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DECOMPRESSION SCENARIOS
IN A NEW
UNDERGROUND TRANSPORTATION SYSTEM

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Abstract

Until now, risks of a public exposure to a sudden decompression have been related to civil aviation and, at a lesser extent, to diving activities. Moreover, recently, engineers have developed plans for vehicle transport in a low-pressure environment in the field of underground transportation. Such solution has been foreseen for the future *Swissmetro*, a high-speed underground train designed for interurban linking in Switzerland.

Decompression risks related to a hypoxic environment in an underground structure are a novelty. Therefore, in order to achieve a safe design regarding the low-pressure environment, a theoretical study of decompression risks has been conducted at an early stage of the *Swissmetro* project. Assuming an isentropic gas flow, a three-compartment model allowing numeric simulation of pressure in both Swissmetro's vehicles and passenger's lungs has been established.

Numeric simulations have been conducted in order to calculate 'decompressions scenarios' for a wide range of parameters, relevant in the context of the Swissmetro main study. A sensitivity analysis has been used to assess the impact of change in design parameters and safety measures. The results obtained show that, such model may be used as a tool to promote a safe design regarding decompression hazards in a new transportation system.

Introduction

Reducing aerodynamic constraints is a major concern in rail tunnels. Because of the limited free space available, several undesirable aerodynamic effects occur in underground structures: aerodynamic drag, unsteady pressure waves (in front of the vehicles), and aerodynamic unsteady transverse forces (at the vehicle tail). A significant reduction of such effects is usually achieved by an increase of the tunnel diameter. This counterbalancing measure is unfortunately expensive because of the high tunnel excavation costs induced. Hence, due to the increase of both foreseen travel speed and tunnel length, such solution is not suitable for future underground high-speed systems.

Swissmetro is a new, high-speed, underground and magnetically levitated (MAGLEV) project designed for interurban linking in Switzerland [1]. In order to reduce aerodynamic drag while maintaining a low tunnel diameter a low-pressure atmosphere will be maintained in the future Swissmetro system. A wide range of tunnel pressures has been studied in order to define an optimum between costs, aerodynamics and safety concerns. The final pressure level in the tunnel will likely range between 10 kPa and 25 kPa. Therefore, regarding decompression risks, a Swissmetro vehicle will be very similar to a plane flying at 34’000- 52’000 ft.

Decompression health effects such as barotraumas, hypoxia and decompression sickness (DCS) have been extensively studied in the fields of aviation and aerospace [2]. Although the same health effects must be considered for the Swissmetro, it’s technical particularities may affect a decompression situation significantly. On the one hand, Swissmetro’s particularities may have a direct effect on decompression kinetics. For instance, contrarily to an aeroplane or a spacecraft, the pressure in the surrounding area, of limited volume, will increase in case of decompression. On the other hand, because of its underground infrastructure, the safety measures against decompression will, most probably, differ from traditional solutions [3].

In order to promote an intrinsic safe design of the Swissmetro system, a safety analysis has been conducted during the Swissmetro main study [4]. Pressure related risks have been investigated using a numerical model to simulate decompression scenarios. The numerical model used and the results obtained are discussed in this paper.

Simulating decompression

Overview

The model used in this study is based on classical fluid mechanics' theory. The decompression is described as a gas leakage, flowing from a 'high-pressure' compartment to a 'low-pressure' compartment. Assuming an isentropic gas leakage through a thin orifice, the instantaneous gas flow may be deduced from the gas state parameters (Pressure, Temperature and Density) inside the high and low-pressure compartments [5][6]. Two leakage process are described, one from the passengers' lung to the cabin, and the other from the cabin to the tunnel. As the cabin compartment is involved in both leakage processes, the result is a three-compartment model. The model used allows calculation of pressure kinetics inside both vehicle's cabin and passengers' lungs. A schematic view of the calculation process is presented in Figure 1.

Figure 1 about here

Depending on the pressure gradient between the two compartments, two types of gas flows may occur: a subsonic or a sonic limited flow. In case of a subsonic flow, the fluid speed is below the Mach value (sonic speed). In case of a sonic limited flow, the gas speed in the narrower part of the flow reaches the Mach value, which is a maximum limit. In the latter case, the flow is no more a function of the state parameters in the low-pressure reservoir. The theoretical model used is detailed in Appendix A. Numerical simulation has been implemented using *Ithink (version 5.0)*, a flow processing software [7].

Parameters

Several parameters, regarded as relevant, have been used to implement the numeric simulation [1][8]. These parameters and the numerical values considered during simulation are summarised in Table 1. Default values, which are based on the current Swissmetro design, are used as references. Minimal and maximal values, which reflect the wide parameters' range still considered in the Swissmetro study, are used for sensitivity analysis.

Table 1 about here

Results

The simulation results, using default values, are shown in Figure 2. Both isentropic and isothermal hypotheses have been considered. Only a slight difference may be observed between these two cases. Nevertheless, in order to consider worse case scenarios, all ensuing simulations are based on isentropic gas flows.

The vehicle pressure, expressed in kiloPascals kPa (100 kPa = 760 mmHg), decreases in less than a minute to the tunnel pressure level. Because of the short travel duration, the pressure in the Swissmetro vehicle will be maintained at a sea-level atmospheric pressure. Thus, contrary to civil aviation, where the pressure is reduced to a level corresponding to a 2000-2300 m altitude, the Swissmetro cabin pressure prior to decompression is about 100 kPa. On one hand, this high initial pressure level will extend the decompression duration and then, delay the hypoxia symptoms. On the other hand, the overall ratio between initial pressure and final pressure will increase and then, intensify risks of barotraumas.

Figure 2 about here

Sensitivity to orifice area

As previously reported in both experimental and theoretical studies, the leaking orifice area has a major impact on decompression kinetics. As shown in Figure 3(a), decompression kinetics for a wide range of orifice areas has been calculated. As a matter of fact, disregarding their likelihood, a large number of scenarios ranging from a single crack or a leaking joint to the sudden loss of a door must be considered. From the viewpoint of hypoxia, the decompressions will lead to similar situations, if more or less quickly. In any case the pressure of 570 hPa (11.4 hPa O_2), corresponding to the limit level for compensated hypoxia, is reached in less than 1 min. 30. A gap of only 1 min. may be observed when comparing the time to reach the compensated pressure limit in a 0.01 m^2 and a 1 m^2 orifice area decompression.

However, considering barotraumas, variation of the orifice area may lead to significantly different results. The potential health damages increase dramatically beyond 1 m^2. Indeed, due to the decompression suddenness, risk of pulmonary overpressure must be taken into account for larger leak areas. According to the current aviation standard, a leaking coefficient below 1/200 m^{-1} or a pulmonary expansion factor below 2.1 (Violette's criteria) must be maintained in order to avoid pulmonary overpressure (open glottis). Considering Swissmetro default values, these standard criterions are not satisfied for orifice areas exceeding 1.5 m^2. For larger orifices, pulmonary overpressure is supposed to occur.

Figure 3 about here

Due to its severe health effects, a specific attention has been given to pulmonary overpressure during simulation. Hence, differential pressure between the pulmonary volume and the vehicle compartment has been calculated. A pulmonary overpressure of 7-8 kPa is generally agreed as a physiological limit for gas embolism occurrence [9]. As shown in Figure 3(b), this value is achieved for an orifice area of 5 m^2. Although surprisingly high, this result is coherent regarding the safe margin taken into account in the aviation standard. The 1/100 m^{-1} leakage coefficient pointed out during animal studies has been extrapolated to 1/200 m^{-1} for human being. Meanwhile, due to the conservative assumptions used for modelling (isentropic flow, lung constant volume) less difference was expected between standard and physiological based criteria.

Sensitivity to Tunnel pressure

A wide range of tunnel pressure has been considered during the Swissmetro study. Decompression scenarios for pressure levels ranging from 1 kPa to 50 kPa, have been computed. Pressure levels over 50 kPa, which do not reduce aerodynamic constraints satisfactorily, have not been considered during Swissmetro main study. It must also be emphasised that, due to the risk of ebullism, pressure levels below 6.3 kPa are not considered for further planning.

Figure 4 about here

As shown in Figure 4(a), a change of the tunnel pressure may affect both barotraumas and hypoxia effects. The range of pressure levels planned in the tunnel is below the compensated hypoxic level (about 57 kPa). Nevertheless, hypoxia consequences and counter-measures may be significantly affected due to *time of useful consciousness* (TUC) variation [10]. As a safety criteria regarding hypoxia, useful consciousness is of major concern. A high TUC allows, for example, successful use of oxygen breathing mask. For tunnel pressure levels varying from 1 kPa to 50 kPa and other parameters set to default values, estimated TUC ranges from 10 s to 1 min.

Reducing the orifice area may also be used to increase TUC, although with little changes regarding consequences. As a matter of fact, a tunnel pressure of 10 kPa and a small orifice area (about 0.01 m^2) may lead to a TUC sufficient to achieve a safe self-rescue action. Unfortunately, using conventional breathing oxygen masks below 30-40 kPa has proven been unsuccessful.

Pulmonary barotraumas (open glottis) are affected at a lesser extent by tunnel pressure levels. As long as the pressure ratio is below the sonic limit criteria ($\frac{P_{Orifice}}{P_{Cabin}} \leq 0.528$), the tunnel pressure does not affect the gas flow kinetic. Thus, the initial decompression kinetic (early 10-50 seconds) is similar disregarding the tunnel pressure. A significant decrease in pulmonary barotraumas effects may only be achieved when Violette's criteria ($\frac{P_0}{P_1} \leq 2.1$) is satisfied, which correspond to a pressure level of about 48 kPa [10].

Other barotraumas, less sensitive to initial decompression kinetic, are dramatically dependent on the tunnel pressure. Intestinal barotraumas, for instance, may become relevant from 57 kPa and acute from 27 kPa.

Sensitivity to tunnel volume

To maintain a low-pressure level the Swissmetro tunnel will be an enclosed space, although of considerable volume. In order to allow regular traffic, the tunnel section between two stations (length of 40 to 60 km) will not be partitioned. The cabin volume of about 300 m^3 is then negligible considering the 1'200'000 m^3-surrounding tunnel. Therefore, during regular operating conditions, the situation will be similar to a vehicle travelling in an open space low-pressure environment.

In case of emergency however, reducing the free space surrounding the vehicle may mitigate the adverse effects of decompression. Until now, two solutions have been considered to reduce the surrounding space; partitioning the tunnel with emergency airtight doors, or isolating the vehicle with, for instance, inflatable joints. The results of simulated decompressions with and without mitigating measures are shown in Figure 4(b). Assuming, that the emergency airtight doors are located under intermediate construction shafts (every 10-15 km) and that the inflatable joints are located at vehicle's extremities, the surrounding volumes becomes respectively 18'000 m^3 and 580 m^3.

Partitioning the tunnel in order to mitigate decompression is of little use because of the large volumes involved. A significant change in decompression kinetics may however be achieved by isolating the vehicle. In this latter case, the volume of the surrounding low-pressure compartment is in the same range as the cabin's volume and the final pressure reached is dramatically increased.

Discussion

Use and relevance of the model

Several side effects in fluid mechanics, assumed irrelevant, have not been taken into account in the theoretical model. The accuracy of the simulation may, for instance, be improved further considering the tunnel walls' effect on the leaking flow. Such improvement seems however of little use, as the theoretical model may become significantly more complex without real benefit regarding safety promotion. Besides, it must be emphasised that, the decompression scenarios obtained are consistent with previous experience in the field of aviation and aerospace [11][12].

The limiting approximations made in the model are issued from human being rather than fluid mechanics. Considering standard criteria, such as Violette's criteria, to interpret decompression health effects does not take into account individual sensitivity. A safety margin is generally included in these 'mean' criteria in order to cover a large proportion of individuals. Nevertheless, using a 'mean' value to interpret health effect is a rough approximation.

This is why, the model discussed in this paper is not intended to depict accurately the pressure-related risks, but to provide a comparison tool for safety promotion. The impact of a parameter change or of a new safety system may be assessed through sensitivity analysis.

Implications for the Swissmetro project

Open glottis pulmonary barotraumas effects are highly dependent on the orifice area. Thus, similarly to aviation, the leakage coefficient will be maintained below 1/200 m^{-1}. It must be emphasised that Swissmetro vehicles will have a reduced number of built-in orifices, as windows are not planned in the current design.

Other barotraumas as well as hypoxic effects following decompression are mainly related to the tunnel pressure level. As this parameter has a dramatic impact on safety, costs and aerodynamics, it must be carefully optimised. Simulation results show that, reducing the volume of free space surrounding the vehicle has an effect similar to raising the tunnel pressure. A significant increase in safety may be achieved when the surrounding free space is in the range of the vehicle's volume. The efficiency of such a solution seems limited, mostly because it may require a previous stoppage of the vehicle. The technical feasibility of such vehicle isolation, even combined with other mitigation measures, must be investigated further.

The pressure levels currently considered, ranging between 10 kPa to 25 kPa, may lead to acute hypoxic situations. Therefore, similar to the current aviation practice, an emergency pressurisation procedure (within 2 min. 30) is planned. In Swissmetro tunnels, an emergency pressurisation may be achieved using intermediate shafts to provide a local air supply or using a pressurised area in the tunnel (pipe, service tunnel) to provide a continuous air supply. As a local air supply generates a pressure wave, which may cause mechanical damage and adverse health effects, the first solution has been discarded. It must be pointed out that, at a further stage of the Swissmetro project, the model discussed in this paper may be implemented in order to include the emergency pressurisation system.

Oxygen masks are not included in the current vehicle design. Indeed, the pressure level in the tunnel will most likely be out of the range of conventional oxygen masks. Positive pressure masks, used for instance by aeroplanes' crews, are of little use for Swissmetro. Indeed, such masks are unsuitable for passengers' use and the vehicles will be driven by remote control (no driver onboard).

Decompression sickness is not considered as a major public hazard in the Swissmetro system. Indeed, the decompression scenarios simulated point out a prevalence of hypoxic and barotraumatic effects. Moreover, considering the emergency pressurisation system planned, the exposure time to a hypobaric environment will be below the delay observed before DCS symptoms [13][14][15]. Marginal cases of occupational exposures resulting in DCS may however occur. For such cases, hypobaric treatment facilities are available in two towns along the Swissmetro lane.

Conclusions

The model used in this study allows description of pressure kinetics inside both a pressurised vehicle and passengers' lungs during an accidental decompression. Numeric simulations have been conducted in order to calculate 'decompressions scenarios' for a wide range of parameters, relevant in the context of the Swissmetro main study. Although somewhat summarised, the results presented in this paper show the interest of such a simulation in regard of safety management. The model may be used as a tool to promote a safe design regarding decompression hazards, for both fitting system parameters or to designing safety measures.

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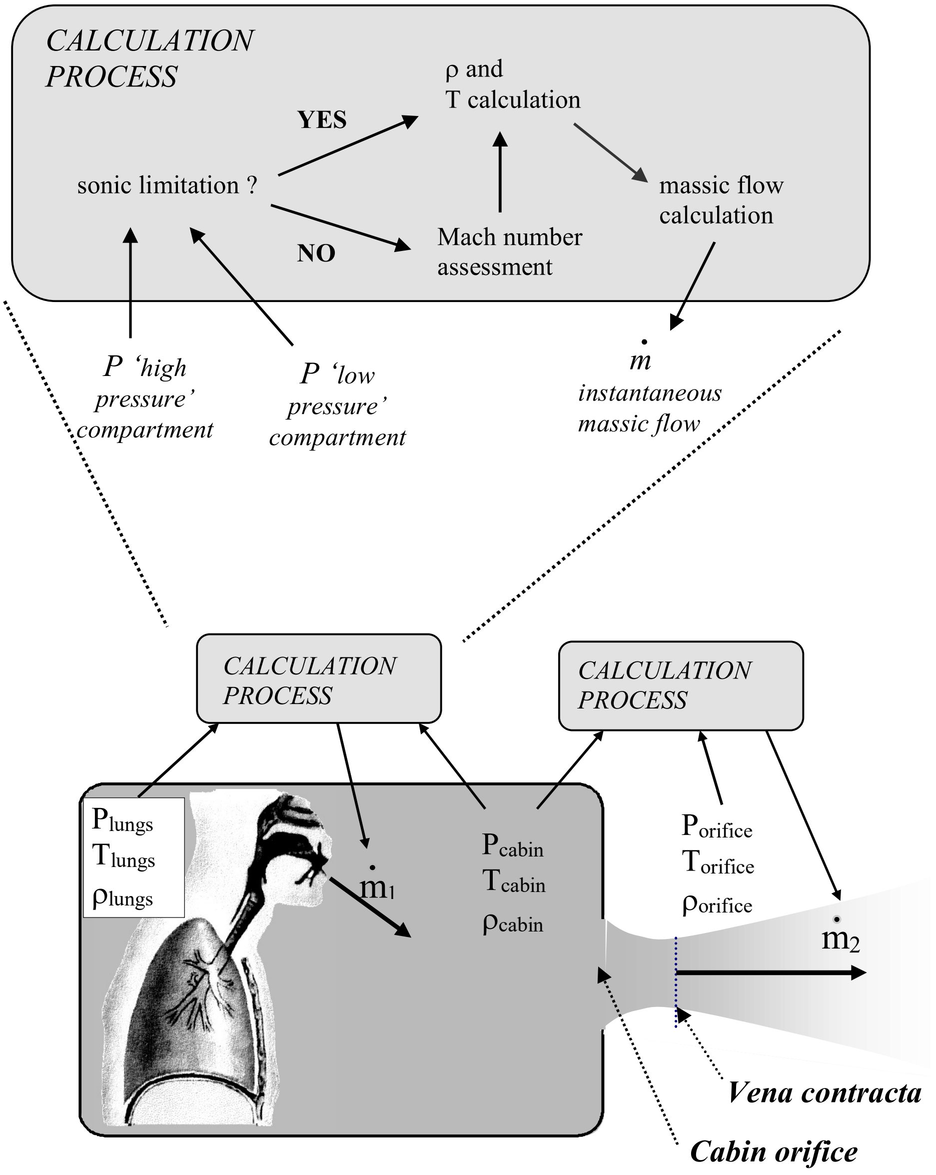

Figure 1 : decompression model, overview

Type	Parameter	Default value	Minimal value	Maximal value
infrastructure	tunnel volume	300’000 m^3	580 m^3 (1)	1’200’000 m^3 (2)
vehicle	vehicle volume	300 m^3	200 m^3	1500 m^3
	numb. of passengers	200	200	800
	orifice area	0.1 m^2	0.01 m^2	5 m^2
	vehicle pressure	100 kPa	-	-
aerodynamic	tunnel pressure	10 kPa	1 kPa	100 kPa
physiology	lung volume	5 dm^3	0.1 dm^3 (3)	6 dm^3 (3)
	orifice area	1 cm^2	-	-

(1) with vehicle airbags
(2) without vehicle airbags or any tunnel partition
(3) ranging from new-born to adult (ending inspiration)

Table 1: Parameters and numeric values used for simulation

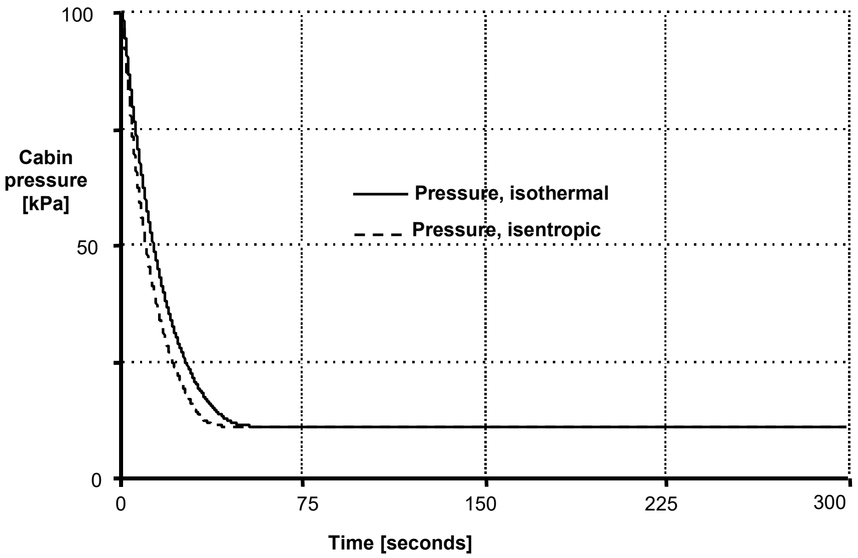

Figure 2 : isentropic and isothermal decompression (default values)

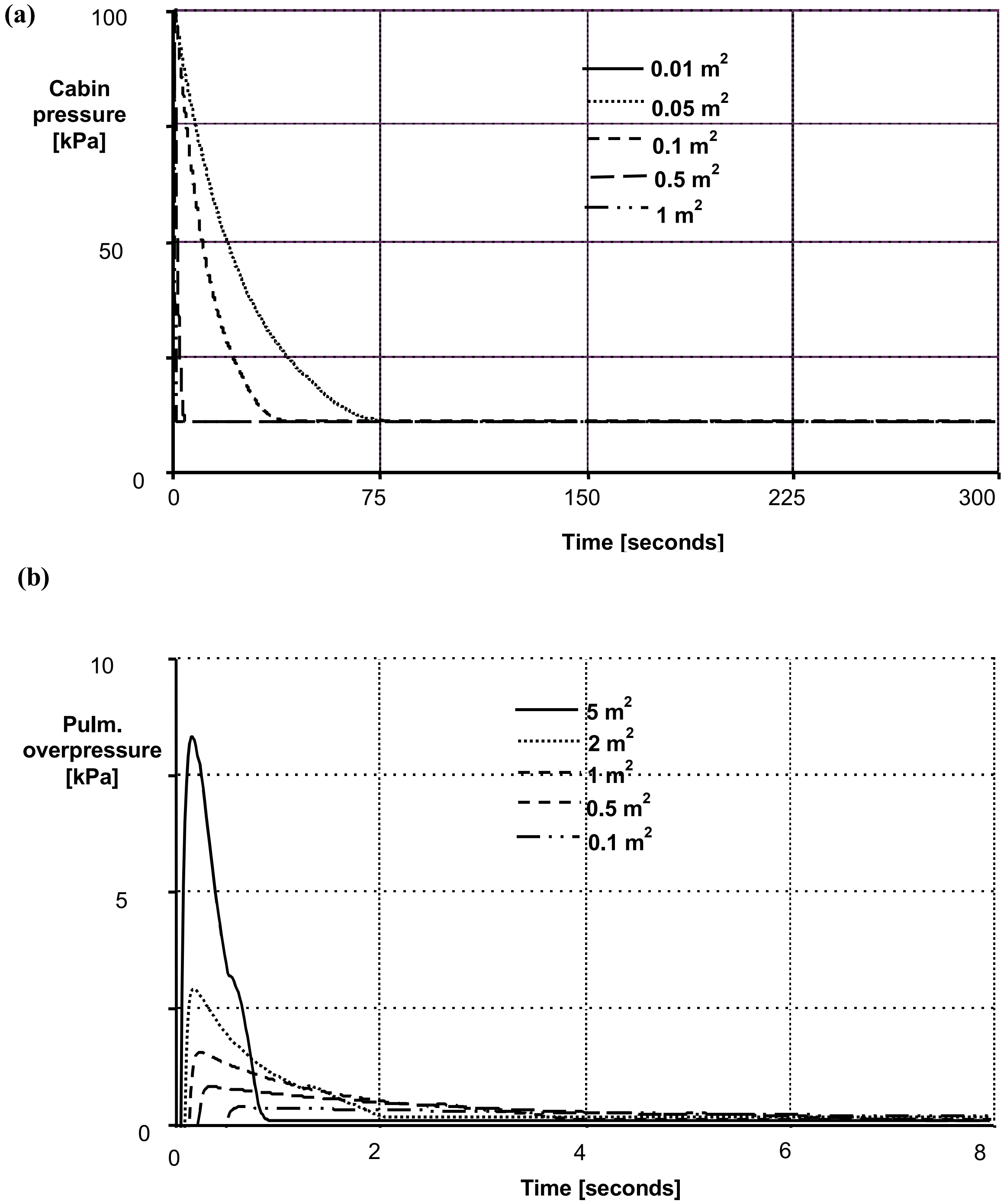

Figure 3 : Sensitivity analysis for several orifices (a) decompression kinetics (b) pulmonary overpressure

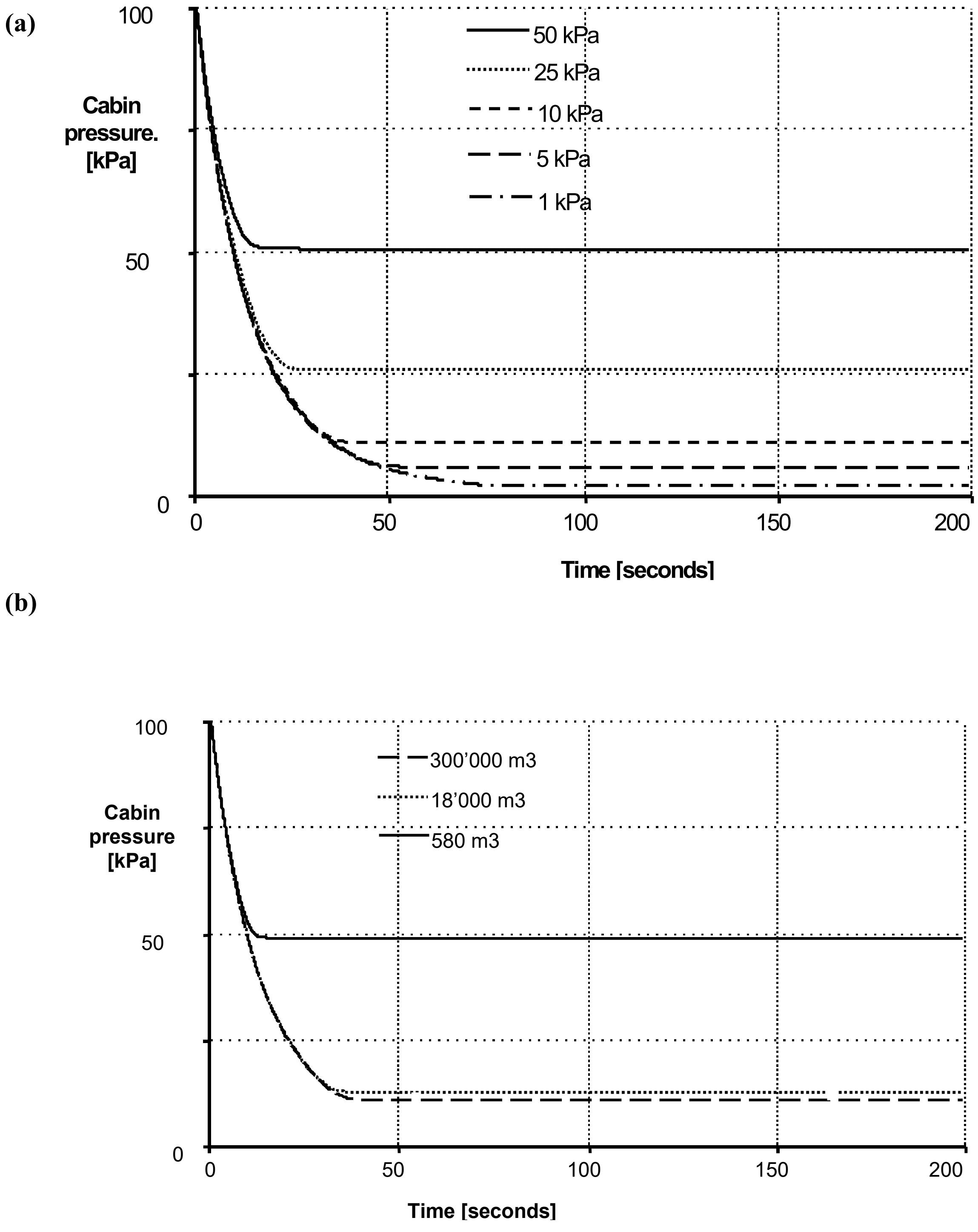

Figure 4 : Sensitivity analysis (a) decompression kinetics for several tunnel pressure levels

(b) decompression kinetics for several volumes of low-pressure compartment

Appendix A

Behaviour of a compressible gas flow

The energy balance of an ideal gas flow may be expressed in terms of pressure and volume fluctuations:

Equation 1

$$\frac{dP}{\rho} + d\left(\frac{v^2}{2}\right) = 0$$

$[m^2/s^2]$

By definition, the isentropic relationships is written as:

Equation 2

$$\frac{P}{\rho^\kappa} = cte$$

$[m^2/s^2]$

The energy balance of an isentropic flow is then obtained by combining equation 1 and equation 2:

Equation 3

$$\frac{P_0}{\rho_0} \cdot \frac{dP}{(P)^{1/\kappa}} + d\left(\frac{v^2}{2}\right) = 0$$

[-]

Introducing *Ma* the Mach number and integrating equation 3 lead to:

Equation 4

$$\frac{T_1}{T_0} = \left[1 + \left(\frac{\kappa - 1}{2}\right) \cdot Ma^2\right]^1$$

[-]

As shown in equation 4, the ratio between the initial temperature T_0 (in the high-pressure compartment) and the temperature after decompression T_1 (in the low-pressure compartment) is a function of the gas velocity.

In an isentropic flow, the relationship between temperature, pressure and density ratios is known:

Equation 5

$$\left(\frac{T_1}{T_0}\right)^{\kappa/(\kappa-1)} = \left(\frac{\rho_1}{\rho_0}\right)^\kappa = \left(\frac{P_1}{P_0}\right)$$

[-]

Thus, pressure and density ratios may also be deduced from the gas velocity:

Equation 6

$$\frac{P_1}{P_0} = \left[1 + \left(\frac{\kappa - 1}{2}\right) \cdot Ma^2\right]^{\kappa/\kappa-1}$$

[-]

Equation 7

$$\frac{\rho_1}{\rho_0} = \left[1 + \left(\frac{\kappa - 1}{2}\right) \cdot Ma^2\right]^{1/\kappa-1}$$

[-]

The flow of a gas through an orifice (surface A) may be expressed with the broad mass balance relation:

Equation 8

$$\dot{m} = \rho \cdot A \cdot v$$

[kg/s]

Sonic speed limit

The sonic speed constitutes an upper velocity limit for the gas flow. Introducing *Ma=1* (the sonic speed) and $\kappa = \frac{c_p}{c_v} = 1.4$ (for air) in equation 4 give $\frac{P_1}{P_0} = 0.528$. Thus, a pressure ratio equal or lower than 0.528, lead to a sonic limited flow. In this case, the gas velocity in the narrower part of the flow has reached the Mach value.

a) Sonic limited flow: $\frac{P_1}{P_0} \leq 0.528$

Introducing the sonic speed in equation 8, the mass flow become:

Equation 9 $$\dot{m} = \rho_0 \cdot 0.634 \cdot \underbrace{A \cdot \mathrm{M_a} \sqrt{\kappa \cdot R \cdot T_0}}_{V_{\mathrm{sonic}}} \cdot 0.834$$ ***[kg/s]***

As shown in equation 9, when limited by sonic speed, the gas flow becomes independent of the state parameters in the low-pressure compartment.

b) Subsonic flow**:** $\frac{P_1}{P_0} > 0.528$

For a subsonic flow, equation 8 become:

Equation 10 $$\dot{m} = \rho \cdot A \cdot \mathrm{M}_0 \cdot \sqrt{\kappa \cdot R \cdot T}$$ ***[kg/s]***

Assuming equivalent pressure amid the orifice and in the low-pressure compartment, the mass flow may be calculated by numeric modelling. Determining the pressure ratio between the two compartments allows calculation of the Mach number (equation 4), of the density and temperature ratios (equation 6, equation 7) and finally of the instantaneous mass flow (equation 9, equation 10).

Real flow, release coefficient

Due to friction forces and contraction downstream orifice, the real flow differs significantly from the theoretical flow. The calculated flow is therefore corrected using the release coefficient C_w.

Equation 11 $$C_w = \frac{\dot{m}_{real}}{\dot{m}_{th.}}$$ ***[-]***

The release coefficient, for a gas flow through a thin round orifice, is given empirically as a function of the pressure ratio during decompression.

Appendix B

List of symbols

A	Area (orifice)	[m^2]
c_p	specific heat (constant pressure)	[J/(kg·°K)]
c_v	specific heat (constant volume)	[J/(kg·°K)]
C_w	discharge coefficient	[-]
D	diameter (orifice)	[m]
e	thickness	[m]
f_R	respiratory frequency	[min^{-1}]
Kn	Knudsen number	[-]
$\dot{m}$	mass flow	[kg/s]
Ma	Mach number	[-]
P	pressure	[Pa]
R	perfect gas constant	[J/(mol.K)]
$\overline{R}$	Haldane over-saturation critical level	[-]
T	Temperature	[°K]
TUC	Time of Useful Consciousness	[s] or [min.]
V	volume	[m^3]
$\dot{V}$	volume flow	[m^3/s] or [l/min.]
v	speed	[m/s]
ε	Violette's criteria (pulmonary overpressure)	[-]
θ	gas fraction	[-]
κ	specific heats ratio	[-]
ρ	specific mass	[kg/m^3]

Indices

A	alveolar
b	barometric
E	expired
0	initial
1	final