could this "new adapted method" be used as an addendum to EN 16798-7 for this specific calculation?

According to EN 16798-7:2017, roof windows always have a negative Cp. **So, the existing simplified cross-ventilation method from EN 16798-7 cannot be used in the case of this attic.** Therefore, when using the existing standard, the simplified single-sided equation shall be used to calculate the airflow rate in this attic, as there are no other options.

The existing simplified single-sided method from EN 16798-7 will be used as reference to be compared with the new developed method.

Theoretically, it is actually possible that an airflow rate due to cross-ventilation occurs through 2 roof windows. According to the literature, a roof window may indeed have a positive wind pressure coefficient when the wind is attacking straight onto the roof, contrary to facade windows for which the coefficient is almost always negative when the wind angle is 45° (see Figure 1).

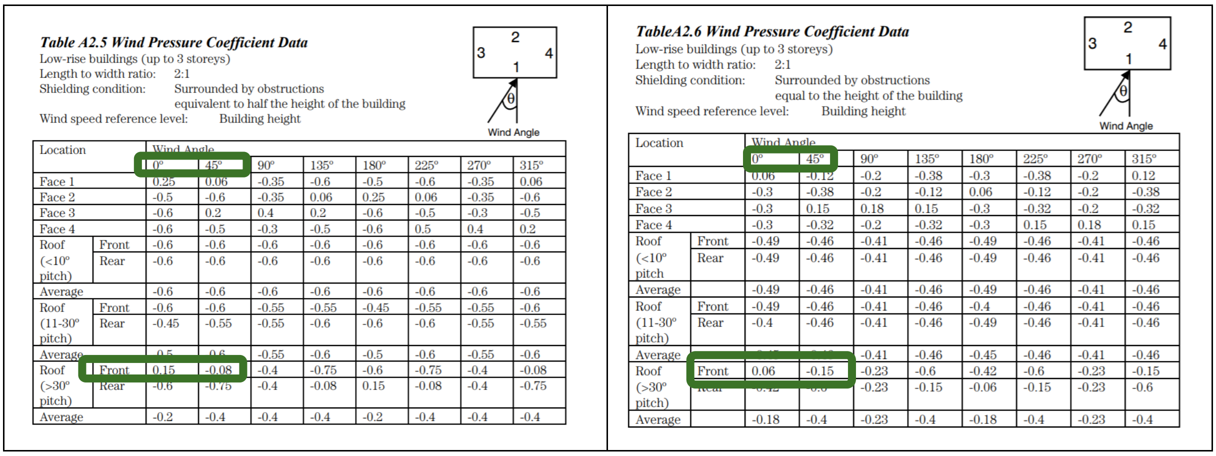


Table A2.5 Wind Pressure Coefficient Data
Low-rise buildings (up to 3 storeys)
Length to width ratio: 2:1
Shielding condition: Surrounded by obstructions equivalent to half the height of the building
Wind speed reference level: Building height

Location		Wind Angle 0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06
Face 2		-0.5	-0.6	-0.35	0.06	0.25	0.06	-0.35	-0.6
Face 3		-0.6	0.2	0.4	0.2	-0.6	-0.5	-0.3	-0.5
Face 4		-0.6	-0.5	-0.3	-0.5	-0.6	0.5	0.4	0.2
Roof (<10° pitch)	Front	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
	Rear	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
Average		-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
Roof (11-30° pitch)	Front	-0.6	-0.6	-0.55	-0.55	-0.45	-0.55	-0.55	-0.6
	Rear	-0.45	-0.55	-0.55	-0.6	-0.6	-0.6	-0.55	-0.55
Average		-0.5	-0.6	-0.55	-0.6	-0.5	-0.6	-0.55	-0.6
Roof (>30° pitch)	Front	0.15	-0.08	-0.4	-0.75	-0.6	-0.75	-0.4	-0.08
	Rear	-0.6	-0.75	-0.4	-0.08	0.15	-0.08	-0.4	-0.75
Average		-0.2	-0.4	-0.4	-0.4	-0.2	-0.4	-0.4	-0.4

TableA2.6 Wind Pressure Coefficient Data
Low-rise buildings (up to 3 storeys)
Length to width ratio: 2:1
Shielding condition: Surrounded by obstructions equal to the height of the building
Wind speed reference level: Building height

Location		Wind Angle 0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.06	-0.12	-0.2	-0.38	-0.3	-0.38	-0.2	0.12
Face 2		-0.3	-0.38	-0.2	-0.12	0.06	-0.12	-0.2	-0.38
Face 3		-0.3	0.15	0.18	0.15	-0.3	-0.32	-0.2	-0.32
Face 4		-0.3	-0.32	-0.2	-0.32	-0.3	0.15	0.18	0.15
Roof (<10° pitch	Front	-0.49	-0.46	-0.41	-0.46	-0.49	-0.46	-0.41	-0.46
	Rear	-0.49	-0.46	-0.41	-0.46	-0.49	-0.46	-0.41	-0.46
Average		-0.49	-0.46	-0.41	-0.46	-0.49	-0.46	-0.41	-0.46
Roof (11-30° pitch)	Front	-0.49	-0.46	-0.41	-0.46	-0.4	-0.46	-0.41	-0.46
	Rear	-0.4	-0.46	-0.41	-0.46	-0.49	-0.46	-0.41	-0.46
Average		[illegible]	[illegible]	-0.41	-0.46	-0.45	-0.46	-0.41	-0.46
Roof (>30° pitch)	Front	0.06	-0.15	-0.23	-0.6	-0.42	-0.6	-0.23	-0.15
	Rear	-0.42	-0.6	-0.23	-0.15	-0.06	-0.15	-0.23	-0.6
Average		-0.18	-0.4	-0.23	-0.4	-0.18	-0.4	-0.23	-0.4

Figure 1: Wind pressure coefficient data from (Liddament 1996) for a rectangular building for 2 different shielding conditions

In this study, it is assumed that Cp coefficients are constant for a roof pitch between 30-60 degrees. In the following example, a roof with a pitch of 45 degrees has been considered as illustrated in Figure 2. A linear extrapolation was used on Cp coefficient from Figure 1 (see green markings in Figure 1 for the line "Roof > 30° pitch") for wind angles between 0° and 45°. As the Cp depends on the surrounding of the building, if the building is surrounded by obstructions equal to:

- half the height of the building (left table), then Cp is positive for wind angles between -30° and +30°
- the height of the building (right table), then Cp is positive for wind angles between -12° and + 12°.

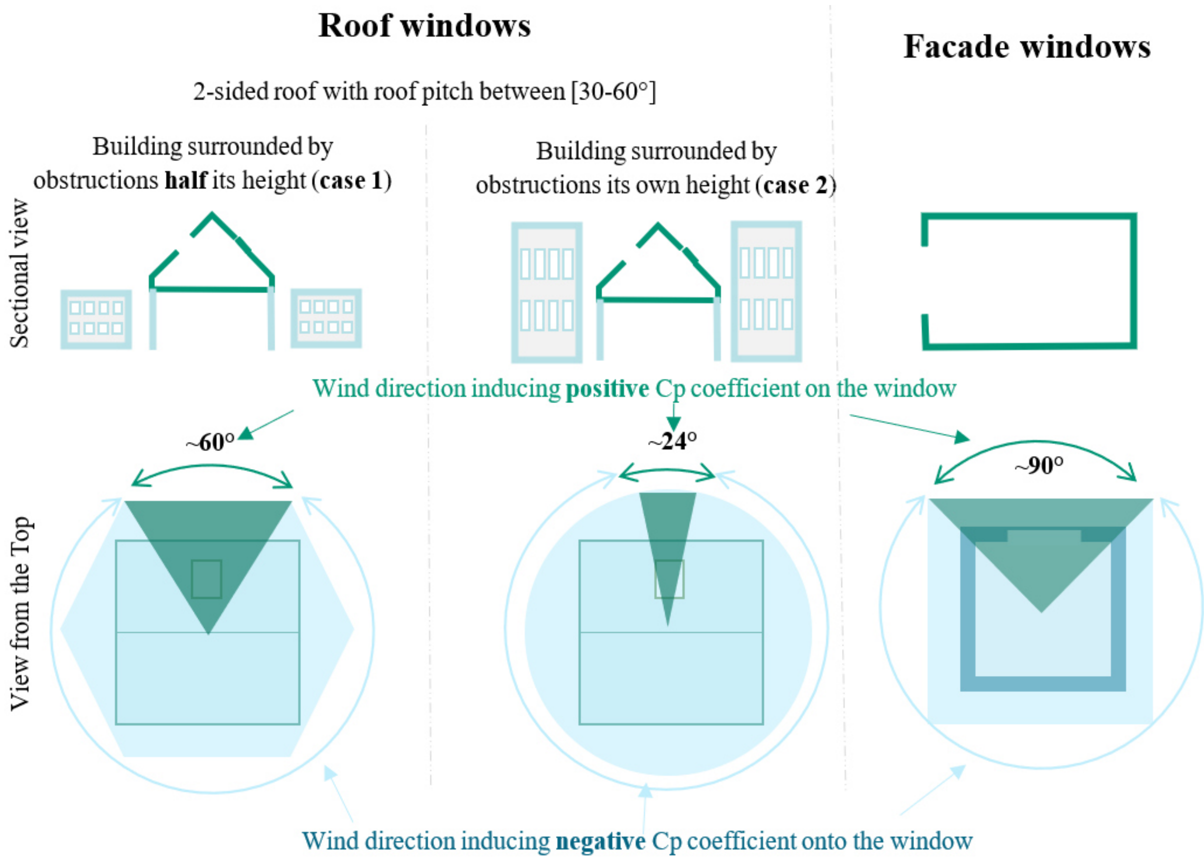


Figure 2: Wind directions that induce positive pressure coefficients on roof and facade windows

Figure 2 compares wind directions that induce positive Cp coefficients for roof windows and facade windows. It highlights that the wind angle that induces positive Cp coefficient is narrower for roof windows than for facade windows. Moreover the range is reduced by roughly 60% if the building is surrounded by buildings with the about same height rather than half the height.

As EN 16798-7:2017 only divides the building into 4 orientations, it considers that Cp coefficients for roof windows are always negative. Therefore, according to EN 16798-7, cross-ventilation cannot occur when there are only roof windows in a ventilation zone (e.g. in an attic).

2 OBJECTIVE AND METHOD

The objective of this study is to test a new method, based on a EN 16798-7 method (called the “adapted cross-ventilation method”), to take into account cross-ventilation occurring through roof windows and find the impact on estimated ventilation airflow rate. The principle of this new method is, when a zone with only roof windows is simulated, instead of dividing the plan into 4 zones, to divide the plane into:

- 6 orientations (=360°/60°, where 60° is the range for positive Cp values) when the zone is surrounded by obstructions half its height (case 1)

- 15 orientations (=360°/24°, where 24° is the range for positive Cp values) when the zone is surrounded by obstructions of the same height (case 2).

2.1 Test Case

Figure 3: Illustration of the test case

The test case is an attic aeraulically independent from the rest of the building. The roof is a two-sided roof with a pitch of 45° and equipped with one roof window on each side of the room. The hypotheses used are detailed in Table 1.

Table 1: Hypotheses of the calculation

Reference air density	ρa_{ref}	1.2	kg/m^3
External air density	ρa_e	1.2	kg/m^3
Discharge coefficient	$C_{D;w}$	0.67	-
Coefficient taking into account stack effect in airing calculations	C_{st}	0.0035	m/s/(m.K)
Useful height for stack effect for airing: height difference between the bottom and the top of the windows	$h_{w;st}$	0.8	m
Coefficient taking into account wind speed in airing calculations	C_{wnd}	0.001	1/(m/s)

The following configurations have been considered for the test case (Table 2):

Table 2: Configurations considered for the test case

Assumption on	**Configurations considered**
Temperature difference between inside and outside (°C)	0; 2; 5; 8; 10; 15; 20
Wind speed, u (m/s)	0; 1; 2; 3; 4; 5
Free window area: $A_{w;1}$=$A_{w;2}$= (m²)	0.15; 0.25; 0.35; 0.5
Difference of wind pressure coefficients between windward and leeward sides (ΔC_p) see Table 1 - Case 1: building surrounded by obstructions equivalent to half the height of the building - Case 2: building surrounded by obstructions equal to height of the building	- 0.75 (case 1) - 0.48 (case 2)

2.2 EN 16798-7: 2017 method for single-sided ventilation

According to EN 16798-7:2017 roof windows always have a negative Cp so the simplified cross-ventilation equation cannot be used in the case of an attic and therefore the simplified single-sided equation shall be used to calculate the airflow rate in our test cases:

$$q_{V;arg;in} = 3600 \times \frac{\rho_{a;ref}}{\rho_{a;e}} \cdot \frac{A_{w;tot}}{2} \cdot \max\left(C_{wnd} \cdot u^2_{10;site} ; C_{st} \cdot h_{w;st} \cdot abs\left(T_z - T_e\right)\right)^{0,5} \quad (1)$$

Results from this equation will be named "Method EN 16798-7 single-sided" and will be used as a reference to be compared with new results from the "adapted cross ventilation method", as seen in the results part.

2.3 EN 16798-7: 2017 method for cross-ventilation

Simplified formulas for cross-ventilation cannot be used in our test cases as there are no facade windows, however, as this method has been used to develop the "adapted method", it is explained here.

To calculate the airflow rate coming in and out of a ventilation zone when cross-ventilation occurs, EN 16798-7:2017 proposes a simplified method based on the following equation:

$$q_{V;arg;in} = 3600 \times \frac{\rho_{a;ref}}{\rho_{a;e}} \cdot \max\left(C_{D;w} \cdot A_{w;cros} \cdot \min\left(u_{10;site} ; u_{10;site;max}\right) \cdot \left(\Delta C_p\right)^{0,5} ; \frac{A_{w;tot}}{2} \cdot \left(C_{st} \cdot h_{w;st} \cdot abs\left(T_z - T_e\right)\right)^{0,5}\right) \quad (2)$$

Where the calculation of $A_{w;cros}$, representing the equivalent cross ventilation area, is made as follows:

$$\alpha_{ref} = (i-1) \times 45° + (j-1) \times 90°$$
$$\alpha_{max} = \alpha_{ref} + 45°$$
$$\alpha_{min} = \alpha_{ref} - 45°$$

For k = 1 to N_w,

$$\text{if } \alpha_{min} \leq \alpha_{w,k} < \alpha_{max} \text{ and } \beta_{w,k} \geq 60° : A_{w;ori,j} = A_{w;ori,j} + A_{w;k} \quad (3)$$

End For k

$$A_{w;cros,i} = \frac{1}{4} \times \sum_{\substack{j=1 \text{to} 4 \\ A_{w;ori,j} > 0}} \left(\frac{1}{\sqrt{\underbrace{\frac{1}{A^2_{w;ori,j}}}_{\text{Windward when wind comes from orientation "i"}} + \underbrace{\frac{1}{\left(A_{w;tot} - A_{w;ori,j}\right)^2}}_{\text{Leeward when wind comes from orientation "i"}}}} \right) \quad (4)$$

The calculation of the airflow rate due to wind takes into account roof windows only on the leeward side (never on the windward side), where roof windows are included in the total window area of the zone $A_{w,tot}$.

2.4 Adapted cross ventilation method for roof windows

To take into account the fact that cross-ventilation may occur through roof-windows located as described in our example, in this study, instead of dividing the plane into 4 angles of 90° each, it will be divided into:

- Case 1: 6 angles of 60° (N_{ang}=6)
- Case 2: 15 angles of 24° (N_{ang}=15)

We propose the following algorithm for a ventilation zone with only roof windows (at least two) that are located on at least 2 different orientations. This algorithm can only apply for ventilation zones with only roof windows (it does not apply when there is a facade window in the zone).

$$A_{w;tot} = \sum_{k=1}^{N_w} A_{w;k} \tag{5}$$

In our example:

$A_{W;1}=A_{W;2}=$	$A_{W;TOT}=$
0.15 m²	*0.3 m²*
0.25 m²	*0.5 m²*
0.35 m²	*0.7 m²*
0.5 m²	*1 m²*

For j = 1 to N_{ang}

$$\alpha_{ref;roof} = (j-1) * \frac{360}{N_{ang}}$$
$$\alpha_{max;roof} = \alpha_{ref} + \frac{360}{2N_{ang}}$$
$$\alpha_{min;roof} = \alpha_{ref} - \frac{360}{2N_{ang}} \tag{6}$$

For k =1 to N_w (number of roof windows in the ventilation zone)

If $\alpha_{min;roof} \leq \alpha_{w,k} < \alpha_{max;roof}$ and $30° \geq \beta_{w,k} \geq 60°$ then $A_{w;ori;j} = A_{w;ori;j} + A_{w;k}$ (7)

It sums the area of each roof window that are:

- *For case 1: located within an angle of 30° on each side of the center of the part*
- *For case 2: located within an angle of 12° on each side of the center of the part.*

End for k

End for j

$$A_{w;cros} = \frac{1}{N_{ang}} * \sum_{i=1}^{N_{ang}} \frac{1}{\sqrt{\frac{1}{A_{w;ori;j}{}^2} + \frac{1}{\left(A_{w;tot} - A_{w;ori;j}\right)^2}}} \tag{8}$$

This equation assumes an equiprobability of wind direction: the wind comes from each direction $1/N_{ang}{}^{th}$ of the time.

In our example this equation is:

For case 1, N_{ang}=6 (6 angles)

$$A_{w;cros} = \frac{1}{6} * \left(\frac{1}{\sqrt{\frac{1}{A_{w;1}{}^2} + \frac{1}{\left(A_{w;2}\right)^2}}} + \frac{1}{\sqrt{\frac{1}{A_{w;2}{}^2} + \frac{1}{\left(A_{w;1}\right)^2}}} \right) = \frac{A_{w;1}}{3\sqrt{2}} \tag{9}$$

For case 2 , N_{ang}=15 (15 angles)

$$A_{w;cros} = \frac{1}{15} * \left(\frac{1}{\sqrt{\frac{1}{A_{w;1}{}^2} + \frac{1}{\left(A_{w;2}\right)^2}}} + \frac{1}{\sqrt{\frac{1}{A_{w;2}{}^2} + \frac{1}{\left(A_{w;1}\right)^2}}} \right) = \frac{2 * A_{w;1}}{15\sqrt{2}} \tag{10}$$

$A_{W;1}$=$A_{W;2}$=	CASE 1, $A_{W;CROS}$=	CASE 2, $A_{W;CROS}$=
0.15 m²	*0.035 m²*	*0.014 m²*
0.25 m²	*0.059 m²*	*0.024 m²*
0.35 m²	*0.082 m²*	*0.033 m²*
0.5 m²	*0.118 m²*	*0.047 m²*

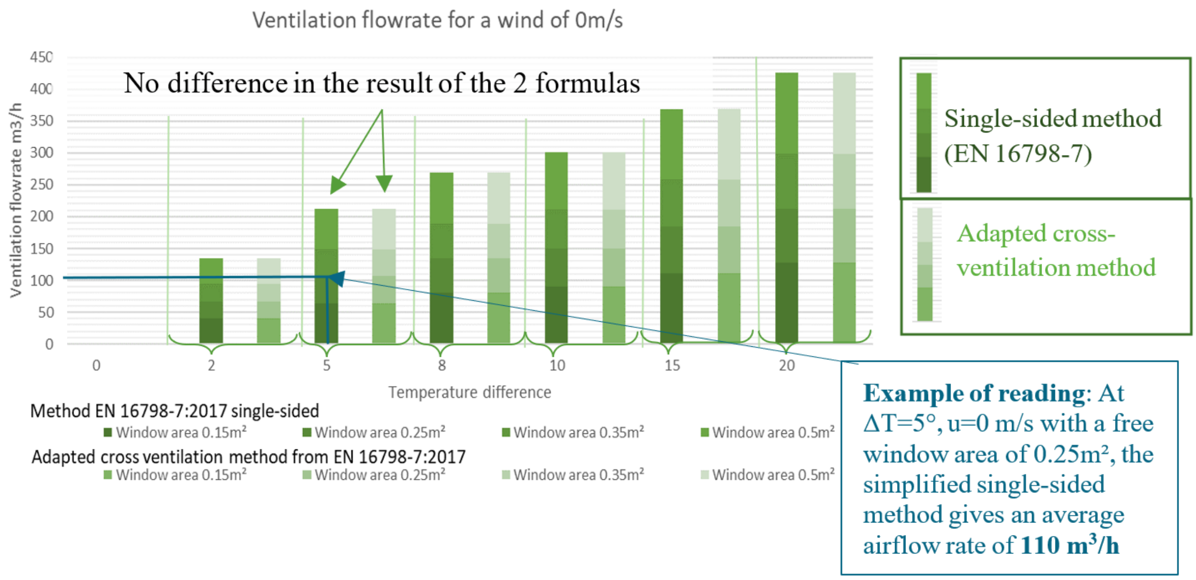
Then formula 47 of EN 16798-7:2017 is applied:

$$q_{V;arg;in} = 3600 \times \frac{\rho_{a;ref}}{\rho_{a;e}} \cdot \max\left(C_{D;w} \cdot A_{w;cros} \cdot \min\left(u_{10;site}; u_{10;site;max}\right) \cdot \left(\Delta C_p\right)^{0,5}; \frac{A_{w;tot}}{2} \cdot \left(C_{st} \cdot h_{w;st} \cdot abs\left(T_z - T_e\right)\right)^{0,5} \right) \quad (11)$$

In this study $u_{10;site;max}$ is considered to be 5m/s.
Results from this equation will be named "Adapted cross-ventilation method from EN 16798-7" and will be compared to the simplified single-sided method.

3 RESULTS

The graphs below compare the ventilation airflow rates calculated with the simplified single-sided method from EN 16798-7 (dark green bars) and the ventilation airflow rate calculated with the "adapted" cross-ventilation method (which takes into account cross ventilation that can occurs in a zone or room with two roof windows) illustrated in light green bars.



As expected, when the wind speed is 0 m/s there is only the stack effect as a driving force for ventilation, so both methods give the same result and there is no difference between case 1 and case 2.
Table 3 gives results for wind speeds from 1 to 5m/s. These results show an important difference between case 1 and case 2:

- when the building is surrounded by buildings of its own height (case 2) there are little differences between the simplified single-sided method of EN 16798-7 and the adapted cross-ventilation method. For 25 out of the 42 cases studied, results are the same and the maximum difference is 28% when wind is the main driver (hence small temperature difference and high wind speed)
- when the building is surrounded by building equivalent to half its height, the difference is significant: only 11 out of the 42 configurations studied provide the same results, the maximum difference reaches 77% and is observed for 11 configurations.

For case 1, with the adapted cross-ventilation method, the wind is the main driver for ventilation from 2m/s as long as the temperature difference remains below 20°C. This is shown by the airflow rates seen in the light green bars being constant (for a given wind speed above 2m/s, they are all having the same height whatever the temperature difference).

The results also show that, for a given case, wind speed and temperature difference, differences in percentage between the 2 methods do not depend on the free window area (as in both methods the flowrate is proportional to the free window area).

Table 3: Results for the simulations for case 1 and case 2

Table 4 gives the airflow rates calculated with both methods for case 1, for three different free window areas ranging from 0.15m² to 0.50m². It confirms that for case 1 there is a big difference between the results given by the simplified single-sided method from EN 16798-7 and the one given by the "adapted" cross-ventilation method. The difference between the two methods increases with wind speeds.

Table 4: Airflow rate trough roof windows calculated with the adapted method and the simplified single-sided method from EN 16798-7 for case 1.

Wind speed (m/s)	Free windows area (m²)	Airflow rates calculated with the adapted method (m³/h)		Airflow rates calculated with single-sided method in EN 16798-7 (m³/h)	
		Min*	Max*	Min*	Max*
1	0.15	74	128	17	128
	0.25	123	213	28	213
	0.50	246	426	57	426
2	0.15	148		34	128
	0.25	246		57	213
	0.50	492		114	426
3	0.15	222		51	128
	0.25	369		85	213
	0.50	739		171	426
4	0.15	295		68	128
	0.25	492		114	213
	0.50	985		228	426
5	0.15	369		85	128
	0.25	615		142	213
	0.50	1231		285	426

* Depends on the temperature difference

4 CONCLUSIONS

The objectives of this study were:

- to develop a more precise calculation method adapted to roof windows to take into account cross-ventilation that may occur through them (even when there are no facade windows in the zone)
- to compare results obtained with this method to the simplified single-sided method from EN 16798-7

The "adapted" calculation method developed is consistent with the one proposed in EN 16798-7:2017, but simply further divides the horizontal plane to better take into account the specific cases of roof windows. The "adapted" method developed shall only be used **for the specific case of zones with only roof windows** with multiple orientations. As the Cp coefficient remains positive for a wider range of angles for facades windows (see Figure 1Figure 2), applying this new method to zones with facade windows may lead to falsely consider cross-ventilation. Combining the two methods would lead to much more complex algorithms.

In this study, where roof windows could have positive Cp values even if they have a pitch between 30-60 degrees, we have shown, that:

- in case 2 (building surrounded by hight obstacles), the new "adapted" cross-ventilation method provides results close to the simplified single-sided method from EN 16798-7,

- in case 1 (building surrounded with lower building) cross-ventilation can theoretically occur quite often and the simplified single-sided method from EN 16798-7 highly under-estimates the average airflow rate in this specific case.

Proposing this new adapted method for cross-ventilation to calculate the airflow rate in the specific case of room with only roof windows would allow to better estimate the airflow rate in the room. This new "adapted" cross ventilation method could be used as an addendum to EN 16798-7 for this specific application of zones with only roof windows.

Nevertheless, while interpreting those results the following limitations shall be kept in mind:

- The given airflow rates are averaged airflow rates which by no mean are instantaneous airflow rates, assuming (among other things) an equiprobability of wind directions which may not be relevant in certain places
- Simplified equations used here have been developed in the context of EN 16798-7:2017 and compared to models performed in CONTAM and to on-site measurements (see (Larsen et al. 2018; Leprince, 2016.)). They slightly underestimate the airflow rate as EN 16798-7 focuses on the calculation of the building energy use in periods when there is a cooling demand, and they have not been checked for very small temperature differences.
- Cp coefficients used in this study are the ones provided in (Liddament 1996), where other sources provide other values.
- The airflow rates only apply when windows are open. In case of high-speed winds or high temperature differences, when windows may only be open for very short periods of time, the averaged airflow rate may not be relevant.

It would be interesting to complete this study with:

- On-site measurements to estimate the real airflow rate,
- Wind tunnel measurements to check if the Cp coefficients are applicable for roof
- CFD simulations to check the impact of the position of the roof windows (angle of opening) on the airflow rate.

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