A Shielded Thermal Flux and Impacted Jet Fire Model

Andrew Lawson, Luke Butcher, Shamsudeen Hassan, Jasmine Stainton, Graham Tickle and Ed Walton,

ESR Technology Ltd, Warrington.

TORCH is an empirical jet fire model for predicting the jet fire size, shape, and orientation and subsequently the radiative heat flux. The model originates from the work of Chamberlain (1987) on flare systems and has subsequently been further developed and improved to include modelling of horizontal jets (Johnson et al. 1994) and has been validated against a range of experimental tests. TORCH is mainly used for the purpose of assessing jet fire hazard ranges for major hazard assessments.

A limitation with empirical correlations and free jet fire modelling is the inability to account for the complex 3D geometry which may potentially shield regions from the thermal radiation produced by a jet fire and may also distort the jet fire flame because of the impaction on large surfaces. This limitation can be overcome with the use of computational fluid dynamics (CFD) fire codes; however, this can often require large computational times, which limits the number of scenarios that can be modelled.

An alternative approach for modelling the impacted jet flame shape is to make simplifying assumptions that ensure both the flame volume and surface emissive power are maintained. This enables real time processing of the impacted flame shape that can be used to inform major hazard assessments. The thermal radiation can then be calculated using ray casting and the view factor, i.e., the surface of the frustum that is visible from the receiver at the given point. By casting thousands of rays in multiple directions, the model can take account of any geometry that may obstruct the view from the receiver to the frustrum, and therefore, shield the receiver from the thermal radiation.

This paper presents a model for simplifying the impacted jet flame shape and determining the resulting shielded thermal radiation and validation of this model. Predictions of the model are compared with those from Fire Dynamics Simulator (FDS) CFD runs and with published correlations for impacted jet flame spread over a flat plate.

Keywords: Jet Fire, Ray Casting, Model Validation, Radiation Shielding, TORCH 3D

Introduction

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A limitation with empirical free jet fire modelling is the inability to account for the complex 3D geometry which may potentially shield regions from the thermal radiation produced by a jet fire and may also distort the jet fire flame because of the impaction on large surfaces. This limitation can be overcome with the use of CFD fire codes; however, this can often require large computational times, which limits the number of scenarios that can be modelled.

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This paper presents a model for simplifying the impacted jet flame shape and determining the resulting shielded thermal radiation and validation of this model. The model is implemented in ESR Technology's TORCH 3D software.

The validation/verification approach adopted by this study is to compare predictions of TORCH 3D with those of other published models, in particular the Fire Dynamics Simulator (FDS, McGratten et al., 2022), which is a Large Eddy Simulation (LES) CFD tool, which is used as a benchmark for the comparisons. Cases modelled have been chosen to match those where FDS has been previously shown to give a good representation of the flame length for the free jet case. For impinged cases, comparisons are with published correlations for the flame spread due to a vertical jet impacting on a large horizontal flat plate and with an FDS run for this impacted jet configuration. Finally, comparisons are made between TORCH 3D and FDS predictions of shielded thermal flux from an impacted jet for a 'real world' case of a jet fire in an offshore platform geometry.

Impacted Jet Fire Model

The free jet fire for the provided input parameters is initially calculated. From this, a relevant impacted jet length scale for the scenario is determined, taken from half of the free jet tip width.

A full 3D plant geometry model is loaded into a physics engine (Bullet Physics Engine, Coumans et al., 2022). The impaction model then uses ray casts oriented along the flame direction, lift-off section and then flame section, to list obstructions starting with the closest to the source location. These obstruction objects are considered in turn, and the first object which is greater than the impacted jet relevant length scale is taken as the point of impaction. For scenarios where the impaction point is within the flame section (i.e. not within the lift-off portion of the jet) the base is kept at a fixed location, the tip centre is set to be at the impaction point and the tip width is widened until the volume of the free jet flame is preserved. The spreading of the tip width is limited by the impacted base to tip distance being capped at the impacted jet length scale as a minimum. This prevents jets from becoming unrealistic infinitesimally thin and infinitely wide flat 'disks'.

For scenarios where the point of impaction is within the lift-off portion of the jet, the base location is moved towards the source location to ensure that the maximum tip width calculated from the minimum impacted jet length is preserved. If the source to tip distance is less than the typical jet length then the entire frustum is flipped, with the jet length set at the typical jet length scale, to represent a spray fire from the wall.

The Surface Emissive Power (SEP) is maintained for each of the base, tip and sides of the flame frustum and the calculation with the modified frustum is performed as per the Johnson model.

Shielded Thermal Flux Calculation

The non-shielded view factor for a modified or free jet frustum to a point in space is calculated. A surface spacing parameter is defined and used to generate emission points approximately evenly distributed over the surface of the flame. The ends and sides of the frustum are considered separately as in the Johnson model. Ray casts are then performed for each surface point to the receiver point and a shielding factor is generated from the ray casts exhibiting a hit using a 3D model loaded into a physics engine (Bullet Physics Engine, Coumans et al., 2022). The ray cast hits are weighted by the area each surface point represents and is performed separately for the two ends and the sides of the frustum. The view factor for each side is then scaled by the shielding factor and summed to give the shielded flame view factor. The rest of the calculation is then performed as per the un-shielded torch model.

Free Jet Fire

As already mentioned, the free jet model for vertically directed releases in TORCH and TORCH 3D is based model of Chamberlain (1987). Therefore, the published validation of Chamberlain (1987) is applicable also to TORCH 3D and verification testing undertaken by ESR Technology (ESR) has confirmed this.

Table 1: Vertical Propane Jet Fire Experimental Conditions

Experiment	Orifice Diameter (mm)	Fuel Mass Rate (kg/s)	Wind Speed (m/s)	Air Temperature (°C)
D10_0.09	10	0.09	n.a.	20
D12.75_0.13	12.75	0.13	1.02	27
D15_0.18	15	0.18	n.a.	21
D20_0.27	20	0.27	1.55	22
D25.5_0.34	25.5	0.34	n.a.	24

The modelled fires correspond to the vertical jet fire scenarios considered by Darnaculleta (2019) which are based on a series of experiments. The release conditions for these experiments are summarised in Table 1. Observed flame heights (measured from the end of the pipe exit) were determined from processing of infrared images (based upon a temperature of 800K). In the modelling, the initial fuel temperature is taken to be the same as the air temperature. Unlike TORCH, FDS cannot directly model sonic releases, instead equivalent expanded jet conditions have to be used subject to the constraint that the initial velocity corresponds to a Mach number of less than 0.3. In this study the expansion model of Ewan and Moodie (1985) has been used to derive the expanded jet conditions for the FDS runs. The Ewan and Moodie expansion model equivalent to a sonic velocity after expansion to atmospheric pressure and this has been further reduced to 70 m/s by mixing in air whilst conserving the momentum of the release. This approach avoids assuming an arbitrary initial momentum to the jet. Since the wind speed is only known in two of the experiments and is relatively low for these, comparisons are with model predictions in zero wind, noting that non-zero wind speed would shorten predicted flame heights.

FDS solves a form of the Navier equations appropriate for low speed, thermally driven flow with an emphasis on smoke and heat transport from fires. The simulation of smoke movement, sprinkler discharge and fuel sprays are through lagrangian particles while computation of thermal radiation is achieved using finite volume technique. The set of partial differential equation derivation of the conservation of mass, momentum and energy are approximated as finite differences and the solution is updated in time on a three-dimensional, rectilinear grid.

The combustion model used in this work is the default mixture fraction, which assumed that upon mixing, the reactant (fuel and oxygen) "mixed burned" i.e., rapid and complete reaction and this is a function of space and time, denoted by Z (x,t) in its simple form. However, the use of the mixture fraction creates uncertainty when the heat release rate is predicted instead of specified. Also, as the model assumes mixed is burned, it does not work well when the fuel and oxygen is allowed to mix and not burn in the case of jet releases where combustion is not taking place at fuel concentrations outside the flammable range.

A radiative transport equation (RTE) for an absorbing and scatting medium is used in the computation of the radiative fluxes. The equation is solved using Finite Volume Method (FVM). Radiation transport is discretized via many solid angles, the default FDS value is 100 and has been used in this work. Using the default is deemed reasonable for targets near the fire. For targets some distance away from the fire the discretization can lead to non-uniform distribution of the radiant energy. This problem might be solved by using more solid angles as employed by Darnaculleta (2019), but this dramatically increases the simulation time.

The determination of the mesh dimension is driven by the dimensionless expression of the characteristic fire diameter, D^*/δ_x that indicates the number of grid cells of dimension δ_x that span the characteristic fire width D^*. The suggested values ranged from 4 to 16. This is only suitable for subsonic releases. For sonic and supersonic releases with dimensionless flow, U^*, higher than 80, which this work is based on, the $D*/\delta_x$ expression no longer applies. The maximum grid size for such scenarios is based on the equivalent nozzle diameters as the geometrical constraint (Darnaculleta 2019). Accordingly, the cell size of each jet fire scenario (in m^3) in this work is modelled with a side equal to the equivalent nozzle diameters (in m).

The initial exterior boundary conditions of the computational domain are taken as having a passive opening to the outside. By default, these opening are assigned ambient conditions. For this work however, initial ambient temperatures for some runs have been changed to aligned with the experimental data.

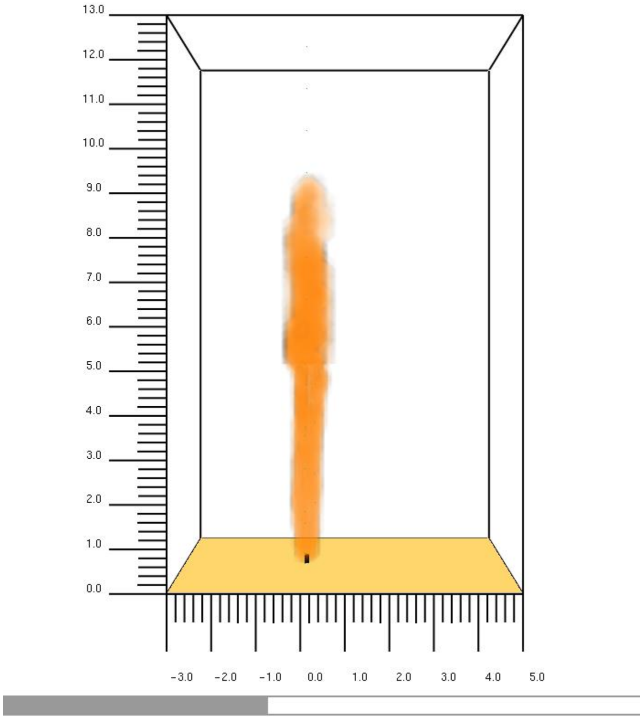


Figure 1: Example FDS instantaneous heat release rate plot for D25.5_0.34 free jet fire

For this comparison, the FDS predicted flame heights are estimated from heat release rate per unit volume plots - Figure 1 showing an example plot at an instant in time. The LES modelling in FDS results in a fluctuating flame, the average height of which has been estimated after allowing for an initial establishment period of approximately 10s in the simulations. The flame height extracted from FDS is measured from the source, however due to its combustion model, FDS burns back to the source and does not predict the lift-off region of the flame close to the source.

In contrast to FDS, flame height is a direct output from TORCH 3D. The flame height is measured from the source and since TORCH 3D includes a correlation for the lift-off distance, the predicted length of the combustion region is less than this flame height. Figure 2 shows the predicted versus observed flame heights (observed values taken from Figure 2.11 in Darnaculleta, 2019). In general, there is very good agreement between the predicted flame heights and the observed values – this agrees with the finding of Darnaculleta (2019) for the FDS model, and suggests also close correspondence between the TORCH 3D and FDS predictions.

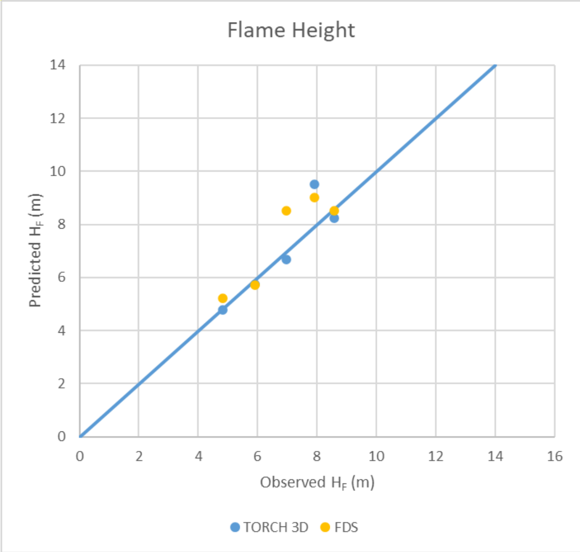


Figure 2: Predicted versus observed flame height

Predicted radiative heat fluxes on a vertical surface facing the flame a location 5m off axis and 1m from the release height are compared with observed values measured by a wide-angle radiometer in the experiments (observed values taken from Figure 2.10 in Darnaculleta, 2019). In general, for these experiments, TORCH 3D overpredicts the radiative flux at this location and FDS underpredicts. These differences may be due to the different way thermal radiative flux is calculated by the models. The scatter indicates a significant level of uncertainty for radiative flux predictions for both TORCH 3D and FDS, despite the good agreement of the model predictions with the experimentally observed flame heights. For the two largest release rate cases, D20_0.27 and D25.5_0.34, the average FDS predicted flux is approximately 17% less than the experimental observed value and the average TORCH 3D prediction is approximately 30% greater than the experimental observed value.

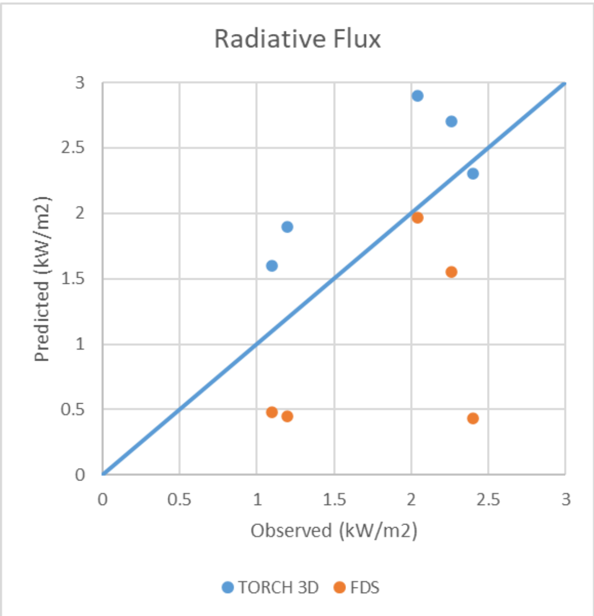


Figure 3: Predicted versus observed radiative heat flux

Impacted Jet Fire

The case considered is a vertical jet fire impacting on a large horizontal plate in zero wind. Zhang et al. (2014) investigated this configuration and presented various correlations for the flame spread over the plate. A convenient way of presenting these data is to plot the width (Wimp = twice the radius) of flame on the plate against the height of the plate (H) above the release with both quantities being made dimensionless by dividing by the free flame height (Hf). Figure 4 shows such a plot with two alternative correlations taken from Zhang et al. (2014) – both these correlations show an increase in the flame width on the surface of the plate as the height of the plate is reduced relative to the free flame height. One of the correlations (equation 8 in Zhang et al, 2014) shows an increasing flame width as the height gets closer to the source height, whereas the other correlation (equation 6 in Zhang et al, 2014) shows a flame width approaching approximately 80% of the free flame length at very close impingement. Also shown in Figure 4 are data points derived from TORCH 3D and FDS runs. The TORCH 3D case is for a sub-sonic vertical propane jet from a 12.75 mm orifice corresponding to the experiment selected by Favrin et al. (2018) for comparison with FDS simulations. For plate distances between about 20% and 80% of the free flame height, TORCH 3D's simple impacted jet model produces predictions similar to and lying between the two correlations from Zhang et al (2014). TORCH 3D's impacted jet model shows a discontinuity from the jet tip width to zero at a plate distance equal to the free flame height and as the plate distance reduces to zero the flame width tends to just over 60% of the free flame height.

Also shown in Figure 4 is a data point obtained from an FDS run of a sonic propane jet (conditions as for experiment D25.5_0.34 in Table 1), with a horizontal plate inserted 6m above the release point. The flame extent over the plate has been estimated in the same way as the flame height was determined for the free jet cases. The FDS run shows a slightly greater spread over the plate, but its deviation from the equation (8) correlation of Zhang et al (2014) is similar in magnitude to the difference between the alternative correlations. Figure 5 shows an example plot of the instantaneous flame predicted by FDS.

The correlations given by Zhang et al (2014) are derived from data up to Wimp/D = 14 and H/D = 15 (where D is the orifice diameter), whereas the TORCH 3D calculations cover the range H/D = 8 to 300 and up to Wimp/D = 370. This suggests the impingement behaviour is mainly controlled by geometry (plate distance divided by free flame length) and we consider the overall agreement between the different approaches as encouraging, especially given the large differences in scale relative to orifice diameter.

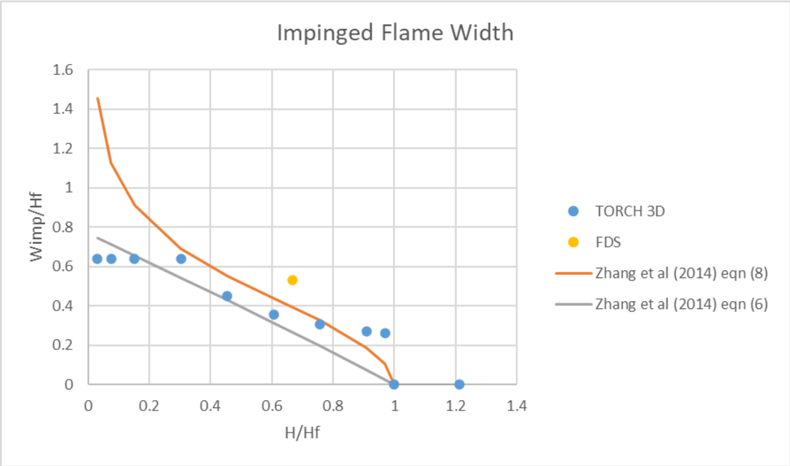


Figure 4: Impinged flame width as a function of the height of the plate above the source

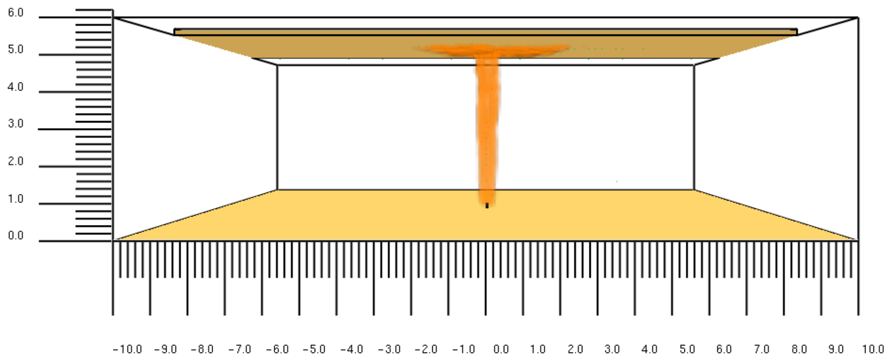


Figure 5: Example FDS instantaneous heat release rate plot for D25.5_0.34 jet fire impinging on plate 6m above source

Thermal Radiation Shielding

The thermal radiation shielding aspects of TORCH 3D are investigated in the context of a 3D geometry that is representative of an offshore platform configuration. Figure 6 shows a screen shot of the 3D model and the release point used for a propane vertical jet fire that impacts on the ceiling above. The vertical jet fire is modelled using the release conditions corresponding to D25.5_0.34 case in Table 1. Figure 6 shows the source location in the model and the orientation of the axes.

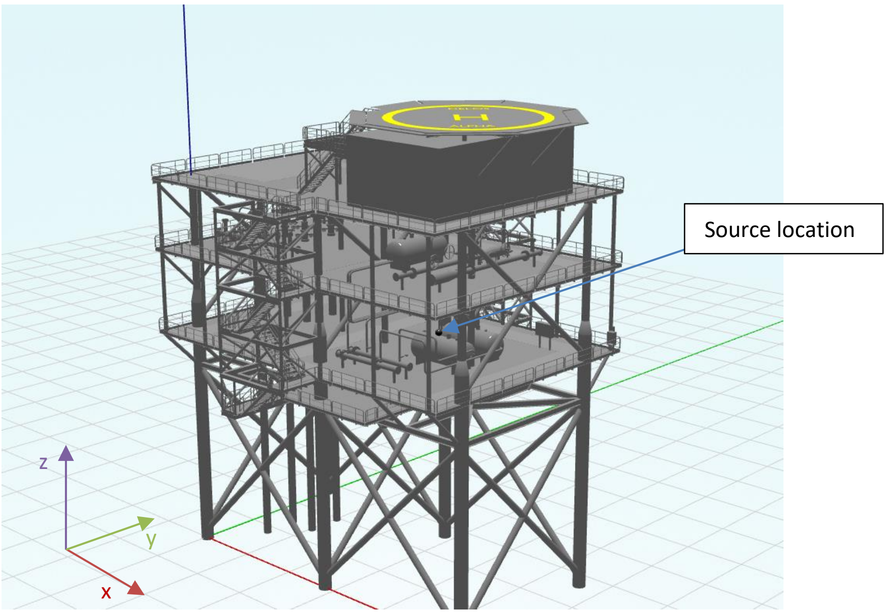


Figure 6: 3D geometry model used for shielded thermal radiation calculations

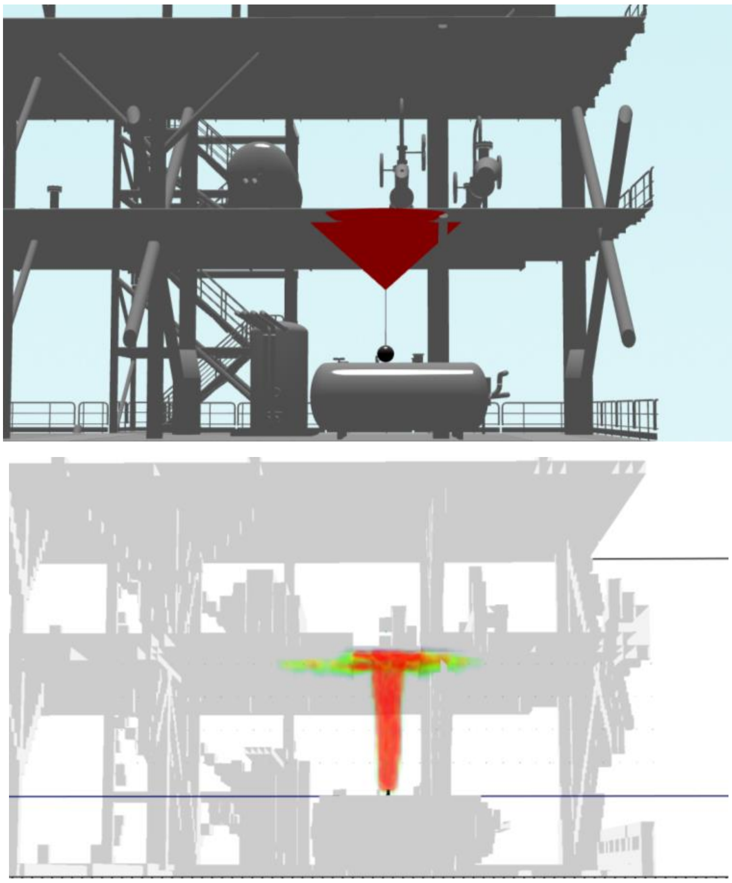


Figure 7: Flame extent in TORCH 3D (top) and FDS (bottom) from vertical impacted jet fire – view from the minus Y direction.

Figure 7 shows a comparison of the predicted impacted flame spread from TORCH 3D (top of figure) and a snapshot of the heat release rate per unit volume from FDS (bottom of figure). The models predict similar spread of the jet on the ceiling but differ in geometric shape with TORCH 3D modelling the impacted jet as a frustrum, including the lift-off distance with no combustion, whereas FDS shows a flat radial wall jet on the ceiling and a relatively narrow jet fire extending all the way from the source without any flame lift-off.

Monitor points (thermal radiation receivers) have been included within both TORCH 3D and FDS to measure the predicted thermal radiation along two transects below the flame. The transects are in the x- and y-directions, 1 m above the deck below and cross directly below the release point. These transects have been chosen to illustrate the effect of screening due to obstacles (vessels and pipework) in the path of the thermal radiation from the fire. The screening of thermal radiation in TORCH 3D and FDS along the transects are compared in upper plots of Figure 8 and Figure 9 – to minimise differences due to the different thermal radiation emission models in TORCH 3D and FDS the radiative fluxes have been adjusted using multiplicative factors based upon the 30% overprediction by TORCH 3D and 17% underprediction observed for the largest release rate free jet cases (D20_0.27 and D25.5_0.34). With this adjustment both TORCH 3D and FDS show very similar transects indicating that the thermal radiation screening by obstacles in TORCH 3D is able to reproduce the screening effect of obstacles in the CFD tool (FDS). The similarity of the transects between the two models also suggests that, at least for this configuration, the differences in impacted flame shape is not producing significant differences at 1m height above the lower deck.

The lower plots in Figure 8 and Figure 9 show contours of the unadjusted radiative flux predicted by TORCH 3D in XZ-plane and YZ-plane cross-sections – these contours are for receiver orientations that maximise the radiative flux and because of this may differ numerically from (be larger than) the transects which are for upwardly pointing receivers, the effect of shielding by obstacles is clearly evident. Also shown in the lower plots is a dashed line corresponding to linear transects in the upper plots.

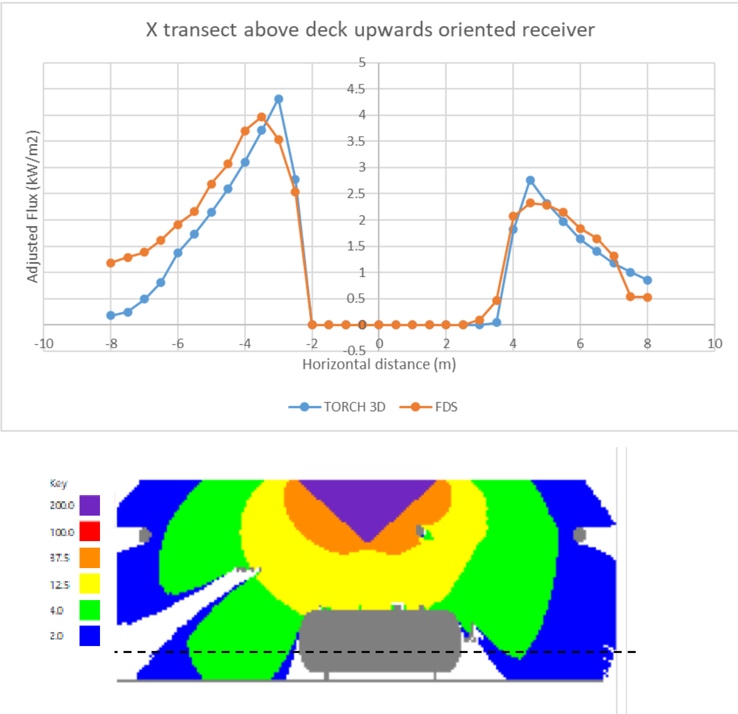
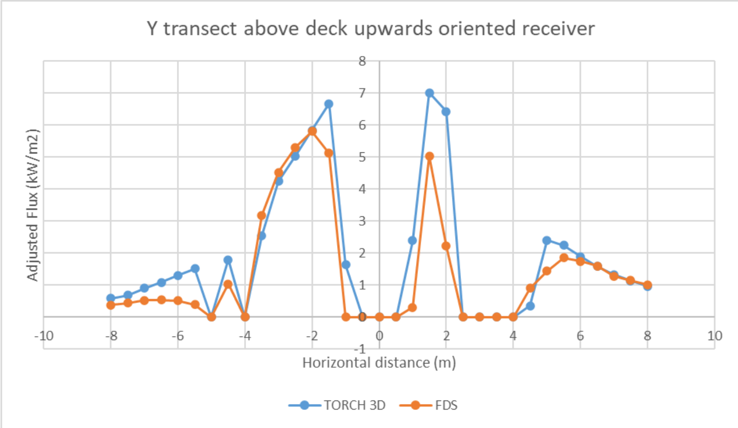


Figure 8: X-direction transect (upper) and TORCH 3D cross-section in XZ-plane (lower) showing shielding of radiative flux. Equipment in lower plot shown in grey.



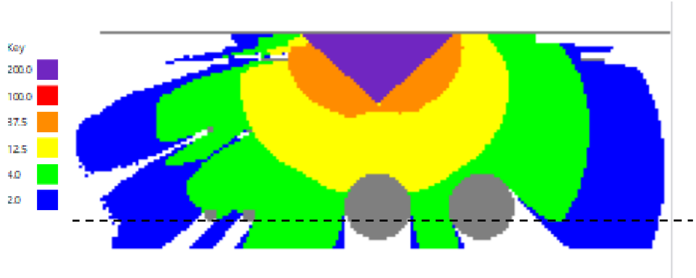
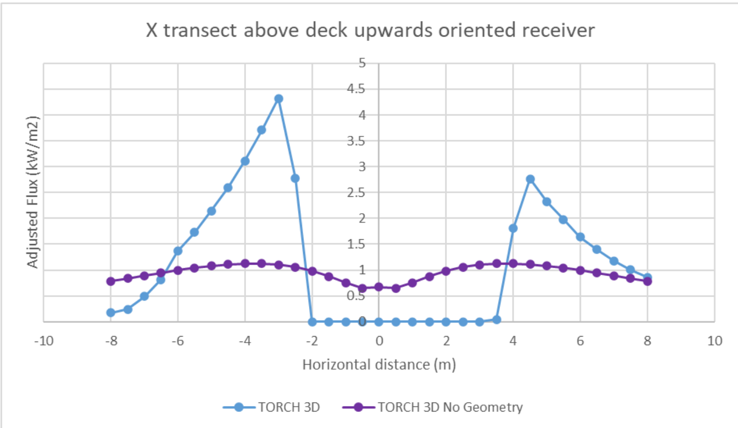


Figure 9: Y-direction transect (upper) and TORCH 3D cross-section in YZ-plane (lower) showing shielding of radiative flux. Equipment in lower plot shown in grey



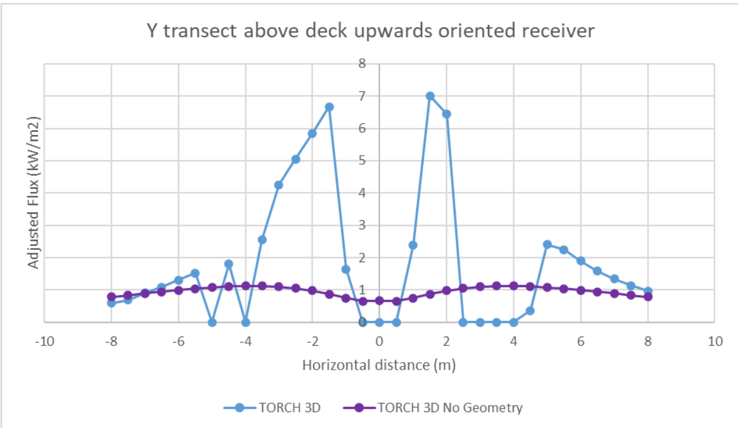


Figure 10: X- and Y-direction transects showing comparison of TORCH 3D predicted thermal radiative flux with and without geometry

Figure 10 shows a comparison of TORCH 3D's predictions of radiative flux along the X- and Y- transects for the model including geometry and with no geometry included. In this case, ignoring the geometry leads to lower predicted radiative flux in the unshielded locations compared to the geometry case, and higher predicted radiative flux in the unshielded locations. The reduction at unshielded locations is simply due to the smaller view factor of the unimpacted vertical flame at these locations, whereas the increased values are a consequence of ignoring shielding. Hence ignoring the geometry can lead to the underprediction of radiative fluxes in the module where the jet fire source is located, and overprediction in neighbouring modules which otherwise would be shielded, e.g., due to the presence of a fire wall or solid deck.

Conclusions and Recommendations

This paper presents a model for simplifying the impacted jet flame shape and determining the resulting shielded thermal radiation and validation of this model. Comparison with free vertical sonic propane jet fire experiments suggest that TORCH 3D is giving a good prediction of the flame height, whereas the thermal radiation is generally overpredicted compared with values reported by the single radiometer in these experiments. FDS is found to also predict the flame heights well, although the observed flame lift-off is not predicted. FDS is found to generally underpredict the measured radiative flux in these experiments. Hence although the flame extent is quite well predicted there is greater uncertainty relating to radiative flux predictions.

TORCH 3D's impacted jet model is found to result in similar flame lateral spread to published correlations for a vertical jet impacting on a horizontal plate. An FDS simulation is found to result in a similar, albeit slightly greater spread than TORCH 3D and the published correlations.

For a 'real world' situation of a vertically impacted jet fire in a 3D model of an offshore platform, TORCH 3D's thermal radiation shielding is found to be very similar to that from an FDS simulation of the same scenario. In the configuration studied, TORCH 3D results ignoring the geometry are found to produce too low thermal radiative flux in the module containing the jet fire source and potentially too high radiative flux in the module above due to ignoring of the shielding effect of a deck (assuming the deck integrity is maintained).

Further validation studies would be beneficial to increase the confidence in applying the impacted jet model to a wider range of situations, for example it would be interesting to compare TORCH 3D impacted jet predictions with correlations for flame spread resulting from horizontal jet fire impaction on vertical plates (e.g., as recently published by Wang et al., 2021).

Since the radiative screening approach in TORCH 3D is based upon the well-established technique of ray casting, there is a good degree of confidence in the radiative screening aspects of the model. By contrast, the impacted jet model is more 'heuristic' in nature and requires the user to remain vigilant to check that the resulting flame geometry is reasonable for the configuration being modelled – despite the far-field radiation being predicted well for real world scenarios, the near-field close to flame presents a greater challenge, a fact which is pointed out by Chamberlain (1987) for the simpler case of free jet – the issue being whether results are sufficiently accurate to inform the engineer.

The comparisons reported in this paper are encouraging in suggesting that the simple jet impaction and thermal radiation screening approach adopted by TORCH 3D can give results similar to other published studies and may provide a viable alternative/complementary approach to CFD for undertaking initial screening assessments, particularly when results are needed quickly and/or there are many scenarios to assess. A strength of the model is its ability to show in real-time the effect of changes made to the release scenario or 3D geometry. This makes it an ideal tool for quickly informing whether geometry changes are likely to have a significant impact on overall safety conclusions, or for identifying key scenarios that would benefit from undertaking more detailed CFD modelling.

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