Similarity Theory when Selecting the Test Fire Parameters During Commissioning Tests of the System of Smoke Ventilation at a Closed Car Park

A V Sverdlov¹, M A Volkov¹, S V Rykov², I V Kudryavtseva²

¹FlaktGroup Russia, Profsoyuznaya Str., 23, Moscow, 117418, Russia
²ITMO University, Kronvergskiy 49, Saint-Petersburg 197101, Russia

E-mail: neva0175@mail.ru

Abstract. Fire protection of closed car parks, where it is possible to have a massive stay of people, is the most important and most crucial task when designing such facilities. The efficiency and effectiveness of smoke ventilation systems is achieved through compliance with design rules and numerical simulation of air distribution. The most reliable method is an experimental check of the efficiency of smoke ventilation. It is not possible to reproduce a real fire in the conditions of an object without damaging the structures of a building or a facility; therefore, tests are carried out with reduced, safe fire parameters. Based on the similarity theory, the article discusses the methodology for scaling test fire parameters and smoke ventilation parameters, which allows obtaining results relevant to the design fire parameters. In this case, the positive test results with lower parameters of the test fire confirm the design limits of the smoke distribution and the possibility of evacuating people from the car park in case of a fire having design parameters. An alternative to these scaling methods can only be the prediction of design test parameters and conditions based on the same calculation method, as well as the case when the prediction of the test results is confirmed by observations.

1. Introduction

The safety of a person staying in a car park is determined by air quality [1] and noise pollution [2–3] in the normal ventilation mode. The greatest risk to humans arises in an emergency during a fire in the car park [4].

A comparative analysis of the design rules for channel smoke ventilation of car parks built in Russia and Europe [5, 6] was performed in this article [7]. It is shown that Russian regulatory documents allow lower performance of smoke exhaust fans, which can be a risk factor in modern multi-storey car parks with a ceiling height of 3.5 to 2.5 m [4].

Installation of a smoke ventilation system should follow all project guidelines. However, the experience of construction and installation works indicates the presence of possible (not taken into account) deviations from the original design, which can lead to errors in CFD modelling.

In this case, to experimentally confirm the design parameters of smoke ventilation and the entire fire protection complex of the car park, an experimental check is carried out: tests using hot artificial smoke.

Based on the above the matter of this article is actual.
2. The history of technology of development a hot smoke test for underground ventilation

Initially, local heating units producing a hot air stream were used to simulate a fire [8, 9]. Construction waste was used to create a test fire [10]. Industrial denatured ethyl alcohol turned out to be more practical for creating a test fire. Small particles are practically absent in the products of alcohol combustion and they are relatively low toxic. Synthetic smoke allows you to visualize the convective flow of combustion products. A study of alcohol combustion in thermostatically water-bath controlled trays using synthetic smoke in Australia led to the development of a standard [11].

The recommended method for checking the correct execution, the effectiveness of the system and its interaction with other safety systems in the building is smoke tests using hot smoke. The hot smoke test is creating a hot air stream using a test fire and introducing an indicator gas into it, which allows illustrating the interaction of the hot rising convective smoke stream with a cold ventilation air stream in the space under study. During the hot smoke test, the system should operate in automatic mode, including automatic fire detection.

In accordance with the requirements [11], the power of the test fire should be at least 300 kW for car parks equipped with stationary water fire extinguishing installations, and at least 450 kW for other car parks. For car parks with a ceiling height of more than 3.20 m, it is recommended to increase the fire power to 1 to 1.5 MW in order to achieve a higher temperature of the smoke layer spreading under the ceiling.

In the standard [11], the main purpose of tests using hot smoke is to check the algorithm for switching on and operating of the smoke ventilation of the car park. However, in the standard [11] there are no clear criteria for the test fire to correspond to the real or design fire scenario, which does not allow experimentally determining the boundaries of smoke distribution in the transverse (by the height of the room) and longitudinal direction.

When testing transverse channel smoke ventilation using hot smoke, it is important to answer the question, if it is possible to stabilize the lower boundary of the smoke with the projected convective fire power \( Q_p \) according to the results of a test fire of lower power. In this case, based on the principle of similarity, it is necessary to determine which design parameters of the fire should be scaled to obtain reliable test results.

3. The principle of relevancy for choosing of parameters for test fire

The authors of the article [12] summarized the experience of experimental works [13–16] in the field of using small-scale physical models for studying ascending smoke streams using the Froude number (Fr). We also analyzed our own experience obtained during commissioning tests of the smoke ventilation system of the multi-level underground park in Kazan, where hot smoke was also used [17–19] and Fr-based modelling was applied to reversible longitudinal jet ventilation systems [20–21].

3.1. Problem statement

This article proposes a technique for scaling test fire parameters and smoke ventilation parameters, which allows obtaining results relevant to the design fire parameters. In this case, the positive test results with the reduced parameters of the test fire determine the limits of smoke distribution and confirm the possibility of safe evacuation of people from the car park in case of a fire having design parameters.

Traditionally, Froude scaling is applied to turbulent flows. It is this type of movement that corresponds to the upward air flow of the combustion products shown in figure 1, for which the Darcy-Weisbach equation holds:

\[
\Delta p = \xi \frac{u^2}{2 \rho},
\]
Figure 1. Scheme of a test fire in closed room. \( H \) is the ceiling height; \( Y \) is the height of the lower boundary of the smoke; \( h_c \) is the thickness of the smoke layer (smoke reservoir); \( m \) is the mass flow rate of the removed combustion products.

where \( \Delta p \) is the pressure loss (Pa), which sets in motion a gas stream (air and/or smoke) with the density \( \rho \) (kg/m\(^3\)) with the speed \( u \) (m/s), with a coefficient of resistance to movement \( \xi \).

From (1) it follows:

\[
\Delta p \propto u^2 \rho. \tag{2}
\]

For the pressure causing the upward flow of smoke gases from the combustion zone to the lower boundary of the smoke at a height \( Y \) (m) from the floor, you can write the equation as follows:

\[
\Delta p = \Delta p gY = \rho_0 \frac{\theta}{T} g Y, \tag{3}
\]

where \( \rho \) (kg/m\(^3\)) and \( T_0 \) (K) are the density and temperature of the cold supply air, respectively; \( \theta \) (K) is the difference between the outdoor temperature \( T_0 \) and the temperature of the hot smoke gas \( T \) (K) at the lower boundary of the smoke layer.

Combining (2) and (3) we get:

\[
u^2 \propto \theta. \tag{4}\]

3.2. Basic regularity received from similarity theory for description of fire testing

Based on the results obtained in the article [12], the scaling ratios (scaling factors) relevant to the design scenario of a fire in a real building or facility are presented as a series of formulas.

Upstream velocity \( u \):

\[
u \propto \theta^{0.5} = K_u. \tag{5}\]

Volume flow with upward flow \( V \):

\[
u \propto \theta^{0.5} = K_v. \tag{6}\]
Figure 2. Graph of the convective power of the test fire $Q_{k\text{test}}$ as a function of the height of the lower smoke boundary obtained when scaling the fire of one car $Q_{k\text{dsg}} = 3000\text{ kW}$, $Y_{dsg} = 2\text{ m}$, for given values of $Q_{\text{test}}$.

Mass flow $M$:

$$M \propto \frac{\theta^{0.5}}{T} = K_M.$$  (7)

Convective heat flow $Q_k$:

$$Q_k \propto \frac{\theta^{1.5}}{T} = K_q.$$  (8)

The time $\tau$ during which the flow process should occur:

$$\tau \propto \theta^{-0.5} = K_{\tau}.$$  (9)

The project specified a number of design (dsg) fire parameters, namely:
- convective fire power $Q_{k\text{dsg}}$, kW;
- fire perimeter $P_{dsg}$, m;
- minimum permissible height of the lower boundary of the smoke $Y_{dsg}$, m.

We should define the mass flow rate of the combustion products of the design fire. To do this, we use the formula (10) [12]:

$$M_{dsg} = C \tau P_{dsg} Y_{dsg}^{1.5},$$  (10)

where $C$ is the capture coefficient 0.21 for large rooms with a low ceiling (for example, an underground car park) and 1.9 for large rooms where the smoke layer is at a considerable height.

Next, we should determine the parameters of the test fire (test). To do this, we should:
- to accept, according to the project conditions, the permissible value of the temperature difference in the test fire centre $\theta_{test}$, which excludes damage to premises and equipment;
- using the formulas of scaling fire parameters (5)–(9) we obtain:
Figure 3. Graph of the relative decrease in the smoke ventilation performance ($K_{V_{\text{test}}} / K_{V_{\text{deg}}}$) of the test fire as a function of the height of the lower smoke boundary for the given values of $Q_{\text{test}}$ obtained when scaling the fire of one car $Q_{\text{dug}} = 3000 \text{ kW}$, $Y_{\text{deg}} = 2 \text{ m}$.

\[
\begin{align*}
  u_{\text{test}} &= u_{\text{deg}} \frac{K_{V_{\text{test}}}}{K_{V_{\text{deg}}}}; \\
  V_{\text{test}} &= V_{\text{deg}} \frac{K_{V_{\text{test}}}}{K_{V_{\text{deg}}}}; \\
  M_{\text{test}} &= M_{\text{deg}} \frac{K_{M_{\text{test}}}}{K_{M_{\text{deg}}}}; \\
  Q_{\text{deg}} &= Q_{\text{deg}} \frac{K_{Q_{\text{test}}}}{K_{Q_{\text{deg}}}}.
\end{align*}
\]

In accordance with (10) $M \propto P$, therefore:

\[
P_{\text{test}} = P_{\text{deg}} \frac{K_{M_{\text{test}}}}{K_{M_{\text{deg}}}}.
\]

4. Conclusions
- The necessity of testing smoke ventilation of car parks using hot smoke for experimental verification of the possibility of safe evacuation of people in the case of a fire is justified.
- Based on the similarity theory, a technique was proposed for scaling the parameters of a test fire and smoke ventilation, which allows obtaining test results relevant to the parameters of a design fire at an object.

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