Competitive analysis of window airing models proposed in prEN 16798-7 and influence of internal resistances

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Abstract
This study compares window airing models defined in prEN 16798-7 and their modifications after public enquiry between themselves and with results obtained with CONTAM on 3 building geometries. We have calculated the total outgoing air flow rate through the windows for various wind speeds (0 to 5 m/s), temperature differences (0 to 15 K), wind directions, and windows distributions for three internal resistance scenarios: no internal partitions, open doors and closed doors.

The major findings are that 1) the single-sided direct method significantly underestimates the air flow rate compared to the implicit method when there is cross-ventilation; 2) the cross-ventilation method gives results in reasonably good agreement with the implicit method; 3) the windows distribution has a significant impact on results obtained with the cross-ventilation method and with the implicit method; 4) the initial cross-ventilation method tends to overestimate the air flow rate at high wind speeds and high temperature differences whereas it underestimates the air flow rates at low wind speeds and low temperature differences; 5) open doors do not significantly affect the air flow rate; 6) closed doors reduce the air flow rate in the range of 30% to 80% depending on the building geometry; 7) the revisions implemented after public enquiry for the cross-ventilation method reduce the risk to overestimate the air flowrate.

Keywords – airing; window; calculation; simplified method

Nomenclature

| $A_{w,i}$ | Free area of window "i" (m$^2$) |
| $A_{w,cross}$ | Equivalent window cross-sectional free area for cross-ventilation (m$^2$) |
| $A_{w,tot}$ | Total windows area of the house (sum of $A_{w,i}$) |
| $C$ | Air leakage coefficient (m$^3$ s$^{-1}$ Pa$^{-n}$) |
| $C_{D}$ | Discharge coefficient (-) |
| $C_{p}$ | Pressure coefficient (-) |
| $C_{st}$ | Coefficient taking into account |

| $u_{10}$ | Meteorological wind speed at 10 m (m s$^{-1}$) |
| $u_{site}$ | Wind speed at the building level (m s$^{-1}$) |
| $u_{10,site}$ | wind speed at the building at 10m (m s$^{-1}$) |

Greek symbols

| $\Delta C_{p}$ | Difference of wind pressure coefficients between the windward and leeward sides (-) |
| $\Delta p$ | Pressure difference (Pa) |
| $\rho_a$ | Air density (kg m$^{-3}$) |
stack effect in airing calculations: 0.0035 m/s/(m·K)

$C_t$ Coefficient taking into account wind turbulence 0.01 m/s

$C_{wnd}$ Coefficient taking into account wind speed in airing calculations 0.001 (1/(m/s))

$g$ Acceleration of gravity (m s$^{-2}$)

$h_{path,i,j}$ Mid-height of path relative to floor level (m)

$h_{w;st}$ Useful height for stack effect for airing (m)

$p$ Pressure relative to external pressure (Pa)

$q$ Volumetric airflow rate (m$^3$ s$^{-1}$)

$T$ Temperature (K)

### Subscripts

- $e$ Pertaining to external conditions
- $i$ Index of a variable for windows
- $j$ Index of a variable for divisions of windows
- $ref$ Pertaining to reference conditions
- $path$ Pertaining to an air flow path
- $w$ Pertaining to windows
- $z$ Pertaining to internal conditions

### 1. Introduction

To help member states meet the requirements of the Energy Performance of Buildings Directive recast [3], the European Commission issued a mandate to European standardisation bodies to revise the first EPBD package standards published in 2007-2008 [4]. This includes the revision of calculation standards to assess the energy performance of buildings.

The determination of airflow rates is a very important element to assess the energy performance of a building. With the revision process, EN 15242 (2007) that deals with this aspect will be replaced by EN 16798-7 and its accompanying technical report (16798-8). The new pre-standard (prEN 16798-7, 2014) submitted for public enquiry gives 4 methods to consider airflows through windows (some of them have been modified after public enquiry in the FprEN 16798-7 version):

- a) A simplified method based on a multiplying factor of the required outdoor air flow rate;
- b) An explicit method based on a correlation for single-sided ventilation. It was based on work performed by de Gids, W. and Phaff, H. in 1982. It has been modified in FprEN 16798-7;
- c) An explicit method based on a correlation for cross-ventilation inspired from the French regulation RT 2012. It has also been modified in FprEN 16798-7.
- d) An implicit method using internal pressure as input.

Methods a) and b) were already in EN 15242 while methods c) and d) were new in prEN 16798-7.

The objectives of the study are:

- a) to compare the results obtained with the various methods;
- b) to evaluate how various assumptions can influence the resulting airflow rates.
2. Methodology

General description

We conducted this study in 2 phases [7]:

- First, we compared window airing models defined in prEN 16798-7 and their modifications after public enquiry between themselves and with results obtained with CONTAM 3.1 [6] on 3 building geometries.

- Second, we investigated the impact of internal doors (closed or open) and of a window located in the staircase on the outgoing air flow rate using CONTAM 3.1. We compared those results to those obtained assuming a uniform pressure within the house as in FprEN16798-7. In addition, these results were compared with the direct single-ventilation method results of phase 1.

Fig. 1 Left: test configurations n°1.1 and 1.2. One-storey house. Front and plan views. (1.1 = West wind; 1.2 = East/North/South wind). Right: test configuration n°2.1, 2.2, 2.3. 1½-storey house with open staircase, no window in staircase

We have used the spreadsheet developed in CEN TC 156 / WG 21 for prEN 16798-7 and FprEN 16798-7 as well as CONTAM 3.1.

Figure 1 gives the geometrical configurations considered for this study. The wind directions represented in figure 1 have been investigated. With CONTAM, we performed simulations on configuration 1.1 and 2.1 with a West-wind only.
A configuration 3 has also been tested with a staircase window. Configuration 3 was similar to configuration 2.1 but part of the roof window area was shifted in a staircase window. The staircase window was set at the same height as the other roof windows to be able to compare precisely configurations 2.1 and 3: only windows positions in rooms vary but the windows areas for each couple of height and wind pressure coefficient remain the same.

Three internal partitions have been tested with CONTAM:

- No partition at all: the building is considered as one zone (as in prEN 16798-7)
- Doors open (door free area 1.6 m², $C_{path}=4921 \text{ m}^3/\text{h}/\text{Pa}$)
- Doors closed (door free area 0.056 m², $C_{path}=172 \text{ m}^3/\text{h}/\text{Pa}$)

Four temperature differences between inside and outside have been tested (0°C, 5°C, 10°C, 15°C). The internal temperature is set to 25°C and analyses are based on the outgoing airflow rate to avoid confusions due to variations in air-density. Six wind speeds ($u_{10}$) were tested from 0 m/s to 5 m/s. Considering the four wind directions, this makes a total of 96 test conditions for each test configuration.

All other flowrate (such as those due to ventilation, leakage, etc.) were set to 0.

Windows properties were defined as follows:

- Windows area see figure 1
- Discharge coefficient: 0.67
- Flow exponent: 0.5
- Wind pressure coefficients:
  - 0.25 for windows upwind
  - -0.5 for windows downwind (lateral is considered as downwind)
  - -0.2 for roof windows
  - For cross ventilation explicit method $\Delta C_p =0.75$ for configurations 2.1, 2.2 and 2.3 and $\Delta C_p =0.45$ for configurations 1.1 and 1.2

- Windows mid-heigh:
  - 1 m for 1st floor windows West oriented;
  - 1.5 m for 1st floor windows East oriented;
  - 2.75 m for roof window in configurations 1.1 and 1.2;
  - 4 m for roof windows in configuration 2.1, 2.2, 2.3 and 3;

To model the air flow through windows in iterative calculations, we have used the default value for the window division in prEN 16798-7 ($N_{w;\text{div}} = 1$), which means that we assumed that the air flow through a window could be modelled with two vertically spaced openings of equal area to take into account that air flow may takes place in both directions. The model describing the two openings is a standard power-law with a flow exponent of 0.5.
In CONTAM, we have used the "Two-way flow, two opening" model, which is based on the same principles. Each zone is assumed to be at the same temperature (25 °C). Therefore, doors are modelled as one-way flow opening with a classical power law model.

**Flowrate model**
The following formulae are used to calculate flowrate leaving the zone through windows ($q_{V,\text{arg, out}}$) for the various methods:

- **Single sided ventilation** Gids, W. and Phaff, H formula (EN 15242 and prEN 16798-7)

\[
q_{V,\text{arg, out}} = -3600 \times \frac{\rho_{a,\text{ref}}}{\rho_{a,z}} \cdot \frac{A_{w,\text{tot}}}{2} \cdot \frac{\left( C_t + C_{\text{wnd}} \cdot u_{10}^2 + C_{st} \cdot h_{w,\text{st}} \cdot \text{abs}(T_{z} - T_e) \right)^0.5}{\left( C_{st} \cdot h_{w,\text{st}} \cdot \text{abs}(T_{z} - T_e) \right)}
\]

(1)

- **Modified formula for single-sided ventilation** (FprEN 16798-7)

\[
q_{V,\text{arg, out}} = -3600 \times \frac{\rho_{a,\text{ref}}}{\rho_{a,z}} \cdot \frac{A_{w,\text{tot}}}{2} \cdot \max \left\{ \frac{C_{\text{wnd}} \cdot u_{10;\text{site}}^2}{C_{st} \cdot h_{w,\text{st}} \cdot \text{abs}(T_{z} - T_e)} \right\}^{0.5}
\]

(2)

\[
u_{10;\text{site}} = 0.9 \cdot u_{10}
\]

(3)

- **Cross-ventilation** (prEN 16798-7)

\[
q_{V,\text{arg, out}} = -3600 \times \frac{\rho_{a,\text{ref}}}{\rho_{a,z}} \cdot \frac{A_{w,\text{tot}}}{2} \cdot \left( \frac{\left( C_{D,w} \cdot A_{w,\text{cros}} \cdot u_{10} \cdot (\Delta C_p)^0.5 \right)^2}{\left( A_{w,\text{tot}}^0.5 \cdot (C_{st} \cdot h_{w,\text{st}} \cdot \text{abs}(T_{z} - T_e))^0.5 \right)} \right)^{0.5}
\]

(4)

- **Modified formula for cross-ventilation** (FprEN 16798-7)

\[
q_{V,\text{arg, out}} = -3600 \times \frac{\rho_{a,\text{ref}}}{\rho_{a,z}} \cdot \max \left( \frac{C_{D,w} \cdot A_{w,\text{cros}} \cdot \min \left( u_{10;\text{site}}, u_{10;\text{site, max}} \right) \cdot (\Delta C_p)^0.5}{A_{w,\text{tot}}^0.5 \cdot \left( C_{st} \cdot h_{w,\text{st}} \cdot \text{abs}(T_{z} - T_e) \right)^0.5} \right)
\]

(5)

$u_{10;\text{site, max}}$ is the maximum wind speed for cross ventilation it is set at 3 m/s.
### Iterative method

\[
q_{V; path,i,j} = \frac{C_{w; path,i}}{N_{w; div} + 1} \cdot \text{sign}(\Delta p_{w; path,i,j}) \cdot |\Delta p_{w; path,i,j}|^{n_w}
\]  

(6)

\[
\Delta p_{w; path,i,j} = p_{e; path,i,j} - p_{z; path,i,j}
\]  

(7)

\[
p_{e; path,i,j} = \rho_{a,e} \left(0.5 \times C_{p; path,i} \cdot u_{\text{site}}^2 - h_{path,i,j} \cdot g\right)
\]  

(8)

\[
p_{z; path,i,j} = p_{z; \text{ref}} - \rho_{a,z} \cdot h_{path,i,j} \cdot g
\]  

(9)

The internal reference pressure used to calculate the mass air flow rates \((p_{z; \text{ref}})\) is calculated by solving the mass balance equation. \(q_{V; \text{arg}; out}\) is then calculated as the sum of negative values of \(q_{V; w; path,i,j}\).

**Wind speed correction – Modified wind speed model**

In our study, it was key to compare results using the same wind speed at building level \((u_{\text{site}})\) in CONTAM and in FprEN 16798-7. To this end, we have used in the spreadsheet the same formula to obtain \(u_{\text{site}}\) as a function of \(u_{10}\) as in CONTAM. Note that for explicit methods the meteorological wind speed \((u_{10})\) was used in prEN 16798-7, whereas the wind speed at site at 10 m \((u_{10}; \text{site})\) is used in FprEN 16798-7.

### Results and discussion

Figures 2 and 3 give the results obtained for three methods proposed in (F)prEN 16798-7. For the iterative method, the bar represents the average of the results for the 4 wind directions simulated and the whiskers represent the minimum flowrate (obtained for North or South wind) and the maximum flowrate (obtained for West wind). Note that using average results in our analysis implicitly assumes that those four wind directions are equi-probable.

**CONTAM versus prEN 16798-7 iterative model**

For the same wind speed very little differences were observed between results of CONTAM versus those of the prEN 16798-7 iterative model (for the same \(u_{\text{site}}\)). The deviations are on average of 1.7% in configuration 1.1 and 1.6% in configuration 2.1; they remain within 7% in configuration 1.1 and 10% in configuration 2.1. We checked that at exactly the same pressure across the orifices, the airflow rates are exactly the same in CONTAM and in the spreadsheet. Differences observed may be due to numerical methods and convergence criteria and also to the variation of the leakage coefficient with air-density and viscosity that is taken into account in CONTAM and not in the standard.
Single-sided versus iterative model

The prEN single-sided direct method was, most of the time, underestimating the outgoing air flow rate compared to the iterative method whatever the wind direction was.

In configuration 1, the former formula was overestimating airflow rates 20 times out of the 96 cases (20%) while the new formula (FprEN) only overestimates 3 times out of the 96 cases (3%). In configuration 2, the former single-sided formula (prEN) was overestimating the airflow rates in 20% of the cases and the new one (FprEN) in only 8%. Therefore, the new formula is more conservative and remains on the "safe-side", which was considered more suitable for a regulatory calculation method.

In configuration 1, the new FprEN single-sided direct method (configurations 1.1, 1.2) gives results on average 26% below the iterative method with an East wind (configuration 1.2) and 38% below the iterative method with a West wind (configuration 1.1). The former method (prEN) was more accurate in average as results were 12% below the iterative method with East wind and 26% below with west wind.

In configuration 2, the new FprEN single-sided method (configurations 2.1, 2.2, 2.3) gives results that are on average 27% below the iterative method with North/South wind (configuration 2.3) and 59% below iterative method with West wind (configuration 2.1). This method underestimates air flow rate up to 88% in our simulations.
Regarding the results on air flow rates, in configurations 1.1 and 1.2 (see Figure 2), for both versions of the standard (prEN and FprEN) there is almost no difference between the cross-ventilation and the single-sided methods. This is logical from a physical point of view since little cross-ventilation occurs in that case.

In configuration 2.1, 2.2, 2.3 (see Figure 3), the air flow rates with the cross-ventilation method are always equal or larger than those obtained with the single-sided method and are closer to those obtained with the iterative method.

The former prEN method was overestimating results 29% of the cases. On average, compared to the iterative method, this method gives air flow rates: 34% below those with the West wind (configuration 2.1, compared to -54% with the single-sided method), 10% below those with the East wind (configuration 2.2) and 24% above those with the North or South wind (configuration 2.3).

This has supported the idea that, to be conservative, only the dominant effect between stack and wind should be taken into account; and, the wind speed used in the calculation should be limited to 3 m/s. With those modifications in the FprEN standard, the new method overestimates results only 12.5% of cases. Compared to the iterative method, it gives, on average: 48% below those with the West wind (configuration 2.1), 10% below those
with the East wind (configuration 2.2), 8% below those with the North or South wind (configuration 2.3).

Assuming those four directions for wind and all weather tested are equiprobable and that the explicit method represents an average of the building air flow rate due to windows, we obtain a global average cross-ventilation method which underestimates by 24% the iterative method for all wind speeds and temperature differences tested. The former prEN method was closer with an overestimation of only 1%.

Internal partitions: doors open
For all configurations tested (1.1, 2.1 and 3), there are little deviations between results obtained in "no partition" and "open doors" scenarios (always less than 5% difference). This was expected as the area of the internal doors is always significantly greater than the cross-ventilation area \( A_{w,cr} \), which can be seen as a metric of the equivalent area of the air flow path crossing the building without partitions.

Internal partitions: doors closed
Closing doors induce a significant pressure drop from one room to another, thereby a significant reduction of the air flow rate. On average, closing internal doors reduce the air flow rate by 72% in configuration 2.1, by 43% in configuration 1.1 (only single-sided rooms), and by 41% in configuration 3 (with open staircase). In configurations 1.1 and 2.1, the decrease is more significant when wind is the dominant driving force: up to 84% reduction in configuration 2.1 when there is no stack effect or a temperature difference of only 5°C, and up to 89% in configuration 1.1 when there is no stack effect.

The FprEN single-sided method simulates very well "doors closed" in configuration 1: on average (on all wind speed and temperature difference) it overestimates results by only 4% (min 2%, max 7%). It also fit well with configuration 3 with an underestimation of 5% (min -49%, max +8%). Of course, it fails to represent configuration 2 doors closed (overestimation of 42%), as in this configuration the useful height for stack effect is no longer consistent with subzone.

4. Conclusions
First of all, this work enables us to validate the iterative model proposed in FprEN 16798-7. If the same wind speed is used, there are very small differences between (F)prEN 16798-7 and CONTAM results.
Also, our simulations have shown that the new formulae for single-sided and cross-ventilation in FprEN 16798-7, although not as good in average,
are more conservative. This appears more suitable for the purpose of a calculation method for an energy performance regulation. Moreover, we have seen that the single-sided explicit method underestimates significantly the air flow rate compared to the iterative method when there is cross-ventilation (configuration 2). The cross-ventilation method gives results closer to those obtained with the iterative method.

Considering a dwelling as a single zone is relevant for small flowrate such as those for hygienic ventilation. But, if internal doors may remain closed, results highlight the need to separate a dwelling into subzones to calculate airflow rates through windows. The single-sided or cross-ventilation explicit methods are then suitable for each zone. This requirement has been added in FprEN 16798-7.

As a perspective, it would be interesting to simulate internal partitions for all wind directions and compare average results with the single-sided and cross-ventilation methods applied to each subzone.

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References