Časopis Pomorskog fakulteta Kotor – Journal of Maritime Sciences (JMS)
god. 27, br. 1/2026; Vol. 27, No. 1/2026

DOI: https://doi.org/10.56080/jms260504 UDC: 614.84:629.5

Original scientific paper

Towards Realistic Maritime Firefighting: Integrating CFD Simulations within Virtual Reality Environments

Darko Glujić, Goran Vukelić, Goran Vizentin, Miroslav Vukičević*

Abstract: The use of Virtual Reality (VR) in maritime safety training is increasing, enabling immersive emergency-response scenarios without exposing trainees to real hazards. However, many existing VR firefighting applications rely on simplified smoke effects generated directly within game engines, which may not adequately represent smoke propagation in confined shipboard environments. This study presents a workflow for integrating Computational Fluid Dynamics (CFD) simulation outputs into a VR engine-room firefighting training environment. A representative Ro-Ro ship engine room was modelled in SmartFire, where transient smoke and temperature fields were generated for a fuel-line fire scenario. The resulting volumetric smoke data were converted into OpenVDB format and imported into Unreal Engine 5 for visualization in an immersive VR environment. A benchmark comparison against the compartment-fire experiments of Steckler et al. [23] showed good agreement between simulated and experimental temperature profiles, providing additional confidence in the adopted CFD methodology. A user evaluation involving 22 professional firefighters compared conventional game-engine smoke rendering with CFD-derived smoke visualization. The results indicated that participants generally perceived the CFD-derived smoke as more representative of enclosed fire conditions. Although the findings are based on a limited sample and subjective perception measures, they suggest that CFD-supported smoke visualization may enhance perceived realism in maritime firefighting training environments and provide a basis for further investigation using objective performance metrics.

Keywords: Virtual Reality, Maritime firefighting, Engine room fires, Smoke propagation, Immersive simulation, Fire dynamics.

1. Introduction

Fire incidents within ship engine rooms remain one of the most significant hazards in maritime operations, endangering human lives, vessel integrity, and cargo while inflicting major economic and environmental consequences. According to the Allianz Global Shipping Review [1], fires and explosions account for nearly 18% of all marine insurance losses globally, with the majority originating in machinery spaces. The Cefor Fire Trend Analysis [2] similarly highlights the prevalence of engine-room fires compared to cargo or accommodation zones.

The International Maritime Organization (IMO), through the Standards of Training, Certification, and Watchkeeping for Seafarers (STCW) convention [3], mandates regular training and certification for shipboard firefighting competence. However, the current training methods rely heavily on mock-up structures, simplified simulations, or analytical case studies [4–9], which fail to capture the complex fluid dynamics and heat transfer processes occurring within confined maritime environments.

In recent years, computational tools-particularly Computational Fluid Dynamics (CFD) - have become essential for analyzing fire development, smoke stratification, and ventilation effectiveness in ship compartments [10–12]. Simultaneously, the evolution of Virtual Reality (VR) technology has enabled immersive training environments in which crew members can interact with simulated emergency scenarios. Yet, existing VR firefighting simulators typically employ game-engine fire models with pre-set particle systems and static animations [13–16]. Such models may inadequately reproduce important physical phenomena associated with compartment fires. These include buoyancy-driven flow, where hot combustion products rise due to density differences and generate characteristic smoke stratification; turbulence, which governs the mixing and transport of smoke and hot gases within confined spaces; and radiative heat transfer, through which thermal energy is transferred from the fire to surrounding surfaces and gases. Together, these processes strongly influence smoke movement, visibility conditions, and fire development within shipboard environments.

To overcome this limitation, this study introduces a coupled CFD–VR framework for maritime firefighting training. The objective is to create a more physically informed VR environment for ship engine rooms, where the visualized fire and smoke fields are derived directly from CFD simulation data rather than pre-programmed effects. This approach offers improved situational awareness, thereby aligning technological capability with pedagogical needs [17].

The research presented here builds upon prior reviews of maritime VR applications [16, 17], identifying a clear gap between realistic fire modelling and immersive educational use. The specific aims of this study are:

1. To develop a CFD model of a representative Ro-Ro ship engine room;

2. To generate transient three-dimensional smoke and temperature fields for a fuel-line fire scenario;

3. To transfer CFD-derived smoke data into a VR environment using a custom conversion workflow;

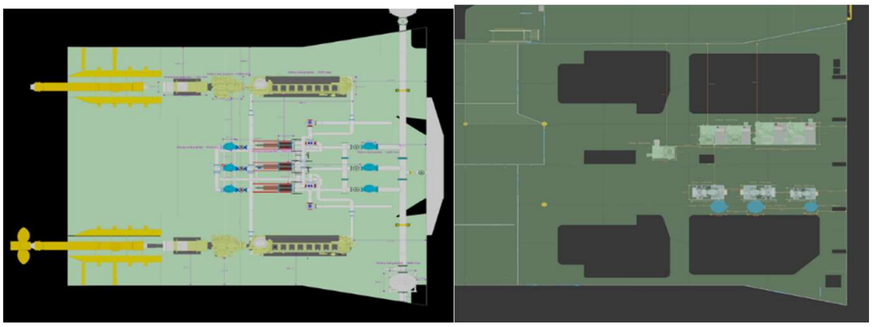
4. To evaluate perceived realism and training relevance among professional firefighters. The result is a unified CFD–VR pipeline capable of transforming numerical fire simulations into an interactive, immersive firefighting scenario.

The contribution of this work does not lie in the general concept of combining CFD and VR, which has already been explored in previous studies, but in the implementation and evaluation of a complete CFD-to-VR workflow for a maritime engine-room fire scenario. The study is presented as a case study demonstrating how transient CFD-generated smoke fields can be converted into volumetric VR assets and subsequently evaluated through user perception testing involving professional firefighters.

2. Materials and Methods

2.1. Ship Engine Room Geometry

The modelled space replicates a real Ro-Ro ship engine room (19.6 m × 16.1 m × 9.0 m) distributed across two decks, comprising two four-stroke main diesel engines, three auxiliary generators, and a ventilation system consisting of 16 interconnected ventilation ducts and openings. The lower deck accommodates the main propulsion machinery, cooling systems and oil pumps, while the upper deck houses purifiers, compressors, and tanks. Ventilation provides approximately 30 air changes per hour (ACH) [18].



a) b)

Fig. 1 - *Engine-room arrangement used in the CFD and VR models: (a) lower deck containing the main propulsion machinery, pumps and cooling systems; (b) upper deck containing auxiliary machinery, tanks and ventilation connections*

Figure 1 illustrates the engine-room arrangement adopted in the CFD and VR models. Figure 1a presents the lower deck containing the main propulsion machinery, cooling systems and associated equipment, while Figure 1b presents the upper deck containing auxiliary systems, tanks and ventilation connections.

2.2. CFD Model Development

The simplification introduced less than 1% deviation in the projected machinery area while preserving the dominant flow-blocking characteristics of the engine-room layout.

The resulting model reproduces all key flow-blocking features and ventilation boundaries.

Meshing employed a structured brick grid of 607,600 cells, which was determined to be optimal after sensitivity tests ranging from 200,000 to 2,000,000 cells. Simulation runtime averaged 30 hours on a 3.0 GHz 16-core CPU with 128 GB RAM.

Figure 2 presents the simplified CFD computational domain. Major machinery components are represented by cuboid geometries, while the principal ventilation openings and flow paths are retained in order to preserve the dominant smoke-transport characteristics of the original engine room.

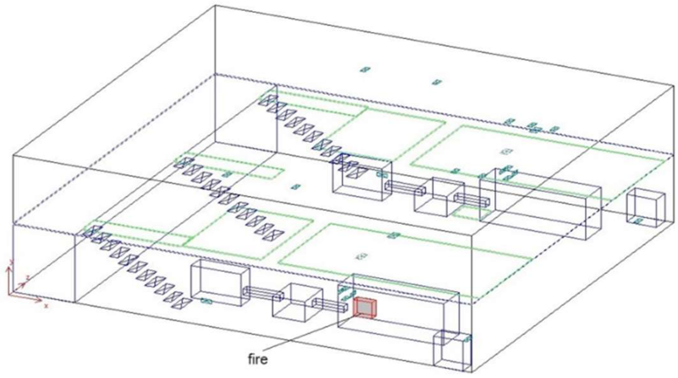


Fig. 2 - *Simplified CFD computational domain showing the cuboid representation of the main machinery together with the retained ventilation openings and flow boundaries used in the simulation*

Boundary conditions were set as adiabatic walls with a no-slip velocity condition, ambient temperature 25 °C and pressure-driven ventilation at 30 ACH.

2.3. Fire Source and Combustion Parameters

A rupture in the main engine fuel line was selected as the ignition source, producing a continuous spray fire modelled using the Eddy Dissipation Model *(EDM)* [21]. The combustion source was defined as a 0.76 × 0.75 × 0.33 m rectangular region adjacent to one main engine.

The instantaneous fuel mass release rate follows:

$P=Ct^2$,

where $C = 6 \times 10^{-7}$ yields a peak fuel release rate of 0.215 kg/s after 600 s. Total fuel mass burnt was 43.13 kg, while total heat generated was 1.73 GJ (heat of combustion = 40 MJ/kg).

Radiative heat transfer was computed using the Six-Flux model [22], solving six directional flux components (I–N).

2.4. Solver Settings

Time step in the solver (Figure 3) was set to 0.2 s (3000 steps for 600 s total). Radiation model Six-Flux was used to model the fire to ensure a robust model and moderate computational cost. The turbulence was taken into account with the k–ε model with buoyancy correction. The pressure–velocity coupling was defined using the SIMPLE algorithm. This generated 3,000 VTU output files (~60 GB) for storing temperature and smoke-density fields within the designated volume.

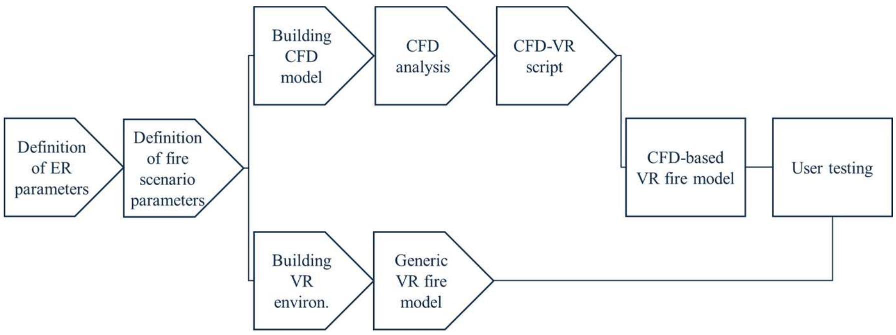


Fig. 2 - *Flowchart of CFD–VR coupling and solver workflow*

2.5. Benchmark Validation

Direct experimental validation of the investigated ship engine-room scenario is not feasible because the modelled engine room does not exist as a physical compartment and full-scale fire testing would be impractical. Therefore, a benchmark validation approach was adopted to assess the credibility of the selected CFD setup.

The validation was based on the well-documented compartment fire experiments conducted by Steckler et al. [23], which are widely used as benchmark cases for compartment-fire modelling. The selected configuration consisted of a 2.8 m × 2.8 m × 2.18 m compartment with a centrally positioned fire source and a doorway opening 0.74 m wide and 1.83 m high. The fire heat release rate was 62.9 kW.

The benchmark scenario was recreated in SmartFire using the same solver framework adopted for the engine-room simulations. The compartment geometry, opening dimensions, fire characteristics and sensor locations were reproduced according to the original experimental configuration. Temperature profiles were recorded at two measurement locations corresponding to the original experiment: a corner sensor stack positioned adjacent to the doorway wall and a sensor stack located within the doorway opening.

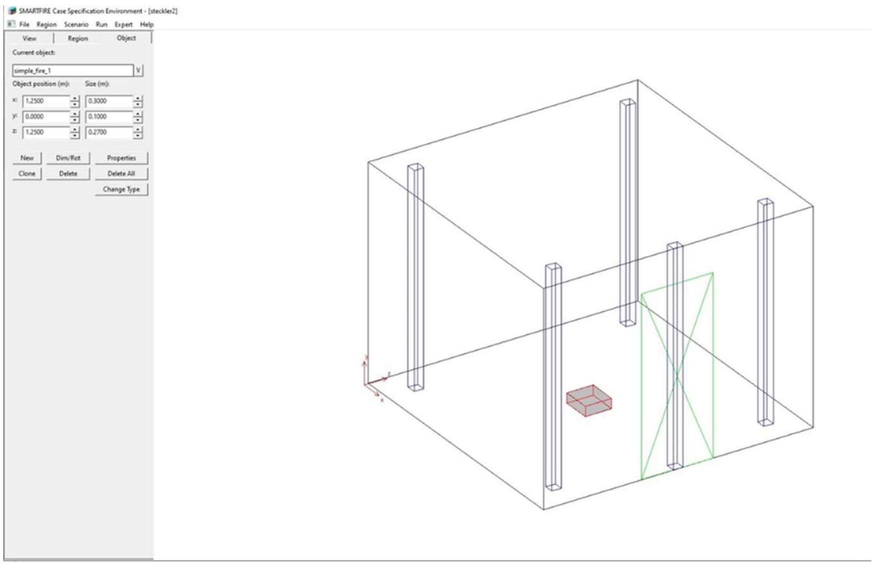


Fig. 3 - *Geometry and fire and sensor locations for Steckler's simulation*

Figure 4 presents the geometry and sensor arrangement used for the benchmark validation. The resulting temperature profiles were subsequently compared with the experimental measurements reported by Steckler et al. [23].

2.6. Data Conversion and Integration into VR

SmartFire output files in .VTU/.VTK format were converted to Unreal Engine–readable OpenVDB files via a custom C++ script, mapping scalar smoke density to volumetric texture fields. Only smoke data were retained, reducing storage to 3 GB (3,000 VDB files).

Each frame corresponds to 0.2 s, ensuring synchronised temporal playback. Spatial scaling was maintained at a 1:1 ratio with the ship geometry.

2.7. VR Environment Configuration

The immersive environment was developed in Unreal Engine 5.3, optimised for Meta Quest 3 VR headsets. Rendering used dynamic global illumination and volumetric fog shaders (Niagara system). Real-time playback achieved 90 fps on RTX 4070 GPUs (12 GB GDDR6X).

Interaction modes included joystick motion, teleportation, and object manipulation. A control scenario featuring generic Unreal smoke served as a baseline for comparison.

Figure 5 presents representative user views from the VR environment. Figure 5a shows the lower engine-room deck in the vicinity of the fire source, while Figure 5b shows the upper deck where smoke accumulates beneath the ceiling and progressively reduces visibility. The geometry shown in the VR environment corresponds directly to the CFD computational model.

a) b)

Fig. 4 - *Representative VR views of the engine-room environment: (a) lower deck in the vicinity of the fire source; (b) upper deck showing smoke accumulation and visibility reduction*

3. Results

3.1. Benchmark Validation

To assess the credibility of the adopted CFD methodology, the simulated temperature distributions were compared with the experimental measurements reported by Steckler et al. [23] at both the corner sensor location and the doorway sensor location.

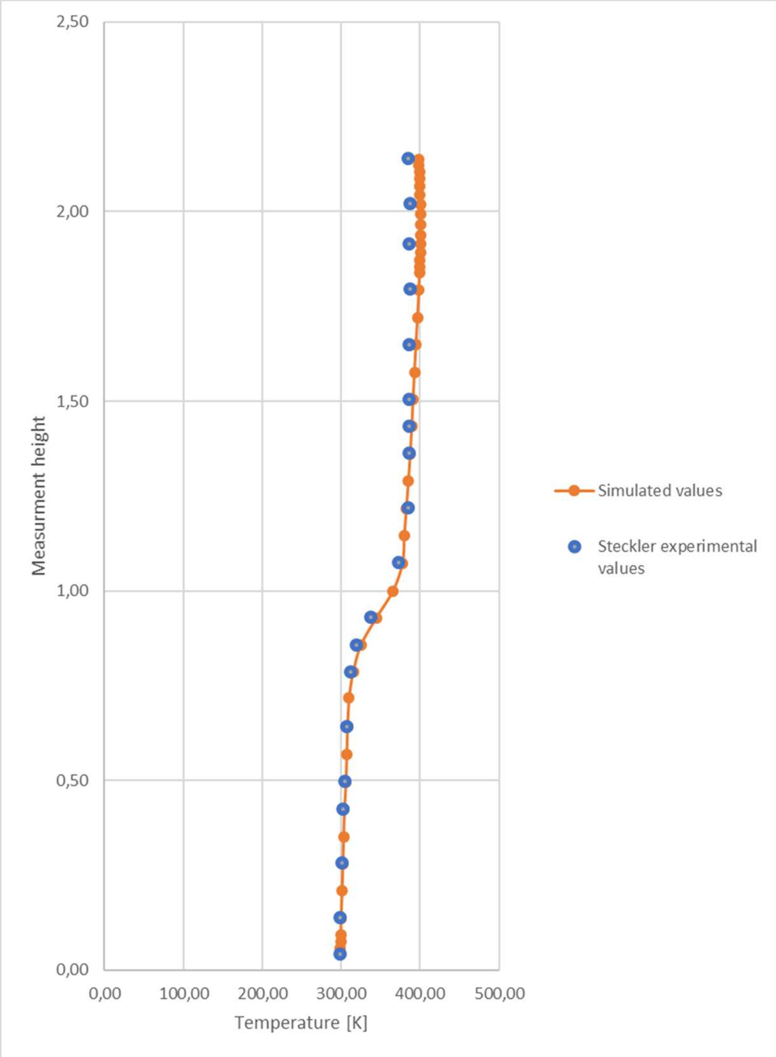


Fig. 5 - *Comparison of the corner sensors for the Steckler's experiment and simulation*

Figure 6 compares the temperature profile obtained at the corner sensor stack with the corresponding experimental measurements. The simulation successfully reproduced the characteristic thermal stratification observed within the compartment, including the transition between the lower cool layer and the upper hot smoke layer. Good agreement was observed throughout the measurement height, with deviations generally remaining below 3%, based on the maximum relative deviation between experimental and simulated temperature measurements.

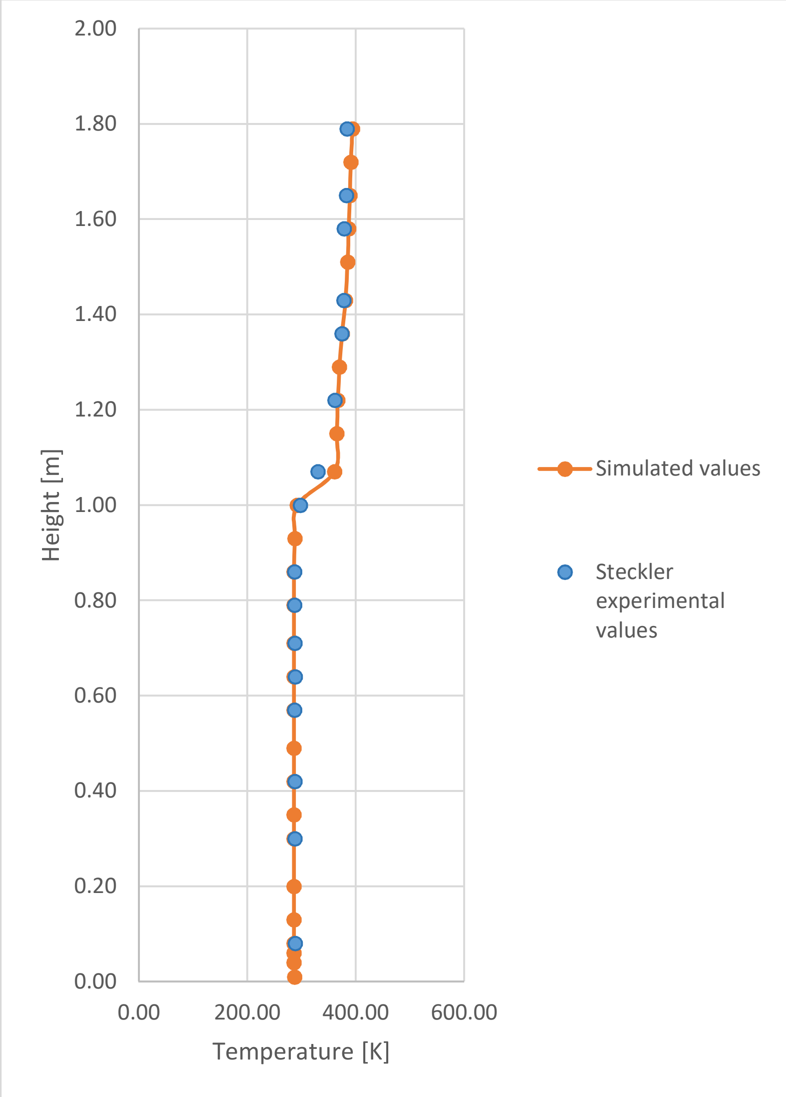


Fig. 6 - *Comparison of the door sensors for the Steckler's experiment and simulation*

Figure 7 presents the comparison for the doorway sensor location. The CFD model reproduced the overall temperature distribution and the position of the neutral plane observed in the experiment. Larger local deviations were observed within the narrow transition region separating the inflowing cool air from the outflowing hot gases. This behaviour is expected because steep temperature gradients amplify the influence of small uncertainties in measurement position and data extraction.

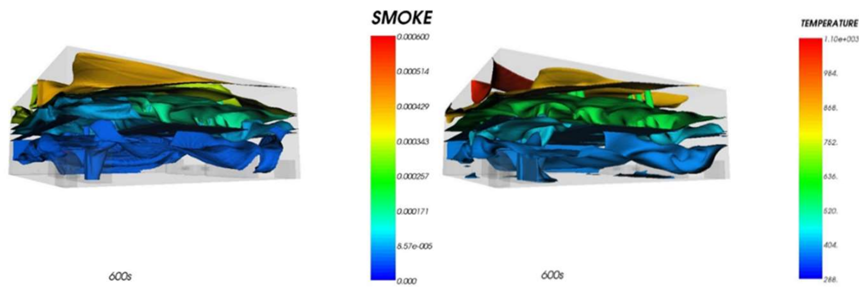
Overall, the comparison demonstrates good agreement between the simulated and experimental temperature profiles and indicates that the selected CFD configuration is capable of reproducing the principal compartment-fire phenomena relevant to the present study, including thermal stratification, smoke-layer formation, and doorway flow behaviour.

The benchmark validation does not constitute validation of the specific ship engine-room scenario investigated in this work. However, it provides additional confidence that the adopted numerical methodology can reproduce characteristic compartment-fire dynamics under controlled conditions.

3.2. CFD Simulation Outcomes

The CFD analysis provided time-dependent distributions of temperature and smoke density throughout the engine room volume. Results are illustrated using isosurfaces at the final simulation step (*t = 600 s*), showing stratified smoke layers and buoyant thermal plumes.

Figure 8 illustrates the CFD results obtained after 600 s of fire development. Figure 8a presents smoke-density isosurfaces, showing the formation of a stratified smoke layer beneath the upper deck ceiling together with lateral smoke transport influenced by the ventilation system. Figure 8b presents temperature isosurfaces, highlighting the buoyancy-driven thermal plume above the fire source and elevated temperatures in the upper compartment region.



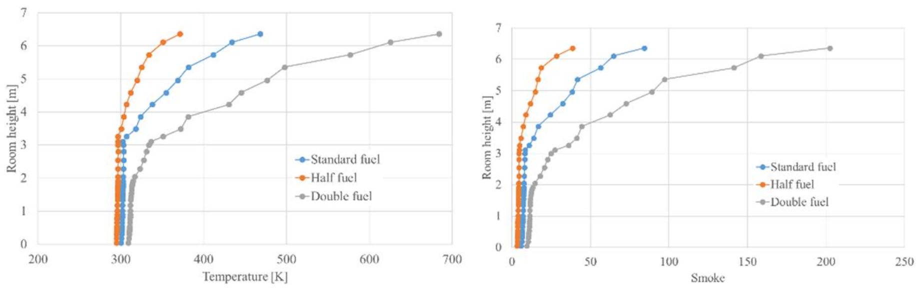
a) b)

Fig. 7 - *CFD results at t = 600 s: (a) smoke-density isosurfaces illustrating smoke-layer formation and transport through the compartment; (b) temperature isosurfaces showing thermal plume development and heat accumulation in the upper deck region*

The maximum local temperature reached approximately 850 °C near the fire source, while average upper-deck air temperature stabilised at 210 °C after 10 minutes. Smoke density peaked beneath the ceiling, forming a stratified layer with visible gradients at 3–5 m above deck level.

Validation of the CFD results through direct experiments is infeasible for safety and logistical reasons. Therefore, *parametric sensitivity tests* were performed by varying fuel release rates (±50%) to evaluate the influence on thermal and smoke profiles.

Figure 9 compares the influence of varying fuel release rates on the predicted temperature and smoke-density distributions. Increasing the fuel quantity produces higher temperatures and more extensive smoke accumulation throughout the compartment, whereas reducing the fuel quantity leads to lower thermal and smoke intensity levels.



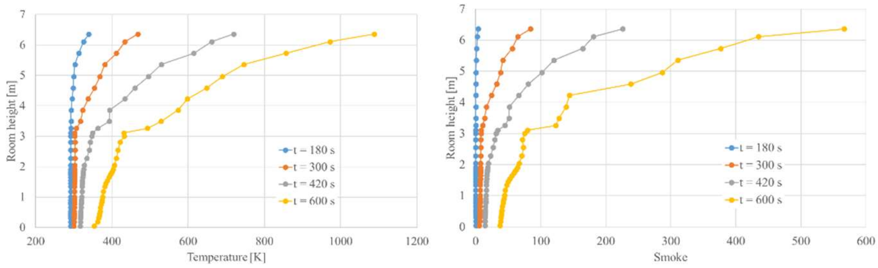
a) b)

Fig. 8 - *Effect of fuel release rate on temperature (a) and smoke density (b) at mid-height of the engine room*

Results show a proportional temperature response: doubling the fuel mass flux increases the mean temperature by ~32%, while halving it decreases it by ~28%. These variations indicate that the CFD setup responds consistently to input scaling.

Furthermore, transient results at multiple time steps (*t = 180 s, 300 s, 420 s, 600 s*) demonstrate progressive smoke accumulation and ceiling-layer thickening.

Figure 10 illustrates the temporal development of the fire scenario at four characteristic simulation times. The results show progressive smoke accumulation beneath the ceiling together with increasing temperatures throughout the upper region of the engine room as the fire develops.



a) b)

Fig. 9 - *Temporal development of (a) temperature and (b) smoke density over four time steps for standard fuel rate*

These results correspond closely with previous CFD studies of compartment fires [8, 23, 24], suggesting the formation of three characteristic thermal and smoke regions within the compartment.

3.3. Visual Integration of CFD Fields into VR

Once converted into OpenVDB volumes, the CFD-derived smoke density fields were rendered directly within Unreal Engine. The resulting volumetric visualisation displayed physically grounded smoke motion driven by ventilation boundary conditions.

In contrast, the generic Unreal Engine fire exhibited symmetrical vertical plumes, independent of ventilation flow, resulting in an unrealistic, static appearance.

a) b)

Fig. 10 - *Comparison of lower-deck fire visualisation: (a) generic game-engine smoke; (b) CFD-based smoke with airflow deflection*

Figures 11 and 12 compare smoke visualisation generated using a conventional game-engine approach and CFD-derived smoke fields. In the generic rendering, smoke remains largely symmetrical and localised around the fire source. In contrast, the CFD-derived visualisation exhibits asymmetric propagation patterns influenced by compartment geometry, ventilation flow, and deck openings.

a) b)

Fig. 11 - *Comparison of upper-deck smoke propagation: (a) generic localised cloud; (b) CFD-based distribution influenced by ventilation and floor openings*

Participants generally reported perceiving differences between the two visualisation approaches: CFD-driven smoke appeared turbulent, asymmetric, and responsive to air motion, while generic smoke followed a uniform upward trajectory.

This finding echoes the aerodynamic visualisation research in other domains such as greenhouse ventilation [24], suggesting that CFD-to-VR mapping may contribute to perceived realism.

3.4. User Experience Evaluation

A structured user study evaluated visual realism and training potential of both simulation types. Twenty-two professional firefighters (average age: 42.2 ± 10.8 years; experience: 19.2 ± 11.2 years) participated voluntarily. None had experience with ship engine-room fires, but all had experience with compartment fires.

Each participant viewed two 2-minute VR videos. The first video was created with generic Unreal smoke simulation, while the other used CFD-based smoke visualisation. The presentation order of the videos was alternated to mitigate sequence bias. After viewing, participants completed a questionnaire containing both closed-ended (Likert 1–6) and open-ended items (Table 1).

Table 1 - *Questionnaire structure and scoring format*
(Rating scale 1 = strongly disagree, 6 = strongly agree)

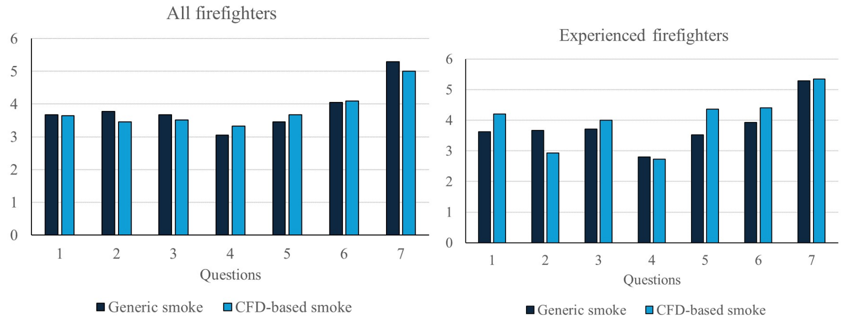
1	The situation presented is realistic.	1 2 3 4 5 6
2	The depicted fire seems too artificial to me.	1 2 3 4 5 6
3	The way the smoke spreads in the room seems realistic to me.	1 2 3 4 5 6
4	The depicted smoke seemed too artificial to me.	1 2 3 4 5 6
5	I have encountered smoke similar to the one shown before.	1 2 3 4 5 6
6	I believe that the presented situation could help me practice dealing with such situations in reality.	1 2 3 4 5 6
7	Considering my previous experience, I believe I could handle solving the situation shown in the video.	1 2 3 4 5 6
8	Please describe in a few words why you stated that the presented situation is realistic or unrealistic.	1 2 3 4 5 6

Descriptive results of the seven key questions are summarised below for all participants and for the subgroup of those with >10 years of firefighting experience (number of respondents N = 15).

For the experienced subgroup, the mean realism scores increased from 3.63 for the generic smoke to 4.20 for the CFD-based smoke, while perceived artificiality decreased from 3.67 to 2.93. The most significant improvement was recorded for Question 5 ("I have encountered smoke similar to this before"), where the mean increased from 3.53 to 4.36 ($p = 0.027$, $\eta^2 p = 0.35$).

These findings suggest that experienced professionals recognised the CFD-based smoke as more representative of real fire conditions. Although other responses did not reach statistical significance, all trends favoured the CFD–VR model, suggesting higher perceived realism among experienced participants.

Open-ended responses revealed three main themes. First, participants highlighted realistic smoke dynamics, noting the presence of lateral airflow, delayed ceiling stratification, and variations in visual smoke thickness within the CFD simulation. Second, users reported improved depth perception, as the physically based smoke volume enabled them to better perceive spatial confinement and the progressive degradation of visibility over time. Third, respondents emphasised the training relevance of the system, suggesting that CFD–VR environments could effectively serve as pre-boarding familiarisation tools, particularly for engine-room operations (Figure 13).



a) b)

Fig. 12 - *Mean response comparison for all (a) and experienced (b) firefighters regarding realism, artificiality, and familiarity*

Typical remarks included:

"The CFD smoke behaves like what I saw in actual building fires-layered, with movement across the ceiling."

"Generic smoke looked static, like a fog machine effect."

4. Discussion

The results of this study suggest that CFD-derived smoke visualisation may provide a different user experience compared with conventional game-engine smoke rendering commonly used in VR firefighting applications. In the presented case study, the CFD-based visualisation produced smoke distributions influenced by compartment geometry, ventilation conditions, and transient fire development, resulting in visibly different propagation patterns from those observed in the generic smoke model.

The user evaluation indicated that experienced firefighters generally perceived the CFD-derived smoke as more representative of enclosed fire conditions. The largest observed difference was associated with the participants' previous exposure to similar smoke behaviour, suggesting that CFD-derived visualisation may better reproduce certain visual characteristics encountered in real compartment fires. However, the observed differences should be interpreted cautiously because the evaluation relied primarily on subjective perception measures and a relatively small participant sample.

Previous VR firefighting studies have frequently relied on procedural smoke effects and particle-based rendering approaches implemented directly within game engines [18–21]. Such methods can generate visually convincing scenarios while maintaining high computational performance. The approach adopted in the present study differs in that smoke propagation was first simulated using a CFD model and subsequently transferred into the VR environment through volumetric data conversion. Rather than attempting to replace conventional VR rendering techniques, the results suggest that CFD-derived visualisation may provide an additional level of environmental detail for specific training scenarios where smoke movement and visibility conditions are important training elements.

The benchmark comparison against the Steckler compartment-fire experiment demonstrated that the adopted CFD configuration reproduced the principal thermal stratification trends observed in experimental measurements. Although this benchmark does not validate the specific ship engine-room scenario investigated in this study, it provides additional confidence that the selected numerical methodology is capable of reproducing characteristic compartment-fire behaviour under controlled conditions.

The presented workflow also demonstrates the practical feasibility of integrating CFD-generated smoke fields into immersive maritime training environments. Nevertheless, the computational requirements associated with CFD simulation, volumetric data storage, and rendering remain higher than those associated with conventional game-engine smoke effects. Consequently, the applicability of the approach should be considered in relation to the intended training objectives and available computational resources.

Several limitations should be considered when interpreting the results of this study. First, the user evaluation involved a relatively small sample of professional firefighters and relied primarily on subjective perception-based responses. Although participant experience provided valuable practical insight, subjective assessments are inherently susceptible to individual bias and cannot directly quantify training effectiveness. Second, the study did not include objective performance metrics such as task completion times, decision quality, situational awareness measures, or physiological indicators. Third, comparisons with alternative CFD–VR implementations reported in the literature were limited. Finally, while benchmark validation against the Steckler compartment-fire experiment was performed to assess the adopted CFD methodology, no direct experimental validation of the investigated ship engine-room scenario was possible. Consequently, the findings should be interpreted as evidence of feasibility and perceived realism rather than definitive proof of training effectiveness or simulation accuracy.

Future research should therefore focus on larger participant groups, objective performance metrics, additional fire scenarios and the integration of collaborative multi-user environments.

5. Conclusions

This study presented a workflow for integrating CFD-generated smoke fields into an immersive VR firefighting environment representing a ship engine room. A CFD model of a representative Ro-Ro engine room was developed in SmartFire, and the resulting smoke-density fields were converted into volumetric data suitable for visualisation in Unreal Engine 5.

A benchmark comparison against the Steckler compartment-fire experiment showed good agreement between simulated and experimental temperature profiles, providing additional confidence in the adopted CFD methodology. The developed conversion workflow enabled the transfer of transient CFD results into a VR environment while preserving the spatial and temporal characteristics of smoke propagation.

The user evaluation involving professional firefighters indicated that CFD-derived smoke visualisation was generally perceived as more representative of enclosed fire conditions than conventional game-engine smoke rendering. Although the findings are based on subjective assessments and a limited sample size, they suggest that CFD-supported smoke visualisation may contribute to improved perceived realism in maritime firefighting training environments.

Overall, the presented case study demonstrates the feasibility of combining CFD-generated fire data with immersive VR technology for maritime safety training applications. Future work should focus on objective performance metrics, additional fire scenarios, larger participant groups and further validation of the proposed methodology.

Funding

This work was conducted within the framework of the INNO2MARE Project – Strengthening the Capacity for Excellence of Slovenian and Croatian Innovation Ecosystems (Horizon Europe Grant No. 101087348).

References

[1] Allianz Global Corporate & Specialty, Safety and Shipping Review 2023. Munich, Germany: Allianz Global Corporate & Specialty, 2023.

[2] The Nordic Association of Marine Insurers, Fires — still burning. Oslo, Norway: Cefor, 2021.

[3] International Maritime Organization, International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1978, as amended, Regulation VI/3. London, U.K.: IMO, 1978.

[4] B. Barlas, R. Ozsoysal, E. Bayraktarkatal, and O. A. Ozsoysal, "A study on the identification of fire hazards on board: A case study," Brodogradnja, vol. 68, no. 4, pp. 71–87, 2017, doi: 10.21278/brod68405.

[5] R. Puisa, S. Williams, and D. Vassalos, "Towards an explanation of why onboard fires happen: The case of an engine room fire on the cruise ship 'Le Boreal'," Applied Ocean Research, vol. 88, pp. 223–232, 2019, doi: 10.1016/j.apor.2019.04.020.

[6] J. Wang et al., "Smoke filling and entrainment behaviors of fire in a sealed ship engine room," Ocean Engineering, vol. 245, p. 110521, 2022, doi: 10.1016/j.oceaneng.2022.110521.

[7] S. Zhang, W. Fang, L. Shi, J. Liu, J. Liu, J. Wang, and B. Cong, "Fire plume characteristics of annular pool fire with different cylindrical obstacles in a ship engine room," Ocean Engineering, vol. 276, p. 114253, 2023, doi: 10.1016/j.oceaneng.2023.114253.

[8] Y. Xie, J. Liu, Z. Hao, Z. Xu, J. Qin, and J. Zhu, "Numerical simulation and experimental study of gas diffusion in a ship engine room," Ocean Engineering, vol. 271, p. 113638, 2023, doi: 10.1016/j.oceaneng.2023.113638.

[9] D. Zeinali, R. Mehaddi, F. Ingold, G. Parent, Z. Acem, A. Collin, J. L. Torero, and P. Boulet, "Experimental study of fire containment using water mist curtains in a reduced-scale deck of a ro-ro ship," Fire Safety Journal, vol. 140, p. 103835, 2023, doi: 10.1016/j.firesaf.2023.103835.

[10] R. Pawling, A. Grandison, P. Lohrmann, G. Mermeris, and C. Pereira Dias, "Methods and tools for risk-based approach to fire safety in ship design," Ship Technology Research, vol. 59, no. 3, pp. 122–133, 2012, doi: 10.1179/str.2012.59.3.003.

[11] I. A. Koromila and K. J. Spyrou, "Design fire methodology for vehicle spaces onboard ships," Fire Technology, vol. 59, no. 4, pp. 1725–1759, 2023, doi: 10.1007/s10694-023-01403-w.

[12] A. Cambaz, Y. F. Görgülü, and H. Arat, "Analysing fluid-structure interaction with CFD and FEA on a marine double-wall LNG piping system," Pomorstvo, vol. 36, no. 1, pp. 51–60, 2022, doi: 10.31217/p.36.1.6.

[13] Y. Fu and Q. Li, "A virtual reality-based serious game for fire safety behavioral skills training," International Journal of Human–Computer Interaction, vol. 40, no. 19, pp. 5980–5996, 2024, doi: 10.1080/10447318.2023.2206598.

[14] N. Akindele, A. Oke, M. Aigbavboa, and C. Aigbavboa, "A state-of-the-art analysis of virtual reality applications in construction health and safety," Results in Engineering, vol. 23, p. 102382, 2024, doi: 10.1016/j.rineng.2024.102382.

[15] P. Braun, M. Grafelmann, F. Gill, H. Stolz, J. Hinckeldeyn, and A.-K. Lange, "Virtual reality for immersive multi-user firefighter-training scenarios," Virtual Reality & Intelligent Hardware, vol. 4, no. 5, pp. 406–417, 2022, doi: 10.1016/j.vrih.2022.08.006.

[16] G. Vukelić, G. Vizentin, and V. Frančić, "Prospects for use of extended reality technology for ship passenger evacuation simulation," Pomorstvo, vol. 35, no. 1, pp. 49–56, 2021, doi: 10.31217/p.35.1.6.

[17] G. Vukelić, D. Ogrizović, D. Bernečić, D. Glujić, and G. Vizentin, "Application of VR technology for maritime firefighting and evacuation training—A review," Journal of Marine Science and Engineering, vol. 11, no. 9, p. 1732, 2023, doi: 10.3390/jmse11091732.

[18] V. Mihai, L. Rusu, and A. Presură, "Main requirements for ventilation of different rooms on ships," The Annals of "Dunărea de Jos" University of Galați, Fascicle XI Shipbuilding, vol. 45, pp. 21–30, 2022, doi: 10.35219/AnnUgalShipBuilding/2022.45.03.

[19] J. Ewer, F. Jia, A. Grandison, I. Frost, E. R. Galea, and M. Patel, SmartFire v4.3: Technical Reference Manual, User Guide and Release Notes. Greenwich, U.K.: Fire Safety Engineering Group, University of Greenwich, 2013.

[20] J. Dujmović and R. Miculinić, "Quantitative analysis of fuel consumption and fuel sediments separation as a function of fuel type and ship operation mode on product/chemical tanker example," Pomorstvo, vol. 37, no. 1, pp. 118–139, 2023, doi: 10.31217/p.37.1.7.

[21] J. X. Wen, "Fire modelling: The success, the challenges, and the dilemma from a modeller's perspective," Fire Safety Journal, vol. 144, p. 104087, 2024, doi: 10.1016/j.firesaf.2024.104087.

[22] Y. Zhang, Z. Liu, Y. Lin, M. Fu, and Y. Chen, "New approaches to determine the interface height of fire smoke based on a three-layer zone model and its verification in large confined space," Fire and Materials, vol. 44, no. 1, pp. 130–138, 2020, doi: 10.1002/fam.2770.

[23] K. D. Steckler, J. G. Quintiere, and W. J. Rinkinen, "Flow induced by fire in a compartment," Symposium (International) on Combustion, vol. 19, no. 1, pp. 913–920, 1982, doi: 10.1016/S0082-0784(82)80284-1.

[24] P. Caserman, A. Garcia-Agundez, and S. Göbel, "A survey of full-body motion reconstruction in immersive virtual reality applications," IEEE Transactions on Visualization and Computer Graphics, vol. 26, no. 10, pp. 3089–3108, 2020, doi: 10.1109/TVCG.2020.2992048.

Submitted: 22/12/2025
Accepted: 16/06/2026

Darko Glujić
University of Rijeka, Faculty of Maritime Studies
Studentska ulica 2, Rijeka, Croatia
Email: darko.glujic@pfri.uniri.hr

Goran Vukelić
University of Rijeka, Faculty of Maritime Studies
Studentska ulica 2, Rijeka, Croatia
Email: goran.vukelic@pfri.uniri.hr

Goran Vizentin
University of Rijeka, Faculty of Maritime Studies
Studentska ulica 2, Rijeka, Croatia
Email: goran.vizentin@pfri.uniri.hr

Miroslav Vukičević
University of Montenegro, Faculty of Maritime Studies Kotor
Put I Bokeljske brigade 44, Kotor, Montenegro
Email: vukicevic.miroslav@gmail.com; miroslav.v@ucg.ac.me