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Kapasitetsløft tunnelsikkerhet

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1 Introduction

Kapasitetsløft tunnelsikkerhet is a project funded by the Norwegian Research Council, Rogaland County Municipality and through own efforts at University of Stavanger and project partners. The main goal is to build research-based expertise that enables the tunnel safety industry to deliver value creating solutions for tunnel safety. The project is organized in six work packages combining elements of research, innovation and technology.

1.1 Background and motivation

The present research is part of work package 3 (AP3) concerning the development of industrially applicable models for traffic, accidents and emergency preparedness in road tunnels. Specifically, this study contributes to activity 3, with the goal of performing a critical assessment of models used to predict consequences of fire scenarios, used in the design of road tunnels. The activity concerns also the identification of model characteristics and model classes (CFD versus simpler models) applicable to different scenarios, with particular attention to the prediction of concentration of toxic gases generated in a tunnel fire.

Gexcon develops innovative products and solutions to promote and improve safety in industry and society. As transport routes continuously extend, in Norway and globally, and new energy sources emerge as alternative to traditional fuels, it is of primary importance to ensure adequate safety in transportation, and especially in critical sections of the road network. Gexcon's flagship product FLACS is a CFD software that simulates accident scenarios involving dispersion, fire and explosion. FLACS supports impact assessments and risk analysis in various industrial and civil applications. In connection to the present project, Gexcon intends to further develop and validate FLACS for applications related to the design of safe road tunnels. Exploring the state of the art and foundations of consequence models used in safety studies on road tunnels poses the basis for model development.

1.2 Outline and scope of the work

1.2.1 Scenarios of interest

Different types of catastrophes may occur in road tunnels, including fire, explosions and release of toxic gases. Based on historical records (Klote, 2016) and recent accidents (Bettelini, 2002), fires are likely the worst scenario in terms of hazard. In Norwegian road tunnels heavy goods vehicles (HGVs) are overrepresented in the fire statistics (Nævestad and Meyer, 2012). HGVs are especially vulnerable in inclined tunnels and, depending on their cargo, HGVs can cause several fire scenarios, usually with the potential for a very large fire. Fuel leaks can also lead to pool fires or explosion, only fire events and their consequences in relation to risk of death are regarded in this study.

Existing tunnels are constructed in different ways and may include various infrastructures: ventilation (longitudinal and or transversal), drains to remove potentially harmful liquid spills from critical areas, escape routes, safety niches, automatic/manual fire suppression systems etc. Various constructive alternatives exist for the elements mentioned above. Fire suppression can be achieved with several techniques and substances, based on chemical and mechanical drivers. Each of these fire suppression artefacts is based on specific physical phenomena which would require a specialized model if its effect was to be accounted for in a consequence analysis.

Even when similar mechanical and technological solutions are implemented - considering the case of Norwegian roads, tunnels typically adopt longitudinal ventilation and no automatic fire suppression systems - tunnels differ in dimensions and longitudinal development.

For these reasons, each tunnel can be regarded as unique. Thus, it is difficult to find general safety standards and procedures that apply to all (or a group of) road tunnels (Barbato et al., 2014). Similarly, different models are applicable only to specific tunnel configurations. For instance, some models or calculation methods only apply to simple geometries and specific ventilation types. As different scenarios involve diverse physical phenomena, it is important to clarify requirements and applicability of a specific model for various scenarios. Two different classes of models can be identified; CFD and integral models.

A limited selection of scenarios will be analysed in this study, considering also the relevance for road tunnels in Norway. Since automatic fire suppression systems are not common in road tunnels, this aspect will not be investigated. The problem of fire toxicity will be analysed with particular care, considering that intoxication is the main cause of fatalities in fire accidents (Hurley et al., 2016). Lastly, as the present study concerns the prediction of physical effects (gas concentrations, temperature, etc.), other types of models used to assess physiological effects from physical effects are not analysed in this study.

1.2.2 The role of consequence models in quantitative risk assessment

When dealing with prediction of the physical effect of accidents, knowledge gaps as well as model uncertainties are important parts of the picture. Consequence modelling is one of the steps and elements of risk analysis required to design safe tunnels. To place consequence models in context it is important to realize that, in quantitative risk assessment, uncertainty is reflected at different stages. Aspects related to uncertainty in risk analysis or usage of the model are not elaborated further in this study, and only uncertainty intrinsically associated with the model will be considered.

Another aspect is the misuse of models, which is often associated to incomplete guidelines and possibly also with user errors in the model setup. In relation to this problem Ang et al. (2020) express their concern over the lack of guidelines in tunnel fire modelling with CFD, highlighting that engineering studies usually do not investigate numerics related issues. Skjold et al. (2019) summarise the results from a blind-prediction benchmark study for models used for estimating the consequences of vented hydrogen deflagrations. The authors report significant spread in the model predictions, including predictions from different modellers using the same model system. The latter must be attributed to lack of guidelines for proper use of models or too complex guidelines that can lead to human errors in their applications. The problem can be alleviated implementing automated procedures for scenario definition and grid generation. On the other hand the difference in simulation results obtained from different models, which stems from the specific model formulation and the underlying assumptions, highlights the importance of a critical interpretation of the results, as part of the analysis. The interpretation is founded on existing model validation studies and knowledge of the model applicability range. Typically, this type of information is limited and not readily available, therefore only expert users have the required knowledge and elements to perform a critical evaluation of the model outputs.

1.2.3 Modelling strategies

Techniques for modelling tunnel fire are described in dedicated books and technical documents, see for instance Ingason et al. (2014), SFPE (2002), PIARC (2016). Two main modelling strategies can be identified to predict the consequences of a tunnel fire: field models (CFD) and zone models. Zone models are integral models that divide the spatial domain in regions characterized by uniform flow. For smoke spread in a tunnel-fire such regions can be identified as (Guo et al., 2020):

- fire plume;
- turning region (impingement);
- radial flow;
- transition region;
- one-dimensional shooting-flow;
- one-dimensional critical flow.

Integral models are based on the same primitive equations employed CFD modelling, integrated over a control volume. Assumptions are made to simplify the integration, which may include: one-dimensional flow, symmetry, prescribed-profile and time steadiness. Additional model parameters arise from these assumptions including friction factors; heat transfer coefficients and the entrainment coefficient. Values of these parameters are obtained from fitting of experimental data.

Zone models are powerful tools to analyse the properties of physical phenomena and their sensitivity to physical quantities. On the other hand, their validity is limited by the mathematical assumptions used in the model formulation and by the parametrization derived from specific experimental data. For instance, in zone models it is common to assume a circular of square fire source, while real fire sources involving multiple cars have typically higher aspect ratio. This limitation is important since the shape of the source has influence on entrainment and thus on development of smoke layer (Ji et al., 2019).

In contrast, CFD permits simulation of complex geometries such as realistic tunnels with interchange roads (Li, 2019). CFD models are also used to validate zone models.With regard to this aspect it must be pointed out that, while comparison between different classes of models is in general instructive, using CFD model results as reference to validate simpler models is questionable.

Two main classes of CFD models are commonly used in engineering applications: Reynolds-Averaged Navier-Stokes equations (RANS) and Large Eddy Simulation (LES). RANS solves the average flow and models turbulence fluctuations with a set of transport equations (2-equations in the most common form). In contrast, LES explicitly solves the turbulent eddies down to (approximately) the grid size and uses turbulence models only for the subgrid-sized eddies. Details of these techniques are provided elsewhere, see for instance Blazek (2015).

A challenge with modelling tunnel fire with CFD is the strong variation of scales, from the thickness of the interface between reactants and combustion products, the order of millimetres, to the full length of the tunnel that can reach several thousands of metres. Combustion models used in other applications (e.g. propulsion) cannot be applied in this case as they demand too high computation resources and time. To solve this issue, modellers had to come up with smart ideas and simplified approaches (submodels) to predict the dependency of combustion rates and heat transfer on turbulence. Some of these simplifications lead to approximations that are easily understood (for instance assuming infinitely fast chemical reactions leads to over-prediction of near-field smoke temperature), some other may have more subtle effect. Major limitations and approximations in CFD for fire and tunnel-fire simulation include combustion modelling (with respect to reaction rate and prediction of combustion products) and in particular, modelling of the pyrolysis process.

Naive use of a CFD code is likely to cause large uncertainties and errors between simulation and experiment (Woodburn and Britter, 1996a). The accuracy of simulation results depends on the expertise of CFD specialist and selection of suitable simulation model/options (Chen and Leong, 2011). Due to this limitation, in spite of the increasing computational resources, simpler zone models continue to be an attractive alternative to CFD for engineering calculations.

Whether the prediction tools are used to anticipate the consequences of fire, at design stage or after, or for investigation of an occurred fire, modelling requires defining the simulated scenario, which includes:

- geometry (dimensions of the enclosures, obstructions);
- ambient conditions (including temperature and ventilation);
- fire magnitude (burning material, ignition type or just power generated by the fire);
- combustion properties of the burning materials and substances (chemical reaction or amount of yields);
- thermal properties of the materials;
- fire suppression if present.

The details of information required depends on the level of complexity of the model. CFD models require large amount of data, the accuracy of model predictions in this case is also related to the quality and accuracy of input data.

Definition of fire magnitude and combustion properties in CFD simulations may follow different approaches. The most common prescribes the heat release rate according to predefined time variation curves designed to mimic the stages in a real fire scenario (PIARC, 2016). This represents a simplification with respect to a realistic scenario where the fire development and the generated heat depend on ambient conditions. A more sophisticated approach prescribes the fuel release rate. In this case the amount of burning fuel is subject to the oxygen availability. In another approach, the time varying release of gaseous fuel is calculated using a pyrolysis model.

The models setup may require selection/definition of a chemical reaction scheme, and related reaction rates representing the bridge from the macroscopic flow and microscopic chemical reaction. More or less complicated approaches exist. Single step reactions combined with yield factors (i.e. the fraction of given species in the combustion products) is the most common approach. The model employed has large effects on the predicted amount of combustion products.

Special care should be taken in defining domain boundary conditions and interaction between fluid and solid surfaces. In relation to heat conduction, isothermal or adiabatic conditions at solid surfaces may not be a good approximation for tunnel fire scenarios where heat conduction is dominant. Response of surfaces to thermal radiation depend on the power spectrum, thus detailed thermal properties are required for accurate CFD simulations. When modelling smoke propagation away from the fire zone, where smoke may move a low speed, natural convection as well as forced convection should be taken into account.

1.3 Methodology

A literature review was conducted to identify:

- open research problems in consequence analysis for road tunnel safety;
- available experimental data;
- available models and methodologies, related assumptions, limitations and validation.

The selection of documents was based on specific keywords. The search engines *Web of Science* and *Scopus* were chosen as they gave the largest number of results with low number of "false positives". Results of this work is presented in the following chapter.

2 Results

2.1 Overview of state of the art

Using Scopus as search engine, a literature survey was performed based on the matching strings “tunnel” and “fire” in either title, abstract or author-defined keywords. The search included only publications in English in the field of Physical Sciences (subject areas: Chemical Engineering, Chemistry, Computer Science, Earth and Planetary Science, Energy, Engineering, Environmental Science, Material Science, Mathematics, Physics and Astronomy). Conference papers were excluded. The corresponding selection query was:

```
TITLE-ABS-KEY ( tunnel )  AND  TITLE-ABS-KEY ( fire )
AND  SUBJAREA ( ceng  OR  chem  OR  comp  OR  eart  OR  ener  OR  engi
OR  envi  OR  mate  OR  math  OR  phys )
AND  ( EXCLUDE ( DOCTYPE ,  "cp" ) )
AND  ( LIMIT-TO ( LANGUAGE ,  "English" ) )
```

2144 documents fulfilled these criteria, out of which 1263 included author-defined keywords. Based on recurring keywords the number of papers on different themes were obtained as shown in table 2.1.

Table 2.1: *Number of documents in Scopus for different author-defined keywords.*

keywords	**number of documents**
model *OR* simulat* *OR* cfd	332
ventilation	284
smoke	271
experiment* *OR* test	174
critical	109
full-scale *OR* full scale	30
buoyan*	24
crosswind *OR* cross wind *OR* cross-wind *OR* crossflow *OR* cross flow *OR* cross air	18
toxic*	12

A second type of classification was performed. In this case, the original search was modified introducing additional string-matching criteria in title, abstract or author-keywords. The number of resulting documents for combinations of these strings is presented in table 2.2.

Table 2.2: *Number of documents in Scopus for different searches.*

model* OR **simulat*** OR **cfd**	**experiment*** OR **test**	**toxic***	**smoke**	**ventilation**	**number of documents**
					2144
				x	727
			x		737
		x			81
x					1177
x				x	518
x			x		534
x		x			41
	x				1190
	x			x	415
	x		x		479
	x	x			38

This survey provides condensed information on the coverage of specific aspects of consequence modelling. Results of both classifications indicate that great amount of literature on simulation and modelling (keywords and search strings “cfd”, “simulat*” and “model*”) of tunnel fires is available. Extensive experimental work on tunnel fire has been produced, however keywords-based selection seem to indicate low number of full scale tests. Many publications have been produced on the topic of ventilation and a large number of them deal with critical ventilation velocity. “Smoke” is well represented, this includes a group of different sub-problems (generation, dispersion, etc.).

The canonical fluid dynamics problem of jet in a cross-flow and buoyant flows are less represented (see table 2.1). A great number of publications on these topics is certainly available in areas different from tunnel fire, however the low number of results from the present search indicates a possible knowledge gap in connection to the problem of smoke dispersion. Research on the problem of toxicity, within the selected fields, appears to be limited. The complexity of the topic and the limited capabilities of simulation models predicting the formation of toxics from combustion may explain this result.

2.1.1 Smoke toxicity

The problem of fire smoke toxicity was chosen as starting point for a more in depth analysis of the literature. The following search string and filter was applied on Scopus to select relevant publications:

```
TITLE-ABS-KEY ( tunnel ) AND TITLE-ABS-KEY ( fire ) AND ( TITLE-ABS-KEY
( toxic ) OR TITLE-ABS-KEY ( toxicity ) OR TITLE-ABS-KEY ( monoxide )
OR TITLE-ABS-KEY ( cyanide ) OR TITLE-ABS-KEY ( lc50 ) ) AND SUBJAREA (
ceng OR chem OR comp OR eart OR ener OR engi OR envi OR mate OR math OR
phys ) AND ( EXCLUDE ( DOCTYPE , "cp" ) ) AND ( LIMIT-TO ( LANGUAGE ,
"English" ) )
```

A second and similar search was performed on Web of Science using the following query:

```
((TS=((lc50 OR toxic* OR cyanide* OR monoxide) AND "tunnel" AND "fire")
)) AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article OR Book OR Book
Chapter OR Data Paper OR Discussion) Timespan: All years. Indexes:
SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI,
CCR-EXPANDED, IC
```

The search produced a total of 137 documents after merging. Based on the abstract, a limited number of publications were discarded as not relevant for the present study. Example of this include literature on innovative fire-resistant materials or ventilation strategy for air pollution control.

For a total of 67 articles, author keywords were available in the corresponding bibliography entry. Besides the keywords *Fire Tunnel fire* and *Smoke*, the following categories of keywords were found in largest number: *Toxic gas/products*; *Computational fluid dynamics*; *Carbon monoxide*; *Critical velocity* and *Asphalt*.

The collection of articles was classified using tags. Tag names and related number of documents is reported below:

```
accident_investigation 1
asphalt 10
book 1
cfd (simulation) 32
co (carbon monoxide) 20
collection (more than one item) 3
design 6
mitigation (water deluge etc.)  4
model (formulation) 11
```

```
not_relevant 51
qra (quantitative risk assessment) 4
rail 6
read_first (based on interest and relevance) 18
sensor 2
smoke 24
tenability 6
test (experimental results) 19
toxic 15
ventilation 38
yield (production rate of chemicals during combustion) 2
```

The documents were also classified according to their content to identify papers reporting results from tunnel fire experiments and papers on numerical investigations of tunnel fire. For these publications it was noted what type of fire source was used, what type of ventilation, whether the tunnel was full size or down-scaled and relevant outcomes of the research. 127 papers resulted from this classification including analysis of road tunnels, subway tunnels, rail tunnels and a few mining tunnels. Out of the 127 papers, 13 included both an experimental study and a numerical study with 6 studies on reduced scale models, 3 studies on subway systems and 1 study on a mining tunnel.

From the classification of tunnel-fire experiments it was obtained that, whether tests are full scale or reduced scale, pools are the most common fire source. The properties of hydrocarbons such as propane and heptane are well known, and by adapting the size of the pool and the amount of fuel the maximum heat release rate can be controlled, and thus a pool fire can represent a burning vehicle in terms of heat release rate. This is of course a simplification as real vehicles are made of a multitude of component with varying combustion properties. Alternatively a gas burner is used as fire source in some experiments. These experiments can be used to validate models calculating the spread of smoke and combustion products; however they do not provide data to develop or validate the generation of combustion products from burning cars. In the Runehamar test (Ingason et al., 2015) a series of full scale tunnel fire experiments with a mock-up HGV were performed. The HGV was made up of pallets and rubber tires and a mix of other materials to mimic a loaded truck. Several measurements were taken during the experiment including carbon dioxide and carbon monoxide concentrations. Only one paper in this selection reported experiments with real cars burnt in a tunnel (Truchot et al., 2018). Truchot et al. (2018) measuerd concentration of various fire effluents including carbon dioxide, carbon monoxide, hydrogen chloride and nitrogen oxides. The heat release rate generated by burning cars was measured and compared to published values from PIARC (World Road Association) and CETU (Centre d'Etudes des Tunnels, France). The given values for peak HRR and total released energy differ between the two sources and differ from the experimental results obtained in the study.

On the modelling side it was observed that, typically, yields of soot and CO and other species are predefined. A multitude of research papers investigate the effect of ventilation as well as the effect of other factors on ventilation effectiveness. Such factors include tunnel slope, ambient pressure, altitude, tunnel geometry and obstacles.

2.2 Key modelling problems

From the review of the scientific literature some key modelling problems were identified which are elaborated herein.

2.2.1 Production of toxicants and asphyxiating substances in real-scale tunnel fires

2.2.1.1 Potentially harmful combustion products

The generation of different chemicals during combustion depends on fuel type, fire development and ambient conditions. According to Chow et al. (2020), when toxicity is concerned, based on effects and relative concentration, the analysis can be limited to the following species: carbon monoxide, hydrogen cyanide, hydrogen chloride, hydrogen bromide, nitrogen monoxide and nitrogen dioxide. In addition, carbon dioxide and oxygen concentrations must be taken into account. Carbon monoxide induces hyperventilation, thus it can influence the relative uptake of the other gases during breathing, while lack of oxygen leads to vitiation.

The standard ISO 13344:2015 “Estimation of the lethal toxic potency of fire effluents” takes also into account additional substances including hydrogen fluoride, sulphur dioxide, acrolein and formaldehyde. The standard provides the potential lethality of products of pyrolysis for 30-min exposure.

Vianello et al. (2012) present results from combustion of a kerosene pool and a prototype car in a laboratory scaled tunnel where chemical composition of the smoke is obtained by gas chromatography/mass spectrometry analysis. They detected presence of different chemicals as result of combustion of a prototype car, including relatively high concentration of pyrene and benzo[a]antrhacene characterized by high toxicity.

2.2.1.2 Combined effect of different substances and conditions

It is important to understand the combined physiological effect of different effluents as they are present in the smoke. Vianello et al. (2012) remark that the combination of many toxics, even below safety thresholds, can lead to incapacitation and subsequent death in a tunnel fire.

The effect of single components is usually determined by dose calculation (concentration integral over time) or, in few cases, using the peak concentrations. Related thresholds exist, common indexes include LC50 (median of lethality dose, measured on 30 minutes exposure) and Teel1,2,3 (thresholds leading to 3 different levels of incapacitation, measured on 1 hours exposure).

Qu et al. (2013) postulates that there is an additive relation on the effects combustion gases. They outline a quantitative risk assessment methodology in which doses of different toxicants, divided by their lethality threshold, are summed to obtain a bulk fractional effective dose. In this methodology the additivity assumption is applied on one hand to convert the fractional effective dose over a reference period of time to the specific period of time of interest, on the other hand the same assumption is used to sum the fractional effective dose of different components (oxygen depletion and the combination of carbon monoxide - carbon dioxide in the specific case).

The calculation of a bulk fractional effective dose can be further detailed by segregating the asphyxiating and irritating components to obtain two different indexes (Truchot et al., 2018). Short-time peaks of concentrations can also be harmful, thus a fractional effective concentration may be taken into account along with dose. In addition Puente et al. (2016) note that evaluating the toxicity in terms of lethality (LC50) is not appropriate when incapacitation is sufficient to cause death in a tunnel fire scenario. Moreover the uptake of gases is also related to the physical activity which is higher during walking (evacuation) comparing to rest conditions.

No specific study has been found in the literature on the effect of increased temperature on the uptake of toxic gases.

2.2.1.3 Yields

ISO 19700 defines the apparatus (the Purser furnace) that can be used to determine heat of combustion and yields for various materials under various temperature and equivalence ratio conditions (Stec et al., 2008). However, in order to evaluate the effect of a fire in a tunnel, it is fundamental to take into account the dynamics of the combustion, where different materials are burnt at different stages and at different rates in time. The medium-scale tests conducted by INERIS give an idea of the how, in a burning car, different products are generated at different rates in time (Truchot et al., 2018). For instance they observed a main peak of hydrogen fluoride in contrast with a more uniform production of hydrogen cyanide. Clearly, in terms of exposure probability a sharp concentration peak in the initial stage of the fire is a more severe condition compared to a uniform constant concentration over several minutes.

2.2.1.4 Other conditions affecting toxic products yields

Zhang et al. (2012) tested liquid heptane combustion in a small scale tunnel, with one closed end, under natural ventilation and different inclination angles, from -10 to 10 degrees. In the experiments they measured carbon monoxide concentration at the exit section, at ceiling height. They found that the peak concentration increases by a factor 2 to 3 when the tunnel is inclined by 10 degrees and the exit section is placed at lower elevation compared to the case with zero inclination.

2.2.1.5 Implications for consequence modelling

A consequence model predicting fire toxicity must predict, with reasonable accuracy, the concentration of toxic components produced during a fire, in the region of the tunnel were the evacuation occurs, at breathing elevation and during the evacuation time.

Physically, the rate of production of different fire effluents depends on combustion conditions, such as equivalence ratio and temperate, as well as the sequence of burning materials.

To accomplish the task, computational fluid dynamics simulation of an accidental tunnel fire and prediction of concentration of species rely on three submodels: the pyrolysis model, the chemical reaction (combustion) model and a turbulence model. The latter is strongly connected with the other two models. Currently, there is hardly any CFD model that is able to account for these three phenomena in detail. Even worse, simplifications commonly used when the models are applied, including constant fuel release and predefined yields ignoring the effect of equivalence ratio.

A way out from modelling the complex chemical mechanisms that determine equilibrium between species and thus their relative concentrations, is given by the experimental yields obtained with the Purser furnace method. However accurate simulation of local, non-constant, equivalence ratio conditions is still required to be able to successfully use tabulated yields in a simulation model.

Alternative to CFD are empirical models, based on fitting of data from experiments reproducing realistic accidental fires. An example of tests providing this type of data is Truchot et al. (2018).

2.2.2 Critical ventilation velocity

Critical ventilation velocity is defined as the air velocity required to avoid upwind smoke dispersion. Longitudinal ventilation dimensioned to provide critical velocity is used to isolate the smoke on one side of the fire and guarantee safe evacuation in unidirectional tunnels.

The critical velocity depends on various conditions among which the magnitude of the fire. In particular, the critical velocity grows with heat power up to a saturation value Hu et al. (2008a). Different semi-empirical formulations have been proposed, for a constant-cross-section empty tunnels with or without slope Atkinson and Wu (1996). These formulations are typically based on energy balance (constant Froude number).

Le Clanche et al. (2014) investigated conditions influencing the critical ventilation velocity. In their work, laboratory tests were performed using helium and varying the source diameter, air velocity, injection velocity and density of the components by mixing helium with air. They observed that the critical ventilation velocity increases with the plume Richardson number (i.e. the ratio between buoyancy flux and momentum flux). On the other hand, the ratio of source diameter to tunnel height and variation of density ratio at constant Richardson number resulted in small variations of the critical ventilation velocity. In addition Le Clanche et al. (2014) gave a physical explanation for saturation of critical ventilation velocity with increasing heat power observed in previous experiments. According to the authors, increased heat power in the performed experiments corresponded to a spatially larger fire source in the horizontal directions with a combined effect corresponding to zero or small variation of the plume Richardson number.

Realistic variations of setup and their relation to the critical velocity have been analysed including complex geometries, presence of vehicles as well as other means of ventilation/extraction (including natural ventilation) either by numerical simulation or experimental testing. Hu et al. (2008b) analysed, using CFD, the effect of moving the fire source from the centre of the tunnel section to the side, near the walls, on the ventilation velocity. They found that the position of the fire (near wall or centre) had a significant effect on ventilation velocity only for small fires. Wang (2012) performed numerical simulations of smoke propagation in a configuration with obstructed tunnel, which mimics the presence of vehicles either upstream or downstream of the fire source, concluding that the common free-tunnel assumption provides a conservative value of the critical ventilation velocity. Li (2019) simulated a fire scenario in a tunnel with interchange. Due to the addition flow resistance in this configuration, the critical ventilation velocity is higher comparing to the case of single-tube tunnel. Tang et al. (2018) analysed the combined effect of longitudinal ventilation and smoke extraction with exhaust outlet positioned just above the fire. In this particular case the critical ventilation velocity decreased with increased ceiling exhaust velocity. From safety point of view, a generalization of this result would prove the positive synergy between ventilation and extraction. It is also noted that increased ventilation can break the smoke stratification, a condition that can be dangerous as the smoke gets closer to breathing height. Jain et al. (2008) studied the two effects by numerical simulation showing that backlayering can be avoided and stratification can be maintained only for small fire.

2.2.2.1 Longitudinal ventilation velocity and relation with fire and smoke development

Increase of ventilation provides fresh air which enhances the burning rate and thus increases the heat release rate. In this sense the heat release rate and the critical ventilation should not be regarded as independent variables when determining safe ventilation conditions.

The possibility that an initial fire extend, meeting new fuel sources, is also related to the ventilation velocity. Fire propagation in queued vehicles has occurred in some of the major road tunnel accidents leading to high heat release rates. Wang (2012), noted that increase of ventilation velocity corresponds to a decrease of flame length and thus reduced probability of fire spread. These results are based on numerical simulation of a 32 MW fire, in which the flame impinges on the ceiling. Different experimental results (Putnam, 1965) showed that, in a free burning fire the horizontal extension of the flame may grow with increased wind.

The ventilation velocity affects also the concentration of smoke in the downstream region. The smoke layer below the tunnel ceiling moves away from the fire location under the effect of buoyancy. The smoke is diluted by entrainment of fresh air from the bottom layer. The entrainment rate decreases as the difference between smoke velocity and air velocity becomes smaller, a situation that occurs when the ventilation velocity is increased. Therefore, increased ventilation velocity up to the smoke velocity leads to persisting smoke concentrations downstream along the tunnel, with possible exposure to toxic concentrations of drivers located at larger distances from the fire source.

Yang et al. (2019) analysed the smoke flow under ventilation and in case of sloped tunnel performing laboratory-scale experiments and CFD modelling. In this configuration the stack effect can counterbalance the longitudinal ventilation when the ventilation is directed downwards. Moreover, the interaction between mechanical ventilation and stack effect results in multiple steady flow patterns with smoke moving in one or the other longitudinal direction. The time required to activate the ventilation is fundamental as the smoke will start propagating upwards during this time lapse and this determines which flow pattern will occur.

2.2.3 Smoke spread and development

Generally smoke include substances that can be in gas phase as well as solid phase, organic (soot) and inorganic, in form of particles or liquid phase in form of or droplets. We refer in this section to smoke as the gaseous combustion products only. Inhalation of gaseous compounds constitutes a major hazard as gases are uptaken by respiration. The combustion products generated in a fire have temperature that is typically around thousand degree Celsius and a density a quarter that of air; in some studies, where no other means or measuring or computing gas concentrations is available, the temperature is taken as an indicator of the presence of smoke (this is not always a good indicator as discussed below).

Turbulence of a buoyant impinging jet is characterized by the following conditions:

- non-isotropy, specially at ceiling and where density gradients appear;
- presence of large vortex structures;
- streamline curvature at the zone of impingement.

In stratified flows non-isotropy is observed also for the Prandtl number. The Prandtl number (the ratio of diffusivity of momentum and diffusivity of heat) has value around 1 in passive flows, and deviates from unity with values depending on orientation in stratified flows. The same is true for the Schmidt number (the ratio of diffusivity of momentum and diffusivity of specie concentration), the phenomenon is associated with ways the development of waves transporting momentum but scalars (heat or concentration of species).

After impingement the flow propagates along the tunnel confined by ceiling and lateral walls. Michaux and Vauquelin (2009) analysed flow patter of a buoyant (helium) jet in a cross-flow confined by a 10 m x 0.5 x 0.25 m channel. Helium was seeded with particles for flow visualization, various density ratios and cross-flow intensities were tested. Experimental time-averages images of the flow showed that the light plume impinges on ceiling and spreads towards the lateral walls. There the plume is directed downwards and then moves upwards again in the centre of the tunnel. Thus the plume depth is not uniform along the cross-section in the near field and medium filed. In particular there is alternation of phases were the smoke depth is larger in the tunnel centre and phases were the smoke depth is larger close to the lateral walls, with increasing distance form the source.

2.2.3.1 Empirical and semi-empirical results

The problem of smoke thickness has been studied in analogy with temperature (or density defect) profile, measured from the tunnel ceiling to the floor. In that case, the thickness of a ceiling jet is defined as the distance from the ceiling where temperature, velocity or other physical variables drops to a defined fraction (i.e. half) of the maximum value. Empirical results and have been collected and zone models have been proposed to predict smoke thickness, some of the these are summarized below.

Oka et al. (2016) analysed velocity and temperature profiles using PIV under naturally ventilated conditions observing that the ceiling-jet thickness derived from the temperature distribution is greater than that from the velocity distribution. This result is in line with the behaviour of free axi-symmetric jets and correspond to a Prandtl number slightly less than unity. In the experiments performed by Oka et al. (2016), in the region away from the source (one-dimensional tranquil flow region), the celing jet thickness remains approximately constant up to a certain distance which varied between 10 to 25 times the tunnel height in the performed experiments. Further downstream the thickness calculated from temperature distribution increased further.

A review of models and experimental results was presented in Guo et al. (2020) in relation to the case of a ceiling jet developing in conditions of natural ventilation. Experimental evidence showed that the longitudinal ceiling temperature follows and exponential decay with single exponential function or combination of two exponential functions. The authors developed a semi-empirical integral model for small fires neglecting radiative heat transfer. From the model solution, they found that the ceiling jet thickness increases with distance from the fire source. In addition, Guo et al. (2020) analysed the sensitivity of model-predicted ceiling thickness, gas temperature and smoke velocity reporting large dependency of the three quantities on the entrainment coefficient in the near field.

Interesting results from full scale tests in a road tunnel including mechanical ventilation carbon monoxide concentrations are given in Hu et al. (2010). These results show that, especially for small fires, temperature decay along the tunnel is faster than decay of carbon monoxide, so the temperature profile cannot be regarded as a good approximation of carbon monoxide concentrations. In the experiments, increased ventilation velocity leads to persistence of carbon monoxide concentrations. The reason is that the longitudinal ventilation velocity gets closer to the smoke velocity and thus the entrainment (proportional to the difference between the two velocities) is reduced.

2.2.3.2 Results from CFD studies

Some studies have evaluated the ability of Reynolds Averaged Navier-Stokes (RANS) first-order turbulence closure, such as the classic $k-\epsilon$ model, simulating smoke propagation in a tunnel. This class of models is common in most engineering applications for its reliability and good balance between model accuracy and simulation time.

Fletcher et al. (1994) performed octane pool fire experiment in a modelled tunnel and used the $k-\epsilon$ model to simulate the same scenario. The turbulence model was enhanced with the Rodi correction (Rodi, 1985) to account for the increase of turbulence production and effect on turbulence dissipation rate associated to buoyancy forces. They observed that this modification to the standard $k-\epsilon$ model is required to correctly predict the stratified flow at the ceiling, back-layering and critical velocity. The model was able to predict temperature with accuracy within 40 K at a distance of 30 m downstream of the fire when accounting for a range of model sensitivities and variations.

Woodburn and Britter (1996a) and Woodburn and Britter (1996b) developed and validated a modified version of the standard $k-\epsilon$ model to account for reduction of turbulence intensity in proximity of the wall. In addition they modelled the Prandlt number variability as function of stratification. They applied the model to the simulation of smoke spread from a tunnel fire. The simulation was performed splitting the domain in a near-fire region and a far region using a one-way coupling between the two: boundary conditions to the far field region (from a distance length of 20 source diameters) are obtained from the simulation of the near field region. They observed that, in the far field, the standard $k-\epsilon$ model lead to similar results as the modified version while in the near field the standard $k-\epsilon$ model caused the results to under-predict seriously the upstream propagation of the hot layer.

Similarly to body forces, streamline curvature has also an effect on turbulence. Streamline curvature occurs when the flow encounter obstacles, for example when the a jet impinges onto a solid surface. Isolated attempts to include this effect in the $k-\epsilon$ model have been made (Xue et al., 1993).

While RANS first-order turbulence closures remains the most popular choice for turbulence modelling in engineering applications, most of the recent work on CFD simulation of smoke dispersion in the literature is based on Large Eddy Simulation (LES). See for instance Oka et al. (2016), Tao et al. (2020), Wang (2009), Gao et al. (2004). In this case, the effect of buoyancy and streamline curvature is explicitly simulated with no need of ad-hoc formulations. For this application (transport and spread of hot combustion products in a tunnel), the computation cost of LES is typically an order of magnitude higher compared to RANS. The agreement of simulations with experiments is superior and usually within the accuracy required for engineering applications.

While model "error" associated with turbulence in LES is drastically reduced comparing to RANS, heat exchange can still be a source of inaccuracy and influence the ability of models to predict smoke spread in a tunnel. Temperature gradient helps mainlining the smoke stratification, thus heat transfer influences smoke dispersion. When the smoke velocity is relatively high, forced convection is the dominant mode of heat transfer from smoke to the ceiling. Natural convection (driven by buoyancy and instability created by interaction of hot fluid with cooler solid surface) becomes relatively important when the smoke slows down, in the far field. A CFD model for tunnel fire smoke dispersion need to incorporate both phenomena (Fletcher et al., 1994).

For large fires, radiation accounts for a significant portion of the heat transfer budget. Radiation from smoke to solid objects and vice-versa is influenced by presence of soot. Model prediction of soot concentration is a complex task due to processes happening at small scales including surface deposition and particle coalescence. The uncertainty in soot concentration is reflected in uncertainty in heat radiation. In addition, heat transfer models are heavily dependent on material properties that including absorption and radiation coefficients for the gas mixture and emissivity of the solid walls.

3 Summary and outlook

Performing a literature survey, this work has analysed some aspects of tunnel-fire modelling, with particular focus on smoke and toxicity. This area of research is characterized by some knowledge gaps and limitations, among which:

- lack of experimental data and limitations in the models makes it difficult to predict smoke composition and related toxicity resulting from realistic tunnel fires with complex sources such as cars;
- there is no uniformity of approaches to fire simulation, the range and types of models is wide with different implications in terms of accuracy and validity of results;
- overall, studies on model sensitivity and uncertainty analysis are scarce. With the current status it is not straight forward to determine specific models or methodologies that are suitable to simulate a tunnel-fire scenario with a given level of accuracy.

From the model validation results available in the literature, requirements for simulation of tunnel-fire can be identified. As far as CFD models are concerned, these include:

- turbulence model that can represent flow stratification with sufficient accuracy;
- thermally thick boundary conditions at solid surfaces;
- modelling of natural convection;
- account for sensitivity in soot content and content of toxic substances.

Use of a design curve for heat release rate in combination with CFD is an oversimplification which neglects the coupling between fire heat and local oxygen content, thus it should be avoided when fuel release rate can be defined or calculated in the model.

Specific results and problems that are worth of further study include:

- Transient stages of smoke generation and activation of ventilation. Yang et al. (2019) reported that this can have big impact on smoke concentrations and flow direction;

- Relation between flame length and ventilation velocity. Wang (2012) noted that increase of ventilation velocity corresponds to a decrease of flame length and thus reduced probability of fire spread. Conversely, different experimental results (Putnam, 1965) showed that, in a free burning fire, the horizontal extension of the flame may grow with increased wind;

- Combined effect of different toxic substances. Vianello et al. (2012) noted that the combination of many toxics, even below safety thresholds, can lead to incapacitation and subsequent death in a tunnel fire;

- No specific study has been found in the literature on the effect of increased temperature on the uptake of toxic gases;

- From design point of view, curtain ventilation systems have not been dedicated enough attention as alternative to longitudinal ventilation. Gao et al. (2012) highlights possible advantages of this technology.

Given the complexity of tunnel fire scenarios, results of consequence models require a critical interpretation in light of the associated uncertainness. For this to be done, uncertainty must be recognized and reasonably quantified.

The scientific research has highlighted some important connections between different aspects of tunnel fires, which include the effect of ventilation on fire heat rate, combustion, generation of products and smoke stratification. There is a risk that these links be not recognized or accidentally neglected in a safety study when simplifications are made to apply specific models or calculations or to isolate specific phenomena of interest. To avoid major biases in the results of a consequence analysis, these relations must not be ignored.

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