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VEHICLE-DECK FIRES ABOARD ROPAX SHIPS: A COMPARISON BETWEEN NUMERICAL MODELLING AND EXPERIMENTAL RESULTS

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ABSTRACT

According to an official study conducted by the IMO Correspondence Group on Casualty Analysis concerning the fire incidents that occurred on the vehicle-decks of RoPax ships, covering the period from 1994 to 2011, it has been shown that a very serious incident has occurred every other year since 2002, resulting in six constructive total losses. The results of this review shed the light on the need to investigate the application of fire models to simulate fire scenarios that may occur on the vehicle-decks aboard RoPax ships. This will be very useful for the RoPax designers who are willing to introduce new technologies or deviate from the current prescriptive regulations of fire safety design in order to reduce the risk of such catastrophic accidents. The aim of this paper is to present the results of a comparison between the predictions of three different fire models and the experimental results of a model-scale fire test that represents a fire scenario on a vehicle-deck aboard a RoPax ship. A statistical analysis technique was used to illustrate the ability of each fire model to predict five outputs of concern. The main conclusion of this comparison is that there is always an optimal fire model that can predict one or more of the five outputs of concern with results in good agreement with the measured values.

Keywords: Vehicle-deck fires; RoPax ships; zone models; field models; model-scale fire tests

INTRODUCTION

Fires aboard RoPax ships are gaining increased interest, and cause the development of new rules & regulations as well as new methods to reduce the risk of fires on board such vessels which is of great importance. Statistical analyses of the records of previous ship accidents covering the periods from 1996 to 2005 (Karlsson and Ulfvarson 2008) and from 2000 to 2012 (Eleftheria et al. 2016) showed that fire is the second frequent type of accident that resulted in the total loss of RoPax ships. Moreover, Wikman et al. (2017), in a very recent study commissioned by the European Maritime Safety Agency, EMSA, reported that around 30% of the fires that occurred aboard RoPax ships during the period from 2002 to 2015 were originated on the vehicle-deck and that about 90% of these accidents are caused by the cargo being transported. Furthermore, considering the number of fatalities that occurred, Karlsson and Ulfvarson (2008) and Eleftheria et al. (2016) have illustrated that RoPax ships were the leaders among all other ship types that have been analysed.

DNV GL is one of the leading classification societies that reported the growing safety concern of fire incidents on vehicle-decks of RoPax ships, Vehicle carriers and general Ro-Ro cargo vessels (DNV 2005), (DNV GL 2016). In their older report (DNV 2005), 25 fires on vehicle-decks (7 of them occurred aboard RoPax ships) between 1990 and 2003 have been identified. In their recent report (DNV GL 2016), 35 fires on vehicle-decks (18 of them occurred aboard RoPax ships) between 2005 and 2016 have been identified. The difference between the findings of the two reports has been clarified by a larger fleet, better accident reporting and most importantly by the more recent fires that have occurred aboard RoPax ships. Figure 1 shows a photograph of one of the most recent fire accidents that occurred on the vehicle-deck of the Italian-flagged RoPax ferry “Norman Atlantic” in December 2014.

Fig. 1. Smoke plumes from the Italian-flagged RoPax ship “Norman Atlantic” that caught fire in the Adriatic Sea on December 2014 (Taylor 2015)

Vehicle-decks can be classified into three types: closed vehicle-decks, open vehicle-decks (opening on sides and at one or both ends) and weather vehicle-decks (no overhead deck). DNV GL (2016) reported that fires resulted in many of the recorded total losses of RoPax ships were originated on open vehicle-decks. The report has clarified this by the fact that open vehicle-decks are well-ventilated and the overhead steel decks reflect heat and accumulate fire effluents. It is worth mentioning here that the fire accident aboard Norman Atlantic has originated at one of her open vehicle-decks, where the temperature was estimated to be more than 1000°C (Croccolo 2015). Moreover, DNV GL (2016) also reported that some of the major fire accidents that occurred aboard RoPax ships were due to fires originated on closed vehicle-deck spaces.

Several literature works have estimated the frequency of occurrence of fire accidents on vehicle-decks of RoPax ships. Table 1 shows a list of the available source literature, the covered periods and the estimated frequencies. These estimates highlight once more the recent increase in the number of vehicle-deck fires aboard RoPax ships and an urge of the interested-parties (especially in the research arena) to gather their efforts to improve the current situation. Improving the fire safety design and utilising the state-of-the-art technology in novel designs could be one way to improve the vehicle-deck fires issue aboard RoPax ships.

Tab. 1. List of the estimated frequencies of fire accidents on vehicle-decks of RoPax ships found in the literature

Source Literature	Period Covered	Estimated Frequency (per ship-year)
(DNV Technica 1996)	1978–1994	8.00E–04
(DNV 2005)	1990–2003	5.83E–04
(Konovessis and Vassalos 2008)	1994–2004	1.02E–03
(DNV GL 2016)	2005–2016	2.00E–03
(Wikman et al. 2017)	2002–2015	5.79E–03

The fire safety design of all types of ships, including RoPax ships, is governed by Chapter II-2 of the SOLAS convention. In its revised copy, in force, since July 01, 2002, SOLAS Chapter II-2 has a new regulation (Regulation 17) that sets out a methodology for approving novel (alternative) designs that deviate from the prescriptive regulations. This methodology allows the use of fire and evacuation simulation models as consequence analysis tools to carry out the approval process. Numerous literature works have tested and used some of these models within a comparative analysis methodology in several studies concerning the fire safety design of both passenger and RoPax ships (Salem 2007; Salem 2010; Salem and Leheta 2011; Salem 2013; Salem et al. 2013; Salem et al. 2016; Salem 2016; Azzi 2010; Azzi and Vassalos 2010; Azzi et al. 2011; Themelis and Spyrou 2012). The results of these studies have shown the capability of the tested consequence analysis tools in assessing the level of fire safety of the ship compartment under consideration. It should be noted here that there is a lack of published research on the utilisation of fire simulation programs in simulating vehicle-deck fires aboard RoPax ships. This, of course, highlights the significance of examining the performance of these programs in simulating this important type of fires.

In general, there are two types of fire simulation models: zone models and field (CFD) models. On one hand, zone models divide the compartment of fire origin into a limited number of control volumes (zones). The widespread type is the two-zone model, where the fire compartment is divided into an upper hot layer (zone) and a lower cold layer. The prime merit of this type is the fact that the computational time for the solution is in the order of seconds, while its main drawback is the generality and uncertainty of its results (Averill 1998). On the other hand, field (CFD) models divide the fire compartment into several tens of thousands of control volumes or zones, hence present a more accurate scientific approach. The most significant limitations of field models are cost and time. Salem (2007) identified the existence of 56 zone models and 26 field models. The most widespread zone models in use in many practical applications are CFAST (Peacock et al. 2016) and BRANZFIRE (Wade 2004), while the most popular and well-founded field model is the Fire Dynamics Simulator, FDS (McGrattan et al. 2017).

The performance of a fire model is always examined by direct comparison of model outputs with experimental data. These data are usually obtained from either large-scale or model-scale fire tests. A literature survey was conducted to search for published experimental data of either large-scale or model-scale vehicle-deck fire tests. A limited number of such data were found. SP Technical Research Institute of Sweden (formerly known as SP Swedish National Testing and Research Institute) is an active firm in the area of fire testing. The firm has conducted and published several large-scale and model-scale RoPax vehicle-deck fire tests (see e.g., Arvidson 1997; Larsson et al. 2002; Arvidson 2009; Arvidson 2014).

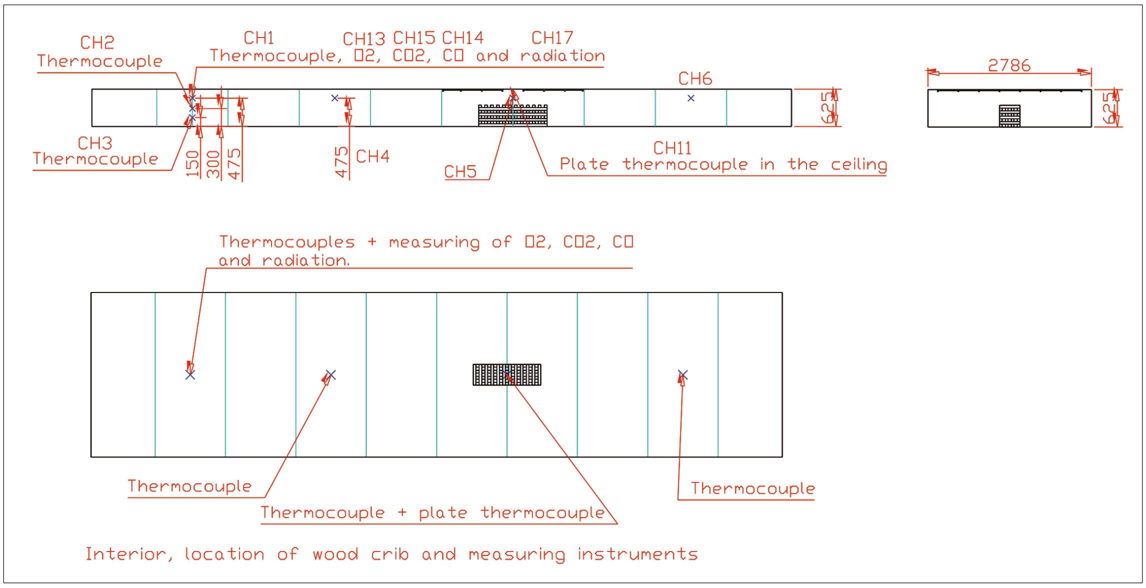

Fig. 2. Schematic drawing of the scale model (Larsson et al. 2002)

AIM AND OBJECTIVE

The aim of the work outlined in this paper is to present the results of a comparison between two fire models of the zone type (CFAST and BEANZFIRE) and one fire model of the field type (FDS) with the experimental results of one of the model-scale fire tests on vehicle-deck aboard a RoPax ship, which was carried out by the SP Swedish National Testing and Research Institute (Larsson et al. 2002). Keeping in mind the fact that no zone fire model is best suited for all applications (Walton 1995) and the fact that field models are more precise than zone models, the main objective of this study is to demonstrate the ability of each of the three fire models to predict the environment inside a vehicle-deck space onboard a RoPax ship in the event of a fire outbreak.

SUMMARY OF THE EXPERIMENTAL TEST SETUP

The SP Technical Research Institute of Sweden conducted a series of model-scale fire tests with the aim to investigate the effect of different ventilation conditions on fire development in a vehicle-deck onboard a RoPax ship. A complete description of the fire tests can be found in (Larsson et al. 2002). In this section, only a brief description of the experimental test setup is presented.

Larsson et al. (2002) explained that the model used in the model-scale fire tests was built on a small scale of 1:8. The model has a rectangular cross-section of 11.425 m in length, 2.786 m in width and 0.625 m in depth (see Figure 2). This would correspond to a full-scale vehicle-deck of approximately 91×22×5 min size. The model was equipped with a stairwell, ventilation shaft, large door openings, drainage scuppers, and a ventilation fan. The walls, ceiling, and floor of the model were constructed of 12 mm nominally thick Promatect–H boards (a fire-resistant material) with thermal properties as shown in Table 2.

Tab. 2. Thermal properties of the Promatect-H board material

Material	Density (kg/m^3)	Thermal Conductivity (W/m K)	Specific Heat (kJ/kg K)
Promatect-H Boards	870	0.190	1.130

Moreover, Larsson et al. (2002) clarified that the experiment has used the wood crib as a source of fire; and the peak value of the heat release rate (HRR) was measured in a free burning test and found to be around 400 kW, which is an equivalent to a burning truck with a fire output of approximately 70 MW in full-scale. By varying the model parameters, Larsson et al. were able to perform 18 tests. Among these tests, the author of this study has chosen "Test # 04" to conduct the comparison between the three fire models and the experimental results (the test number used here corresponds to the test number mentioned in (Larsson et al. 2002)). In Test # 04, the ventilation shaft and the drainage scuppers were left open to maintain a natural ventilation condition. During the test, the fire was self-extinguished due

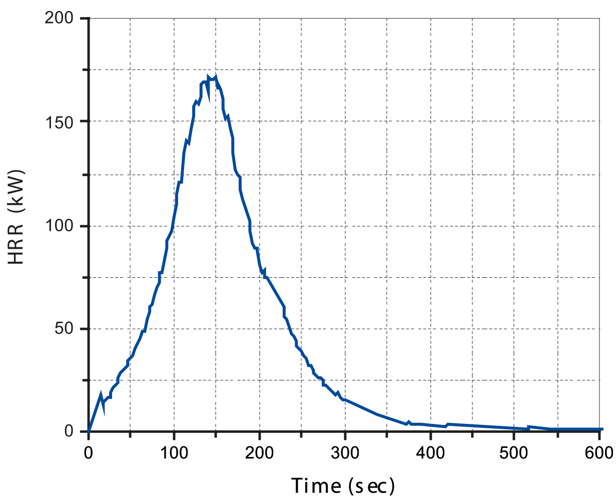

Fig. 3. Measured HRR-time history of Test # 04

to a low oxygen concentration in the hot gas layer formed near the model ceiling. This condition occurred immediately after the hot gas layer reached the floor level of the model, where oxygen concentration within the layer was measured and found to be between 13 and 17 percent. Figure 3 shows the measured HRR-time history for Test # 04.

NUMERICAL MODELLING OF THE SELECTED MODEL-SCALE FIRE TEST

Two zone fire models, namely *CFAST 7.2.0* (Peacock et al. 2016) and *BRANZFIRE 2012.01* (Wade 2004) and one CFD fire model, namely *FDS 6.5.3* (McGrattan et al. 2017), have been selected to simulate the fire scenario representing the selected model-scale fire test, Test # 04. For this purpose, the input file for each fire model was carefully prepared using the data provided from the experimental setup. Table 3 summarizes these input data. The hot layer temperature, the smoke layer height, and the concentrations of oxygen, carbon monoxide & carbon dioxide were the output of interest which were decided to be predicted by each of the three fire models and compared with the experimental results.

Tab. 3. Summary of the input parameters

Input Parameter	Value
Compartment Dimensions (L×W×H)	11.425×2.786×0.625 m
Boundary Surface Material	12 mm thick Promatect-H Boards (for specs see Table 2)
Fire Source	Actual HRR from the experimental result was used in the simulation (see Figure 3)
Vents	Ventilation shaft was simulated by assuming a horizontal opening at the ceiling (Area = 0.02 m^2)
Ambient Conditions	Interior Temp. = 20°C Exterior Temp. = 15°C Relative Humidity = 65%

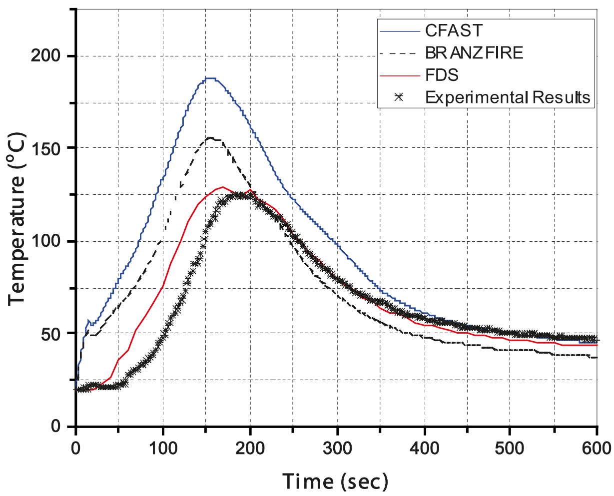

Fig. 4. Predicted and measured hot layer temperatures

Figures 4 through 8 show the results of the comparison between the values of the 5 outputs of interest, which were predicted by the two zone fire models and the field model, and those measured by the experimental model test (Test # 04).

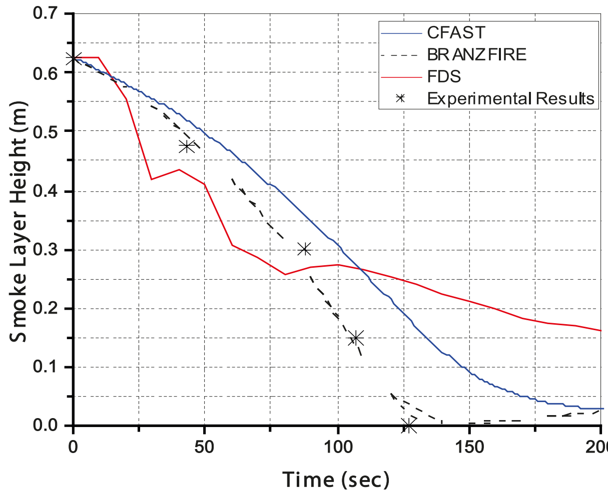

Fig. 5. Predicted and measured smoke layer heights

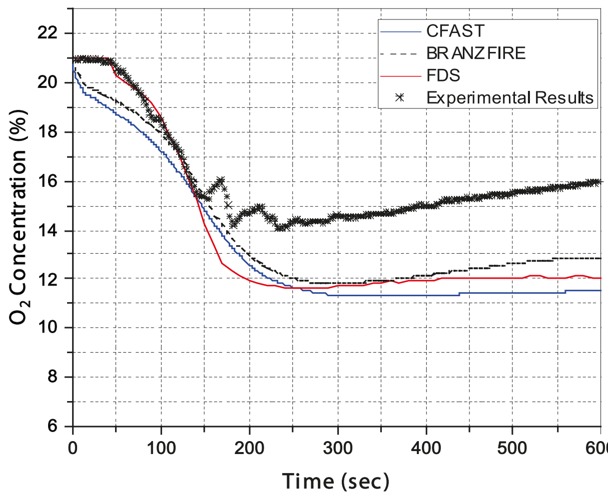

Fig. 6. Predicted and measured oxygen concentration

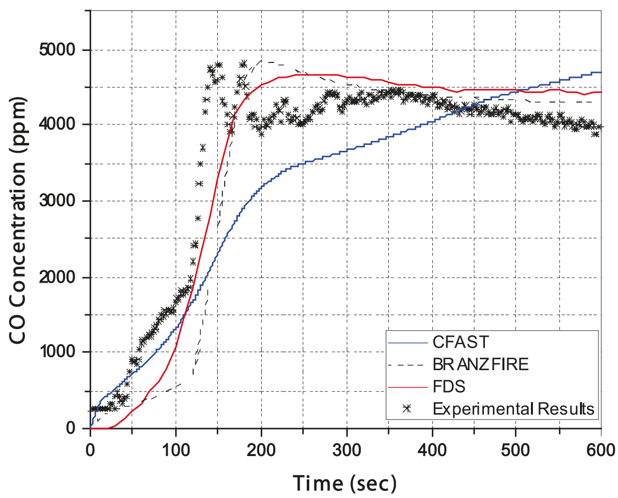

Fig. 7. Predicted and measured carbon monoxide concentration

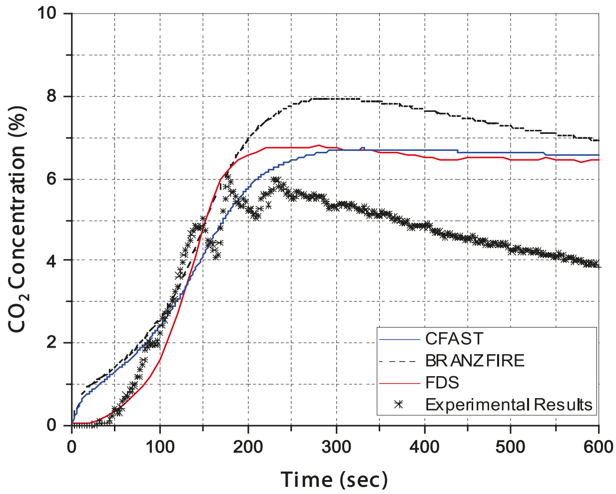

Fig. 8. Predicted and measured carbon dioxide concentration

To evaluate the predictive power of the three fire models, the author decided to use an approach introduced by Kobayashi and Salam (2000) and called mean squared deviation (*MSD*). In their work, Kobayashi and Salam (2000) highlighted the usefulness of their approach in quantifying the deviation of model outputs from measurements and its ability in locating possible cause(s) of the deviation. A brief description of the *MSD* approach is presented below.

The difference between the predicted values from simulation (x_i) and the measured values from the experiment (y_i) for (n) measurements is calculated with the *MSD* as:

$$MSD = \frac{1}{n} \sum_{i=1}^{n} (x_i - y_i)^2 \tag{1}$$

The *MSD* can be divided into three components, namely:

$$MSD = SB + SDSD + LCS \tag{2}$$

where, *SB* is the squared bias, given as;

$$SB = (\bar{x} - \bar{y})^2 \tag{3}$$

where, $\bar{x}$ and $\bar{y}$ are the mean of x_i and $y_i (i = 1, 2 \ldots n)$, respectively.

SDSD is the squared difference between predicted and measured standard deviations given as;

$$SDSD = (SD_s - SD_m)^2 \tag{4}$$

where, SD_s and SD_m are the standard deviations of the simulation and the measurement, respectively. The value of *SDSD* measures the difference of the magnitude of fluctuation between measured and predicted values.

LCS is the lack of positive correlation weighted by the standard deviations of simulation and measurement given as:

$$LCS = 2\ SD_s + SD_m\ (1 - r) \tag{5}$$

where: r is the correlation coefficient between the simulation and the measurement. *LCS* measures the pattern of fluctuation between predicted and measured values.

According to Kobayashi and Salam (2000), when comparing the simulation to the measurement, the lower the value of the *MSD*, the closer the simulation is to the measurement. Moreover, a smaller value of *SB* shows good agreement between the predicted and measured means. A smaller value of *SDSD* indicates the ability of the model to simulate the magnitude of fluctuation between the (n) measurements, while a smaller value of *LCS* shows the ability of the model to simulate the variation pattern of the (n) measurements.

Figures 9 through 13 show the results of the comparison of the *MSD* and its three components (*SB*, *SDSD* & *LCS*) for the predicted values of the 5 outputs of interest, which predicted by the three fire models.

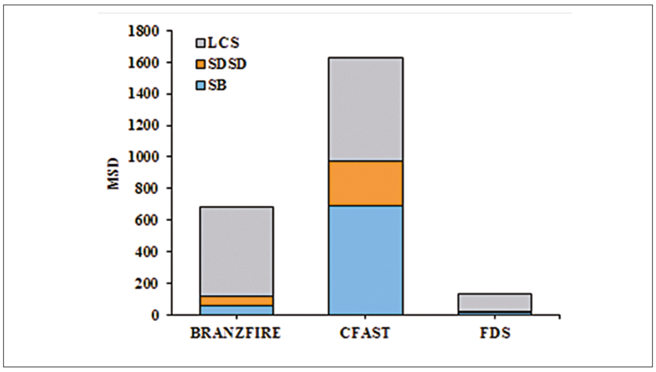

Fig. 9. Comparison of the MSD and its components for the three fire models for hot layer temperature predictions

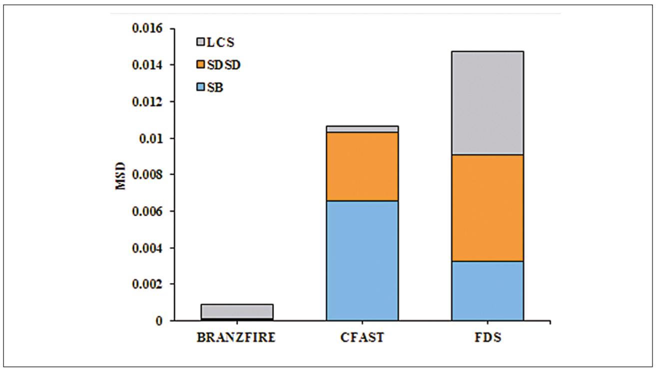

Fig. 10. Comparison of the MSD and its components for the three fire models for smoke layer height predictions

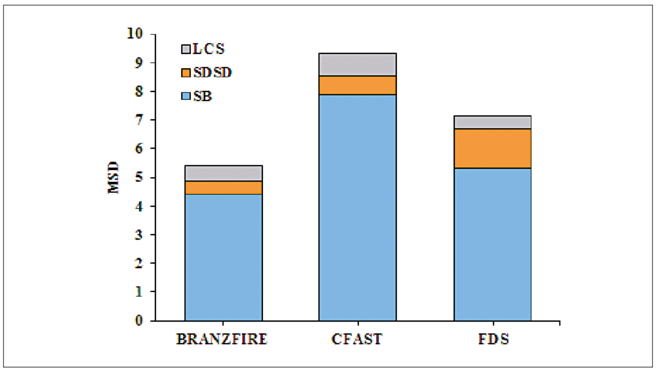

Fig. 11. Comparison of the MSD and its components for the three fire models for oxygen concentration predictions

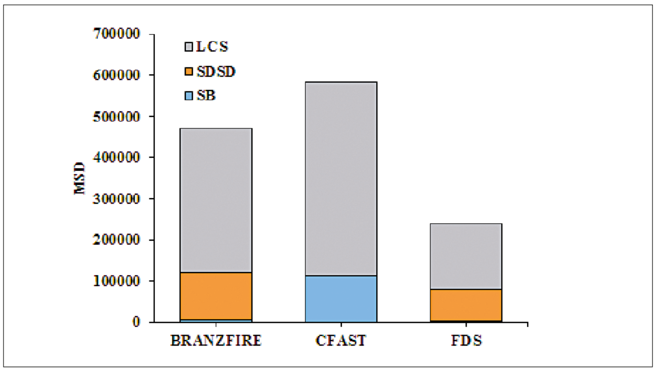

Fig. 12. Comparison of the MSD and its components for the three fire models for carbon monoxide concentration predictions

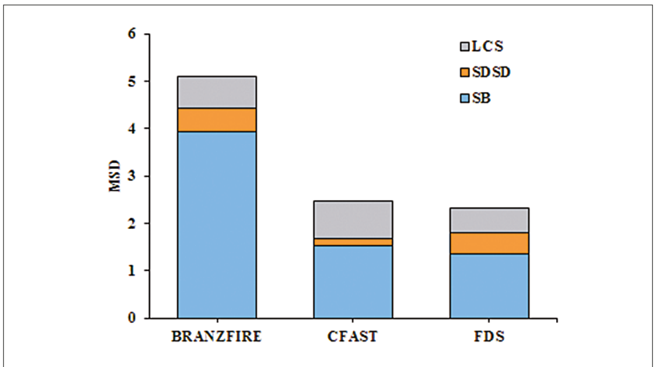

Fig. 13. Comparison of the MSD and its components for the three fire models for carbon dioxide concentration predictions

ANALYSIS OF THE RESULTS

Figures 4 through 13 show the results of the comparison between the three fire models and the model-scale fire test of the five outputs of concern. It is apparent from these results that:

1) **With regard to the "Hot Layer Temperature"**, and considering Figures 4 & 9, not surprisingly, *FDS* is the model with the best prediction (being it has the least *MSD*). In addition, the *CFD* model (*FDS*) was able to obtain the same profile as the experimental results (being it has the least *SDSD* and *LCS*). It should be noted that *FDS* fairly over-predicted the hot layer temperature during the fire growth period and there was a slight shift in the peak value. Among the two zone fire models, *BRANZFIRE* is the model that obtained reasonably good results of hot layer temperature. In spite of being initially highly over-predicted the hot layer temperature, *CFAST* was able to show very precise predictions in the last 200 seconds of simulation.
2) **Regarding the "Smoke Layer Height"**, and taking into account Figures 5 & 10, *BRANZFIRE* is the model with the best prediction. *CFAST* came in second with a reasonably good prediction of the smoke layer height. It should be noted that, in *CFD* models such as *FDS*, there are generally no distinct zones, but rather a continuous temperature profile. However, there are methods that can be utilised to estimate the height of the smoke layer from a continuous vertical temperature profile, and *FDS* uses one of these methods (Coyle and Novozhilov 2007). From the results of this comparison, it is clear that *FDS* over-predicted the smoke layer height until the time of approximately 90 sec with a maximum error of approximately 11 percent and under-predicted it for the remainder of the simulation time with a maximum error of approximately 75 percent. The higher values of both *SDSD* and *LCS* indicate that *FDS* failed to simulate the magnitude of oscillation and the variation pattern of the experimentally measured values of smoke layer height.
3) **With regard to the "Oxygen Concentration"**, and considering Figures 6 & 11, *BRANZFIRE* was the model with the best-predicted O_2 concentration results. Despite coming in second, *FDS* managed to obtain very precise predictions of O_2 concentration during the first 150 sec, in which the model began to show over-predicted results, as did the other two zone fire models.
4) **Regarding the "Carbon Monoxide Concentration"**, and taking into account Figures 7 & 12, *FDS* is the model with the least *SB*, *SDSD* and *LCS*, i.e., *FDS* is the model with the best prediction of CO concentration. Though *BRANZFIRE* came in the second place, *CFAST* was able to display the lowest *SDSD* value compared to the other two fire models. This means that *CFAST* was the model that was able to simulate the magnitude of oscillation between experimental results.
5) **With regard to the "Carbon Dioxide Concentration"**, and considering Figures 8 & 13, *FDS* is the model that shows the best prediction of CO_2 concentration. The results of *CFAST* are very close to the results of *FDS*. *BRANZFIRE* has shown over-predicted results with greater bias than the bias shown in the results obtained by both *FDS* and *CFAST*. The three fire models over-predicted the CO_2 concentration during the decay period of the fire.

Table 4 shows the recommended fire model to use when predicting each of the five outputs of concern in similar Vehicle Deck fire scenarios.

Tab. 4. The best fire model to use in similar Vehicle Deck Fire Scenarios

Output Parameter	Recommended Fire Model
Hot Layer Temperature	FDS
Smoke Layer Height	BRANZFIRE
Oxygen Concentration	BRANZFIRE
Carbon Monoxide Concentration	FDS
Carbon Dioxide Concentration	FDS/CFAST

CONCLUDING REMARKS

A comparison was performed between the predictions of three different fire models, namely, *CFAST*, *BRANZFIRE* and *FDS*, and the experimental results of a model-scale fire test representing a fire scenario on a vehicle-deck aboard a RoPax ship. The results have been analyzed using a statistical analysis technique. The most important conclusion of this comparison is that there is no fire model that can predict each of the five outputs of concern. In addition, there is always an optimal fire model that can predict one or more of the five outputs of concern with results that are in good agreement with the measured values. While both zone fire programs (*BRANZFIRE* and *CFAST*) are based on the same assumptions and limitations, their outputs are different. The *BRANZFIRE* developer, Colleen Wade, commented on this issue by saying that the differences in outputs between *BRANZFIRE* and *CFAST* may be due to the differences in many of the algorithms used to build the program. Attention should be paid to some of the outputs of concern when using the results of zone models due to the prior knowledge of the deficiency in their predictions. For example, the results of the comparison show that *CFAST* always significantly over-predicts the temperature of the hot layer. Similarly, it is well known that *BRANZFIRE* uses a conservative model to predict the carbon monoxide concentration that causes the program to over-predict it.

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