EGRESS WAY VENTILATION FOR ESCAPE ROUTES IN TUNNELS –
THE DESIGN OF OVERPRESSURE SYSTEMS

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ABSTRACT
Escape routes like corridors, cross connections, adjacent tunnel tubes and stairwells should be kept smoke-free during a tunnel fire. Ventilation systems are often used to keep the smoke out of the escape routes. In practice, current tunnel-design projects show that principals and designers have difficulties in choosing applicable systems, and setting realistic requirements and boundary conditions. A worldwide overview of laws, standards and recommendations show that there is little information on these systems. There are hardly any publications on this subject, not even on other applications such as in buildings; especially high-rise buildings. So far, no proven calculation methods and validated boundary conditions have been found. A research project has been launched to collect and develop knowledge on egress way ventilation systems. The first results are presented in this paper.

Keywords: escape routes, egress way ventilation systems, tunnel fires, tunnel ventilation

1. INTRODUCTION
Similar to other buildings tunnels have escape routes to provide safe escape in case of fire and other severe circumstances. In some cases the tunnel tube itself is the escape route but more common is the use of cross connections to the other tube if present of the use of escape corridors alongside the tunnel tube or stairwells to the surface. The purpose is to provide a safe area to road users as soon as they left the tunnel tube during an incident and, when fitting in the action plans, to provide safe access to the tunnel tube for emergency services. So between tunnel tube and the safe area escape doors are placed and often the escape routes are pressurized to keep them smoke free.

![Figure 1: Arrangements of escape routes](image)

Such pressurisation systems will provide a safe escape route granted that it complies with these aspects:
- It must be possible to open the escape doors (the differences in air pressure over an escape door should be limited)
- The escape route must be kept free of smoke and hazardous gases (minimum air flow through an open escape door)
- The airflow may not counteract the evacuation (limitation of the air velocity)
In case of cross connections or stairwells adjacent to the tunnel tubes the possibility of keeping the escape routes smoke free is mainly directed by the tunnel ventilation system. The reason is the high capacity of tunnel ventilation compared to the pressurisation system of escape routes which capacity is smaller just because of the available space for these systems. For the design of these pressurisation systems reliable calculation methods are in use.

The design of overpressure systems for escape corridors alongside tunnel tubes is more difficult. Depending the location and size of the incident more or less escape doors to the corridor can be opened simultaneously which has its influence on the capacity of the system. Often it is only possible to supply air at one or both ends of the escape corridor which requires transport of air over long distances. Pressure differences over escape doors can be very different from door to door and are even dependent on the fire location and fire size and functionality of the tunnel ventilation system. This leads to the question how to control the overpressure system in a dynamic situation where doors are opened and closed.

In practice tunnel design projects show that clients and designers have difficulties in choosing applicable systems and setting realistic requirements and boundary conditions. A worldwide overview of laws, standards and recommendations show that there is little information about these systems. There are hardly any publications on this subject for tunnels and not that much on other applications as in buildings, especially high rise buildings. For tunnels no proven calculation methods and validated boundary conditions have been found so far.

These facts concluded in launching a research project, to collect and develop knowledge on pressurisation systems for escape corridors. The goal of this research project is to provide realistic boundary conditions for pressure differences over escape doors and for the minima and maxima of air velocities in opened escape doors and escape corridors. Another goal is to find design solutions and methods for controlling the system. The results will be collected in a recommendation on overpressure systems for escape routes in tunnels providing possible solutions and calculation models.

The research project contains the following steps:

- Collecting information from publications, recommendations, standards and national laws
- Collecting information on existing systems in use and their functionality
- Definition of realistic boundary conditions
- Definition of a design model based on results of measurements in tunnels & CFD analysis
- Recommendation on control systems for overpressure systems in escape corridors

2. COLLECTED INFORMATION FROM REGULATIONS

Information has been collected from documents dealing with tunnels but also from documents dealing with pressurisation systems in buildings, especially for high rise buildings. An analysis was made of Dutch standards and regulations related to pressurisation equipment in tunnels and the operation of these systems. Dutch regulation for high-rise buildings and stairwells were included as additional input. Several foreign standards have been analyzed as well, to find out how the subject is handled in other countries. Useful standards from Europe and US were included, in order to get a complete picture of global legislation, and its mutual similarities and differences.

The regulations and standards for tunnels taken in account are the Dutch law suit WARVW/RARVW, the Dutch standard for highway tunnels (LTS 1.2), the German standard RABT 2006, the French interministerial circular n° 2000-63, the Austrian standard, the Swiss guideline FEDRO 2003 and the USA standard NFPA 502. As far as known standards, guidelines and laws on tunnels published by other countries do not contain conditions for pressurisation systems. An overview of the results is shown in table 1.
Table 1: Overview of prescriptions for pressurisation of escape routes in tunnels

<table>
<thead>
<tr>
<th>country</th>
<th>document</th>
<th>pressure difference door [Pa]</th>
<th>Air velocity door [m/s]</th>
<th>Nr. of simultaneous open doors</th>
<th>Air velocity corridor [m/s]</th>
<th>Door open force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL</td>
<td>RARVW</td>
<td>≥ 10</td>
<td>n/a</td>
<td>30%, min. 3</td>
<td>n/a</td>
<td>≤ 100</td>
</tr>
<tr>
<td>NL</td>
<td>LTS 1.2</td>
<td>n/a</td>
<td>≤ 6.5</td>
<td>30%, min. 3</td>
<td>n/a</td>
<td>≤ 2 (fire ≤ 25MW) ≤ 5 (fire &gt; 25MW) Additional force 15 nominal; Add. Force 20 for first 10 cm</td>
</tr>
<tr>
<td>DE</td>
<td>RABT2006</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>≤ 100</td>
</tr>
<tr>
<td>F</td>
<td>CIRC2000</td>
<td>≥ 80</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>A</td>
<td>RVS</td>
<td>n/a</td>
<td>≥ 2.5</td>
<td>n/a</td>
<td>n/a</td>
<td>≤ 100</td>
</tr>
<tr>
<td>S</td>
<td>FEDRO2003</td>
<td>≥ 50</td>
<td>≥ 3.0  ≥ 1.5 ≥ 1.5</td>
<td>1  3 adjacent 2 unfavourable</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>US</td>
<td>NFPA502</td>
<td>n/a</td>
<td>≥ 0.75  ≤ 11</td>
<td>n/a</td>
<td>≤ 11</td>
<td>67 (release latch) 133 (opening)</td>
</tr>
</tbody>
</table>

Likewise conditions for overpressure systems in buildings were derived from the European standard EN 12101-6 (2005) and several other publications. The results are shown in table 2.

Table 2: Overview of prescriptions for pressurisation of escape routes in buildings

<table>
<thead>
<tr>
<th>country</th>
<th>document</th>
<th>pressure difference door [Pa]</th>
<th>Air velocity door [m/s]</th>
<th>Nr. of simultaneous open doors</th>
<th>Air velocity corridor [m/s]</th>
<th>Door opening force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU</td>
<td>EN12101-6</td>
<td>≥ 50 ≥ 10</td>
<td>≥ 0.75  Not given</td>
<td>1, other closed Doors opened</td>
<td>n/a</td>
<td>≤ 100</td>
</tr>
<tr>
<td>other</td>
<td>several</td>
<td>≥ 50</td>
<td>≥ 0.75</td>
<td>n/a</td>
<td>n/a</td>
<td>≤ 100</td>
</tr>
</tbody>
</table>

The following conclusions can be drawn from the literature study regarding pressurisation systems:

- Most standards include design requirements for dimensions of escape doors. These standards often contain requirements to “prevent smoke and heat from reaching the escape routes behind emergency exit”, like stated in the EU 2005-54.
- Requirements for the minimum of pressure difference through an escape door vary from 10 Pa onto 50 Pa.
- There are no requirements to the maximum differential pressure across an escape door. This may seem sensible when a limit is set to the maximum opening force of an escape door. However, high pressure in the escape corridor could result in high air flows through open escape doors. This would create dynamic behavior of air between the escape route and the tunnel tube, which are completely unknown at the time. In addition, none of the standards indicate whether it is static or total pressure and where it needs to be measured exactly. In buildings it is reasonable to calculate with static pressure but in tunnels due to air movement through the tunnel tube and escape corridors it is not clear at first sight.
- Only the NFPA502 sets a minimum and maximum value for the air speed through an escape door. Some other give a minimum, which differs from the standard for buildings. The Dutch LTS sets a maximum but not a minimum.
- Aside from the US and the Netherlands, no requirements are set for the maximum air velocity in the escape corridor. In the Netherlands, the LTS prescribes a limit of 2.0 m/s for tunnel fires smaller than 25 MW, and 5 m/s for tunnel fires above 25 MW. In the US this value increases to 11.0 m/s.
- The Number of open emergency doors is only prescribed in the Dutch and Swiss standards.
There appears to be an international agreement for the opening force of doors. In many cases this is prescribed as 100N for the opening force of the door. Although most standards prescribe a maximum opening force with ventilation enabled, the Dutch LTS and the US NFPA prescribes a maximum opening force required when unlocking the door.

The variety of boundary conditions raises the question which are right, reasonable and reachable.

Research done by Li et al at the Southwest Jiaotong University, China (2009) shows that the minimum air velocity through an open door with dimensions of 2,1 m height should be in the range of 0,5 – 0,8 m/s which is good order with the standard EN 12101-6.

3. COLLECTED INFORMATION FROM PRACTICE

Static and total pressure vary along the length of a tunnel tube. Wall friction losses, pressure losses due to traffic, stack effects and the influence of longitudinal ventilation result in certain pressure lines as illustrated in Figure 2 for a particular tunnel. In this figure the static pressure is given because the static pressure is the actuating force on the air flow through open doors. The pressure can be an overpressure in the direction to the escape corridor, but downstream the fire the pressure is negative and in the direction of the tunnel tube because of stack effects in the tunnel tube. The figure is given for a certain fire location, other locations result in different pressure behavior. Also the influence of the fire size is illustrated.

Measurements on sliding escape doors searching for the influence of pressure differences on the opening force of sliding doors were done by Rijkswaterstaat (Wim Janssen et al, The Netherlands). This resulted in a behavior as given in Figure 3. It can be seen that door opening forces easily exceed a limit of 100 N if pressure differences are higher than 50 Pa. However pressure differences higher than 50 Pa are to be expected based on results as shown in Figure 2. It is also known that poor maintenance on doors result in excessive opening forces. Measurements on rotating doors show that pressure differences can result in not being able to open the door during incidents – so sliding doors are normally recommended for tunnels.
Measurements of air velocities in escape routes show that air velocities in escape corridors can easily be in the range of 3 – 7 m/s and air velocities in the opening of escape doors are up to 10 m/s depending on which door is opened.

4. PRESSURISATION SYSTEMS FOR LONGITUDINAL ESCAPE CORRIDORS

Systems commonly used in Dutch road tunnels are as shown hereafter. These corridors are mainly between the tunnel tubes as shown in Figure 4. Between the tunnel tubes is a “middle tube” containing in the upper part a service corridor for cabling and installations and in the lower part the escape corridor. Typical lengths of Dutch tunnels are between 500m and 2000m, some are longer. The floor of the service corridor can be completely closed but can also be of an open structure to combine service corridor and escape corridor to one aerodynamic space.
In case of underwater tunnels it is only possible to supply air to the “middle tube” at both ends of the tunnel. Due to the use of longitudinal tunnel ventilation it depends on the location of the air intake air if supply can be provided at both ends or only at one end of the middle tube. Tunnels in urban areas are just below ground level and depending on the use of the space on top of the tunnel air intakes somewhere along the tunnel are possible. This has resulted in two type of air supply as shown in Figure 5.

Other solutions of air supply to the escape corridor are using a specific ventilation duct allowing for higher transportation speeds. By means of controlling the air velocities in the escape corridor it would be preferable to partition the corridor in compartments, the best in one compartment per escape door. However this is often not preferable in an escape corridor because that would hinder the escaping process. So we have to deal somehow with air flows through the escape corridor.

5. CALCULATION METHODS

There are two existing methods often used to calculate the air pressure and air flow in escape corridors in road tunnels. One method is a model as used in designing mechanical ventilation duct systems. This model considers the tunnel and the escape routes as air ducts. In the calculation escape door between tunnel tube and escape corridor are examined as a T-component as shown in Figure 6. For T-components in ventilation ducts pressure drop figures are known from literature.

![Figure 6: Escape door considered as T-part of an air duct](image)

Another method is using the calculation methods of pressurising systems for staircases in buildings. With this method an escape door in a tunnel is considered equal as the door of a staircase. The most used formulae for flow through an emergency door is

\[ \text{[Volume Flow Door]} = 0,83 \times [\text{Door Cross section}] \times [\text{pressure difference}]^{(1/n)} \]

n = 2 for large openings en n = 1,6 for small openings.

Both calculation models are an approximation of reality, but the results of the research done by Li et al at the Southwest Jiaotong University, China (2009) show that better calculation methods are needed.

Preliminary attempts in our research project using CFD has been done and show results for the relation between pressure difference and the square of the air velocity in de door opening are as shown in Figure 7. The air velocity in the escape corridor has influence on the amount of flow through an open escape door.
6. CONTROL SYSTEM

In buildings are systems in use to control the pressure in staircases and shafts by pressure measurements in the shaft and pressure relief valves. Sometimes measurement of the pressure difference over each emergency door is used. The same types of systems are also in use for escape corridors in tunnels.

It is desirable to maintain a certain pressure in the escape corridor during normal tunnel operation. This in order to prevent debris and dirt flowing into the escape corridor. Because all doors are closed a relatively small volume flow is required related to leakages of the structure.

During an emergency opening and closing of doors requires a dynamic control system which controls the deliverance of an air flow adjusted to the actual need and maintaining pressures on a certain level. The length of corridors, the number of doors and the large variety of possible pressure differences over escape doors makes it difficult to find a reliable control system based on pressure differences. And maintaining a minimum pressure level in the escape corridor itself may result in high velocities through open doors. Other control systems take in account the number of doors opened or even which doors are open.

It is considered as wise to use pressure relief valves. In an emergency situation a door may suddenly be opened requiring immediate air flow in the escape corridor. This can only be reached if the fan – which can be at a large distance from the open door – is already delivering air flow with an initial pressure. With all doors closed this air flow is relieved via the valve to the outside. When other doors are opened, the fan accelerates and increases airflow until the desired pressure in the corridor is reached.

Although, if one of the exit doors gets closed after the fan has reached its operating point, there may be a pressure peak in the corridor that can reach rather high values. This pressure peak can cause the exit doors to be clamped into the rabbet. To prevent these pressure peaks a pressure relief valve is needed in every ventilation compartment. The pressure relief valve will open at an adjustable pressure. The required pressure to open the valve can be determined by calculations.

The peaks in excess pressure are mainly caused by the inertia of the fan and to a lesser extent by the electronic control. The use of a pressure relief valve, the end of each compartment in the escape corridor, this problem could best avoided.

7. CONCLUSION AND RECOMMENDATIONS

The definition of the boundary conditions for pressurisation systems in escape corridors alongside tunnel tubes differ from country to country and even differ with the boundary conditions set for buildings. Also it is not clear if the actual boundary conditions can be met in practice – it seems that the conditions are exceeded very easily. The establishment of realistic
and reachable boundary conditions is needed. Existing calculation methods do not fit well for the situation. This conclusion is supported by research results reported in literature. Validated calculation models, based on measurements and simulation models, will improve the reliability of such systems in real emergency situations providing the desired level of safety. Because the functionality of pressurisation system in escape corridors in strongly related to tunnel ventilation design recommendations are desirable. Ideas about the functionality of control systems, which can handle the variety of scenario’s of number and location of simultaneously opened doors, must be developed.

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