Validation of the simulation tool for environmentally friendly aircraft cargo fire protection system

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Validation of the simulation tool for environmentally friendly aircraft cargo fire protection system

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Abstract. One of the objectives of CleanSky-2 project is to develop an Environmentally Friendly Fire Protection (EFFP) system (halon free fire suppression system) for the aircraft cargo hold. For this, an Aircraft Demonstrator including the cargo hold has been equipped with a nitrogen suppression system. The demonstrator is located in the Flight Test Facility low pressure vessel and can thus be subjected to realistic cruise pressure conditions and take-off and descent pressure variations. As a design tool, a zonally refined simulation model to predict the local oxygen and nitrogen concentration distribution in the cargo hold has been developed using the Indoor Environment Simulation Suite (IESS). The model allows for fast transient simulations of the suppression system operation. This paper presents a model validation case of a knockdown during cruise, followed by a holding phase and descent (repressurization of the cargo hold).

1. Introduction

A homogeneous and efficient fire suppression agent distribution inside an aircraft cargo hold is the key for protecting the aircraft from a cargo hold fire and for achieving the fire protection goals. Aircraft cargo hold fire suppression systems must provide fire protection for several hours. Thus the system must be adequate to maintain a safe fire suppressive atmosphere inside the cargo hold for the specified diversion time.

The aircraft cargo fire suppressant system has a dual phase of fire suppression, a fire knockdown phase that shall diminish fire either by cooling the fire or reducing oxygen concentration as described in Minimum Performance Standard (MPS) [1], followed by the constant metering phase to maintain fire suppressive environment inside the cargo hold throughout the flight and landing phase. In current aircrafts, both phases (i.e. knockdown phase and constant metering phase) are performed by halon bottles. However, due to high ODP of halon, airliners are looking towards halon free systems. The use of nitrogen as a suppression agent, diluting the cargo hold oxygen concentration below flammability point, is one such alternative under research within the CleanSky2 Large Passenger Aircraft Innovative Aircraft Demonstrator Platform subproject “Environmentally Friendly Fire Protection”. Within this project, a simulation toolchain is developed that predicts the agent concentration distribution within the cargo hold and a physical full scale demonstration is implemented in the Flight Test Facility, a low pressure chamber hosting the front section of a former in-service A310 including the underfloor area and forward cargo bay.

This paper presents transient validation results of a knockdown followed by a holding phase and descent.

Several modelling activities have been performed for halon replacement technology with water mist, inert gasses and solid-propellant gas-generators suppression systems [2],[3],[4][5]. These models include CFD simulations and single or two-zone models. However these models simulate agent

distribution at constant pressure, single operating points or non-locally refined. In cargo fire suppression system, the transient phase of knockdown, holding and descent have significant impact on the agent distribution inside the cargo hold. The location of air ingress ports, like the pressure management system or leakages in the cargo interiors, further influence the local agent distribution gradient in the cargo hold. Single or two-zone models are quick to simulate, however these models do not provide the suppressant distribution gradient inside the cargo hold. The CFD models provide the details of suppressant distribution gradient, however computation cost is very high especially when transient phases are considered. The IESS uses hybrid simulation approach, where high momentum flow regime close to nozzle discharge has been pre-simulated by CFD and the results of this near-field domain have been integrated with the zonal model of the cargo hold. The IESS provides an effective option for transient simulations with local resolution and good simulation accuracy.
In this paper, a validation result for such a transient simulation is shown. For this, a nitrogen based knockdown and holding system has been integrated in the Flight Test Facility aircraft mock-up. The cargo hold has been equipped with sensors to measure the local oxygen concentration. A realistic cabin pressure profile of take-off, cruise and descent is implemented. For this, the aircraft is located in a low pressure vessel, that is able to generate an ambient pressure like in cruise conditions (750 hPa, corresponding to an equivalent height of 8.000 ft.).

2. Method

The following sections describe the simulation method applied by the IESS as well as the experimental method.

2.1. Indoor Environment Simulation Suite (IESS)

The Indoor Environment Simulation Suite (IESS, Figure 1) provides indoor climate simulation using the zonal approach. In contrast to CFD or multi-zone models, the zonal modelling approach subdivides the indoor space into typically 10^2 to 10^3 zones. In addition to this airflow modelling, the IESS provides interfaces for walls, sources and sinks, radiation, conduction and species distribution. Through this, a transient, multiphysics simulation is enabled. A toolchain has been developed to ease the setup, customization and post-processing of the models.

2.1.1 IESS model generator

The IESS Model Generator is a pre-processing tool developed in C++ language. It translates a CAD model exported into the .stl format to Modelica code that can be simulated in the Modelica simulation environment [6]. This tool automatically distributes the zonal grid, attributes the adjacencies of zones and walls and provides top level parameters for easy model customization.

2.1.2. Airflow model (VEPZO)

The aim of a zonal model is to perform quick simulations of the airflow patterns and temperature distributions in an indoor space. Therefore an air volume is subdivided into several discrete zones. Zonal models are a compromise between the more complex CFD calculations and the approximation of a perfectly mixed air volume (as assumed by single node models). A new formulation of such models has been developed by Fraunhofer IBP, the VElocity Propagating ZOnal model (VEPZO model). The VEPZO model is using the airflow velocity as a property of a zone and a viscous loss model in order to better match the physics of airflows. Two main components of VEPZO model are a volume model and a flow model. The volume model considers mass conservation and conservation of enthalpy while the flow model calculates the mass flow rate from pressure difference. The advantages of the VEPZO Model are: a very small amount of information on the boundary conditions is necessary, the delivery of a local resolution of air temperatures, agent concentrations and air flow within a domain as well as moderate computational cost, which finally allows parametric variation also for transient situations [7].

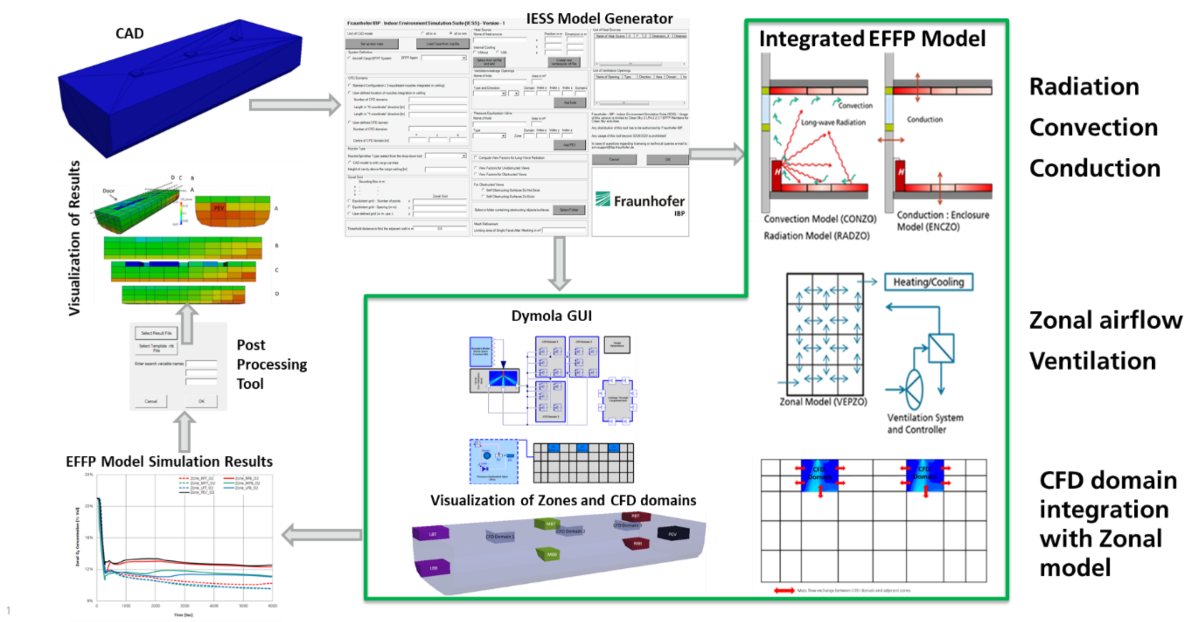

Figure 1: Indoor Environment Simulation Suite (IESS)

2.1.3. Longwave radiation model coupled with zonal model (RADZO)
Determination of the long-wave radiant heat exchange between surfaces requires the view factor matrix. The simplified radiation approach (i.e without computation of view factors) distributing radiation proportionally on surfaces may result in high errors of surface temperatures due to wrong estimation of view factors, which can further cause error in energy balance. Furthermore the wrong estimation of surface temperature leads to error in estimated air temperature stratification which further leads to error in airflow pattern and concentration of agents in each zone. To avoid the inaccuracy of the simplified radiation model more detailed long-wave radiative heat exchange model was developed. The radiation model coupled with zonal model (RADZO) computes view factors between finely refined surface mesh elements and allocates accurate view factors to the course zonal grid mesh. The RADZO model calculates long wave radiant heat exchange between "n" surfaces [8].

2.1.4. Conduction through enclosure model (ENCZO)
Enclosure models are based on a suite of thermal capacitances and thermal resistances. The parameterization of these models yields the different materials that can be used. Enclosure model can be 1D, 2D or 3D. The hybrid modelling approach allows coupling high resolution radiation models with a course grid zonal model as well as 1D or 2D enclosure model with 3D airflow model and radiation model. The enclosure model can be simulated as single layer enclosure or multiple layer enclosure. The model generator exports a template wall model in the initial code, that is later customized to the actual wall layers by the modeller.

2.1.5. Convection model coupled with zonal model (CONZO)
Since the boundary layer flow in the IESS tool chain is not resolved, the numerical determination of the convective heat transfer coefficient h_c is not possible. This depends on the orientation of the surfaces, the temperature difference to the air and the prevailing flow. The IESS-CONZO library therefore provides a collection of correlations for various installation situations that determine the h_c value, which calculate the h_c value based on the local air exchange in a zone [9].

2.1.6. CFD domain

The CFD domain was specifically developed for increasing the accuracy of the zonal modelling approach for the cargo fire suppression application. The inerting agent typically is provided from pressurized bottles and distributed through nozzles in the ceiling of the cargo hold. This results in local high momentum flow around the inlet nozzle. The scale of such flows is far smaller than the typical size of a zone, however these determine the flow field in the entire compartment. In order to maintain the high simulation speed possible with the zonal modelling approach, the concept of CFD zone has been selected. In this concept, the nearfield around the injection nozzle is simulated by CFD. Due to the small size of this domain, the CFD computation converges relatively fast. Sizing criteria of CFD domain depends on the cargo hold architecture and nozzle type. The simulation result is used as a supply / sink boundary condition in the zonal model in order to transmit the effect of the nozzle to the large space of the cargo hold.

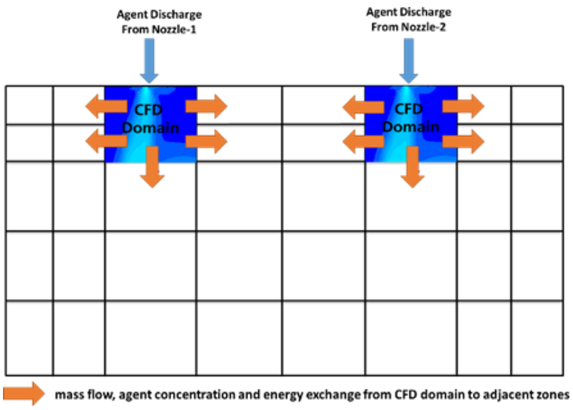

Figure 2: Empty Cargo Hold Zonal Model Coupled with two CFD Domain

To numerically solve the high momentum flow and turbulent eddies in the vicinity of the agent discharge, the CFD simulation of Airbus single aisle nozzle and A350 nozzle have been performed. Figure 2 shows schematic of CFD domain (volume around the nozzle discharge) coupled with zonal model. Each block around the CFD domain represents a zone (single node volume). These zones are connected further with adjacent zones through flow resistance models.

2.1.7. Integrated Cargo Hold Model

Figure 3 shows the integrated EFFP cargo model of the A310 forward cargo hold generated by IESS model generator. Each block represents an air volume which is further connected to flow model, leakage model or convection model depending on the location of the air volume. It contains three discharge nozzles and a leakage profile along the periphery of the door. The pressure management system (PMS) model is connected to the AFT wall of the cargo hold. The boundary condition model is connected with the nozzle distribution model. This nozzle distribution model distributes the flow of discharge agent to the zone adjacent to the CFD domain through correlations developed by CFD studies of each type of nozzle.. This model was used to make parametric study for different discharge profiles, different descent profiles and different fire suppression strategies [10] and is now validated with experiments.

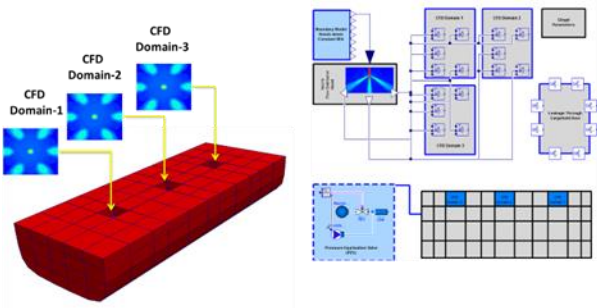

Figure 3: Integrated EFFP cargo model (geometrically correct cargo zonal model visualization – left, generated model GUI – right)

2.2 Test setup

Experiments were conducted in the A310 mock-up of the Flight Test Facility (FTF) located at the Fraunhofer-Institute for Building Physics in Holzkirchen, Germany. A schematic view of the FTF is presented in Figure 4. The front part of a former in service twin-aisle long range aircraft containing cabin, crown, galley, cockpit, avionics bay, cargo and bilge is placed in a low pressure vessel. Through the variation of the pressure in the vessel, the cabin pressure evolution of a real flight can be simulated. The mock-up is equipped with a ventilation system to replicate the ECS. In order to generate a similar heat load in the cabin, thermal dummies are placed on the seats. Through this, a realistic airflow pattern in the cabin is ensured. Recirculation air is aspired from the triangle area and exhaust air is ejected from the bilge.

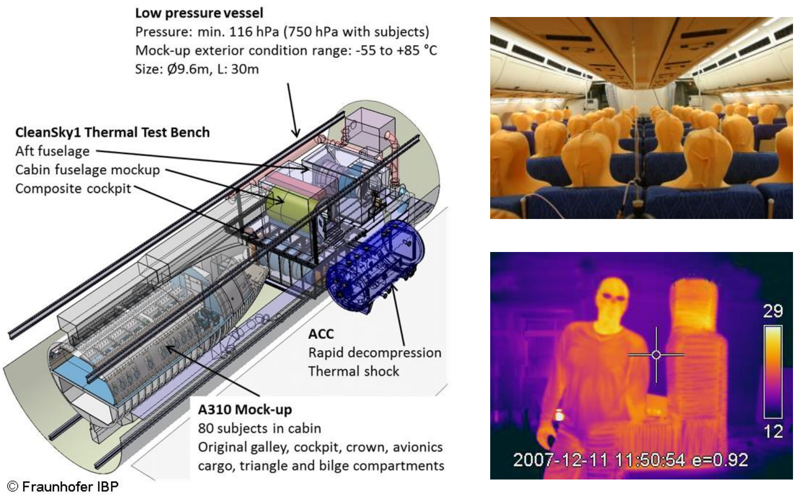

Figure 4: Overview of the Flight Test Facility, cabin equipped with thermal dummies and IR-picture of human compared to dummy

2.2.1. Cargo bay refurbishment

For the environmentally friendly fire protection system tests, the cargo bay was refurbished with original lining (Figure 5, left). The main items of the refurbishment are:

- Original lining and ceiling panels from ordered spare parts and A350 production series (except the center line, where Plexiglas was used to keep the agent distribution line visible)
- Sealing to meet airtightness requirements
- Integration of high pressure piping and three injection nozzles with protective cavity in the ceiling
- Integration of the pressure management system allowing for the equalization of pressure between cargo bay and adjacent bays to avoid opening of rapid decompression panels.
- Cargo door leakage simulation according to the MPS standard [1] to simulate the airflow leaking through the door seal in flight
- Distributed oxygen concentration measurement to assess the local distribution

The nitrogen needed to perform the inerting task was taken from industrial bottles placed outside the low pressure vessel. The bottles were on a scale to measure the consumed amount of nitrogen. Furthermore, an On-Board Inert Gas Generating System (OBIGGS, Figure 5, right) demonstrator, derived from the fuel tank inerting technology, has been integrated in the flight test facility. The OBIGGS consists of selective air separation membranes that separate hot pressurized air into a nitrogen rich fraction used for cargo bay inerting and an oxygen rich fraction dumped overboard.

Figure 5: Refurbished cargo hold (left) and integrated OBIGGS (right)

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2.2.2. Typical test conduct

At the beginning of the test, heat dummies in the cabin and the cabin ventilation system are turned on. Then, the pressure in the low pressure vessel is reduced from ambient pressure to 750 hPa (8000 ft.). The leakage flow simulation through the cargo door is activated. Due to this suction, air from the underfloor area enters the cargo bay through the pressure management system and through leakages in the enclosures. When pressure, airflow rates and temperatures are stabilized, the test begins:

- Phase 1: Knockdown
  A large amount of nitrogen is supplied in a short timeframe to bring down the oxygen concentration in the cargo hold below flammability point
- Phase 2: Holding
  A metered flow of pure bottled nitrogen or nitrogen enriched air provided from an On-Board Inert Gas Generating System (OBIGGS) is supplied. This flow compensates for fresh air ingress through cargo leakages
- Phase 3: Descent
  The descent phase is critical in terms of oxygen concentration due to the repressurization from 750 hPa to ground pressure. This repressurization is performed by supplying ambient air. Thus, a noticeable amount of fresh air enters the cargo hold and increases the oxygen concentration. There are two strategies to cope with this, either the holding system increases its flow accordingly or the oxygen concentration is kept sufficiently low prior to descent to meet the requirement at end of descent.

3. Model validation results

In this section, the test and model validation results are presented.

3.1 Test sequence and result

For model validation, the test sequence set out in Table 1was performed. It simulates a normal flight where the fire suppression system gets activated until landing at the airport.

Table 1: Performed test sequence

Test sequence	Start in min	End in min	Performed step
Ground	0	5	normal operation of cabin
Takeoff	5	23	reduction of pressure to 750 hPa
Normal cruise	23	37	normal operation of cabin
Knockdown (KD)	37	41	supply of 41.5 kg of nitrogen from bottles
Holding without leakage simulation	41	51	supply of 9 l/s nitrogen enriched air with residual O_2-concentration of 7-8 %
Holding with leakage simulation	51	60	supply of 9 l/s nitrogen enriched air (NEA) from OBIGGS with residual O_2-concentration of 7-8 % Activation of cargo door leakage at 9 l/s
Descent	59	68	Re-pressurization to ambient pressure, leakage and NEA flow maintained
Ground	68	70	NEA flow and leakage turned off

The pressure chart is shown in Figure 6 (left). To increase the pressure in the cargo bay from 750 hPa to 940 hPa, an air amount of approx. 11.7 m³ is needed. Taking into account the time of 9 min to reach ground pressure, this corresponds to an average air ingress rate of 21.6 l/s and thus noticeably higher than the leakage rate though the door seal. Therefore, the re-pressurization phase leads to a higher gradient of oxygen concentration throughout the cargo hold, whilst the distribution is uniform in the rest of the experiment (Figure 6, right). At the back wall, the pressure management system allowing air to ingress the cargo hold is located, therefore the local concentration becomes higher in this region during descent. The experiment shows that the OBIGGS stably delivers NEA with 7-8 % residual oxygen concentration throughout the mission profile. The effect of applying the door leakage is hardly visible in the test data.

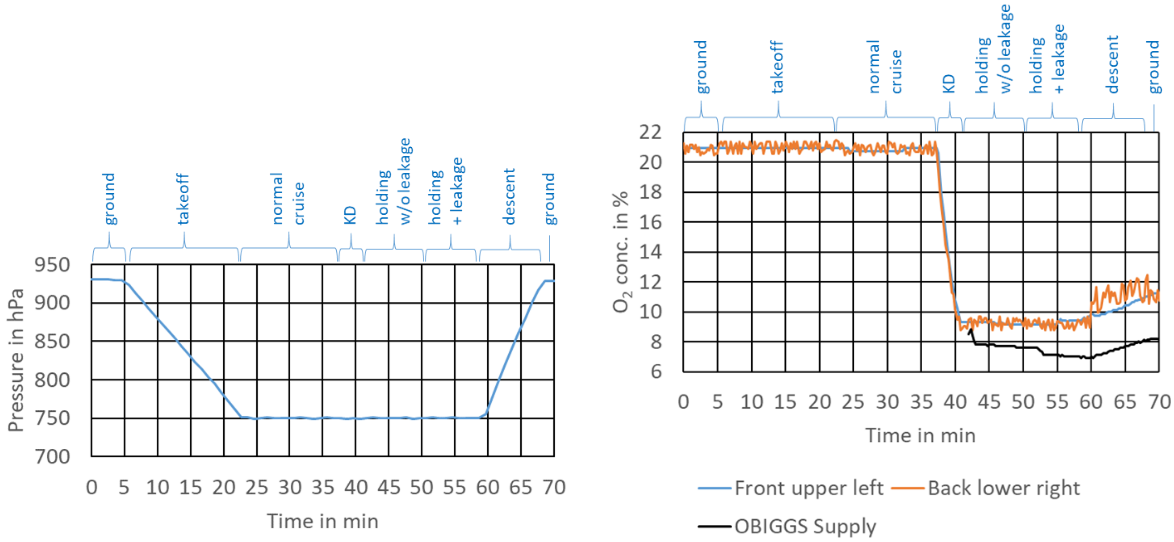

Figure 6: Left: Pressure boundary condition in test, Right: Evolution of cargo hold oxygen concentration in the extremities of the bay

The same mission profile, starting with knockdown and ending with landing, was applied to the simulation model (Figure 7). The zonal modelling approach shows to well predict the magnitude of the oxygen concentration gradient and the oxygen concentration levels within the cargo hold. The deviation is less than 1%. The dynamic response of the simulation model shows to be faster than the actual test data substantiates. One reason could be time delay in the sensors to react to such changes. A plot of the oxygen distribution during descent in the cargo hold is shown in Figure 8.

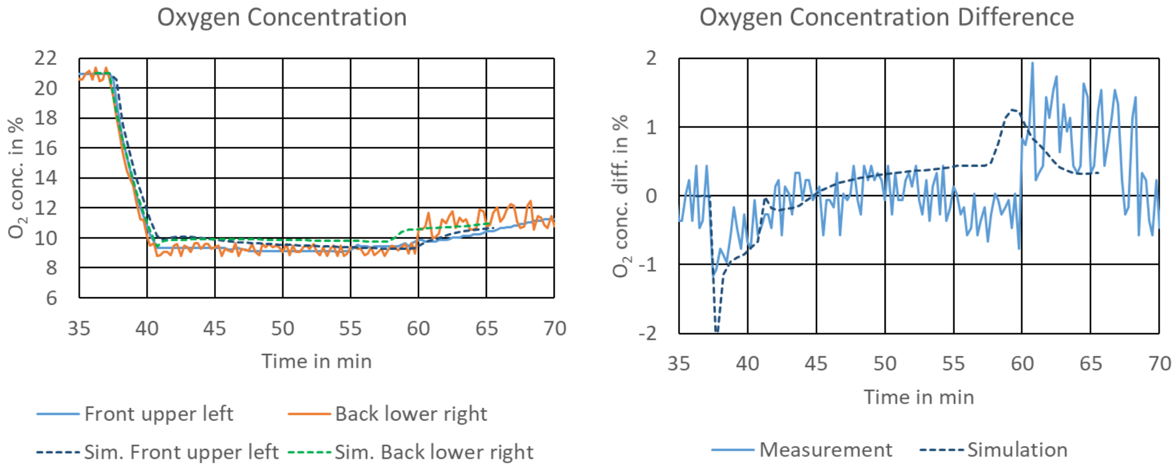

Figure 7: Left: Comparison of measured (bold) and simulated (dotted) oxygen concentrations. Right: Oxygen concentration difference between the extremities

4. Conclusion

This paper presented a model validation case for the agent distribution of environmentally friendly fire protection systems. The validated model can now serve to predicts critical load cases for the cargo hold, the effect of geometry change, e.g. when considering a different aircraft size and is extendable for other agents. Through this approach, a transient design tool for the cargo fire protection mission has been developed.

The presented example considers the empty cargo hold. Future research will even consider the effect of containers placed in the cargo hold leading to obstruction of the airflow paths.

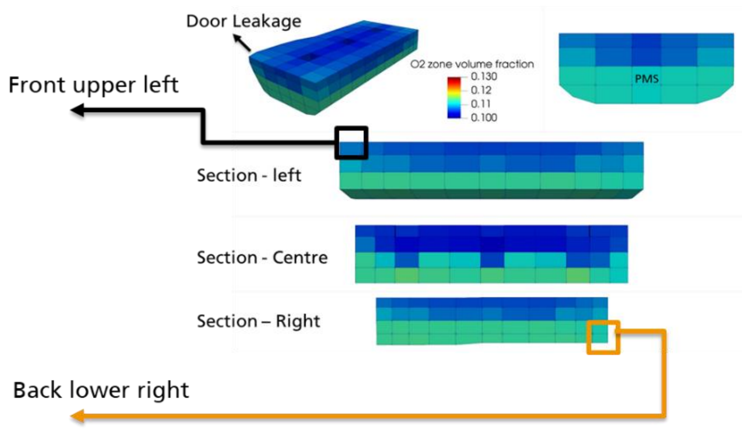

Figure 8: Simulated oxygen gradient during descent

5. Acknowledgements

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