Wind influence on air flow inside road tunnels

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Abstract

The paper presents the results of an investigation into wind influence on the air flow inside and around road tunnels. Experiments were performed in a boundary wind tunnel at Wind Engineering Laboratory at Cracow University of Technology, Poland. Two models of road tunnels were examined in the wind tunnel. The influence of the wind parameters (mean wind speed profile, turbulence intensity profile) and the angle of wind attack on the distribution of the mean wind pressure coefficients on the internal surface were considered during the tests.

Keywords: wind tunnel, wind influence, road tunnel, air flow inside road tunnel, natural ventilation of road tunnels

1 Introduction

An important factor in ensuring the safety in use and fire safety of construction works such as a tunnel, is the effective evacuation of contaminants, smoke and heat to ensure acceptable conditions for traffic and the evacuation of people and, of course, to enable fire fighting (Sztarbała, 2012). This is achieved by ensuring the proper direction and velocity of air flow in the tunnel. In short tunnels natural ventilation is used, where the flow of air is caused by the movement of vehicles, natural convection phenomena and weather conditions. In such cases, contaminants, smoke and heat are evacuated via both tunnel heads. In other types of tunnels mechanical ventilation is used, where the direction and the velocity of the air flow are decided by fans.

The author’s observations were made during in-situ tests of ventilation for day-to-day and fire modes in existing road and railway tunnels and indicate that weather conditions, in particular wind, can substantially affect the conditions inside a tunnel. In one of the existing road tunnels, during a smoke test with hot smoke, wind at the opening of the tunnel prevented the removal of smoke, even though there was a mechanical longitudinal ventilation system.

Previous research into the safety in use and fire safety in tunnels has focused on predicting the air velocity necessary to evacuate contaminants and smoke from a tunnel, and influence of air velocity on the fire heat release rate. The mathematical models used to determine the required air velocity in these studies, are based on the results of scale modelling. These models ignore wind influence, which means
there ends up being an assumption of calm weather in the neighbourhood of the tunnel openings. Such conditions occur rarely and make up only a brief fraction of the meteorological period.

Considering the extensive nature of the underlying scientific problem, the scope of the research which is presented in this paper is focused on short, naturally ventilated, ground level tunnels of rectangular cross-section, with zero gradient. It is also assumed that there are no obstacles reducing the internal cross-sectional area of the tunnel.

The work consists of the results of measurements of pressure distribution on the internal surfaces of two road tunnels and an analysis of these results. For each of these tunnels an angle of wind attack from 0° to 90°, every 10°, was considered.

2 Description of the research

2.1 Wind tunnel

The wind tunnel where the measurements were carried out has a mixed circulation, either open or closed. The measurements were made with closed circulation. The basic dimensions of the wind tunnel are: width - 2.20 m, height from 1.40 m at inflow to 1.60 m at the end of the measurement space, length – 10.0 m. Formation of the wind structure takes place in the first part of the measurement space at a distance of 6.0 m. Turbulizing barriers, spires and blocks of appropriate geometry and height were used. The maximum mean flow speed in the measurement space during the tests was 40.0 m/s. A more detailed description of the wind tunnel can be found in papers (Flaga et al., 2004) and (Flaga, 2008).

2.2 Physical models of road tunnels

Physical models of a road tunnel were prepared at a scale of 1:50 and had the following dimensions:

- tunnel A: 10.0 x 10.0 cm (width x height) and length 100 cm.
- tunnel B: 20.0 x 10.0 cm (width x height) and length 100 cm.

The models were made of 0.2 cm thick transparent panels of plexiglass, joined together by special adhesive connections. Inside the walls between the plates forming the outer and inner surfaces of the tunnels there were air spaces, where impulse silicone wires with an internal diameter of 0.2 cm were mounted. These wires connected pressure measurement points located on the walls of the tunnel with pressure scanners. The gaps between the plexiglass walls at the head of the tunnel were sealed with airtight tape. The model of road tunnel A and the elements used to generate the wind structure are presented in figure 1.

Figure 1: A view of tunnel A in the working section of the boundary wind tunnel.
2.3 Wind parameters

Two flow structures used in the research were described by a vertical wind speed profile and turbulence intensity profile and were formed by the following elements:

- triangular cross-section spires of height 100 cm set at inflow, (iv);
- zig-zag barriers with heights: 20 and 40 cm set at inflow, (bz);
- blocks with height 20 cm, on the floor between inflow and the measurement space, (kl).

The first wind structure was formed by a zig-zag barrier with 20 cm height and marked as bz2kl0. The second one by triangular cross-section spires of height 100 cm, a zig-zag barrier of 40 cm and blocks with height 20 cm. This wind structure was marked as Iv10bz4kl20. The following formulae were applied for the wind speed profile (1), and the turbulence intensity profile (2):

\[ u(z) = k \cdot z^\alpha \]  \hspace{0.5cm} (1)

\[ I_u(z) = \frac{\sigma(z)}{u(z)} \]  \hspace{0.5cm} (2)

where: \( k \) and \( \alpha \) are the coefficients of the wind profiles and \( z \) is the height [cm], \( u(z) \) is the wind velocity [m/s], \( I_u(z) \) is the turbulence intensity, \( \sigma(z) \) is the standard deviation of the wind speed, and \( u(z) \) is the mean wind velocity [m/s].

The values for the wind profiles used (Bęc et al., 2011, Lipecki et al., 2011) have been presented in table 1 and the turbulence intensity profiles have been shown in table 2. The wind profiles and turbulence intensity profiles have been presented in figure 2.

<table>
<thead>
<tr>
<th>No</th>
<th>Symbol</th>
<th>( k )</th>
<th>( \alpha )</th>
<th>( z_{min} ) [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>bz2kl0</td>
<td>4.26</td>
<td>0.20</td>
<td>1.70</td>
</tr>
<tr>
<td>2</td>
<td>Iv10bz4kl20</td>
<td>0.92</td>
<td>0.55</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Table 2: Turbulence intensity functions.

<table>
<thead>
<tr>
<th>No</th>
<th>Symbol</th>
<th>( I_u(z) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>bz2kl0</td>
<td>( 4.341 \times 10^{-6}z^4 - 1.097 \times 10^6z^3 + 9.685 \times 10^7z^2 + -4.605 \times 10^3z + 0.231 )</td>
</tr>
<tr>
<td>2</td>
<td>Iv10bz4kl20</td>
<td>( -1.907 \times 10^{-6}z^4 + 9.583 \times 10^7z^3 + 1.187 \times 10^{-2}z^2 + + 7.448 \times 10^{-4}z + 0.440 )</td>
</tr>
</tbody>
</table>
2.4 Pressure measurements

To assess the wind influence on the flow inside and around the road tunnels, pressure measurements for 15 points at 15 sections of the internal walls were made (see figure 3 and figure 4). The mean pressure was obtained at each point of the model from dynamic pressure measurements. The mean pressure was normalized by the reference pressure which was measured in the right front of the model at a height of 10 cm.

The data from the pressure taps was archived with a frequency of 500 Hz in the time range of 30 s, which gave 6,000 data points. The measuring scheme is presented in figure 5.

The mean wind static pressure coefficient $C_p$ was calculated using the following equation:

$$C_p = \frac{p}{0.5 \rho u_{ref}^2}$$

(3)

where: $p$ is the mean dynamic pressure in the given point of the model, $\rho$ is the air density, $u_{ref}$ is the wind speed in undisturbed flow at the reference point, at the top edge of tunnels, at height $z = 10$ cm.
The angle of wind attack changed within the range 0° - 90° a step of 10°. The angle of attack 0° represents a direction perpendicular to the head of the tunnel (see figure 6).

Figure 4: Pressure measurement points on the external walls of tunnel B.

Figure 5. Measuring scheme.

Figure 6. Angle of wind attack diagram.
3 Results and analyses

3.1 Results for tunnel A

The mean wind pressure coefficients $C_p$ are presented for two tunnel models. In figures 7 – 8 the mean pressure coefficients at 7 measurement sections are presented (sections 1, 7 and 8) in tunnel A for an angle of wind attack of $0^\circ$ and $90^\circ$, and wind profile bz2kl0. The mean $C_p$ values in tunnel A for wind profile iv10bz4kl20 at the same sections are presented in figures 9 - 10.

Figure 7. Distribution of pressure coefficient at the internal walls of the tested tunnel A with $0^\circ$ angle of wind attack, wind profile bz2kl0.

Figure 8. Distribution of pressure coefficient at the internal walls of the tested tunnel A with $90^\circ$ angle of wind attack, wind profile bz2kl0.

Figure 9. Distribution of pressure coefficient at the internal walls of the tested tunnel A with $0^\circ$ angle of wind attack, wind profile iv10bz4kl20.
3.2 Results for tunnel B

The mean wind pressure coefficients $C_p$ are presented for two tunnel models. In figures 11 – 12 the mean pressure coefficients at 7 measurement sections are presented (sections 1 and 8) in the tunnel B for angle of wind attack $0^\circ$ and $90^\circ$, and wind profile bz2kl0. The mean $C_p$ values in tunnel A for wind profile iv10bz4kl20 at the same sections are presented in figures 13 – 14.

Figure 11. Distribution of pressure coefficient at the internal walls of the tested tunnel B with $0^\circ$ angle of wind attack, wind profile bz2kl0.

Figure 12. Distribution of pressure coefficient at the internal walls of the tested tunnel B with $90^\circ$ angle of wind attack, wind profile bz2kl0.
3.3 Analyses of the results

While analysing the distribution of the mean wind pressure coefficients for both tunnels it is noticeable that the air flow inside the tunnel depends on the wind profile, the angle of wind attack and the width of the tunnel.

In a tunnel exposed to wind three areas within the flow can be distinguished. Two of them are associated with the phenomena occurring in the neighbourhood of the head of the tunnel. The third one is the area between the above-mentioned areas and is characterized by a lack of flow or a circulation flow at low speed. The size of these areas and their relative proportions depend on the angle of attack of the wind.

The results of $C_p$ for angle 0° show that the direction of air flow in both tunnels corresponds to the wind direction. Vortexes penetrating into the tunnel were created on the edges of the tunnel exposed to wind influence for angles of wind attack other than 0°. The size of these vortexes depends on the angle of wind attack: the larger the angle, the greater the range of influence of a vortex. The range of the penetrating vortexes depends also on the width of the tunnel. It can be observed that a vortex caused by the influx of a windward edge has a smaller range than tunnel B in the relation to tunnel A.

Most important results for designers of ventilation systems for tunnels are the results of the mean wind pressure coefficient for a wind angle larger than 60°. For these angles the directions of air flow inside the tunnels were opposite those for an angle lower than 60°.
For an angle equal to 90° the results of the mean wind pressure coefficient are similar for each of the tunnel surface excluding the area close to the head of the tunnel. Such a distribution of mean wind pressure coefficients shows the flow blockage in this area. In practice this means that contaminants, smoke and heat will be blocked in tunnels and the requirements for ensuring safety in use and fire safety will not be met.

4 Conclusion

The results of the tests carried out at the Wind Engineering Laboratory of Cracow University of Technology confirm the importance of the influence of wind on the air flow in tunnels.

The use of natural ventilation to evacuate contaminants, smoke and heat from short tunnels is inappropriate due to ineffective functioning, especially in cases of fire and wind involvement.

References

Sztarbala G., Influence of wind on the air flow in a tunnel in the event of fire, Ph. D. dissertation Warsaw: Building Research Institute, 2012 (in Polish)


