Energy and Buildings 126 (2016) 463–476

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

On-site assessment of the discharge coefficient of open windows

Hildebrando Cruz, João Carlos Viegas *

Laboratório Nacional de Engenharia Civil, Av. do Brasil, 1700-066 Lisboa, Portugal

ARTICLE INFO

Article history:
Received 14 October 2015
Received in revised form 16 May 2016
Accepted 17 May 2016
Available online 19 May 2016

Keywords:
Natural ventilation
Discharge coefficient
Flow rate
Windows flow

ABSTRACT

For assessing the discharge coefficient of an opening it is necessary to measure, as accurately as possible, the flow rate and the corresponding pressure difference that occurs when the fluid passes through it. When the openings are as big as windows applied in common building spaces the open section of the window is not negligible when compared with the cross-section of the room. In these conditions, the flow velocity in the room is not negligible and the obstructions (e.g., furniture) are prone to have a higher influence on measurements. In addition, the external windows are subject to the wind action, which may also impair the measurement. Even though these are not the ideal conditions, they are the common conditions in which natural ventilation occurs. In this paper, on site measurements of the discharge coefficient of open windows were carried out and the feasibility of these measurements was evaluated. Two methods were used (flow driven by a fan and flow driven by wind action) and compared. It is shown that the discharge coefficient of a side-hung casement window with a roller shutter may range from $C_d = 0.41$ to $C_d = 0.81$ and that the discharge coefficient of a bottom hung casement window is $C_d = 0.84$.

1. Introduction

Current lifestyle in most developed countries is responsible for people spending, on average, in their daily activities, more than 80% of their time in buildings [1], which fosters longer exposures to high concentrations of indoor pollutants. Ventilation is currently used to exhaust indoor air pollutants to the exterior and to keep their indoor concentration as low as reasonable. In Mediterranean countries, natural actions are commonly used to produce ventilation, improve indoor thermal comfort and reduce indoor pollutant concentration. In tropical and temperate climates, window opening is intended to intensify ventilation rates and thus provide high flow rates for summer comfort, the latter depending mainly on wind action [2]. This ventilation process, when compared to the mechanical one, leads to energy savings, but depends on wind direction and intensity and on the temperature difference between the interior and the exterior [3].

Within the framework of ENVIRH (Environment and Health in Children Day Care Centres) and GERIA (Indoor Air and Respiratory Health in residents of Elderly Care Centres) research projects, funded by the Portuguese Foundation for Science and Technology (FCT), it was necessary to develop accurate computational simulation tools for building ventilation. Even though the simulation methodology does not pose major difficulties, the careful characterization of the building envelope, of the inner obstacles to flow [4] and of the wind action on the building (usually expressed in terms of pressure coefficients) is a complex task. An inadequate assessment of these characteristics can easily lead to large deviations between the computational predictions and the measured ventilation conditions. In this research, it was observed that the windows of the buildings under study (day care centres) remain open for ventilation during a significant part of the day. Thus, it is necessary to characterize in detail the flow driven by the wind through these openings. With this purpose, a test method was developed, with a view to determine the on-site discharge coefficients for windows; this paper addressing the development of this method. These discharge coefficients depend on the opening position of windows and on the position of shutters [5].

For assessing the discharge coefficient of an opening it is necessary to measure the flow rate and the pressure difference that occurs when the fluid passes through it. Usually these measurements are carried out in laboratory in order to avoid disturbances that could affect accuracy [3–7].

Chiu [8] carried out some experiments to determine the discharge coefficient (C_d) value for a sharp-edged circular orifice in still-air conditions. He found some dependence of C_d on the Reynolds number (Re), the average value of C_d, for the highest Re, being about 0.71, which is nearly 10% higher than that normally

* Corresponding author.
E-mail addresses: hildebrando.cruz@gmail.com (H. Cruz), jviegas@lnec.pt (J.C. Viegas).

http://dx.doi.org/10.1016/j.enbuild.2016.05.051
0378-7788/

Nomenclature

A	cross section of the door measurement
A_{md}	area of the measurement device opening
A_{window}	window opening area
C_d	discharge coefficient
D_h	hydraulic diameter
n	number of readings
P	perimeter of the cross section of the door measurement
Q	flow rate
Re	Reynolds number
Re_{door}	Reynolds number of the flow through the door measurement device
Re_{window}	Reynolds number of the flow through the wide-open window
$U_{95\%}(C_d)$	expanded uncertainty of the discharge coefficient
$U_{95\%}(v)$	velocity expanded uncertainty
$U_{95\%}(\dot{V})$	flow rate expanded uncertainty
$U_{95\%}(\Delta P)$	pressure difference expanded uncertainty
V	flow velocity
V_{window}	average velocity of the flow through the window
V_{md}	average flow velocity in the measurement device opening
$\bar{V}$	average velocity
$\dot{V}_{mro}$	air permeability of windows and of the roller shutter boxes of the meeting room and office
$\dot{V}_{window}$	flow rate across the window
ΔP	pressure difference between adjacent spaces
ΔP_{din}	weighted dynamic pressure difference
ΔP_{window}	pressure difference across the window
v	kinematic viscosity of air
ξ	pressure loss coefficient
ρ	flow density

associated with sharp-edged circular orifices. He suggests that the real shape of the orifice edges is different from the theoretical sharp-edged and that the opening does not lie in an infinite plane surface (e.g., porosity is not negligible). Furthermore, the author [8] found a dependence of the C_d value on the external wind action, in which values as low as 0.25 may be reached. This influence of wind action varies with the opening shape (orifice or long opening) and with the flow direction (exposed inlet or exposed outlet). He found that, for the long opening, the wind effect on the C_d value was negligible when the outlet was exposed to the external flow.

Usually, the C_d adopted for windows is the same as the one adopted for the sharp edged orifice, which ranges from 0.60 to 0.65 [2]. Awbi [9] mentions that although the discharge coefficient is almost independent from the Reynolds Number, the value of C_d is not constant and depends on the geometry of the opening and on the variation in the pressure difference with the environmental conditions (inside and outside the building). Moreover, Awbi [9] recommends using building pressurization and depressurization tests to assess the effective leakage area (C_dA, where A is the free area of the opening). It is known that the value of the discharge coefficient may vary with the opening area. Heiselberg [6] reports that, for a side-hung window, C_d lies between 0.65 and 0.77, for opening areas of 0.49 m^2 and 0.62 m^2 and between 0.83 and 1.0, for areas of 0.16 m^2, 0.10 m^2 and 0.04 m^2. He reports also that, for a bottom-hung window, C_d lies between 0.78 and 1.0 for opening areas of 0.019 m^2 to 0.045 m^2. He shows also that there is a reduction in the C_d value for bottom-hung window when the pressure difference increases and that an almost constant value is obtained above 10 Pa.

It is relevant to stress that for the natural ventilation process the pressure difference is commonly below 10 Pa, whenever the reported [6] C_d values for a bottom-hung window are higher than 0.82. Regarding this feature, Awbi [9] states that only for large openings the C_d value is close to 0.6. It is also known that the C_d value may change if the porosity of the wall is higher than 20% [3]. In Heiselberg [6], the tests were performed with the flow coming from the outside face of the window to the inside (inflow).

The variation in C_d shows that this value depends on several factors and therefore, the estimation of this coefficient may involve significant errors. In order to reduce such errors, it is relevant to develop techniques for performing on site measurements as easily and accurately as possible. Such techniques should allow measuring C_d in real conditions, including the furniture that is inside the rooms and which may cause disturbances in the flow. In fact, the on-site measurements are conditioned by the position of the opening in the room, by the shape and volume of the room and by the position of obstacles [4]. Moreover, the devices used to measure the flow rate may condition the pressure difference measurements, if the two measurements are carried out simultaneously on the same opening. When the openings are as big as windows applied in common building rooms the open section of the window is not negligible when compared with the cross section of the room in the flow path [4]. In these conditions, the flow velocity in the room is not negligible and the obstructions (such as furniture) are prone to have a higher influence on measurement. The wind action may impair the measurement on the outside face of the window [7,8,10]. However, it should be recognized that these are the common conditions in which natural ventilation occurs. Thus, the measurement of the window discharge coefficients under the same conditions as the real ventilation flows has a high potential interest. Moreover, in this particular case, the outflow (air flow from indoors to outdoors) conditions are studied. Finally, if the measurement technique is not too complex, on site measurements become less expensive than laboratory measurements, because in the latter it is necessary to reproduce the site characteristics.

For the purpose, a test method for determining on site discharge coefficients for windows has been developed. This method consists in pressurizing a room (using a blower door; this device includes an axial fan that can replace the door leaf and allows for pressurizing or depressurizing a compartment) so as to obtain an approximately constant pressure differential and relatively independent from the direction and intensity of the wind. Furthermore, a complementary and innovative method was developed and compared with the blower door method, which makes it possible to measure C_d using the wind action, being hence very close to the actual conditions of a window use for natural ventilation.

This paper refers to the development of on-site measurements of the open window discharge coefficient and evaluates their feasibility, validation and application, with emphasis on the use of wind-driven flow. The two methods used (fan-driven flow and wind-driven flow) are compared, the latter proving to be a good means to assess the discharge coefficient. From this study, it was possible to conclude that the discharge coefficients depend on the opening position of windows and on the position of shutters [11].

2. Theoretical and experimental background

The airflow through a building compartment under natural ventilation can be considered as an incompressible flow. Eq. (1), obtained from Bernoulli equation, relates the pressure difference across the window, ΔP_{window}, with the flow rate, $\dot{V}_{window}$, for a given pressure loss coefficient ξ, an opening area A_{window} and a flow density ρ, and considering a fully turbulent flow. Very often