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DEVELOPMENT OF AN EMPIRICAL METHOD FOR CALCULATING DISCHARGE COEFFICIENTS FOR CONTAM MODELS

Hao Zhou, Yichun Huang, Gavin Xue, Chen Chen
EMSI, Shanghai, China

ABSTRACT

Computational Fluid Dynamics (CFD) is a powerful and expensive technique to simulate natural ventilation. CONTAM, as an alternative computer program, is based on the bulk airflow network model therefore it is less computationally expensive. However, some key inputs, such as discharge coefficients, require user specifications.

This study develop empirical equations for calculating window discharge coefficients of two common types of opening configurations: awning windows and blinds. An automated process combining CFD, Rhino scripts and the Grasshopper plug-in is introduced for data generation for the regression study. Derived from the regression analysis, the empirical equations can help designers to simplify natural ventilation study with acceptable quality.

INTRODUCTION

Natural ventilation is of great importance to people's comfort and health as well as environmental sustainability related to wind environment. CFD tools, such as FLUENT, are powerful and credible to simulate indoor and outdoor wind environment. However in actual projects, given the geometrical complexity of ventilation devices resulting in enormous mesh cells, it is impossible to carry out holistic CFD simulation on every building with intricate ventilation devices, as it would cost unnecessary and unaffordable computational resource. Thus, systematic software is developed to deal with the situation, and to precisely predict behavior of fluid usually requires corporation between systematic software, such as CONTAM, and CFD methods (Tan and Glicksman 2005).

Previously, models of discharge coefficient in ASHRAE handbook were studied, and were developed mathematically into new expressions, which were compared with CFD simulation and experimental results to confirm the accuracy before applied to CONTAM software (Wang and Chen 2012) (Wang, et al. 2015).

When modelling natural ventilation in CONTAM, flow coefficients as shown in Figure 1 need to be specified when defining each airflow path (such as window), if discharge coefficient model is referred. In CONTAM user guide, common reference conditions given in ASHRAE book are introduced, and users are suggested to set the coefficient as constant (1.00 or 0.611) regardless of the type of flow path, which would actually bring about error (Dols and Polidoro 2015). Thus, expressions to predict the coefficient based on geometrical parameters of various ventilation devices are needed, so that the systematic simulation would be credible and accurate.

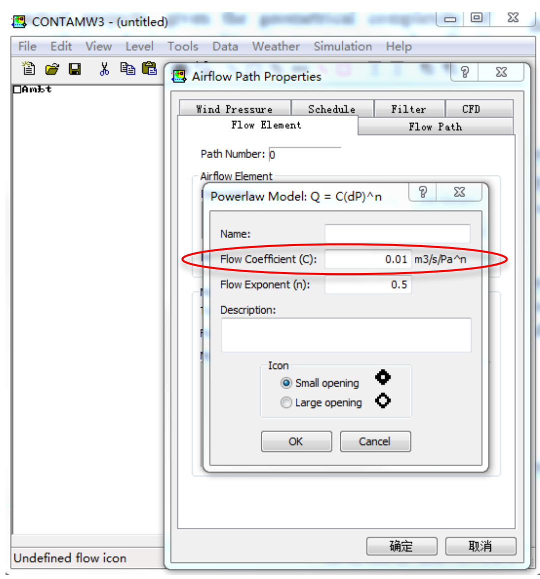


Figure 1 Input of flow coefficient in CONTAM

Previous studies have provided qualitative analysis of relationship between the discharge coefficient and potentially relevant geometric parameters (Zhou, et al. 2006) (Gong, et al. 2009) (Wang, et al. 2012). Nonetheless, a detailed study with credible quantified analysis is still required.

This paper aims to give empirical relationship between coefficients and parameters to which can be referred in systematic simulation software. Not only awning windows but also venetian blinds are involved in the study. The empirical study and expressions in the paper provide a database and methodology to approach this type of problem.

THEORY AND FLUENT MODEL

The concept of Applied Discharge Coefficient (ADC) is introduced in this chapter. The discharge coefficient is defined in fluid mechanics as

$$\mu = \sqrt{\frac{\frac{1}{2}\rho v^2}{\Delta p}}. \qquad (1)$$

where μ is the discharge coefficient, $\frac{1}{2}\rho v^2$ is the dynamic pressure, Δp is the static pressure. Replace velocity v with fluid flux Q

$$Q = vA \qquad (2)$$

where v is the flow velocity crossing the device, and A is the open area, i.e. window height times width, and after rearrangement, we can get

$$Q = \sqrt{\frac{2}{\rho}} \cdot \mu \cdot A \cdot \Delta p^{0.5} \qquad (3)$$

where $C_a = \sqrt{\frac{2}{\rho}} \cdot \mu$ can be defined as ADC, $C = C_a \cdot A$ can be defined as flow coefficient which is used by CONTAM.

A wind tunnel model (See Figure 2) in ANSYS FLUENT is built with pressure controlled import and export surface, and both upstream and downstream are fully developed. The turbulence model is based on the Realizable *k*-*ε* two-equation model that solves two transport equations and models the Reynolds Stresses using the Eddy Viscosity approach. The governing equations are composed of continuity equation, momentum equation, turbulent pulsating kinetic energy *k* equation, turbulent energy dissipation *ε* equation and determining turbulence coefficient equation. The boundary conditions and physics models are shown in Table 1.

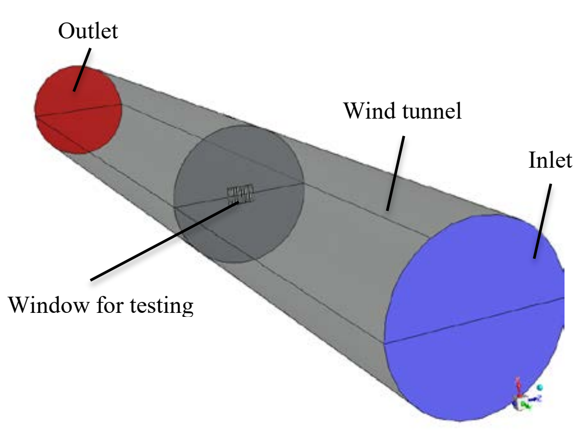
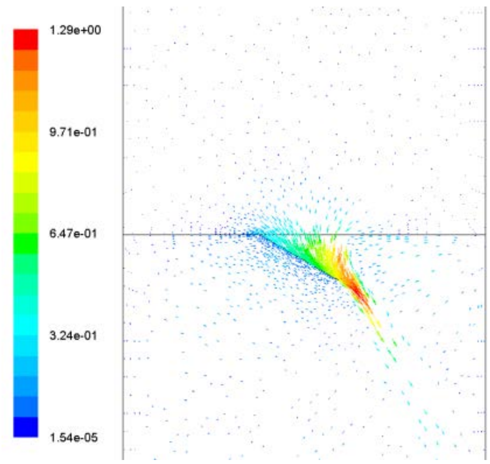


Figure 2 The wind tunnel CFD model

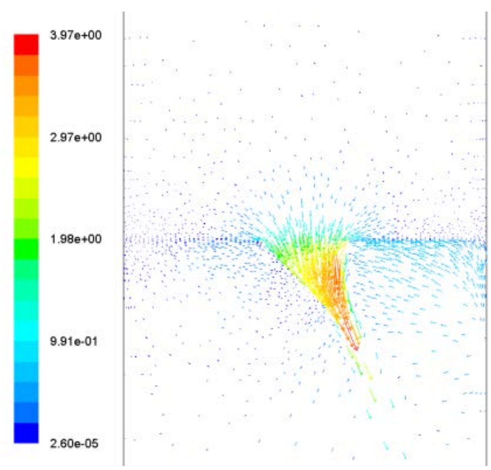
Table 1 CFD model setup

INLET	Pressure inlet
OUTLET	Pressure outlet
FLUID DOMAIN	Symmetry
FLUID MATERIAL	Air (constant density)
TURBULENCE MODEL	Realizable *k*-*ε* two-equation model

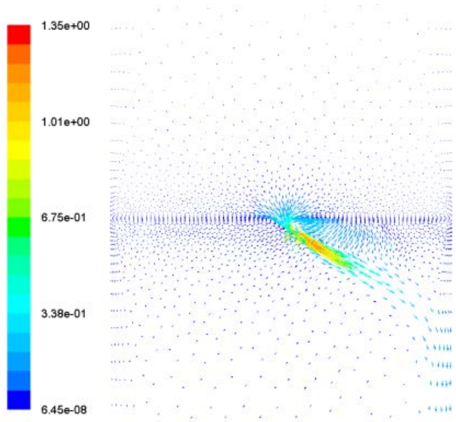
Some of the simulation results are demonstrated in Figure 3.



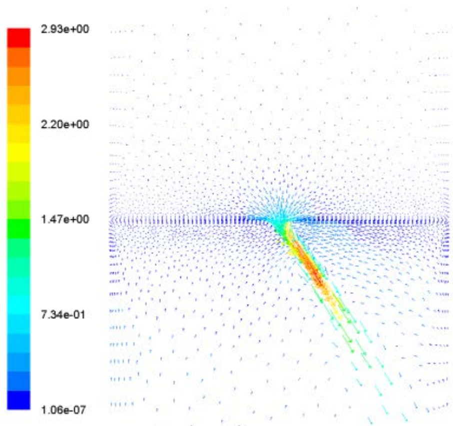
(a) *500*1000mm awning window with a 30° open angle*



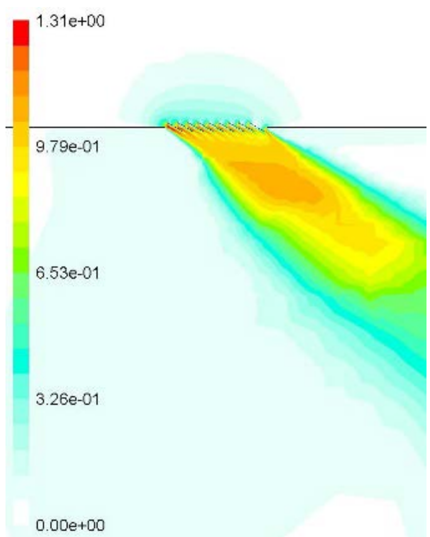
*(b) 500*300mm awning window with a 45° open angle*



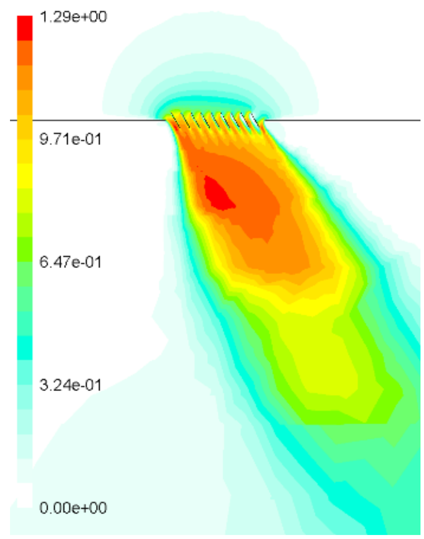
*(c) 500*300mm awning window with a 30° open angle*



*(d) 500*300mm awning window with a 45° open angle*



(e) blind window with 72mm fin interval distance, 120mm fin length and a 30° incident angle



(f) blind window with 72mm fin interval distance, 120mm fin length and a 60° incident angle

Figure 3 Vector grams and velocity contours

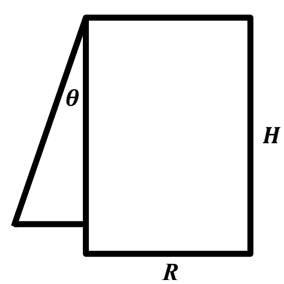
Velocity unit: m/s; pressure difference: 1Pa

RELEVANT PARAMETER SIFTING

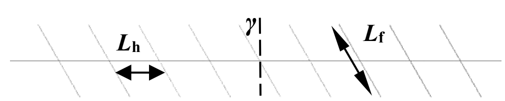
As for an awning window, the potential relevant geometrical parameters of ADC are: open angle θ, window width R_{window} and window height H_{window}.

As for a Venetian blind, the potential relevant geometric parameters of ADC are: incident angle γ, fin interval distance L_h, fin length L_f, blind width R_{blind} and blind height H_{blind}.

The brief illustration of the geometries is shown in Figure 4.



(a) Awning window



(b) Venetian blind

Figure 4 Ventilation device geometries

Previous research indicated that the value of ADC remains approximately constant when increasing H_{window} and R_{window}, but keeping $r = H_{\text{window}} / R_{\text{window}}$ as constant (Zhou, et al. 2006) (Gong, et al. 2009) (Wang, et al. 2012). The paper verified the conclusion, thus for awning window:

$$C_a = \emptyset(\theta, H_{\text{window}}, R_{\text{window}}) = \emptyset(\theta, r) \tag{4}$$

There are 5 potential relevant geometrical parameters of ADC of Venetian blind, but not every parameter might have significant effects on the value of ADC, the following process uses mathematical methods to filter relevant parameters.

First of all, we discovered that when increasing L_f and L_h, but keeping $t = L_f / L_h$ as constant, the value of ADC remains approximately constant in the range of ordinary specifications of venetian blinds ($L_f \leq$ 120mm, $L_h \leq$ 75mm). The approximation errors are shown in Table 2.

Table 2 Error (e) analysis

γ	t	$\left(\frac{L_f}{L_h}\right)_1$	$\left(\frac{L_f}{L_h}\right)_2$	e (%)	γ	e (%)	γ	e (%)
60	0.67	$\frac{20}{30}$	$\frac{50}{75}$	2.6	**45**	2.9	**30**	2.6
60	1.25	$\frac{50}{40}$	$\frac{90}{72}$	1.2	**45**	1.8	**30**	2.1
60	1.67	$\frac{50}{30}$	$\frac{120}{72}$	3.9	**45**	3.8	**30**	4.6
60	3	$\frac{90}{30}$	$\frac{120}{40}$	2	**45**	2.1	**30**	1.3

Secondly, the paper defines the impact factor P_x as

$$P_x = \frac{S_{Ca}/(C_a)_{st}}{S_X/(X)_{st}} \tag{5}$$

where X is a geometric parameter,

i.e. X={ γ, t, R_{blind}, H_{blind}} (6)

The subscript *st* means to calculate the sample mean value. *S* is the variance.

The impact factor can be used to identify elements that have a greater impact on the ADC and ignore the secondary factors whose impact factors are not in the same order of magnitude. The original CFD simulation data are processed and the calculation results are recorded in Table 3.

Table 3 The impact factors of geometric parameters

n	γ	$\mathbf{t < 1.5}$	$\mathbf{H_{window}}$	$\mathbf{t > 1.5}$	$\mathbf{W_{window}}$
$\boldsymbol{P_x}$	0.6511	0.2340	0.0536	0.0269	0.0061

It is obvious that γ and t plays more important roles in defining ADC. Thus, for Venetian blinds:

$$C_a = \emptyset(\gamma, H_{\text{window}}, R_{\text{window}}, L_f, L_h) = \emptyset(\gamma, t) \tag{7}$$

ADC POLYNOMIAL FITTING

After carrying out 36 sets of experiments on awning windows in FLUENT, the trend is shown in Figure 5.

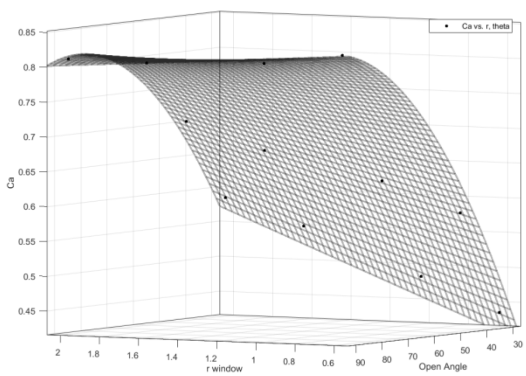


Figure 5 Discharge Coefficient Surface of awning windows

The result of second order polynomial fitting is

$$C_a = p_{00} + p_{10} \cdot r + p_{01} \cdot \theta + p_{20} \cdot r^2 + p_{11} \cdot r \cdot \theta + p_{02} \cdot \theta^2 \tag{8}$$

where p_{00} = -0.07865 , p_{10} = 0.1678 , p_{01} = 0.01753 , p_{20} = 0.0007429 , p_{11} = -0.002037 , p_{02} = -8.19e-05. The fitting variance is 0.9991, and SSE is less than 0.0002, and the actual error is about 1%.

After 60 sets of experiments on venetian blinds in FLUENT, the trend is shown in Figure 6.

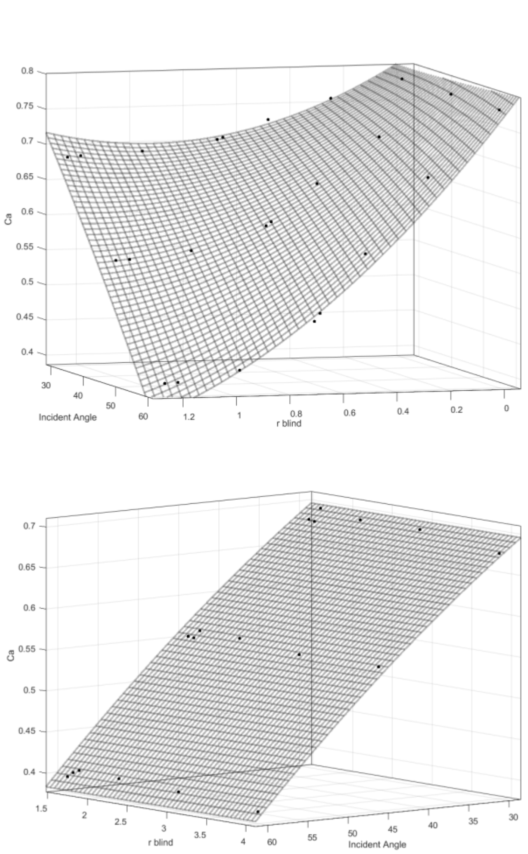


Figure 6 Discharge Coefficient Surface of venetian blinds

When t<1.5, the result of third order polynomial fitting is

$$C_a = p_{00} + p_{10} \cdot t + p_{01} \cdot \gamma + p_{20} \cdot t^2 + p_{11} \cdot t \cdot \gamma + p_{02} \cdot \gamma^2 + p_{30} \cdot \gamma^3 + p_{21} \cdot t^2 \gamma + p_{12} \cdot \gamma^2 t \quad (9)$$

where p_{00} = 0.7486 , p_{10} = 0.269 , p_{01} = 0.001436 , p_{20}= -0.1694 , p_{11}=-0.0117 , p_{02} = 0.00001159, p_{30}= 0.03966, p_{21} = 0.004569, p_{12} = -0.00002138. The fitting variance is 0.9972, and SSE is less than 0.001, and the actual error is about 1%.

When t<1.5, the result of second order polynomial fitting is

$$C_a = p_{00} + p_{10} \cdot t + p_{01} \cdot \gamma + p_{20} \cdot t^2 + p_{11} \cdot t \cdot \gamma + p_{02} \cdot \gamma^2 \quad (10)$$

where p_{00} = 0.7665 , p_{10} = -0.01218 , p_{01} = 0.002181 , p_{20}= 0.1256 , p_{11}= -0.007613 , p_{02} = -0.00003327. The fitting variance is 0.9859, and SSE is less than 0.005, and the actual error is about 2%.

When t>1.5, the result of second order polynomial fitting is

$$C_a = p_2 \cdot \gamma^2 + p_1 \cdot \gamma + p_0 \quad (11)$$

where p_2 = -0.00009919 , p_1 = -0.0004648 , p_0 = 0.7827. The fitting variance is 0.9993, and SSE is less than 0.0001, and the actual error is about 1%.

EVALUATION ON THE PROCEDURE

Taking the huge number of sets of experiments into consideration, there would be over a hundred ventilation models to be established by CAD tool. However, they are similar in geometry, and are controlled by several parameters. If the models are manually established one after another, tedious and meaningless repetition would waste large amounts of time. Introducing parametric modelling by programming Rhino scripts and assembling Grasshopper (GH) batteries would improve the efficiency.

GH can automatically control Rhino to adjust the size of the windows, while Rhino scripts can realize to generate geometric files in batch.

The logic of the Rhino scripts and GH plug-in interacting with each other is shown in Figure 7. The automated modelling procedure greatly improved the efficiency of the researching process.

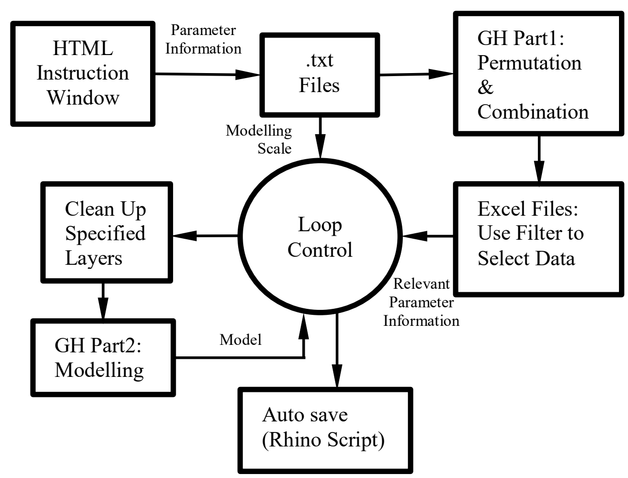


Figure 7 Parametric modelling logic

Above all, the whole procedure of finding the discharge coefficients can be concluded as a guideline shown as a flow chart in Figure 8.

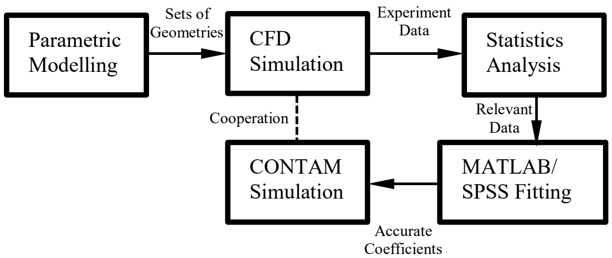


Figure 8 The complete workflow of the development methodology

CONCLUSION

The paper discovered quantified relationships between Applied Discharge Coefficients and geometrical parameters of different types of ventilation devices. It provides a guideline to build up virtual connection between systematic simulation (CONTAM) and CFD simulation (FLUENT), with the help of parametric modelling, statistics analysis and fitting tools, so that efficiency and accuracy can be ensured.

REFERENCES

Tan, Gang. and Glicksman L R (2005). Application of integrating multi-zone model with CFD simulation to natural ventilation prediction. *Energy and Buildings 37(10)*, 1049-1057.

Wang, Haojie. and Chen, Qingyan (2012). A new empirical model for predicting single-sided, wind-driven natural ventilation in buildings. *Energy and Buildings 54*, 386-394.

Wang, Haojie. Karava P. and Chen, Qingyan (2015). Development of simple semiempirical models for calculating airflow through hopper, awning, and casement windows for single-sided natural ventilation. *Energy and Buildings 96*: 373-384.

Dols, W S. and Polidoro, B J. CONTAM User Guide and Program Documentation Version 3.2. [1/9/2017]. http://dx.doi.org/10.6028/NIST.TN.1887 : 55, 257-260.

Zhou, J. Zhang, G. Xu, Y. et al (2006). Discussion on influencing factors of opening discharge coefficient in natural ventilation. *HV&AC 36(12),* 42-45

Gong, Binbin. Gao, Hongbo. and Qian, Ji (2009). Effects of Greenhouse Side-window Opening Forms on the Value of the Flow Coefficient. *Journal of Anhui Agricultural Sciences 37(20):* 11-15

Wang, Long. Pan, Yiqun. and Huang, Zhizhong (2012). Analysis of Influence Factors of Natural Ventilation Flow Coefficient of Exterior Window. *Building Energy Efficiency 40(6)*: 12-14