European Train the Trainer Programme for Responders

Lecture 11

Confined spaces

LEVEL IV

Specialist officer

The information contained in this lecture is targeted at the level of specialist officer and above.

This topic is **ONLY** available at LEVEL IV

This lecture is part of a training material package with materials at levels I – IV : Firefighter, crew commander, incident commander and specialist officer. Please see the lecture introduction regarding competence and learning expectations

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Clean Hydrogen Partnership

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Summary

This lecture provides Responders with an overview of the use of FC and hydrogen technologies in confined spaces, for example in e. g. indoors, in carparks and tunnels. It is stressed that the information covered in the previous lectures is all applicable and thus only additional recent research is included here. This lecture highlights the specific hazards related to FCH systems located indoors. It covers the important topics of passive and forced ventilation, well-ventilated and under-ventilated hydrogen fires including two regimes of self-extinction, and external flame. This lecture also discusses the pressure peaking phenomenon, which is specific for hydrogen.

Keywords

Enclosure, ventilation, pressure peaking phenomenon, carparks, tunnels, well-ventilated fires, under-ventilated fires, self-extinction flame, external flame.

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1. Target audience

The information contained in this lecture is targeted at the level of specialist officer. The role description, competence level and learning expectations assumed at specialist officer level are described below.

1.1 Roll description: Specialist

Specialists assist Incident Commanders with advice and by directing and supervising technical operations that involve the use of knowledge, skills or equipment related to a specific risk or response activity. Typical incidents involve hazardous materials, transportation vehicles, climatic events, structural and other built environment failures and emergency response logistics.

1.2 Competence level: Specialist

A scientific, engineering and empirical foundation in the subject area with skills, extended by experience, to apply that information, knowledge in an interpreted and useful way to enable the Incident Commander and other first responders under the specialist's direction to respond effectively and safety to the emergency situation.

1.3 Prior learning: Specialist

EQF 5 Comprehensive, specialised, factual and theoretical knowledge within a field of work or study and an awareness of the boundaries of that knowledge. A comprehensive range of cognitive and practical skills required to develop creative solutions to abstract problems. Exercise management and supervision in contexts of work or study activities where there is unpredictable change; review and develop performance of self and others.

2. Introduction and objectives

The use of FCH technologies in confined spaces is associated with the higher probability of hydrogen accumulation. Due to the growth of these technologies, it is possible to find FCH installations not only outdoors but also indoors. Examples include: FC forklifts inside warehouses; FC vehicles located in car parks, tunnels and garages; electrolysers and fuel cells for home use etc. In case of an incident involving indoor FCH installations, the following developments are possible: the occupants may be unable to leave a building/facility; Responders may be unable to perform their duties without putting their own life at risk; the partial or complete demolition endangers the lives of both Responders and members of the general public. Therefore, the topic of safe use of hydrogen and fuel cells in confined spaces is of high importance for Responders. While for a hydrogen release outdoors buoyancy is a natural safety asset providing its rapid release/dispersion, for releases indoors this may not be the case. Fast hydrogen release indoors can lead to either a build-up of pressure or to its accumulation and hence to more severe consequences.

UU was one of the partners in the European funded project Hyindoor "Pre-normative research on safe indoor use of fuel cells and hydrogen systems" (www.hyindoor.eu). The main outcomes of this project led to a deeper understanding of the phenomena associated with the releases from hydrogen installations in the indoor settings and the guidance on hydrogen use indoors and in tunnels [1, 14].

By the end of this lecture Responders/trainers will be able to:

- Identify the main hazards of hydrogen use indoors,
- Distinguish between passive and forced ventilation,
- Describe the main regimes on hydrogen indoor fires,
- Understand the effect of deflagration venting,
- Explain pressure peaking phenomenon,
- Use nomograms to evaluate the possibility of pressure peaking phenomenon (PPP).

3. Hazards and associated risk for the use of hydrogen in enclosures

There is a range of scenarios involving FCH applications located in enclosures (see Deliverable D1.1 of HyResponder [2]). The total volumes of enclosures may vary, from a small garage to a box-like enclosure for a stationary fuel cell (FC), up to a large-scale warehouse. Hydrogen release rates may vary as well, from a small mass flow rate release from a feed line to a FC up to a large-scale release from high pressure storage, for example a release from a FC car's TPRD parked in a residential garage. In case of incidents or accidents occurring on FCH systems located indoors the priorities for Responders are: to safe human life, to protect property and the environment. Harm criteria for humans and damage criteria for structures are discussed in detail in the relevant lecture.

The hazards related to an incident/accident on indoor FCH installations include:

- Oxygen depletion and a subsequent asphyxiation,
- Effects of high temperature and heat flux from jet fires,
- Cold burns from liquid hydrogen spill
- Overpressure effects,
- Injury and a loss of life,
- Structural collapse,
- "Domino" effects,
- Damage to the environment.

Those who design/approve/own the indoor FCH installation should give careful consideration to the reduction of 'the damage to infrastructure structures and equipment and to minimise disruption of business, preserve corporate image and reduce direct and indirect financial losses' [3, 4]. 'Attention should be paid to preventing the escalating effects of objects, events and layouts on damages and to value and importance of the property in and around a facility' [3].

In the event of a release whether big or small there are a number of potential phenomena which may happen. They may include:

- Unignited hydrogen release. If this happens indoors, the issues which need to be considered include: evaluating the size of the flammable envelope; determining the level of potential overpressure (without ignition); assessing the relationship between the ventilation rate and the release.
- Ignited release. If release is ignited with a formation of a jet fire a range of issues should be considered such as: the heat transfer to the surroundings; sustainability of a fire (i.e. is there a sufficient amount of oxygen to support it or will it go off); relationship between the ventilation and fire behaviour; possibility of fire reigniting.
- Explosion: Here, the questions should be asked: if an unignited release accumulates and subsequently ignites resulting in either a deflagration or detonation what are the consequences? What is the relationship between venting and the deflagration overpressure?

Hydrogen has a high propensity to leak and this can become a problem in an indoor environment. Obviously, hydrogen accumulation in enclosures can lead to the formation of a flammable mixture with the air (or oxygen). There are also other issues associated with unwanted releases such as pressure peaking phenomenon (PPP) and effect of oxygen depletion.

An adequate ventilation can mitigate against these effects. If a hydrogen leak is ignited the fire (jet fire or plume) will spread and grow within an enclosure. In addition to the flame and hazards associated with it such as temperature and heat flux, there will be hot combustion gaseous products formed which may also represent a hazard. As these gaseous products rise a hot layer of gases may be formed under the enclosure ceiling. The way of fire growth will depend on the type of combustion, the interaction with the surroundings and access to oxygen [5]. Depending on the size and the location of the leak the flame itself may impinge on construction elements of enclosure.

Safety related phenomena and potential consequences associated with indoor incidents/accidents involving FCH systems are summarized in the diagram shown in Figure 1.

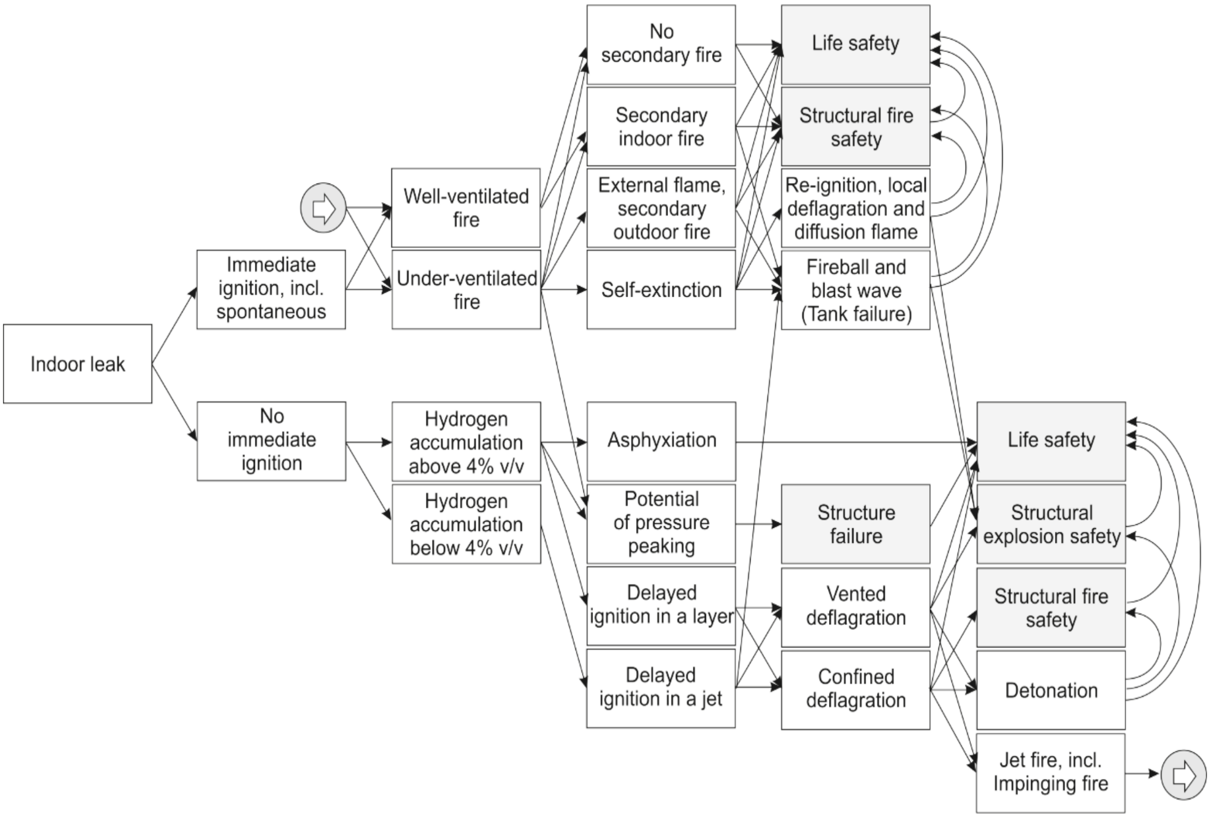


Figure 1. Safety related phenomena and consequences. White boxes correspond to hydrogen phenomena; grey boxes – to the consequences [4].

As shown in Figure 1, following a hydrogen leak in confined spaces, two options are possible: no immediate ignition (bottom branch of the diagram) and immediate ignition including spontaneous ignition (top branch of the diagram). The ignition of a hydrogen leak can be caused by the presence of an open fire, a hot surface, an electric or mechanical spark and other factors, as well as hydrogen-specific phenomenon of *spontaneous ignition* (within air-filled piping) by so-called diffusion mechanism [6].

If the leak is ignited immediately, a subsequent fire can develop in two modes: *well-ventilated* and *under-ventilated*. *Well-ventilated fire* is characterized by a relatively low hydrogen release rate and complete combustion of hydrogen within the enclosure. The hazards associated with the well-ventilated fire include:

- direct effect from the flame and hot combustion products current,
- radiation from the hot layer formed under the ceiling,
- hot solid surfaces such as roofs, structural failure of load bearing construction elements due to direct flame impingement, etc.

An increase in hydrogen release rate can result in the transition to *under-ventilated fire*, when oxygen is consumed at a faster rate than it can be replenished through the ventilation. This in turn may lead to two sub-regimes: *an external flame* occurring in the vents (with no combustion inside the enclosure) and full *self-extinction* of fire within the enclosure. The additional actions are required from Responders after the self-extinction of fire, e.g. in a FC container, to ensure hydrogen is not accumulated above the hazardous limit in the enclosure accommodating the FC.

Both types of fire can result in the ignition of flammable materials inside the enclosure, generating *secondary indoor fire.* Thus, the fire will continue to burn even after hydrogen release is being stopped e.g. by shutting of safety valves, and additional hazards, such as release of toxic fumes, are possible. The under-ventilated fire is characterised by relatively high hydrogen release rate. Thus, there is a potential for PPP, endangering structural integrity of the enclosure [6, 7]. It is worth noting that both unignited and ignited releases can generate hazardous overpressure due to PPP. However, calculation of the overpressure due to PPP is different for unignited release and jet fire. The under-ventilated fire may also lead to an external flame, i.e. *secondary outdoor fire.*

If both types of fires as well as secondary fires are not extinguished and continue to burn, this potentially may lead to a catastrophic failure of storage tank(s) located indoors, resulting in a rapid release of energy followed by ignition of large quantities of hydrogen, producing *fireball* and *blast wave*. External flame and secondary outdoor fires can also result in failure of outside hydrogen storage tank(s). Thus, measures should be taken to prevent this, e.g. by placing external hydrogen storage vessels at a distance from the enclosure vents.

The self-extinguished under-ventilated fire may re-ignite when a fresh supply of air enters the enclosure. It can potentially lead to a *localized deflagration* and a diffusion flame in the zones containing hydrogen above the lower flammability limit (LFL), i.e. 4 vol. %. All types of fires present *life safety* hazards (direct thermal damage from the flame, radiation thermal damage, overpressure due to the PPP, and toxicity of combustion products produced by secondary fires) and *structural fire safety* hazards (weakening of the structural integrity and eventual collapse of the enclosure due to prolonged fires) [4].

If a hydrogen leak is not ignited immediately upon release, it would lead to gradual hydrogen accumulation within the enclosure. A release with a high flow rate which exceeds the ventilation capacity can produce hydrogen concentration above the LFL, which creates the possibility for t *delayed ignition in a layer* and its deflagration. Additionally, a high flow rate release can result in asphyxiation and PPP. Although hydrogen is not poisonous/toxic it does not support metabolism. Similar to any other gas (with the exception of oxygen) a risk of asphyxiation exists mainly in confined areas as a result of oxygen depletion [8]. Hydrogen release with a lower rate, which does not lead to the accumulation of hydrogen above 4 vol. % in a layer, can still result in a *delayed ignition in a jet.* Both types of delayed ignition can result in deflagration of hydrogen-air mixture with overpressure, which potentially can destroy the enclosure. Mitigation of explosions by deflagration venting is a widespread technique. When the enclosure is equipped with the vents, which provide a relief of deflagration overpressure, *vented deflagration* may happen**.** *A confined deflagration* differs from the vented deflagration by the absence of significant openings leading to the atmosphere, thus preventing pressure relief in the enclosure. The pressure peak in a closed vessel for a stoichiometric hydrogen-air mixture, initially at NTP, can reach up to 815 kPa [9], which would destroy any civil structure (generally able to withstand overpressures of about 10-20 kPa).

In some cases, deflagration can result in a transition to *detonation*. Due to the higher flame propagation velocity and higher levels of overpressure detonations present greater hazards compared to deflagrations. Both deflagration and detonation pose *life safety* hazard through the pressure and thermal effects. They also present *structural explosion safety* hazard, in the worst-case scenarios leading to the collapse of the enclosure. Finally, both delayed ignition events discussed earlier can be associated with jet fires, including *fire impinging* effect on walls and/or ceiling of the enclosure. Once the jet fire is established, it can burn in either well-ventilated, or in under-ventilated regime, and the subsequent phenomena and safety consequences would follow the pattern indicated in the top branch of the diagram (Figure 1) corresponding to immediate ignition as illustrated by the arrow () in a circle pictograms.

4. Permeation leaks

Permeation of hydrogen through storage tanks is not foreseen as a problem for responders. However, for completeness the phenomena are described in Lecture 3 – Hydrogen Storage, Lecture 4 – Compatibility of Hydrogen With Different Materials, and Lecture 6 – Unignited Hydrogen Releases Outdoors and Their Mitigation.

5. Indoor hydrogen releases and dispersion

Hydrogen energy applications often require that systems are used indoors, e.g. industrial trucks for materials handling in a warehouse facility, fuel cells located in a room, or hydrogen stored and distributed from a gas cabinet. It may also be necessary or desirable to locate some hydrogen system components/equipment inside indoor or outdoor enclosures for security or safety reasons, to isolate them from the end-user and the public.

Using of hydrogen in confined environments requires detailed assessments of hazards and associated risks, including potential risk prevention and mitigation features. The release of hydrogen can potentially lead to the accumulation of hydrogen and the formation of a flammable hydrogen-air mixture, which potentially results in jet-fires.

The knowledge gaps in the following four main topics were closed through the HyIndoor project (https://hydrogeneurope.eu/project/hyindoor).

- Hydrogen release inside a confined or semi-confined enclosure;
- Indoor hydrogen-air deflagration;
- Jet fire and underventilated fire;
- Hydrogen detection for confined spaces.

The generated knowledge has been translated into state-of-the-art safety guidelines including specific engineering tools supporting their implementation. Recommendations have been formulated with regards to evolutions needed in the Regulations Codes and Standards framework at European and International levels to support the safe introduction of fuel cells and hydrogen in early markets.

There are three generic safety objectives for any safety system, including the use of hydrogen systems indoors: life safety, property protection and environment protection. Primary consideration should be given to life safety, e.g. site workers, customers and general public. The life safety objectives include, but not limited to [3]:

- The occupants are able to leave building/facility in reasonable time, or consequences to occupants are acceptable low;
- First responders are able to operate in reasonable safety;
- Collapse or debris does not endanger bystanders, first responder and other people likely to be near facility.

The general safety rules, strategies and recommendations for hydrogen infrastructure design and utilization include:

- Consider whether it is really necessary to house the hydrogen system within a room/enclosure, or whether it could be relocated outdoor where accidental leak would less likely lead to accumulation of hydrogen in flammable concentrations due to better ventilation;
- Reduction of hydrogen supply pipeline diameter and operational pressure to the minimum required to satisfy technological requirements for mass flow rate. If decrease of pipe diameter is impossible or undesirable, utilization of flow restrictors;
- Minimization of hydrogen operational pressure whenever possible;
- Sighting of hydrogen infrastructure in a way ensuring jet decay before impingement on neighboring obstacles in order to prevent formation of the layers with flammable hydrogen concentration;

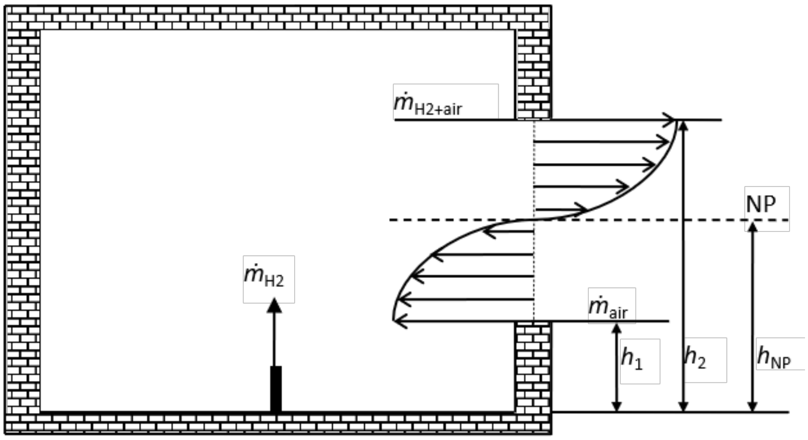
- Identification, and, where possible, reduction of number and separation of potential ignition sources;
- Utilization of storage tanks with high fire resistance rating to ensure at least sufficient time for evacuation of people;
- Minimization of hydrogen inventory to prevent formation of flammable mixture in confined enclosure even after complete release and dispersion of hydrogen or limit it below amount which will produce structural damage in low strength equipment and buildings in case of deflagration;
- Evaluation of deterministic separation distances before quantitative risk assessment (QRA). Deterministic separation distances can be calculated for unignited releases and for well-ventilated jet fires using published and validated nomograms;
- Consider preferential use of side vents over roof vents in order to improve passive ventilation and vertical versus horizontal vents of the same area;
- Consider preferential use of several vents over a single vent of the same area with difference in height of vents location as large as possible and vents located on all sides of the building to enhance wind-assisted venting irrespective of its direction;
- Consider exclusion of venting pipes and ducts as much as possible.

The guidelines and mitigation strategies of indoor hydrogen application could be found in the output report of the HyIndoor project (https://hal-cea.archives-ouvertes.fr/cea-02429488).

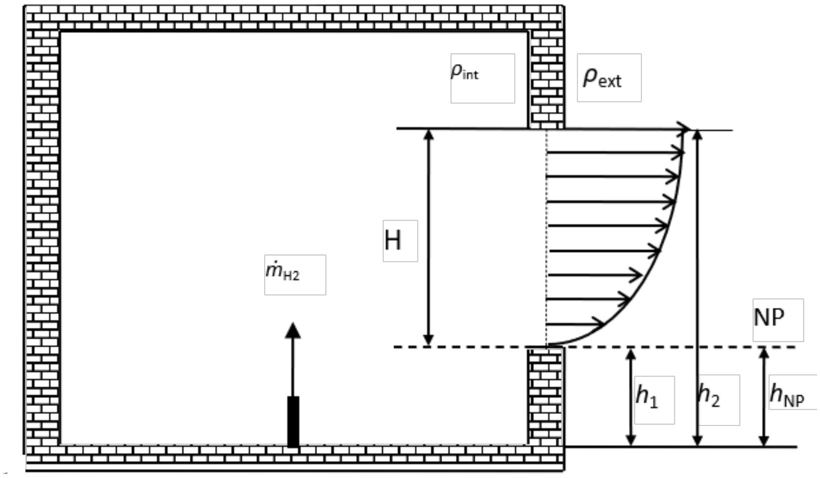
6. Natural and forced ventilation

Ventilation can be *natural/passive* or *forced/mechanical/active*. Natural ventilation is a preferable option as it is cheap and reliable, it does not depend on a power source and is always operational. Natural ventilation is provided through permanent vents. The location of these vents in important and should ensure maximum air flow and dispersion of the flammable gas. With hydrogen a combination of upper and lower vents is recommended. If it can be verified, natural ventilation should be permitted to provide all required ventilation and makeup air.

The neutral plane (NP) is a horizontal plane where pressure inside and outside the enclosure are equal. Below the NP air enters the enclosure and above the NP lighter hydrogen-air mixture exits the enclosure. For natural ventilation, the NP is at half vent height (Figure 2a). In the case of passive ventilation of the enclosure with release of gas lighter than air, the NP is located at or below the half height of the vent for steady-state conditions as shown in Figure 2b.



(a)



(b)

Figure 2. Flow velocity through the vent for natural (a) and passive (b) ventilation.

Natural ventilation equations for the air ventilation are derived in the assumption of the equality of flow in and out of the enclosure. In the case of passive ventilation, the NP for lighter than air gases can be anywhere below a half of vent height.

Maximum hydrogen concentration level in the enclosure with one vent in the assumption of sustained leak can be evaluated using the following equation [10]:

$$X = f(X) \cdot \left[\frac{Q_0}{C_D A (g' H)^{1/2}} \right]^{2/3} \tag{1}$$

where X is the hydrogen volume fraction, Q_0 is the release rate (m^3/s), C_D is the discharge coefficient, A is the vent area (m^2), H is the vent height (m), g is reduced gravity (m/s^2), $g' = g(\rho_{air} - \rho_{H_2})/\rho_{air}$, ρ_{air} and ρ_{H_2} are density of the air and hydrogen, respectively, (kg/m^3) and $f(X)$ is function equal to:

$$f(X)=\left(\frac{9}{8}\right)^{1/3}\cdot\left\{\left[1-X\left(1-\frac{\rho_{H_2}}{\rho_{air}}\right)\right]^{1/3}+\left(1-X\right)^{2/3}\right\} \tag{2}$$

Equation (1) is derived with the assumption that:

- the release flow rate remains constant,
- gas mixture is uniform across the enclosure, i.e. hydrogen concentration is not a function of location inside the enclosure.

A comparison with experiments had shown, however, that the equation (1) can be used to predict the maximum hydrogen concentration in the case of hydrogen forming layers [10], i.e. it can be considered conservative. Based on equations of (1) and (2) an engineering nomogram for calculation of sizes (height and width) of a vent in case of a uniform mixture in the enclosure with a single vent [10] was developed (Figure 3). Note that although in practice hydrogen-air mixture can form layers even in the enclosure with one vent, equations and the nomogram in Figure 3 will provide results close to the maximum concentration values, i.e. it is conservative and can be applied to non-uniform mixtures. The nomogram can be used to calculate hydrogen maximum concentration at steady state condition by known height and width of a vent and release rate. The nomogram is valid for both uniform and non-uniform mixtures in an enclosure with one vent. The procedure for hydrogen concentration calculation (red arrows) is as follows:

1. Select the mass flow rate of hydrogen leak at the vertical axis of the lower panel of the nomogram and project it horizontally until intersection with one of the diagonal lines corresponding to different vent heights. There are 15 such lines in the nomogram in Figure 3, covering practically all possible vent heights ranging from 0.5 mm to 10 m.
2. From the point of intersection, draw a vertical line up until it intersects one of the diagonal lines in the top right panel of the nomogram, which corresponds to different vent widths. There are 15 such lines in the nomogram in Figure 3, covering vent widths in the range between 0.5 mm and 10 m.
3. From the point of intersection, draw a horizontal line left until intersection with the function curve in the top left panel of the nomogram.
4. Draw a vertical line from the point of intersection to the horizontal axis of the top left panel. The value on the horizontal axis correspond to the hydrogen concentration in vol. %.

The nomogram in Figure 3 can also be used for the opposite evaluation, i.e. for the calculation of the vent size required to ensure that for the given hydrogen release rate the concentration will not exceed a specified value (blue arrows in Figure 3). In this case the process of calculation is performed in the reverse order, starting with the desirable concentration value (see example with 2 vol. % mixture in Figure 3). If it is required to evaluate the dimensions of the vent, which will provide hydrogen volume percentage below a certain level, e.g. below 2 vol. % (blue arrows) one would start with the desired volume percentage value at the horizontal axis of the upper left panel and draw vertical line until the intersection with the function curve in this panel. From this intersection point one can draw horizontal line to the right towards upper right panel, passing across the vent width curves. Next, one should select the release mass flow rate (e.g. 0.2 g/s) in the lower left panel of the nomogram, drawing horizontal line to right across lower right panel, passing through the vent height curves. It is now possible to determine the dimensions of the vent required for the enclosure as to provide hydrogen concentration not exceeding 2 vol. % for a specified hydrogen release. In the example demonstrated in Figure 3, to keep hydrogen concentration below 2 vol. % with the given release rate 0.2 g/s the enclosure should be equipped with the vent 1 m in height and 1 m in width.

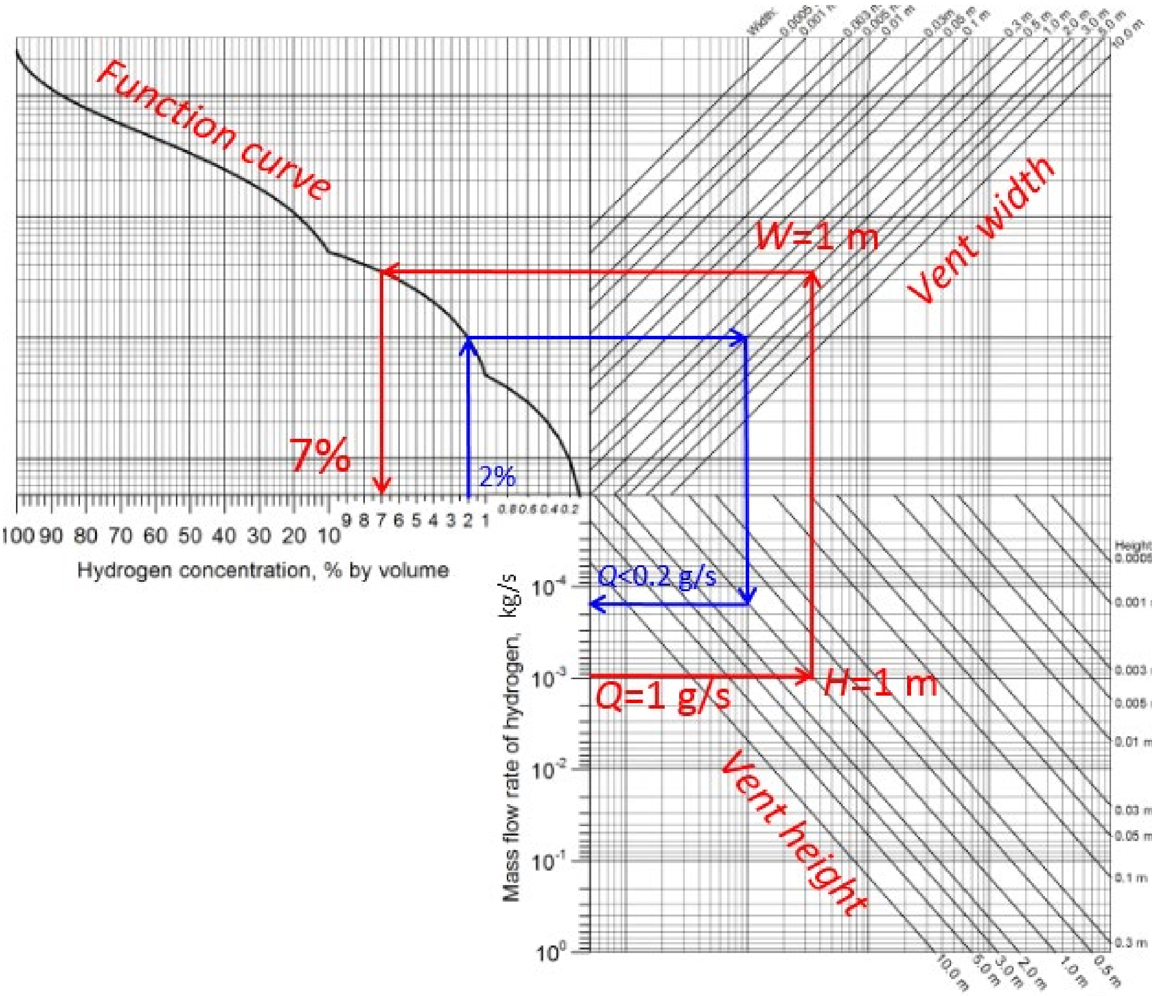


Figure 3. An engineering nomogram for calculation of the maximum value of steady-state concentration of hydrogen in the enclosure with one vent (discharge coefficient *C*=0.6).

7. Pressure peaking phenomenon

Pressure peaking is the phenomenon observed for the gases which are very light (lighter than air), which can result in overpressure exceeding the structural strength limit of an enclosure or a building in the case of sufficiently high hydrogen release rate. Pressure peaking would occur if hydrogen release flow rate is high enough to result in complete displacement of the air from the enclosure, i.e., hydrogen concentration within enclosure must reach 100 vol. %.

It is known that in FC vehicles hydrogen is commonly stored as a compressed gas in tanks, which are equipped with thermally activated pressure relief devices (TPRDs) as per EU No 406/2010 Commission Regulation [17]. The PRD is fitted to the fuel tank and begins to release hydrogen when temperature of about 110 ºC is reached, e.g. in fire conditions. The TPRD can provide rapid release of hydrogen, if large orifice diameter is used, thus minimising the possibility of tank explosion during too long exposure to fire. High mass flow rates from TPRDs are probably "acceptable" for outdoors. However, the hazards resulting from a rapid release indoors are different.

Let us consider a hypothetical scenario involving a release from a typical on-board hydrogen storage tank at 35 MPa, through a 5.08 mm diameter orifice [18]. The release is assumed to occur vertically upward in the centre, 0.5 m above the floor, of a small garage of size L×W×H=4.5×2.6×2.6 m [19] and volume of 30.4 m^3 with a single vent equivalent in area to a typical brick L×H=25×5 cm located flash with the ceiling. A conservative approach is taken, i.e. a constant mass flow rate of 0.39 kg/s is applied (ignoring a pressure drop in the storage tank) after the TPRD opening. Thus, a worst-case scenario i.e. high mass flow rate in a small garage with minimal venting is considered.

The application of mathematical models for the steady state subsonic release (when hydrogen fully occupies the enclosure) gives the predicted overpressure values in the enclosure in range between 15 (resulting from Bernoulli's equation with zero velocity in the vessel) and 17.9 kPa (from orifice flow equation for subsonic flow) for a discharge coefficient C in both cases taken as commonly recommended C=0.6 [20]. However, these estimates do not account for the initial sate of injection of a lighter gas (hydrogen) into a heavier gas (air). The predicted transient pressure load in the vented enclosure is given in Figure 4.

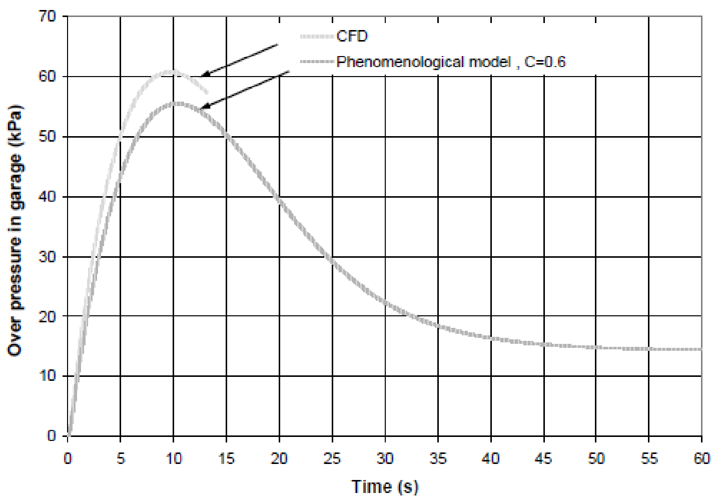


Figure 4. Predicted overpressure in the garage with time, a comparison between CFD and a phenomenological model [18].

Figure 4 illustrates how the overpressure within the enclosure resulting from the injection of hydrogen reaches a level capable of demolition the garage [9] within only 3 s for the selected scenario. As it follows from Figure 4 if the garage is not destroyed first, the pressure within the garage, for this particular scenario, reaches a maximum level in excess of 60 kPa. The pressure then drops off and tends towards a steady state value, considerably lower, and equal to that predicted by the simple steady state estimations. Once again please note that this represents a worst-case scenario with a constant mass flow rate. Therefore, continuation of a constant mass flow rate for 60 s included in Figure 4 is purely for illustrative purposes to show the time frame before steady state conditions are reached when practically all the garage is occupied by 100 vol. % hydrogen. It should also be noted how the maximum pressure is reached in less than 10 s: within this time the entire garage would be demolished, without even considering the consequences of ignition.

It should be noted that the overpressure level reached inside the garage increases with the decrease of molecular mass of the gas injected into the garage, i.e. lighter gas such as hydrogen results in a significantly higher pressure than a heavier one, e.g. propane. This should be taken into account when designing TPRDs for use with hydrogen, i.e. the same technology used for e.g. CNG should not be assumed to behave in the same way for hydrogen.

Figure 5 demonstrates the predicted overpressure values versus time for a range of gases with the same mass flow rate (0.39 kg/s) in the same garage-like enclosure (volume 30.4 m^3, vent 0.0125 m^2). Discharge coefficient C=0.6. The molecular masses of hydrogen, helium, methane and propane are 0.002, 0.004, 0.016 and 0.044 kg/mol, respectively. It is clear that the peak of overpressure drops with the increasing molecular mass of the gas. The higher the molecular mass of the gas, the closer the maximum pressure is to steady state values predicted using simple methods. The volumetric flow rate out of the enclosure is inversely proportional to the square root from the density of gas escaping the enclosure. Thus, in the beginning of the process when the density of the hydrogen-air mixture is very high and close to the density of the air, the constant volumetric inflow of pure hydrogen is essentially higher than the volumetric outflow of the heavier hydrogen-air mixture and this explains why the overpressure for lighter incoming gas grows to a higher level compared to that for a heavier incoming gas and pressure dynamics has a characteristic peak for hydrogen only.

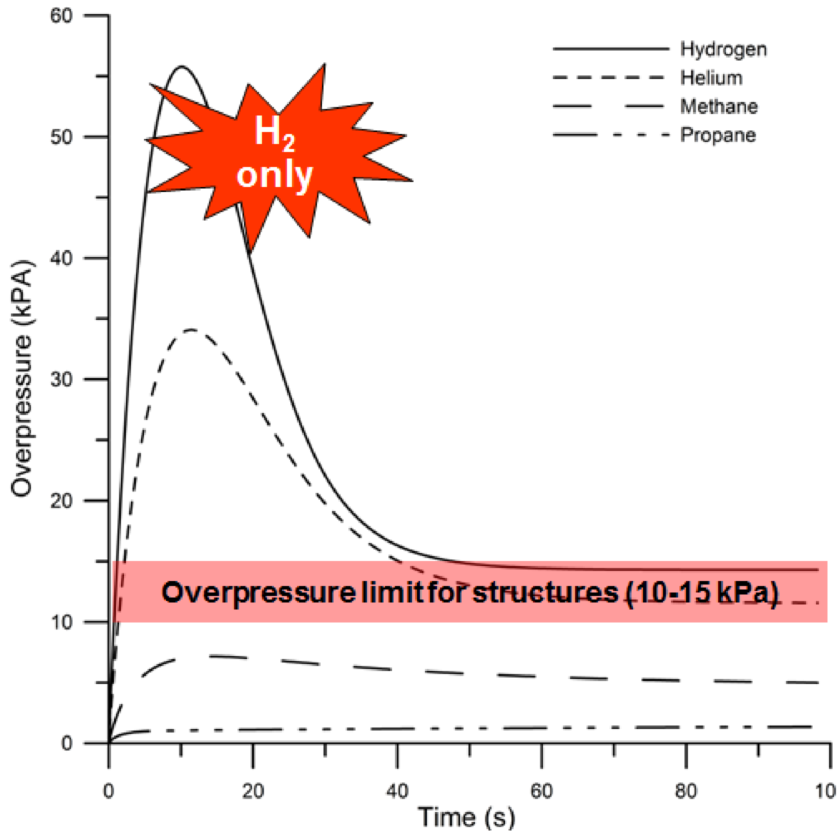


Figure 5. Predicted overpressure values for hydrogen, helium, methane and propane released in a garage versus time, release rate of 0.39 kg/s [18].

Pressure peaking phenomenon only occurs when hydrogen release rate is sufficiently high to completely displace air from the enclosure with time of sustained leak. Therefore, before estimating overpressure produced by PPP, it is necessary to confirm whether the release rate is sufficient to fill the enclosure with 100% of hydrogen if a leak is sustained. An engineering nomogram in Figure 6 can be used to verify this [10]. The nomogram allows one to calculate the maximum vent dimensions which for a given steady release will eventually result in a 100 vol. % hydrogen concentration in the enclosure. In order to find the maximum vent dimensions, select hydrogen release rate on the vertical axis and draw a horizontal line until its intersection with one of the diagonal lines corresponding to an appropriate vent width. Draw a vertical line from the intersection point to horizontal axis to find the required vent height. Alternatively, the nomogram in Figure 6 can be used to find the minimum release rate for a known vent size when calculation of PPP is needed, in which case the above steps are reversed. If the release rate found through this nomogram is lower than the actual one, or the actual vent dimensions are smaller than found using nomogram in Figure 6, 100 vol. % hydrogen concentration will be reached and PPP can occur and the nomogram for PPP (Figure 7) should be used.

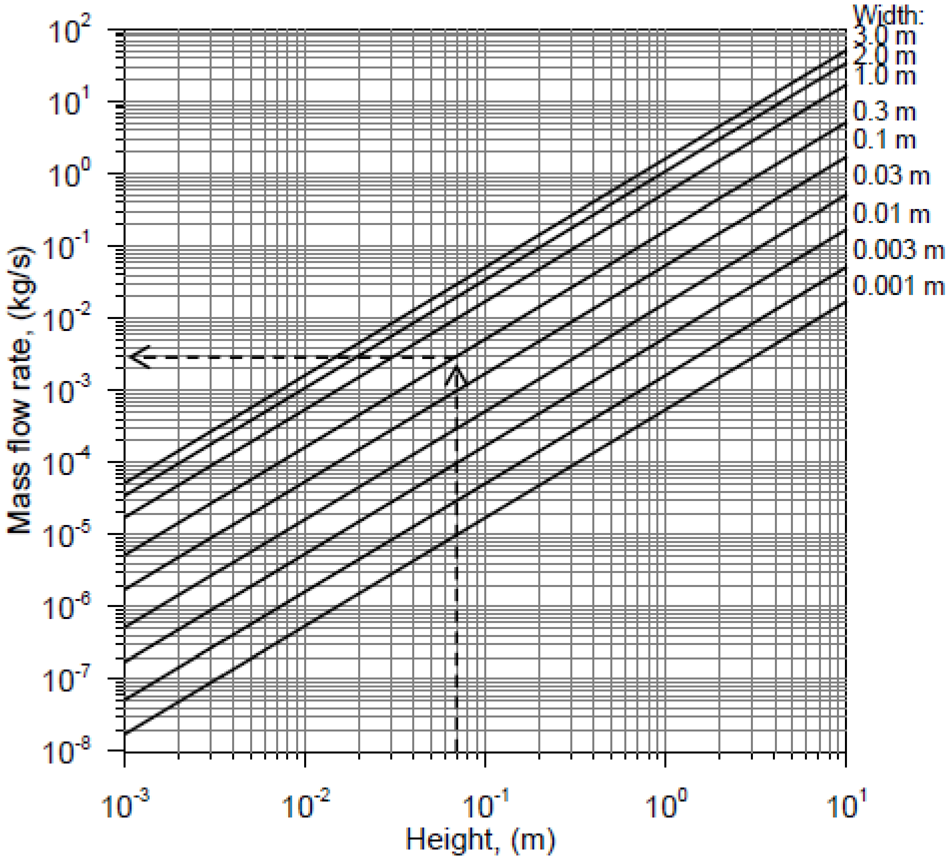


Figure 6. The nomogram for graphical evaluation of hydrogen leak mass flow rate in an enclosure with one vent, which leads to 100 vol. % of hydrogen concentration [10].

Figure 7 shows a nomogram for PPP evaluation, which allows calculation of the maximum overpressure peak produced by high rate hydrogen release from the known mass flow rate and leak diameter. To use the nomogram in Figure 7, follow the following procedure:

- Start with the vertical axis on the lower panel of the graph and select storage pressure, read across horizontally to the leak diameter.
- Read vertically upwards to calculate the mass flow rate of the leak. Continue vertically upward from the mass flow rate to the point of intersection with the line for the appropriate vent area in the upper panel.
- Read horizontally to the left until the intersection with the vertical axis. The point of intersection provides the maximum overpressure in the enclosure.

Alternatively, the nomogram in Figure 7 can be used to determine the area of the vent required to keep the overpressure below the specified limit. In this case, follow the first two steps and then draw a horizontal line from the desired overpressure value found on the vertical axis of upper panel of the graph. The closest to the intersection curve in the upper panel will correspond to the required vent area (if the intersection falls between two curves, use rightmost in order to obtain a conservative value).

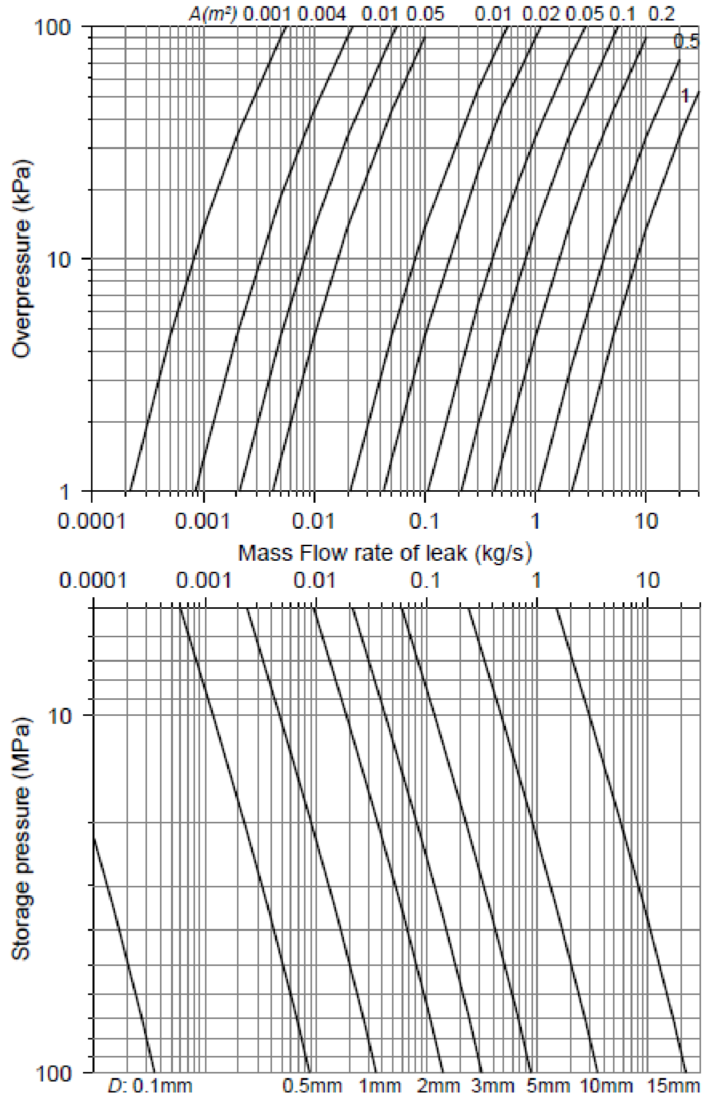


Figure 7. Pressure peaking nomogram for various release rates [4].

8. Carparks

Carparks, either underground, open, or covered, are essential to the increasing number of hydrogen-powered vehicles in use world-wide. It becomes important to consider practical scenarios and issues which may arise with day to day use of such vehicles. By understanding the hazards arising due to placement of hydrogen-fuelled vehicles in confined environments, steps can be taken towards reduction of associated hazards and risk by inherently safer design. In the majority of passenger cars hydrogen is commonly stored as compressed gas in tanks. Typical storage pressures are in the range of 350 to 700 bar. The inventory of hydrogen varies with the size of the vehicle and, according to the US Department of Energy, onboard hydrogen storage in the range of approximately 5-13 kg is required to enable a driving range of greater than 300 miles for the full platform of light-duty automotive vehicles using fuel cell power systems [26].

Pressure relief devices (TPRDs) are typically equipped on onboard hydrogen storage tanks, which provide rapid release of hydrogen to minimise the possibility of catastrophic failure of the tank during exposure to fire. In case of accidental hydrogen release, high mass flow rates from TPRDs are probably acceptable outdoors, where the buoyancy of hydrogen is an advantage in aiding dispersion below the LFL. However, a rapid release indoors could favour its accumulation and formation of flammable hydrogen-air mixture. From a safety perspective a number of hazards arise following a high mass rate release. The pressure peaking phenomena in a scenario of a typical TPRD (diameter of 5.08 mm) with a small vent was discover and explained [27]. It was found that a constant hydrogen release rate of 0.39 kg/s into a 30.4 m^3 garage with a single vent the size of one brick the overpressure could rapidly reach a level of 10-20 kPa in 2 s, which is capable of causing major damage and possible collapse, depending on the nature of the structure and the duration of the impulse. Thus, in the case of hydrogen release, the high volumetric flow rate of hydrogen results in significant overpressures even without combustion. It was demonstrated that the pressure within the garage reaches the maximum level in excess of 50 kPa for 350 bar storage and 100 kPa for 700 bar. This maximum pressure then drops off and tends towards a steady state value, an order of magnitude lower, and equal to that predicted by the simple steady state estimations [27].

The above analysis indicates that the 'typical' TPRD diameter of 5.08 mm may not be 'safe' for enclosures, e.g. indoor carpark with limited ventilation. Therefore, the pressure dynamics within garage-like enclosures was studied to screen the optimal TPRD diameter based on the theory of under-expanded jets and a blow-down model at Ulster [28]. A study was performed to investigate the relationship between TPRD diameter, air changes per hour (ACH), and volume of releases in enclosures with a single vent from onboard storage tanks of 1, 5 and 13 kg at 350 and 700 bar. The 'safe' diameter was determined as that TPRD diameter which would not result in an overpressure exceeding 20 kPa in a garage in the event of a leak. The dynamic pressure rise, which is unique for a release of hydrogen within a ventilated enclosure, should be accounted for when performing hydrogen safety engineering for indoor use. The study of pressure dynamics for a 5 kg Hydrogen stored in a 350-bar tank in a 30 m^3 garage with ACH of 0.18 indicated that the decrease in TPRD diameter from 5 to 0.55 mm could effectively avoid the pressure peaking phenomena in the garage. It was clear that the current arrangements of TPRDs, lacking fire resistance of onboard storage, generate unacceptable performance of systems in enclousures if the TPRDs are activated even with an unignited release. Thus, simplified 'redesign' of the TPRDs to protect the garage structure from collapse puts hardly realisable requirements to fire resistance of up to several hours. Further research is needed to develop safety strategies and engineering solutions to tackle the problem of fire resistance of onboard storage tanks and requirements to TPRD performance.

Recently, the unignited hydrogen releases from onboard vehicle storage in a naturally ventilated covered carpark was studied in UU [29]. This novel study presents findings, which are relevant to vehicle manufactures, standard development organisations (SDOs) and the wider Built Environment. The developed numerical model was validated against experimental data of KIT (Germany) on helium impinging jet, and a good numerical and experimental agreement was achieved within an acceptable engineering error. Simulations were carried out for a carpark with dimensions of 30 × 28.6 × 2.6 m^3 in accordance with British Standard BS 7346-7:2013. Eleven release cases from 700 bar storage were considered including four upward releases from a pipe of 0.5 m above the floor, and an upward and six downward releases. As expected, a constant mass flow rate release resulted in a larger flammable could within the carpark compared to a blowdown release through the same TPRD diameter. The smaller diameter of 0.5 m resulted in a considerably smaller flammable could than that produced by larger diameters of TPRDs, e.g. 2 and 3.34 mm. For 'typical' TPRD diameters in enclosure scenarios, the pressure peaking in not of concern when the ventilation is sufficient.

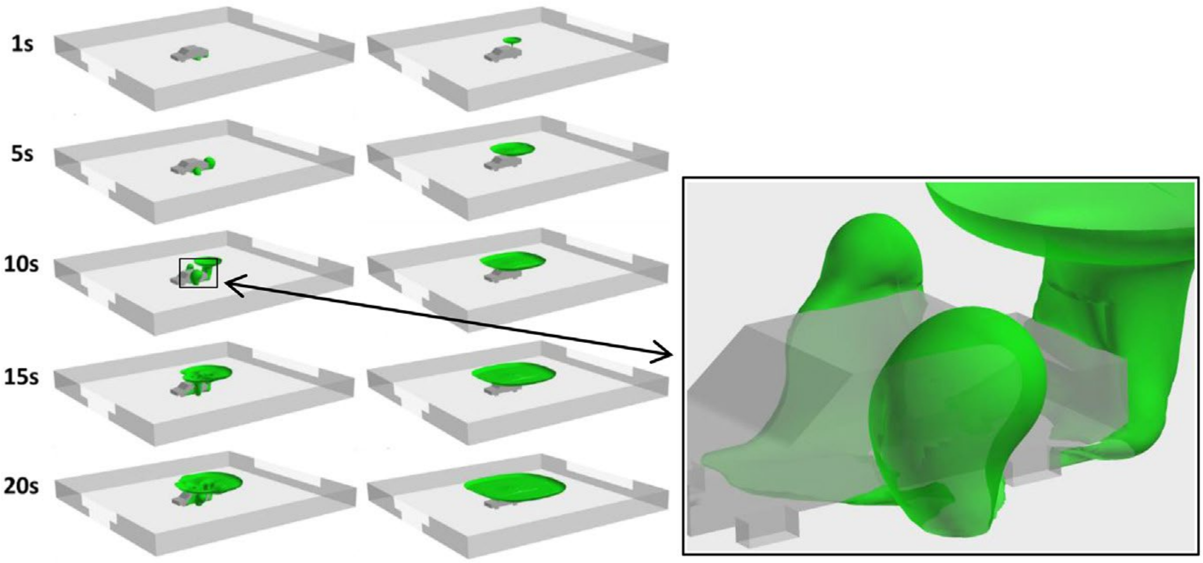


Figure 8 Iso-surface showing 1% hydrogen mole fraction for release from 700 bar through a 0.5 mm TPRD diameter for downward release (left) and upward release (right) [29].

As one of the novelties of this work, the downward and upward releases from 700 bar storage through a 0.5 mm TPRD were compared. As shown in Figure 8, it was found that the downward release resulted in a larger flammable envelope in the vicinity of the car. However, the average hydrogen concentration within the flammable could was lower than that of the upward release case. In contrast, the upward release led to a great flammable envelope beneath the ceiling, but not surrounding the car. Both downward and upward releases from 700 bar through a 0.5 mm diameter in a covered carpark can be considered as a safter choice, when coupled with appropriate tank design, producing a limited flammable could which disperse quickly. Particularly, three different downward release angles (0°, 30° and 45°) were compared to understand the effects of hydrogen release orientation. As shown in Figure 9, the straight downward release produced a flammable hydrogen could around the car, albeit briefly but this may present challenges for first responders to access the vehicle occupants in case of ignition. Downward releases at angles of 30° and 45° toward the back of the car pushed the flammable gas away from the car surrounds, making it safer for uses to escape. These factors should be considered in the design of TPRDs for onboard storage in hydrogen vehicles.

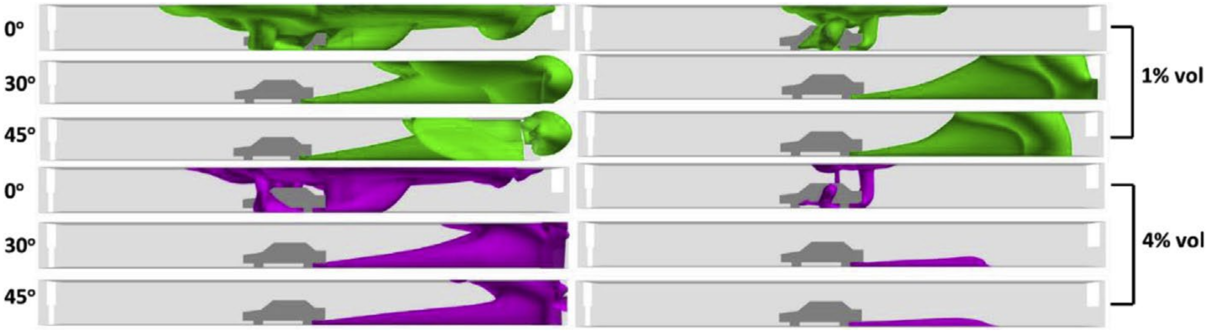


Figure 9 Iso-surface plots of 1% and 4% vol of hydrogen mole fraction for 2 mm TPRD diameter (left) compared to 0.5 mm diameter (right) for different release direction at 20 s of flow time.

Other analysis of hazard and associated risks relevant to the use of FCH vehicles in the underground transport systems could be found in the HyTunnel-CS project (https://hytunnel.net/), especially the Deliverable D3.1 – Detailed research programme on hydrogen firs in confined structures (https://hytunnel.net/wordpress/wp-content/uploads/2019/12/HyTunnel-CS_D3.1_Detailed-research-programme-on-hydrogen-fires-in-confined-structures.pdf).

9. Tunnels

The use of FCH vehicle or transport of compressed gaseous hydrogen (CGH_2) and cryogenic liquid hydrogen (LH_2) in tunnels and similar confined spaces creates new challenges to provision of life safety, property and environment protection at acceptable level of risk. Several studies have showed that confinement or congestion can promote more severe consequences compared to the accidents in the open atmosphere. A critical analysis of hazards and associated risks relevant to the use of FCH vehicles in the underground transportation systems were performed in the Deliverable 1.2 of HyTunnel-CS project (https://hytunnel.net/wordpress/wp-content/uploads/2019/09/HyTunnel-CS_D1.2_Risks-and-Hazards.pdf).

Relevant fundamental knowledge on hydrogen release, fire, and explosion have been given previously, e.g. ventilation (Section 5 in this lecture), pressure peaking phenomena (Section 6 in this lecture), hydrogen jet release (Lecture 9 – Separation from hydrogen flames and fire fighting) and hydrogen explosion (Lecture 10 – Dealing with hydrogen explosions). There are few other unique features for the case of tunnels should be discussed separately.

9.1 Effect of ventilation velocity on dispersion in tunnels

Passive ventilation is usually present in a tunnel due to the piston effect initiated by moving vehicles or the meteorological condition, e.g. pressure difference across the portals. Active ventilation is also very likely to exist, especially in long tunnels, in order to remove the pollutants of vehicle emission or the smoke in case of fire.

Ventilation strongly influences hazardous gases dispersion. The exact location of vehicles and the geometry of the tunnel can be important because they affect the generated flow field. Ventilation can have both positive and negative effects on hydrogen dispersion.

The positive aspects are:

- it can dilute hydrogen concentrations minimizing the size of the flammable cloud;
- it can safely transport unlimited amount of hydrogen out of the tunnel through its portals and shafts if hydrogen concentration is below LFL.

The negative aspects are:

- a flammable could may be extended further away from the release;
- the turbulence may be induced by ventilation which can enhance the combustion rate thus overpressures in case of ignition.

In longitudinal ventilation, a minimum air speed is required to remove the hazardous gas and smoke. Hydrogen behaves similarly to smoke from a fire due to its high buoyancy. For fires in tunnels, the critical velocity as a function of heat release rate were studied and the ventilation velocity value of 3.5 m/s seems to be sufficient for most tunnel fires to prevent the 'back-layer' effect, including large fires of more than 100 MW (https://hytunnel.net/wordpress/wp-content/uploads/2019/09/HyTunnel-CS_D1.1-Effectiveness-of-conventional-safety-measures-.pdf).

Ventilation in a tunnel has generally a beneficial effect on diluting the hydrogen could and safely removing hydrogen, making the areas with hydrogen concentration dropped below 4% vol (LFL). However, in certain conditions ventilation may transport and further extend the flammable cloud, leading to the movement of flammable cloud towards other vehicles or along ventilation ducts and shafts. As a result, further experimental studies must be conducted to investigate the optimal ventilation velocity in this scenario and create the basis for more general universal recommendations on the effectiveness of ventilation in tunnels. Moreover, the effect of a tunnel slope on the flow and dispersion of hydrogen must be included in the future research. The maximum slope allowed by the European Directive 2004/54/EC is 5% for new built longitudinal tunnels. Furthermore, the Directive states that for gradients above 3%, additional measures are required to increase the level of safety.

9.2 Deflagration-to-Detonation transition (DDT) in tunnel

The DDT phenomena has been discussed in detail in Lecture 10, in which the DDT criteria were mainly developed for enclosed geometry with uniform concentration of hydrogen in oxidiser (air or oxygen). However, due to hydrogen leak or an accidental hydrogen release from high-pressure tank in a tunnel, a non-uniform, e.g. stratified, hydrogen-air mixture can be formed preferentially at the ceiling part of a tunnel structure.

Several experiments and numerical simulations have been done with respect to combustion and detonation in a semiconfined stratified layer of hydrogen-air mixture typical for accident scenario in a tunnel geometry. Experiments on hydrogen combustion in a thin semiconfined layer have been performed inside the safety vessel with a volume of 100 m^3 [22]. The cylinder volume has 3.5 m internal diameter and 12 m length. A wall thickness of 80 mm allows to perform detonation experiments directly inside the volume. A rectangular box with dimension of $9 \times 3 \times 0.6$ m^3 was installed inside the safety vessel, as shown in Figure 10. With respect to geometry and dimensions, such experimental layout is very suitable to experimentally simulate hydrogen accident in tunnel environment.

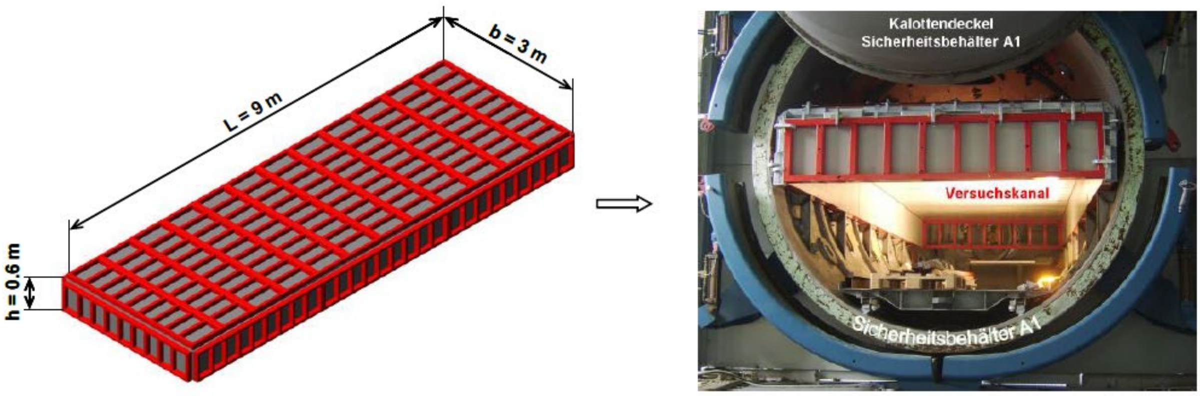


Figure 10 Main dimensions of the flat layer box (left) and the thin layer box installed inside the safety vessel (right) [22].

The experimental data on characteristic pressure and flame velocities for uniform compositions indicated that the threshold between the slow and fast flame regimes in semi-open channels is the sonic speed in reactant, while it is the sonic speed of the products in closed channels [23]. The higher hydrogen concentration or more reactive mixture must be to reach the speed of sound when the thinner layer (thickness h) is applied. The expansion ratio is a critical indicator of the potential for flame acceleration [23, 24]. Figure 11 summarised the experimental data of expansion ratio σ as a function of the dimensionless vent area (defined as the ratio of layer thickness h and spacing between obstacles for semi-confined layer s). A linear correlation between the critical expansion ratio σ^* for fast flame propagation in a flat layer and the reciprocal layer thickness $1/h$ or spacing between the obstacles s was derived. For uniform mixtures the detonation occurs at different hydrogen concentration depending on layer thickness, e.g. 27% for h = 0.15 m, 23% for h = 0.3 m and 21% for h = 0.6 m. The results suggested that thinner layer needs more reactive mixture to be detonated than the thicker layer. Since the energy losses and the mixture reactivity are reciprocally correlated with layer thickness h and detonation cell width λ, the dimensionless ratio of the layer thickness over the detonation cell width can be expected to be a constant for the critical detonation conditions.

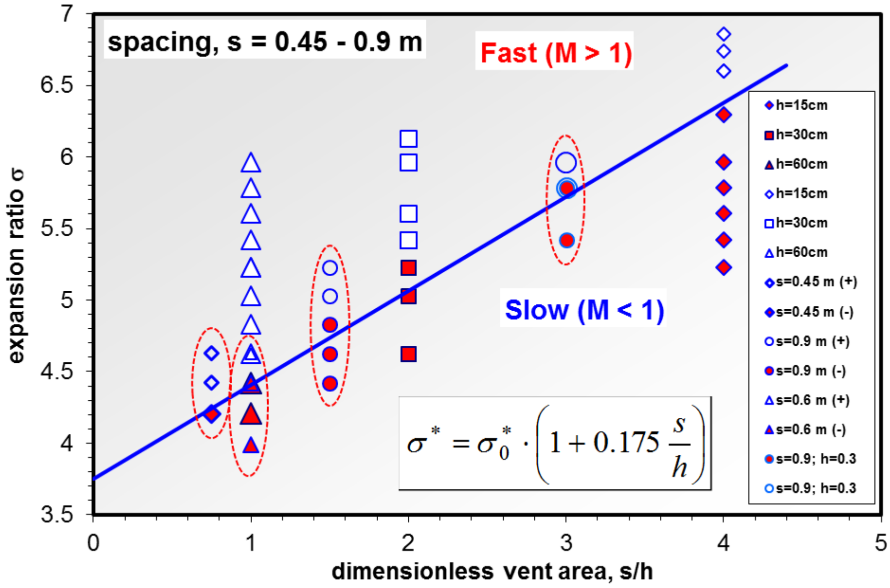


Figure 11 Critical conditions for an effective flame acceleration as function of expansion ratio vs. dimensionless vent area: sonic flame and detonations (open points), subsonic flame (solid points) [22].

Figure 12 confirms that the dimensionless layer thickness for critical conditions for detonation onset are almost the same, h/λ = 13-14, for three investigated layer thicknesses from 15 to 60 mm [22]. This value agree well with previous experiments performed on a smaller scale facility h/λ = 7-15 [23].

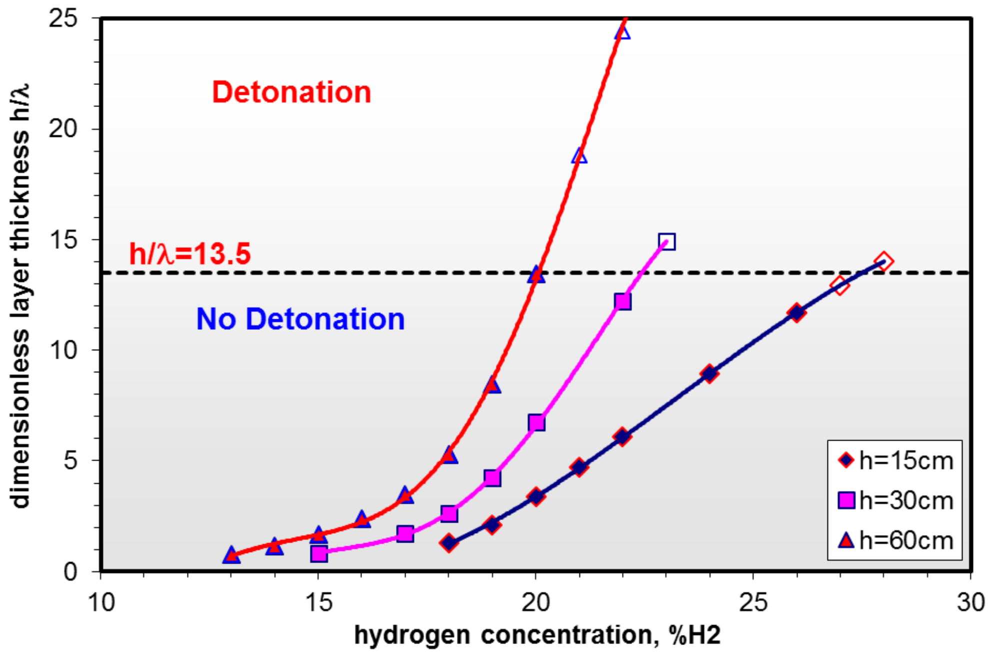


Figure 12 Critical conditions for DDT in the relationship between the dimensionless layer thickness and hydrogen concentration: detonation (open points); no detonation (solid points) [22].

10. Regimes of indoor hydrogen fires

The topic of hydrogen fires was discussed earlier in the relevant lecture. In the case of indoor hydrogen fires, if the fire is sufficiently short and if it does not impinge on a wall or any other surface the nomogram presented in the previous lecture is applicable for predicting the flame length. The work described in 'Lecture 10 – Dealing with hydrogen explosions' on the effects of walls and barriers is also relevant to jet fires impinging directly on obstacles within the enclosure. A hydrogen release in the enclosure frequently occurs near, or along a wall or a surface, which can increase the length of the jet flame or the extent of unignited jet, by reducing the entrainment of the air. Thus, hazard distances can increase. This is important when considering the position of equipment and hydrogen storage (particularly the location of TPRDs on any storage) in relation to walls, and to the ground. Behaviour of the fire also depends on the release conditions and geometry of the enclosure and the ventilation. Indoor hydrogen fires can be well-ventilated and under-ventilated.

10.1 Well-ventilated fires

If the enclosure is equipped with the ventilation, oxygen required to sustain hydrogen combustion will enter the enclosure through the vents. When the ventilation is sufficient in the enclosure, the flame will be fuel-controlled and can be considered to be well-ventilated [11].

The general rule for an indoor fire with one upper vent is as follows: the increase of hydrogen release flow rate changes the fire regime from:

- well-ventilated fire (for small flow rates), to
- under-ventilated fire with external flame (for moderate flow rates), to
- under-ventilated fire with self-extinction of combustion (for higher flow rates), and again to
- under-ventilated fire with external flame (for very high flow rates).

A numerical study was carried out with the use of a contemporary model to understand underlying physical phenomena of the indoor hydrogen fire. The CFD model used has been described in [12, 13]. Seven numerical experiments with a single vent were performed for a FC-like enclosure with the dimensions L×W×H=1×1×1 m and with the vent located centrally at the top of one wall (Table 1). The release was directed vertically upwards. Hydrogen release pipe was of 10 cm length with internal diameter of 5.08 mm located in the centre of the enclosure floor, 10 cm above the floor. The thickness of the enclosure aluminium walls was 2 cm. Further details on the calculation domains can be found in [13].

Table 1. Details of the numerical experiments [13].

No.	Vent size, HxW	Velocity, m/s	Flow rate, g/s	Result
1	Horizontal 3×30 cm	600 m/s	1.0857	**Self-extinction**
2	Horizontal 3×30 cm	300 m/s	0.5486	**Self-extinction**

3	Horizontal 3×30 cm	150 m/s	0.2714	**External flame**
4	Vertical 30×3 cm	600 m/s	1.0857	**External flame**
5	Vertical 30×3 cm	60 m/s	0.1086	**Well ventilated**
6	Vertical 13.9×3 cm	600 m/s	1.0857	**Self-extinction**
7	Vertical 13.9×3 cm	300 m/s	0.5486	**External flame**

Figure 13 shows the dynamics of well-ventilated hydrogen jet fire in the numerical experiment No. 5, with the lowest velocity of the release, 60 m/s. The vertical vent is located at the left wall. At the end of numerical experiment, the fire was at quasi-steady state conditions. The reaction zone, which is associated with the presence of hydroxyl radicals OH, increases slightly in the time period from 10 s to 65 s (Figure 13a). There is practically no hydrogen leaving the enclosure (Figure 13b). Hydrogen mole fraction in the vent is negligible of the order of 2×10^{-4}. This indicates that the fire is well-ventilated in the conditions of simulation No. 5.

Figure 13c demonstrates a very slow depletion of the initial oxygen layer at the bottom of the enclosure that can be explained by the fact that an intake of oxygen from outside through the lower part of the vent sustains the flame (the intake of air is clearly seen in snapshots). Temperature contours (Figure 13d) confirm the presence of the layer at the bottom of the enclosure, where the initial temperature is preserved. In a room-like enclosure this would create favourable conditions for the evacuation of the occupants. It is worth noting that radiation is not accounted for in this model that would affect acceptability of a safety engineering design based on harmful criteria of thermal radiation flux. The temperature decays from 2300 K in the flame to about 750-1000 K in the hot current under the ceiling. This temperature is probably insufficient to ignite any combustible materials especially in the presence of water vapour (H_2O mole fraction under the ceiling is in the range 0.11-0.13 at 65 s). Yet some components within the FC box could be destroyed. The only difference of numerical experiment No. 4 is a tenfold increase of the hydrogen release flow rate. The well-ventilated fire is observed for hydrogen release velocity of 60 m/s, and an under-ventilated fire with transition to an external flame is observed for release velocity of 600 m/s.

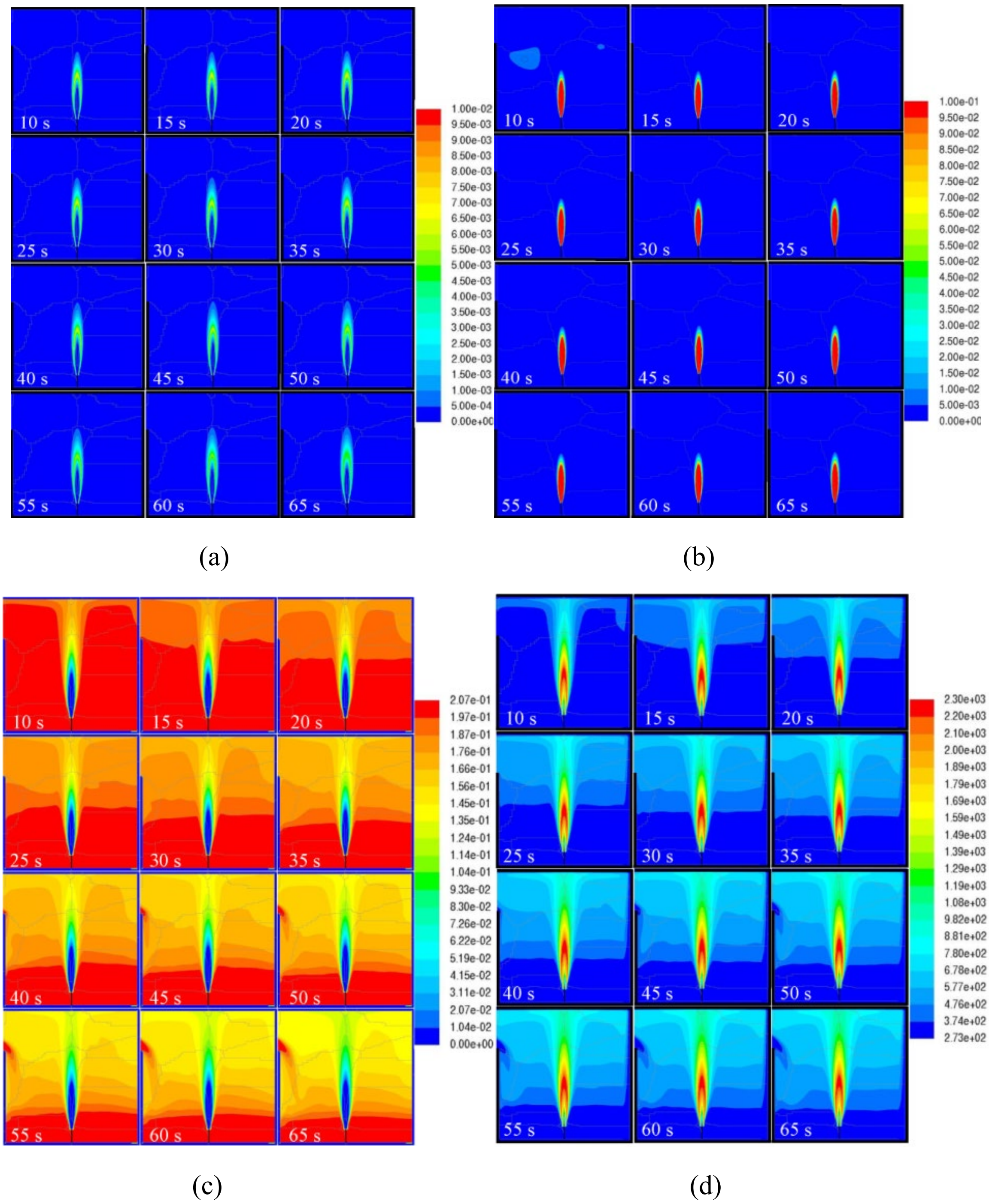


Figure 13. 2D slice along the enclosure centre-line, simulation No. 5 (well-ventilated fire) [13]: (a) OH radicals mole fraction, (b) H_2 mole fraction, (c) O_2 mole fraction, and (d) temperature.

10.2 Under-ventilated fires

In the case where there is insufficient ventilation the flame will be ventilation-controlled and could be considered as *under-ventilated.* In the case where the flame is under-ventilated all hydrogen will not be consumed in the vicinity of the leak and will only burn where oxygen is available, therefore there will be both hot products and potentially hydrogen or an external flame at the vent [14].

The development of a hot layer at the ceiling depends on the size and the location of the vents (if any) relative to the size of the leak. In the case of insufficient ventilation relative to the leak the hot layer will grow downwards through the enclosure. This presents both thermal and asphyxiation hazards.

As the flame becomes increasingly under-ventilated the level of oxygen is decreased in the enclosure until the moment when oxygen and hence combustion are present in the vicinity of the vent producing an external flame. There may be little or no combustion in the rest of the enclosure where hydrogen will accumulate. In this case if the leak were subsequently stopped (shut-off) or reduced through blow-down then the external flame may burn back into the enclosure where a premixed flammable atmosphere may potentially exist, leading to an explosion [14].

If the enclosure has no ventilation then it will not be possible for oxygen to enter the enclosure, thus the flame will deplete the oxygen in the enclosure until either fuel or oxygen is consumed and the flame extinguishes [14].

The product of hydrogen combustion is water, thus it is possible in the case of minimum ventilation and a small flame, that water vapour produced by hydrogen combustion combined with the depletion in oxygen may lead to a self-extinguishment of the flame. If self-extinguishment was to occur and the hydrogen leak was not stopped at the point of extinguishment, then a scenario would develop whereby the enclosure would be filled with unburnt hydrogen. If the leak was subsequently shut off the hydrogen was blown down, then a premixed flammable atmosphere would develop in the enclosure. The presence of hot surfaces or a similar ignition source could lead to re-ignition and a potential explosion. At the limit of an under-ventilated case the external flame exists at the vent. In the case of self-extinguishment, no flame exists, either internally or externally. The details of numerical experiments (Table 1) on under-ventilated hydrogen jet fire and self-extinction dynamics in an enclosure are extracted from [13] and described below.

10.3 Self-extinction flame mode

Let us consider a scenario with a jet fire from a TPRD in a small garage with sizes L×W×H=4.5×2.6×2.6 m and volume 30.4 m^3. A single vent equivalent in the area to a typical brick L×H=25×5 cm is located flush with the ceiling and excludes consideration of pressure effects. Hydrogen is released through the 5.08 mm pipe at the rate 390 g/s. Combustion of the released hydrogen within the garage consumes oxygen in the air and produces water. A self-extinction of hydrogen in the enclosure could be expected shortly. Indeed, numerical simulations of this scenario demonstrated a decrease in temperature within the enclosure as shown in Figure 14 and the regions of hydroxyl (OH) associated with reaction zones after 3 s already.

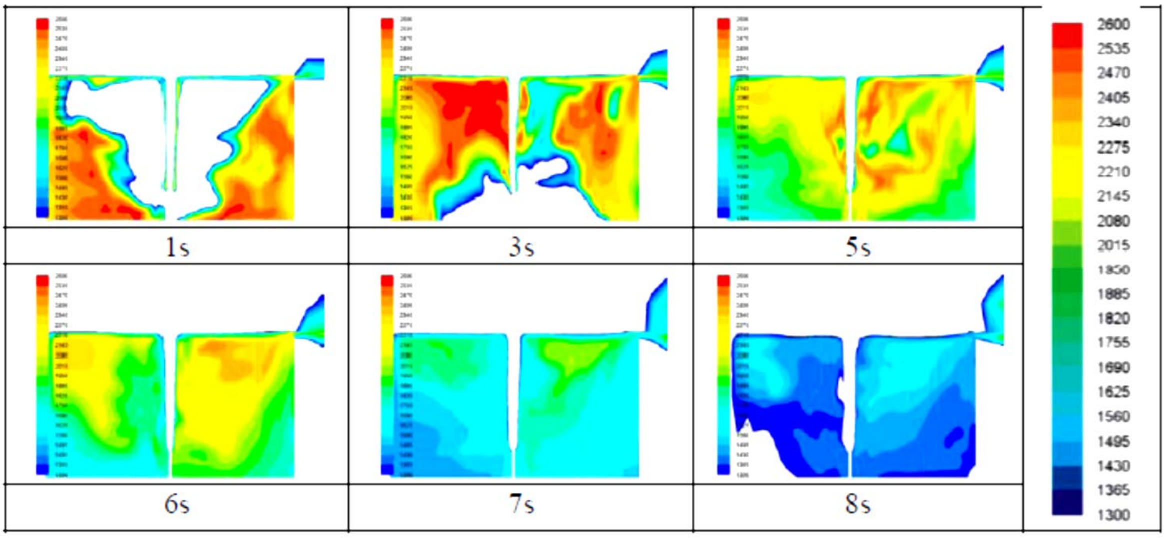
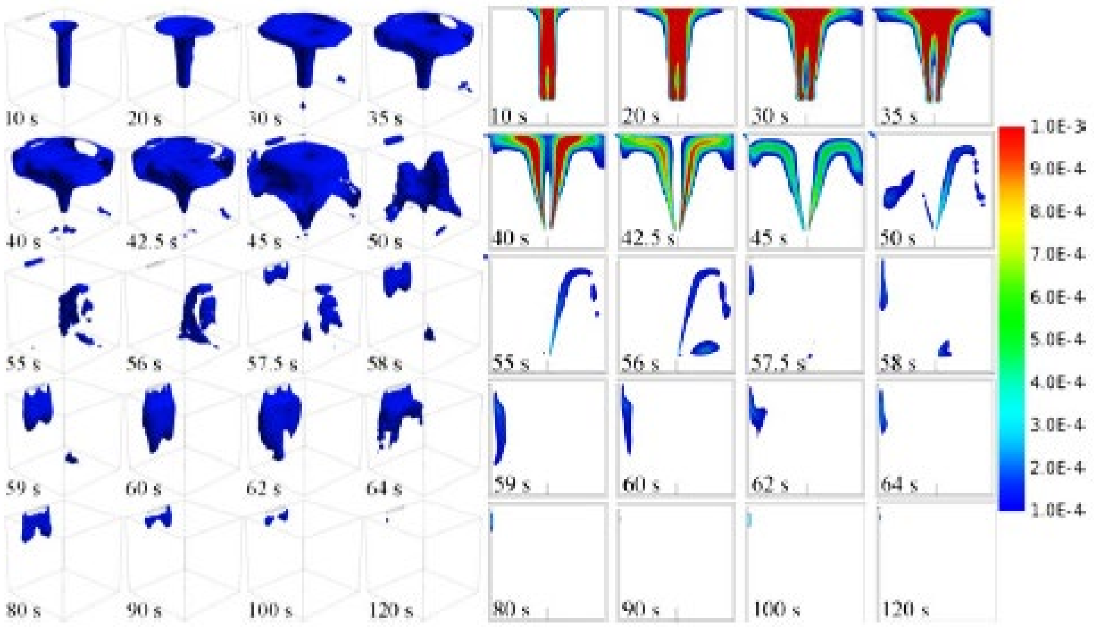


Figure 14. Contours of static temperature ranging from 1300 to 2600 ºC corresponding to the visible flame (2D slice through centre of the garage) [15].

The self-extinction of a hydrogen flame in the enclosure with one horizontal vent located at the top of one wall was reported for the first time in [12]. The analysis of the numerical experiment, especially of hydroxyl (OH) concentration, assisted in understanding of the self-extinction process. The use of averaged throughout the enclosure volume parameters during the under-ventilated fire can give an indication of the moment when combustion is reduced, however, it can significantly underestimate the timing when the flame is fully ceased. The numerical experiments demonstrated a complex pattern of flow through the vent in both directions during the under-ventilated fire. The complete self-extinction was observed when the entire vent area was occupied for a finite period by the air intake into the enclosure. The reason of this observation was assumed to be the cooling of hot combustion products by the sustained hydrogen release and, to some extent, by heat transfer to the enclosure walls. The work [13] expands the initial numerical experiments and aims at understanding of indoor hydrogen fires in the enclosure with one horizontal or vertical vent located at the top of one wall and a sustained hydrogen release of constant flow rate and temperature.

Self-extinction of hydrogen flames indoors was also simulated in the numerical experiment No. 1 with the horizontal vent (Table 1) [12]. Let us consider the dynamics of self-extinction observed in the simulation No. 2 (the release velocity of 300 m/s) and compare it with the simulation No. 1 (the release velocity of 600 m/s). Figure 15 shows the dynamics of OH mole fraction for simulation No. 2 in 3D (Figure 15a) and 2D (Figure 15b). The reaction contour (OH mole fraction iso-surface of 1×10^{-4}) shows location of flaming combustion and moves out of the enclosure at about 30 s. This zone of the reaction outside the enclosure separates from the reaction zone inside the enclosure at 45 s and exists until about 56 s. The size of this external small reaction zone does not exceed two vent heights. At about the same time of 56-57 s there is air ingress into the enclosure that supports a weak reaction just below the vent. This internal reaction zone practically ceases at about 120 s. Contrary to the experiment No. 4 with the external flame, in the simulation No. 2 with the self-extinction, the combustion in the jet ceases first on the left side, which is closer to the vent, at 55-56 s. This can be explained and consistent with the presence of a bit larger amount of oxygen at this time at the bottom on the right-hand side of the jet (Figure 15a).

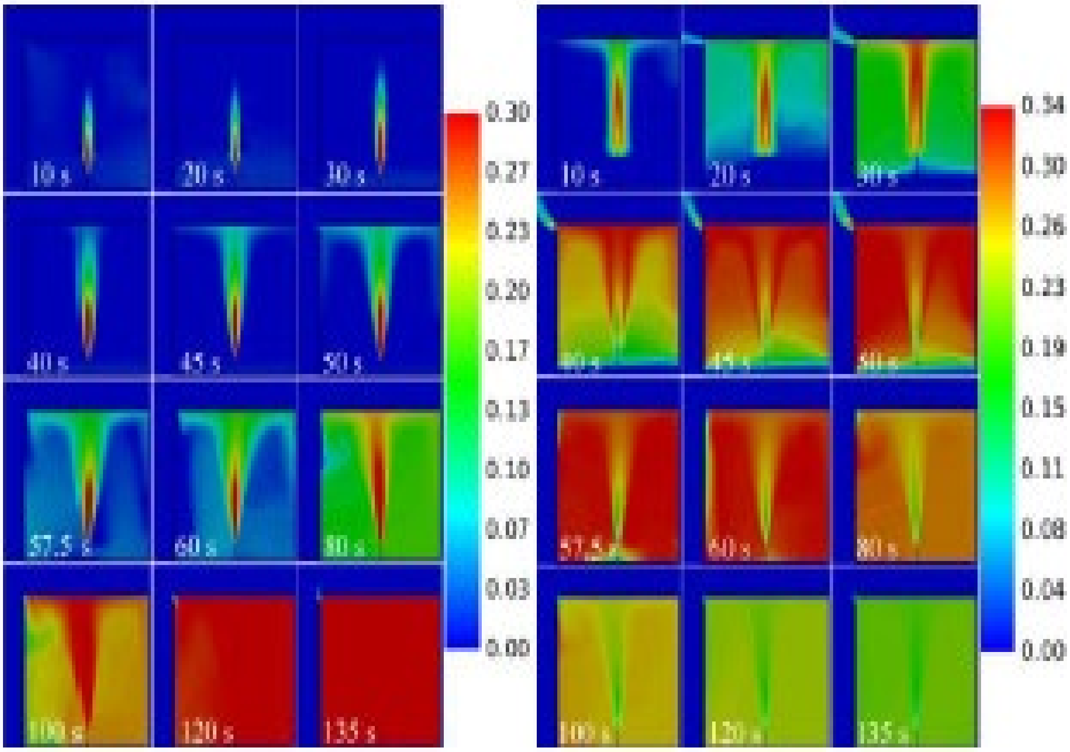


(a) (b)

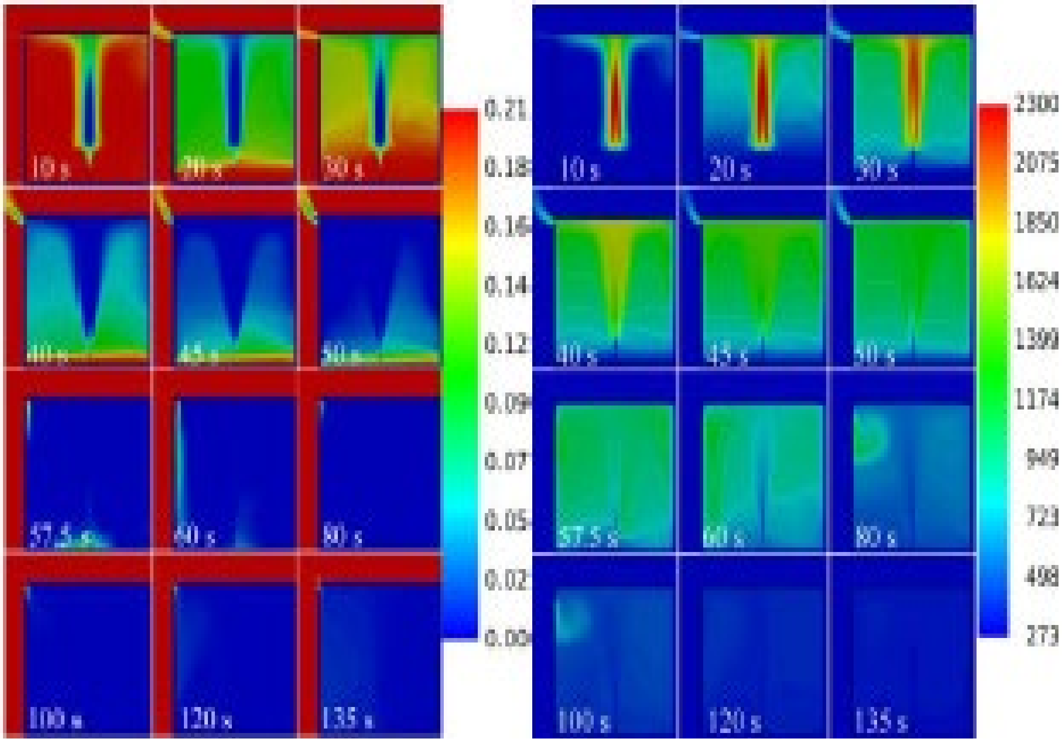
Figure 15. Hydroxyl OH mole fraction in 1×1×1 m enclosure, simulation No. 2 (hydrogen jet fire self-extinction) [13]: (a) 3D view of iso-surface of OH 1×10^{-4}, (b) 2D slice along the enclosure centre-line.

The small size of the reaction zone outside of the enclosure in the period 30-56 s can be explained by analysis of species concentrations presented in Figure 16. Indeed, during this period hydrogen concentration in the flow out of the enclosure does not exceed about 7-10 vol. %, concentration of water is increasing from about 15 to more than 34 vol. %, and oxygen concentration drops from about 10 vol. % to 0 vol. %. The flammability diagram shows that this mixture with the air is just on the border of the flammable region [16]. In the simulation No. 2 this mixture reacts with air in conditions when temperature of the mixture is quite high and drops to about 800 K only at the end of this period.

As it follows from Figure 16 the flow out of the enclosure finishes after 50 s and there is only inflow into the enclosure (see the snapshots corresponding to 57.5 s through to 120 s). Thus, in the agreement with simulation No. 1 for the self-extinction to happen there has to be a prolonged period of time when, after the initial stage of internal combustion followed by the cooling of hot products by "cold" hydrogen, there is an intake of air through the whole area of the vent into the enclosure.



(a) (b)



(c) (d)

Figure 16. 2D slice along the enclosure centre-line simulation No. 2 (hydrogen jet fire self-extinction) [13]: (a) H_2 mole fraction, (b) H_2O mole fraction , (c) O_2 mole fraction , and (d) temperature .

Figure 16 (a) shows that, after 2 minutes of the release the enclosure is filled in with hydrogen with mole fraction above the stoichiometric level, > 0.30. Similar to the simulation No. 4 with the vertical vent the jet is slightly inclined to the wall with the vent. The maximum mole fraction of water is observed at 50-60 s. There is a strong "stratification" of oxygen at the time of 40-50 s, with practically zero concentration at the top and practically initial concentration of oxygen of 20.7 vol. % at the bottom. Temperature falls to about 100 degree above initial temperature after 2 minutes of ignited release. This result can be used as an indication of fire resistance time to components within the fuel cell enclosure.

The former conclusion that the self-extinction is always observed when there is a period of time when there is air intake into the enclosure through the whole vent area is confirmed in experiment corresponding to conditions of simulation No. 6 (Table 1) with the vertical vent of the smallest area. To further support this rule, in the simulation No. 7 (external flame) there was no such period.

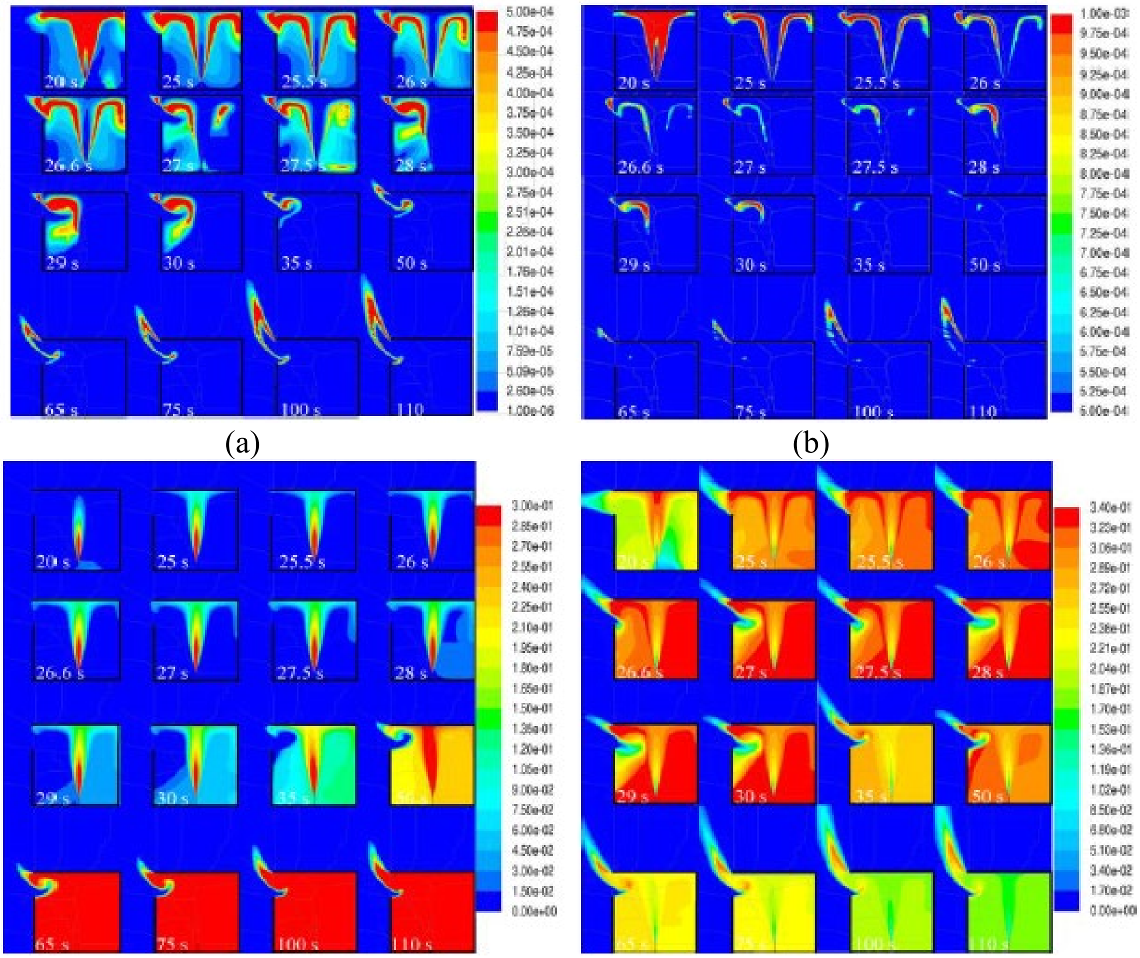
10.4 External flame mode

Figure 17 demonstrates the results of the simulation No. 4 for the release with the velocity of 600 m/s, when a transition of an internal jet fire in the enclosure to an external flame mode occurs. The mole fraction of hydroxyls in the flame at 10 s is equal 0.01, which is characteristic for combustion at normal atmospheric conditions. Then, the maximum OH mole fraction reduces along with shrinking of the zone where the highest mole fraction of OH is present. This is thought due to dilution of the jet flame by entrained combustion products. The maximum mole fraction of OH does not exceed 7.5×10^{-3} at time of 20 s.

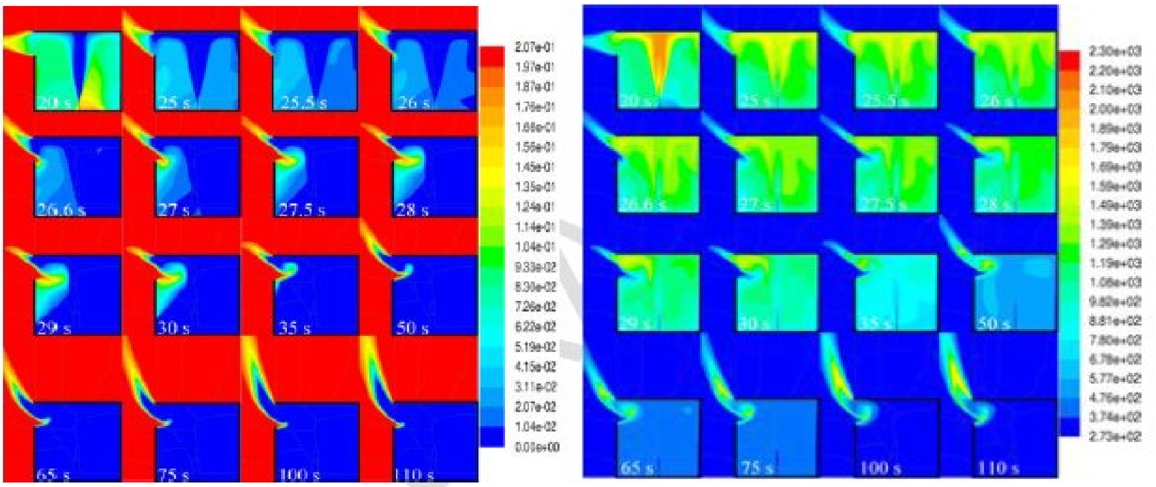
Figure 17a shows the evolution of the reaction zone during the transition of the internal combustion to the external flame by visualization of OH mole fraction in the range from 1×10^{-6} to 5×10^{-4}, whilst an image in Figure 17b corresponds to the range 5×10^{-4}-1×10^{-3}. There is no or very little reaction outside the enclosure up to 20 s. While the combustion rate inside the enclosure decreases after 20 s the reaction zone starts to move out of the enclosure through the vent with the external flame being visible above the enclosure after 50 s. Figures 17a and 17b clearly show that the reaction ceases first on the jet flame side that is opposite to the vent which is located at the top of the left wall. Figure 17b demonstrates that there is a continuous reaction zone on both sides of the vent. This zone connects the internal reaction in the area where fresh air is entering the enclosure with the external flame of flowing out of the enclosure mixture of hydrogen and combustion products in the atmospheric air. These two opposite flows through the vent create a reacting eddy that seats within the enclosure close to the vent and stabilises the lower flame edge. The upper edge of the external flame is attached to the top edge of the vent.

The evolution of hydrogen mole fraction in the enclosure is shown in Figure 17c. Fire is in the well-ventilated regime until about 20 s when there is no hydrogen leaving the enclosure due to its complete combustion inside. The accumulation of hydrogen is somewhat higher at the side of the jet opposite to the wall with the vent. There is some inclination of the jet towards the vent (see the snapshot at 50 s). The mole fraction of hydrogen is above 0.30 practically throughout the whole enclosure at time of 65 s with exclusion of small region close to the vent where the air is entering. The mole fraction of hydrogen at 110 s is 0.48 to 0.50 at floor and ceiling levels, respectively.

The maximum amount of water vapour is observed at 27-30 s (Figure 17d), similar to the simulation No. 1 with a horizontal vent of the same area reported in [12]. After this, the mole fraction of water is monotonically decreasing in time due to water entrainment into the sustained hydrogen jet and flow out of the enclosure (as a part of flammable mixture).



(a) (b) (c) (d)



(e) (f)

Figure 17. 2D slice along the enclosure centre-line, simulation No. 4 (hydrogen jet fire external flame mode) [13]: (a) OH mole fraction, range 1×10^{-6}–5×10^{-4}, (b) OH mole fraction, range 5×10^{-4}–1×10^{-3}, (c) H_2 mole fraction, (d) H_2O mole fraction, (e) O_2 mole fraction, and (f) temperature.

At a critical for flame "survival" time point of about 50 s, when the transition to the external flame commences, the mole fraction of hydrogen in outflow increases to about 0.2, and that of water (diluent) drops to 0.2-0.3. This mixture composition is deemed to be in the flammable range following the flammability diagram for hydrogen-air-diluent mixture at atmospheric pressure and temperature, if the effect of temperature is neglected. Thus, the availability of flammable mixture flowing out of the enclosure and the presence of reaction (ignition source) provide conditions for transition of combustion outside of the enclosure.

Figure 17e shows that oxygen mole fraction within the enclosure gradually decreases and is practically equal to zero at the time of 35 s, excluding a small area close to the vent. Then, the air entering the enclosure to some small depth burns and is immediately entrained into flow of hydrogen and combustion products flowing out of the enclosure through the upper part of the vent. Temperature dynamics inside and outside the enclosure is shown in Figure 17f. The snapshot corresponding to 50 s demonstrates an important role of the reacting eddy, which is formed in the vent shear layer between mixture leaving the enclosure and air entering the enclosure, on the flame sustainability and the transition of under-ventilated internal fire to the external flame mode.

For the horizontal vent of the same area the establishment of the external flame was observed in the simulation No. 3 at a lower velocity of hydrogen, 150 m/s. The same velocity of the release as in the simulation No. 4 (vertical vent), i.e. 600 m/s, for the horizontal vent resulted in the flame self-extinction (simulation No. 1). The self-extinction was observed also at the velocity of 300 m/s (simulation No. 2). Thus, a velocity limit separating the external flame mode and the self-extinction mode is between 150 m/s and 300 m/s for the given enclosure geometry.

The external flame is observed in the simulation No. 7 with a vertical vent of the smallest area and for the release velocity of 300 m/s. The increase of release velocity to 600 m/s (simulation No. 6) resulted in the self-extinction. It is noted that a characteristic feature of the self-extinction phenomenon is the existence of a period when there is air intake into the enclosure through the whole area of the vent (not a part of the vent area).

11. Utilisation of e-Laboratory

11.1 Passive ventilation in an enclosure with one vent: uniform hydrogen concentration

This tool consists of three options to allow the calculation of the following three features:

1. Steady-state hydrogen uniform concentration for the given release rate and vent size;
2. Parameters of the vent to get desired concentration for the given release;
3. The release rate to get desired concentration for the given vent sizes.

The theories could be found in Section 5 in this lecture. To implement the tool, as shown in Figure 18, the first step is to select the model, which is used for particular problems.

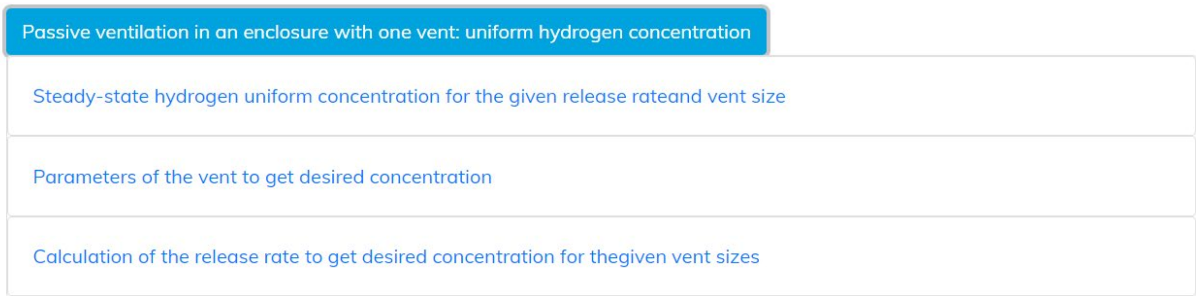


Figure 18 Selection of proper model for a particular problem

Problem 1: Steady-state hydrogen uniform for the given release rate and vent size.

The input parameters are shown in Table 2 and the screen shot of the setting of the tool is shown in Figure 19.

Table 2 Input parameter for problem 1

Parameter name	Symbol	Unit	Limits (min-max)	Defaults
Hydrogen mass flow rate	$\dot{m}_{H2}$	kg/s	0.0001-1	0.001
Ambient pressure	p_2	Pa	33700-107900	101325
Ambient temperature	T_2	K	240-350	293
Vent height	H	m	0.001-10	2
Vent width	W	m	0.001-10	1
Discharge coefficient	C_D	-	0.4-1	0.6

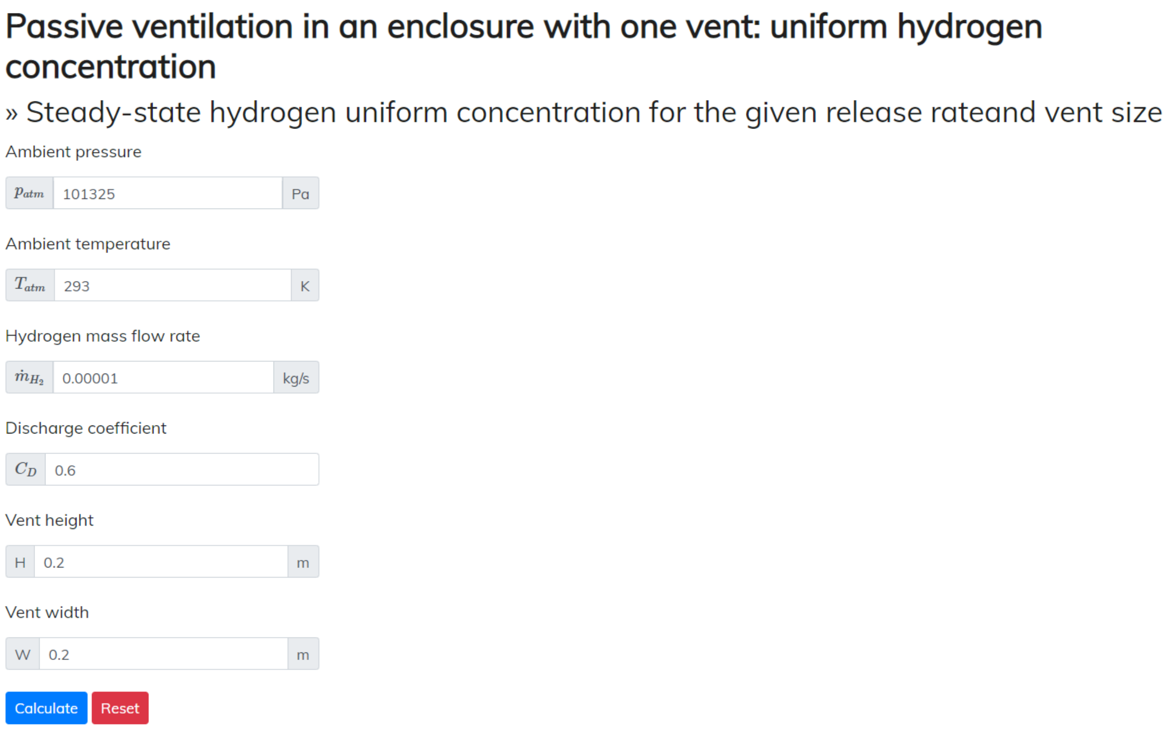
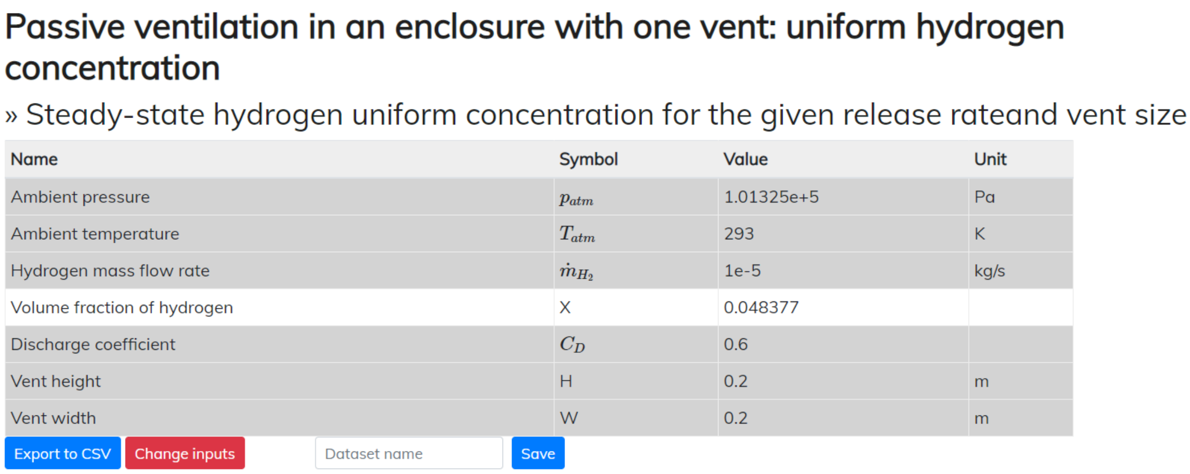


Figure 19. The setting of the tool for problem 1

The output parameter is the hydrogen volume fraction. An example of the output parameter is shown in Figure 20, which indicates that, for the given value of the input parameters in Figure 19, the calculated hydrogen volume fraction is 0.048377 in the enclosure.



Passive ventilation in an enclosure with one vent: uniform hydrogen concentration

» Steady-state hydrogen uniform concentration for the given release rateand vent size

Name	Symbol	Value	Unit
Ambient pressure	p_{atm}	1.01325e+5	Pa
Ambient temperature	T_{atm}	293	K
Hydrogen mass flow rate	$\dot{m}_{H_2}$	1e-5	kg/s
Volume fraction of hydrogen	X	0.048377	
Discharge coefficient	C_D	0.6	
Vent height	H	0.2	m
Vent width	W	0.2	m

Export to CSV | Change inputs | Dataset name | Save

Figure 20. The output of the tool for problem 1

Problem 2: Parameters of the vent to get desired hydrogen concentration.

This tool allows user to calculate the parameters of the vent, e. g. width or height, for the possible release in order not to exceed the required level of hydrogen concentration e. g. 25% from lower flammability limit of 4% (LFL).

The input parameters are shown in Table 3 and the screen shot of the setting of the tool is shown in Figure 21. It is worth of noticing that, in this case, either vent height, *H*, or vent width, *W* must be given by typing a value either for *H* or *W* and leaving the unnecessary parameter (*H* or *W*) blank. For example, if *H* is used as input parameter, *W* must be blank of the setting, and vice versa.

Table 3 Input parameter for problem 2

Parameter name	**Symbol**	**Unit**	**Limits (min-max)**	**Defaults**
Hydrogen mass flow rate	$\dot{m}_{H2}$	kg/s	0.0001-1	0.001
Ambient pressure	p_2	Pa	33700-107900	101325
Ambient temperature	T_2	K	240-350	293
Choose either height or width	H/W	m	0.001-10	2
Discharge coefficient	C_D	-	0.4-1	0.6
Desired mole fraction of hydrogen	X	-	0-1	0.04

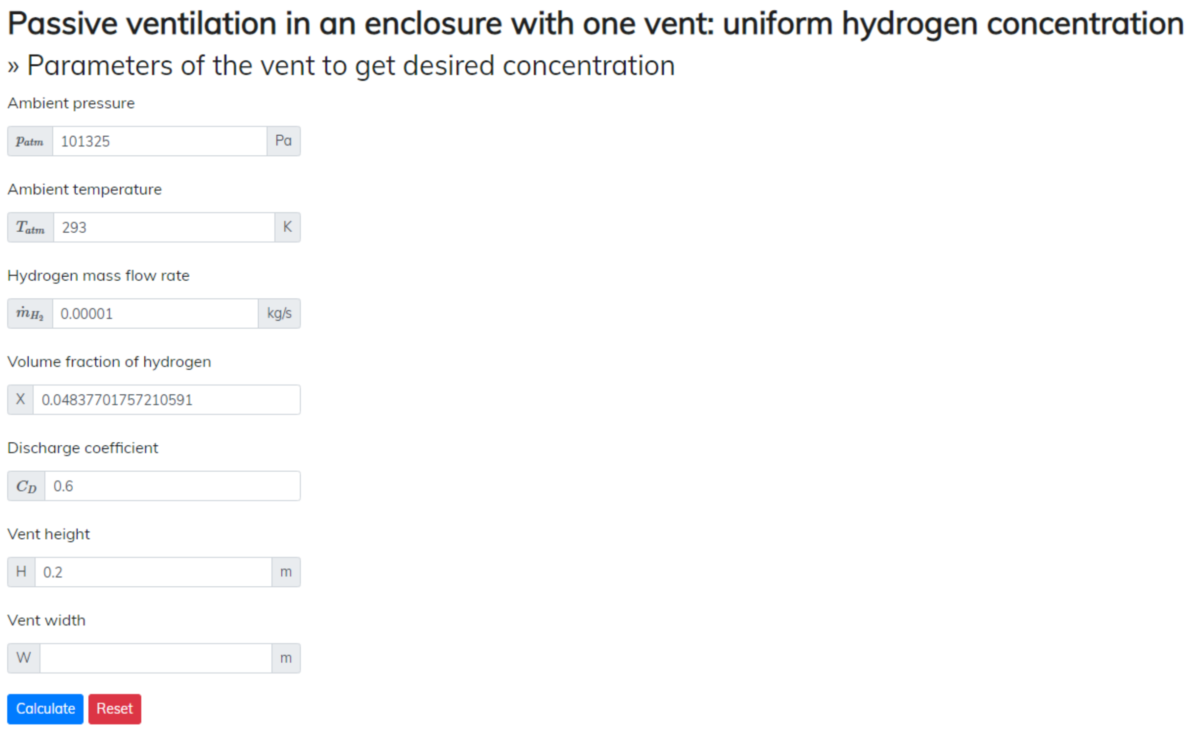


Figure 21. The setting of the tool for problem 2

The output parameter is either the vent height or vent width at given mass flow rate. An example of the output parameter is shown in Figure 22, which indicates that, for the given value of the input parameters in Figure 21, the required vent width is 0.2 m when the vent height is set to be 0.2 m.

Passive ventilation in an enclosure with one vent: uniform hydrogen concentration

» Parameters of the vent to get desired concentration

Name	Symbol	Value	Unit
Ambient pressure	p_{atm}	1.01325e+5	Pa
Ambient temperature	T_{atm}	293	K
Hydrogen mass flow rate	$\dot{m}_{H_2}$	1e-5	kg/s
Volume fraction of hydrogen	X	0.048377	
Discharge coefficient	C_D	0.6	
Vent height	H	0.2	m
Vent width	W	0.2	m

Export to CSV Change inputs Dataset name Save

Figure 22. The output of the tool for problem 2

Problem 3: Release rate to get desired concentration of given vent sizes

This tool allows calculating the mass flow rate which could be allowed for the particular vent parameters not to exceed the required level of hydrogen concentration e. g. 25% from lower flammability limit of 4% (LFL).

The input parameters are shown in Table 4 and the screen shot of the setting of the tool is shown in Figure 23.

Table 4 Input parameter for problem 3

Parameter name	**Symbol**	**Unit**	**Limits (min-max)**	**Defaults**
Ambient pressure	p_2	Pa	33700-107900	101325
Ambient temperature	T_2	K	240-350	293
Vent height	H	M	0.001-10	2
Vent width	W	m	0.001-10	1
Discharge coefficient	C_D	-	0.4-1	0.6
Desired mole fraction of hydrogen	X	-	0-1	0.04

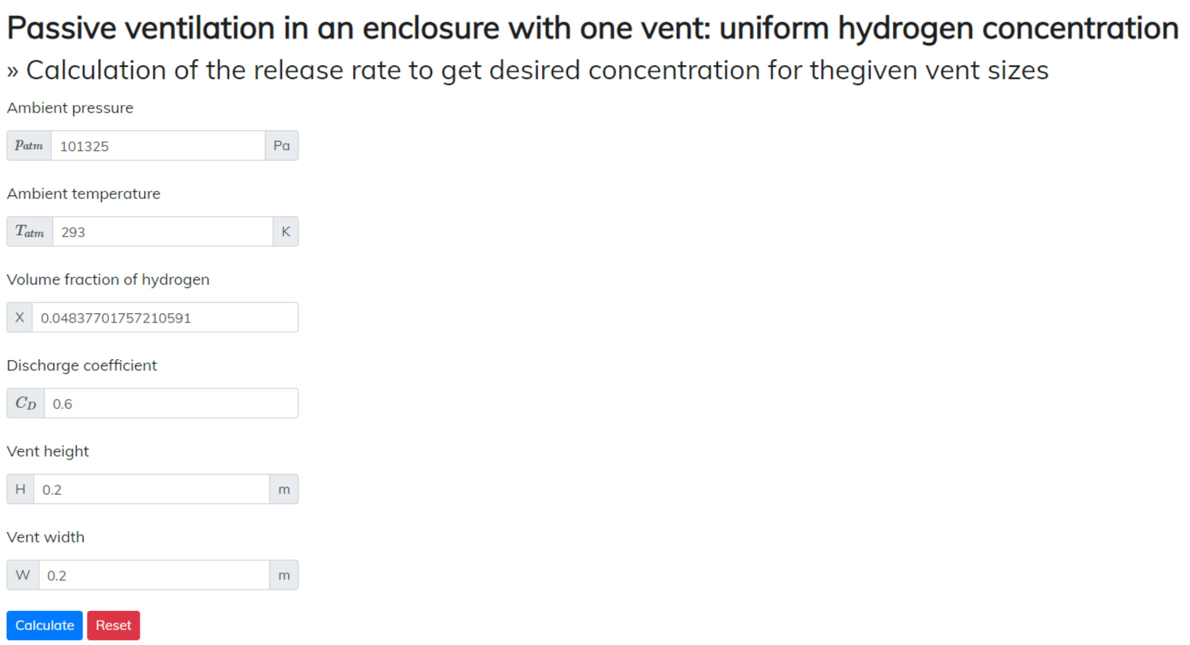
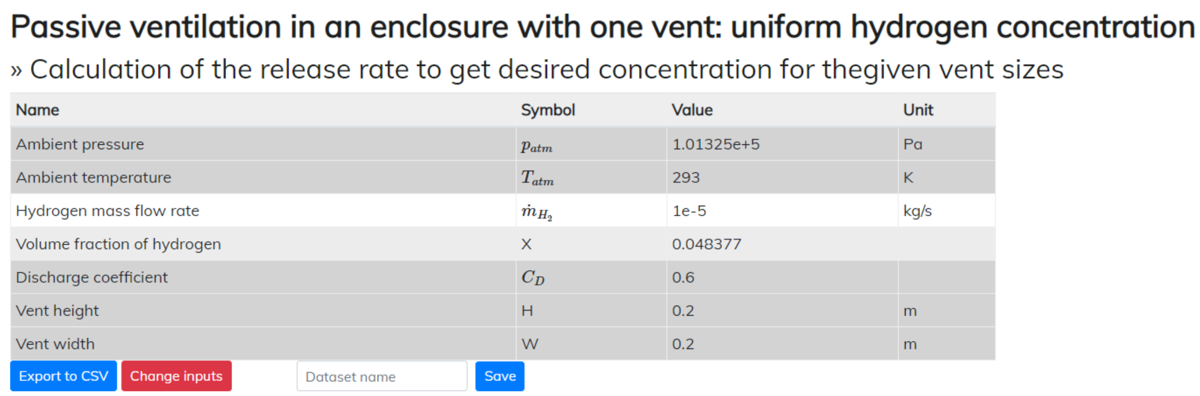


Figure 23. The setting of the tool for problem 3

The output parameter is the required hydrogen mass flow rate. An example of the output parameter is shown in Figure 24, which indicates that, for the given value of the input parameters in Figure 23, the required hydrogen mass flow rate is 1e-5 kg s^{-1}.


Passive ventilation in an enclosure with one vent: uniform hydrogen concentration

» Calculation of the release rate to get desired concentration for thegiven vent sizes

Name	Symbol	Value	Unit
Ambient pressure	p_{atm}	1.01325e+5	Pa
Ambient temperature	T_{atm}	293	K
Hydrogen mass flow rate	$\dot{m}_{H_2}$	1e-5	kg/s
Volume fraction of hydrogen	X	0.048377	
Discharge coefficient	C_D	0.6	
Vent height	H	0.2	m
Vent width	W	0.2	m

Figure 24. The output of the tool for problem 3

11.2 Pressure peaking phenomenon for unignited release

This tool consists of two options to allow solving of the following two problems:

1. Pressure peaking phenomenon with constant mass flow rate
2. Pressure peaking phenomenon with tank blowdown

The theory of pressure peaking phenomenon (PPP) has been discussed in detail in section 6 of this lecture. To implement the tool, as shown in Figure 25, the first step is to select the model, which is used for particular problems. Model description should appear upon pressing the appropriate button on the home screen of the tool.

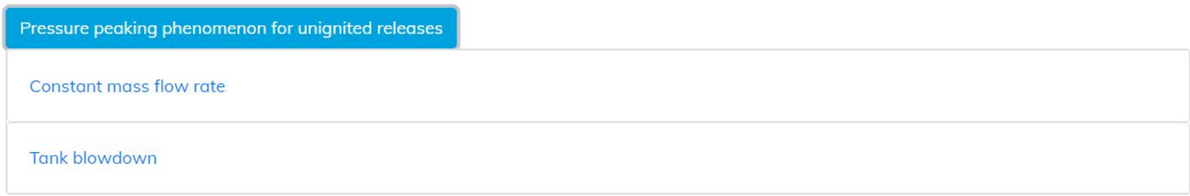


Figure 25. Selection of proper model for a particular problem of PPP

Problem 1: Pressure peaking phenomenon with constant mass flow rate.

The input parameters are shown in Table 5 and the screen shot of the setting of the tool is shown in Figure 26.

Table 5 Input parameter for problem 1 of PPP (unignited case)

Parameter name	Symbol	Unit	Limits (min-max)	Defaults
Atmospheric pressure	p_{atm}	Pa	101325 – 90,000,000	101325
Enclosure temperature	T_{encl}	K		293.15
Enclosure volume	V_{encl}	m^3		30.42
Vent height	H_{vent}	m		0.05
Vent width	W_{vent}	m		0.25
Mass flow rate of hydrogen	$\dot{m}_{H_2}$	kg/s		0.39
Coefficient of discharge	C_D	-		0.6
Time step for integration	Δt	s		1
Number of time steps for integrations	n_{last}	-	500-100000	1000

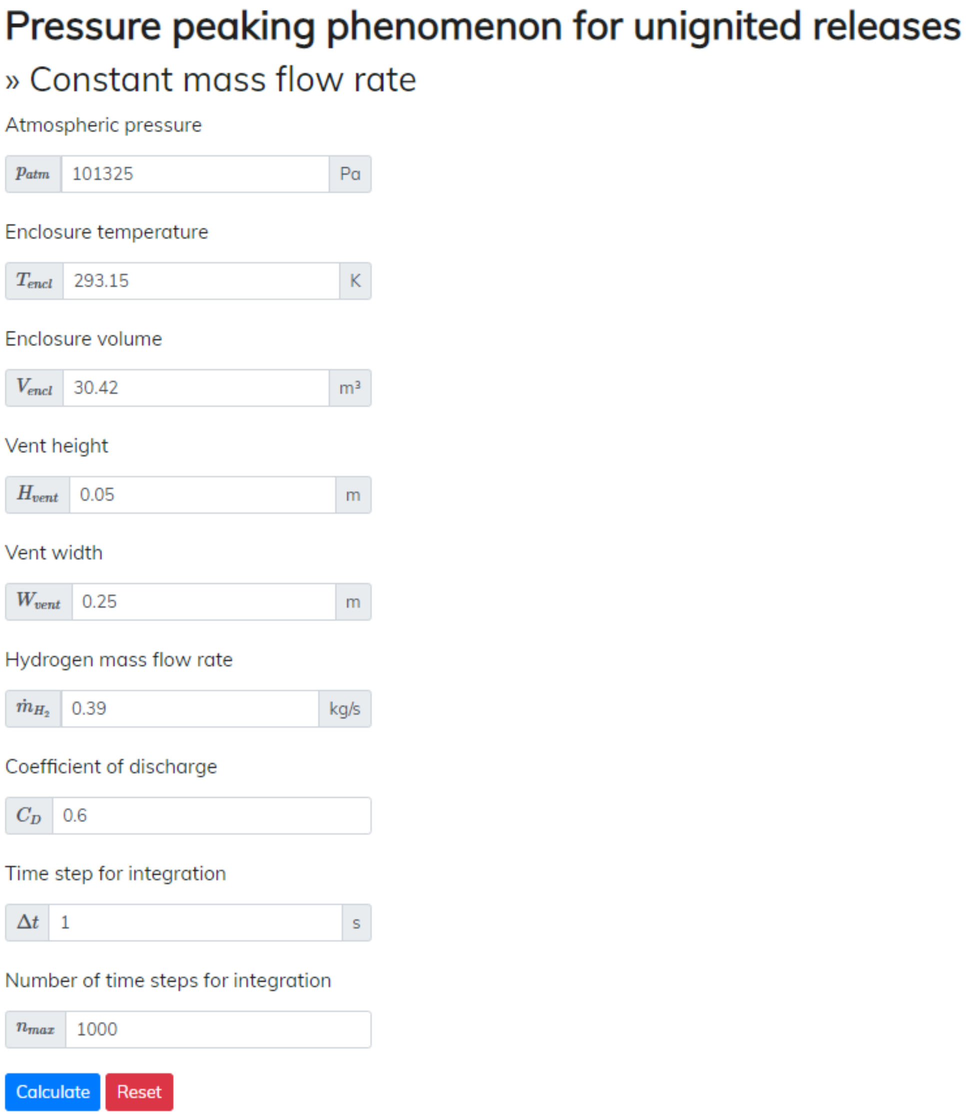


Figure 26. Input parameters of problem 1 of PPP (unignited case)

Upon calculation finished, the graph for the pressure p_{g_encl} (Y-axis) against time t (X-axis) PPP should be plotted. The pressure axis should have axis title with respect to the pressure units chosen at the beginning e. g. Pressure (bar/Pa/kPa etc.). An example of the output parameter is shown in Figure 27.

Pressure peaking phenomenon for unignited releases

» Constant mass flow rate

Name	Symbol	Value	Unit
Atmospheric pressure	p_{atm}	1.01325e+5	Pa
Enclosure temperature	T_{encl}	293.15	K
Enclosure volume	V_{encl}	30.42	m³
Vent height	H_{vent}	0.05	m
Vent width	W_{vent}	0.25	m
Hydrogen mass flow rate	$\dot{m}_{H_2}$	0.39	kg/s
Coefficient of discharge	C_D	0.6	
Time step for integration	Δt	1	s
Number of time steps for integration	n_{max}	1000	
Time	t	view	s
Mass of gases in enclosure	m_{encl}	view	kg
Vent mass flow rate	$\dot{m}_{vent}$	view	kg/s
Overpressure	$p_{g_{encl}}$	view	Pa

Plot Export to CSV Change inputs Dataset name Save

Figure 27. The output of the tool for problem 1 of PPP (unignited case)

The plot of pressure as a function of time is shown in Figure 28.

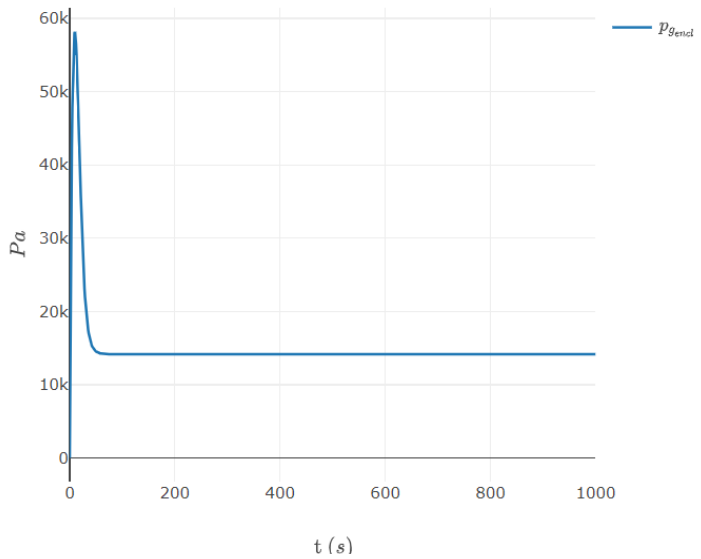


Figure 28. The plot of pressure vs. time of problem 1 of PPT (unignited case)

Problem 2: Pressure peaking phenomenon with tank blowdown.

The input parameters are shown in Table 6 and the screen shot of the setting of the tool is shown in Figure 29.

Table 6 Input parameter for problem 2 of PPP (unignited case)

Parameter name	Symbol	Unit	Limits (min-max)	Defaults

Atmospheric pressure	p_{atm}	Pa	101325 – 90,000,000	101325
Enclosure temperature	T_{encl}	K		
Enclosure volume	V_{encl}	m^3		
Vent height	H_{vent}	m		
Vent width	W_{vent}	m		
Coefficient of discharge	C_D	-		0.6
Initial hydrogen pressure in reservoir	p^0_{res}	Pa		
Initial hydrogen temperature in reservoir	T_{res}	K		
Reservoir volume	V_{res}	m^3		
Orifice diameter	d_3	m		
Initial guess for integration time	t_{f0}	s		
Number of time steps for integrations	i_{last}	-		

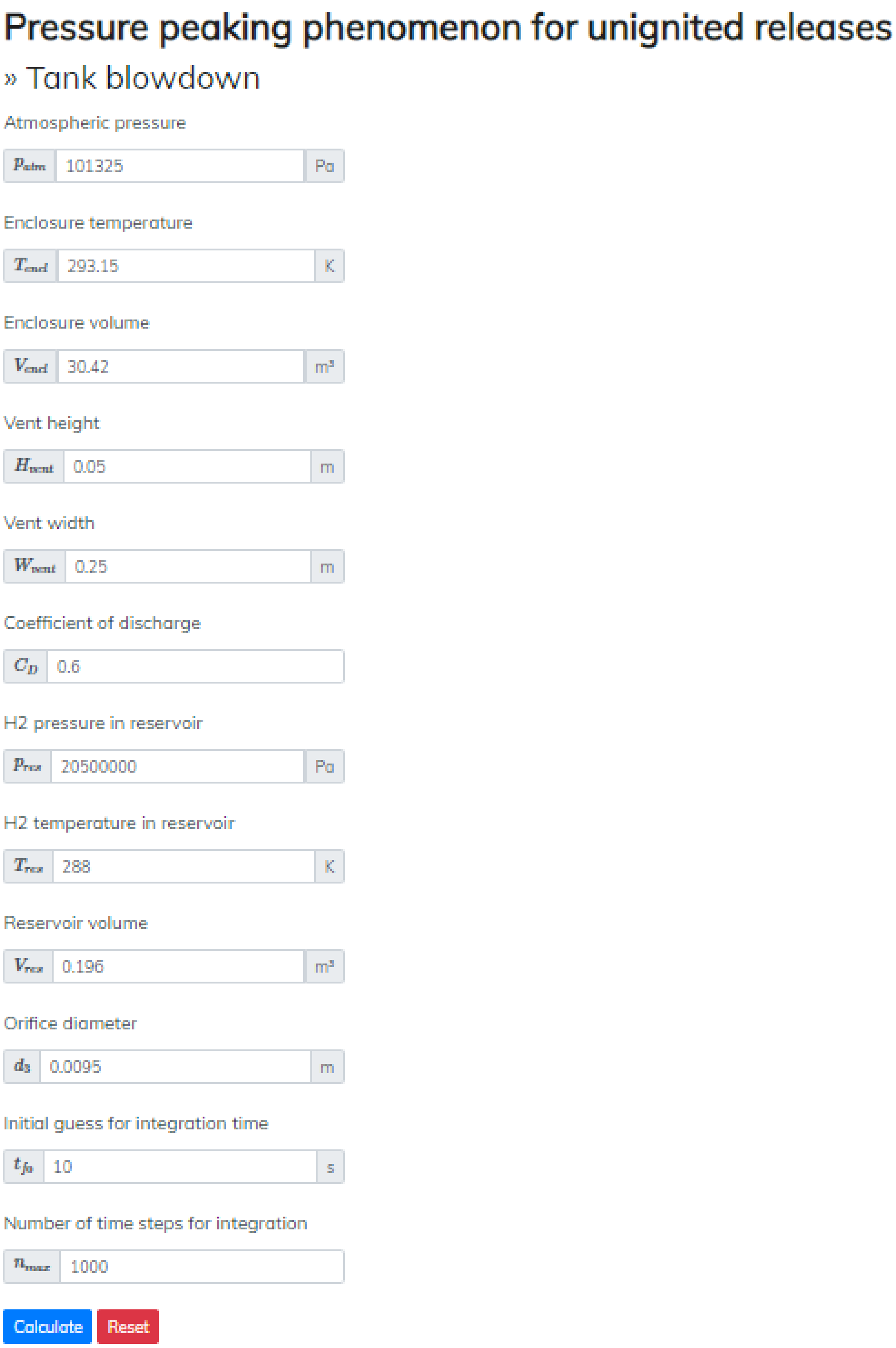


Figure 29. Input parameters of problem 2 of PPP (unignited case)

Once the calculation is finished, the graph for the pressure p_{g_encl} (Y-axis) against time t (X-axis) PPP is plotted. The pressure axis should have axis title with respect to the pressure units chosen at the beginning e. g. Pressure (bar/Pa/kPa etc.). An example of the output parameter is shown in Figure 30.

Pressure peaking phenomenon for unignited releases

» Tank blowdown

Name	Symbol	Value	Unit
Atmospheric pressure	p_{atm}	1.01325e+5	Pa
Enclosure temperature	T_{encl}	293.15	K
Enclosure volume	V_{encl}	30.42	m³
Vent height	H_{vent}	0.05	m
Vent width	W_{vent}	0.25	m
Coefficient of discharge	C_D	0.6	
H2 pressure in reservoir	p_{res}	8.45344e+5	Pa
H2 temperature in reservoir	T_{res}	114.878	K
Reservoir volume	V_{res}	0.196	m³
Orifice diameter	d_3	0.0095	m
Initial guess for integration time	t_{f_0}	10	s
Number of time steps for integration	n_{max}	1000	
Time	t	view	s
H2 mass in reservoir	m_{H_2}	view	kg
Hydrogen mass flow rate	$\dot{m}_{H_2}$	view	kg/s
Density in notional nozzle	ρ_4	view	kg/m³
Velocity in notional nozzle	V_4	view	m/s
Notional nozzle diameter	d_4	view	m
Mass of gases in enclosure	m_{encl}	view	kg
Vent mass flow rate	$\dot{m}_{vent}$	view	kg/s
Overpressure	$p_{g_{encl}}$	view	Pa

Plot | Export to CSV | Change inputs | Dataset name | Save

Figure 30. The output of the tool for problem 2 of PPP (unignited case)

The plot of pressure as a function of time is shown in Figure 31.

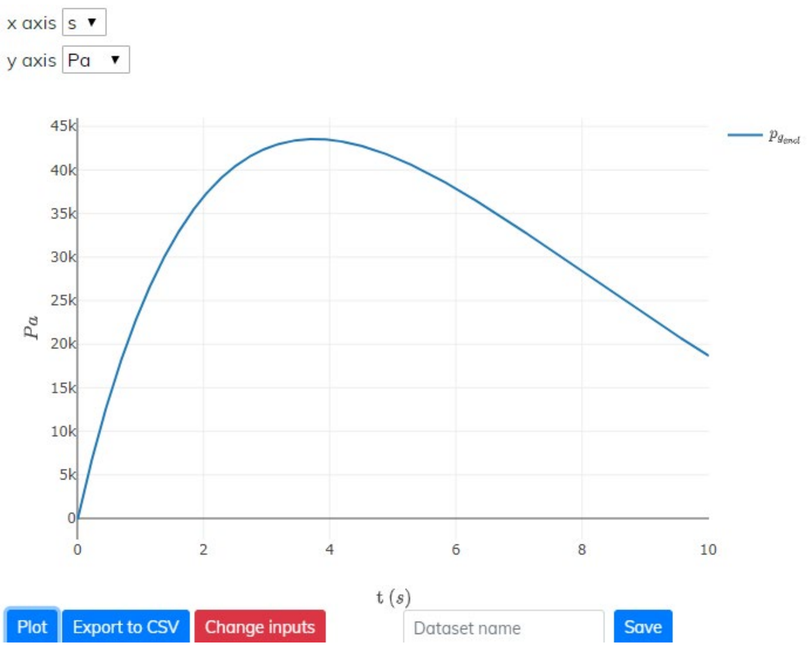


Figure 31. The plot of pressure vs. time of problem 2 of PPT (unignited case)

11.3 Pressure peaking phenomenon for ignited release

Similar to the pressure peaking phenomenon (PPP) for unignited release, the tool to calculate PPP for ignited release also consists of two options, with respect to two different problems as same as those of PPP for unignited release.

First of all, users need to choose the tool entitled Pressure peaking phenomenon for ignited release from the listed tools of e-Laboratory. Then select Pressure peaking phenomenon ignited (constant mass flow rate) to solve problem 1 or Pressure peaking phenomenon ignited (tank blowdown) to solve problem 2, as shown in Figure 32.

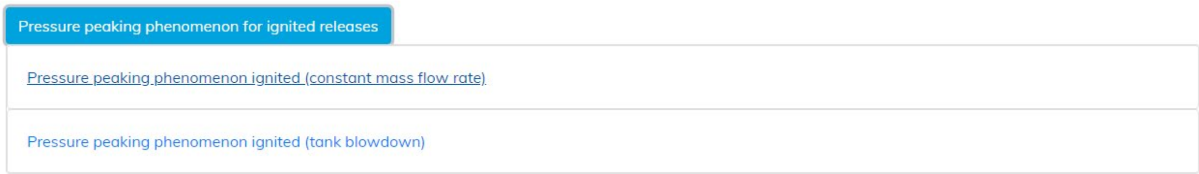


Figure 32. Selection of proper tool for a particle problem.

Problem 1: Pressure peaking phenomenon with constant mass flow rate.

The input parameters are listed in Table 7 and screen shot of tool setting is show in Figure 33, respectively. The difference of input parameters of the ignited case is the requirement of an additional parameter, C_I.

Table 7 Input parameter for problem 1 of PPP (ignited case)

Parameter name	**Symbol**	**Unit**	**Limits (min-max)**	**Defaults**
Atmospheric pressure	p_{atm}	Pa	101325 – 90,000,000	101325
Enclosure temperature	T_{encl}	K		293.15
Enclosure volume	V_{encl}	m^3		30.42
Vent height	H_{vent}	m		0.05
Vent width	W_{vent}	m		0.25
Mass flow rate of hydrogen	$\dot{m}_{H_2}$	kg/s		0.39
Coefficient of discharge	C_D	-		0.6
Time step for integration	Δt	s		1
Number of time steps for integrations	n_{last}	-		1000
Coefficient for ignited release	C_I	-		1

Note: Input value for C_I highlighted in yellow should appear only for ignited case.

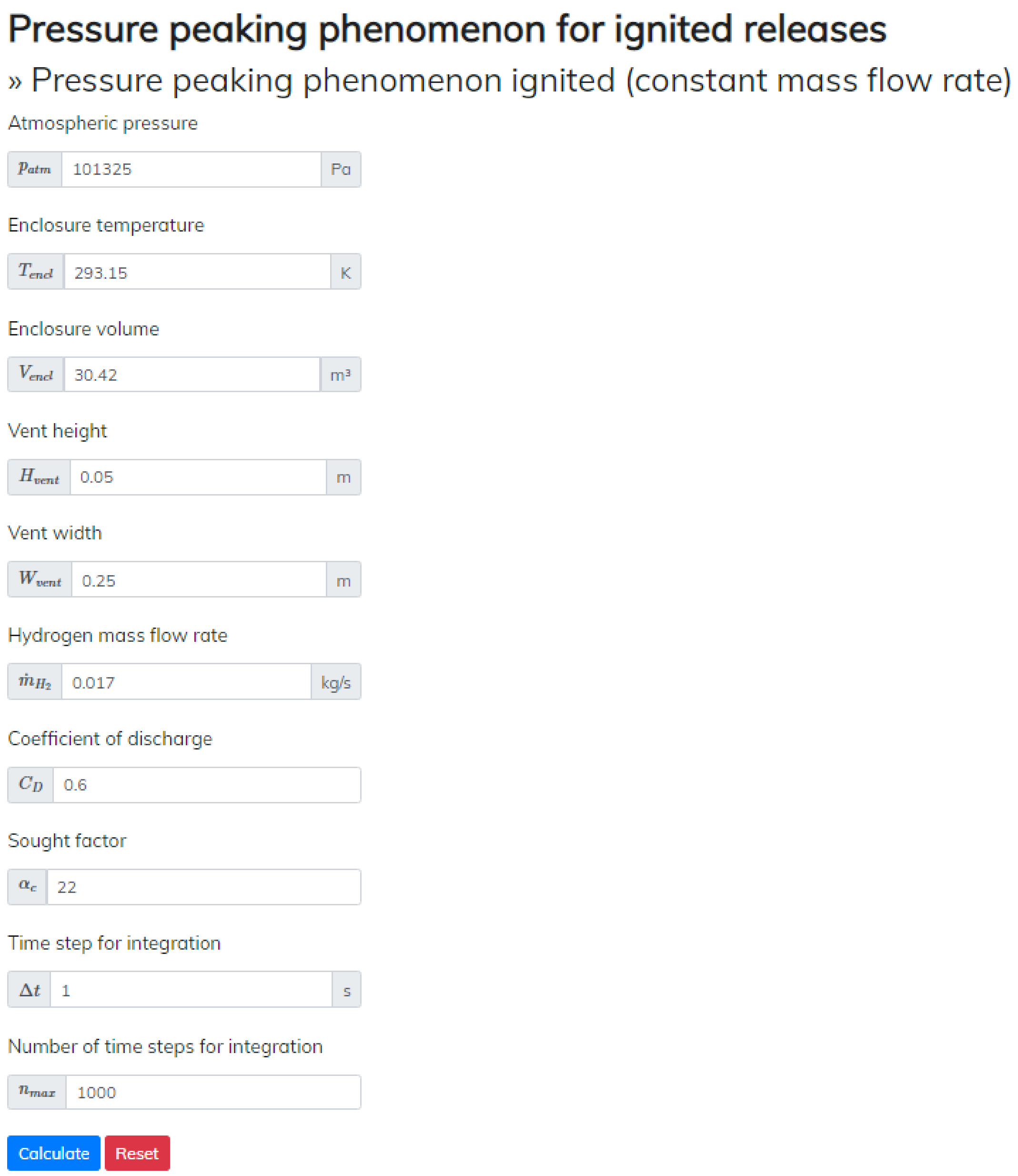


Figure 33. Input parameters of problem 1 of PPP (ignited case)

The screen shot of the output parameters and an example of the plot of pressure as a function of time are shown in Figure 34 and Figure 35, respectively.

Pressure peaking phenomenon for ignited releases

» Pressure peaking phenomenon ignited (constant mass flow rate)

Name	Symbol	Value	Unit
Atmospheric pressure	p_{atm}	1.01325e+5	Pa
Enclosure temperature	T_{encl}	293.15	K
Enclosure volume	V_{encl}	30.42	m³
Vent height	H_{vent}	0.05	m
Vent width	W_{vent}	0.25	m
Hydrogen mass flow rate	$\dot{m}_{H_2}$	0.017	kg/s
Coefficient of discharge	C_D	0.6	
Sought factor	α_c	22	
Time step for integration	Δt	1	s
Number of time steps for integration	n_{max}	1000	
Time	t	view	s
Mass of gases in enclosure	m_{encl}	view	kg
Vent mass flow rate	$\dot{m}_{vent}$	view	kg/s
Overpressure	$p_{g_{encl}}$	view	Pa

Plot Export to CSV Change inputs Dataset name Save

Figure 34. The output of the tool for problem 1 of PPP (ignited case)

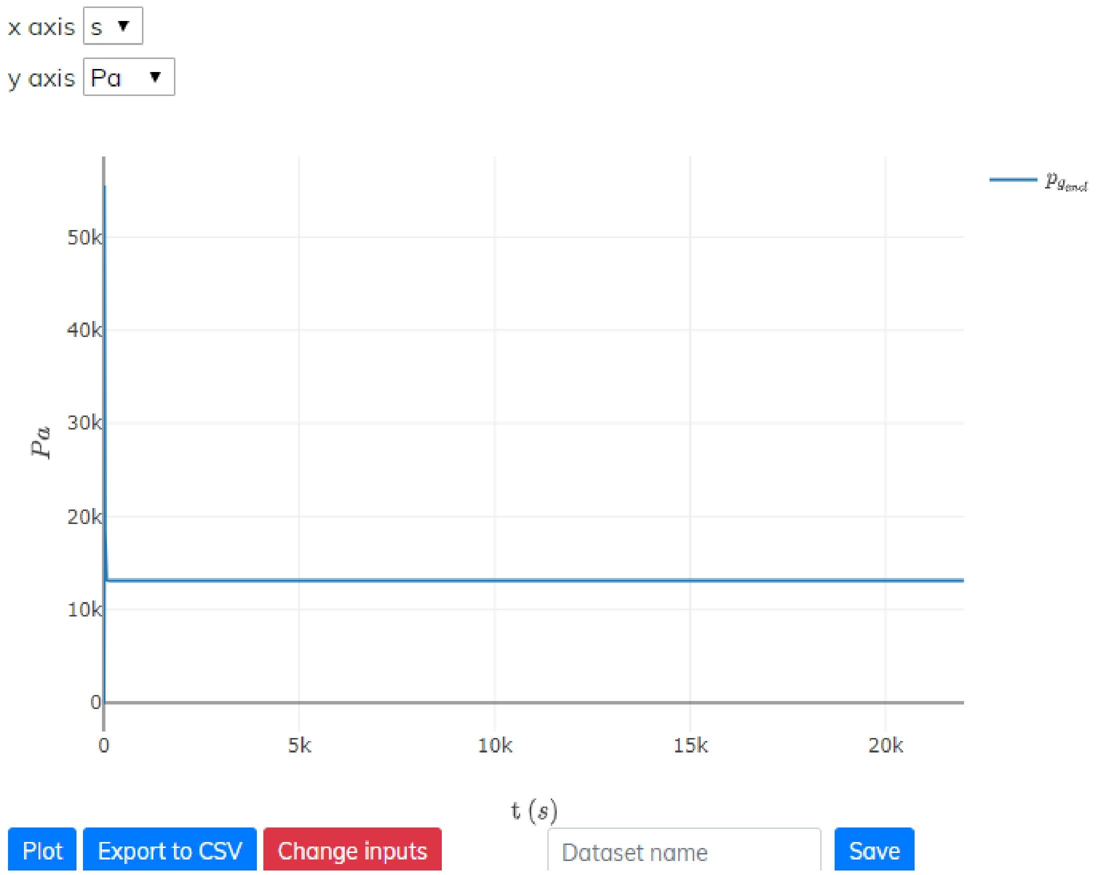


Figure 35. The plot of pressure vs. time of problem 1 of PPT (ignited case)

Problem 2: Pressure peaking phenomenon with tank blowdown.

The input parameters are listed in Table 8 and screen shot of tool setting is show in Figure 36, respectively.

Table 8 Input parameter for problem 2 of PPP (ignited case)

Parameter name	Symbol	Unit	Limits (min-max)	Defaults
Atmospheric pressure	p_{atm}	Pa	101325 – 90,000,000	101325
Enclosure temperature	T_{encl}	K		
Enclosure volume	V_{encl}	m^3		
Vent height	H_{vent}	m		
Vent width	W_{vent}	m		
Coefficient of discharge	C_D	-		0.6
Initial hydrogen pressure in reservoir	p^0_{res}	Pa		
Initial hydrogen temperature in reservoir	T_{res}	K		
Reservoir volume	V_{res}	m^3		
Orifice diameter	d_3	m		
Initial guess for integration time	t_{f0}	s		
Number of time steps for integrations	i_{last}	-		
Coefficient for ignited release	C_I	-		1

Pressure peaking phenomenon for ignited releases

» Pressure peaking phenomenon ignited (tank blowdown)

Atmospheric pressure

p_{atm} 101325 Pa

Enclosure temperature

T_{encl} 293.15 K

Enclosure volume

V_{encl} 30.42 m³

Vent height

H_{vent} 0.05 m

Vent width

W_{vent} 0.25 m

Coefficient of discharge

C_D 0.6

Sought factor

α_c 22

H2 pressure in reservoir

p_{res} 20500000 Pa

H2 temperature in reservoir

T_{res} 288 K

Reservoir volume

V_{res} 0.196 m³

Orifice diameter

d_3 0.0095 m

Initial guess for integration time

t_{f0} 10 s

Number of time steps for integration

n_{max} 1000

Calculate Reset

Figure 36. Input parameters of problem 2 of PPP (ignited case)

The screen shot of the output parameters and an example of the plot of pressure as a function of time are shown in Figure 37 and Figure 38, respectively.

Pressure peaking phenomenon for ignited releases

» Pressure peaking phenomenon ignited (tank blowdown)

Name	Symbol	Value	Unit
Atmospheric pressure	p_{atm}	1.01325e+5	Pa
Enclosure temperature	T_{encl}	293.15	K
Enclosure volume	V_{encl}	30.42	m³
Vent height	H_{vent}	0.05	m
Vent width	W_{vent}	0.25	m
Coefficient of discharge	C_D	0.6	
Sought factor	α_c	22	
H2 pressure in reservoir	p_{res}	8.45344e+5	Pa
H2 temperature in reservoir	T_{res}	114.878	K
Reservoir volume	V_{res}	0.196	m³
Orifice diameter	d_3	0.0095	m
Initial guess for integration time	t_{f_0}	10	s
Number of time steps for integration	n_{max}	1000	
Time	t	view	s
H2 mass in reservoir	m_{H_2}	view	kg
Hydrogen mass flow rate	$\dot{m}_{H_2}$	view	kg/s
Density in notional nozzle	ρ_4	view	kg/m³
Velocity in notional nozzle	V_4	view	m/s
Notional nozzle diameter	d_4	view	m
Mass of gases in enclosure	m_{encl}	view	kg
Vent mass flow rate	$\dot{m}_{vent}$	view	kg/s
Overpressure	$p_{g_{encl}}$	view	Pa

Plot | Export to CSV | Change inputs | Dataset name | Save

Figure 37. The output of the tool for problem 2 of PPP (ignited case)

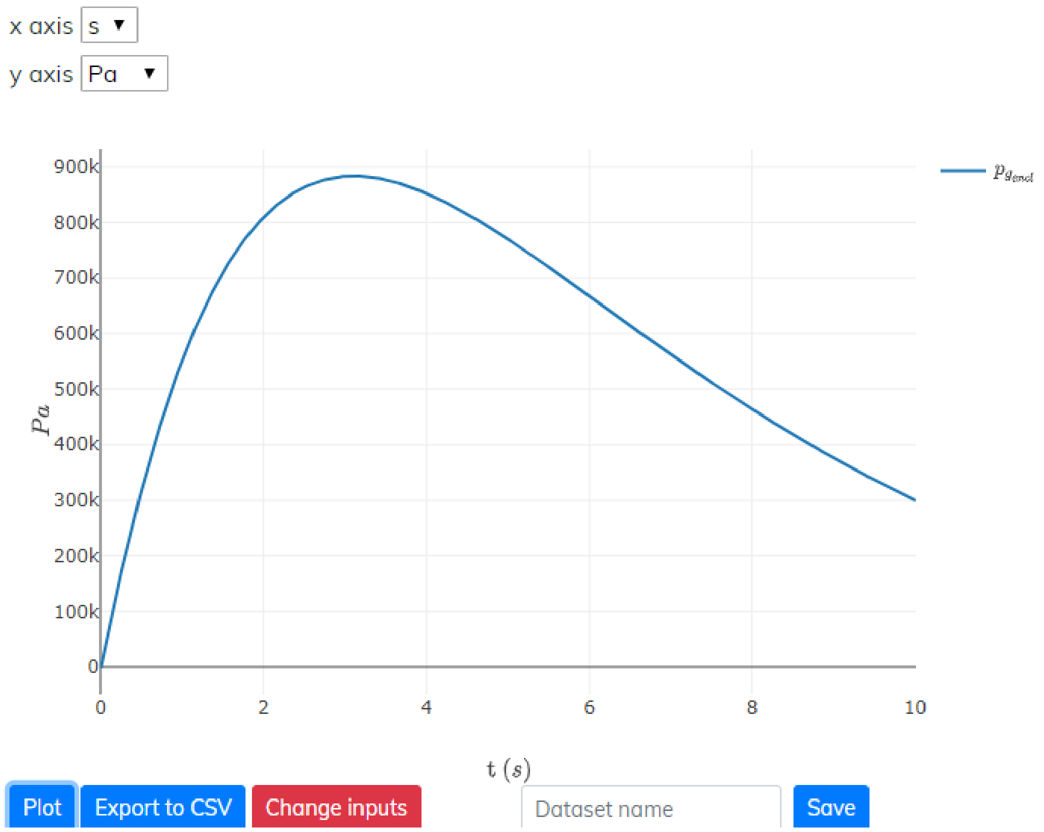


Figure 38. The plot of pressure vs. time of problem 2 of PPT (ignited case)

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