Review and comparative assessment of engineering correlations for the fire-induced air inflow rate through a compartment opening

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ABSTRACT

In a building fire, the initial fire compartment is rarely airtight, since it is quite common for some opening (e.g. door, window) to be present, either by chance (e.g. a window left open) or due to the failure of the glazing in a high temperature environment. The opening provides essentially a physical connection of the fire compartment to either the ambient environment or an adjacent room. The developing fire-induced buoyant flow is significantly affected by the presence of an opening, since an open vent provides a means for ambient air to enter the compartment (air inflow through the bottom section of the opening) and for gaseous combustion products, or even flames, to exit the compartment (plume outflow through the top section of the opening). In the context of building fire safety design, it is commonly required to estimate the characteristics of the fire-induced opening flow (or “vent flow”), since the ambient air inflow rate is the main parameter affecting fire ventilation conditions and can thus determine whether over- or under-ventilated fire conditions will prevail. As a result, the air inflow rate through an opening has a significant impact in several important fire development characteristics, such as fire spreading rate, compartment temperature, flashover or backdraft hazards etc.

There are several works available in the open literature that focus on developing appropriate fire engineering correlations to accurately estimate the fire-induced opening air inflow rate. These correlations are commonly used in simplified pre-flashover fire simulation tools (e.g. two-zone models). However, despite the importance of this parameter, a general consensus has yet to be achieved. The majority of the available correlations are semi-empirical in nature, where a general analytic opening flow model is combined with experimental results obtained in relevant fire tests. In addition, there are certain empirical parameters appearing in various correlations (e.g. flow discharge coefficient) or other parameters that require prior experimental observations, which may not always be available (e.g. thermal discontinuity height). Motivated by this observation, this work is aimed at evaluating a broad range of available fire engineering correlations for the estimation of the fire-induced air inflow rate through an opening; the correlations are validated and comparatively assessed by comparing the respective predictions with experimental data obtained in eight large-scale fire tests, all performed in fire compartments with a single door-type opening.

Nine different correlations available in the open literature are evaluated in this work; the original correlations are cast in a common format, using identical symbols to facilitate comparison. Aiming to evaluate the various correlations’ performance, measurements of air mass flow rate through the opening, obtained in eight different large-scale fire tests, are used; the employed fire tests span a broad range of operational conditions, such as fire heat release rate (32 - 320 kW), burner position (back, centre, front), burner elevation (0 - 0.3 m) and ventilation factor (1.83 - 2.17 \(m^{5/2}\)).

In general, the investigated correlations are found to exhibit disparate levels of prediction accuracy. The majority of correlations over-predict the measured air inflow rate values, therefore yielding “conservative” results, appropriate for fire engineering design purposes. The correlation of Tewarson (1984) is found to provide the most accurate results (average error: 12.9%). Predictions are further analysed to determine the main physical parameters affecting the prediction accuracy; changing the burner location and elevation is found to significantly affect the quality of the obtained results.

KEYWORDS:

modelling; compartment fires; fluid dynamics; vent flow; fire-induced flow; fire engineering design; two-zone models
1. INTRODUCTION

In a building fire, the initial fire compartment is rarely airtight, since it is quite common for some opening (e.g. door, window) to be present, either by chance (e.g. a window left open) or due to the failure of the glazing in a high temperature environment. Openings provide a means of physical connection between the fire compartment and the ambient environment. A fire-induced buoyant flow is developed through the opening; in general, gaseous combustion products (or flames) exit the compartment (outflow) through the top section of the opening, whereas ambient air enters the compartment (inflow) through the bottom section of the opening. In the context of building fire safety design, it is commonly required to quantify the fire-induced opening flow (or “vent flow”); for instance, the ambient air inflow rate is the main parameter affecting fire ventilation conditions and can, therefore, determine whether over- or under-ventilated fire conditions will prevail. As a result, the air inflow rate through an opening has a significant impact in several important fire development characteristics, such as fire spreading rate, compartment temperature, flashover or backdraft hazards etc.

In a typical simplified pre-flashover fire safety engineering approach (e.g. two-zone model) there are two main opening flows taken into account, i.e. the air inflow rate and the gaseous combustion products outflow rate (Fig. 1). In order to estimate the air mass flow rate entering the fire compartment through an opening, a broad range of semi-empirical engineering correlations are available in the open literature. These correlations are commonly used in the context of fire safety engineering analysis, since the air mass flow rate determines the development of either over- or under-ventilated fire conditions inside the compartment, thus significantly affecting the fire growth rate. The semi-empirical nature of the available air mass inflow rate correlations means that the values of several parameters are either empirically determined (e.g. discharge coefficient) or require prior experimental measurements, which may not always be available (e.g. thermal discontinuity height).

In this context, this work aims to comparatively assess a broad range of semi-empirical correlations available in the literature, used for the estimation of the fire-induced air inflow rate through a compartment opening. Nine different correlations are evaluated by comparing their predictions to available measurements, obtained in eight large-scale fire compartment tests; all the considered cases corresponded to a single compartment with a single door-type opening.

2. FIRE-INDUCED OPENING FLOWS

A sketch of an idealised fire-induced opening flow in a pre-flashover compartment fire is depicted in Fig. 1. The initial transient stage is neglected, therefore it is assumed that steady-state conditions have been achieved. In this case, the compartment is essentially divided in two, vertically separated, “zones”: the fresh ambient air, entering through the opening, is assumed to occupy the bottom part of the compartment, from the floor level up to the discontinuity height ($Z_D$), whereas the top part of the compartment, spanning from $Z_D$ to the compartment ceiling height, is considered to be occupied by the combustion products. The interior of the compartment is assumed to be completely stratified, i.e. no mixing occurs between the two zones and each zone is considered to exhibit uniform temperature and density over its entire volume. Due to the developing thermal buoyant flow field, the warm combustion products are forced to exit through the top section of the opening, whereas the colder
fresh ambient air enters the compartment through the bottom section of the opening. The height at the opening where the flow reverses its direction, corresponding to the interface between the incoming air flow and the outgoing combustion products flow, is commonly called the neutral plane height (\(Z_0\)). Experimental measurements have shown that the neutral plane height at the opening (\(Z_0\)) lies usually higher than the discontinuity height developing inside the compartment (\(Z_D\)).

By employing the standard incompressible flow equations (e.g. continuity equation, Bernoulli’s law) and using a number of plausible assumptions, e.g. negligible fuel mass flow rate, physical properties of the gaseous products identical to the properties of air, a set of equations can be derived to estimate the steady-state mass flow rates of the two main flows entering and exiting the compartment [1, 2]. More specifically, estimations for the mass flow rate of the combustion products exiting the compartment (index: “out”) and the ambient air entering the compartment (index: “in”) are obtained using Eqs. (1) and (2), respectively [3, 4]. The discharge coefficient \((C_d)\) is empirically determined; based on literature reports, a value of 0.68 is used in this work. The neutral plane height at the opening (\(Z_0\)) is estimated by using Eq. (3) [5], where \(H_o\) is the opening height. When values for the neutral plane height and the temperatures of the inflow and outflow streams are known, the discontinuity height inside the compartment (\(Z_D\)) is estimated by solving Eq. (4) [3]. Symbols “\(w\)” and “\(A\)” are used to represent the opening width and the total opening area, respectively.

\[
\dot{m}_{in} = \frac{2}{3} C_d \rho_{in} \left( H_o - Z_N \right)^{1/2} \sqrt{\frac{2g}{\rho_{in}}} \left( \rho_{in} - \rho_{out} \right) \rho_{out} \tag{1}
\]

\[
\dot{m}_{out} = \frac{2}{3} C_d \rho_{out} Z_N^{1/2} \sqrt{\frac{2g}{\rho_{in}}} \left( \rho_{in} - \rho_{out} \right) \rho_{in} \tag{2}
\]

\[
Z_N = \frac{H_o}{1 + \left( \frac{\rho_{out}}{\rho_{in}} \right)^{1/3}} \tag{3}
\]

\[
\frac{T_{in}}{T_{out}} \left( \frac{1}{Z_N} - 1 \right) = \left( 1 - \frac{Z_D}{Z_N} \right) \left( 1 + \frac{Z_D}{2Z_N} \right) \tag{4}
\]

3. FIRE ENGINEERING CORRELATIONS FOR AIR INFLOW RATE THROUGH THE OPENING

A broad variety of engineering correlations for estimating the fire-induced opening air mass inflow rate, \(\dot{m}_{in}\) (kg/s), has been developed and is available in the literature. Based on the assumptions used by the various research groups, each correlation presents either small or large discrepancies when compared against Eq. (2). The nine correlations evaluated in this work are presented in Table 1; they all refer to pre-flashover conditions, thus employing the two-zone model assumption. The only exception is correlation IN6, which is also able to account for post-flashover conditions, while a variation of correlation IN9 can also be used for post-flashover fires, when the combustion product gas temperature exceeds 573 K [11]. The parameter \(\delta^*\) that appears in IN1 corresponds to an empirical layer depth correction term which, for door-type openings, is assumed to be equal to 0.023 [2]. Correlation IN5 is the only equation that utilises the mass flow rate of the fuel (\(\dot{m}_{fuel}\)); based on suggestions found in the literature [1, 12] this term can be considered negligible and is omitted here. Evidently, correlations IN8 and IN9 are essentially simplified forms of the main equation (Eq. (2)); they are formulated by directly substituting a set of typical values for the main physical quantities (e.g. \(g = 9.81\) m/s\(^2\), \(T_{in} = 20^\circ C\), \(T_{out} = 527^\circ C\), \(\rho_{in} = 1.2\) kg/m\(^3\), \(\rho_{out} = 0.435\) kg/m\(^3\)). In certain correlations (e.g. IN1, IN2, IN7), the value of the thermal discontinuity height (\(Z_D\)) is required; in these cases, the respective value is estimated using Eq. (4).
4. LARGE-SCALE TESTS OF FIRE-INDUCED FLOWS

Aiming to determine the accuracy of the correlation predictions, experimental results obtained in eight full-scale fire tests, available in the literature, are used for validation (Table 2); in all cases, a door-type opening was used.

Table 2. Main characteristics of the 8 large-scale compartment fire tests used for validation.

| Test case | Fire power (kW) | Burner position | Burner elevation (m) | Ventilation factor (m²/s) | References |
|-----------|----------------|-----------------|----------------------|--------------------------|------------|
| 1         | 32             | Centre          | 0.3                  | 2.17                     | [13], [14], [15] |
| 2         | 160            | Centre          | 0.3                  | 2.17                     |            |
| 3         | 320            | Centre          | 0.3                  | 2.17                     |            |
| 4         | 62.9           | Centre          | 0.3                  | 1.83                     |            |
| 5         | 105.3          | Centre          | 0.0                  | 1.83                     |            |
| 6         | 62.9           | Back            | 0.0                  | 1.83                     |            |
| 7         | 62.9           | Front           | 0.3                  | 1.83                     |            |
| 8         | 62.9           | Centre          | 0.3                  | 1.83                     |            |

The first three fire tests (test cases 1-3) were performed by Bryant [13-15] in an ISO 9705 compartment (3.60 m x 2.40 m x 2.40 m). The compartment had a single door-type opening, measuring 0.79 m x 1.96 m, located at the centre of one 2.40 m x 2.40 m wall. The 0.3 m jamb of the doorway, used to accommodate the PIV measurement system, extended beyond the exterior framework of the enclosure. A natural gas fired square burner (0.31 m x 0.31 m) was placed at the centre of the compartment’s floor; the top surface of the burner was located 0.30 m above the floor. The three test cases considered here covered a broad range of fire heat release rate values (i.e. 32, 160 and 320 kW). The remaining five fire tests (test cases 4-8) were performed by Steckler...
et al. [16] in a 2.8 м x 2.8 м x 2.18 м compartment. A single door-type opening was also used in this case, measuring 0.74 м x 1.83 м. A methane burner was employed as a fire source; different burner positions and elevations have been investigated. In addition, the effect of the fire heat release rate was taken into account, by considering fire tests where different fire power values (62.9 and 105.3 kW) were used.

5. COMPARATIVE ASSESSMENT OF FIRE ENGINEERING CORRELATIONS

Predictions of the nine engineering correlations (c.f. Table 1) are evaluated by comparing the respective predictions against the experimentally determined air mass inflow rate values. A comparison of the obtained results against the available fire test data is presented in Fig. 2. It is evident that correlations IN4 and IN5 exhibit better levels of agreement with the experimental data, while predictions of the remaining correlations are quite spread out. However, it is important to note that the majority of correlations over-predict the air mass inflow rate, thus providing “conservative” results (higher values), appropriate for fire engineering design purposes. In Fig. 2 (right), prediction errors for all the investigated correlations are presented as a function of the fire heat release rate; in general, no statistically significant trend can be observed, apart from the fact that increasing the fire power results mostly in smaller prediction errors and reduced differences among the various correlations.

Fig. 2 Comparison of predicted and measured air mass inflow rates (left); effect of fire heat release rate on the prediction error (right).

Table 3. Absolute error values (%) of correlation predictions compared to air mass inflow rate measurements.

| Test case | IN1  | IN2  | IN3  | IN4  | IN5  | IN6  | IN7  | IN8  | IN9  |
|-----------|------|------|------|------|------|------|------|------|------|
| 1         | 84.0 | 15.4 | 98.08| 21.9 | 15.3 | 53.9 | 89.8 | 150.65| 163.1|
| 2         | 47.8 | 21.4 | 64.96| 30.0 | 20.9 | 41.0 | 36.7 | 52.52 | 62.4 |
| 3         | 24.2 | 28.0 | 49.36| 39.3 | 27.1 | 37.5 | 13.0 | 36.66 | 47.9 |
| 4         | 52.4 | 20.8 | 63.18| 3.6  | 2.2  | 27.7 | 45.4 | 57.52 | 65.6 |
| 5         | 52.7 | 57.4 | 62.94| 5.9  | 0.3  | 28.1 | 36.6 | 40.77 | 48.2 |
| 6         | 116.6|      | 130.14| 20.5 | 18.0 | 67.6 | 96.0 | 88.79 | 91.2 |
| 7         | 121.9| 84.9 | 135.41| 8.6  | 10.6 | 65.8 | 105.3| 94.99 | 90.0 |
| 8         | 118.7|      | 132.02| 6.5  | 8.8  | 62.8 | 97.3 | 82.79 | 77.5 |
| Average   | 77.29| 37.98| 92.01| 17.04| 12.90| 48.05| 65.01| 75.59 | 80.74|

An overview of the absolute error for each correlation is given in Table 3; the last line corresponds to the arithmetic mean over all eight considered test cases. The presented percentage (%) error values are estimated as the fraction of the absolute difference between the predicted and experimental values over the corresponding experimental values. Missing values represent cases where the experimental measurements lied outside the “definition domain” of the respective correlation. It is evident that correlation IN5 exhibits the lower error values in the majority of the eight test cases and also the lower “average” error over all fire tests. A closer look at the obtained results reveals that certain fire tests (e.g. test cases 1, 6, 7 and 8) result in quite high prediction errors.
among all correlations; at a first glance, these test cases cannot be easily grouped in a single category. However, based on the test case characteristics (c.f. Table 2), it seems that the position of the burner may have a relatively large impact on the correlations’ prediction accuracy. Test cases 1, 7 and 8 employ an elevated burner, while in test cases 6 and 7 the burner is positioned either at the “back” or the “front” side of the compartment. However, solid conclusions cannot yet be drawn; more test cases have to be considered.

6. CONCLUDING REMARKS

The aim of this study was to comparatively assess nine fire engineering correlations, available in the literature, that are commonly used (e.g. in two-zone compartment fire models) for the estimation of the fire-induced air inflow rate through a compartment opening. Experimental results, obtained in eight different large-scale compartment fire tests, covering a broad range of operational parameters (e.g. fire power, ventilation factor, burner position and elevation), were used to evaluate the obtained predictions. Correlation IN5 was found to provide the most accurate results, exhibiting an absolute average error of 12.9% over all the considered experimental test cases. The obtained prediction errors showed that the burner’s position and elevation may affect the accuracy of the mass inflow rate calculations. Predictions of fire tests where the burner was located at the centre of the compartment flush to the floor, achieved, in most cases, higher levels of accuracy.

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