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Premixed Layer Formation Modelling in Stratified Melt-Coolant Configuration

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ABSTRACT

During a hypothetical severe accident in a light water nuclear power plant, the molten reactor core may come in contact with the coolant water. One of the consequences can be a vapour explosion, which can be a credible threat to the structures, systems and components inside the reactor containment. It can also threaten the integrity of the reactor containment itself, which would lead to release of radioactive material into the environment and threaten the general public safety.

The purpose of our research is to improve the knowledge, understanding and modelling of the fuel-coolant interaction and vapour explosion in stratified configuration.

Firstly, the overview of the previously performed experimental and analytical research is given and the mechanisms for the premixed layer formation are identified and evaluated. Further, our developed models for the melt-coolant premixed layer formation in stratified configuration are presented. Implementation of our developed combined model into the code MC3D as a patch is described. Finally, the model validation on available PULiMS and SES experimental results is discussed. At the end, perspectives for possible future work are also enlightened.

1 INTRODUCTION

During a hypothetical severe accident in a light water nuclear power plant, the molten reactor core may come in contact with the coolant water. The interaction between them is known as a fuel-coolant interaction (FCI). One of the consequences can be a rapid transfer of a significant part of the molten corium thermal energy to the coolant in a time scale smaller than the characteristic time of the pressure relief of the created and expanding vapour [1]. Such a phenomenon is known as a vapour explosion. Given possibly large amount of thermal energy, initially stored in the liquid corium melt at about 3000 K, and pressure peaks of the order of 100 MPa, vapour explosion can be a credible threat to the structures, systems and components inside the reactor containment. It can also threaten the integrity of the reactor containment itself, which would lead to release of radioactive material into the environment and threaten the general public safety.

The importance of the in-vessel and ex-vessel vapour explosions was recognized also by the OECD, which started the SERENA (Steam Explosion Resolution for Nuclear Applications)

research programme in the year 2002. The main objectives of the programme were evaluating the capabilities of the FCI computer codes for vapour explosion simulations. As a part of SERENA programme, experimental tests were performed on the TROI (KAERI, S. Korea) and KROTOS (CEA, France) facilities. The ex-vessel FCI was one of the priority safety issues identified also in the frame of SARNET (Severe Accident Research NETwork of excellence) programme. The aim of the programme was to network the European research capabilities on severe accidents. Some experimental research related to the vapour explosions in stratified configuration was performed within the SAFEST (Severe Accident Facilities for European Safety Targets) project. In the frame of a French Post-Fukushima Research Program, the ICE (Interaction Corium-Eau) project, related to FCI was launched in 2014. Its aim is to close various gaps, identified in the SERENA and SARNET programmes. Currently, from 2019 to 2024, the OECD ROSAU (Reduction Of Severe Accident Uncertainties) programme is aiming to reduce the knowledge gaps and uncertainties associated with the severe accident progression.

Typically in nuclear safety, the vapour explosions are mostly analysed in the melt jet-coolant pool configuration. Some experimental work had been done in the past related to the stratified configuration. In most cases non-prototypical materials, with melting temperatures lower than that of the reactor fuel, were used. Based on the conclusions from the past experimental and analytical research, the stratified melt-coolant configuration was believed to be incapable of producing a strong energetic interaction between the fuel and coolant. However, the recently performed experiments in the SES and PULiMS facilities at KTH (Sweden) with a superheated high melting temperature eutectic corium simulant melt resulted in relatively strong spontaneous vapour explosions and consequently raised the interest in stratified vapour explosions again. The clearly observed premixed layer in the PULiMS and SES experiments with splashes of melt reached up to 10 cm in height [2] is in contradiction with the previous assumption about the absence of the premixing phase in the stratified melt-coolant configuration.

The purpose of our research is to improve the knowledge, understanding and modelling of the fuel-coolant interaction and vapour explosion in stratified configuration. For the vapour explosion in stratified configuration, few models were developed in the past. They describe the initiation of interaction, its propagation and mixing right in front or just behind the vapour film collapse during the vapour explosion propagation. However, none of the models describes the premixed layer formation prior to the vapour explosion as observed in some of the experiments (e.g. PULiMS and SES). The mechanisms for the premixed layer formation were also not yet completely understood. In the frame of our research, we try to fill this gap in modelling and describe the premixed layer formation.

Based on the comprehensive overview of the recent and past experiments the mechanisms for the premixed layer formation were identified and evaluated [3]. In the paper, our first objective is to present our developed models for the melt-coolant premixed layer formation in stratified configuration. The models are based on available theoretical and experimental results from literature and international cooperation of our research department with other laboratories around the world. The second objective is to present how our developed model is implemented into the Eulerian computational fluid dynamics code MC3D (IRSN, France) as a patch. Namely, the implementation approach of the developed model into the simulation codes with Eulerian description of the droplet field has to be developed. Final objective is related with validation of the model on available PULiMS and SES experimental results by performing simulations of selected experiments. The aim is to ensure that the model provides the best possible predictions for the fuel-coolant interaction in stratified configuration.

2 MODEL FOR PREMIXED LAYER FORMATION

In the literature some possible mechanisms for the premixed layer formation are discussed, but no definitive conclusions were given about the main mechanism responsible for the premixed layer formation.

Different experiments in stratified configuration with observed premixed layer and/or vapour explosion were studied [3]. It can be observed, that one of the most common plausible mechanisms for the premixed layer formation seems to be the formation, growth and collapse of vapour bubbles [4]. Thus, our developed models for the premixed layer formation in the area of formed stratified melt-coolant configuration [5] are based on it. Indeed, in the PULiMS experiments, in the early stage of the melt propagation, vapour bubble formation, growth and collapse in the subcooled water was clearly observed. However, other mechanisms, relevant for the individual experimental geometry (e.g. jet break-up), could serve as additional source of the melt instabilities. Additionally, a contribution to the amount of melt-coolant mixture, which could participate in the vapour explosion, can be a consequence of mixing during the explosion itself.

During the bubble collapse, water at the bubble interface accelerates and the water impact can produce melt splashes. Due to the uncertainties and lack of the detailed information about the melt surface fragmentation, two different mechanisms, i.e. water entrapment and pressure perturbation, are followed in modelling within our research [5].

In the proposed water entrapment model (Figure 1 left), firstly, bubbles are being formed at the vapour-coolant interface. They grow and when the bubbles detach from the hot melt, they condense and collapse. Growth and collapse of bubbles take place near the melt surface, collapse is asymmetric and a coolant micro-jet directed towards the melt is being formed. The coolant micro-jet penetrates into the melt and evaporates. The formed vapour inside the melt expands and pushes the melt above into the coolant, producing a coarse mixture of melt drops in the coolant layer.

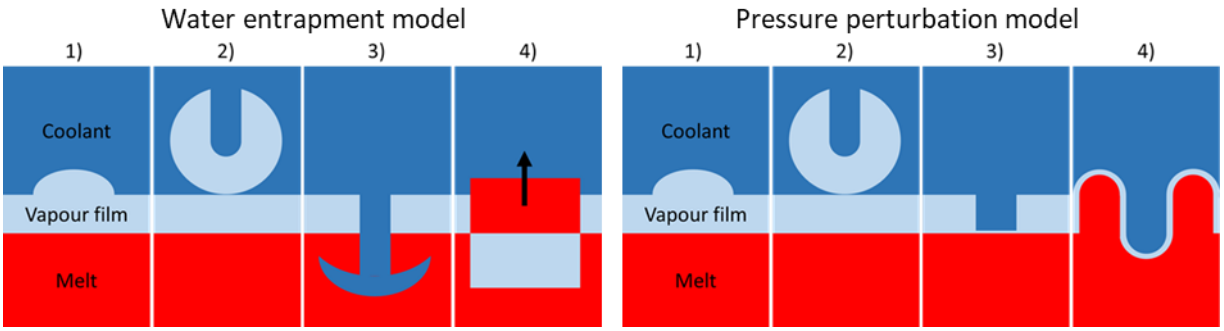

Figure 1: Stages of the water entrapment model for premixed layer formation (left): 1) bubble formation during the film boiling, 2) asymmetric collapse of the bubble with a coolant micro-jet formation, 3) penetration of the coolant micro-jet into the melt and 4) evaporation of the coolant micro-jet followed by an ejection of the melt above it. Stages of the pressure perturbation model for premixed layer formation (right): 1) bubble formation during the film boiling, 2) asymmetric collapse of the bubble with a coolant micro-jet formation, 3) coolant micro-jet impact and vaporization followed by 4) melt ejection.

Because there seems to be no consensus about the coolant micro-jet penetration, another model is proposed. In the pressure perturbation model (Figure 1 right), the initial processes of bubble formation, growth and collapse and coolant micro-jet formation are the same as in the previous model. The main difference as opposed to the water entrapment model is that there is no coolant micro-jet penetration into the melt. The coolant micro-jet hits the melt surface and causes a pressure pulse either as a stagnant pressure due to the kinetic energy of the coolant

micro-jet or a vapour pressure because of the rapid coolant vaporization. This pressure pulse leads to fragmentation of the melt surface.

Both previously developed models are describing the premixed layer formation. With the third model (further on called "our model"), we are trying to at least partly combine both previous models while simultaneously satisfying the description of the experimental phenomena.

The melt drop diameter (d) is defined by the most dangerous wavelength of the Rayleigh-Taylor instabilities (Λ). It is the same in both previous models to the value of a constant (difference of 5%). However, in the water entrapment model, the coolant micro-jet penetration and its spreading is very roughly estimated. Therefore, for our model, the diameter of the ejected melt drops from the pressure perturbation model is taken into account. Due to the uncertainties, it is multiplied with the factor C_{OMd}:

$$d = C_{OMd} \cdot 0.25 \cdot \Lambda \,. \tag{1}$$

The fragmentation rate is the same (relatively according to the melt drops size) in both previous models. It is defined by the most dangerous wavelength, the melt drop diameter (Eq. 1) and the frequency (F) of bubble releases at the vapour film – liquid coolant interface derived by Berenson [6]. Due to the uncertainties, it is multiplied with the factor C_{OMf}:

$$\Gamma = C_{OMf} \cdot \frac{\pi d^3 F}{3\Lambda^2} \,. \tag{2}$$

The ejected melt drop initial velocity is not the same in both previously addressed models. The velocity in the water entrapment model is constant, i.e. it does not depend on the surrounding properties. The available energy in the water entrapment model is more than enough for ejecting the melt drop to the experimentally observed height. Because of the lack of related models and correlations in the literature, the description of the coolant micro-jet behaviour is not detailed and made with large uncertainty. As the hypothesis about the coolant micro-jet penetration into the melt drop is also lately considered as more unlikely, the velocity correlation from the pressure perturbation model is taken into account in our model. As shown for their experiments by Caldarola and Kastenberg [7], the available energy (and consequently velocity) lies between the transmitted and acoustic energy limits. The velocity, as calculated from the acoustic energy (lower limit), is in our model multiplied with a factor C_{OMv}:

$$v = C_{OMv} \cdot \sqrt{0.009664 \cdot \frac{(\rho_M - \rho_L)\rho_L^{1.9}}{(\rho_M + \rho_L)\rho_M^2 \rho_G^2} \cdot \frac{\lambda_L^{\frac{4}{3}} c_p^{\frac{2}{3}}}{c g^{0.2} L^2 \sigma_L^{0.2} \mu_L^{\frac{8}{15}}} \cdot \frac{(p_{max} - p_0)^2 \Delta T_{sub}^2}{\Lambda^{0.8} \sqrt{\Delta p}}} \,, \tag{3}$$

where ρ stands for density, λ is thermal conductivity, c_p coolant specific heat, c sound velocity, g gravity, L latent heat, σ surface tension, μ dynamic viscosity, $p_{\max}$ maximum of stagnant or vaporization pressure, p_0 surrounding pressure and Δp pressure difference between inside and outside of bubble. Indexes M, L and G stand for melt, liquid coolant and gaseous coolant, respectively.

With our model, reduced to the three equations for the melt drops diameter, fragmentation rate and ejected melt drop initial velocity, we can mathematically describe the phenomenon of the premixed layer formation in stratified configuration.

3 MODELLING WITH MC3D

The developed model is implemented as a patch in the computational fluid dynamic MC3D code V3.9.0.p1, which is being developed at IRSN (France) with fuel-coolant

interactions in mind. MC3D is one of the leading codes in the field of fuel-coolant interactions and it is suitable for the planned purpose, because it covers both the premixing phase and the explosion phase of the fuel-coolant interaction. The premixing phase module [8] deals with the initial mixing of the melt and the coolant and this module is upgraded with the premixed layer formation model, developed in the frame of our research work. In case that a vapour explosion occurs, the results from the premixing phase module serve as an input for the explosion phase module. The explosion phase module concerns the fine fragmentation of the melt during the explosion and the heat transfer between the created fine fragments and the coolant.

MC3D is an Eulerian code in which for each phase (melt drop, continuous melt, liquid, vapour, non-condensable gases) a set of continuity equations for the mass, momentum and energy are solved. For the melt drop description of the premixed layer formation, where the emerging melt drops are ejected from the continuous melt layer into the overlying coolant layer and after reaching the highest position fall back into the continuous melt layer, a two-melt-drop-group approach is used, i.e. one group for the drops moving upward and one group for the drops falling downwards (Figure 2). The group for the drops moving upward is feed by the continuous melt fragmentation at the fragmentation rate and with the drop size and the initial drop velocities as defined in Section 2.

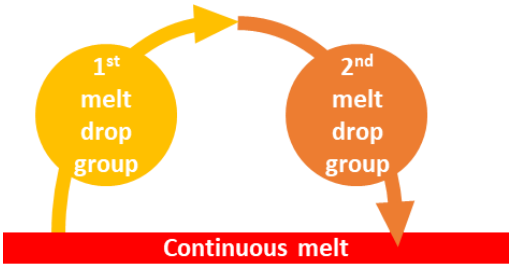

Figure 2: Schematic overview of the two-melt-drop-group approach.

4 APPLICATION TO EXPERIMENTS AND DISCUSSION

With the developed model for the premixed layer formation, implemented as a patch to the MC3D code, we simulated two recent experiments with the stratified configuration – PULiMS E6 (Figure 3) and SES S1. In both of them the same material was used and both of them resulted in a spontaneous vapour explosion. The geometry was also similar, but while the PULiMS E6 test had the melt nozzle above the water pool, in the SES S1 test, the nozzle was under water, just above the bottom plate. The explosion in the SES S1 test occurred earlier compared to the PULiMS E6 test, in which the premixing phase lasted for almost 7 seconds.

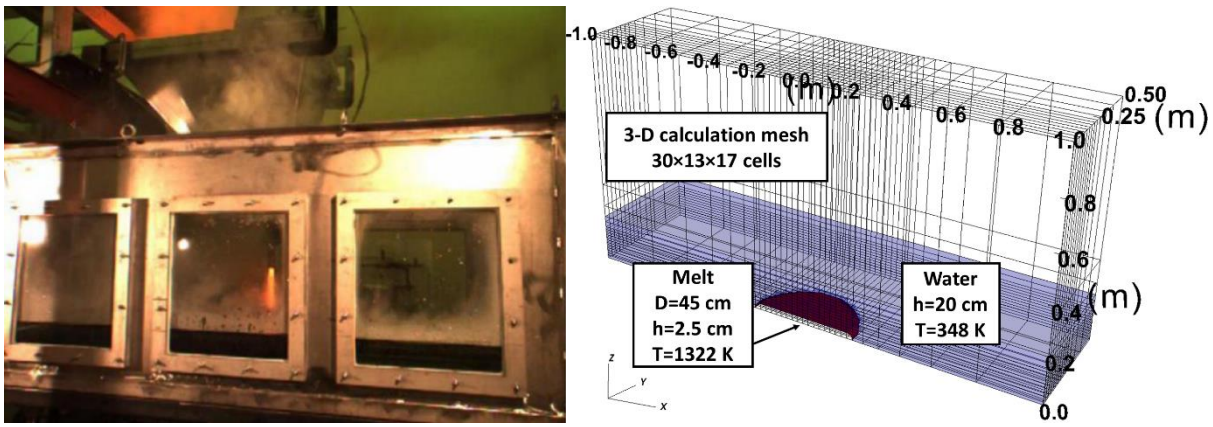

Figure 3: On the left snapshot of PULiMS E6 experimental test [2], on the right applied MC3D calculation mesh for PULiMS E6 simulations.

To assess our model for the premixed layer formation, different analyses were performed [5]. In the premixing phase, mixing of melt and water according to our model is simulated. The direct comparison of the model for the premixed layer formation with the experiments is limited to the visual observations. It seems that the formation of the premixed layer in the premixing phase of simulations with the factor C_{OMv} = 6 is visually comparable to the experimental observation. Time development of the premixed layer is similar in simulations of both experimental tests.

Further assessment of our model is made for the explosion phase, indirectly assessing the premixed layer properties via strength and development of the explosion. For both simulated experimental tests, as seen in Figure 4 and Figure 5, the strength of the explosion increases with the increased C_{OMv} factor because of the larger premixed layer, but the total gained impulse of the explosion is underestimated in all the calculated cases. Additionally, although not shown in figures, the effects of the melt fragmentation rate (C_{OMf}) and melt drop diameter (C_{OMd}) were studied too. The melt fragmentation rate most affects the duration of the explosion. With larger fragmentation rate and consequently larger amount of melt drops in the premixed layer, a shorter vapour explosion is produced with a larger maximal force. This indicates that the mixture, richer in the melt drops, enhances faster explosion development. The trend of producing shorter explosion with a larger maximal force is observed also for decreasing the melt drop diameter. This could be explained by the shorter and faster fine fragmentation of the smaller melt drops. The fine fragmentation rate is in the code simulated to be inversely proportional to the melt drop diameter. The most comparable simulation cases to both considered experimental tests seems to be achieved with the factors C_{OMv}, C_{OMd} and C_{OMf} being 6, 1.25 and 0.5. The C_{OMv} factor 6 presents the best replication of the experimentally observed premixed layer. The C_{OMd} factor 1.25 (melt drop diameter of around 8.5 mm) presents also close match with the experimental observations.

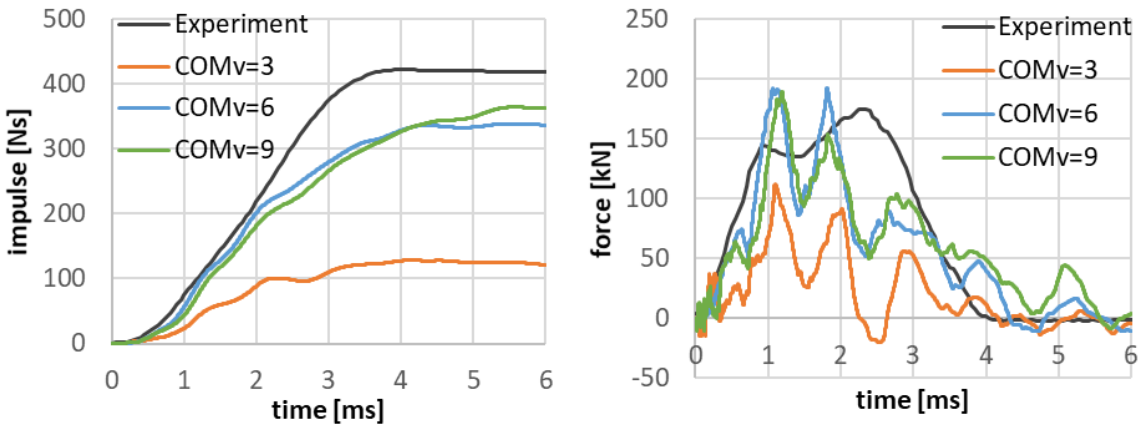

Figure 4: Comparison of the force and total gained impulse on the bottom plate for different melt drops ejection velocity factors C_{OMv} with C_{OMd} = 1.25 and C_{OMf} = 0.5 for SES S1 experimental test.

As seen in Figure 4 and Figure 5, the simulations accurately describe the initial phase of the vapour explosion in both aspects – force and impulse, indicating similar initial development of the explosion, but underestimate the explosion strength of the second part. The discrepancy is larger for the PULiMS E6 case, while it is around 20 % for the SES S1 case. The explosion underestimation could be related to the amount of melt, participating in the explosion [9]. Possible underestimation in the mass of melt drops in our simulations could be related to considering only the bubble formation, growth and collapse mechanism for the premixed layer formation. The experimental phenomena are complex and it would be expected that some amount of mixing could be a consequence of other possible mechanisms. Firstly, in the

experiments, the melt is poured as a jet, which is not modelled in the simulations. The jet fall distance in the SES S1 experimental test was short and therefore only limited amount of jet breakup can be considered. On the other hand, in the PULiMS E6 experimental test, the melt jet felt from 20 cm above the water surface and then travelled further through 20 cm of water. This could present possibility for significant melt breakup, if compared to the SES S1 test. The simulation results support this hypothesis. The larger discrepancy in the PULiMS case compared to the SES case could indicate, that in the PULiMS E6 case, important part of the explosion impulse can be the consequence of the melt-coolant mixing caused by the melt jet breakup. Further, as the melt was poured in water and was spreading, some water could be entrapped under the melt, which would cause rapid vaporization and melt ejection. The melt spreading is not simulated. Instead the final melt pool radius is prescribed from the beginning of the simulations. Additional contribution to the amount of melt, participating in the explosion, can be a consequence of mixing during the explosion itself. This mixing could present the discrepancy in the explosion strength for the SES case and the remaining part of discrepancy for the PULiMS case.

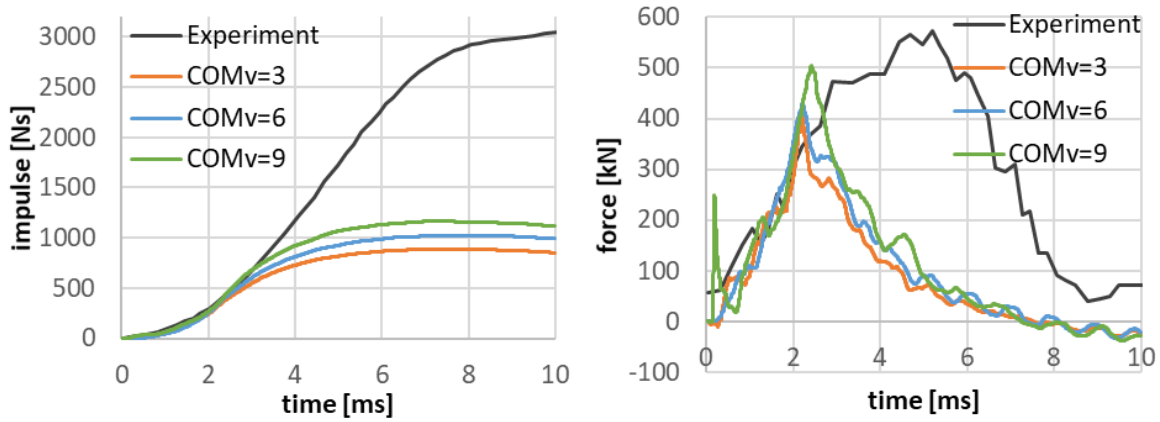

Figure 5: Comparison of the force and total gained impulse on the bottom plate for different melt drops ejection velocity factors C_{OMv} with C_{OMd} = 1.25 and C_{OMf} = 0.5 for PULiMS E6 experimental test.

5 CONCLUSIONS

The goal of the FCI related research was to improve nuclear safety with the improved predictability of the vapour explosion strength, enabling better risk assessment in LWR. This is necessary for the risk management to be able to implement the optimal severe accident management approaches (e.g. flooding of reactor cavity, in-vessel retention, core catcher). The research presents an original contribution to the improvement of understanding and modelling of the fuel-coolant interaction and vapour explosion in the stratified configuration. It also examines the influence that the choice of different premixed layer formation parameters has on the simulation results of complex vapour explosion experiments.

We have developed a model for premixed layer formation based on physical background of two conceptually different physically based models i.e. the water entrapment model and the pressure perturbation model. To enable the implementation of the proposed model into the Eulerian fuel-coolant interaction codes, a description of melt drops with a two-melt-drop-group approach was introduced. The proposed model was implemented into the FCI code MC3D (IRSN, France). This enables to describe more complex geometry, more realistic conditions and intertwined phenomena and can be used for better assessment of vapour explosions also for reactor cases, which is considered to be of utmost importance for nuclear safety. Finally, the

model was validated on available experimental results of the PULiMS E6 and SES S1 experimental tests (KTH, Sweden). The simulation results are qualitatively and quantitatively in reasonable agreement with the experimental results regarding the expected premixed layer height, the strength of the vapour explosion and the duration of the energetic event.

Although our research is based on what is currently state of the art in the field of vapour explosions in stratified configuration, perspectives for possible future work can also be enlightened. Because of the difficulties in the experimental observations, the simulated premixed layer is not easily directly compared to the experimental one. The assessment of the simulation results indicates some other plausible contributions, for research of which future experimental and analytical work would be needed. With improved experimental observations, more detailed comparison of the premixed layer characteristic would also be possible.

Based on the performed research more reliable assessment of the stratified vapour explosions risk in nuclear power plants and in other industries is possible.

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