A REVIEW OF VENTILATION OPENING AREA TERMINOLOGY

Benjamin M. Jones*[1,2]

Malcolm J. Cook[1,3]

Shaun D. Fitzgerald[1,4]

Christopher R. Iddon[1,5]

1. The Chartered Institution of Building Services Engineers Natural Ventilation Group, Balham, London, UK

2. Department of Architecture and Built Environment, University of Nottingham, Nottingham, NG7 2RD, UK

3. School of Civil and Building Engineering, Loughborough University, Loughborough, LE11 3TU, UK

4. Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK

5. SE Controls, Hood Innovation Centre, Wellington Crescent, Fradley, Lichfield, WS13 8RZ, UK

*corresponding author: benjamin.jones@nottingham.ac.uk

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ABSTRACT

The design of a natural ventilation strategy requires the establishment of the location and size of a series of purpose provided ventilation openings (PPOs). The success of the design is dependent on knowledge of the aerodynamic performance of the PPOs often described by their geometry (normally an area) and resistance to airflow. The incorrect interpretation of this information can lead inappropriate ventilation strategies and buildings that overheat and have an excessive energy demand.

Many definitions of PPO area are used by standards, guidelines, text books, and software tools. Each can be assigned multiple terms and a single term can be assigned to different definitions. There is evidence that this leads to errors in practice. An *effective* area of a PPO, defined as the product of its discharge coefficient and its *free* area, is proposed as a standard description because it is unambiguous and its measurement is governed by recognised standards. It is hoped that PPO manufacturers will provide an *effective* area as standard and that its use will be recognised as best practice. It is intended that these steps will reduce design errors and lead to successful natural ventilation strategies and better buildings.

HIGHLIGHTS

- Definitions of *free*, *effective*, and *equivalent* ventilation opening areas are given

- A review of current definitions highlight contradictions in national standards and guidelines

- The contradictions are shown to lead to unintended design errors

- An unambiguous term that describes ventilation opening performance is proposed

- This will help to mitigate against design errors in ventilation strategies

KEYWORDS

Natural Ventilation; Design; Standards; Effective area; Equivalent area; Free area; Policy.

1   INTRODUCTION

Openings located in the thermal envelope of a building comprise those that are intentional, known as purpose-provided openings (PPOs), and those that are unintentional, known as adventitious openings (Etheridge, 2012). It is desirable to minimize adventitious openings to minimize a building's energy demand and to ensure the satisfactory operation of a system of PPOs (Jones *et al.*, 2015). When designing a ventilation strategy that comprises a system of PPOs, a fundamental objective is to establish their location and size. Both factors depend on the airflow rates required through each PPO for a given pressure drop in order to maintain adequate indoor air quality (IAQ) and to dissipate heat gains under limiting conditions (CIBSE, 2005). Accordingly, a description of the geometry of each PPO and its resistance to airflow are required in order to enable a designer to establish the performance of a system using envelope flow models (CIBSE, 2005; Etheridge, 2012). The same information can also be used when working with more complex simulation tools to ensure that a building meets relevant energy and indoor environment quality (IEQ) criteria, such as indoor air quality (IAQ), thermal comfort, overheating, and noise levels. The geometrical information and resistance to airflow of a specific PPO can also be used to compare the relative aerodynamic performance of other PPOs.

The information about a PPO should comprise an indication of opening geometry, normally an area, a coefficient of discharge and an indication of its dependence on Reynolds number[*]. These factors are related and cannot be considered in isolation. An incorrect interpretation of the resistance to flow through an opening can have serious consequences, such as inadequate airflow through a space with consequent overheating and/or air quality issues, or PPOs that are oversized and hence too expensive.

This paper reviews existing terminology used to describe the geometry and aerodynamic performance of PPOs. A brief overview of relevant theory and terms is given in Section 2 and these are then used in Section 3 in order to review the terminology used by regulatory and guideline documents and software tools. Here, examples of similarities, differences, and even contradictions, are given. Section 4 briefly considers an emerging body of anecdotal evidence of confusion in the industry about the terminology used to describe the geometry and aerodynamic performance of PPOs. It also provides an example of the consequences of term conflation. In Section 5 we state preferred definitions of terms and recommend those that should be used by standards and guidelines, both in the UK and elsewhere.

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[*]A Reynolds number (Re) is the non-dimensional ratio of the inertial and viscous forces in a fluid, in this case air. Therefore, Re is a function of the mean velocity of air, $\bar{u}$ (m/s), that passes through a PPO. It follows that a discharge coefficient that is dependent on Re is therefore also dependent on $\bar{u}$.

2 THEORY

2.1 SINGLE OPENING

A circular *sharp-edged orifice* (see Figure 1) can be defined as an opening of circular geometry with unsmoothed edges, and a length, L (m), that is significantly shorter than its hydraulic diameter, d_h (m)[†], so that $L/d_h < 2$ (Etheridge, 2012).

The turbulent uni-directional airflow rate, Q (m³/s), through any sharp-edged opening is proportional to its cross-sectional (measurable, geometric) area, often known as a *free area, A_f* (m²). It is also a function of the pressure drop across the opening ΔP (Pa), the density of the air ρ (kg/m³), and the shape of the opening so that

$$Q = C_d A_f \sqrt{\frac{2\Delta P}{\rho}} \qquad (1)$$

Here, C_d is a dimensionless discharge coefficient used to account for the constriction of streamlines after flow passes through the orifice. The cross-sectional area of the flow downstream of the orifice is smaller than that of the orifice itself and so C_d is a positive number less than 1. Figure 2 shows a series of *streamlines* through an orifice that are tangential to the direction of airflow at every point so that airflow does not occur across a streamline. Figure 2 also shows that as air passes through the orifice it accelerates and contracts to form a *vena contracta*, the point at which streamline velocity is highest, u_{max} (m/s), the streamlines are parallel, and the flow area is smallest, A_{min} (m). The phenomenon occurs because the streamlines cannot readily change direction as they pass through the orifice. The air in contact with the edge of the opening is stationary because of the *no-slip[‡]* boundary condition at that point. For a given *free area* (A_f) of an opening, the resistance to the flow provided by the stationary fluid in contact with the edge increases with the length of the perimeter of the opening. Therefore, the discharge coefficient is a function of the shape of the opening; the greatest ratio of cross-sectional area to perimeter length occurs with a circular opening, and hence as opening shapes become less circular the discharge coefficient decreases.

If the airflow is not fully turbulent then caution is required and measurements should be taken to establish an appropriate relationship between Q and ΔP. In practice, this issue may arise if a single PPO is comprised of a number of small openings in parallel, such as an insect mesh.

An orifice is an ideal tool for measuring the rate of flow of a fluid, such as air, because the location of streamlines is fixed so that C_d is independent of the mean velocity of air, $\bar{u}$ (m/s), when $Re > 100$ (Etheridge,

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[†] An hydraulic diameter (d_h) is a characteristic length used to describe openings of non-circular geometry (Fox *et al.*, 2010). For a circular opening d_h is equal to its diameter.
[‡] The condition states that at a solid boundary a viscous fluid has zero velocity relative to that boundary.

2012). A C_d is measured under still-air conditions with uniform density so that the airflow through the opening is exclusively generated by a fan. The discharge coefficient of a standard circular sharp-edged orifice, C_{d_o}, is frequently given as $C_{d_o} = 0.61$ (ASHRAE, 2013; Etheridge, 2012; CIBSE, 2005).

The *free area* of a circular orifice is easily calculated to be $A_f = \pi {d_h}^2/4$. Short sharp-edged PPOs ($L/d_h < 2$) are common in practice but their geometries are generally non-circular and complex, which can make A_f ambiguous; see Figure 3. Accordingly, confusion arises when comparing the performance of different PPOs or when predicting performance using airflow models. Other terms are required. One approach is to calculate a *net* or *effective area*, A_{eff} (m), through which air flows where

$$A_{eff} = C_d A_f = A_{min}. \qquad (2)$$

Another approach is to calculate the *equivalent area*, A_{eq} (m), of a hypothetical circular sharp-edged orifice that allows air to pass at the same volume flow rate as the PPO at an identical pressure difference. From Equation (1) it follows that

$$C_{d_o} A_{eq} = C_d A_f \qquad (3)$$

and so

$$A_{eq} = \frac{C_d A_f}{C_{d_o}} = \frac{A_{eff}}{C_{d_o}} \qquad (4)$$

where $C_{d_o} = 0.61$.

The A_{eff} and A_{eq} terms described here are obtained using a standard test rig that comprises a sealed chamber to which a PPO is attached. Air is drawn through it using a fan located at the outlet of a long duct, which is also connected to the chamber; see for example EN13141 (2004). It should be noted that A_{eff} and A_{eq} are given other definitions and terms elsewhere (see Etheridge, 2012; CIBSE, 2005). These are discussed in Section 3. Finally, when there is bi-directional airflow through a PPO, A_{eff} is reduced further; see CIBSE (2005). Bi-directional airflows are not well understood and can increase the uncertainty in A_{eff}.

2.2   MULTIPLE OPENINGS

In the case where a number of openings are formed in series through which air passes (see Figure 4) then Equation (1) can be extended in order to determine the *effective area* (A_{eff}) of the combined openings. In this case the total pressure drop, ΔP (Pa), across all of the openings is the sum of the pressure drops across each opening individually. Let us denote the pressure drop across the ith of j openings as Δp_i (Pa). Applying Bernoulli's principle along a streamline we may write

$$\Delta p_i = \frac{1}{2}\rho \bar{u}_i^2 \tag{5}$$

so that for all j openings

$$\Delta P = \sum_{i=1}^{j} \frac{1}{2}\rho \bar{u}_i^2 \tag{6}$$

Given that

$$Q = C_{d_i} A_{f_i} \bar{u}_i \tag{7}$$

we may write

$$\Delta P = \frac{1}{2}\rho Q^2 \sum_{i=1}^{j} \frac{1}{\left(C_{d_i} A_{f_i}\right)^2} \tag{8}$$

Re-writing Equation (1) for a series of openings gives

$$A_{eff} = C_d A_f = Q\sqrt{\frac{\rho}{2\Delta P}} \tag{9}$$

and so the *effective area* of multiple openings in series is defined as

$$A_{eff} = \frac{1}{\sqrt{\Sigma_{i=1}^{j}\left(\frac{1}{C_{d_i}A_{f_i}}\right)^2}} \tag{10}$$

or

$$\frac{1}{A_{eff}^2} = \sum_{i=1}^{j}\left(\frac{1}{C_{d_i}A_{f_i}}\right)^2 \tag{11}$$

Equation (11) applies when the spacing between a series of openings is sufficiently large that the streamlines through one opening are unaffected by other openings. If the openings are close together then measurements should be taken to establish an appropriate relationship between Q and ΔP; see EN13141 (2004).

Finally, it should be noted that equations for multiple openings in parallel can be found in Table 4.25 of CIBSE Guide A (2015).

3 EXISTING TERMINOLOGY

Table 1 details terms used to describe the areas of PPOs in a number of international and national documents relevant to the design of natural ventilation systems. Here, user guidance for well-known software tools is included because they are an integral part of the design process.

The table shows that there are matters of uncertainty regarding term definitions, contradictions, and deviations. Firstly, terms are used without definition in several guideline documents (CIBSE, 2002; 2005; 2007; 2015; AIC,

1981), software guidance (Walton & Dols, 2014; DoE, 2015a,b), text books (Hensen & Lamberts, 2011; Mumovic & Santamouris, 2009; Oughton & Wilson, 2015), and national standards (BSI, 1991). Here the reader must interpret the term using their own domain knowledge or a companion document. The latter approach can be problematic because some documents give different definitions of the same terms; for example, ASHRAE (2013) defines the term *effective area* using Equation (2) whereas CIBSE (2005) uses Equation (4). It is interesting to note that CIBSE (2005) introduces uncertainty into its definition (see Table 1) thus asserting that other definitions may exist. One national standard (BSI, 1991) defines the term *equivalent area* but also uses the undefined term *effective equivalent area*. This is potentially confusing, especially if one is aware of differing definitions of *effective* and *equivalent* areas; see Section 2.

Further divergence in terms occurs in documents pertaining to non-standard PPOs such as smoke ventilators. For example, the statutory document B2 (ADB2) (H.M. Government, 2010b) uses the term *aerodynamic free area* to describe an area based on the length d_2 (shown in Figure 3) and is the same as the definition of *free area* given by Equation (1). ADB2 also states that an *aerodynamic free area* can be "declared […] in accordance [with] BS EN 12101-2". However, EN 12101-2 (BSI, 2003a) defines *aerodynamic free area* as the "product of the *geometric area* multiplied by the coefficient of discharge", which is the same as the definition of *effective area* described by Equation (2). EN 12101-2 also uses the term *geometric area* whose definition is equivalent to that of the *free area* described by Equation (1). Similarly, AIVC GU03 (Liddament, 1996) uses the terms *cross sectional* and *openable* area in place of the *free area* described by Equation (1). These are all direct contradictions that only serve to confuse the reader and lead to engineering failures.

These examples demonstrate the importance of clear terminology; for example, it is possible that the term *aerodynamic*, used by ADB2 and EN 12101-2, is unhelpful because it is not clear why a particular area is more or less aerodynamic than any other. They also highlight the importance of defining a term before it is used. The statutory Approved Document F (H.M. Government, 2010a) gives clear definitions of *free* and *equivalent* areas (and other key terms in a glossary) that agree with the European standard EN 12792 (BSI, 2003b). The text book *Ventilation of Buildings* (Awbi, 2003) includes a glossary of the terms *free* and *equivalent* areas at the beginning of its chapter on air diffusion devices that agree with those given in Equations (1) and (2), respectively. Accordingly, any error in their application is solely the responsibility of the reader.

The need for software manuals to define terms can depend on the function of the tool. For example, CONTAM (Walton & Dols, 2014) and EnergyPlus (DoE, 2015a,b) have an academic or scientific focus where users may wish to simulate atypical scenarios and so the software rarely checks the validity of user inputs. Therefore, users

require extensive domain knowledge to avoid design failures. This is reflected in their engineering manuals; see Table 1. Other software tools, such as TAS or IES, have a more commercial focus and so they check user inputs. They require the input of an *equivalent* area for each PPO and the software calculates an *effective* area using $C_{d0} = 0.62$. Here, the user must understand the difference between *free*, *effective*, and *equivalent* areas to avoid prediction errors.

Some computational fluid dynamics (CFD) programs do not provide the opportunity to input discharge coefficients directly, leaving it to the user to provide these implicitly by defining the orifice flow equation at openings (equation 1). Those CFD codes where there is an option for specifying the amount of discharge vary in the way the information is requested. Some ask for the discharge coefficient, C_d, and others ask for the loss coefficient, f, (e.g. Durrani *et al.*, (2015) and defined by Fox *et al.*, (2010)), where

$$f = \frac{1}{C_d^2} \tag{12}$$

This is more commonly used when considering loss coefficients along pipes as in the following equation:

$$\Delta P = \frac{1}{2} f_i \rho \bar{u}_i \tag{13}$$

Alternatively, it is also possible to represent the effects of discharge in CFD by using a physically reduced opening area as shown in Ji *et al.* (2007).

Finally, it should be noted that the academic community could also improve clarity by explicitly stating definitions. For example, Jones & Kirby (2010, 2012) discuss the area of PPOs in real buildings but do not explicitly define the term, although it can be inferred from the text that they apply the *free* area described by Equation (1). Similarly, Flourentzou *et al.* (1998) uses the term *effective* area without a definition, but it is possible to infer that it agrees with Equation (2). When investigating airflow through PPOs empirically, Iqbal *et al.* (2015), Karava *et al.* (2004), and Chiu and Etheridge (2007) use the term *opening* area to describe the *free* area given by Equation (1), whereas Heiselberg and Sandberg (2006) use the term *geometrical opening* area and Chu *et al.* (2009) use the term *cross-section* area to describe the same thing.

A variation in terms is also seen in theoretical studies that use models to predict airflow through PPOs. Das *et al.* (2014) use the term *openable* area to mean either *free* or *equivalent* area as an input to their CONTAM models. Here a discharge coefficient of $C_d = 0.6$ is used and so either could be true. Belleri *et al.* (2014) input discharge coefficients and areas for a number of PPOs into an Energy Plus model of an office building. Although the PPO area isn't defined it is clear from the text that a *free* area given by Equation (1) is applied. Martins and Garça (2016) use a number of undefined terms to describe PPO area, such as *effective opening*,

window opening, *relative window opening*, and *relative average window opening*. Iddon and ParasuRaman (2015) do not explicitly define the terms used to describe PPO area but infer that $C_d = C_{d_o} = 0.62$ for their modelled window and use the term *geometric free* area to describe a *free* area given by Equation (1). They also use the term *effective free* area to describe an *effective* area given by Equation (2). Finally, Schulze and Eicker (2013) use an *effective cross-section opening* area to describe the *free* area given in Equation (1) when simulating ventilation airflow rates.

Although it is unlikely that undefined terms in academic work will lead directly to design failure, it is possible that reported findings are misinterpreted or that obfuscation means good work is ignored.

4   EVIDENCE OF ERRORS

Missing or contradictory definitions of PPO area can lead to errors in practice. Section 4.1 highlights anecdotal evidence of confusion in the industry about the terminology used to describe the geometry and aerodynamic performance of PPOs. Section 4.2 provides a theoretical example of the consequences of term conflation.

4.1   IN PRACTICE

There is emerging evidence of errors in practice that are directly attributable to missing or contradictory definitions of PPO area. Connick (2015) gives two examples that highlight existing problems.

The first example is of a contractor who compared two roof-mounted natural ventilation elements from different manufacturers with identical cross-sectional areas making a selection based on element cost. The ventilation engineer identified that one element had a smaller *equivalent area* (defined by Equation (4)) than the other and so would provide a lower airflow rate under the same environmental conditions. Accordingly, a cost benefit analysis considering façade opening area, element cost, and element aerodynamic performance was performed and the error identified before purchase and installation.

The second example is of a contractor who mistook *equivalent area* for *free area* when installing a series of acoustic attenuated vents and so they were undersized. This was identified after installation. The potential consequences are highlighted in Section 4.2.

4.2   SIMULATED

Unintentional errors occur when A_{eff} and A_f are conflated, which can lead to over or under-sized PPOs. This can occur at the design stage; for example, when designing a new naturally ventilated school classroom. Its opening areas must be big enough to allow natural ventilation that complies with the UK Facilities Output Specification (FOS) (H.M. Government, 2013) summertime overheating limit. The limit is comprised of two sections. The first assesses overheating as a function of ΔT (K), the difference between the actual operative

temperature in the room at any time, T_{op} (°C), and the limiting maximum acceptable temperature, T_{max} (°C). For a category II building (normal expectations) T_{max} is given by

$$T_{max} = 0.33T_{rm} + 21.8 \tag{14}$$

where T_{rm} (°C) is a running mean of the ambient air temperature (see CIBSE TM52, 2013). In order to comply with the first section, two of the following criteria must be met:

> 1) *For schools, the number of hours that ΔT is greater than or equal to one degree (K) during the period May to September inclusive shall not be more than 40 hours;*

> 2) *The weighted exceedance (We) must be less than or equal to 6 in any one day.*

Following CIBSE (2013), We is given by

$$We = \sum_{y=0}^{3} h_{ey} \times wf = (h_{e0} \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) + (h_{e3} \times 3) \tag{15}$$

where $wf = 0$ if $\Delta T \leq 0K$, otherwise $wf = \Delta T$ and h_{ey} is the time in hours when $wf = y$.

The second section of the FOS prescribes an maximum ΔT.

> 3) *The value of ΔT shall not exceed 4°C.*

Accordingly, the room must be designed so that the average internal operative temperature does not exceed the average ambient air temperature by more than 4K, both temperatures being averaged over the time period when the external air temperature is 20°C or higher.

If we consider an example classroom in the Norwich area of the UK that has the properties given in Table 2, then a dynamic thermal modelling exercise can be undertaken to determine the *effective* free area (given by Equation (2)) required to meet the summertime overheating design criteria. In this case, by providing openings at both high and low levels each with and *effective* area of $A_{eff} = 0.49\text{m}^2$ (see Equation (2)) the classroom passes all of the criteria. The number of hours of exceedance is $h_e = 2.5$, the maximum weighted exceedance on any given day is $We = 2.5$, there are zero hours when $\Delta T \geq 4K$, and the maximum difference in air temperature between inside and outside is $T_{max} = 4.9$°C. The correct combination of A_f and C_d required to achieve $A_{eff} = 0.49\text{m}^2$ is given by the curve in Figure 6. The product of A_f and C_d that lies above the curve gives an opening that is oversized, whereas one that lies below gives one that is undersized.

If both the high and low level openings now have a *free* area of $A_f = 0.49\text{m}^2$ (see Equation (1)) and a discharge coefficient of $C_d = 0.5$ then their *effective* areas are halved; see the × in Figure 6. Now, the classroom fails all four overheating tests. In this instance the number of hours of exceedance is $h_e = 58$, the maximum weighted

exceedance on any given day is $We = 16.5$, there are 9 hours when $\Delta T \geq 4\text{K}$ and the maximum difference in air temperature between inside and outside is $T_{max} = 8.3°\text{C}$.

This highlights the importance of ensuring that a contractor who builds this school, or any other building, understands the requirements for an opening area in terms of the definitions discussed herein.

5 RECOMMENDED TERMINOLOGY AND PRACTICE

Sections 3-5 show there is a need for clear, simple, and common terminology. The terms should describe the PPO accurately and should be unambiguous. However, although it is desirable to have common terminology, where a term used in different documents means the same thing, this may be optimistic because of historic differences between engineering fields. The difference in definitions between ADF and ADB2 is a good example of this.

It is desirable to have a single document to which all standards, guidelines, academic papers, and text books refer. Ideally this should be a revision of EN 12792 (BSI, 2003b) that corrects its conflicting definitions of *effective area*.

It is our view that the terms *free*, *effective*, and *equivalent* area are defined by Equations (1), (2), and (4), respectively. Section 2 shows that the application of a *free area* is problematic in practice and so we recommend that it is avoided. An *equivalent area* has a clear theoretical meaning but requires normalizing using the discharge coefficient of a standard circular sharp-edged orifice. This process could introduce uncertainty into its value. Accordingly, we believe that an *effective area, A_{eff}*, is the most parsimonious metric that has the least uncertainty in its value. Manufacturers of PPOs should report A_{eff} as a matter of best practice, in the absence of a legal requirement, and software tools should be amended to accept this metric. Design engineers should explicitly state A_{eff} on their drawings.

It should be noted that it is obviously problematic to use metrics measured under laboratory conditions to predict airflow found *in-situ*, especially for wind-driven ventilation (Etheridge, 2012). Nevertheless, this approach does facilitate the comparison of PPO performance and is currently the most parsimonious and pragmatic method available.

For most air vents and windows, where $L/d_h < 2$ (see Section 2.1), A_{eff} is likely to be weakly dependent on Re so that it can be considered negligible (Etheridge, 2012). Then, A_{eff} can be applied for all working environmental conditions. For PPOs with a variable A_f, such as windows, an indication of the change in A_{eff} with opening angle should be given. For longer openings, where $L/d_h > 2$, A_{eff} is likely to be dependent on Re and so a PPO manufacturer must be able to demonstrate this, perhaps using a plot of Re or $\bar{u}$ versus A_{eff}. For an

explanation of the underlying physics see Etheridge (2012, Section 3). Finally, the A_{eff} of tortuous airflow paths, such as through insect meshes or acoustic baffles, can be dependent on both Re and temperature difference (Holford & Hunt, 2001).

6   CONCLUSIONS

This paper shows that there are currently many definitions of areas used by standards, guidelines, text books, and software tools to describe the geometry of purpose provided ventilation openings. It also shows that each definition can be given multiple terms and that a single term can be assigned to different definitions. Some documents contradict themselves. This confusion can lead to unintended errors in practice, and there is emerging evidence of this. Accordingly, we propose three standard definitions of *free*, *effective* (A_{eff}), and *equivalent* areas. Standards, guidelines, and software tools should use an A_{eff} that is defined by Equation (2) as their default description of PPO area. It is imperative that PPO manufacturers give A_{eff} as standard and designers stipulate this in their designs. Guidelines and standards should recommend the provision of A_{eff} by manufacturers as best practice. These steps will help to reduce errors in the design of ventilation strategies that can lead to over or under ventilation, overheating, air quality and acoustic issues, excessive energy demand and associated carbon emissions, and high capital and running costs.

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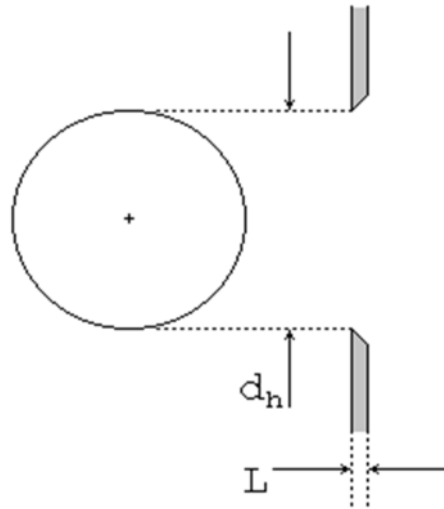
FIGURES

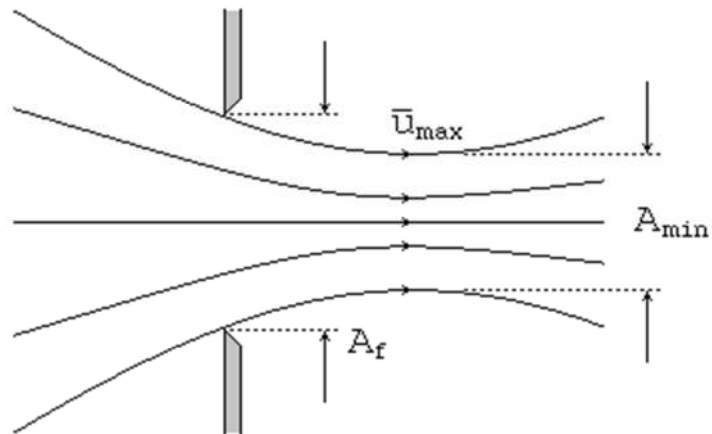Figure 1: Circular sharp-edged orifice where $d_h \gg L$.

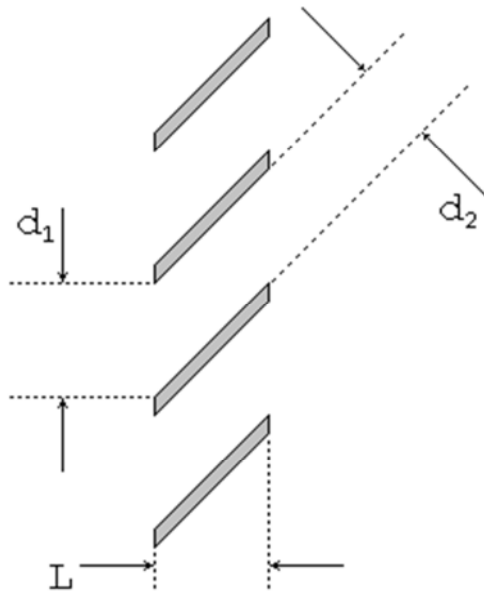Figure 2: A *vena contracta* located downstream of a sharp-edged orifice where $A_f > A_{min}$.

Figure 3: Ventilation opening with Louvres.

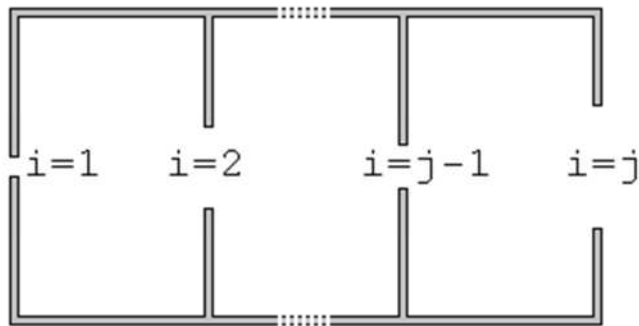Ambiguity in the specification of free area, A_f, where $d_1 \neq d_2$.

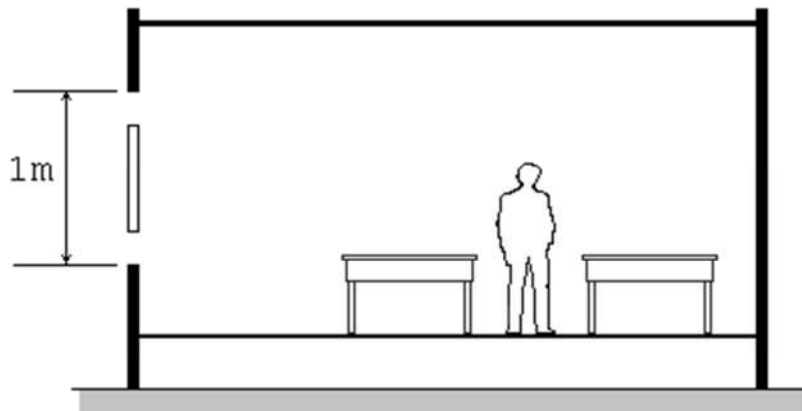Figure 4: A series of openings whose areas can be described by a single effective area, A_{eff}.

Figure 5: Example school classroom whose dimensions are given in Table 2.
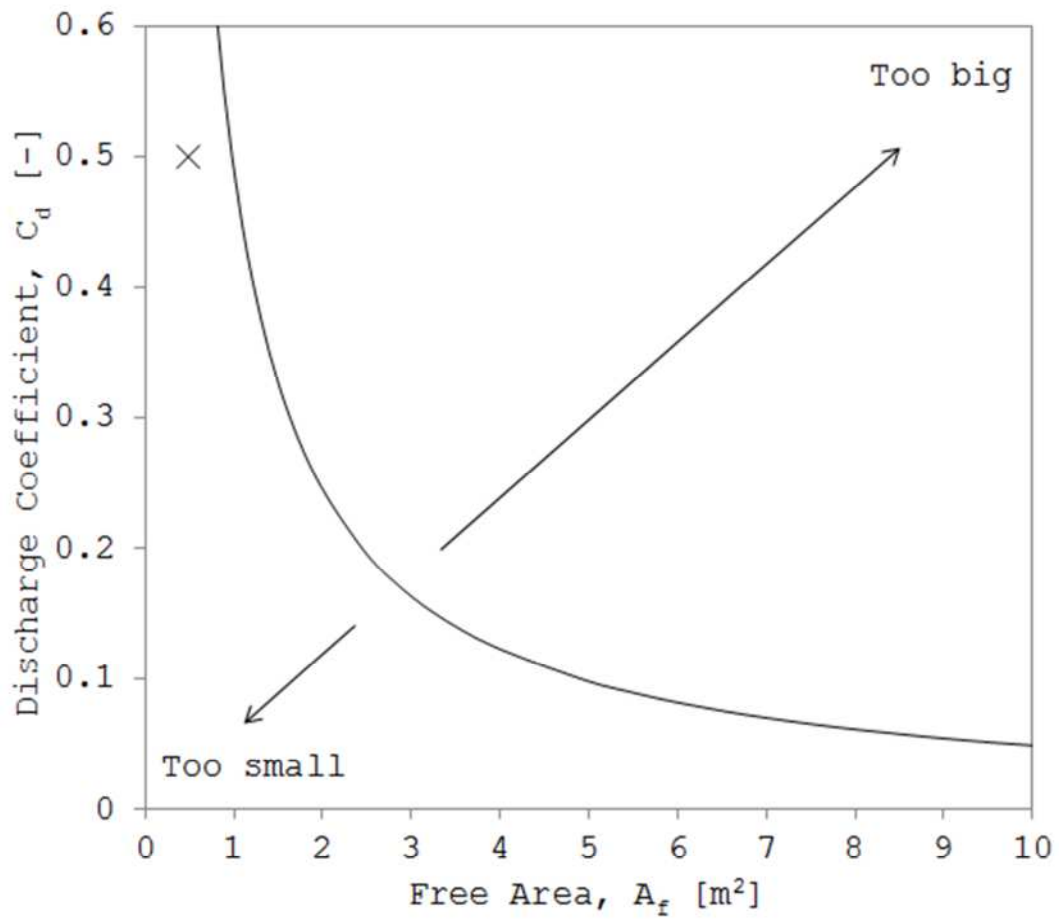
Figure 6: The simultaneous *free* area, A_f, and discharge coefficient, C_d, of an opening required

to achieve an *effective* area of $A_{eff} = 0.49\text{m}^2$.

×, marks $A_f = 0.49\text{m}^2$, $C_d = 0.5$, and $A_{eff} = 0.245\text{m}^2$.

TABLES

Table 1: Terms used to describe the areas of purpose provided openings used in documents relevant to the design of natural ventilation systems.

Origin	Document	Application of Terms
International	AIC (1981) [Now known as the Air Infiltration and Ventilation Centre] TN05. AIRGLOSS: Air Infiltration Glossary.	The term *effective orifice area* (page 26) is defined as the "area derived by assuming the value of the discharge coefficient associated with a sharp-edged orifice, generally speaking the area varies with flow rate."
		The term *open area* is used but undefined. From the document it can be assumed that this term is the same as the *free area* defined in Section 2.
		The term *equivalent area* is not used.
	Building Ventilation Theory and Measurement (Etheridge & Sandberg, 1996)	The terms *effective area* and *equivalent area* are described as equivalent (Section 2.6.3) and so are both defined by Equation (4), which we term A_{eq}.
	Natural Ventilation of Buildings. Theory Measurement and Design (Etheridge, 2012)	The term *free area* is not used but instead the term *defined area* is used (pages 31 and 341) to describe the area given in Equation (1).
		The term *effective area* is defined (page 341) using Equation (4), which we term A_{eq}.
		The term *equivalent area* is not used.
	Ventilation of Buildings (Awbi, 2003)	The term *free* area (page 187) is defined as the "sum of the smallest areas of all openings of an [Air Terminal Device] through which air can pass." This agrees with Equation (1).
		The term *effective* area is defined using Equation (2).
		The term *equivalent* area (page 127) is only used with reference to air leakage.

Origin	Document	Application of Terms
	Building Performance Simulation for Design and Operation (Hensen & Lamberts, 2011)	The term *effective* area (pages 166, 168) is not defined but may be inferred to agree with Equation (2). The terms *free* and *equivalent* area are not used.
	Air Conditioning Engineering (Jones, 2003)	The term *free* area (page 438) is used and, although it is undefined, it can be inferred that it agrees with Equation (1). The terms *effective* and *equivalent* area are not used. A term *reduced* area is used (page 423) that agrees with the definition of *effective area* given by Equation (2).
	AIVC GU03: A Guide to Energy Efficient Ventilation (Liddament, 1996)	The terms *cross sectional* (page 100) and *openable* (page 241) area are used to mean *free* area and defined by Equation (1). The terms *effective* and *equivalent* areas are used interchangeably (page 220) with specific reference to air leakage.
	A Handbook of Sustainable Building Design and Engineering (Mumovic & Santamouris, 2009)	The term *free* area (page 375) is used but undefined. The term *effective* area (page 240) is undefined but it can be inferred that it agrees with the definition of *free* area given by Equation (1). The term *equivalent* area is not used.
	Faber & Kell's Heating and Air-Conditioning of Buildings (Oughton & Wilson, 2015)	The term *free* area is used (pages 323, 527, 685, 909) but undefined. The *effective area* of a square or rectangular chimney is defined (page 334) as "the circle or ellipse which may be inscribed within them. The *equivalent diameter* of such flues is therefore the square root of the

Origin	Document	Application of Terms
		square or rectangular area."
	Passive Cooling of Buildings (Santamouris & Asimakopoulos, 1996)	The term *free* area is defined (page 225) using Equation (1). The terms *equivalent* and *effective* area are not used.
	Building Ventilation (Santamouris & Wouters, 2006)	The term *free* area is defined (page 220) using Equation (1). The term *effective* area is defined (page 141) using Equation (3) with specific relation to air leakage. The term *equivalent* area is defined mathematically (pages 5) and agrees with the definition of *free* area given by Equation (1).
Europe	EN 12792:2003 (BSI, 2003b) Ventilation for buildings. Symbols, terminology and graphical symbols.	The term *free area* is defined (number 188) as the "sum of the cross-sectional areas of all unobstructed openings measured in the plane of maximum restriction and at right angles to the flow through the opening." The terms *equivalent* and *effective areas* are defined (number 136) as the "area of a sharp edged circular orifice which would pass the same airflow rate and the same applied pressure difference as the product or device being tested." The term *effective area* is defined (number 42) as the "quotient resulting from measured airflow rate and measured air velocity as determined in a specified manner with a specified instrument".
	EN 13141-1 (BSI, 2004) Ventilation for buildings - Performance testing of components/products for residential ventilation.	Terms *effective area* is not used. The term *geometrical free area* is defined (section 3.14) as the "sum of the cross sectional areas of all unobstructed openings measured in the plane of maximum restriction and at right angles to the flow through the openings."

Origin	Document	Application of Terms
	EN 12101-2:2003 (BSI, 2003a) Natural smoke and heat exhaust ventilators (NSHEV)	The term *equivalent area* is defined (Section 3.13) as the "area of a sharp edged circular orifice which would pass the same airflow rate and at the same applied pressure difference as the product or device being tested." The term *aerodynamic free area* is defined (Section 3.1.2) as the "product of the geometric area multiplied by the coefficient of discharge." The term *geometric area* is defined (Section 3.1.11) as the "area of the opening through a NSHEV, measured in the plane defined by the surface of the construction works, where is contacts the NSHEV." The terms *equivalent area* and *effective area* are not used.
Ireland	Building Regulations Technical Guidance Document F: Ventilation (DEHLG, 2009)	The term *free area* is defined as "the geometric open area of a ventilator." The term *equivalent area* is defined (page 7) as "the area of a single sharp-edged hole that passes the same air volume flow rate at the same applied pressure difference as the vent being tested". It also states that and *equivalent area* is measured in accordance with EN 13141 (2004), but when unavailable the *free area* "may be used to assess compliance but the area of the ventilator required should be increased by 25%." The term *effective area* is not used.
USA	ASHRAE Fundamentals (2013)	The term *effective area* is defined (page 20.2) as the "net area of an outlet or inlet device through which air can pass equal to the free area times the coefficient of discharge." The term *equivalent area* is defined (page 16.15) in relation to air leakage only, and agrees with Equation (3).
UK	Building Regulations Approved Document F	The term *free area* is defined (page 8) as the "geometric open area of a ventilator."

Origin	Document	Application of Terms
	(2010a): Ventilation.	The term *equivalent area* is defined (page 8) as a "measure of the aerodynamic performance of a ventilator. It is the area of a sharp-edged circular orifice which air would pass through at the same volume flow rate, under an identical applied pressure difference, as the opening under consideration."
		The term *effective area* is not used.
	Building Regulations Approved Document B2 (2010b): Fire Safety	The term *aerodynamic free area* is defined (page 138) as the "total unobstructed cross sectional area, measured in the plane where the area is at a minimum and at right angles to the direction of airflow". It also states that the term can be "declared in accordance with EN 12101-2".
		The term *equivalent area* is not used.
		The term *effective area* is not used.
	BS 5925:1991 (BSI, 1991) Code of Practice for Ventilation Principles and Designing for Natural Ventilation.	The term *effective area* is not used.
		The term *equivalent area* is defined (Section 2.3) as the "area of a sharp-edged orifice through which air would pass at the same volume flow rate, under an identical applied pressure difference, as the opening under consideration."
		The term *effective equivalent area* is used (Section 12.2) but undefined.
	CIBSE (2005) Applications Manual 10: Natural Ventilation in Non-Domestic Buildings	The terms *equivalent area* is not used.
		The term *effective area* (page 56) is "usually defined as the area of a sharp-edged circular orifice that gives the same flow rate as the opening at a given pressure difference."
		The term *free area* is defined (page 56) as the "geometric area." It is noted that this may also be called the

Origin	Document	Application of Terms
		open area.
		The term *effective free area* is also used (page 22) but undefined.
	CIBSE (2015) Guide A: Environmental	The term *free area* is not used.
	Design	The term *effective area* is used but undefined. It is stated (page 4-27) that that the *effective areas* of a number of openings can be combined and agrees with the definition given in Section 2.
		The term *equivalent area* is used but undefined (page 4-17). It shows that Equation (1) can be used to obtain an equivalent area of a PPO using a pressure test. However, the text is ambiguous enough that a definition of *equivalent area* as Equation (2) or (4) cannot be determined.
	CIBSE (2002) Guide B: Heating, Ventilating,	The term *equivalent area* is used (page 2-111) but undefined.
	Air Conditioning and Refrigeration	The term *effective area* is defined (page 2-111) as the "area of a single sharp-edged hole (in a thin plate) that passes the same volume airflow rate and at the same applied pressure difference as the vent being tested."
	CIBSE (2007) Guide C: Reference Data	The terms *effective* and *equivalent areas* are not used.
		The term *free area* is used (Table 4.12) but undefined.
Software	EnergyPlus (DoE, 2015a,b)	All area terms used but undefined. The text frequently refers to ventilation models given in ASHRAE (2013) and to those from academic sources.
	Design Builder[§] (2015a,b)	The terms *free*, *effective* or *equivalent* areas are not used.

[§] There are a number of dynamic thermal software tools that use EnergyPlus as their calculation engine; a comprehensive list can be found at https://energyplus.net/interfaces.

Origin	Document	Application of Terms
		A C_d can be defined for any PPO using the *advanced model options*. A user draws the *free area* of the vent, specifies an opening percentage, and the C_d is applied to this opening by the EnergyPlus Airflow Network.
	CONTAM (Walton & Dols, 2014)	The terms *free* and *effective area* are used but undefined.
		The term *cross-sectional area* is defined (page 54) as the "observable area of an opening."
	IES (2015)	The terms *free* and *effective area* are not used.
		The term *equivalent area* is defined as the "area of a sharp edged orifice through which air would pass at the same flow rate, under an identical applied pressure difference, as the opening under consideration."
		The terms *openable area* and *geometric free area* are used but undefined. It can be inferred that the *openable area* is the proportion of the modelled PPO geometry that allows airflow.
		The term *equivalent orifice area* is defined as the "actual sharp edge orifice area as a percentage of the gross physical opening drawn in the model, and is a means for the user to define the equivalent area of a vent."
		PPO geometry is defined by the user using Macroflo (IES 2015). The opening type and openable percentage can also be defined. A C_d for a PPO is pre-set to 0.62 and cannot be defined by the user. An *equivalent* area (see Equation (4)) is calculated from these inputs.
	TAS (2015)	The terms *free*, *equivalent* and *effective area* are not used when discussing flow through PPOs, with the exception of information pertaining to plume flow through horizontal openings, where the term *effective aperture area* is used but undefined.
		A C_d for a PPO is pre-set to 0.62 and cannot be defined by the user. To create a PPO, the *free* area of the vent

Origin	Document	Application of Terms
		is drawn and an opening percentage is specified. The drawn *free* area must be adjusted to account for any vents where $C_d \neq 0.62$. In essence, the user must draw an *equivalent area* (see Equation (4)) rather than a *free area* (see Equation (1)).

Table 2: Classroom properties.

Location	Norwich, UK 52.6N, 1.3E
Geometry	Floor area: $55m^2$ Floor to ceiling height: 3m
Glazing	Area: $8m^2$ Orientation: South West
Casual heat gains	Number of occupants: 32 (at approximately 70W per person) IT equipment: 300W Lighting: $8W/m^2$
Fabric	Floor: timber Ceilings and walls: plasterboard
Ventilation	Controlled natural ventilation via single sided high and low openings (height difference of 1m) Secure night cooling available