buildings

MDPI

Review

A Review of Performance Specifications and Studies of Trickle Vents

Ahmet Biler [1,2,*], Aslihan Unlu Tavil [2], Yuehong Su [1] and Naghman Khan [3]

[1] Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, Nottingham NG7 2RD, UK yuehong.su@nottingham.ac.uk
[2] Faculty of Architecture, Istanbul Technical University (ITU), 34437 Istanbul, Turkey; tavil@itu.edu.tr
[3] Integrated Environmental Solutions Limited Helix Building, West of Scotland Science Park, Glasgow G20 0SP, UK; naghman.khan@iesve.com
* Correspondence: biler@itu.edu.tr; Tel.: +44-7463-957-577 or +90-506-325-5556

Received: 6 August 2018; Accepted: 24 October 2018; Published: 6 November 2018

Abstract: The air quality of indoor spaces is the most significant parameter in providing a healthy living environment. Low indoor air quality (IAQ) leads to Sick Building Syndrome—one of the major reasons for labor loss in office buildings. The fundamental measure to ensure indoor air quality is ventilation, which includes two basic types: mechanical ventilation and natural ventilation. Natural ventilation is an exchange of stale indoor air with fresh outdoor air by means of a pressure difference due to wind and/or stack effect. Trickle Vents, known also as background ventilators, are natural ventilation devices which can be integrated into façades or window systems as an alternative to operable vents, specifically in high-rise buildings. The major design criteria of Trickle Vents are ventilation capacity, controllability, actuation, thermal insulation, air permeability, water tightness, climatic adaptation, security, and acoustic attenuation. Other important parameters in Trickle Vents design are positioning, equivalent area, and control strategy. This paper aims to review all these aspects, particularly with reference to building regulations and commercial products. Furthermore, simulation, experimental, monitoring, and survey studies of Trickle Vents are also discussed. This literature review is presented from the perspective of performance parameters, control strategies, positioning, etc., with an aim to provide a comprehensive overview of such technology.

Keywords: literature review; natural ventilation; trickle vents; performance specifications; commercial product; design; measurement

1. Introduction

The population in built-up areas has increased dramatically because of urbanization. Since people living in urban areas spend 90% of their time in closed areas such as homes, schools, offices, etc., indoor air quality (IAQ) has never been so important [1]. The World Health Organization reported that 99,000 deaths in Europe and 81,000 in the USA were related to poor indoor air quality in 2012 alone [2].

Sick Building Syndrome (SBS) is the term used to describe situations in which building occupants experience acute and negative health and comfort effects that appear to be linked to time spent in a building (WHO, 1984). The building occupants may suffer from headaches and dizziness, nausea, aches and pains, fatigue, poor concentration, shortness of breath, eye and throat irritation, irritated or runny nose, skin irritation, allergy, and others. Based on research, the value of labor loss due to Sick Building Syndrome in the USA economy in 1998 was estimated at around $180 billion (USD) [3,4]. The main reason for Sick Building Syndrome is the provision of better insulation performance at the expense of indoor air quality.

2. Ventilation Requirement

The main reason for ventilating a room is for the health and comfort of the occupants, such as control of internal humidity, removal of both background and specific pollutants, and providing enough oxygen for combustion processes, if any. Thermal comfort, durability, fire safety, noise, and energy use parameters are the main concerns for ventilation design [5]. On the other hand, safe ventilation rates have been established based on research including testing in the U.S. in the last century. To really justify a certain ventilation rate, one should look at the sources of pollution and their behavior (interaction with other pollutants, schedules, source strengths, etc.). Therefore, the main way to control/improve the IAQ is through source control. Moreover, that is where the identification of the pollutants takes place. A parameter cannot be controlled unless it is known and measured, either because they are unknown (i.e., it is not known what pollutants are being emitted), or because there is no measurement [6]. CO_2 can be calculated based on occupancy when there are people or combustion processes in a space. Radon, ozone, formaldehyde, NO_x, SO_x, etc., are more toxic to occupants and may need higher ventilation rates [6].

CO_2 is used frequently to monitor and control the supply of fresh air. Even though CO_2 is a good indicator of contamination caused by occupants, it is usually a poor indicator and measure of perceived air quality [6]. Figure 1 illustrates measured CO_2 concentration outdoors and measured CO_2 versus percentage of dissatisfied occupants.

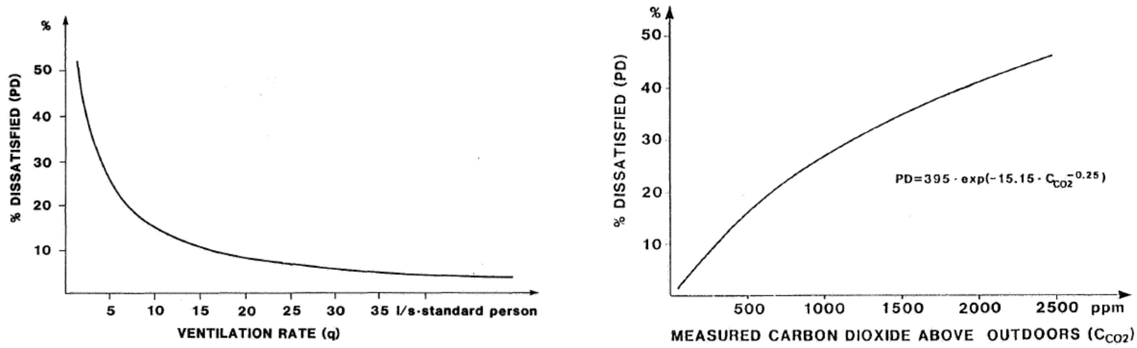


Figure 1. Ventilation rate vs. percentage dissatisfied occupants (**left**); measured CO_2 vs. percentage dissatisfied occupants (**right**) [6].

The CO_2 concentration in the atmosphere was 280 ppm before the Industrial Revolution [7]. It increases considerably each year. For example, the outdoor CO_2 concentration was defined as 390 ppm in CEN CR1752, published in 1999 [8]. However, measurements taken in 2016 show that the CO_2 concentration level reached 403.3 ppm [9]. The assumed outdoor CO_2 concentration varies in different studies. For instance, the study by Lavarge et al. [10] uses an outdoor CO_2 level of 350 ppm. The use of an incorrect value might lead to misleading results. In addition to this, indoor air quality is acceptable for CO_2 concentrations lower than 600 ppm according to EN 13779-2007 [11]. A level of 1000 ppm is one of the most common set points in buildings to open vents.

Cornara et al. specifies that a CO_2 concentration typically higher than 1000 ppm leads to a considerable drop in the cognitive ability of pupils in schools. However, 1500 ppm was chosen as the limit CO_2 concentration as indicated in U.K. standards [12].

Ventilation Rates are determined by considering indoor pollutant levels such as CO_2 and other related contaminants in ASHRAE 62.1-2016 [13]. The ventilation rate requirements of some areas are indicated in Table 1.

Table 1. Occupancy category vs. required ventilation [13].

Occupancy Category	Outdoor Air Rate	
	per Person (L/s·Person)	per Area (L/s·m^2)
Lecture Classroom	3.8	0.3
Computer Lab	5	0.12
Restaurant	3.8	0.9
Conference/Meeting	2.5	0.3
Bedroom/Living Room	2.5	0.3
Office Space	2.5	0.3
Health Club	10	0.3

One of the significant parameters for management of indoor air quality (IAQ) is ventilation by means of mechanical ventilation or natural ventilation. There is also infiltration, described as adventitious leakage, over which there is no control and which is usually negligible [14].

3. Natural Ventilation

Natural ventilation is the method of supplying fresh air through environmental driving forces such as temperature differences or wind pressure differentials without using any additional mechanical system. Since environmental driving forces are quite variable over short time intervals, effective design of natural ventilation in buildings is crucial. While excessive ventilation could cause discomfort and heat loss, low ventilation could lead to overheating and insufficient Indoor Air Quality (IAQ) [15,16].

Ventilation of buildings has three different purposes: maintaining IAQ, satisfying thermal comfort, and night cooling [17]. Natural ventilation is challenging due to driving forces like wind and buoyancy because of variation in the climate and weather [18]. Moreover, temperature differences and wind direction parameters are crucial considerations during the design of natural ventilation. Specifically, the control of humidity is a challenging issue in naturally ventilated spaces. For instance, the level of challenge is higher in south-eastern U.S. cities which have high temperatures and relative humidity in summer or in places which have dry winter conditions [19]. On the other hand, natural ventilation is more effective in places and seasons where heating is not needed [20].

Natural ventilation is commonly used in summer nights, specifically in places where cooling loads are high, in order to discharge excessive heat [21]. Thus, this ventilation strategy satisfies thermal comfort during the first hours of the next working day and supplies fresh air to the indoors. This method also decreases the air conditioning loads in naturally ventilated buildings. Opening of vents is carried out mostly for night temperatures lower than 26 °C, which is the maximum allowed indoor comfort temperature [4,22]. On the other hand, A. Dogbeh et al. specifies that natural ventilation as night cooling in the heating season through Trickle Vents helps to satisfy thermal comfort and remove pollutants from the indoors [23].

Natural ventilation solutions are considered as less effective in comparison with mechanical ventilation solutions. However, they are broadly preferred due to energy efficiency and cost concerns [12]. On the other hand, passive ventilation is commonly preferred due to the advantageous aspects of low embodied energy, silent operation, low maintenance & operation (M&O), low return of investment (ROI), no supply-side ducting, less complicated retrofit, and its intuitive cooling control in specifically low-energy buildings [15]. Nevertheless, the window opening behavior of occupants has a significant effect on the energy and cost performance of natural ventilation systems. G. Evola et al. presented the performance of Controlled Mechanical Ventilation (CMV) systems from energy and financial aspects in dwellings [24]. The results of various CMV configurations were compared with occupant-controlled natural ventilation. While the thermal energy requirement for an unwisely managed natural ventilation system was E_{th} = 3210 kWh/year in Rome, this value diminished 83.5% by using hygro-adjustable mechanical ventilation (E_{th} = 528 kWh/year). Additionally, the study claimed that the payback period stayed below 3 years for single-flow ventilation systems applied in cold climates. This study illustrates that the window opening behavior of the occupants is an essential parameter in natural ventilation.

R. Andersen et al. [25] quantified the window opening behavior of the occupants with respect to environmental conditions in Danish Dwellings in their research. The probability of opening and closing behavior was statistically modelled through multivariate logistic regression in 15 dwellings. Temperature, relative humidity, and illuminance values indoors and air temperature, RH, wind speed, global solar radiation, and total sunshine hours outdoors were taken into consideration in the statistical modelling. The results revealed that while the CO_2 concentration significantly affects the behavior of opening, the most important variation outdoors is the temperature for closing behavior. It is interesting to underline that wind speed had no influence on window opening/closing behavior. In addition to this, this experimental study might help simulation models as an input to provide realistic results by considering the actual behavior of the occupants.

Effective natural ventilation design is quite crucial in schools. Particularly, the level of CO_2 has a considerable effect on the learning ability of pupils. It also influences the power of attention by 5% according to Griffiths and Efecthari [26]. Additionally, Cornara et al. specified that a CO_2 concentration typically higher than 1000 ppm leads to a considerable drop in the learning skills of pupils in schools [12].

3.1. Driving Forces in Natural Ventilation

There are basically two main driving forces, which are wind pressure and the stack (chimney) effect, during ventilation design calculations. The target is mostly sufficient fresh air, satisfactory indoor environment quality, and energy efficiency [27].

3.1.1. Wind-Driven Ventilation

Wind-driven ventilation, in which air is pulled indoors by means of a wind-induced pressure difference, is generally more effective. It is mostly the cheapest, most common, and most energy efficient method of ventilation. The most common devices used for wind ventilation are operable windows, louvres, trickle vents, and rooftop vents.

Wind pressure on the ventilation opening is mostly determined by the equation below [28].

$$\Delta P = \frac{\rho \cdot C_p \cdot v^2}{2} \tag{1}$$

ΔP: Pressure Difference Due to Wind (Pa);
C_p: Pressure Coefficient;
ρ: Air Density (kg/m^3);
v: Wind Speed (m/s).

The orifice equation is the most common equation used to determine the air flow rate on opening, as seen below.

$$Q = C_D.A.\left(\frac{2.\Delta P}{\rho}\right)^{0.5} \tag{2}$$

Q: Air Flow Rate (m^3/s);
C_D: Discharge Coefficient;
A: Flow Area (m^2);
ΔP: Pressure Difference across the Opening;
ρ: Air Density (kg/m^3).

3.1.2. Buoyancy-Driven Ventilation

This is due to the density difference caused by temperature difference. Hot air is less dense than cold air, so the hot air would rise due to buoyancy, forming a so-called stack effect (Figure 2). A larger height difference would give a higher buoyancy due to a larger density difference between indoors and outdoors. Usually, there is a 4 Pa pressure difference in each floor in the cold season and a 1.5 Pa pressure difference in the summer season [29,30].

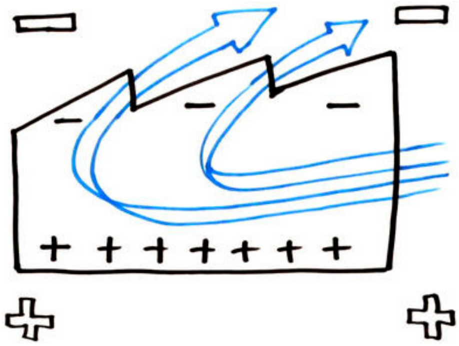


Figure 2. Stack ventilation [29].

The most simple pressure difference formula used to calculate stack pressure is given in the equation below [31].

$$\Delta P = \rho_o \cdot g \cdot z \cdot \frac{T_i - T_o}{T_i} \quad (3)$$

ΔP: Pressure Difference due to Stack Effect (Pa);
ρ_o: Outside air density (kg/m^3);
z: Height between two openings (m);
g: gravity (m/s^2).

Higher buoyancy is induced by a larger temperature difference [15].

3.2. Designs and Operation of Natural Ventilation

Various natural ventilation principles in the literature are specified in this section.

3.2.1. Single-Sided Ventilation

This is one of the simplest ventilation principles. The main strategy is ventilating a building through openings like windows or ventilation devices such as Trickle Vents. The air exhaust might be through different openings which are still on the same wall, as indicated in Figure 3. Single-sided ventilation is convenient for spaces of less than 6 m depth [31]. Furthermore, thin and tall vents are more efficient in comparison with wide and short vents due to taking greater advantage of the stack effect. This point should be considered in design specifically for summer when there is a slightly lesser temperature difference between indoors and outdoors according to Building Bulletin 101 Ventilation of School Buildings [32].

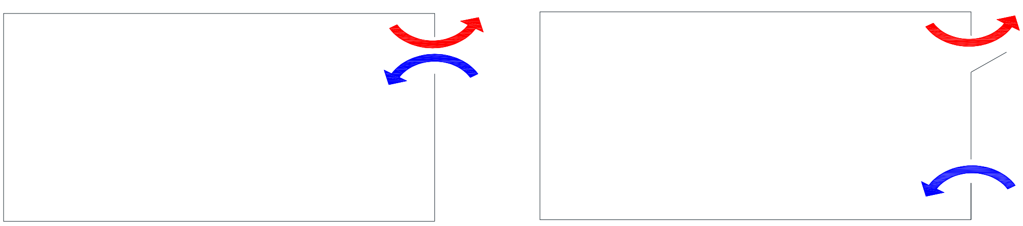


Figure 3. Single operable vent or device (**left**); bottom vent and single operable vent (**right**).

3.2.2. Cross-Flow Ventilation

Openings are formed in two or more opposite walls in the same space in order to create cross ventilation (Figure 4). This kind of ventilation is convenient for space depths of more than 6 m and less than 12 m. There is greater potential here for taking advantage of wind pressure in comparison with single-sided ventilation. Therefore, cross ventilation as a ventilation method has a larger air change capacity in most cases [31]. It is recommended that there should be an acceptable height difference between the inlet and outlet to provide sufficient buoyancy driving force for the no-wind case [32]. Cross-flow ventilation is mostly the main ventilation mechanism in office buildings, since they have large spaces [33]. According to research carried out by A. Mochida et al., cross ventilation could be used as part of a satisfactory mechanism of indoor thermal comfort. This study attempted to keep predicted mean vote (PMV) values within the thermal comfort range by the automatic control of windows [34].

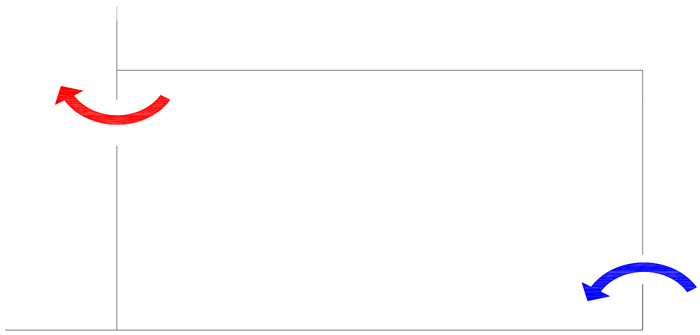


Figure 4. Cross ventilation.

3.2.3. Purge Ventilation

Purge ventilation is a rapid exchange of air by opening doors and windows with considerable angle. Purge ventilation enables the satisfaction of thermal comfort and assists in removing VOCs, pollutants, or heavy smells [35]. Shock ventilation and trickle ventilation are two different special terms of Purge Ventilation with respect to opening angles.

Shock Ventilation

Shock ventilation is a more specific type of purge ventilation and is defined as opening all the windows simultaneously. The Federal Environment Agency claims that opening windows completely for 5 min is more effective than opening them partially for long periods, since the walls, ceiling and furniture lose their internal heat considerably less in comparison with opening windows partially for long periods [36]. Galvin R. mentions in his article that shock ventilation can be up to 20 times more efficient than trickle ventilation (Section "Trickle Ventilation") due to causing overventilation in spite of contrary public opinion according to some surveys [36].

Trickle Ventilation

Trickle ventilation is the passive ventilation strategy that provides air flow to the indoors by means of vents with small angles, unlike purge ventilation. Adamu et al. [18] investigated four different ventilation strategies—single window, dual-opening, inlet and stack, and ceiling-based strategies—with different opening angles using Computational Fluid Dynamics (CFD) and Dynamic Thermal Modelling (DTM) (Figure 5). The performance criteria were 60 L/s per patient (WHO) and six air changes per hour (ACH) (HTM 03-01), even though there was noise concern [37,38]. A typical model ward room with 3.78 m × 6.23 m × 3.5 m dimensions were modelled. The C_d value for the single opening was assumed to be 0.25 [39], and for the dual opening in the same side of the wall it was assumed to be 0.6. The results were evaluated in terms of ventilation rate, heating/cooling load, and thermal comfort (PMV). Moreover, the other objective of the study was to evaluate opening fractions to satisfy sufficient Trickle Ventilation for all cases in the winter period. Figure 5 illustrates the monthly heating loads with respect to different cases by considering different opening fractions in different parts of the year. One result in this study was that Trickle Ventilation with 25% opening has the best performance for achieving the required airflow rate and satisfactory thermal comfort. It is significant to note that the term "Trickle Ventilation" is different from the use of Trickle Vents.

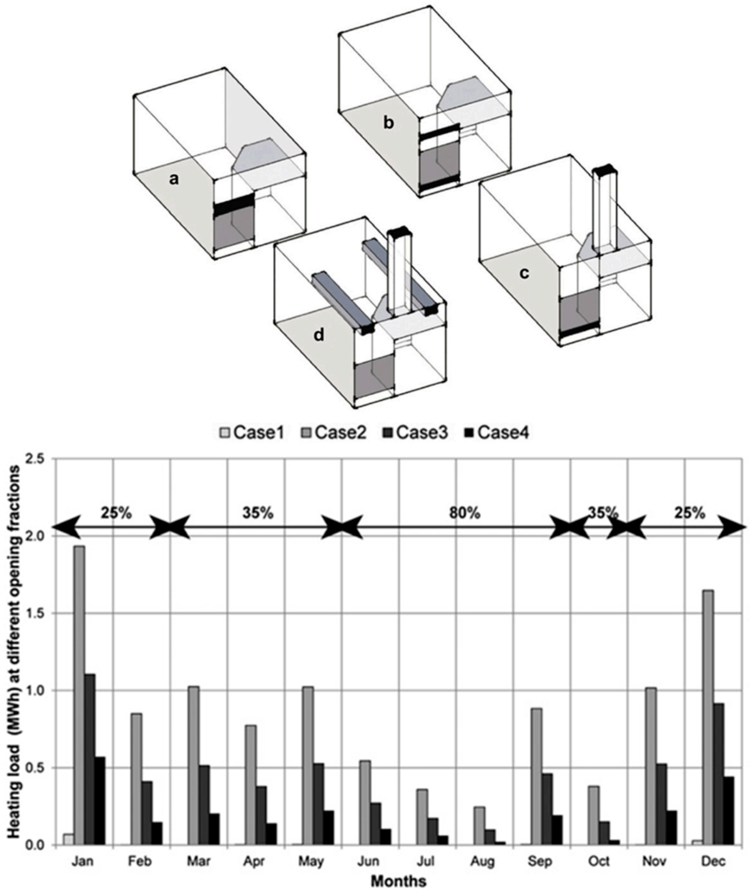


Figure 5. Monthly heating loads with different opening fractions. (a) Single window opening (Case 1), (b) same-side dual opening (Case 2), (c) inlet and stack (Case 3), and (d) ceiling-based natural ventilation (Case 4) [18].

3.2.4. Trickle Vents (Background Ventilators)

Trickle Vents, which may also be called Background Ventilators, are a natural ventilation device to provide background ventilation in addition to other forms of ventilation and are usually incorporated into the frame of a window. They might optionally have a perforated aluminium screen on the supply side to prevent dust, insect, and bird passage from the outside. They can generally transfer fresh air from the outside to the inside by controlling wind gusts and turbulence. Moreover, the acoustic performance is considerably better in comparison with that of windows (see also Section 4.8). Since it is operable independently, a design with a much larger glass size is possible.

Trickle Vents (Background Ventilation) are defined in Building Regulations 2010 Approved Document Part F [40] as a small ventilation opening which is designed to satisfy the ventilation requirements for an entire building. Provisions for Trickle Vents are illustrated in Figure 6. Even though they are mainly specified as Trickle Vents in the market, some technical documents call them background ventilators as well [41]. They are mostly positioned 1.7 m above floor level in order to prevent probable cold draughts [35,40].

Trickle Vents are typically controlled manually. Some types of Trickle Vents have intermediate positions as well as open and closed positions with respect to the fresh air requirement. Opening, closing, and other intermediate positions are operated by the help of flaps. There are also self-balancing Trickle Vents that control the amount of air intake by changing the opening area depending on the pressure difference between indoors and outdoors in order to minimize draught risk (Pressure-Controlled Trickle Vents) [14,42]. Besides this, integration into a building automation system of Trickle Vents can improve the performance significantly [4].

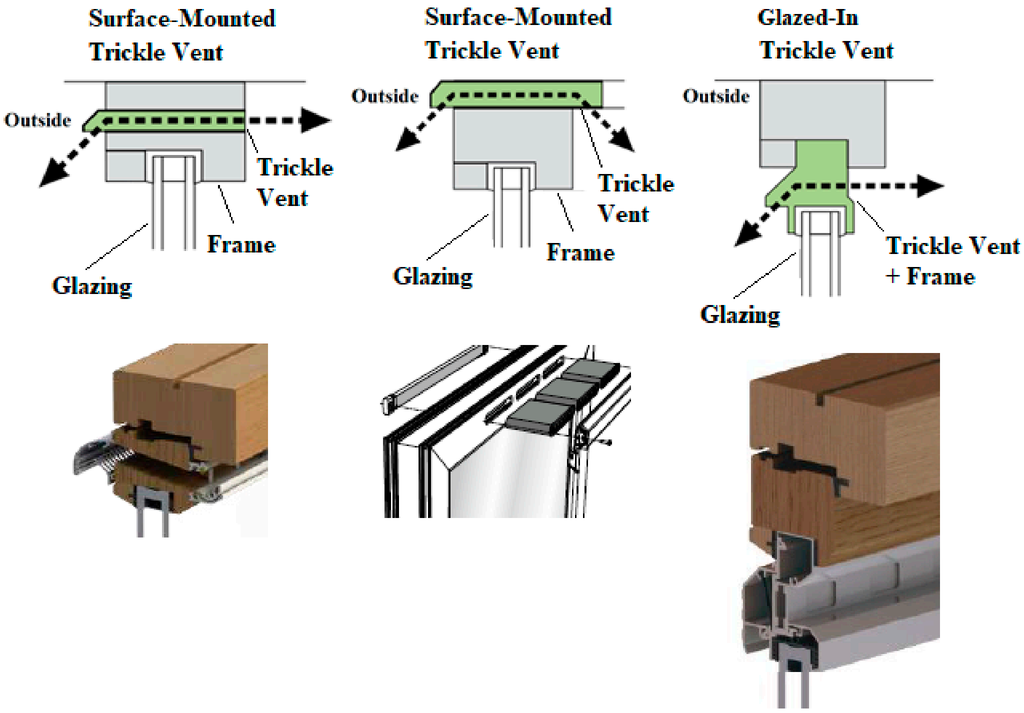


Figure 6. Trickle vents [40,43,44].

Classification according to Control Methods

There are two different control methods for Trickle Vents: pressure or slot controlled. Karava P. investigated the air leakage characteristics of pressure-controlled and slot-controlled Trickle Vents through various experimental methods [45].

Pressure-Controlled Trickle Vents

Pressure-controlled Trickle Vents have an interior part which has a fixed opening area and an exterior flap. The exterior flap moves in order to control the amount of air passing through the ventilator. The main driving force of air transfer through the inlet is the pressure difference between indoors and outdoors due to wind and stack effects. The inlet area becomes larger in lower pressure differentials and it becomes smaller in higher pressure differentials. Therefore, it has a higher airflow potential at lower ΔP ($\Delta P < 10$ Pa) in comparison with slot-controlled Trickle Vents (Figure 7). The experiment results presented by P. Karava [45] indicate that the air flow rate is constant at 0.006 m^3/s for a pressure difference $\Delta P > 10$ Pa (Figure 7). Due to the fact that the control of airflow is simpler in higher pressure differences, application of pressure-controlled vents in climates with low outside temperatures is more convenient in comparison with slot-controlled vents. In other words, there is superior performance in the heating season. Pressure-controlled background vents are not compatible for use in cross ventilation cases.

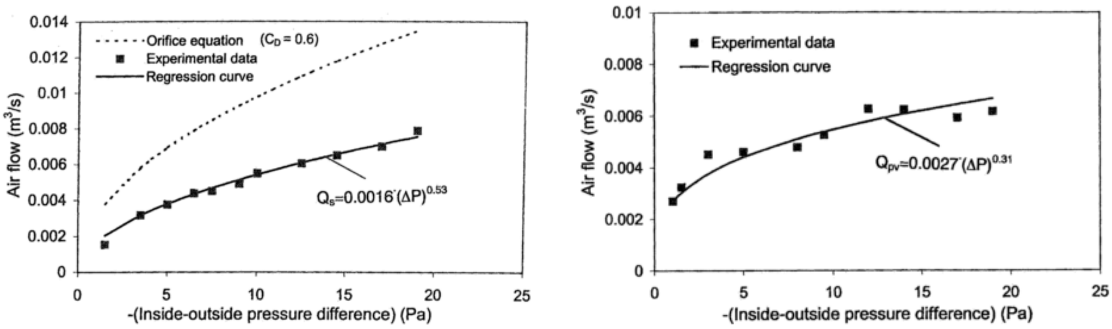


Figure 7. Air flow through slot- (**left**) and pressure-controlled (**right**) Trickle Vents [45].

Slot-Controlled Trickle Vents

Slot ventilators are another type of Trickle Vents (background vent). They have a fixed opening area, unlike pressure-controlled Trickle Vents. Properly designed slot ventilators can be recognized as passive inlets. There is a lower risk of draught due to its design with air cavities and an exterior mesh. There is a higher airflow rate potential in higher pressure differences ($\Delta P > 10$ Pa) compared to pressure-controlled background vents, as specified in the experiment presented by P. Karava. A simulation of slot-controlled Trickle Vents gives sensitive results in contrast with pressure-controlled Trickle Vents [45].

Classification according to Mounting Types

Trickle Vents can be also classified into two categories with respect to mounting types in the market. These are over-frame flap ventilators and flap ventilators glazed in transoms/mullions [41,46–49]. Some brands have products in both categories.

Over-Frame Flap Ventilators (Surface-Mounted Trickle Vents)

The companies which produce over-frame flap ventilators (Surface-Mounted Trickle Vents) are Titon, Greenwood, AWS, Masko, Brookvents and RW Simon (Figures 6 and 8).

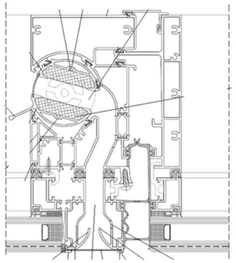
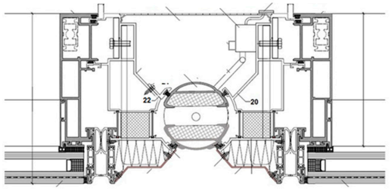
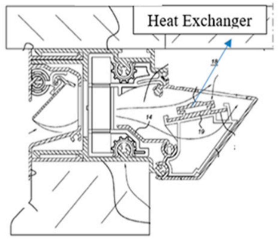
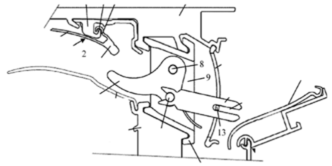
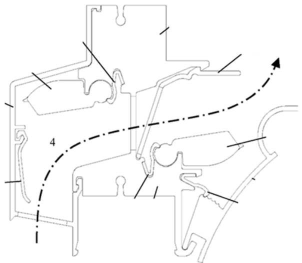
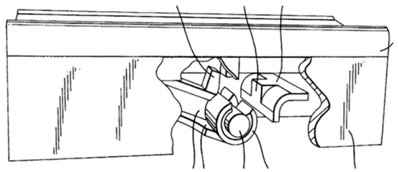
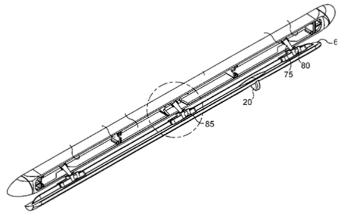
Figure 8. Surface-Mounted Trickle Vents (**left**); Glazed-In Trickle Vents (**right**) [50,51].

Flap Ventilators Glazed in Transom/Mullion (Glazed-In Trickle Vents)

Glazed-In Trickle Vents (Flap Ventilators Glazed in Transom/Mullion) are commercially available similar to Over-Frame Flap Ventilators. Renson, Metal Yapi, Brookvent, Amesbury, and RW Simon companies are the major players in production of this type of Trickle Vent (Figures 6 and 8).

A list of some patented vents of both types available in the market is shown in Table 2.

Table 2. Some of the patented vents available in the market.

Image				
Applicant	Metal Yapi	Metal Yapi	Renson	Renson
Name of Patent	Partial Natural Ventilation System Developed for Unitized Curtain Wall	Vertical Natural Ventilation Device	Ventilation Device with Internal Heating System	Ventilation Grille
Application Number	TR 2013/08326 [52]	TR 2016/17175 [53]	EP 2 639 519 A1 [54]	EP 2 995 879 A1 [55]
Image				
Applicant	Renson	Titon	Titon	
Name of Patent	Ventilation Device	Slot Ventilator	Slot ventilator mounted on a window or door to be ventilated	
Application Number	EP 2 141 424 A3 [56]	US005702297A [57]	GB 2432656 A [58]	

4. Trickle Vent Design and Performance Requirements

Different performance requirements are identified in different sources. Building Bulletin 101—Ventilation of School Buildings [32] specifies that the main design criteria of natural ventilation systems are ventilation capacity, controllability, security, sealing, vent actuators, and acoustic attenuation. Controllability is slightly different from vent actuators. While "controllability" is about easiness of control by occupants, "vent actuators" is about the performance of the ventilation system within the building automation system. Operation of the ventilation system should be as quiet as possible during operation with the building automation system.

The main performance requirements are given in this section.

4.1. Performance Test Methods

The airflow capacity of Trickle Vents and other externally and internally mounted devices is determined according to BS EN 13141-1 [40]. If testing conditions are different from 20 °C and 101,325 Pa, the results should be corrected using the formula below [59].

$$q_{v\ cor} = q_{v\ meas} \cdot \frac{293}{273 + \theta_a} \cdot \frac{P_a}{101325} \tag{4}$$

$q_{v\ cor}$: Corrected air flow rate ($L \cdot s^{-1}$);
θ_a: Ambient temperature (°C);
Pa: Atmospheric pressure (Pa).

NBS 2010b for England and Wales, Part F, defines background ventilation and different Trickle Vent types and how to determine their performance from different aspects such as air flow rate, equivalent area, noise control, etc. [40]. Besides this, Building Research Establishment (BRE) published General Trickle Ventilator Guidance in 1998 [49].

The standards that describe the way of determining Trickle Vents performance is illustrated in Table 3.

Table 3. The Standards which are used to determine Trickle Vent performance [48].

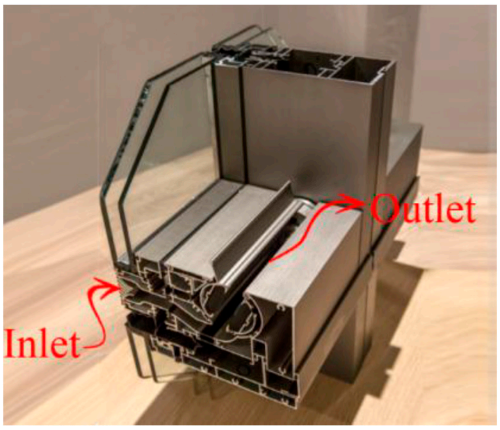
Performance	Standard	The Name of Standard
Ventilation Capacity	EN 13141-1 [59]	Ventilation for Buildings—Components/Products for Residential Ventilation—Part 1: Externally and internally mounted air transfer devices
Acoustics	BS EN 20140:10:1992 [60]	Acoustics—Measurement of sound insulation in buildings and of building elements
Acoustics	BS EN 140:10 [61]	Acoustics—Measurement of sound insulation in buildings and of building elements
Acoustics	BS EN ISO 717-2 [62]	Acoustics—Rating of sound insulation in buildings and of building elements Part 1: Airborne sound insulation
Water Tightness	BS EN 1027: 2016 [63]	Windows and doors—Water tightness—Test method
Air Permeability	BS EN 1026: 2016 [64]	Windows and doors—Air permeability—Test method
Thermal	BS EN ISO 10077-2: 2017 [65]	Thermal performance of windows, doors and shutters—Calculation of thermal transmittance
Burglar Proof	EN 1627:2011 to EN 1630:2011 [66–69]	Pedestrian doorsets, windows, curtain walling, grilles and shutters—Burglar resistance

4.2. Positioning on the Wall

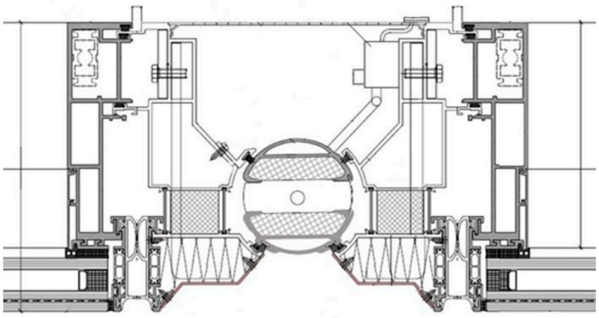
Trickle Vents could affect energy load to a significant level if they are sized and positioned correctly. For instance, a cold draught which directly influences the heating load and thermal comfort of the indoors could be minimized by using Trickle Vents in convenient positions [49].

Trickle Vents should be positioned 1.7 m above floor level in order to prevent potential draughts [40]. Besides this, positioning airflow openings higher than desk level prevents the risk of paper scatter. Therefore, separate openings like Trickle Vents are essential to preventing flight of paper in the summer term during high ventilation rates, even though it could be beneficial for providing thermal comfort [49].

Most Trickle Vent applications are on top of windows. However, there are some exceptional applications. For instance, Trickle Vents applied in San Francisco Federal Building are located under windows and baseboards [70]. There are also vertical Trickle Vents developed by Metal Yapi which were applied in a project in Moscow [14]. This system enables advantage to taken from the stack effect as well as from wind ventilation. Moreover, there is another Trickle Vents mock-up which is applied to the bottom of glazing, as seen in Figure 9 [4]. The plan section of a vertical Trickle Vent and a Trickle Vent applied to the top of glazing are illustrated in Figure 9 as well.



(**a**)



(**b**)

(**c**)

Figure 9. (**a**) A Trickle Vent applied to the bottom part of glazing [4]; (**b**) a vertical Trickle Vent [14]; (**c**) a Trickle Vent applied to the top part of glazing [48].

4.3. Opening Area

The opening areas of Trickle Vents are given in the literature mostly as geometrical free areas and equivalent areas, which are two different methods to measure.

- **Geometrical Free Area and Equivalent Area**

While the geometrical free area corresponds to the total of all sectional free opening areas, the equivalent area is the same sharp-edged circular orifice area which allows for the same amount of airflow passage under the same pressure difference [59]. The geometrical free area is defined for the products which are fully open [71]. It is the minimum cross-sectional area perpendicular to the air flow path (Figure 10). Both terms are crucial to defining the airflow capacity of Trickle Vents and similar internal and external air transfer devices.

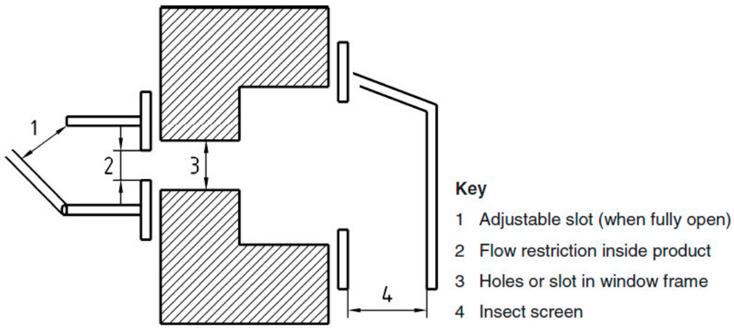


Figure 10. Geometrical free area [59].

The equivalent area of a ventilation device is defined using the formula below [59]. C values are given in the Table 4 with respect to different pressure differences.

$$A = C \cdot q_v \quad (5)$$

A: Equivalent area (mm^2);
C: Table 4;
q_v: Volume flow rate under certain pressure difference.

Table 4. C values under certain pressure differences [59].

ΔP Pa	C mm^{-1} s
1	1272.5
2	899.7
4	636.2
8	449.9
10	402.4
20	284.5

Alternatively, the background ventilator equivalent area is determined with the formula below [40].

$$A = 1000 \cdot \left(\frac{Q}{C_d}\right) \cdot \left(\frac{\rho}{2} . \Delta P\right)^{0.5} \quad (6)$$

A: Equivalent area of background ventilator (mm^2);
Q: Air supply rate (L/s);
C_d: Discharge coefficient (assumed as 0.61);
ρ: Air density (kg/m^3) assumed as 1.2 kg/m^3;
ΔP: Pressure difference (1 Pa for multistory buildings, 0.6 Pa for single-story buildings).

The total equivalent area should be double the equation above, since half of the openings act as air discharge units. The pressure differences specified above are given by considering a 15 °C temperature difference, 4 m/s wind speed, and 10 m height according to BS 5925:1991 [40,72].

The Building Regulations 2010—Approved Document F [40] states that the minimum available equivalent area of Trickle Vents should be more than 5000 mm^2 in habitable rooms and 2500 mm^2 in kitchens, utility rooms, and bathrooms in dwellings. Moreover, the total equivalent area of Trickle Vents is illustrated in Table 5. If the dwelling is lower than five floors, a further 10,000 mm^2 equivalent area should be added to this list.

Ventilation rates in all buildings are determined by considering Table 6. However, if the air permeability of a dwelling is higher than 5 $m^3/(h \cdot m^2)$, the air supply rate can be diminished to 0.15 ACH in order to allow for infiltration.

Table 5. Total equivalent ventilator area of Trickle Vents for dwellings [40].

A—Total Equivalent Ventilator Area a (mm^2) for a Dwelling with Any Design Air Permeability					
Total Floor Area (m^2)	**Number of Bedrooms**				
	1	**2**	**3**	**4**	**5**
≤50	35,000	40,000	50,000	60,000	65,000
51–60	35,000	40,000	50,000	60,000	65,000
61–70	45,000	45,000	50,000	60,000	65,000
71–80	50,000	50,000	50,000	60,000	65,000
81–90	55,000	55,000	60,000	60,000	65,000
91–100	65,000	65,000	65,000	65,000	65,000
>100	Add 7000 mm^2 for every additional 10 m^2 floor area 5				

Table 6. Building ventilation rates [40].

	Number of Bedrooms				
	1	2	3	4	5
All building ventilation rate (L/s)	13	17	21	25	29

A minimum 400 mm^2 opening area of Trickle Vents for each m^2 of floor area is required for office spaces according to Kolokotroni M. et al [41].

Building Bulletin 101—Ventilation of School Buildings [32] claims that Trickle Vents have limited benefits in the ventilation of school buildings. For instance, a 16,000 mm^2 inlet free area and a 8000 mm^2 outlet free area only satisfies 1/12th of the ventilation requirement of a typical classroom in mid-year conditions and with single-sided ventilation.

If the opening area and its position is not designed precisely to satisfy the required ventilation rate, excessive ventilation could lead to an energy penalty for buildings. Moreover, it is hard to provide Passive Stack Ventilation (PSV) with energy efficiency, effectiveness, and IAQ guarantee without controlling ventilation through ventilation demand control [15].

4.4. Climatic Adaptation

Trickle Ventilators and other single-sided openings are convenient in a moderate climate. However, there are some complications to using them in the winter period [31]. Nevertheless, Trickle Vents are essential for various floor heights between 2.5 m and 3.1 m in various heat gain cases in winter conditions [49]. Moreover, pressure-controlled Trickle Vents have some superiorities in comparison with slot ventilators in the heating season when temperature differences are comparatively higher, since they supply more constant and relatively less air flow in high pressure differences ($\Delta P > 10$ Pa) and supply more air flow in low pressure differences ($\Delta P < 10$ Pa) [45].

Due to lower temperature differences between indoors and outdoors, thin and tall openings would be more effective in summer cases. Therefore, the vertical Trickle Vent design as part of a curtain wall frame produced by Metal Yapi shall be more beneficial in summer cases [32].

The application of Trickle Vents in San Francisco Federal Building apparently gives another perspective regarding climate. Wood A and Ruba Salib mention that occupants tend to use Trickle Vents instead of windows to prevent cold draughts in the winter term. On the other hand, since the climate gives the opportunity to have night cooling in summer times, the Building Management System (BMS) opens Trickle Vents to decrease the cooling load in this project [70].

4.5. Control Strategy

The most significant effects on ventilation performance come from the wind velocity, airtightness level of the building, number of the occupants and schedule of occupancy, and other wind-related parameters. Available control options are classified in CIBSE Guide B2—Ventilation and Ductwork [49] as manual control, humidity controlled, pressure controlled, and pollutant controlled (smoke, CO_2, CO). However, the ventilation requirement is mainly tracked and controlled by the change in relative humidity or CO_2. Tracking relative humidity has some negative impacts due to being dependent on many parameters such as ventilation rate, outdoor climate conditions, and hygroscopic buffering. However, CO_2 change is only dependent on the number of people inside, in contrast to relative humidity [10,28].

Cristina Cornaro mentions that the best method of ventilation evaluation in her study is CO_2 concentration generated by occupants [12].

The control strategy of Trickle Vents is based on the change of indoor CO_2 concentration in the research by Lavarge, J. et al. It was assumed that the outdoor CO_2 concentration was 350 ppm. In addition to this, indoor air quality is considered acceptable for a CO_2 concentration lower than 600 ppm according to EN 13779 [11]. A set point was arranged at 1000 ppm, which is the most common set point in buildings. If there is less CO_2 than 1000 ppm, the opening size of the Trickle Vents is reduced to 10% of the actual size. The main target is satisfying 36 m^3/h per person, which is specified in IDA 2 in EN 13779. On the other hand, 11.875 L/h/met CO_2 production and 34.375 g/h/met moisture production should be considered for simulations with respect to BS EN 15251 [10,73,74].

Even though there is robust heat loss, there is greater saving potential in a CO_2-based control strategy compared to other control strategies for the use of Trickle Vents as ventilation apparatus [10].

Trickle Vents and windows connected with a BMS (Building Management System) are controlled with respect to indoor temperature, wind velocity, and its direction. The BMS can collect pressure data to determine windward and leeward sides in order to conclude whether there is sufficient air flow potential through or not during the cooling season. Thus, the BMS gives an order to have additional air by means of Trickle Vents. Furthermore, the BMS opens only Trickle Vents to provide an adequate amount of air flow in the case of stormy weather [70].

DCPV (Demand-Controlled Passive Ventilation) requires experimental investigation according to Southall R.G. [15].

G. Guyot et al. mention that there are substantial energy savings of up to 60% from the use of DCV (Demand-Controlled Ventilation) with the right control strategy. Besides this, there would be 26% additional energy consumption in some cases [1].

Caillou et al. investigated 35 different DCV systems with different control strategies in Belgium. The most IAQ-friendly and energy-efficient system was found to be supplying air through Trickle Vents and other additional systems while controlling humid areas through relative humidity and dry areas through CO_2 concentrations [1,75].

Savin, Jean-Luc et al. [76] investigated relative-humidity-controlled Trickle Vents, demand-controlled exhaust units in wet rooms, and centralized fans connected with these units in order to determine the performances in terms of energy efficiency and indoor air quality aspects through in situ monitoring in living rooms and bedrooms of dwellings. The sensor measurements were obtained instantly by means of Wi-Fi [1]. The article presents a correlation between CO_2 levels and humidity levels for toilets, bathrooms, and kitchens. The study claims that the absolute humidity level (g/m^3) is correlated with CO_2 levels in toilets (Figure 11). The CO_2 concentration was measured on an hourly basis as a complementary study in a low occupied bedroom (1 adult) and a high occupied bedroom (4 adults) for a one-year period (Figure 12). It is apparent that the system satisfies 1500 ppm even in the high occupied bedroom except for a few hours [76]. However, the paper does not consider the volume of air in the rooms, which will have a significant impact on the CO_2 concentrations.

Figure 13 illustrates that relative-humidity-controlled Trickle Vents tracked pretty well in the changes of relative humidity values in a bedroom under 10 Pa pressure difference over one week of monitoring [76].

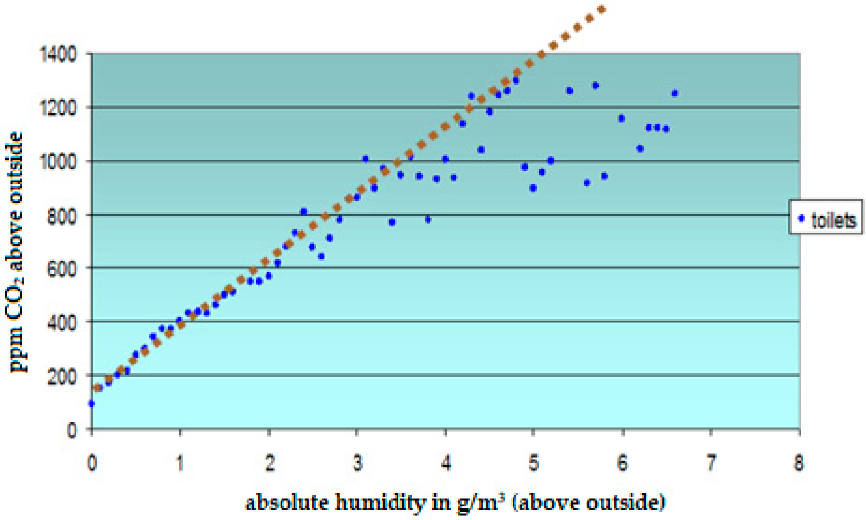


Figure 11. Correlation between CO_2 and absolute humidity in toilets [76].

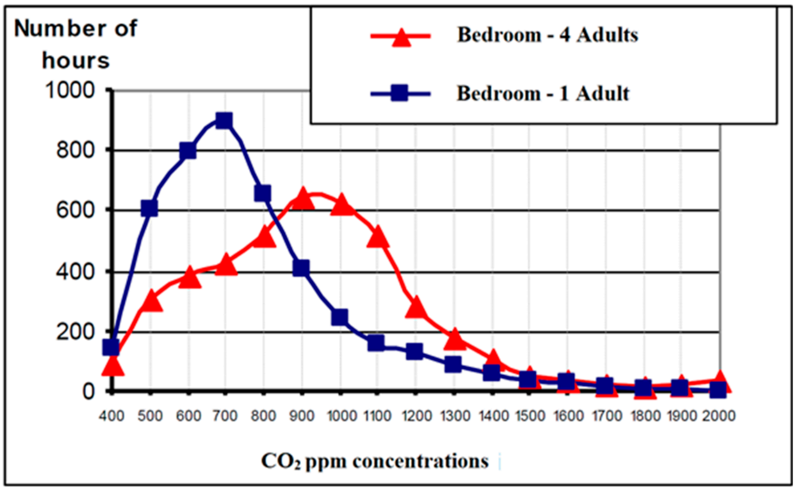


Figure 12. Hourly CO_2 concentration measurements in two different bedrooms with low occupancy (1 adult) and high occupancy (4 adults) periods annually [76].

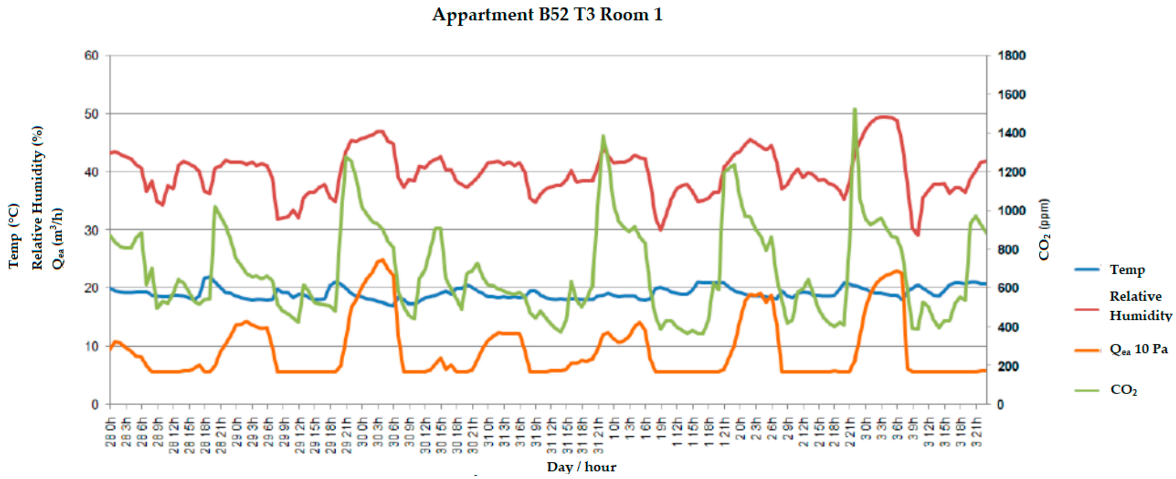


Figure 13. CO_2, temperature, Q@10Pa, and relative humidity distribution during one week of monitoring [76].

Since airflow was supplied not more than required due to control of IAQ by considering change of relative humidity, there were considerable energy savings between 30% and 55% in the winter case by avoiding additional heat loss [76]. Simply relative-humidity-controlled Trickle Vents without hybrid ventilation would determine the performance in a clearer way.

4.6. Ventilation Performance

According to some reports, 40% of all energy consumption occurs in dwellings. Furthermore, it has been predicted that 57% of overall energy usage in dwellings is consumed for heating and cooling spaces [10,77]. Optimization to determine the required air flow rate is crucial, since excessive ventilation causes an energy penalty as well as leading to insufficiency in ventilation and poor IAQ [78].

The most conventional way to indicate ventilation performance is to use the geometric free area or equivalent ventilation area according to BRE-1998 [49,79]. The equivalent ventilation area is the most realistic method to measure the air flow rate because Trickle Vents with the same equivalent area have the same airflow capacity even if they have different free areas [49]. Besides this, the most frequently used method to measure air flow rate is described in the EN 13141-1 standard [59], according to which air flow rate values should be determined under 1, 2, 4, 8, 10, 15, 20, 30, 40, 60, 80, and 100 Pa pressure differences.

The building ventilation rate is determined by considering Table 6. These values should not be lower than 0.3 L/s per m^2. In addition to this, the occupancy is assumed as two persons in the main bedroom and one person in other bedrooms. In the case of higher occupancy, 4 L/s should be added for each additional person [40].

Several commercial brands present the air flow rate of their product with respect to 1, 2, 10, and 20 Pa pressure differences. Some commercial brands prefer to only present the equivalent area to illustrate ventilation performance [80].

A performance measurement comparison of a Trickle Vent between testing and CONTAM software is illustrated in Figure 14. Besides this, test results of the air flow rate of a Metal Yapi horizontal Trickle Vent according to EN 13141-1 are given in Figure 15 for each meter length [14].

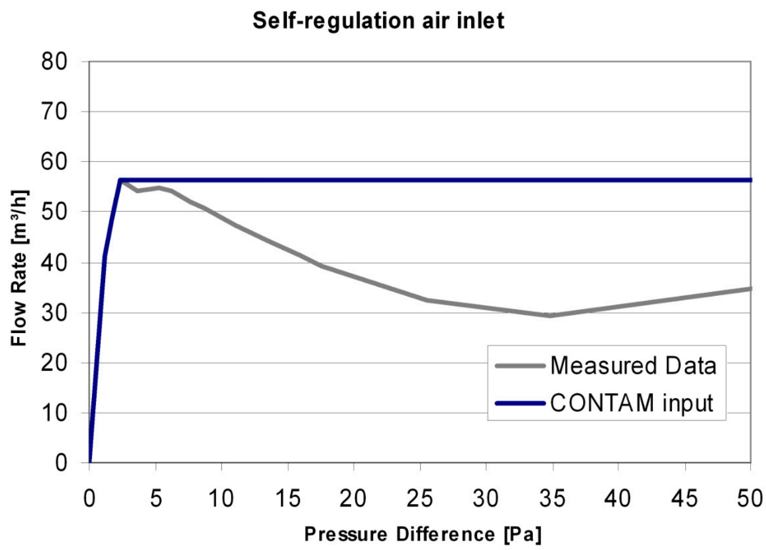
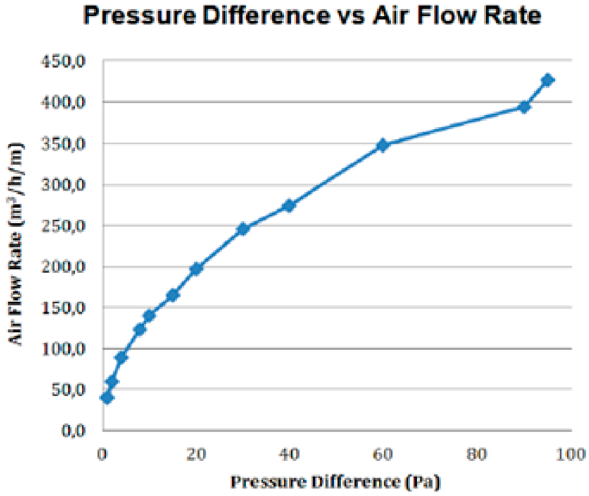


Figure 14. Comparison of Trickle Vent performance through CONTAM and experiment [78].

P. Karava et al. [45] conducted a study to determine the ventilation performance comparison of slot- and pressure-controlled Trickle Vents based on ASTM E783 [81] as illustrated in Figure 7.

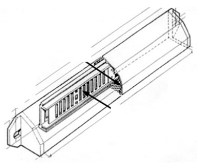
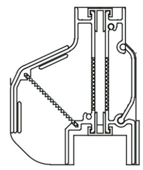
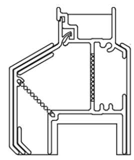
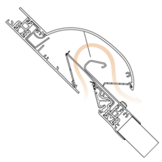
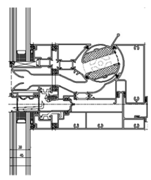
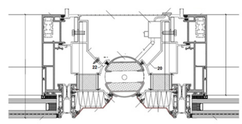
The ventilation capacities of various randomly chosen products in the market are illustrated in Table 7. Some of the Trickle Vent brands give equivalent area information instead of airflow rate in their technical data sheets.



Pressure Difference IN-OUT (Pa)	Air Flow Rate (m^3/h /m)
1	41.0
2	60.0
4	88.9
8	123.7
10	140.5
15	165.4
20	197.3
30	245.9
40	274.0
60	347.6
90	394.5
95	427.6

Figure 15. Performance of Metal Yapi horizontal Trickle Vents [14].

Table 7. Ventilation capacities of randomly chosen various products under various pressure differences for each module in the market.

Geometry		n.a.		
Product	P. Karava et al. Pressure Controlled [45]	P. Karava et al. Slot Controlled [45]	RW Simon Airstrip 19000 [82]	RW Simon Airstrip 200 [83]
Air Flow Rate	27.0 m^3/h (20 Pa)	21.6 m^3/h (20 Pa)	168.5 m^3/h (20 Pa)	96.3 m^3/h (20 Pa)
Geometry				
Product	Renson Oxyvent (20 Pa) [80]	Renson AK80evo [84]	Metal Yapi Horizontal Trickle Vents [14]	Metal Yapi Vertical Trickle Vents [85]
Air Flow Rate	190.4 m^3/h (20 Pa)	70.6 m^3/h (20 Pa)	197.3 m^3/h (20 Pa)	241.9 m^3/h (10 Pa)

4.7. Thermal Bridging

The heat transfer rate of Trickle Vents as a building envelope element is discussed in this section. Its influence on thermal comfort and HVAC load is also discussed in Section 6 of this paper for each study or each case separately.

The thermal performance of Trickle Vent products is determined with respect to the EN 10077-2 “Thermal performance of windows, doors and shutters—Calculation of thermal transmittance” standard. Trickle Vents are generally thermal bridge areas compared to the surrounding building envelope components. Therefore, design should be carefully considered from the thermal aspect. The Time-Lapse Thermography for Building Defect Detection study by Fox M. et al. indicated that the Trickle Vent zone of a building surface was 6 K warmer due to heat escape by means of air leakage (Figure 16) [86].

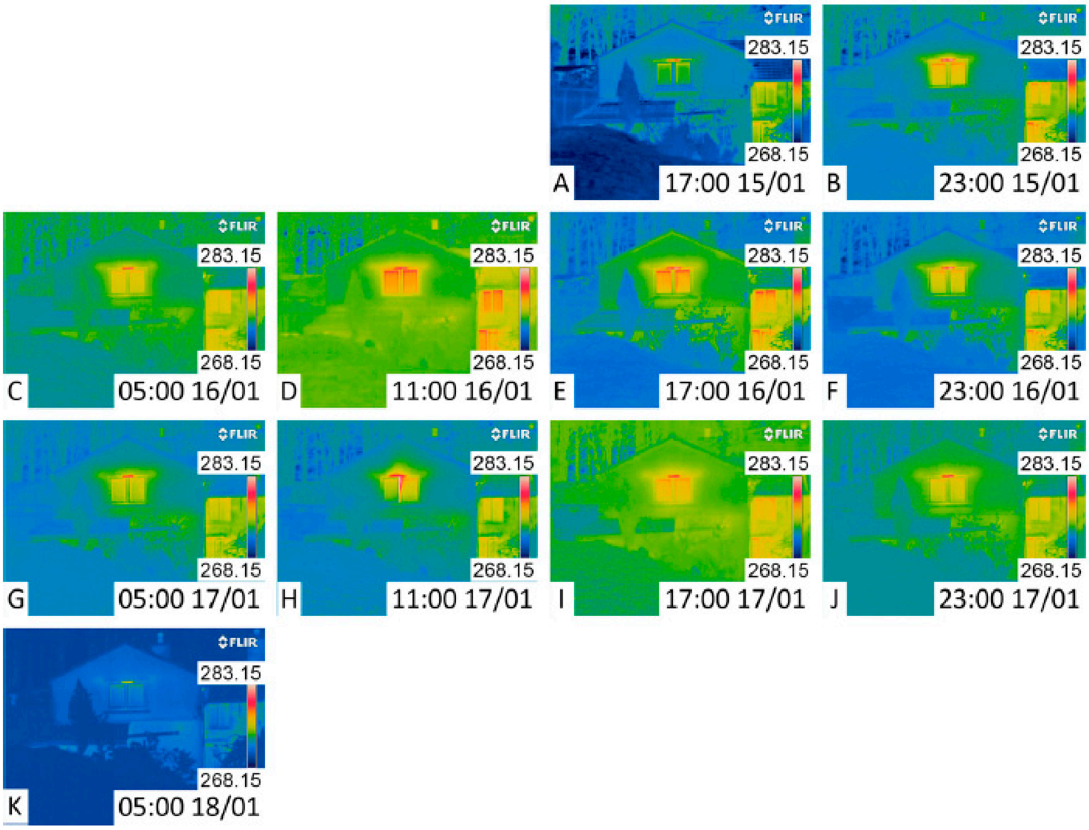


Figure 16. Thermographic images of a building envelope taken every 6 h [86].

4.7.1. Risk of Condensation

Condensation prevention is highly crucial to keep materials sustainable, to conserve them from corrosion and other environmental effects, and to supply visual aesthetics in building envelopes. Energy efficiency in buildings has also a significant role in decreasing environmental pollution as well as in the minimization of initial cost and operating cost. Moreover, high energy efficiency without condensation risk in building envelopes is highly essential to supplying thermal comfort conditions in the indoor environment with lower cost [87].

There is a condensation risk assessment study of various Trickle Vents in a study by Biler [14]. The condensation risk analysis shown in Figure 17 is for Vertical Trickle Vents with discontinuous brackets. Since the project was in Moscow, the outdoor temperature was assumed to be −28 °C which is actually quite challenging in terms of condensation risk. Additionally, the indoor temperature was assumed to be 20 °C and with 50% relative humidity. If there is 20 °C and 50% relative humidity indoors, the corresponding dew point is 9.3 °C according to calculation based on the August Magnus approach [88]. The minimum temperature on an aluminium surface is 11.2 °C, which is greater than 9.3 °C. Therefore, there is no condensation risk on aluminium surfaces. The analysis was done through the Trisco 3D steady-state heat transfer program.

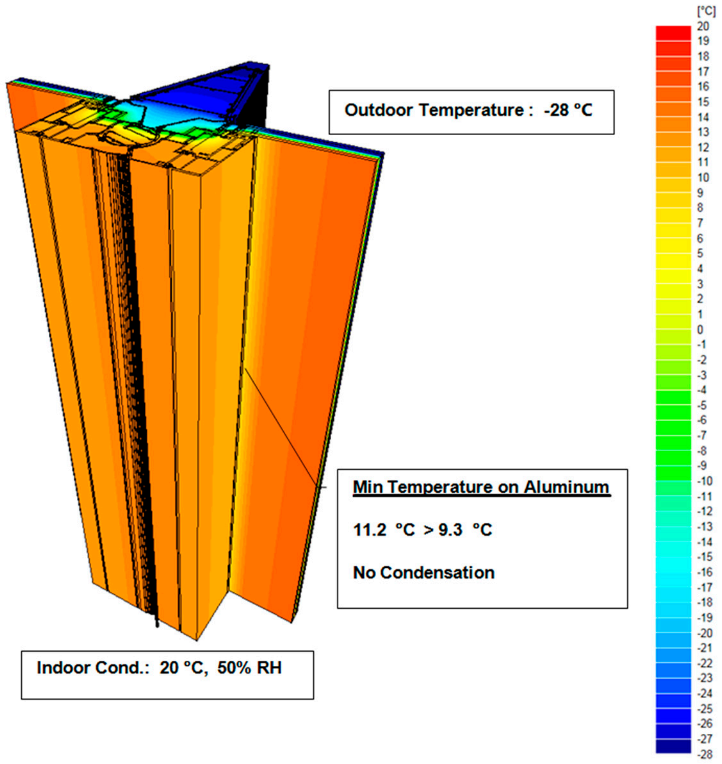


Figure 17. 3D steady-state heat transfer analysis of a vertical Trickle Vent [14].

4.7.2. U Value

Thermal transmittance values (U_f values) of Trickle Vents are calculated according to the EN ISO 10077-2 [65] standard. The main formula [89] used to calculate the frame component is given below (Figure 18).

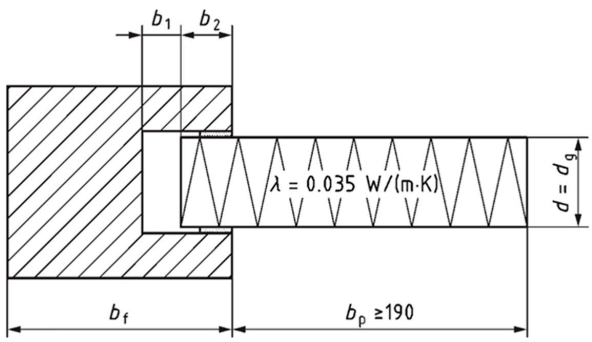


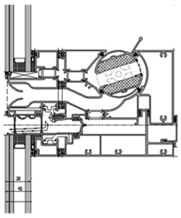
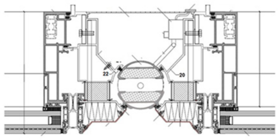
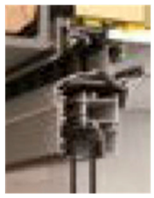
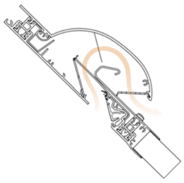
Figure 18. The view of frame and installed panel section in EN 10077-2 [65].

$$U_f = \frac{L_f^{2D} - U_p b_p}{b_f} \tag{7}$$

U_f: Thermal transmittance of the frame section, in (W/m^2 K);
Lf^{2D}: Thermal conductance of the section (W/mK);
U_p: Thermal transmittance of the center of the panel (W/m^2 K);
b_p: Visible width of the panel (m);
b_f: Projected width of the frame section (m).

Different U values for vents on the market are specified in Table 8. Trickle Vents integrated into curtain walls are mostly presented in the technical datasheets of various brands.

Table 8. U values of various brands in the market.

Geometry			
Product	Metal Yapi Horizontal Trickle Vent [85]	Metal Yapi Vertical Trickle Vent [85]	Renson Invisivent^{EVO} [90]
U Value	2.1 W/m^2 K	2.7 W/m^2 K	2.8 W/m^2 K
Geometry			
Product	Renson Oxyvent [80]	Renson AK80^{EVO}/4 [84]	
U Value	2.8 W/m^2 K	2.1 W/m^2 K	

4.8. Acoustic Performance

Trickle Vents with higher acoustic performances usually lead to higher pressure drops [49]. Furthermore, "effective area" and "equivalent area" are the most common ways used to determine acoustic effectiveness [49,79].

The Sound Insulation levels ($D_{n,e}$) of Trickle Vents and other air transfer devices are determined according to EN 20140 [59,60]. Even though the EN 13141-1 standard recommends calculation of acoustic performance with the $D_{n,e}$ value, some brands prefer to announce it with the R_w value which includes the overall curtain wall model. There is no specific minimum required sound reduction limit in EN 13141-1. Measurement should be conducted with maximum aperture.

$D_{n,e}$ (dB) is defined as the element-normalized level difference. The calculation formula is given below.

$$D_{n,e} = L_1 - L_2 + 10\lg\left(\frac{A_0}{A}\right) \tag{8}$$

L_1: Average sound pressure level—Source room (dB);
L_2: Average sound pressure level—Receiving room (dB);
A_0: Reference area (m^2) (for the lab, A_0 = 10);
A: Equivalent absorption area in the receiving room (m^2).

On the other hand, the R_w value, which is also known as TL (Transmission Loss in English-speaking countries), is the sound reduction index that is calculated with the formula below from measurements in the lab.

$$R = L_1 - L_2 + 10\lg\left(\frac{S}{A}\right) \tag{9}$$

L_1: Energy average sound pressure level—Source room (dB);
L_2: Energy average sound pressure level—Receiving room (dB);
S: Free test opening area where the test element is installed (m^2);
A is the area of equivalent sound absorption in the receiving room, in m^2 [91].

$D_{n,e}$ values of various Trickle Vent products on the market are given in Table 9 and R_w values are given in Table 10.

Table 9. $D_{n,e}$ values of various Trickle Vent products.

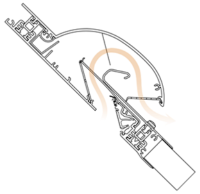
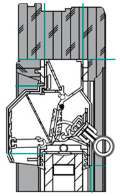
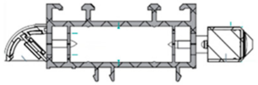
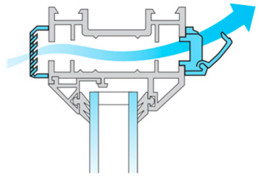
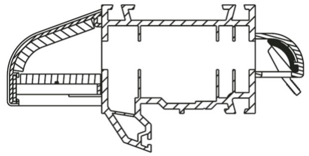
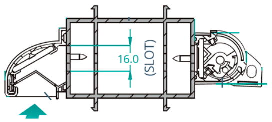
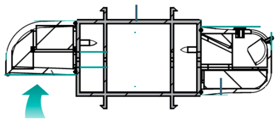
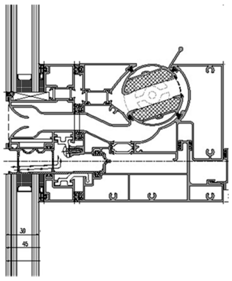
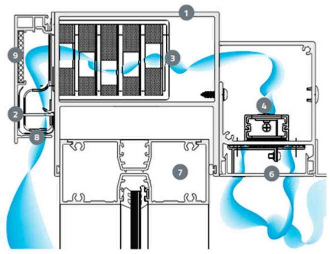
Geometry				
Product	Renson AK80^{EVO}/4 [84]	Renson Oxyvent [80]	Renson Invisivent^{EVO} [90]	Brookvent Airvent DG1500 [92]
$D_{n,e}$ **(dB)—Open**	33 (−1;−2)	27 (−1;−2)	27 (−1;−1)	28
$D_{n,e}$ **(dB)—Closed**	n.p.d.	40 (0;−2)	49 (−1;−1)	33
Geometry				
Product	Brookvent Airvent SM 1000 [44]	AmesburyTruth SM1200 [93]	Greenwood 8000HD [94]	R.W. Simon Acoustic F V [95]
$D_{n,e}$ **(dB)—Open**	29	30	31	33
$D_{n,e}$ **(dB)—Closed**	47	47	33	40
Geometry				
Product	Brookvent Airvent SM 1400 [96]	Brookvent SM Acoustic [97]	Titon Select S13 [98]	
$D_{n,e}$ **(dB)—Open**	32	40	33 (−1;0)	
$D_{n,e}$ **(dB)—Closed**	39	44	45 (−1;−2)	

Table 10. R_w values of various Trickle Vent products [14,99].

Geometry		
Product	Metal Yapi—Horizontal Trickle Vent	AWS Ventient Series fixed window 10.38 mm lam glass
R_w **(dB)—Open**	25.8	30
R_w **(dB)—Closed**	40.1	n.a

4.9. Air Permeability

Air permeability tests are conducted for Trickle Vents in the closed position according to EN 1026 [64]. Air leakage rates of various Trickle Vents in the market are specified in Table 11.

4.10. Water Tightness

Water tightness performance testing of Trickle Vents is based on EN 1027 [60]. Trickle Vents should be tested when they are completely closed [59]. Water spraying durations are shown in Table 12 for each test pressure differences.

The water tightness performance levels of various Trickle Vents in the world market are given in Table 13.

Table 11. Various Trickle Vent products and their air permeability rates in different pressure differences.

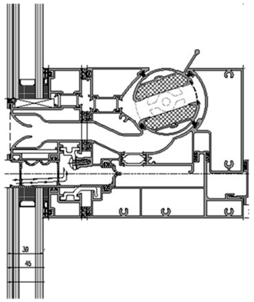
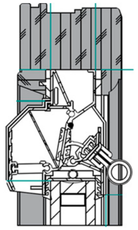
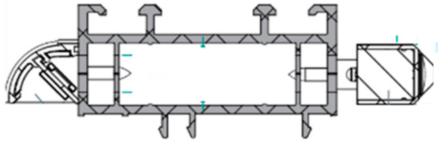
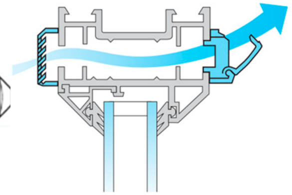
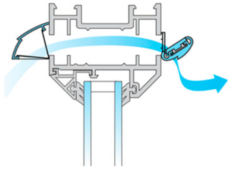
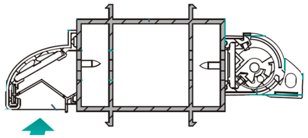
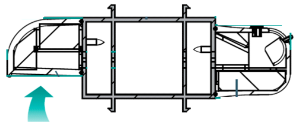
Geometry				
Product	Metal Yapi—Horizontal Trickle Vents	Brookvent Airvent DG1500 [92]	Brookvent Airvent SM 1000 [44]	Greenwood 8000HD [94]
ΔP	600 Pa	50 Pa	50 Pa	50 Pa
Air Flow Rate	1.5 m^3/h	1.5 m^3/h	0.5 m^3/h	2.6 m^3/h
Geometry				
Product	Greenwood 5000EA [100]	Brookvent Airvent SM 1400 [96]	Brookvent Airvent SM Acoustic [97]	
ΔP	50 Pa	50 Pa	50 Pa	
Air Flow Rate	0.6 m^3/h	1.1 m^3/h	15.5 m^3/h	

Table 12. Δ*P* and water spraying duration [59].

Pressure Difference between the Chamber and Exterior (Pa)	Duration of Water Spraying (s)
10	
20	
50	120
100	
150	

Table 13. Water tightness performance of various Trickle Vents.

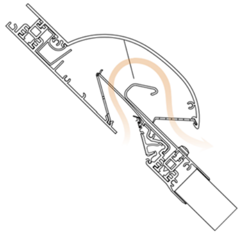
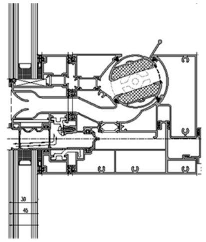
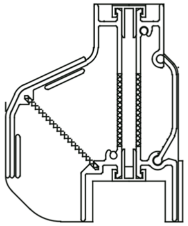
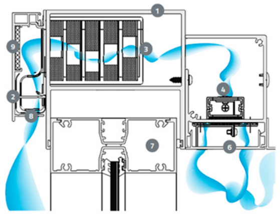
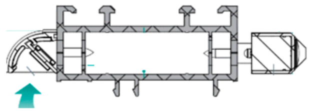
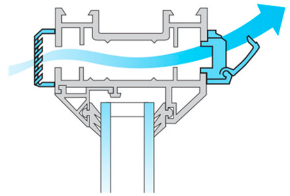
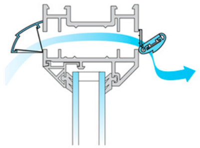
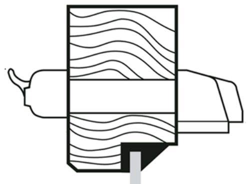
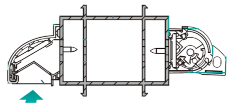
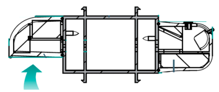
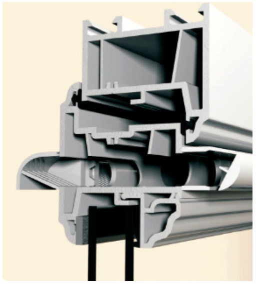
Geometry				
Product	Renson AK80EVO [84]	Renson Oxyvent [80]	Renson InvisiventEVO [90]	Metal Yapi Horizontal Trickle Vent [14]
Open (Pa)	50 Pa	50 Pa	50 Pa	n.a.
Closed (Pa)	650 Pa	650 Pa	650 Pa	600 Pa
Geometry				
Product	RW Simon Airstrip 19000 [82]	AWS Ventient Series with Soundout [99]	Brookvent Airvent SM 1000 [44]	Greenwood 8000HD [94]
Open (Pa)	n.a.	450 Pa	n.a.	n.a.
Closed (Pa)	600 Pa	n.a.	600 Pa	300 Pa
Geometry				
Product	Greenwood 5000EA [100]	RW Simon TFF Slimline [101]	Brookvent Airvent SM 1400 [96]	Brookvent Airvent SM Acoustic [97]
Open (Pa)	n.a.	450 Pa	n.a.	n.a.
Closed (Pa)	600 Pa	n.a.	600 Pa	300 Pa

Table 13. *Cont.*

Geometry	
Product	Titon Select S13 [98]
Open (Pa)	n.a.
Closed (Pa)	600 Pa

5. Modeling and Monitoring Techniques

Modeling and monitoring techniques regarding Trickle Vents are defined and evaluated in this section.

5.1. Modeling Techniques

"Modelling" is demonstrating real life conditions on a computer by using laws of physics, mathematics, and computational methods [102]. The main softwares used for modelling Trickle Vents in the literature are Computational Fluid Dynamics (CFD) softwares EnergyPlus and CONTAM.

CFD is the method used to simulate airflow behavior under various boundary conditions. Use of CFD has increased incredibly since 2002 due to having a user-friendly interface and reliable results, as well as being easier and cheaper in comparison with experimental methods [13,97]. EnergyPlus was developed to model and analyze whole buildings in terms of heating, cooling, lighting, and ventilation loads [103]. IAQ in multizone models, ventilation performance, contaminant concentrations, and personal exposures can be determined by means of CONTAM software [99].

Simulations in general require considerable running time and high system requirements.

EnergyPlus has outstanding performance to have different design alternatives rather than predicting energy consumption values. EnergyPlus has poor quality in terms of user interface and user friendliness. This software can be used along the life cycle of building including commissioning, design, and construction. Even though it consumes time, complex systems can be modelled in EnergyPlus [104].

CFD is mainly used to solve problems related with heat transfer and flow. It is cheaper and faster than experimental techniques even though it requires long running time and high system requirements. It allows us to theoretically simulate physical conditions. It also enables us to access results of various parameters in large numbers of locations, unlike experimental techniques. However, this technique might lead to numerical errors similar to truncation error or round-off error. Boundary conditions are quite critical to reaching reliable results [105].

CONTAM enables us to analyze and calculate contaminant concentration, smoke distribution, airflow rates, relative pressure between spaces, and IAQ-related issues for existing buildings and projects in the design phase [106]. Therefore, the number of inhabitants and their behavior, weather conditions, air permeability of the façade, pollutant parameters, dimensions and temperature data of the indoors, and many similar datapoints are required to reach reliable results [107]. CONTAM has some superiorities such as enabling very large and complicated building configurations, sophisticated duct system modelling, and more options to model air leakages in comparison with EnergyPlus in terms of airflow. When it comes to contaminant transport, CONTAM has some superiorities compared to EnergyPlus, like the ability to define limitless contaminants, sources, and sinks within the model; 1D convection/diffusion transport between zones and pipes; and CFD models with coupled zero-order turbulence in terms of contaminant transport [108].

When it comes to the performance of pressure-controlled Trickle Vents, the exterior flap leads to interior pressure variations; this type of vent is complicated. Therefore, experimental studies are required for such vent types [45].

5.2. Monitoring Techniques

"Monitoring" is observation and physical change through probes or sensors during a project, programme, or experiments [109]. It is also known as "field measurement" for a certain period. Tracer gas techniques and directly measuring the ventilation rate are two main techniques used to measure ventilation rate in the field. Section 5.2.1 in this paper presents how to calculate ventilation rates during monitoring [110].

J. C. Salcido et al. [111] specifies that the main limitation of simulation techniques is inconsistency between simulation performance and monitored (actual) performance. Concordantly, this research claims that energy savings in the actual case might not be as visible as savings in simulated conditions. There is also a gap in the literature concerning the difference between simulated performance and actual performance specifically for Mixed-Mode Ventilation.

5.2.1. Calculation of Ventilation Rate by Using Measurements

Occupant-generated CO_2 could be also used in a tracer gas technique to determine the ventilation rate of Trickle Vents, as Cornaro et al. presented in [12]. Two different methods can be applied as a tracer technique: the constant tracer gas method and the decay tracer gas method [12].

The constant tracer gas method is directly related with the state of equilibrium. CO_2 production and ventilation rates are two different parameters which are assumed in this method. The CO_2 concentration is assumed to be constant over time. Ventilation rates are calculated by using a mass balance equation as indicated below [12].

$$V = \frac{C_{gen}\left(\frac{\text{cm}^3}{\text{h.person}}\right).n(\text{person})}{C_{int} - C_{est}\left(\frac{\text{cm}^3}{\text{m}^3}\right)} \tag{10}$$

V: Ventilation rate (m^3/h);
C_{gen}: CO_2 generation by a person ($cm^3/(h{\cdot}person)$);
n: Number of persons;
C_{est}: CO_2 concentration outdoors (cm^3/m^3);
C_{int}: CO_2 concentration indoors (cm^3/m^3).

The reference data used to calculate Equation (10) are as follows. CO_2 production per capita is defined in EN15251 [74] as 19 L/h. Besides this, the outdoor CO_2 concentration is assumed to be 390 ppm based on CEN CR1752 [8]. The ventilation rate could be calculated as follows [12].

$$V = \frac{19,000\left(\frac{\text{cm}^3}{\text{h}\cdot\text{person}}\right).n(\text{person})}{(C_{int} - 390)\left(\frac{\text{cm}^3}{\text{m}^3}\right)}$$

Furthermore, the tracer gas decay method is used to determine the performance of Trickle Vents systems when there is no source of CO_2 indoors. Decay in the CO_2 concentration after a certain time can be explained by the equation below [12].

$$ln\frac{C(t) - C(o)}{C(0) - C_{out}} = at \tag{11}$$

$C(0)$: Indoor CO_2 concentration at t = 0 (cm^3/m^3);
$C(t)$: Indoor CO_2 concentration at t = t (cm^3/m^3);
C_{out}: Outdoor CO_2 concentration (cm^3/m^3);
α: Air change rate (h^{-1}).

It can be used with the measurements of indoor concentration at two different times; the average specific air flow rate at a particular time is determined using Equation (11) with the h^{-1} expression [112].

6. Studies of Trickle Vent Performance and Their Results

Simulation, experimental, and survey studies about draught risk and cost studies are reviewed in this section.

6.1. Simulation Studies about the Effect of Trickle Vents and Their Control

Computer simulations and measurements do not perfectly superpose each other due to actual occupation, metabolic rate, and window openings varying compared to the design case [26]. This implication is discussed in Section 5.2 in this paper.

Simulation studies with EnergyPlus, CONTAM, and CFD software tools are presented in this section.

6.1.1. EnergyPlus

Passive stack ventilation (PSV) and Demand-Controlled Passive Ventilation (DCPV) performance of Trickle Vents were evaluated by means of EnergyPlus in R.G. Southall's research [15]. The model dimension is 9 m × 6 m × 2.85 m for each two floors in the model. The U value of the walls is 0.113 W/m^2 K, which is typical for lightweight insulation, and the U value of the glazing is 0.77 W/m^2 K, which is typical of argon-filled, low-e, triple-glazed windows. These values could apply to standard low-energy homes. The designed occupancy is two adults and two children who emit 80 W per person internal gain and 3.82×10^{-3} CO_2 production rate, as specified by ASHRAE 62.1 [13]. the additional internal gain is 2.1 W/m^2 K, as declared in the PassivHaus [113] standard. Besides this, the Trickle Vents are sized considering U.K. building regulations which are 72,000 mm^2 in total and 8250 mm^2 per external wall section. Air leakage ratings with 0.6, 1, 2, and 3 ACH (air change per hour) @50Pa are assumed as well as the three different climates of Porto, Plymouth, and Bergen in the model separately. There are 12 different simulation results considering 3 different locations and 4 different air leakage ratings. The CO_2, humidity level, and temperature of each space is tracked by means of the EnergyPlus run-time language (EMS). The control strategy in DCPV is opening in the case of a CO_2 ratio in excess of 800 ppm and closing below that concentration. In addition to this, trickle vents are opened in case of exceeding 24 °C or 70% RH, regardless of the indoor CO_2 concentration. On the other hand, trickle vents are only closed when the CO_2 level is below 300 ppm in PSV. Moreover, the heating set-point is 20 °C.

The results of this study indicate that the average wind speeds of climates influence the results significantly more in comparison with temperature differences in different seasons. While the flow rates are the highest in Plymouth, which has the relatively highest wind speed, the lowest stack flow is obtained in Porto, which has the lowest wind speed and temperature differences. Since the increase in the fabric leakage level is not parallel to the stack flow rates, from the outcomes can be concluded that the stack sizing in U.K. regulations is quite appropriate. Average vent flow at the ground floor ranging between 78 and 105 m^3/h is considerably higher than that at the first floor, ranging between 22 and 50 m^3/h in PSV. The average ventilator inflow at the ground floor ranging between 30 and 44 m^3/h is slightly higher compared to that at the first floor with 20 and 40 m^3/h in DCPV; DCPV shows more consistent results, contrary to the extreme differences in PSV. Outflow from the first floor is considerably decreased from a 20 to 30 m^3/h range to a 0 to 2 m^3/h range in DCPV with efficient control. DCPV takes a longer time to evacuate CO_2. The PSV system exceeds the 1000 ppm CO_2 limit in the least windy and warmest climate (Porto). Relative Humidity levels are never higher than the 70% RH needed to lead Trickle Vents to open in the DCPV case. The highest energy savings are achieved in the coldest climate (Bergen) with 25 kWh/m^2 in DCPV. The heating load decrease is between 40 and 95% in DCPV compared with PSV. The windward side leads to a greater heating load in cold weather due to having excessive ventilation. The positioning of the trickle ventilator is crucial to preventing cold draught, which affects thermal comfort.

A DCPV system might be used to follow other pollutants. Experimental studies might give more reasonable and reliable results.

6.1.2. CFD

Computational Fluid Dynamics (CFD) is the method used to simulate airflow behavior under various boundary conditions. Use of CFD has increased incredibly since 2002 due to having a user-friendly interface and reliable results, as well as being easier and cheaper in comparison with experimental methods [18,114].

K. Arendt and M. Krzaczek modelled 0.02 m × 1.50 m Trickle Vents as inlet ducts in their CFD simulation, which is quite rough [77]. The air inlet velocity was defined as 0.6 m/s with 19 °C temperature, which corresponds to 1 h^{-1} ACH. Moreover, the air inlet temperature was defined as −10 °C in another case. The assumed internal gain indoors was 6.15 W/m^3 between 7 a.m. and 5 p.m. and 1.54 W/m^3 at nights. Various numbers of meshes were tried, from 2900 up to 28,100, in order to reach the most realistic model. The finest mesh was 15 times more time consuming compared to the coarsest one. While a major amount of air followed the upper side of the closed area in the 19 °C air inlet case, the air dropped instantly and followed the bottom side in the −10 °C case, as illustrated in Figures 19 and 20. The surface heat transfer coefficients were determined to be h_{cn} = 1.83 W/m^2 K (19 °C case) and h_{cf} = 5.03 W/m^2 K (−10 °C case) as a result of simulations, unlike the surface heat transfer coefficient of h = 7.7 W/m^2 K specified in ISO 6946 [115].

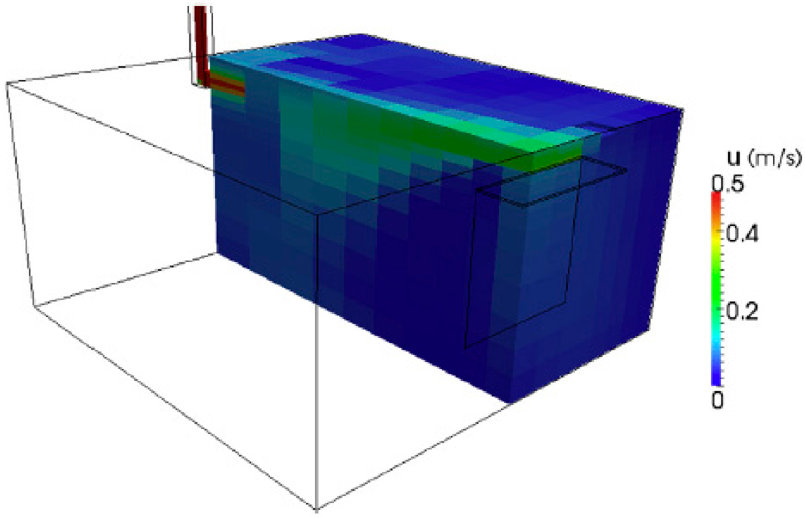


Figure 19. Air velocity distribution found using computational fluid dynamics (CFD) [77].

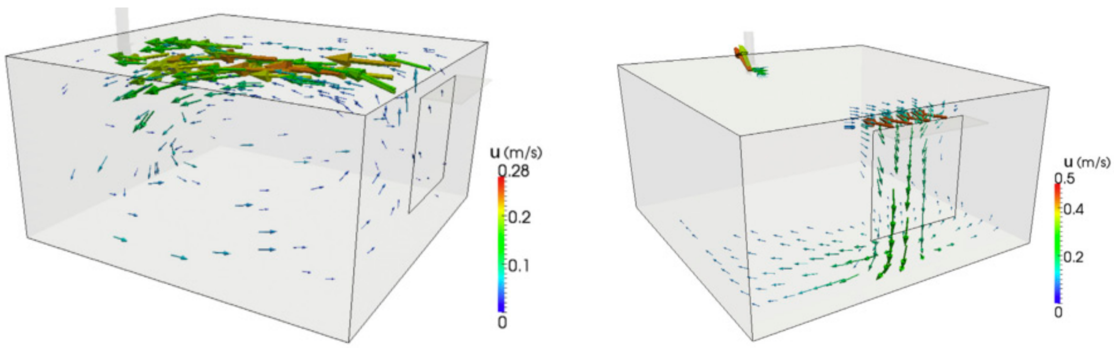


Figure 20. Air inlet with 19 °C (**left**); −10 °C (**right**) [77].

This study investigated the indoor environment of a house rather than the performance of Trickle Vents itself. Apart from this study, there has been no significant CFD study to determine the performance of Trickle Vents individually. The main limitation is the model itself does not focus on Trickle Vent performance. Moreover, it is hard to precisely simulate outdoor conditions, which are another crucial parameter in natural ventilation. This is another major limitation in this method.

6.1.3. CONTAM

IAQ in multizone models, ventilation performance, contaminant concentrations, and personal exposures can be determined by means of CONTAM software [116]. Manual Trickle Ventilators which simply allow discharge are modelled in CONTAM based on Relative Humidity Demand-Controlled Ventilation (DCV) and in a standard Belgian dwelling by Van Den et al. [78]. The results of the analysis are compared with simply discharge, constant-airflow vents. The modelled occupancy is four persons including two children in Uccle, Belgium. Airflow is controlled in the range of 20%–100% opening as parallel to the 30–100% RH range in humid rooms with two switch levels. The performance of Trickle Vents (Self-Regulating Inlet) that are applied to dry rooms is illustrated in Figure 14. The airflow rate becomes stable when it exceeds 6.5 Pa. Results indicates that the IAQ is somewhat worse than in each CO_2-IDA class of EN 13779 [11] and the LKI_{1200} index of the NEN 8088. In addition to this, time percentage is used as an indicator of when RH is not in the 30% to 70% range; DCV is in this interval 67% of the time while the reference system is in it 90% of the time. Moreover, the main outcome of this research is that there is a 1100–1200 kWh energy saving potential that corresponds to 27% for an airtight dwelling and 14% for standard airtightness [1].

6.2. Experimental Studies about the Effect of Trickle Vents

Kolokotroni, M. et al. conducted an experimental study for 14 days to determine the performance of Trickle Ventilators in terms of ventilation rate, air velocity, and temperature in two different mock-up rooms. Office A had single-sided ventilation with a trickle ventilator that has 5000 mm^2 openable area. Office B had cross ventilation with a trickle ventilator that has 7000 mm^2 openable area by using 400 mm^2 per m^2 criteria in an office area similar to Office A. Trickle ventilators were shut during the first week. They were open in the second week. The internal air velocity was tracked using ultrasonic anemometers at desk height and ankle height in order to measure whether there was potential for air draughts or not. The air velocity was significantly lower than 0.3 m/s, which is the limit value to not feel cold draughts in the heating season at both desk height and ankle height (Figure 21) [41].

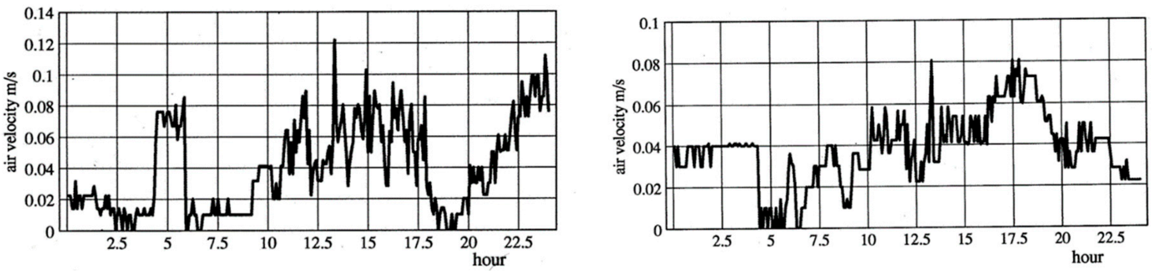


Figure 21. Air velocity distribution at desk height (**left**) and ankle height (**right**) [41].

Moreover, CO_2 concentrations were never higher than 1000 ppm while Trickle Vents were open during the second week (Figure 22). The value of 1000 ppm corresponds to a 5 L/s per person ventilation rate in an occupied area. On the other hand, Figure 22 clearly shows that the CO_2 concentration is increased considerably reaching the corridor level in the case when trickle ventilators are in the closed position [41].

In spite of the cold outdoor weather and trickle vents being open in the second week, the average indoor temperature was at close to the same level [41].

The study demonstrates that Trickle Vents with 400 mm^2 per m^2 floor area can a supply sufficient amount of fresh air for an 8 m^2 per person office environment, as well as providing good IAQ. However, there is a lack of analysis in regards to comparison of single-sided ventilation and cross ventilation in this research [41].

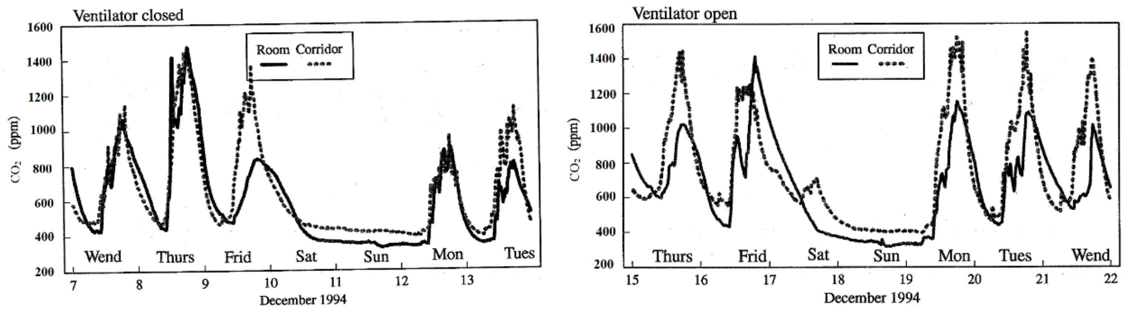


Figure 22. CO_2 distribution—Office A with ventilators closed (**left**); Office B with ventilators open (**right**) [41].

Secondly, since the exterior flap leads to interior pressure variations, simulation of pressure-controlled background vents is complicated. Therefore, experimental studies are required for such vent types [45].

A monitoring study was conducted in a classroom with 30 students located in East London for five days in March. The classroom has five coupled upper and lower windows and two trickle vents. The change in CO_2 ratio was tracked by using a nondispersive infrared CO_2 sensor. Trickle Vents were the only sources of ventilation in the first day. Even though the classroom was not fully occupied all day long, the average CO_2 ratio was measured as 1504 ppm, which is slightly higher than the limit (1500 ppm) specified in the paper (Figure 23). Purge ventilation for 10 min was applied two times on the Tuesday. The mean concentration of CO_2 was 1691 ppm, which is higher than the limit (Figure 23). Moreover, 10 min purge ventilation led to a 1000 ppm decline in the CO_2 level in the classroom. On the other hand, the room temperature decreased 3 °C during purge ventilation, which is not good for thermal comfort. Upper windows were left open throughout the day on Wednesday. This case caused a thermal comfort problem. Adaptive control by occupants was preferred on Thursday and Friday. The mean CO_2 concentrations on Wednesday, Thursday, and Friday were 735 ppm, 691 ppm, and 1208 ppm, respectively. It can be concluded that Trickle Vents alone are not adequate to satisfy the ventilation requirement in the classroom according to BB 101 [26,32].

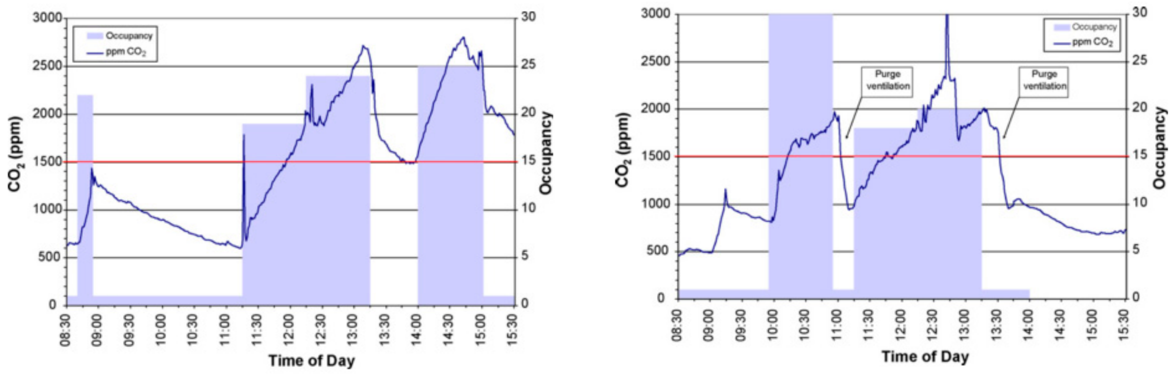


Figure 23. CO_2 and occupancy levels (Monday (**right**), Tuesday (**left**)) [26].

In order to determine the performance of Trickle Vents, all the vents were shut on Night 1. All the vents except Trickle Vents were shut during Night 2. This study illustrates that the ventilation rate of Trickle Vents is 0.75 L/s per person. This rate is not sufficient by itself to satisfy the required ventilation. Besides this, night cooling leads to additional energy loss in the heating season, although it helps to diminish the CO_2 concentration in the classroom [26].

Cornaro et al. carried out a comprehensive monitoring study in eight different classrooms in Rome. The main target of the study was short-term and long-term CO_2 concentration and temperature monitoring of the classes in order to evaluate the ventilation performance of Trickle Vents in the 2009/2010 scholastic year and for four days in February 2010. Trickle Vents were positioned over shutters as shown in Figure 24. Trickle Vents were controlled by means of an automation system. Trickle

Vents were closed below 800 ppm and opened in cases exceeding 1000 ppm. There was also one window behind the hall opening which was left opened consistently. A weather station was constructed in order to track ambient wind speed, wind direction, temperature, and humidity. Long-term measurements of the indoors and outdoors were obtained each half hour. Besides this, short-term measurements were obtained in 1 min intervals in February. Pupils were also used to eliminate extraordinary days in terms of activities, the number of pupils entering and exiting, and operation of windows [12].

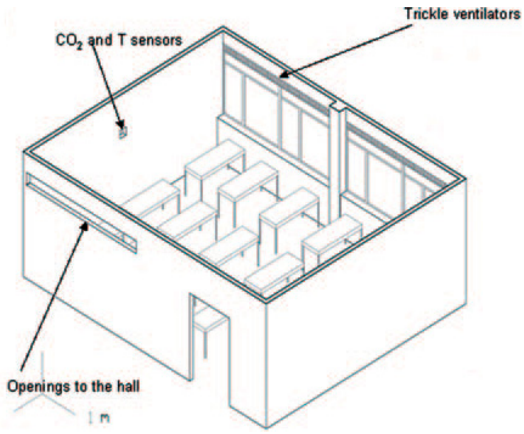


Figure 24. Typical classroom [12].

Ventilation rates were determined with respect to generated CO_2 by occupants, which is used as a tracer gas. The constant tracer gas method and decay tracer gas method were used as calculation methods; these are described in Section 5.2.1 in this paper [12].

The average indoor temperature between 08:00 and 15:00 throughout the 2009–2010 scholastic year is illustrated in Figure 25. Moreover, 20 °C was not achieved in the major part of the heating season. This situation demotivates occupants to control windows for air change.

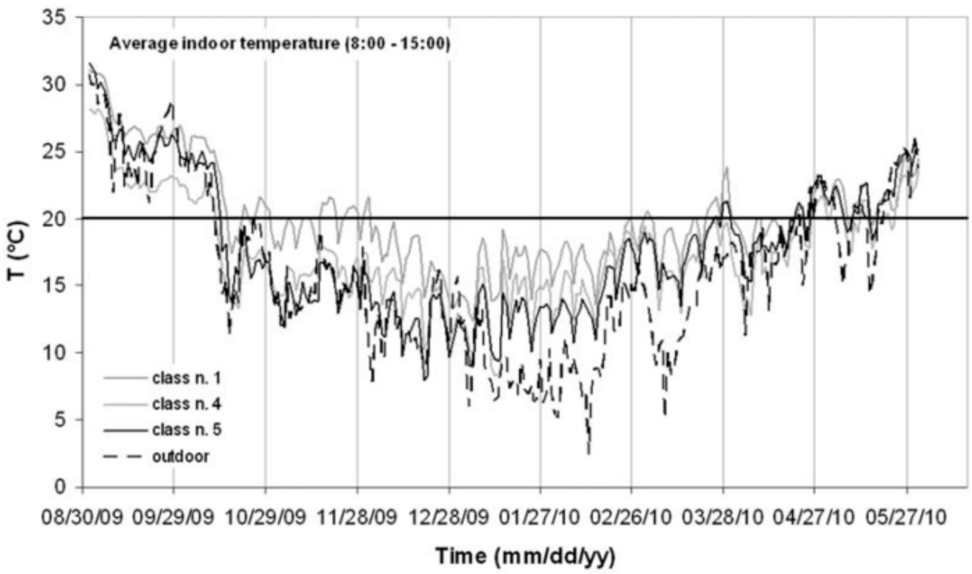


Figure 25. Average temperature throughout the 2009–2010 scholastic year [12].

Moreover, the average CO_2 concentration is shown in Figure 26. A limit of 1500 ppm was chosen for the CO_2 concentration, as indicated in U.K. standards. The classrooms on the ground floor exceeded this relatively more often in comparison with classrooms on the first floor due to wind. Besides this, there is also correlation between CO_2 concentration and indoor temperature as seen from Figure 27.

Trickle Vents applied in the southeast benefitted the most and those in the southwest benefitted the least, considering the wind directions shown in Figure 28.

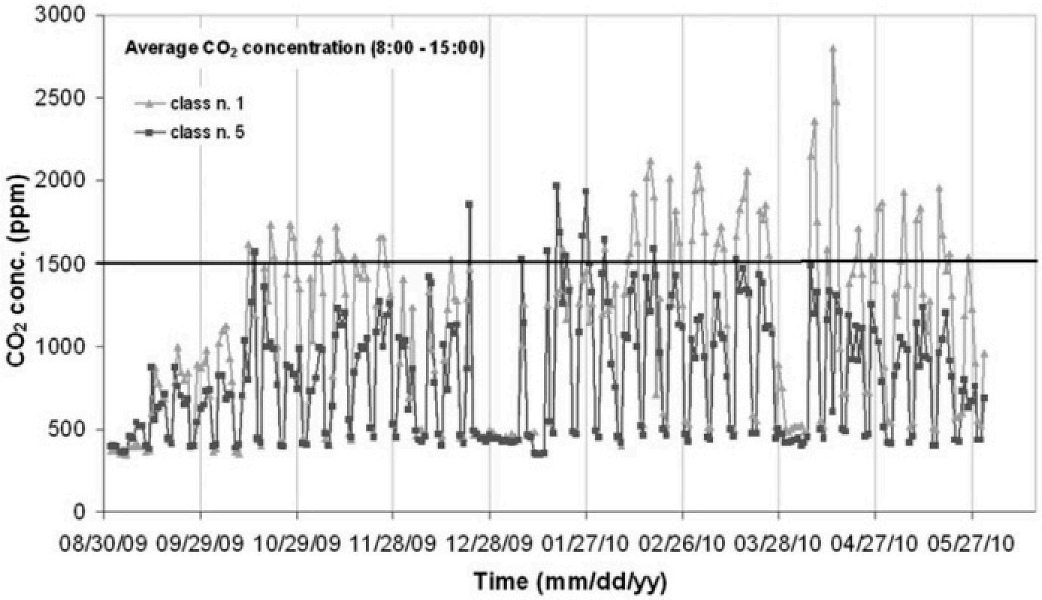


Figure 26. Average CO_2 concentration throughout the 2009–2010 scholastic year [12].

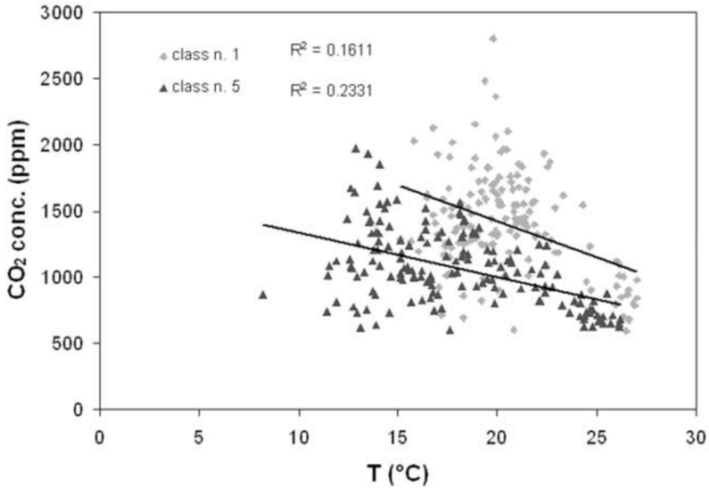


Figure 27. Correlation between temperature and CO_2 concentration [12].

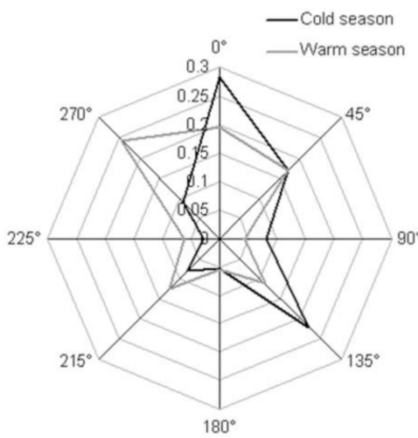


Figure 28. Wind directions in the warm season and the cold season [12].

Probes took measurements in one-minute intervals in short-term monitoring. Since the direction and velocity of wind vary, the average daily CO_2 concentration for all classrooms was highest on 16 February and lowest on 19 February. The highest and lowest CO_2 concentration days clearly indicate the most and least efficient directions of wind in terms of IAQ.

Even though the effectiveness of Trickle Vents gave good results and considerable consistency with long-term and short-term evaluations, the questionnaire part of the study, which actually has big potential, was quite limited. Trickle Vent openings are apparently not adequate for the designed spaces. Designing Trickle Vent openings with appropriate direction could lead to a more effective ventilation strategy in the school where study was conducted.

6.3. Survey Studies about the Draught Risk of Trickle Vents

Survey studies conducted by Kolokotroni, M. et al. [41] indicate that there is no cold draught complaint from cold draughts during the use of only Trickle Ventilators in the heating season. This is probably largely because of the designing of Trickle Vents to direct incoming air upwards.

Cornaro et al. carried out a daily questionnaire among pupils to get reliable data more easily during their monitoring study regarding the determination of Trickle Vent ventilation performance. The daily questionnaire was about student's entry and exit, control of windows, and occupancy activities. Sudden changes in CO_2 concentrations were highly correlated with questionnaires and measurement results [12]. However, the questionnaire is not given in detail. Besides this, the involvement of pupils could be more effective.

6.4. Costing

Biler et al. conducted a cost performance study by comparing the initial investment cost with mechanical ventilation in cases with and without Trickle Vents. The calculated savings were up to 46% in comparison with the case without Trickle Vents. Moreover, due to taking advantage of night cooling as well as savings from the reduction of mechanical ventilation capacity, there were also additional annual electricity cost savings of around $140,000 in an office building with 33 floors in Istanbul [4].

However, the study by Griffiths, M. and Eftekhari, M. indicates that a reduction of background ventilation in winter night scenarios leads to 635 kWh annual savings, which equals to £1000 per year. [26].

Literature review analysis shows that there has been no significant cost study in this field.

7. Summary and Conclusions

A literature review on Trickle Vents was conducted and concluded from the aspects of performance parameters, control strategies, positioning, etc., aiming to produce a comprehensive overview of this technology.

The main performance concerns of Trickle Vents are the ventilation rate, thermal insulation, acoustic resistance, water tightness, and air permeability. Burglar-proof performance is desired in some cases. Nineteen different Trickle Vents are reviewed from some of the performance aspects in this paper. The research indicates that ventilation performance is between 21 m^3/h and 242 m^3/h under 10 Pa pressure difference, thermal transmittance is between 2.1 W/m^2 K and 2.8 W/m^2 K, and acoustic resistance is between 27 dB and 40 dB in the open position and 33 dB–49 dB in the closed position for the reviewed products on the market. Furthermore, air permeability is between 0.6 m^3/h and 15.5 m^3/h under a 50 Pa pressure difference, and water tightness is between 50 Pa and 450 Pa in the open position and 300 Pa–650 Pa in the closed position for the related Trickle Vents. Since ultimate performance from one aspect leads to sacrifice in another performance criterion, an effective optimization study should be conducted by considering needs during the design phase.

The control strategy of Trickle Vents can affect their contribution to energy performance and thermal comfort in buildings significantly. This literature review study reveals that the major control strategy for Trickle Vents is based on the CO_2 concentration. The performance might also be investigated by considering other IAQ parameters such as relative humidity, NO_2, etc. Even though there are relative-humidity-based control studies, there are no significant conducted studies simply of Trickle Vents controlled by the use of other control strategies to ensure IAQ or energy efficiency.

Trickle Vents alone are not adequate to satisfy ventilation requirements in school buildings. Besides this, some implications from various researchers in terms of energy performance are as follows:

- A heating load decrease between 40% and 95% in DCPV in comparison with PSV in Plymouth conditions.
- DCV results in energy savings of 27% in comparison with an air-tight standard Belgian dwelling.
- Night cooling in the heating period leads to additional heat loss.

Energy-related results indicate that type of the climate and the control method significantly influence the amount of savings.

Most Trickle Vents are applied to tops of windows 1.7 m from the ground. Even though this inhibits cold draught risk and contributes to thermal comfort, it might prevent the psychological effect of fresh air inside. There is a lack of studies on Trickle Vents positioned differently from this.

Annual wind direction and wind speed profile have a significant effect on ventilation performance and thermal comfort during the positioning of Trickle Vents. However, this parameter is not taken into consideration in most of the studies. Besides this, an unachieved thermal comfort temperature demotivates occupants to control Trickle Vents and other related ventilation devices. This situation causes poor IAQ.

There is no comprehensive CFD study which evaluates Trickle Vents from the aspects of thermal performance, air flow rate, and other related parameters. However, CFD has big potential to improve performance during the initial design phase. Moreover, there has been no significant CFD study to determine the performance of Trickle Vents themselves.

Trickle Vent performance with a heat exchanger would be a new and exciting upcoming topic. Even though there are some patent applications in this subject and available products in the market, there is no available published study in the literature.

Despite the whistling noise assessment commonly requested in reputable project specifications, there is no significant scientific study either in Trickle Vents or on natural ventilation devices in general.

Since an exterior flap leads to interior pressure variations, simulation of pressure-controlled background vents is quite complicated. Therefore, experimental studies are required for such Trickle Vent types. In addition to this, experimental studies are required in demand-controlled Trickle Vent applications.

Another gap in the literature is that there is no remarkable cost analysis, even though cost analysis is one of the major parameters used to prove the applicability of this system.

Funding: This research received no external funding.

Acknowledgments: Special thanks to Turkish National Agency for supporting me as part of the Erasmus Programme to be a Visiting PhD Researcher in the Department of Architecture and Built Environment, University of Nottingham. Special thanks to Metal Yapi for encouraging me to start PhD thesis in this topic. Special thanks to Cagri Kutlu and Constanza Molina Carvallo, School of Architecture and Built Environment, University of Nottingham for their valuable assistances.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Guyot, G.; Sherman, M.H.; Walker, I.S. Smart ventilation energy and indoor air quality performance in residential buildings: A review. *Energy Build.* **2018**, *165*, 416–430. [CrossRef]
2. World Health Organization. Burden of Disease from Household Air Pollution for 2012. 2014. Available online: http://www.who.int/phe/health_topics/outdoorair/databases/FINAL_HAP_AAP_BoD_24March2014.pdf (accessed on 2 July 2018).

3. Sick Building Syndrome. Hon Kong Lung Foundation. Available online: http://www.hklf.org/index/education-information/sick-building-syndrome (accessed on 5 June 2018).
4. Biler, A.; Ozgul, Z.; Burch, P. New Generation Ventilation System: Trickle Vent. In Proceedings of the Facade Tectonics World Congress Conference, Los Angeles, CA, USA, 10–11 October 2016; pp. 417–427.
5. European Committe for Standardization (CEN). *CEN/TR 14788:2006 Ventilation for Buildings—Design and Dimensioning of Residential Ventilation Systems*; CEN: Brussels, Belgium, 2006.
6. European Collaborative Action (ECA). *Indoor Air Quality & Its Impact on Man—Report No. 11—Guidelines for Ventilation Requirements in Buildings*; ECA: Luxembourg, 1992.
7. World Meteorological Organization. *Green House Gas Bulletin*; WHO: Geneva, Switzerland, 2017.
8. CEN. *PD CR 1752-1999: Ventilation for Buildings-Design Criteria for Indoor Environment*; CEN: Brussels, Belgium, 1999.
9. United Nations. Carbon Dioxide Levels Surge to New High in 2016, UN Weather Agency Reports. 2017. Available online: http://www.un.org/en/sections/issues-depth/climate-change/%0Ahttp://www.un.org/en/sections/issues-depth/climate-change/index.html (accessed on 21 October 2018).
10. Laverge, J.; van den Bossche, N.; Heijmans, N.; Janssens, A. Energy saving potential and repercussions on indoor air quality of demand controlled residential ventilation strategies. *Build. Environ.* **2011**, *46*, 1497–1503. [CrossRef]
11. British Standards Institution. *BS EN 13779:2007 Ventilation for Non-Residential Buildings—Performance Requirements for Ventilation and Room-Conditioning Systems*; British Standards Institution: London, UK, 2007.
12. Cornaro, C.; Paravicini, A.; Cimini, A. Monitoring indoor carbon dioxide concentration and effectiveness of natural trickle ventilation in a middle school in rome. *Indoor Built Environ.* **2013**, *22*, 445–455. [CrossRef]
13. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). *ASHRAE 62.1 Ventilation for Acceptable Indoor Air Quality*; ASHRAE: Atlanta, GA, USA, 2016.
14. Biler, A. The ICBEST Conference, Istanbul, Turkey, 15–18 May 2017. Available online: http://www.itu.edu.tr/en/search/events/2017/05/15/itu-etkinlik/-icbest-istanbul-2017- (accessed on 5 November 2018).
15. Southall, R.G. An assessment of the potential of supply-side ventilation demand control to regulate natural ventilation flow patterns and reduce domestic space heating consumption. *Energy Build.* **2018**, *168*, 201–214. [CrossRef]
16. Autodesk Sustainability Workshops. Natural Ventilation. Available online: https://sustainabilityworkshop.autodesk.com/buildings/natural-ventilation (accessed on 21 May 2018).
17. Kuismanen, K. Climate and Ventilation. ECONO. 2007. Available online: http://www.kuismanen.fi/VentEn.pdf (accessed on 10 September 2018).
18. Adamu, Z.A.; Price, A.D.F.; Cook, M.J. Performance evaluation of natural ventilation strategies for hospital wards—A case study of Great Ormond Street Hospital. *Build. Environ.* **2012**, *56*, 211–222. [CrossRef]
19. Price Industries Ltd. *Engineering Guide Natural Ventilation*; Section K; Price Industries Ltd.: London, UK, 2011.
20. Concepts and Types of Ventilation. Available online: https://www.ncbi.nlm.nih.gov/books/NBK143277 (accessed on 31 August 2018).
21. Passivent, Night Cooling. Available online: http://www.passivent.com/night-cooling (accessed on 5 July 2018).
22. Autodesk Sustainablility Workshops. Night-Purge Ventilation. 2015. Available online: https://sustainabilityworkshop.autodesk.com/buildings/night-purge-ventilation (accessed on 24 April 2018).
23. Dogbeh, A.; Jomaas, G.; Bjarløv, S.P.; Toftum, J. Field study of the indoor environment in a Danish prison. *Build. Environ.* **2014**, *88*, 20–26. [CrossRef]
24. Evola, G.; Gagliano, A.; Marletta, L.; Nocera, F. Controlled mechanical ventilation systems in residential buildings: Primary energy balances and financial issues. *J. Build. Eng.* **2017**, *11*, 96–107. [CrossRef]
25. Andersen, R.; Fabi, V.; Toftum, J.; Corgnati, S.P.; Olesen, B.W. Window opening behaviour modelled from measurements in Danish dwellings. *Build. Environ.* **2013**, *69*, 101–113. [CrossRef]
26. Griffiths, M.; Eftekhari, M. Control of CO_2 in a naturally ventilated classroom. *Energy Build.* **2008**, *40*, 556–560. [CrossRef]
27. Autodesk Sustainablility Workshops. Wind Ventilation. Available online: https://sustainabilityworkshop.autodesk.com/buildings/wind-ventilation (accessed on 14 May 2018).
28. Liddament, M.W. *A Guide to Energy Efficient Ventilation*; Air Infilteration and Ventilation Center (AIVC), 1996. Available online: http://www.aivc.org/sites/default/files/members_area/medias/pdf/Guides/GU03GUIDETOENERGYEFFICIENTVENTILATION.pdf (accessed on 25 April 2018).

29. Autodesk Sustainablility Workshops. Stack Ventilation and Bernoulli's Principle. Available online: https://sustainabilityworkshop.autodesk.com/buildings/stack-ventilation-and-bernoullis-principle (accessed on 14 May 2018).
30. Green Building Advisor. The Stack Effect: When Buildings Act Like Chimneys Welcome to Green Building Advisor. Available online: http://www.greenbuildingadvisor.com/stack-effect-when-buildings-act-chimneys (accessed on 14 May 2018).
31. Awbi, H.B. Design Considerations For Naturally Ventilated Buildings. *Renew. Energy* **1994**, *5*, 1081–1090. [CrossRef]
32. Department for Edcuation. *Building Bulletin 101—Ventilation of School Buildings*; Department for Edcuation: London, UK, 2006; pp. 1–62.
33. Khan, N.; Su, Y.; Riffat, S.B. A review on wind driven ventilation techniques. *Energy Build.* **2008**, *40*, 1586–1604. [CrossRef]
34. Mochida, A.; Yoshino, H.; Takeda, T.; Kakegawa, T.; Miyauchi, S. Methods for controlling airflow in and around a building under cross-ventilation to improve indoor thermal comfort. *J. Wind Eng. Ind. Aerodyn.* **2005**, *93*, 437–449. [CrossRef]
35. The Basics of Home Ventilation. Available online: https://www.myglazing.com/be-informed/trickle-vents-and-types-of-ventilation/ (accessed on 16 April 2018).
36. Galvin, R. Impediments to energy-efficient ventilation of German dwellings: A case study in Aachen. *Energy Build.* **2013**, *56*, 32–40. [CrossRef]
37. Department of Health/Estates and Facilities Division. *Health Technical Memorandum 03-01: Specialised Ventilation for Healthcare Premises. Part A—Design and Installation*; Department of Health and Social Care: London, UK, 2007.
38. Atkinson, J.; Chartier, Y.; Pessoa-Silva, C.L.; Jensen, P.; Li, Y.; Seto, W.-H. Natural Ventilation for Infection Control in Health-Care Settings. *World Heal. Organ.* **2009**, *1*, 133.
39. CIBSE. *Natural Ventilation in Non-Domestic Buildings, CIBSE Application Manual AM010*; CIBSE: London, UK, 2005; p. 64.
40. HM Government. *NBS 2010b The Building Regulations 2010 For England and Wales, Part F*; HM Government: London, UK, 2013.
41. Kolokotroni, M.; Marshall, S.G.; Perera, M.D. Trickle Ventilators: Effective Natural Background Ventilation for Offices. In Proceedings of the AIVC Conference, Palm Springs, CA, USA, 19–22 September 1995.
42. Wiki, D.B. Trickle Ventilation in Buildings. Available online: https://www.designingbuildings.co.uk/wiki/Convection_in_buildings (accessed on 16 April 2018).
43. Renson, Sonoslot Range. Available online: dam.renson.eu/Sites/A/Public_Publications/2034?encoding=UTF-8 (accessed on 27 July 2018).
44. Brookvent, Window Ventilation Product Technical Data Sheet. 2016. Available online: https://brookvent.co.uk/wp-content/uploads/2018/04/Window-Ventilation-Brochure.pdf (accessed on 29 August 2018).
45. Karava, P.; Stathopoulos, T.; Athienitis, A.K. Investigation of the performance of trickle ventilators. *Build. Environ.* **2003**, *38*, 981–993. [CrossRef]
46. Brookvent, Surface Mounted Window Vents. Available online: https://brookvent.co.uk/surface-mount-window-vents/ (accessed on 18 April 2018).
47. Brookvent, Glazed-in Window Vents. Available online: https://brookvent.co.uk/glazed-in-window-vents/ (accessed on 18 April 2018).
48. RENSON. Window Ventilators. 2007. Available online: http://www.rensonuk.net/documentation-united-kingdom_2.html (accessed on 19 April 2018).
49. CIBSE. *CIBSE Guide B2—Ventilation and Ductwork*; CIBSE: London, UK, 2016.
50. Brookvent—SM 1000 Trickle Vent. Available online: https://brookvent.co.uk/product/airvent-sm-1000-trickle-vent/ (accessed on 24 July 2018).
51. Brookvent Ventilation Systems. Available online: https://brookvent.co.uk/product/dg-1500-window-vent/ (accessed on 23 July 2018).
52. Erguner, B. Partial Natural Ventilation System Developed for Curtain Walls. TR 2013/08326, 10 July 2013.
53. Biler, A.; Erguner, B. Vertical Natural Ventilation Device. TR 2016/17175, 24 November 2016.
54. Renson, L.L. Ventilation Device with Internal Heating System. EP 2 639 519 A1, 6 February 2013.
55. Meinster, J.P.; de Neve, A.D.M.A. Ventilation Grille. EP 2995879A1, 16 March 2016.

56. Dewachter, R.J.P. Ventilation Device. EP2141424A2, 1 July 2009.
57. Anderson, J.N.; Stoney, A. Slot Ventilator. U.S. Patent 005702297A, 30 December 1997.
58. Peak, R.A.; Anderson, J.N. Slot Ventilator Mounted on a Window or Door to Be Ventilated. GB 2432656 A, 30 May 2007.
59. British Standards Institution. *BS EN 13141-1:2004 Ventilation for Buildings—Components/Products for Residential Ventilation*; British Standards Institution: London, UK, 2004.
60. British Standard Institution. *BS EN 20140:10:1992 Acoustics—Measurement of Sound Insulation in Buildings and of Building Elements*; British Standard Institution: London, UK, 1992.
61. Comittee European de Normalisation. *EN ISO 140-10 Acoustics—Measurement of Sound Insulation in Buildings and of Building Elements*; CEN: Brussels, Belgium, 2009.
62. British Standard Institution. *BS EN ISO 717-2 Acoustics—Rating of Sound Insulation in Buildings and of Building Elements Part 1: Airborne Sound Insulation*; British Standard Institution: London, UK, 2013.
63. British Standard Institution. *BS EN 1027: 2016 Windows and Doors—Water Tightness—Test Method*; British Standard Institution: London, UK, 2016.
64. British Standard Institution. *BS EN 1026: 2016 Windows and Doors—Air Permeability—Test Method*; British Standard Institution: London, UK, 2016.
65. British Standard Institution. *BS EN ISO 10077-2: 2017 Thermal Performance of Windows, Doors and Shutters—Calculation of Thermal Transmittance*; British Standard Institution: London, UK, 2017.
66. Comittee European de Normalisation. *EN 1627:2011 Pedestrian Doorsets, Windows, Curtain Walling, Grilles and Shutters—Burglar Resistance—Requirements and Classification*; CEN: Brussels, Belgium, 2011.
67. Comittee European de Normalisation. *EN 1628: 2011 Windows, Curtain Walling, Grilles and Shutters—Burglar Resistance—Test Method for the Determination of Resistance under Static Loading*; CEN: Brussels, Belgium, Brussels, 2011.
68. Comittee European de Normalisation. *EN 1629: 2011 Pedestrian Doorsets, Windows, Curtain Walling, Grilles and Shutters—Burglar Resistance—Test Method for the Determination of Resistance under Dynamic Loading*; CEN: Brussels, Belgium, 2015.
69. Comittee European de Normalisation. *EN 1630: 2011 Pedestrian Doorsets, Windows, Curtain Walling, Grilles and Shutters—Burglar Resistance—Test Method for the Determination of Resistance to Manual Burglary Attempt*; CEN: Brussels, Belgium, 2011.
70. Wood, A.; Ruba, S. *Natural Ventilation in High-Rise Office Buildings*; CTBUH: Chicago, IL, USA, 2013.
71. British Standard Institution. *BS EN 12792-3 Ventilation for Buildings—Symbols, Terminology and Graphical Symbols*; British Standard Institution: London, UK, 2003.
72. British Standard Institution. *BS 5925: 1991 Ventilation Principles and Designing for Natural Ventilation*; British Standard Institution: London, UK, 1991.
73. Nielsen, T.R.; Drivsholm, C. Energy efficient demand controlled ventilation in single family houses. *Energy Build.* **2010**, *42*, 1995–1998. [CrossRef]
74. British Standards Institution. *BS EN 15251: 2007 Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics*; British Standard: London, UK, 2008.
75. Caillou, S.; Heijmans, N.; Laverge, J.; Janssens, A. *Méthode de calcul PER: Facteurs de Réduction Pour la Ventilation à la Demande*; Ghent University: Ghent, Belgium, 22 April 2014.
76. Savin, J.; Berthin, S.; Jardinier, M. Demand-controlled ventilation 20 years of in-situ monitoring in the residential field. In Proceedings of the 35th AIVC Conference "Ventilation and airtightness in transforming the building stock to high performance", Poznań, Poland, 24–25 September 2014.
77. Arendt, K.; Krzaczek, M. Co-simulation strategy of transient CFD and heat transfer in building thermal envelope based on calibrated heat transfer coefficients. *Int. J. Therm. Sci.* **2014**, *85*, 1–11. [CrossRef]
78. Van den Bossche, N.; Janssens, A.; Heijmans, N.; Wouters, P. Performance Evaluation of Humidity-Controlled Ventilation Strategies in Residential Buildings. In Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings X, Clearwater Beach, FL, USA, 2–7 December 2007; pp. 1–7.
79. Rennie, D.; Parand, F. *Environmental Design Guide For Naturally Ventilated Daylit Offices*; BRE Rep. No. BR 345; Construction Research Communications: London, UK, 1998.

80. Renson, Oxyvent Product Catalogue. Available online: http://www.rensonuk.net/products/downloads.aspx?productgroep=Ventilatie&product=Window+vent+Oxyvent%3A+Flap+ventilator+for+conservatories (accessed on 28 June 2018).
81. American Society for Testing and Materials. *Standard Test Method for Field Measurement of Air Leakage through Installed Exterior Windows and Doors*; ASTM: West Conshohocken, PA, USA, 2010.
82. R.W. Simon Ltd. Airstrip 19000 Product Technical Data Sheet. Available online: https://www.rwsimon.co.uk/wp-content/uploads/2018/07/Airstrip-19000.pdf (accessed on 28 June 2018).
83. R.W. Simon Ltd. Airstrip 200 Product Technical Data Sheet. Available online: https://www.rwsimon.co.uk/wp-content/uploads/2015/02/Simon-Airstrip200-NEW-STYLE-red.pdf (accessed on 28 June 2018).
84. Renson Ventilation, AK80 Product Evo Technical Data Sheet. Available online: http://rensonuk.net/documentation-united-kingdom_2.html (accessed on 28 June 2018).
85. Biler, A. Trickle Vent—Integrated Curtain Wall Natural Ventilation System. In Proceedings of the ICBEST Conference, Istanbul, Turkey, 15–18 May 2017.
86. Fox, M.; Coley, D.; Goodhew, S.; de Wilde, P. Time-lapse thermography for building defect detection. *Energy Build.* **2015**, *92*, 95–106. [CrossRef]
87. Biler, A. *Identification of Closed Cavity Façades in Terms of Condensation Risk and Energy Performance*; Istanbul Technical University: Istanbul, Turkey, 2015.
88. Alduchov, O.A.; Eskridge, R.E. Improved Magnus Form Approximation of Saturation Vapor Pressure. *J. Appl. Meteorol.* **1996**, *35*, 601–609. [CrossRef]
89. Ozgul, Z.; Biler, A.; Burch, P. Slide and Push: Integrated Curtain Wall Sliding System. In Proceedings of the Facade Tectonics World Congress Conference, Los Angeles, CA, USA, 10–11 October 2016; pp. 429–438.
90. Renson Ventilation, Invisivent Evo. Available online: http://www.rensonuk.net/documentation-united-kingdom_2.html (accessed on 29 June 2018).
91. British Standards Institution. *BS EN ISO 10140-2:2010 Acoustics—Laboratory Measurement of Sound Insulation of Building Elements Part 2: Measurement of Airborne Sound Insulation*; British Standard Institution: London, UK, 2010.
92. Brookvent, Airvent DG 1500 Technical Data Sheet. Available online: https://brookvent.co.uk/wp-content/uploads/2017/06/airvent-DG-1500-Brookvent-Brochure-2017.pdf (accessed on 29 June 2018).
93. AmesburyTruth, Trickle Vent Product Comparison Table. Available online: http://www.amesburytruth.com/downloads/products/ComparisonTable1200.pdf (accessed on 29 June 2018).
94. Greenwood, HD Vent Technical Data Sheet. Available online: http://www.greenwood.co.uk/uploads/docs/313.pdf (accessed on 29 June 2018).
95. Simon, R.W. Airvent. Available online: https://www.rwsimon.co.uk/wp-content/uploads/2018/07/Simon-Acoustic-Range.pdf (accessed on 29 June 2018).
96. Brookvent, Airvent SM1400 Technical Data Sheet. Available online: https://brookvent.co.uk/product/airvent-sm-1400/ (accessed on 29 June 2018).
97. Brookvent, Airvent SM Acoustic. Available online: https://brookvent.co.uk/product/airvent-sm-acoustic/ (accessed on 29 June 2018).
98. Titon, Trimvent Select S13 Technical Data Sheet. Available online: http://www.titon.co.uk/pages/window-door-hardware/ventilators/slot-vents/trimvent-select-xtra-xs13.php (accessed on 29 June 2018).
99. AWS, Passive Ventilation Solutions. Available online: https://www.awsaustralia.com.au/Content/cms/awscdn/files/AWS_VENTIENT_BROCHURE.pdf (accessed on 29 June 2018).
100. Greenwood, 5000EA Slotvent Technical Data Sheet. 2016. Available online: http://www.dmtf.org/standards/cim/cim_schema_v2480 (accessed on 29 August 2018).
101. Simon, R.W. TFF Slimline Trickle Vent Product. Available online: https://www.rwsimon.co.uk/wp-content/uploads/2018/07/Slimline.pdf (accessed on 29 June 2018).
102. Computational Modeling | National Institute of Biomedical Imaging and Bioengineering. Available online: https://www.nibib.nih.gov/science-education/science-topics/computational-modeling (accessed on 10 September 2018).
103. EnergyPlus. 1996. Available online: https://energyplus.net/ (accessed on 10 September 2018).
104. Rallapalli, H.S. *A Comparison of EnergyPlus and eQUEST Whole Building Energy Simulation Results for a Medium Sized Office Building*; Arizona State University: Tempe, AZ, USA, 2013.
105. Bakker, A. *Lecture 1—Introduction to CFD Applied Computational Fluid Dynamics*; Fluent Inc.: Queens, NY, USA, 2002.

106. Dols, W.S.; Polidoro, B.J. *CONTAM User Guide and Program Documentation—Version 3.2 (NIST Technical Note 1887)*; NIST: Gaithersburg, MD, USA, 2015; p. 1.
107. Das, P.; Shrubsole, C.; Jones, B.; Hamilton, I.; Chalabi, Z.; Davies, M.; Mavrogianni, A.; Taylor, J. Using Probabilistic Sampling-based Sensitivity Analyses for Indoor Air Quality Modelling. *Build. Environ.* **2014**, *78*, 171–182. [CrossRef]
108. Dols, W.S.; Emmerich, S.J.; Polidoro, B.J. Coupling the multizone airflow and contaminant transport software CONTAM with EnergyPlus using co-simulation. *Build. Simul.* **2016**, *9*, 469–479. [CrossRef] [PubMed]
109. Phil, B. What Monitoring Is; Definition and Purpose. The Nature of Monitoring and Evaluation. 2011. Available online: http://cec.vcn.bc.ca/cmp/modules/mon-wht.htm (accessed on 17 September 2018).
110. Etheridge, D. A perspective on Fifty Years of Natural Ventilation Research. *Build. Environ.* **2015**, *91*, 51–60. [CrossRef]
111. Salcidoa, J.C.; Raheem, A.A. From simulation to monitoring: Evaluating the potential of mixed-mode ventilation (MMV) systems for integrating natural ventilation in office buildings through a comprehensive literature review. *Energy Build.* **2016**, *127*, 1008–1018. [CrossRef]
112. British Standards Institution. *BS EN ISO 12569: 2017 Thermal Performance of Buildings and Materials—Determination of Specific Airflow Rate in Buildings—Tracer Gas Dilution Method*; British Standards Institution: London, UK, 2017.
113. Cotterell, J.; Dadeby, A. *The Passivhaus Designer' s Manual: A Technical Guide to Low and Zero Energy Buildings*; Routledge: Abingdon, UK, 2012.
114. Li, Y.; Nielsen, P.V. Commemorating 20 years of Indoor Air: CFD and ventilation research. *Indoor Air* **2011**, *21*, 442–453. [CrossRef] [PubMed]
115. British Standard Institution. *BS EN ISO 6946—Building Components and Building Elements—Thermal Resistance and Thermal Transmittance—Calculation Method*; British Standards Institution: London, UK, 2017.
116. CONTAM. Available online: https://www.nist.gov/services-resources/software/contam (accessed on 21 May 2018).