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IMPACT OF ALTERNATIVE DISPERSION MODEL VALIDATION METHODS: A CASE STUDY ON THE LNG MODEL VALIDATION DATABASE USING DRIFT

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Abstract: This paper assesses the impact of using different methods to compare dense-gas dispersion model predictions to experimental data, using the DRIFT integral model and the field-scale experimental data presented in the Liquefied Natural Gas (LNG) Model Validation Database. Three different model comparison methods are tested, which relate to different interpretations of the predicted maximum arc-wise concentration. Method 1 takes the predicted maximum arc-wise concentration to be the maximum concentration at any radial position and any height on a given arc. Method 2 takes it to be the maximum at any radial position but at the height of the sensors in the experiments. Method 3 takes it to be the maximum of the predicted concentrations at the sensors positions (at both their radial position and height). The motivation for this work is that Method 3 is adopted in the LNG Model Evaluation Protocol used by the US Pipelines and Hazardous Materials Safety Administration to approve models for use in LNG siting studies. Methods 1 and 2 have been used in other model assessment exercises.

The results show that the choice of method has a significant effect on the outcome of the model evaluation exercise. Method 1 makes it appear that DRIFT over-predicts the measured concentrations on average, whereas Method 2 and (more so) Method 3 make it appear that the model under-predicts the concentrations. One of the difficulties in applying Method 3 is that narrow plumes sometimes miss all of the sensors on an arc, which causes problems in calculating the geometric mean and variance. Results from a modified wind-meandering model in DRIFT are also presented, which gives improved agreement with the data when using Method 3.

Key words: *Dense-gas dispersion, LNG, model evaluation, validation, DRIFT, arc-wise maximum concentration*

INTRODUCTION

It is important to have a consistent approach to validation within the context of the regulatory use of dispersion models to ensure that models are evaluated on a common basis. If different models are evaluated using different approaches (e.g. by outputting the predicted concentrations at different locations) then this could bias the results of the validation exercise and defeat the purpose of a standardised validation procedure.

The use of dispersion models to determine the size of exclusion zones around Liquefied Natural Gas (LNG) facilities in the US is regulated by the Pipeline and Hazardous Materials Safety Administration (PHMSA), who require models to be approved using the procedure defined in the LNG Model Evaluation Protocol (Ivings *et al*., 2007). An important part of this approval process involves the comparison of dispersion model predictions to experimental data given in the National Fire Protection Association's (NFPA) LNG Model Validation Database (Coldrick *et al*., 2010) and the calculation of Statistical Performance Measures (SPMs). The experimental data consist of maximum concentrations at sensors on each downstream measurement arc (i.e. maximum arc-wise concentrations), plume widths and maximum concentrations at individual sensors in 33 dispersion experiments. These include field-scale experiments from the Burro, Coyote, Falcon, Maplin Sands and Thorney Island trials and wind-tunnel experiments from the BA-Hamburg, BA-TNO and CHRC experiments. Three dispersion models have been subject to this approval process to date (FLACS, PHAST and DEGADIS) and other model developers have expressed an interest in seeking approval for their models following this process.

A consistent methodology for comparing models to measurements has been applied by PHMSA in evaluating models, but other dispersion modellers have adopted different methods when they have independently tested their models against the LNG Model Validation Database. Specifically, the way in which maximum arc-wise concentrations have been output from models has differed. Previous dense-gas dispersion model evaluation exercises (e.g. Havens, 1992) have suggested that these different approaches could have a significant effect on the outcome of the model evaluation exercise.

To investigate this matter, the present work compares three different methods to calculate the arc-wise maxima using the DRIFT integral dispersion model. The analysis only considers the experimental data from four of the field-scale tests in the LNG Model Validation Database (Burro, Coyote, Falcon and Maplin Sands). The wind-tunnel tests are not considered because the three different methods would give identical results in those cases. Only short-time-averaged concentrations are examined, since the primary interest is in assessing the flammable hazard.

METHODS FOR DETERMINING ARC-WISE MAXIMUM CONCENTRATIONS

The different methods used to determine the maximum arc-wise concentrations are summarised in Figure 1. The experimental data in the LNG Model Validation Database was processed by first taking the maximum of the time-varying concentrations at each of the sensors along the arc. The highest of these maximum concentrations was then taken as the measured maximum arc-wise concentration (i.e. from any of the sensors along the arc, at any radial position or height). For the unobstructed field-scale tests, the highest concentrations were nearly always measured at the sensors nearest to the ground, typically at a height of 1.0 m.

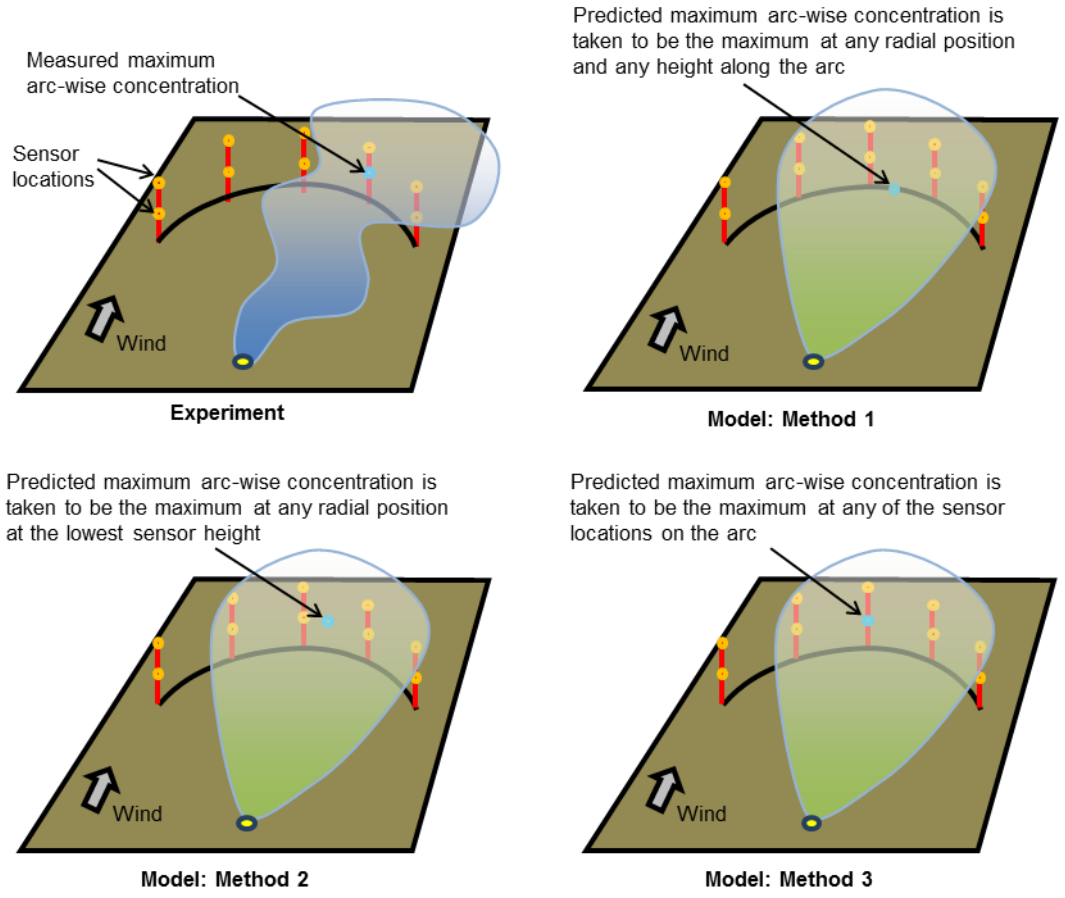

Figure 1 Illustration of methods for determining the predicted arc-wise maximum concentration

The three methods shown in Figure 1 for determining the predicted maximum arc-wise concentration are:

- **Method 1**: which takes the "absolute" maximum concentration at any radial location and height. Typically, this will be at ground level on the centreline of the cloud.

- **Method 2**: which takes it to be the maximum concentration at any radial position but at the height of the lowest sensors in the experiments.

- **Method 3**: which takes it to be the maximum of the predicted concentrations at the sensors positions (at both their radial position and height). This is the method used by PHMSA.

DRIFT INTEGRAL DISPERSION MODEL

DRIFT (Dispersion of Releases Involving Flammables or Toxics) is an integral model for dispersion of dense, passive or buoyant gas clouds produced from instantaneous, time-varying or continuous releases (Tickle and Carlisle, 2008), which is currently developed by ESR Technology and GT Science and Software, and used by HSE for land-use planning purposes in the UK. To model evaporating pools of LNG, the model uses the GASP source model (Webber, 1990). Details of the configuration of DRIFT for the cases considered here can be found in the report by Coldrick (2014).

The effect of lateral plume meandering is accounted for in DRIFT by making the plume width a function of the averaging time and plume travel time. For a given release (at a fixed distance downwind), the model predicts a narrower plume with a higher peak concentration for a shorter averaging time (see Figure 2a). The predicted concentrations are ensemble-mean values, i.e. an average over multiple "snapshots" of the meandering plume, not a single snapshot in time.

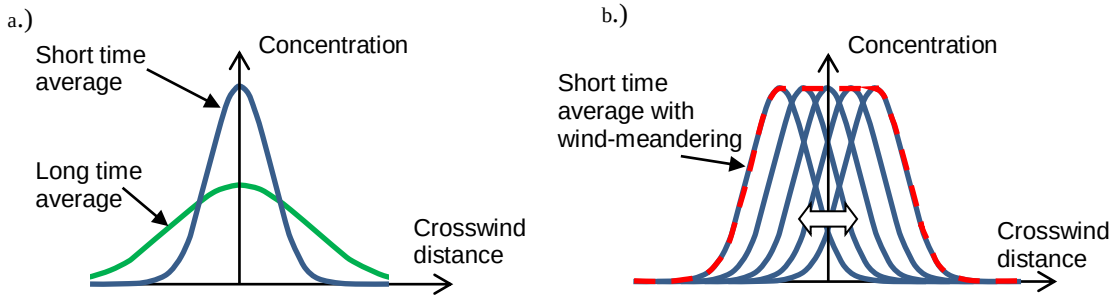

Figure 2 Typical lateral profiles of the plume concentration using: a.) short and long averaging times; b.) short averaging time with wind-meandering

In contrast to these notions of ensemble mean concentrations, the measured maximum arc-wise concentrations in the LNG Model Validation Database are taken as the highest concentration measured at any of the sensors across the arc at any point in time as the cloud passes the sensors. The measured maximum arc-wise concentrations are not determined from an ensemble mean. Lateral meandering of the plume causes high instantaneous concentrations to be distributed across the plume width in the experiments, producing a more flat-topped profile for the short time-averaged peak concentrations than that produced by an ensemble mean (as shown in Figure 2b).

These differences between the quantities output by DRIFT and those measured in the experiments has a significant impact on the model evaluation results when Method 3 is used to determine maximum arc-wise concentrations. Method 3 relies on the location of individual sensors and the DRIFT model with short time averaging and no meander produces a relatively narrow plume that sometimes misses the sensors, whereas the measured meandering plume is more likely to pass through the sensors. To compare to the experiments on a more like-for-like basis, DRIFT's plume meandering model has been used to produce results denoted "**Method 3a"**. These results are based on meandering the short time-averaged concentrations, replicating the process used to produce the dashed red line shown in Figure 2b. Formally,

Method 3a calculates the new concentration profile by laterally displacing the short time averaged plume up to a maximum distance corresponding to the 5% level of DRIFT's cumulative probability distribution for plume meander, i.e. the centreline is predicted to be displaced by this lateral distance 5% of the time.

RESULTS

Sample results are presented from DRIFT in Figure 3 for the Maplin Sands 27 experiment, which involved a continuous spill of LNG onto the surface of the sea with a wind speed of 5.5 m/s. The four different methods for determining the predicted maximum arc-wise concentration all produce different results for this case. Close to the source, the vertical gradient in concentration is such that the concentrations predicted at the sea surface (Method 1) were roughly twice as high as those predicted at 1.0 m height (Method 2). The narrow plume predicted by DRIFT missed most of the sensors and so Method 3 gave practically zero concentrations at most of the measurement arcs. Using the meandering model (Method 3a), DRIFT predicted a wider plume and therefore higher concentrations at the sensor positions, but the measurements were still under-predicted by around a factor of three.

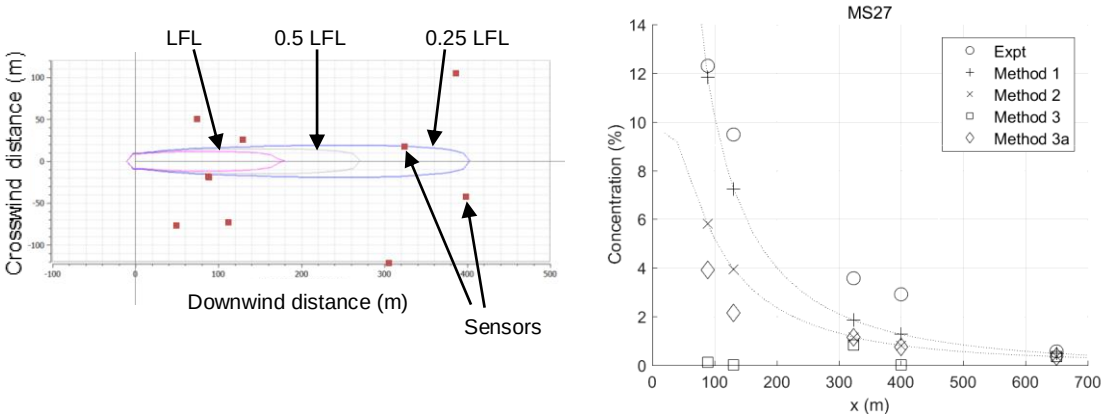

Figure 3 Maplin Sands 27 results showing contours of predicted Lower Flammability Limit (LFL) concentration on a horizontal slice at a height of 1.0 m (left) and comparison of predicted and measured maximum arc-wise concentration (right)

Table 1 and Figure 4 present a summary of the results for all four of the field-scale tests (Burro, Coyote, Falcon and Maplin Sands) in terms of predicted versus measured maximum arc-wise concentrations and the SPMs (for the definition of the SPMs, see Ivings *et al*., 2007). These show that Method 1 makes DRIFT appear to over-predict the measurements on average (MRB < 0), whilst Methods 2, 3 and 3a make it appear that DRIFT under-predicts the measurements on average, by varying degrees. Using Methods 1 and 2, DRIFT falls within the bounds of what is considered "acceptable" model performance according to the LNG Model Evaluation Protocol (MEP) (Ivings *et al*., 2007). Method 3 gives very large values for the MG and VG, since they are calculated from the ratio of measured to predicted concentrations, and the predicted concentrations are close to zero in some cases. Method 3a suffers less from these problems, but low concentrations in the Maplin Sands and Coyote 3 experiments still produce very high values of MG and VG.

Table 1. Statistical Performance Measures for Methods 1, 2, 3 and 3a and their acceptable limits as specified in the LNG MEP (Ivings *et al*., 2007). Unacceptable values are highlighted in bold.

Method	Mean Relative Bias (MRB)	Mean Relative Square Error (MRSE)	Geometric Mean (MG)	Geometric Variance (VG)	Factor of Two (FAC2)
Acceptable	-0.4 < MRB < 0.4	MRSE < 2.3	0.67 < MG < 1.5	VG < 3.3	FAC2 > 50%
1	-0.21	0.34	0.79	1.5	78%
2	0.31	0.38	1.4	1.6	61%
3	**0.59**	1.1	**6.6**	**1.8×10^{13}**	54%
3a	**0.41**	0.59	**1.9**	**15**	56%

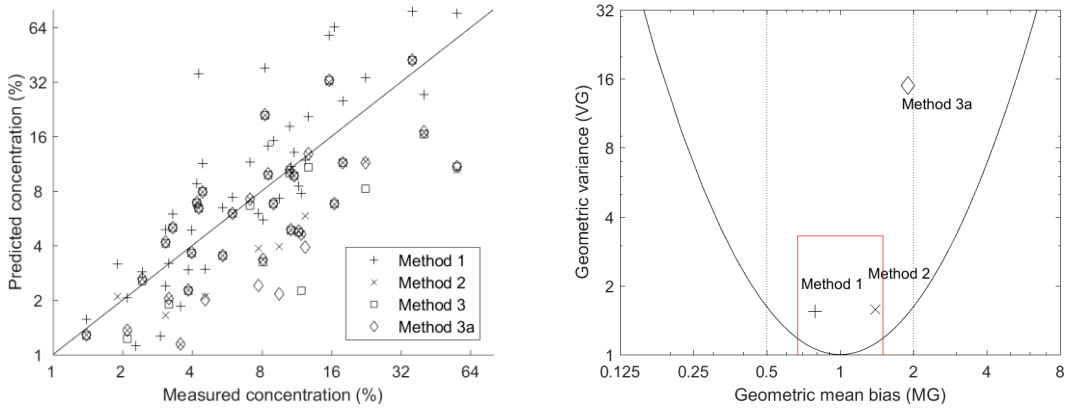

Figure 4 Scatter plot of predicted versus measured concentrations (left) and geometric mean versus geometric variance (right). Some points fall outside the bounds of the plots

DISCUSSION AND CONCLUSIONS

This work has shown that the choice of method used to output predicted maximum arc-wise concentrations can have a strong effect on the conclusions of a dense-gas model validation exercise. Depending on the method used, DRIFT was found to either under-predict or over-predict the measurements on average. The method used by PHMSA (Method 3) made it appear that DRIFT significantly under-predicted the measurements. This behaviour was mainly due to DRIFT producing a narrow plume for a short averaging time that sometimes missed all of the sensors on a given arc, whereas the way in which the measurements were processed produced a wider plume which was more likely to pass through the sensors. As a refinement, DRIFT's plume meandering model was used to output a quantity from the model that more closely matched the type of quantity measured in the experiments. This refined output (Method 3a) showed improved agreement with the measurements. Further work is needed to assess this approach in more detail.

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