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*Now and ahead*

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*Published in:*
Energy and Buildings

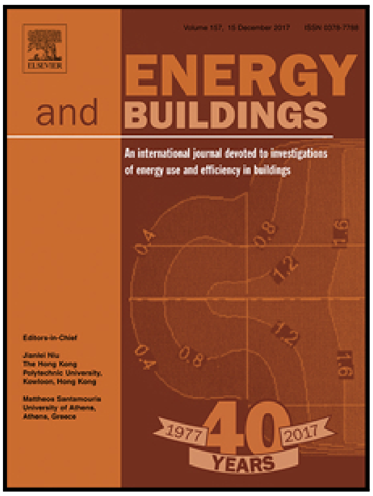
*DOI (link to publication from Publisher):*
10.1016/j.enbuild.2018.06.047



*Publication date:*
2018

*Document Version*
Accepted author manuscript, peer reviewed version

Accepted Manuscript

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PII: S0378-7788(17)33303-0
DOI: 10.1016/j.enbuild.2018.06.047
Reference: ENB 8649

To appear in: *Energy & Buildings*

Received date: 10 April 2017
Revised date: 15 June 2018
Accepted date: 23 June 2018

Please cite this article as: Tine Steen Larsen , Christoffer Plesner , Valérie Leprince , François Rémi Carrié , Anne Kirkegaard Bejder , Calculation methods for single-sided natural ventilation – now and ahead, *Energy & Buildings* (2018), doi: 10.1016/j.enbuild.2018.06.047

# Calculation methods for single-sided natural ventilation – now and ahead

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**ABSTRACT**

In order to reduce the energy consumption for cooling in our buildings, the use of passive cooling solutions is necessary. One of these solutions is natural ventilative cooling, where airflows generated by single-sided natural ventilation, until today have mainly been calculated from the De Gids & Phaff equation in the European Standard EN 15242:2007. In the revised standard EN 16798-7:2017, a new version of the equation for single-sided natural ventilation is released. The work in this paper will compare the results from the new equation with earlier equations for single-sided ventilation and hold them up against wind-tunnel measurements, full-scale measurements and CONTAM calculations to clarify whether and why the new equation is to be preferred for future design solutions for single-sided natural ventilation and ventilative cooling. Due to the implementation in calculation standards and regulations, the new calculation model should underestimate rather than overestimate the airflow rates, so as to remain on the safe side when estimating ventilative cooling potential.

The work in this paper concludes that the new simple direct calculation model in EN 16798-7:2017 predicts the airflows through windows in a more conservative way than earlier equations, by representing an average of the airflow rate in the building that is generally on the safe side. The accuracy of the EN 16798-7:2017 equation was found by comparison to wind tunnel measurements to be 29% but with underestimations in 88% of the cases investigated. For the CONTAM calculations, it was found that the use of the new EN 16798-7:2017 equation (with room based height for the stack effect) slightly underestimates the airflow rate as desired, as soon as the temperature difference across the opening is above 0°C.

Based on the comparisons presented in this paper, the authors consider the new calculation model in EN 16798-7:2017 well suited for the use in calculation standards to integrate natural ventilative cooling effects from single-sided ventilation.

## 1. INTRODUCTION

Within the last couple of decades, increasing requirements for buildings' energy performance have increased the amount of insulation and level of building airtightness in cold or temperate climate zones. Combined with poor design (e.g. inadequate solar shading devices, large glazed areas, excessive thermal mass or insufficient ventilation), overheating has become an increasing problem both at the design phase and during operation [1], and many buildings experience overheating not only during summer and midseason, but also during winter. The resulting cooling demand to maintain acceptable indoor climate conditions can be expensive in regard to energy. Studies have shown that overheating issues can be caused by the lack of ventilation or solar shading and might have been reduced or avoided with a different design solution [1–3]. Several solutions can be implemented to overcome these problems, such as different natural and passive cooling strategies, including natural ventilative cooling, where large airflow rates remove heat accumulated in the building structure. Ventilative cooling is a low-cost solution defined as the use of natural ventilation, mechanical ventilation or a combination (hybrid) using increased ventilation air flow rates and night ventilation to cool indoor spaces referred to as either natural ventilative cooling, mechanical ventilative cooling or hybrid ventilative cooling [4]. Ventilative cooling mitigates overheating in both existing and new buildings and can save cooling energy and give more flexibility and design options for buildings, enabling a broader range of design solutions to fulfil building energy legislations. Ventilative cooling has shown to reduce energy demand for cooling or overheating risk in new and refurbished buildings through examples of well documented case studies that use ventilative cooling [5]. A successful natural ventilative cooling system can decrease office building energy consumption for cooling by 50%, indicating the relevance of ventilative cooling systems [6].

In this context, the European Commission issued mandate M/480 to CEN (European Committee for Standardisation) to support requirements of the EU directive 2010/31/EC on the energy performance of buildings (EPBD), where CEN was to revise the first EPBD package standards published in 2007-2008 [7]. The mandate required more focus on passive cooling techniques, which include natural ventilative cooling, where the determination of air flow rates in buildings is a very important element in order to assess the energy performance of a building. Therefore, work on making a new and improved calculation model for determining airflow rates in buildings using natural ventilation has been encouraged, more precisely for the revised standard EN 16798-7:2017 published in 2017, previously EN 15242:2007 [8]. The revised standard includes a new and improved simple direct calculation model for single-sided natural ventilation, which takes its starting point in the original De Gids & Phaff equation [9], and a new simple direct calculation model for cross-ventilation. The latter is not described in this paper, but is evaluated as giving results close to those obtained from the detailed iterative model [10]. The aim for the work was to create a new model that has the same accuracy (or better) as previous models, but in general underestimates the airflow rate in order to consider the risk of excessive temperature and fluctuating natural ventilation airflows on a cooling method. The calculation model for natural ventilation from EN 16798-7:2017 was primarily developed to be used to assess the energy performance of buildings, but may also be used in the early scoping of the building design phase to ensure compliance early on, where assumptions and simple/quick calculations on overheating risks or achievable airflow rates are crucial.

One of the risks using natural ventilation is the fluctuating airflow rates due to the dependency on natural driving forces. Large variations in airflow rates in the same building might result in uncertainties in the use and trust of natural ventilation. The impact of natural ventilative cooling can, however, be significant with window airing, e.g. during summer nights when the accumulated heat from the building thermal mass needs to be removed from the building. On the one hand, a proper building design is vital to achieve increased airflows through single-sided ventilation, stack ventilation and cross-ventilation. Proper building design can enhance the natural cooling of the building, e.g. through optimal height differences between façade and roof windows and through night ventilation to cool down building materials. On the other hand, overestimating natural ventilation airflow rates used for cooling will, in practice, result in overheated buildings, reduced thermal comfort and most likely also distrust in natural ventilation used for cooling purposes. Therefore, facilitating the integration of natural ventilative cooling using simple, fair and safe-side standardised models to assess the energy performance of buildings is an important element to achieve well performing low-energy buildings in the future.

To answer this need, the new simple direct equation for single-sided natural ventilation from EN 16798-7:2017 is compared to existing equations to evaluate the applicability and accuracy to finally ensure a safe-side calculation. The comparisons are made with results from full-scale measurements and wind tunnel measurements of airflow rates in a single-sided naturally ventilated room and CONTAM simulations on a partitioned house in a scenario with closed internal doors corresponding to single-sided natural ventilation.

## 2. REVIEW OF PREVIOUS MODELS FOR SINGLE-SIDED NATURAL VENTILATION

The starting point for evaluation of the new simple direct single-sided calculation in EN 16798:2017 is found in other existing equations for single-sided natural ventilation. The equations presented in this paper all use a simple opening area as input. The calculation of the equivalent window area according to the window type is not part of this work. Nevertheless, earlier work by [11] has proven that the type of window (hopper, awning, casement) has an impact on the air-flow rate obtained by single-sided ventilation. The technical report TR 16798-8 associated to the European standards EN 16798-7 gives information to estimate the equivalent window area according to the type of window.

The following sections present some of the existing equations for wind driven single-sided natural ventilation, buoyancy driven flows or a combination of the two driving forces. Advantages and disadvantages of the various equations are described and discussed in order to define the baseline for development of a new equation.

### 2.1 Airflows driven by wind

Forty years ago, Warren conducted experiments determining airflows in both full-scale and wind tunnel tests [12]. From these experiments, Warren concluded that the airflow rate through a single window is based on a combination of buoyancy forces, wind speed and the turbulent convection caused by the level of turbulence in the wind near the window opening. Warren found a division between cases dominated by wind and cases dominated by temperature difference across the opening. Larsen made the same observation [13], which is described further in section 3.

Based on observations, Warren concluded that the best way to handle the combination of wind and buoyancy was to calculate the effect from each parameter separately and then use the largest of them. In later work, Warren and Parkins [14] derived the equations (1) and (2) for wind driven flows. The effect from turbulent convection is built into the use of $U_L$. Also, it was noted that higher airflow rates may be achieved for other combinations of windows, certain wind directions and tall buildings. If $U_L$ is available, equation (1) is to be preferred, however, Warren and Parkins estimated the relation between $U_L$ and $U_{ref}$ stating $U_L$ to be ¼ of $U_{ref}$. [14] This is further described in section 2.4.

$$Q_v = 0.1 \cdot A \cdot U_L \quad (1)$$

$$Q_v = 0.025 \cdot A \cdot U_{Ref} \quad (2)$$

Where $Q_v$ is the Volume flow rate [$m^3/s$], $A$ is the Area of the opening [$m^2$], $U_L$ is the local air speed at the surface of the building near the window [m/s] and $U_{Ref}$ is the reference wind speed [m/s].

In more recent literature Wang & Chen [15] look further into the turbulent flow addressed by Warren and propose in their work a model that calculates both a ventilation rate and a fluctuating ventilation rate coming from the pulsating flow and eddy penetration in the opening in case of wind-driven single-sided natural ventilation. Their work was based on Computational Fluid Dynamics (CFD) simulations using large eddy simulation (LES) in combination with experimental data. Their equation for the mean velocity found in the opening (normal to the opening) at the height z is found in (3).

$$\bar{U}(z) = \begin{cases} \frac{C_D\sqrt{\left|C_p\left(z^{2/7} - {z_0}^{2/7}\right)\right|}}{{z_{ref}}^{1/7}}\bar{U}_{ref} & \text{when } C_p\left(z^{2/7} - {z_0}^{2/7}\right) > 0 \quad \text{a.)} \\ -\frac{C_D\sqrt{\left|C_p\left(z^{2/7} - {z_0}^{2/7}\right)\right|}}{{z_{ref}}^{1/7}}\bar{U}_{ref} & \text{when } C_p\left(z^{2/7} - {z_0}^{2/7}\right) \leq 0 \quad \text{b.)} \end{cases} \quad (3)$$

Where, $C_D$ is the discharge coefficient (takes the shape of the opening into consideration) [-], $C_p$ is the pressure coefficient [-], z is the position in the opening [m], $z_0$ is the position of the neutral plane, $z_{ref}$ is the reference height used for the reference velocity, $\bar{U}_{ref}$ [m/s]. Equation (3)a.) is valid when the flow is inwards equation (3)b.) is valid when the flow is outwards.

**2.2 Airflows driven by thermal buoyancy**

Warren & Parkins investigated airflows going through a plane opening in both wind tunnel and full-scale tests [14]. The airflow driven by buoyancy in a single opening will be bidirectional, which means that the direction of the velocity changes at the level of the neutral plane in the opening. The volume flow rate for a single opening which is fully opened, can be found from equation (4) derived by Warren & Parkins in [14].

$$Q_v = \tfrac{1}{3} \cdot C_D \cdot A \cdot \sqrt{\frac{(T_i - T_e) \cdot g \cdot (H_t - H_b)}{\bar{T}}} \quad (4)$$

Where, $T_i$ is the internal temperature [K], $T_e$ is the external temperature [K], $\overline{T}$ is the average temperature [K], $g$ is the gravitational acceleration [m/s$^2$], $H_t$ is the altitude of the top of the opening [m] and $H_b$ is the altitude of the bottom of the opening [m].

**2.3 Airflows driven by a combination of thermal buoyancy and wind**

One of the earliest design equations for single-sided natural ventilation was developed by W. De Gids and H. Phaff [9], who split the driving forces up into two parts - the wind contribution and the stack effect contribution - and added a third constant contribution coming from turbulent flows near the opening ($C_t$):

$$U_m = \sqrt{(C_w \cdot U_{10}{}^2 + C_{st} \cdot h \cdot \Delta T + C_t)} \qquad (5)$$

Where, $U_m$ is the mean air velocity in opening [m/s], $U_{10}$ is the mean wind speed in H=10 m [m/s], h is the height of the opening [m], $\Delta T$ is the temperature difference across the opening [K], $C_w$ is the dimensionless coefficient depending on the wind effect, $C_{st}$ is the buoyancy constant and $C_t$ is the turbulence constant.

The equation by De Gids & Phaff is used in "prediction of air flows due to windows opening" in the European standard, EN 15242:2007 [16]. It is simple to use due to the combination of the driving forces, but it will always generate a positive air flow contribution even at low wind speeds and at no or very low temperature difference due to the $C_t$-value and will thereby possibly overestimate airflows in these cases.

From fitting the constants to the measurements made by De Gids & Phaff, the values in equation (6) are found [9]:

$$U_m = \sqrt{(0.001 \cdot U_{10}{}^2 + 0.0035 h \Delta T + 0.01)} \qquad (6)$$

From $U_m$ the volume flow rate can be found from De Gids & Phaff (1982)

$$Q_v = A_{eff} \cdot U_m = ½ \cdot A \cdot U_m \qquad (7)$$

Where $A_{eff}$ is the effective area of the opening [m$^2$].

As seen on the right side of equation (7), $A_{eff}$ is considered to be half of the total area since only half of the window area is used as inlet. The shape of the opening and the effect of this are not included in the De Gids & Phaff equation as was the case in equation (4), where the $C_D$-value was used.

In the revision of standard EN 15242:2007 (EN 16798-7:2017), there is a new simple direct calculation model, which is based on the original De Gids & Phaff equation, but now split into the use of the maximum contribution coming from either wind or stack. The contribution coming from wind turbulence in the original equation, in the form of a fixed constant ($C_t$), is removed as is the case in the French thermal regulation, RT 2012 [8,17] due to the problem with a constant contribution coming from $C_t$, which will increase the risk of overestimations rather than underestimate the airflow rate which was the desired result for the new EN 16798-7:2017.

The new simple direct single-sided equation (see equation (8)) also uses the original useful height for stack effect.

$$U_m = \max\left(\sqrt{C_w \cdot U_{10}^{2}}\right);\left(\sqrt{C_{st} \cdot h \cdot \Delta T}\right); \quad (8)$$

Further analyses showed that choosing the highest of stack and wind effect as design airflow was the most conservative and in line with the former thoughts of Warren [12], who initially stated that the best way to handle the combination of wind and buoyancy was to calculate the effect from each parameter separately and then use the largest of them [18].

In EN 16798-7:2017, to meet mass balance in the opening, Equation (8) is multiplied by the relation between internal and external air densities. This is another alteration from the original equation.

The new simple direct equation for single-sided ventilation from standard EN 16798-7:2017 [8] thus becomes:

$$q_{\mathrm{V;arg}} = 3600 \times \frac{\rho_{\mathrm{a;ref}}}{\rho_{\mathrm{a;e}}} \cdot \frac{A_{\mathrm{w;tot}}}{2} \cdot \max\left(C_{\mathrm{wind}} \cdot u^{2}_{10\,\mathrm{site}}\,; C_{\mathrm{st}} \cdot h_{\mathrm{w;st}} \cdot abs\left(T_z - T_{\mathrm{e}}\right)\right)^{0,5} \quad (9)$$

Where $q_{V;arg}$ is the airflow through the window [$m^3$/h], $\rho_{a;ref}$ and $\rho_{a;e}$ are the reference and external air densities [kg/$m^3$], $A_{w;tot}$ is the total window opening area [$m^2$], $C_{wind}$ is the wind speed coefficient [-], $h_{w;st}$ is the useful stack effect height for airing [m], $T_z - T_e$ is the temperature difference between the ventilation zone and outdoor air [K].

Another equation that includes the combination of thermal buoyancy and wind driven ventilation was developed by Larsen [13], who also included the wind direction into the equation. The equation developed by Larsen for single-sided natural ventilation is shown in (10). The equation is valid for wind velocities between 1 and 5 m/s. [13,19]

$$Q_v = A \cdot \sqrt{C_1 \cdot f(\beta)^2 \cdot \left|C_p\right| \cdot U_{ref}^2 + C_2 \cdot \Delta T \cdot H + C_3 \cdot \frac{\Delta C_{p,opening} \cdot \Delta T}{U_{ref}^2}} \quad (10)$$

Where the constants $C_1$ is connected to the wind induced flow including wind direction, $C_2$ is linked to the thermal forces and $C_3$ is linked to the fluctuations across the opening. f($\beta$) is a function transforming the local velocity into the use of a reference velocity ($U_{ref}$). $\Delta C_{p,opening}$ is defined as the largest deviation between the $C_p$-values in the opening.

The wind direction is included in equation (10) by the use of $C_p$, and f($\beta$), which both depend on the wind direction and the effect of different local velocities near the opening compared to the reference velocities. The fluctuations are defined by the pressure difference across the opening included in $\Delta C_{p,opening}$.

Larsen found that the wind is most dominating on the windward side of the building, the temperature difference is most dominating on the leeward side of the building, and the pressure difference caused by wind depends on the incidence angle of the wind. The constants $C_1$, $C_2$ and $C_3$ are, therefore, divided into three different intervals of wind direction, see Table 1.

**Table 1. Constants $C_1$, $C_2$ and $C_3$ as a function of the wind direction, β, used for equation (10).**

| Direction | Incidence angle, β | $C_1$ | $C_2$ | $C_3$ |
|---|---|---|---|---|
| Windward | β=285°-360°, β=0°-75° | 0.0015 | 0.0009 | -0.0005 |
| Leeward | β=105°-255° | 0.0050 | 0.0009 | 0.0160 |
| Parallel flow | β=90°, β=270° | 0.0010 | 0.0005 | 0.0111 |

**2.4 Use of local ($U_L$) or reference ($U_{ref}$) velocities for the calculations**

Some equations for single-sided natural ventilation are based on the use of local velocities measured close to the window opening ($U_L$), others use a reference velocity ($U_{ref}$) measured in free wind away from the building, typically 10 m above ground level. The advantage in using $U_L$ is a more accurate prediction of the airflow rate through the opening. This is due to the eliminated uncertainty in how $U_{ref}$ is reduced near the opening due to the wind direction and the position of the opening in the façade. The disadvantage in using $U_L$ is the uncertainty in the prediction of the value if it is not measured.

Warren and Parkins [14] presented a correlation between the two parameters $U_L$ and $U_{ref}$ based partly on their full-scale measurements and partly on experience from other low rise buildings, where the experience showed that the relation between the two usually is higher than 0.25. The relation can be derived from the equations (1) and (2) and is shown in (11).

$$U_L = 0.25 \cdot U_{Ref} \tag{11}$$

Furthermore, Larsen [19] defined the function f(β) to describe the relation between $U_L$, $U_{ref}$ and $|C_p|^{1/2}$ as a function of the wind direction. The lowest values of f(β) are found for wind directly towards the opening and at leeward side (β=0° and β=180°) where f(β) gets close to 0.2. The highest values are found for flow parallel to the opening where f(β) is close to 1.

**2.5 Summary – what is important for a new equation for EN 16798-7:2017?**

Section 2 has given an overview of different equations for design of single-sided natural ventilation. The overview included equations where the driving forces were purely based on wind (eq. (1) to (3)), thermal buoyancy (eq. (4)) or a combination of these (eq. (5) to (10)). Besides being based on different driving forces, the equations also differ when it comes to the level of information required for using the different equations. Hence, it ranges from the very simple equation from Warren & Parkins in eq. (1) where the window area and a reference velocity are the only inputs [14] to the more detailed equations developed by Wang & Chen [15] or Larsen [19]. Wang & Chen require information about the shape of the opening but still only handle airflows caused by wind whereas Larsen also includes wind direction in the equation which includes a combination of wind and thermal buoyancy.

All equations were developed with the purpose of estimating the airflows. This was also the aim when the new equation for EN 16798-7:2017 was developed. However, in this case a specific demand was set up to find an equation which underestimates rather than overestimates the airflow in order to keep the trust in passive cooling by avoiding situations where lack of ventilation results in overheated rooms. Experiences from literature resulted in a suggestion for EN 16798-7:2017 based on the original equation from De Gids & Phaff [9] (see eq. (6)) used in EN 15242:2007. The experiences from Warren & Parkins [14] on handling the driving forces separately was taken into consideration and resulted in a division of the original equation into wind and temperature difference respectively. This was done to solve the issue with overestimations targeting the new equation towards results being on the safe side.

In section 4 the equation by Warren & Parkins (eq. (2)), De Gids & Phaff (eq. (6)) and Larsen (eq. (10)) will be compared to the new equation for EN 16798-7:2017 (eq. (9)) in order to evaluate the new equation against the target of having an estimation of airflow rates which are on the safe side. However, prior to the comparison of equations in section 4, the evaluation methods for applicability of equations for single-sided ventilation are described in section 3.

## 3. EVALUATING APPLICABILITY OF EQUATIONS FOR SINGLE-SIDED VENTILATION IN EUROPEAN STANDARDS

In order to evaluate the applicability of the different calculation models for single-sided ventilation described in section 2 for a case where accuracy is needed but underestimations are preferred over overestimation, the equations are applied and compared to detailed full-scale measurements of airflow rates in single-sided natural ventilation as a function of both temperature difference, wind velocity and wind direction.

This is followed by evaluation of a full building through CONTAM modelling  with rooms or zones at different pressures (e.g. with closed internal doors) using some of the same equations. Calculating air flow rates in multi-zone buildings usually entails laying-out and solving a system of non-linear equations with as many equations as pressure zones (pressure-network model). However, in the context of building Energy-Performance regulations, simplified calculations are needed, so the objective of this section is to determine whether a single-sided model with equations described in section 2 could represent partitioned single-family houses.

### 3.1 Evaluating through measurements of single-sided natural ventilation

The equation developed by Larsen in 2006 was based on wind tunnel measurements and afterwards compared to full-scale outdoor measurements. The following sections will describe the background and methods used for the measurements.

### 3.1.1 Measurements in wind tunnel

The wind tunnel measurements were carried out on a full-scale building at the Japanese Building Research institute (BRI). The building could be fully rotated in the tunnel and all wind directions could therefore be included in the measurements. Figure 1 shows a photo of the building with indication of the opening used for measurements with single-sided ventilation.


**Figure 1. The wind tunnel building at the Japanese Building Research Institute.**

The size of the building was 5.56 m x 5.56 m x 3 m. The opening was 0.86 m x 1.4 m (w x h) and positioned 0.54 m away from the right edge of the building and 0.69 m below the top of the building. The internal room height was 2.4 m and the thickness of the walls was 0.1 m. The room volume was 68.95 $m^3$. Due to the size of the building, scale effects were not considered.

The wind velocity in the wind tunnel was set to 1 m/s, 3 m/s and 5 m/s respectively. The temperature difference across the opening was created by electric heaters inside the building and varied between 0°C, 5°C and 10°C. During the experiments, the model was rotated between 0° and 345° with either a 15° or a 30° increase. By combining different situations of wind direction, wind velocity and temperature difference, the air change rate was measured in a total of 159 different cases. During all measurements, the air change rate was measured by the tracer gas decay method and the velocity in the opening was measured by 3D ultrasonic anemometers at a frequency of 10 Hz in 24 different points distributed in three different columns. To avoid blocking of the opening area, the velocity was measured in one column at a time. This was possible since a constant wind velocity was used [13].

### 3.1.2 Outdoor full-scale measurements

The outdoor full-scale experiments with single-sided natural ventilation were made at the top floor in a 2½-storey office building situated in Aalborg, Denmark. The size of the room was 6.15 m x 3.45 m with a room height varying from 2.65 m to 3.00 m due to decreasing ceiling height from the window (3.00 m) to the opposite wall (2.65 m). This gave a total room volume of 59.9 $m^3$. Figure 2 shows a plan of the test office.

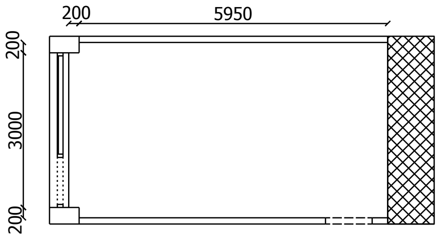



**Figure 2. Plan of the office used for the outdoor full-scale measurements**

The opening towards the outdoors was a side-hinged window, which was kept fully open during the experiments. The size of the opening was 91 cm x 116.5 cm. The position of the opening in the external wall is shown in Figure 3a. During the experiments the remaining glass area was shaded from the sun to avoid uncontrollable solar heat gains.


a.) b.)

**Figure 3. a.) Position of the office and the window opening in the full-scale experiments made at the office building. b.) Measurement of wind velocity and wind direction above roof level**

During the outdoor experiments, the tracer gas constant-injection method was used. The wind velocity and wind direction were measured both 4 m above the roof of the building and 1 m away from the façade near the opening (position is seen at Figure 3). The temperature difference was measured as the difference between the average temperature in the room and the temperature just outside the room.

Due to the variable outdoor wind conditions, the outdoor full-scale measurements were more complicated in regard to the velocity in the opening. In the outdoor case it was not possible to move the anemometers during a test case, since the wind suddenly could change and thereby change the conditions in the opening radically. The velocity in the opening was measured by 8 anemometers uniformly distributed in two columns across the opening. Four of these anemometers were 2D ultrasonic anemometers in order to take the direction of the wind crossing the opening into account. These were positioned at the corners of the opening.

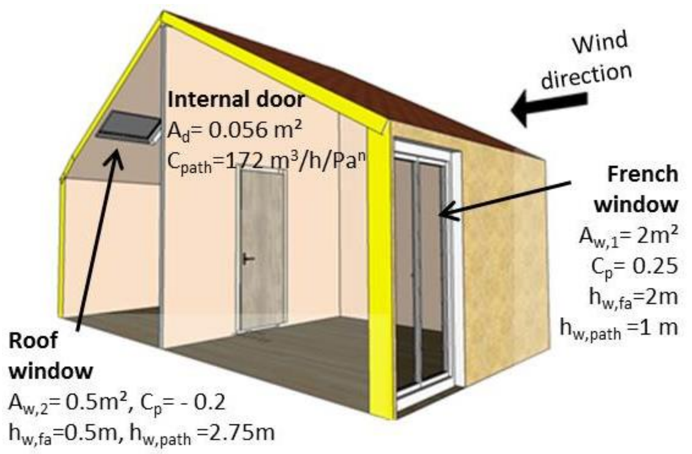
Another problem during the outdoor experiments was the difficulty in obtaining variations in wind direction, wind speed and temperature from one case to the next. Often the wind direction just outside the window changed during a measurement period, which lasted for 20 minutes. Furthermore, the main wind direction measured at the roof was shifting, although mainly coming from the West during the 1½ month the experiments were running. 75 different cases were measured in the full-scale measurements. Out of these cases, eastern wind was present in 6 cases; southern wind was recorded in 7 cases; and south-eastern wind in 4 cases. The rest of the cases were mainly western directions corresponding to wind directly towards the opening. The wind velocities recorded at the roof were between 1 m/s and 4.5 m/s. Temperature differences between 2°C and 12°C were measured but with a small drop during the 20 minutes it took to complete the measurements for a single case [13]. Out of the 75 cases only 48 cases were used for analysis due to the problems with unsteady conditions.

### 3.2 Evaluating airflow rates in a multi-zone building with a pressure-network model

CONTAM 3.1 was used to assess the relevance of applying single-sided models to represent buildings with internal partitions (closed internal doors). CONTAM is a pressure network code which implements the model developed in AIRNET [20,21]. It is not possible with the software to accurately represent a purely single-sided configuration; however, a network of single-sided zones can be modelled with very small airflow paths connecting them. The benefit of using CONTAM in addition to measurement is that it includes the interaction between single-zones as it happens in real buildings. Indeed, true single-sided does not exist and always interact with other zones through internal leakages.

Three single-family house configurations were tested (see Figure 4).

**Configuration 1**

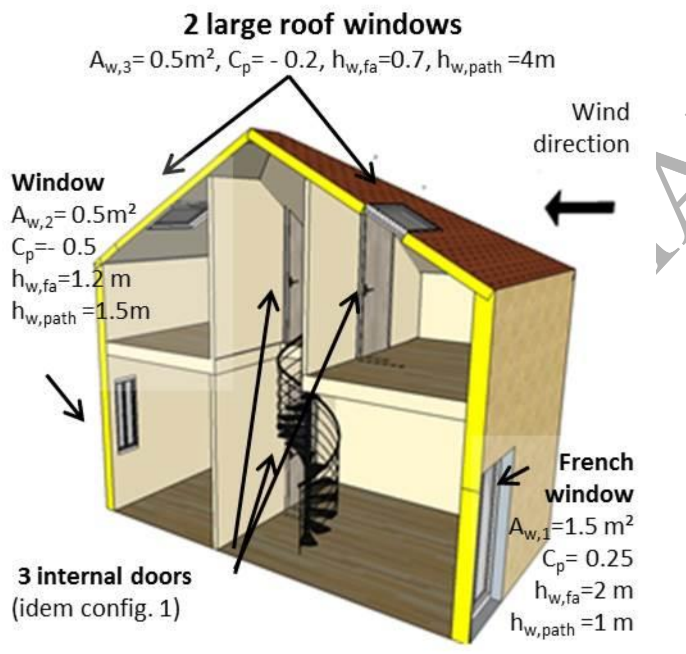



**Variables**

$A_w$: Window free area (m²)
$A_d$: Closed door free area (m²)
$C_p$: wind pressure coefficient (-)
$h_{w;path}$: Mid-height of the window relative to the low floor level (m)
$h_{w;fa}$: free area height of window (m)
$C_{path}$: Flow coefficient of the door ($m^3/h/Pa^n$)

**For all windows and door**
$C_d$: discharge coefficient = 0.67
n: flow exponent =0.5

**Configuration 2**




**Configuration 3**

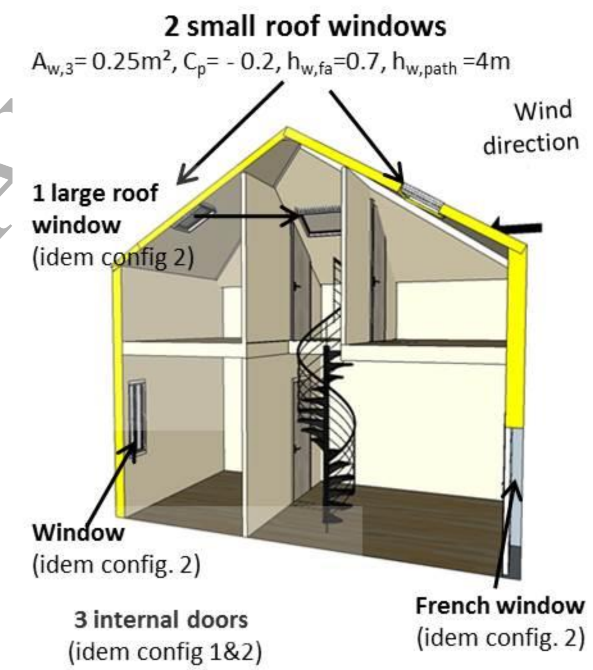



**Figure 4. Test configurations 1 (One-storey house), 2 (1½-storey house with open staircase no window in staircase) and 3 (1½-storey house with open staircase and window in staircase). Roof angle is 30° so wind pressure coefficients are negative**

The total window area was the same in configurations 2 and 3. In configuration 3, part of the window areas of the second level was transferred to the staircase in order to increase the thermal buoyancy. Temperature difference between inside and outside was set to 0, 5, 10 and 15°C. Internal temperature was set to 25°C. All analyses were based on the outgoing airflow rate to avoid confusions due to variations in air density. The meteorological wind speed at 10 m ($u_{10}$)

varied from 0 m/s to 5 m/s with a 1 m/s step. All other air flow rates (e.g. due to mechanical ventilation, combustion appliance, building leakage, vents) were set to 0.

In CONTAM, to calculate the wind speed at opening level, the local terrain constant was set to 0.9, and the velocity profile exponent to 0.28 [21]. In the EN 16798-7:2017 (equation (9)), to be consistent with CONTAM data $u_{10;site}=0.9\cdot u_{10}$. In De Gids & Phaff (5) $u_{10}$ was used.

In CONTAM, the "Two-way flow, two openings" model was used, which then was based on the assumption that the airflow through a window could be modelled with two vertically spaced openings of equal area to take into account that an airflow may take place in both directions. The model describing the two openings was a standard power-law model with a flow exponent of 0.5.

Each zone was assumed to have the same temperature (25°C), but the outside temperature was set between 10°C and 25°C. Therefore, doors were modelled as one-way flow openings with a classical power-law model:

$$q = C_D \cdot A \cdot \sqrt{\frac{2\,\Delta p}{\rho_a}} \qquad (12)$$

To estimate the impact of internal partitions, each configuration was tested with no internal partition, open doors and closed doors (see Figure 4).
However, for each configuration, only the CONTAM results for closed doors, corresponding to single-sided ventilation, were compared to results obtained with:

- De Gids & Phaff equation (EN 15242:2007, see equation (6))
- EN 16798-7:2017 equation (see equation (9)) with the useful height for stack on house basis (see below)
- EN 16798-7:2017 equation with useful height for stack effect on room basis (for configuration 1 and 2) ($h_{st}$=2m) (see below)

The useful height for stack effect ($h_{st}$) is the height difference between the top of the highest window in the house and the bottom of the lowest window in the house; therefore the original $h_{st}$ is 3.00 m for configuration 1 and 4.35 m for configurations 2 and 3.
Nevertheless, when internal doors are closed, the useful height for stack effect may have to be calculated for sub-zones and not for the entire building. Therefore, for configurations 1 and 2, the calculation was also performed for $h_{st}$ = 2 m which corresponds to the height of the highest windows. For configuration 3, which has a roof window in the main room, $h_{st}$ is kept at 4.35 m.

Since the total window area of configurations 2 and 3 are the same, the direct calculations (De Gids & Phaff and EN 16798-7:2017) gave exactly the same results for configurations 2 and 3.

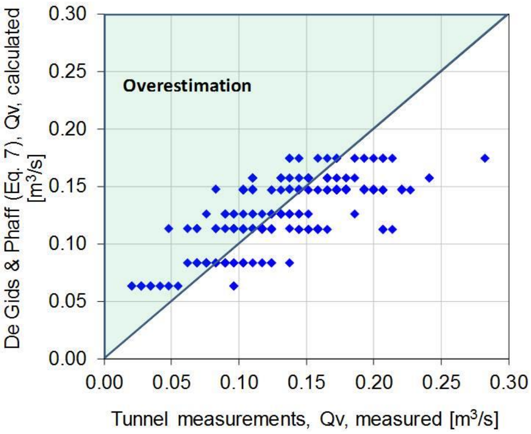
## 4. RESULTS

In order to evaluate the new equation from EN 16798-7:2017, calculated volume flow rates from this equation together with results from other existing equations was compared to wind-tunnel and full-scale measurements and CONTAM calculations. The results are described in the following sections.

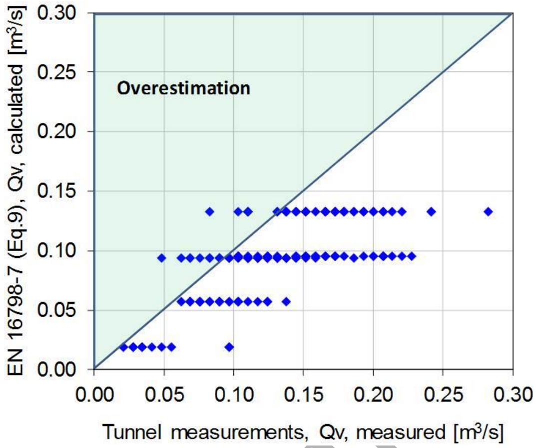
**4.1 Comparison of existing equations and the new EN 16798-7 equation with measurements**

In Figure 5, the volume flow rates calculated from three existing equations for single-sided ventilation (De Gids & Phaff, Warren & Parkins and Larsen) and the new EN 16798:2017 equation are compared to wind tunnel measurements. The different combinations of measurements and calculations are shown by points, where overestimated calculated values appear above the black diagonal line (x=y). There are different horizontal combinations starting from the bottom indicating the measurements/calculations at different temperature and wind conditions. In the equations where wind direction is absent from the equation, measurements with the same temperature difference and wind velocity but with different wind directions will result in the same calculated values but a variety of measured values. This is seen by the horizontal "lines" obtained in Figure 5a.) to Figure 5c.) but not in Figure 5d.) where wind direction is included in the Larsen equation. Figure 6 shows the effect on the volume flow rate from changing wind directions at constant temperature difference and wind velocities.

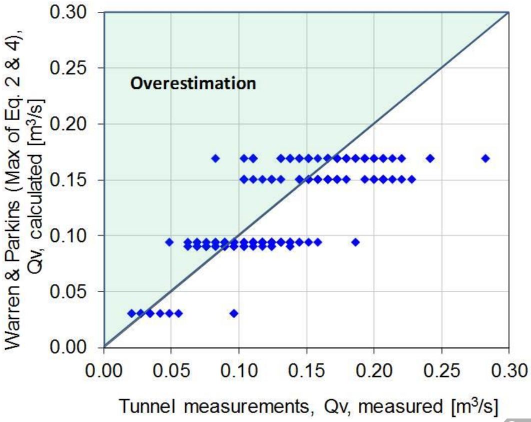
The original De Gids & Phaff equation from EN 15242:2007 shows a general overestimation of the air flow rates as seen in Figure 5a [13,22] and, more specifically, shows an overestimation at low wind speeds and at no or very low temperature difference in Figure 6a. The Larsen equation (12) from Figure 5d also takes the wind direction into consideration - in contrast to the other equations - and shows a slight underestimation. Another comparison was made using the equation from EN 16798-7:2017 for single-sided ventilation and comparing it to wind tunnel measurements as seen in Figure 5b. The equation shows very conservative air flow rates for 88% of the cases indicating underestimation compared to wind tunnel measurements [18]. Comparing the new equation to the Warren & Parkins results (Figure 5c) shows that the Warren & Parkins equation underestimates slightly less, but also overestimates more than the new equation, making the new equation a better fit for the intended use, generally being on the safe side which is needed in standards and regulations to assess ventilative cooling potential.



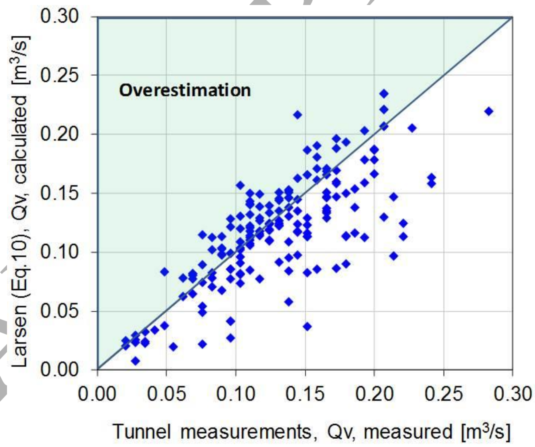

a.) Existing EN 15242 equation (De Gids & Phaff)




b.) New EN 16798-7 equation



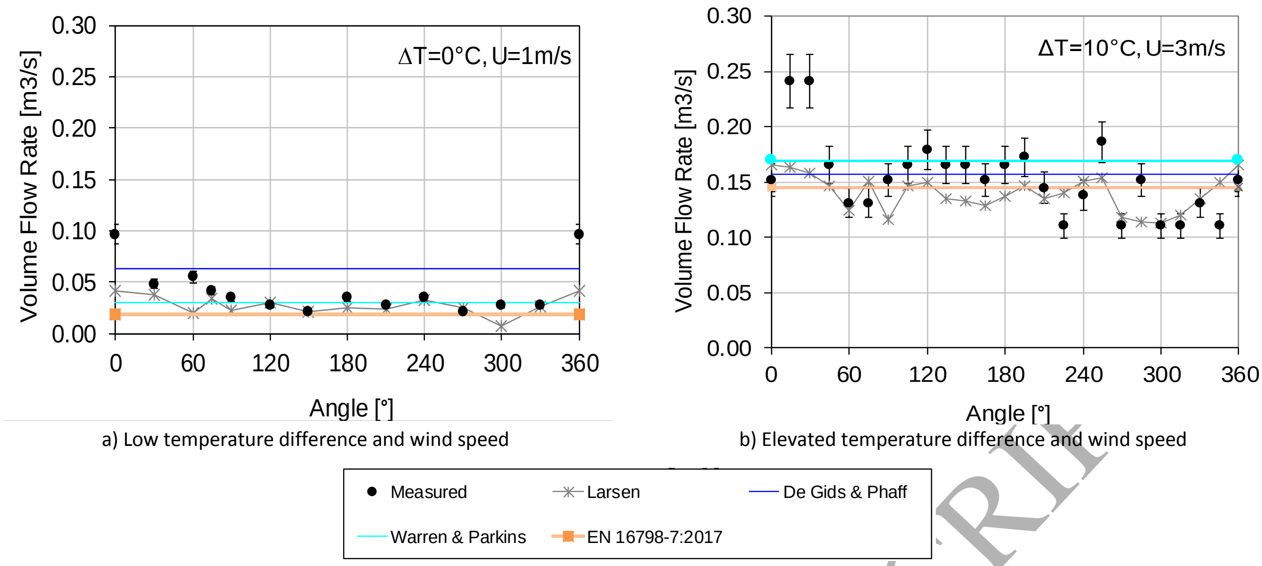

c.) Warren & Parkins equation




d.) Larsen equation

**Figure 5 - Comparison between measured and calculated values for the mentioned equations**

A more detailed comparison is made in Figure 6. Here the Warren & Parkins equation shows slight overestimations at low temperature difference and wind speeds compared to the EN 16798:2017 equation (as seen in Figure 6a). The Warren & Parkins equation also overestimates compared to the new equation for elevated temperature difference of 10°C and wind speed of 3 m/s (as seen in Figure 6b). The comparison between Larsen and the EN 16798:2017 equation shows agreement for the different wind directions and could also be a good suggestion for a new design method, however, it is important that the EN 16798:2017 provides a simple design method for the early design phases, which is not the case for the Larsen equation. The uncertainties marked in Figure 6 are based on the uncertainties coming from the use of the tracer gas decay method. This was estimated to be 10% [13].




a) Low temperature difference and wind speed

b) Elevated temperature difference and wind speed

**Figure 6 - Comparison between measured and calculated values for the different equations**

The accuracy of the new and old equations used in the EN-standards (calculated as the absolute deviation between the calculated airflow and the measured values from the wind tunnel measurements) shows that the accuracy of the new equation is 29% but underestimates in 88% of the wind tunnel cases and, thus only overestimates 12% of the time. In comparison, the original De Gids & Phaff equation also has an accuracy of 29%, but overestimates in 50% of the cases, showing a much lower degree of overestimation compared with the new equation. This shows that the new equation in average performs well, and underestimates rather than overestimates the airflow rate which was the aim.

As mentioned in section 3.1.2, problems with variations in wind directions occurred during the full-scale measurements. The comparison with these measurements is therefore not a general example of the performance of the EN 16798:2017 equation but an example, however, still giving good results being on the safe side.[18] When comparing the full-scale measurements to the EN 16798:2017 equation underestimations are found for 83% of the cases. For the full-scale measurements overestimations are also smaller (in average 14%) than found for the wind tunnel measurements (20%). The results from the full-scale comparisons are shown in Figure 7.

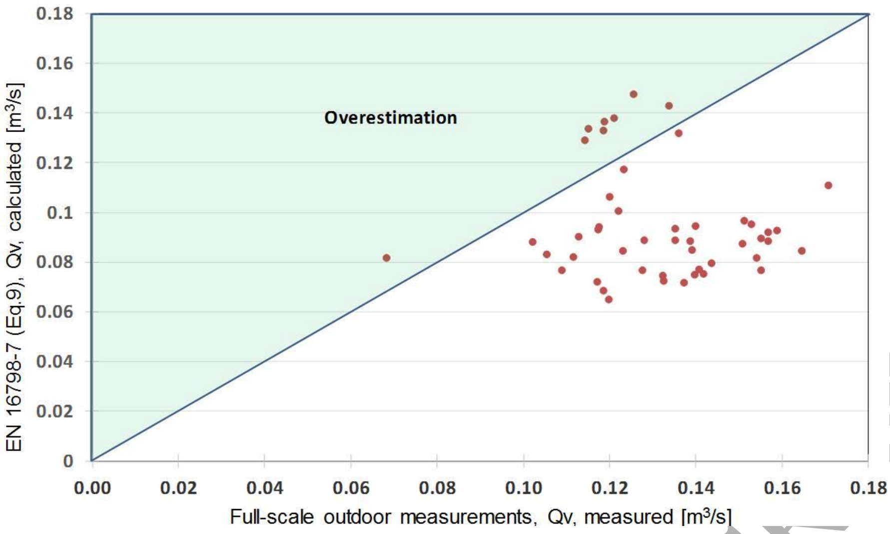



**Figure 7. Comparison of full-scale measurements and calculations made by the EN 16798:2017.** [18]

### 4.2 Comparison of existing and new equations with calculations for partitioned houses in CONTAM

**Impact of internal partition (closed doors)**

For all configurations tested with CONTAM, only small deviations between results obtained in "no partition" and "open doors" scenarios are observed (always less than 5% difference).

Closing the doors induces a significant pressure drop from one room to another, and thereby a significant reduction of the airflow rate. CONTAM calculations show that closing internal doors reduces the air flow rate by:

- 43% in configuration 1
- 72% in configuration 2
- 41% in configuration 3 (with open staircase)

In configurations 1 and 2, the decrease is more significant when wind is the dominant driving force. The calculations show up to 84% reduction in configuration 2 when there is no stack effect or a temperature difference of only 5°C, and up to 89% reduction in configuration 1 when there is no stack effect.

**Comparison between CONTAM results with closed doors and direct calculations (De Gids & Phaff and EN 16798-7:2017)**

Figure 8 to Figure 10 compare CONTAM results (closed internal doors) with the three equations mentioned in section 3.2 (De Gids & Phaff, EN 16798-7:2017, and EN16798-7:2017 with corrected $h_{st}$).

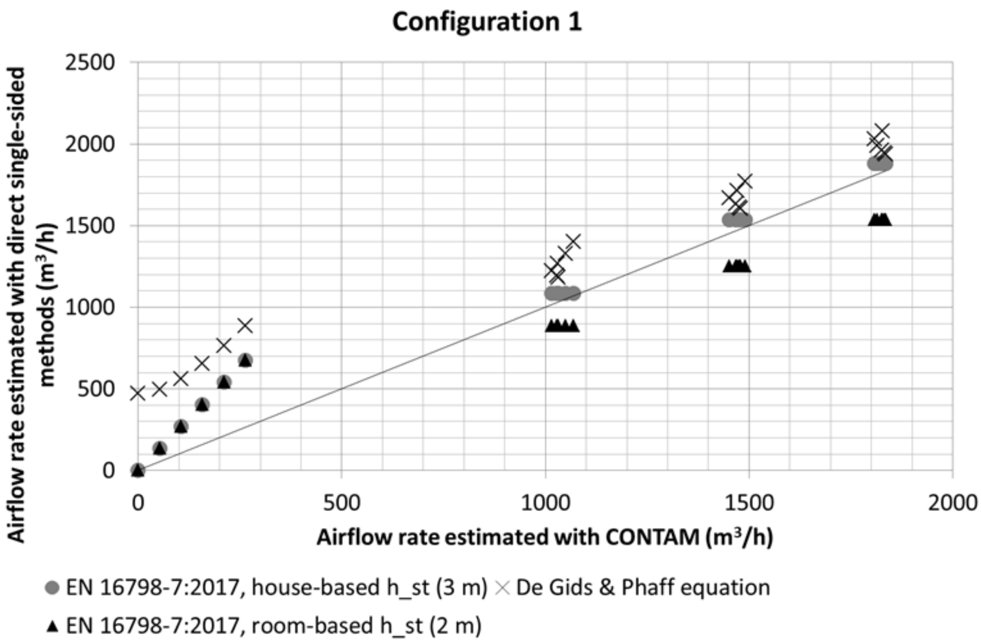



**Figure 8: Results for configuration 1: Single-sided models are applied to the whole house and compared to CONTAM results with closed internal doors.**

Figure 8 shows that in Configuration 1 the De Gids & Phaff equation overestimates the airflow rate, whereas the EN 16798-7:2017 equation performs better, as long as the temperature difference is above 0°C. The EN 16798-7:2017 equation with room-based height for stack effect slightly underestimates the airflow rate when the temperature difference is above 0°C.

When the temperature difference between indoor and outdoor is zero, all equations overestimate airflow rates compared to CONTAM. For these cases, airflow rates calculated with CONTAM are very low. However, the configuration without stack effect is close to a limiting case for CONTAM as it does not consider unsteady two-way flows through openings without stack effect.

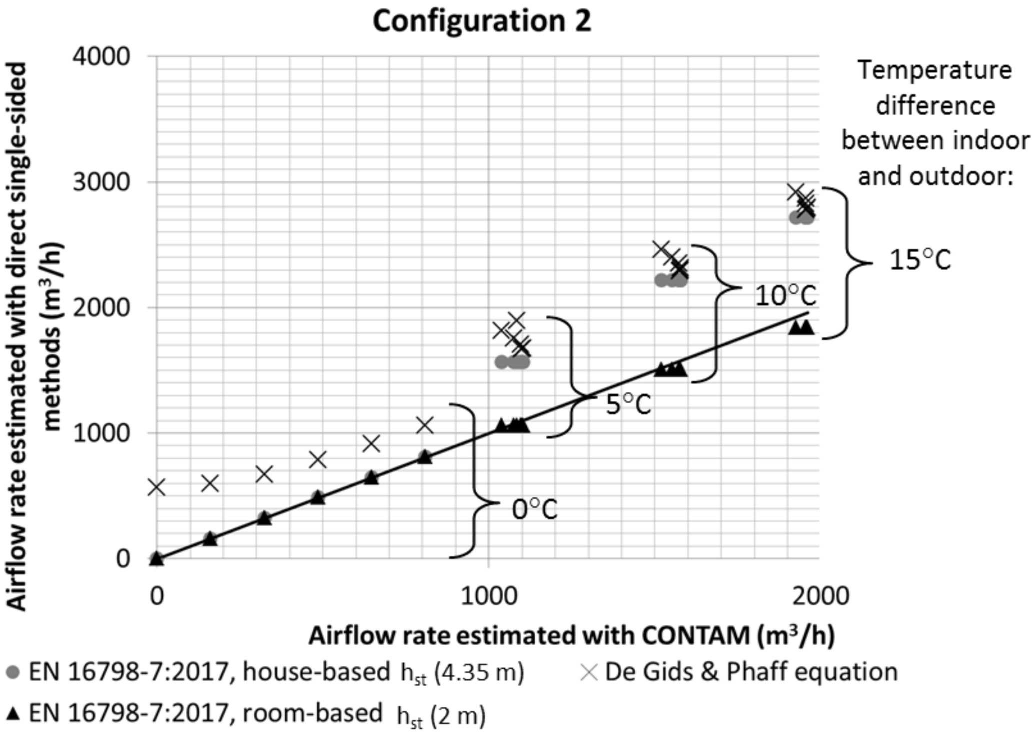



**Figure 9: Results for configuration 2. Single-sided models are applied to the whole house and compared to CONTAM results with closed internal doors**

In configuration 2, shown in Figure 9, the De Gids & Phaff equation overestimates the airflow rates, whereas the EN 16798-7:2017 equation with room-based $h_{st}$ performs remarkably well for every temperature and wind speed.

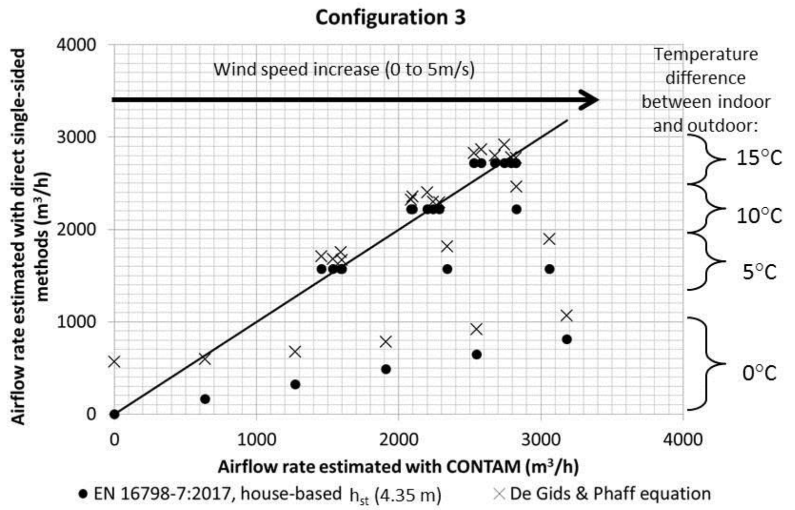



**Figure 10: Results for configuration 3. Single-sided models are applied to the whole house and compared to CONTAM results with closed internal doors**

In configuration 3 shown in Figure 10, the EN 16798-7:2017 equation performs very well when thermal buoyancy is the main driving force, but when wind is the main driving force, the two equations highly underestimate airflow rates. This result was expected in this case since cross ventilation occurs in the main room between the main window and the roof window and the situation thereby not can be regarded as fully single-sided.

## 4. DISCUSSION

Based on the results from the comparison of the new EN 16798:2017 equation with other calculation models for single-sided natural ventilation, the overall impression is that the new model fulfils the aim on underestimating rather than overestimating the airflow rates. However, a series of issues, which will be mentioned in the following, are important to keep in mind when working with design of single-sided natural ventilation.

One of the difficulties in the prediction of airflow rates with single-sided natural ventilation is the uncertainty in prediction of the flow pattern in the opening which greatly influences the amount of air going through the opening and, thereby, also the amount of air available for ventilation of the room. Sometimes, wind and thermal buoyancy forces will counteract; in other cases they will assist each other. Sometimes, the level of fluctuations near the opening will be high and, thereby, contribute to airing of the room, where at other times this contribution is negligible.

From the 159 different cases measured in the wind tunnel by Larsen [13,19], it was shown that the different situations are formed and highly influenced by the different combinations of wind velocity, temperature difference and wind direction. In the isothermal situation, the flow directions in the opening mainly correspond to the distribution of $C_p$-values at the facades. However, the measurements also show different influence on the flow from turbulence, indicating that the turbulence level is closely connected to the wind direction. When there is flow parallel to the opening, the situation where the opening is farthest away from the windward side shows the expected flow pattern with air flowing in through the opening at the side closest to the windward façade and out again through the opposite side of the opening. This results in a velocity close to 0 m/s at the vertical axis across the middle of the opening. In the case with the opening closest to the windward façade, the flow pattern shows that the largest amount of air goes in through the top right side of the opening (see from outside) and out through the bottom left side. As before, this shows that the largest pressure is found towards the windward façade, but it also shows a more unstable flow indicating a higher influence from turbulence near the corner towards the wind.

From the same study, the cases with a combination of wind and temperature difference showed that some cases are clearly wind driven; some cases are driven by temperature difference; and some by a combination. The difficult part can be to separate the cases and find the point where the flow will change from one type to another and, thereby, divide the flows into either wind driven, buoyancy driven or combined. If the calculation model is based on the assumption of combined driving forces, the variation between the main driving forces should also be reflected in the equation, which is the case in the new EN 16798:2017 equation.

A challenge for the EN 16798-7:2017 equation is that is does not perform well at no or low temperature differences. However, this has little impact on the energy assessment, and the influence from ventilation in the case with equal temperatures outside and inside can be considered as minor in the case of cooling.

As far as the objective is to provide a simplified model for building energy calculation, the EN 16798-7:2017 equation applied to the entire building has proven to perform well in our simulated test cases with closed internal doors provided that:

- The useful height for stack effect is "the maximum height for stack effect for each sub-zone" (room based, here 2 m in configs. 1 and 2) and not the height for stack effect of the full building.
- Each sub-zone can be considered as single-sided.

If at least one of the sub-zones is not single-sided, as in configuration 3, the equation logically underestimates the airflow rates when wind is the main driving force. It is therefore important to know the type of flow (single-sided or cross ventilation) expected in the different rooms of the building.

**5. CONCLUSION**

The aim with this paper was to compare the new calculation model in EN 16798-7:2017 for single-sided natural ventilation with other existing design methods, all held up against measured and simulated data. The new model should preferably underestimate rather than overestimate the airflow rates since a consequence of overestimations could be doubt in the use of natural ventilation as a passive cooling method due to overheated buildings and discomfort.

Based on the comparisons presented in this paper, it is found that the new simple direct calculation model in EN 16798-7:2017 predicts the airflows through windows in a more conservative way than earlier equations, representing an average of the airflow rate in the building which is generally on the safe side. The accuracy of the EN 16798-7:2017 equation was found by comparison to the wind tunnel measurements to be 29% but with underestimations in 88% of the cases.

The results from the application of the EN 16798-7:2017 equation in CONTAM show that there is a risk of significantly overestimating the airflow rate in buildings with internal partitions (internal closed doors) if they are considered as a single-zone building using an iterative airflow model. Therefore, it is suggested to calculate the airflow rates on a room-by-room basis (separated with closed doors); rooms without cross-ventilation could be assessed using the single-sided calculation, whereas a cross-ventilation calculation would be used to calculate the airflow through the other rooms.

Based on the investigations made during this work, the authors consider the new model in EN 16798-7:2017 well suited for the use in calculation standards to integrate natural ventilative cooling effects from single-sided ventilation.

**REFERENCES**


[1] M. Kolokotroni, P. Heiselberg, Ventilative Cooling (State-of-the-art review), Aalborg, Denmark, 2015. http://venticool.eu/wp-content/uploads/2013/09/SOTAR-Annex-62-FINAL.pdf.

[2] T.S. Larsen, Vurdering af indeklimaet i hidtidigt lavenergibyggeri : med henblik på forbedringer i fremtidens lavenergibyggeri, 2011. http://vbn.aau.dk/ws/files/45541977/Vurdering_af_indeklimaet_i_hidtidigt_lavenergibyggeri.pdf.

[3] C. Brunsgaard, P. Heiselberg, M.-A. Knudstrup, T.S. Larsen, Evaluation of the Indoor Environment of Comfort Houses: Qualitative and Quantitative Approaches, Indoor Built Environ. 21 (2012) 432–451. doi:10.1177/1420326X11431739.

[4] INIVE EEIG - International Network for Information on Ventilation and Energy Performance, Venticool, (2017).

[5] P. O'Sullivan, A. O'Donovan, Ventilative Cooling Case Studies Energy in Buildings and Communities Programme, 2018. http://venticool.eu/wp-content/uploads/2016/11/VC-Case-Studies-EBC-Annex-62-May-2018-Final.pdf (accessed June 15, 2018).

[6] G. Carrilho da Graça, P. Linden, Ten questions about natural ventilation of non-domestic buildings, Build. Environ. 107 (2016) 263–273. doi:10.1016/j.buildenv.2016.08.007.

[7] G. Bara, Mandate M/480 EN, 2010. http://ec.europa.eu/growth/tools-databases/mandates/index.cfm?fuseaction=refSearch.search#.

[8] CEN/TC 156, 16798-7:2017 Energy performance of buildings – Ventilation for buildings – Part 7: Calculation methods for the determination of air flow rates in buildings including infiltration (Modules M5-5), 2017.

[9] W. De Gids, H. Phaff, Ventilation Rates and Energy Consumption Due to Open Windows, Air Infiltration Rev. 4 (1982) 4–5.

[10] V. Leprince, F.R. Carrié, Comparative analysis of window airing models proposed in prEN 16798-7 and influence of internal resistances, in: P. Heiselberg (Ed.), CLIMA 2016 - Proc. 12th REHVA World Congr. Vol. 5., Aalborg University, Department of Civil Engineering, 2016.

[11] H. Wang, P. Karava, Q. Chen, Development of simple semiempirical models for calculating airflow through hopper, awning, and casement windows for single-sided natural ventilation, Energy Build. 96 (2015) 373–384. doi:10.1016/J.ENBUILD.2015.03.041.

[12] P.R. Warren, Ventilation through openings on one wall only, in: C.J. Hoogendorn, N.H. Afgar (Eds.), Energy Conserv. Heating, Cool. Vent. Build., Hemisphere, Washington DC, 1977: pp. 189–209.

[13] T.S. Larsen, Natural Ventilation Driven by Wind and Temperature Difference, Department of Civil Engineering, Aalborg University, 2006.

[14] P.R. Warren, L.M. Parkins, Single-sided ventilation through open windows, in: Conf. Proc. Therm. Perform. Exter. Envel. Build. ASHRAE, Florida, ASHRAE, 1985: p. 20.

[15] H. Wang, Q. Chen, A new empirical model for predicting single-sided, wind-driven natural ventilation in buildings, Energy Build. 54 (2012) 386–394. doi:10.1016/j.enbuild.2012.07.028.

[16] CEN/TC156, EN 15242:2007 - Ventilation for buildings - Calculation methods for the determination of air flow rates in buildings including infiltration, 2007.

[17] MEDDE, Order concerning the evaluation of the calculation method Th-B-C-E provided for in Articles 4, 5, and 6 of Order 26 October 2010 relating to thermal characteristics and energy

performance of new buildings and new parts of buildings, (2013).

[18] C. Plesner, T.S. Larsen, V. Leprince, Evaluation of single-sided natural ventilation using a simplified and fair calculation method, in: E. Van Kenhove, J. Laverge, P. De Vlieger (Eds.), Indoor Air 2016 - Conf. Proc. 14th Int. Conf. Indoor Air Qual. Clim., International Society of Indoor Air Quality and Climate, 2016: p. 8.

[19] T.S. Larsen, P. Heiselberg, Single-sided natural ventilation driven by wind pressure and temperature difference, Energy Build. 40 (2008) 1031–1040. doi:10.1016/j.enbuild.2006.07.012.

[20] G.N. Walton, AIRNET—A Computer Program for Building Airflow Network Modeling., NISTIR. (1989) 89–4072.

[21] G.N. Walton, W.S. Dols, CONTAM User Guide and Program Documentation, NISTIR 7251, 2013.

[22] T.S. Larsen, C. Plesner, V. Leprince, Calculation methods for single-sided natural ventilation - simplified or detailed?, in: Proc. Clima 2016, Aalborg, Denmark, 2016: p. 10.