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Coupling CFD and VR for Advanced Fire Training in Ship Engine Room

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Abstract: Fire hazards on marine structures and vessels affect significantly the structural design, engineering decision making and crew training procedures. An on-board fire is extremely dynamic and case dependent phenomenon. New technologies, such as virtual reality (VR) offer a valid alternative for training in such dangerous situations. Fire and smoke exhibit fluid like behavior so computational fluid dynamics (CFD) modelling approach is necessary to ensure the realism of fire models in VR. A CFD and VR integration methodology for development of improved fire hazard marine training, comprising of ship engine room vector and bitmap model generation, CFD fire behavior analysis, results validation and CFD/VR integration, is presented here. SMARTFIRE, an advanced CFD software package, is used to calculate fire parameters, analyze its development and spreading. Heat and smoke progression in a ship engine room environment are visualized in a VR system based on Unreal Engine. The evaluated model is then transferred to the VR environment by linking the fire visualization parameters to the CFD analysis data. In this first phase of the research the CFD-VR integration is done on case to case scenario basis, using the CFD time dependent results with the goal is to produce an interactive dynamical VR simulator realistic fire training environment.

Keywords: marine fire training; CFD fire modeling; VR engine room

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1. Introduction

Various documents, rules and recommendations issued by regulatory organizations like International Association of Classification Societies (IACS) (Cowley 2002; Olsen 2023), International Convention for the Safety of Life at Sea (SOLAS) (IMO 2009) cover basic principles of the design, construction, use, and maintenance of firefighting and fire safety systems on marine structures and vessels. The main points of ship firefighting safety drill procedures are designed to ensure that the crew members are prepared to handle fire emergencies at sea. The fire hazard response procedures typically involve the following actions:

- alerting the crew,
- activating the firefighting systems,
- assessing the situation,
- evacuation of the affected area,
- using firefighting equipment.

Great emphasis is given to the fact that “every member of the crew has a personal responsibility to be competent in identifying the presence of fire, of knowing the correct actions to take in raising an alarm, in taking actions to ensure the safety of passengers and in taking the necessary actions to prevent fire spread whilst ensuring the utmost precautions for personal safety”. Extensive training is performed on regular basis on every marine structure and vessel with crews in order to achieve the necessary knowledge level, competence and confidence necessary for adequate behavior during the stressful fire hazard situation.

It is quite self-explanatory that experimental real fire hazard training is not an option for safety reasons due to the unpredictable and dynamic case to case dependent nature of the fire phenomenon. On the other hand, the development of emerging technologies such as virtual reality (VR) may open opportunities for training in dangerous situations (Cha et al. 2012; Ting et al. 2018; Ooi et al. 2019; Lovreglio et al. 2021). The quality and realism of the computer-generated simulation of a fire environment used in VR that adheres to the actual characteristics of a real-life fire (Huang et al. 2014) is paramount if applicability of the VR model for training is to be achieved (Vukelic et al. 2021). Special attention needs to be given to the realism of flames, heat, smoke, user interaction with the virtual environment and the accuracy of the physics simulation of the dynamic behavior of the fire in the VR model. Using a VR training system crew members can be trained in a safe and controlled environment, which effectively simulates the challenging and hazardous conditions of a real fire emergency in various scenarios. In addition, the trainees can practice different firefighting techniques and strategies on the actual layout of the marine structure or vessel, i.e. tryout different fire extinguishing materials, apply different firefighting equipment, thus accumulate knowledge and experience without exposing themselves to real danger.

A CFD and VR integration methodology for development of improved fire hazard marine training, comprising of ship engine room vector and bitmap model generation, CFD fire behavior analysis, results validation and CFD/VR integration, is presented here.

2. Methodology

2.1. Geometry modeling

A ship engine room CAD model, comprising of two main and two backup engines, two generators and various auxiliary equipment, has been built and then loaded to the SMARTFIRE case specification tool. The dimensions and layout are shown in figure 1.

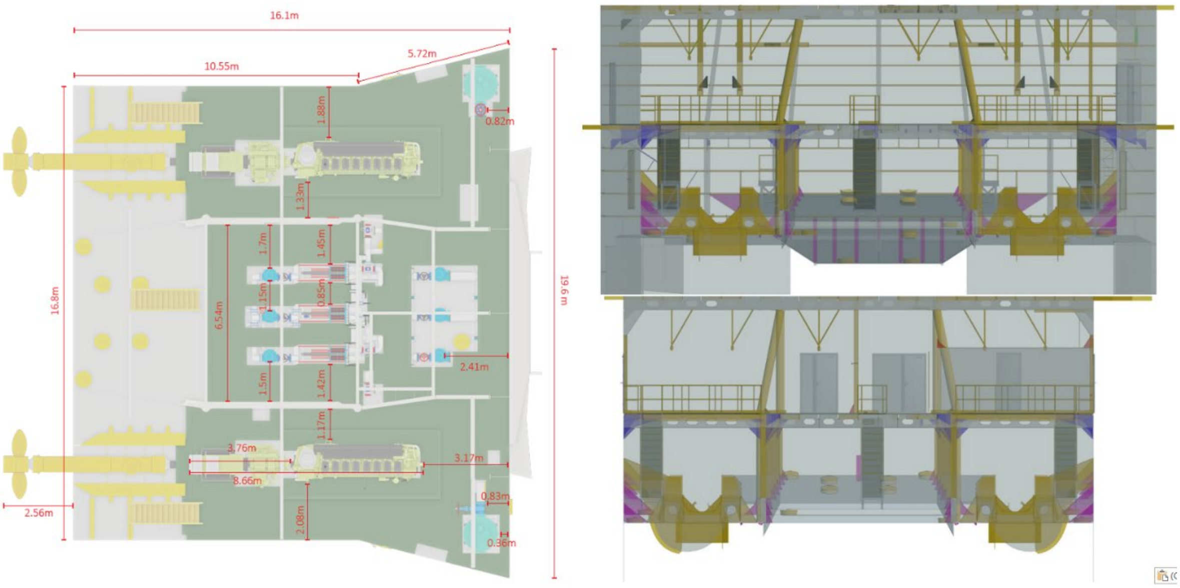


Figure 1. Ship engine room CAD model

2.2 CFD fire model

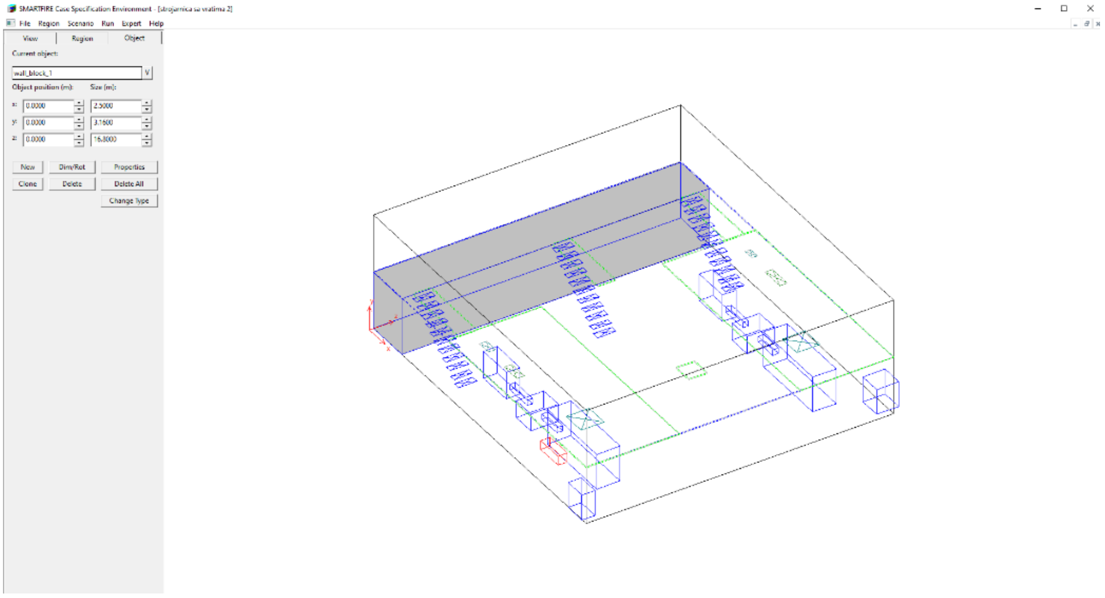
As fire and smoke in real life behave as a fluid, Computational Fluid Dynamics (CFD) approach in best suited to physically model fire (Solmaz and Van Gerven 2022). The CFD model must be based on fluid dynamics simulation of fire spreading, heat transfer a combustion of the material present in the environment, accurate representation of the environment geometry including the boundary conditions (temperature, humidity ventilation outlets etc.).

An advanced CFD fire simulation environment SMARTFIRE (Greenwich), developed by the Fire Safety Engineering Group (FSEG) at the University of Greenwich, is used to simulate fire in a ship engine room. The definition of a CFD simulation fire model consist of the following steps (Galea and Patel 2013):

1. Pre-Processing
    1.1. designing the case scenario,
    1.2. defining environment specificities,
    1.3. mesh definition and generation)

2. CFD Computational Analysis
    2.1. solution process parameters definition calculation
    2.2. run-time data generation,
    2.3. results data generation.
3. Post-processing
    3.1. data visualization
    3.2. results analysis.

The previously developed engine room CAD model has been imported to the SMARTFIRE scenario designer and case specification tool and used as definition of geometrical boundary conditions. The software's Case Specification Environment is then used for advanced configuration (physics options, transient effects, detailed object configuration) and meshing. The meshing strategy and parameters are defined based on the engine room geometry type, additional physical features as walls, vents, inlets, outlets, fans etc. as shown in figure 2.



SMARTFIRE Case Specification Environment - [strojarnica sa vratima 2]

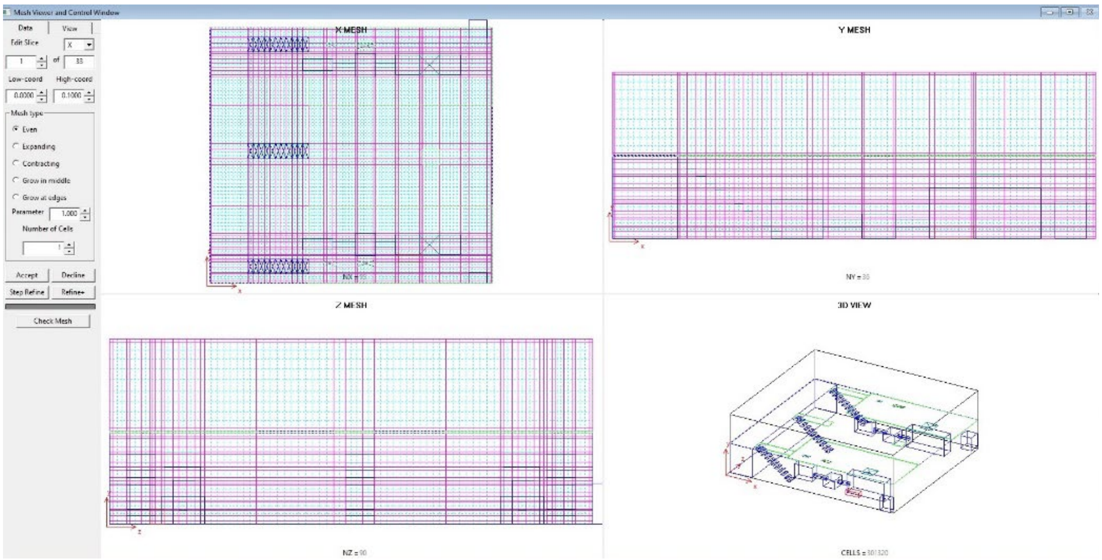
Current object: wall_block_1

Object position (m): x: 0.0000 y: 0.0000 z: 0.0000

Size (m): x: 2.5000 y: 3.1600 z: 16.8000

Figure 2. Engine room in SMARTFIRE

The mesh consisted of 301320 cells (elements) defining the domain for the CFD analysis, figure 3.



Mesh Viewer and Control Window

Edit Slice: X

1 of 33

Low-coord: 0.0000 High-coord: 0.1000

Mesh type: ● Even ○ Expanding ○ Contracting ○ Grow in middle ○ Grow at edges

Parameter: 1.000

Number of Cells: 1

NX = 93

NY = 36

NZ = 90

CELLS = 301320

Figure 3. Meshed environment

Next, a fire scenario and fire model are defined. The fire source can be simulated using a volumetric heat release rate or as a mass source of combustible material. The later was used in this case, resulting in a modeled fire with characteristics shown in table 1.

Table 1. Fire properties.

Property	Value	Units
Peak fuel output	0,0898201	kg/s
Total fuel	8,9865	kg
Equivalent peak heat output	4491	kW
Equivalent total heat output	449,33	MJ
Equivalent maximum rate of heat rise	59,8	kW/s
Equivalent average heat output	1497,75	kW
Theoretical peak smoke output	0,0013473	kg/s
Total smoke	0,134798	kg

The initial location and size of the fire is defined during the geometry input phase (red outlined block in figures 2 and 3). The solver accounts for all burnable material in the environment. All geometry surfaces have combustion properties attributes (surface ignition temperature, flame spread rate, critical temperature and critical heat flux) assigned to them, so surface heat flux exposure, pyrolysis front and flame envelope propagation can be used to determine the spreading dynamics of the fire in the engine room. All the combustible material becomes new fuel for the fire during time. A so called, simple fuel generation rate governing quadratic equation is used as a fire growth model, in the form of:

$$P = 10^{-6}\, t^2, \tag{1}$$

where:

- P fuel generation rate
- t – time, seconds.

The CFD engine component of SMARTFIRE is a C++ code based that uses a 3D unstructured mesh enabling irregular geometries to be meshed. The tool uses SIMPLE pressure correction algorithm and can solve coupled turbulent (two equation k-epsilon closure with buoyancy modification) or laminar flow problems under transient or steady state conditions (Ewer et al. 2013). The basic physical rules used during calculations are mass, momentum and energy conservation laws. The dynamic movement of smoke is calculated using the buoyancy modified two-equation (k-ε) turbulence model (Ewer et al. 2013). Heat transfer and energy balance are considered by convection (transport equations) and radiation modeling (radiosity, the Six-Flux Radiation model and Multiple Ray Radiation models).

The analysis parameters considered are time-dependent temperature and smoke density at various points throughout the entire engine room volume. This data is to be used as input for modeling of fire propagation it the VR environment.

3. Results

3.1 Virtual reality integration

The engine room CAD model has been converted to a virtual environment in Unreal Engine. The results are illustrated in figure 4.

Figure 4. Ship engine room in the VR environment

3.2 CFD analysis

The simulation yields time dependent smoke density (concentration) and heat propagation (temperature distributions) dynamics. The evaluation of the simulation results comprises of visual analysis of the fire behavior using a software generated video animation. In this case a 10-minute analysis time period is chosen. Figure 5 shows the changes in smoke density during time using frame from the video file. For clarity of depiction, only 4 smoke density time dependent values variation have been chosen for display.

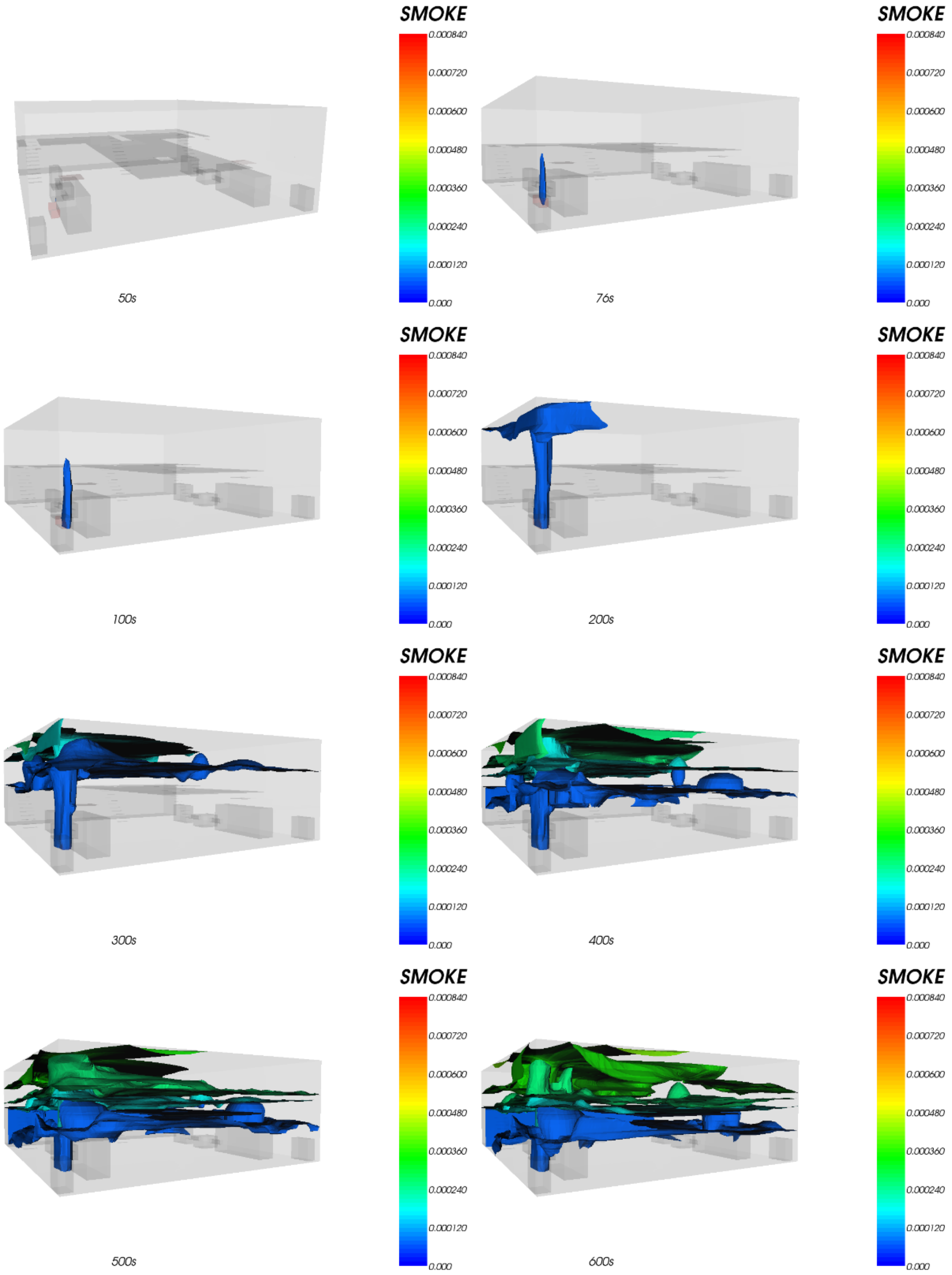


Figure 5. Smoke concentration in 10-minute period after ignition

3.3 VR environment fire display

The CFD calculation results are used to model the fire and its dynamic growth realistically. A rendering of the fire initial phase is shown in figure 6.

Figure 6. Virtual fire

4. Discussion and Conclusion

A methodology for integrating CFD and VR for enabling advanced fire hazard training possibilities in ship engine room is proposed in this paper. Fire hazard on marine structures and vessels is an extremely important issue equally for crew members, shipowners and regulatory bodies and organizations. Great care an effort is given to training procedures to raise the adequacy and quality of crew members reaction in this dangerous situation. Introducing new technologies such as VR can contribute to both safety and realism of the fire training itself. Numerical CFD analysis using well established tools yields the necessary data to enable realistic fire modeling in VR environment. Initial trails of the VR fire training system have shown promising results and elevated acceptance of the proposed training methodology on behalf of trainees.

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