Developing a solid-flame model for assessing consequences of large-scale rectangular pool fires and trench fires

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Most research and model development for pool fires have been for circular pool fires. In practice, larger spills are usually constrained by bunds or other obstacles and many bunds in the process industries have non-circular shapes, very often these bunds are rectangular. Apart from the technical and practical challenges faced by circular pool fires in modelling, rectangular pool fires bring extra complexities, such as effects of aspect ratio of the fire and directional wind effects. There can also be scaling effects that are sensitive to the pool shape. A new solid-flame model is developed for large-scale rectangular pool fires and trench fires based on empirical relationships as well as correlations derived from CFD simulations of a series of designed cases using KFX (a CFD tool), the predictions are validated against measurements of LNG trench fires by Croce, Mudan & Wiersma (1986) and rectangular pool fires of gasoline by LASTFIRE (2021).

Key words: rectangular pool fire, trench fire, solid-flame model, thermal radiation, KFX.

1. Introduction

Pool fires are a potential consequence of releases of liquid and 2-phase flammable materials from storage and transportation. Most models assume pool fires from circular liquid pools which could be formed from liquid spreading on substrates after rainout, tank fires or fires in circular bunds. Several reviews on tests and models for circular pool fires can be found in literature, such as Rew (1996) and the theory document of Phast/Safeti (2019). The assumption of a circular shape is adequate if a spill can spread equally in all directions. In practice, larger spills will be constrained by bunds and many bunds in the process industries have non-circular shapes; very often these bunds will be rectangular.

For this kind of fire scenarios, CFD would be the ideal analytic tool because it can cope with bunds of any shape and size. However, CFD has a high demand on computing power and it is still not feasible to use CFD for routine QRA work. Simple solid-flame models have been widely used for QRA assessments due to its simplicity and accuracy for circular pool fires. But it is difficult for the models developed for circular pool fires to give reliable predictions for pool fires in rectangular bunds or trenches, especially when the aspect ratios of the bunds or trenches are high. To fill this gap, this paper presents a new solid-flame model developed for rectangular pool fires based on empirical relationships as well as CFD simulations using KFX. Predictions by KFX for large-scale pool fires have been validated against the Montoir and Phoenix tests of large-scale LNG pool fires (DNV, 2016) and KFX has been widely used for fire modelling in the process industry for many years.

2. Literature study

Moorhouse (1982) has published sets of correlations for rectangular pool fires based on large-scale experimental results of LNG tests. A total of 29 tests were carried out with pool area varying from 7.2 -185.8 m2 with aspect ratios between 1-2.5. Correlations were derived for conical or cylindrical flame representations of the fire. Aspect ratio of the bund was not specifically represented in the correlations. Instead, an equivalent circular pool diameter of rectangular bunds is used in the correlations. Based on test results, the author concluded that the preferred flame geometry for calculating thermal radiation of LNG pool fires consists of a flame with an elliptical cross-section at all horizontal planes, axis of the ellipses being determined by the bund dimensions and the wind speed. The approach can be applied for pool fires of relative low aspect ratios similar to those studied, i.e. between 1-2.5.

For pool fires of rectangular bunds with higher aspect ratios, Croce, Mudan &Wiersma (1986) developed a model for LNG trench fires based on full-scale experimental results of LNG pool fires with aspect ratios between 5 – 30. From observations, they found that trench fires are more strongly influenced by wind, and the flame shapes are close to tilted rectangular prisms. When the aspect ratio is higher than 5, trench fires behave more like a line source fire. In the model, parameters of flame shape are correlated to a Froude number based on wind speed and trench width.

Wind speed has a large impact on pool fires. Lam and Weckman (2015) compared measured flame geometry with predictions by empirical correlations for wind-blown pool fires. Several correlations referred to in the paper were based on test results of rectangular pool fires, including the work by Moorhouse (1982). The study has concluded that flame tilt can be predicted successfully by empirical correlations based on Froude number and non-dimensional heat release rate, but predictions by similar correlations for flame drag and flame length are less satisfactory.

In recent years, studies have been carried out on rectangular pool fires in China. Hu et al (2009) investigated burning rates of square/rectangular pool fires of gasoline and methanol in a wind tunnel and has found the increase of burning rate with wind speed is faster in the length direction than in the width direction. Ji et al (2019) has measured burning rate and flame height of n-heptane rectangular pool fires with a width of 8cm and aspect ratios up to 14. The study reported an increasing trend of burning rate with aspect ratio. The measured burning rate increased sharply with aspect ratio when the ratio is less than 3 and linearly between 3 & 10 and remains constant when aspect ratio is larger than 10. However, these studies are for small-scale pool fires and the fire may behave differently from large-scale pool fires.

Jiang et al (Jiang 2016) carried out an experimental study of large-scale rectangular pool fires of n-heptane and gasoline at low wind conditions (wind speed <1.2m/s). The study measured steady burning rate of rectangular pool fires with a width of 1m and aspect ratios between 0.5 and 4. At high aspect ratio, the observed flame height becomes constant about 4 times of bund width, which is consistent with measurements of LNG trench fires by Croce et al (Croce 1986).

3. The modelling approach

Apart from the technical and practical challenges faced by circular pool fires in modelling, rectangular pool fires have extra complexities. The main differences between circular and rectangular pool fires are:

- Shape effect. One important factor in studying rectangular pool fires is the ratio of bund length (longer side of the bund) to the width (shorter side of the bund), normally referred to as aspect ratio. This can vary from 1 (square bund fires) to large numbers (fires in long trenches).
- Directional wind effect. Rectangular pool fires are directional and depend on relative orientation between wind and the bund. When wind is in the direction of bund length, the pool fire can be very different from the fire if the same strength wind is in the direction of the bund width when the aspect ratio is high.

Figure 1 illustrates the conceptual solid flame used to represent rectangular pool fires in this new model. If the fuel is considered to be smoky then the flame has two-zones, i.e., a luminous flame base takes a rectangular cross-section at the flame base and a smoky top section having an elliptical cross-section gradually varies between flame base and top. If the fuel is not smoky (i.e. luminous), the top section represents the whole flame. Variables that define the solid flame are:

- Flame length
- Length of the luminous base section
- Flame tilting angle into the downwind direction
- SEP (surface emissive power) of the luminous and smoky flames
- Flame base length & width (including flame drag due to wind)
- Major and minor axes of the elliptical top

Based on an initial analysis of rectangular pool fire results, two assumptions are made to develop correlations for these flame variables:

(1) Each of the flame variables of rectangular pool fires can be correlated to the pool fire of a reference square pool which has its side length equalling the shorter side of the rectangular pool.

(2) Fire characteristics of the reference square pool fire, i.e. flame length, tilting angle and SEP, can be approximated to that of a circular pool of the same pool area and can be predicted using the pool fire model implemented in Phast/Safeti.

Assumption (1) can be expressed by a formula below:

$$\frac{\boldsymbol{P(rectangular\ pool)}}{\boldsymbol{P(reference\ square\ pool)}} = \boldsymbol{Func\_P(aspect\ ratio, relative\ wind\ angle)} \qquad \text{Equation 1}$$

Where

P: Flame variables needed for pool fire calculation, i.e. flame length, tilt angle, SEP, flame drag and flame shape

Reference square pool:

The square pool which has its side length equalling the shorter side of the rectangular pool. Flame variables of the reference square pool is estimated using the correlations for circular pool fire as given by Mudan (1995) and in the theory manual of Phast/Safeti (2019).

Aspect ratio (AR):

Ratio of bund length to bund width

Relative wind angle:

Relative angle between wind direction and bund width as shown in Figure 2.

Correction factor: Func_P:

Correlations developed based on KFX simulations for each of the flame variables. Instead of deriving the correlations, correlation tables are used for each of the variables based on KFX simulations of selected cases as given in Figure 3. The selected cases cover aspect ratio up to 4 and four wind directions between bund length and width directions. *Axx* in the graphs indicates wind angles relative to the pool orientation as illustrated in Figure 2, A30 means wind is 30 degrees from X axis. In theory, this model can only be applied for rectangular pool fires with aspect ratio less than 4. However, the model is allowed for rectangular pool fires with higher aspect ratios as shown in the test cases below in model validation. In current model, correlation factors are interpolated for aspect ratios between 1-4, extrapolated between 4 - 5 and remain constants beyond 5.

Once the flame variables are obtained using equation (1), incident radiation received by an observer from the fire can be calculated as:

$$I = VF * SEP$$

I is incident radiation, *SEP* is surface emissive power (W/m^2) of the flame. View factor, *VF* ($0 \le VF \le 1$) is an integrated value depending on the relative position between the target and the flame.

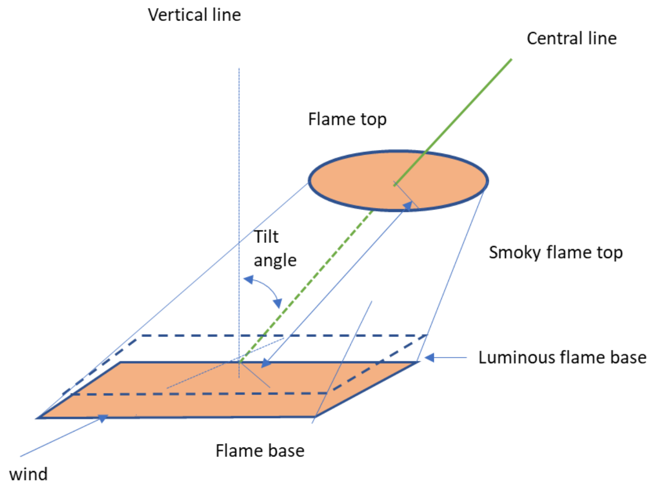

Figure 1 flame variables defining a rectangular pool fire in the model

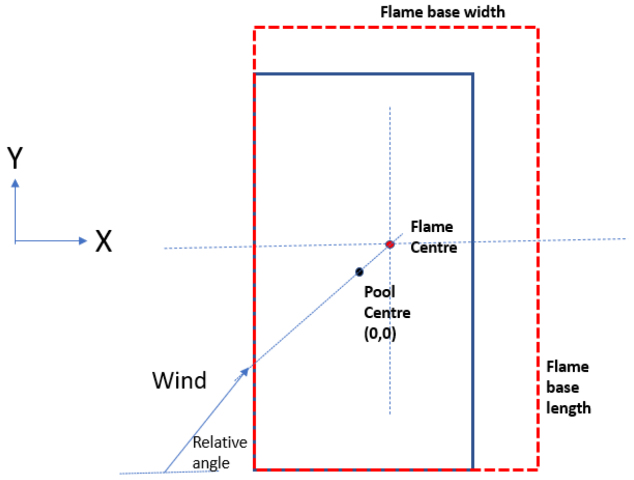

Figure 2 Plan view of a rectangular bund and wind direction

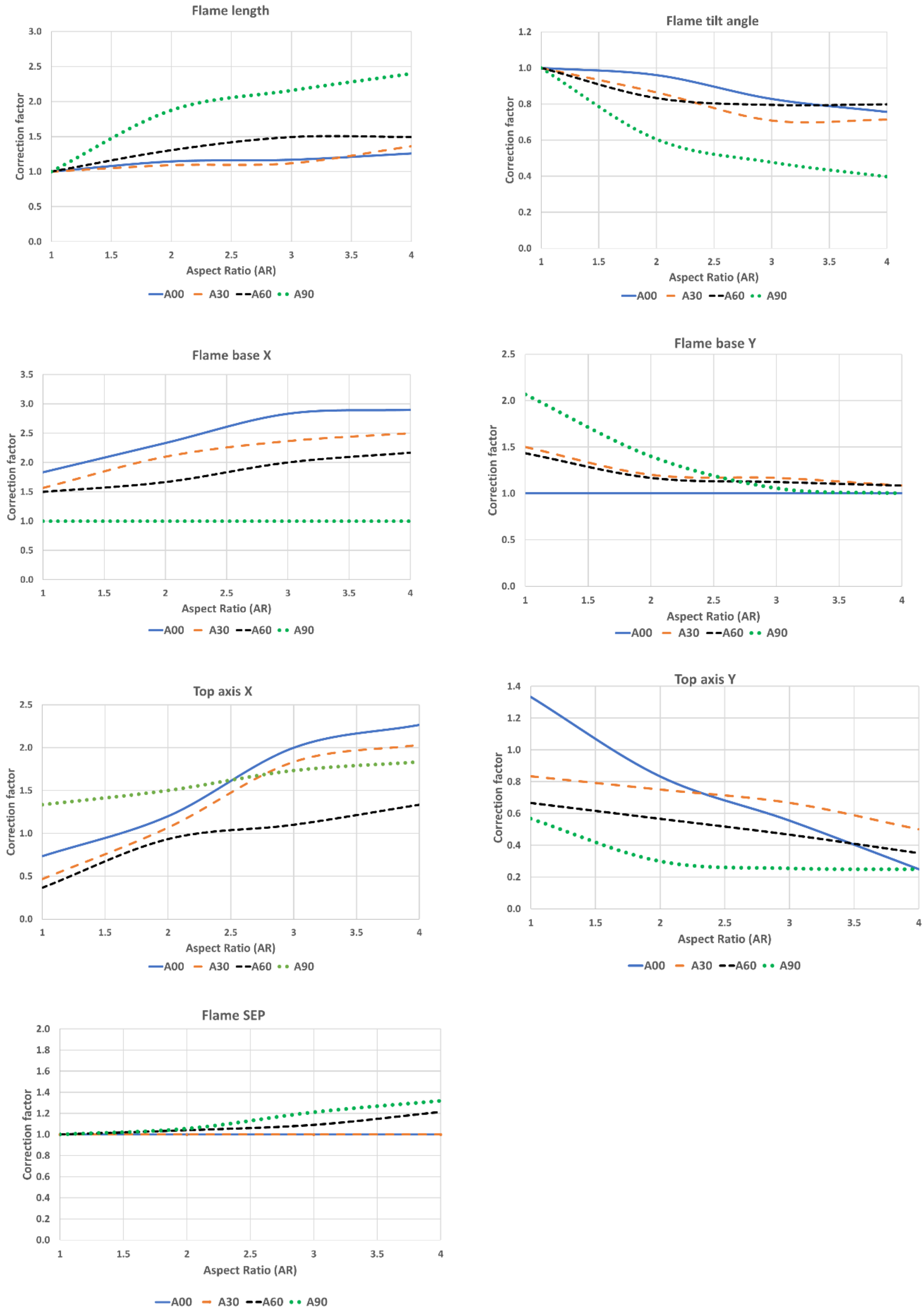

Figure 3 Correlations tables developed based on KFX simulations

4. Model validation

Gasoline rectangular pool fires by LASTFIRE (2021)

On behalf of a consortium of 16 oil companies a project was initiated in the late 1990s to review the risks associated with large diameter (greater than 40m) open top floating roof storage tanks. The project was known as the LASTFIRE project (Large Atmospheric Storage Tanks). In 2021, the LASTFIRE consortium, as part of an extensive programme to assess the performance of new firefighting foams with less environmental consequences than those used currently, conducted a series of tests of trench fires at the GESIP facility in Vernon, France (Plastow, 2021). The test trench is a specially constructed concrete pit with a size of 50 m x 6 m (300 m^2) as shown below in Figure 4. Fuel used in the tests is gasoline and is a relatively "clean" C7 based fuel. Fuel was pumped into the test pit using onsite equipment so that the depth of the fuel was approximately 150 mm in the ends of the test pan and 50 mm in the middle section. Between tests the fuel level was topped up as appropriate. Water was used in the bottom of the test pit such that a freeboard of approximately 300 mm was available in the tests. An overview of the fuel properties used in the pre-experiment simulations is given in the table below.

Table 1 Fuel properties of the LASTFIRE tests

Properties	*Symbol*	*Value*
Heat of combustion [MJ/kg]	ΔH_c	43.7
Max. mass burning of fuel [kg/m²s]	$\dot{m}''_\infty$	0.055
Mean beam length corrector extinction coefficient product [m^{-1}]	kβ	2.1
Max. surface emissive power [kW/m²]	E_∞	130

Tests were conducted in June and November 2021. In each test, the fire was burning freely up to 120 seconds from the start, after which it was extinguished. Radiation was measured around the test pit by radiometers as shown below in Figure 4, locations of radiometers varied between tests. Ambient conditions were measured at the site during the tests and Table 2 summarises the ambient conditions used for model validation.

Figure 5 shows the pool fire of Test 6 of the November tests. At a wind speed of 3m/s, strong flame tilt and flame drag were observed in this test.

Figure 6 compares the predicted radiation and measurements for Test 1 of the June tests. The model has produced good predictions which have matched the measured trend closely. Figure 7 compares model predictions against measurements of all tests. Here, the diagonal line in the figure represents predictions that match perfectly with measurements. The lower dotted line represents a predicted incident radiation that is a factor of two below the measured incident radiation. The upper dotted line represents predicted incident radiation that is a factor of two above the measurements.

Observations of the modelling results are:

- Most of the predictions are within factor of 2 of the measurements, i.e. within the two dotted lines as shown in Figure 7. On average, there is an overprediction of 39.3% comparing with the measured maximum radiation of all tests.
- There are a few outliers of overpredictions as shown in Figure 7. Most of the locations with overprediction higher than 50% are for radiometers located very close to the trench, radiation at these locations turns to be very sensitive to fluctuations of wind speed and direction.

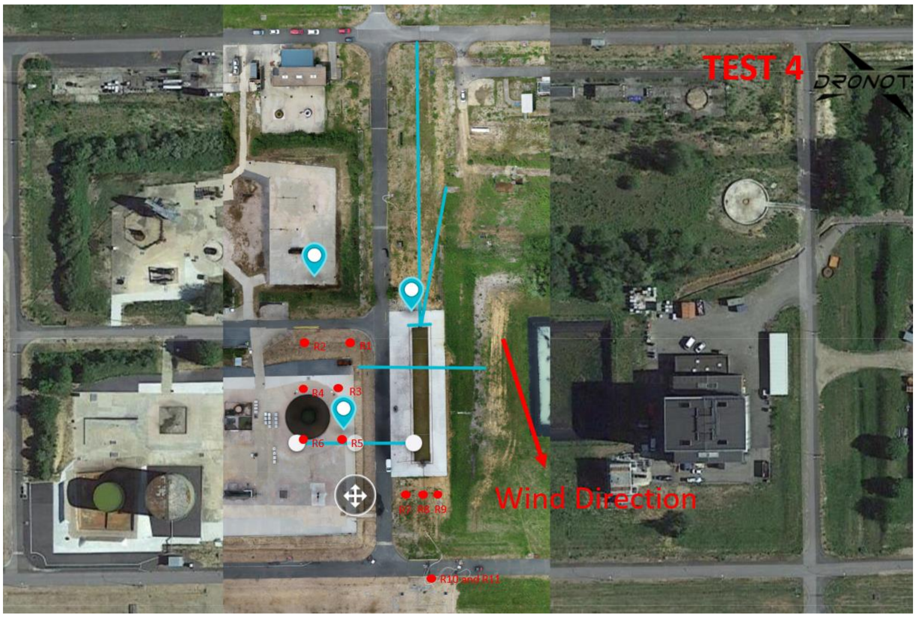

Figure 4 Plan view of the test site and locations of radiometers (location of radiometers varied between tests)

Table 2 Ambient conditions for the LASTFIRE tests

	Ambient temperature	Ambient humidity	Wind speed	Wind direction
Test 1	13	67	2	-100
Test 2	20	68	4	-100
Test 3	15	69	3	-70
Test 4	19	50	2	-75
Test 5	20	43	1	-90
Test 6	15	91	1	70
Test 7	20	68	0.8	0
Test 8	17	86	0.2	90
Test 9	18	78	0.9	-100
Test 10	21	72	0.9	145
Test 11	14	90	0.4	-50
Test 1*	5.2	72.5	3	72.5
Test 2*	7.3	67.2	3	67.2
Test 3*	8.4	66.4	3	66.4
Test 4*	3.6	90	1.3	90
Test 5*	3.8	90	3.1	90
Test 6*	5.6	81	0.7	81
Test 7*	2.1	92	0.4	92
Test 8*	3.8	91	1.6	91
Test 9*	5.9	92	1.5	92

* Tests in November 2021. All other tests were carried out in June 2021

Figure 5 Test 6 of the November test

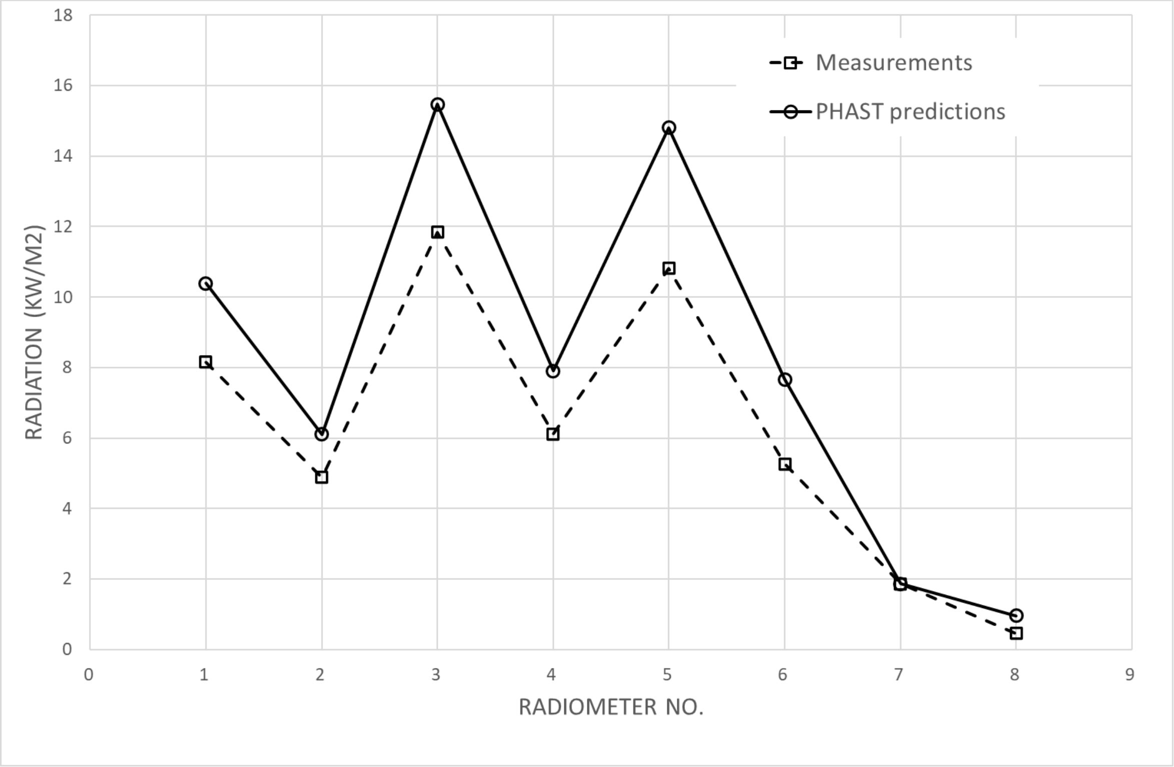

Figure 6 Comparing predicted radiation against measured max radiation for test 1 of the June test

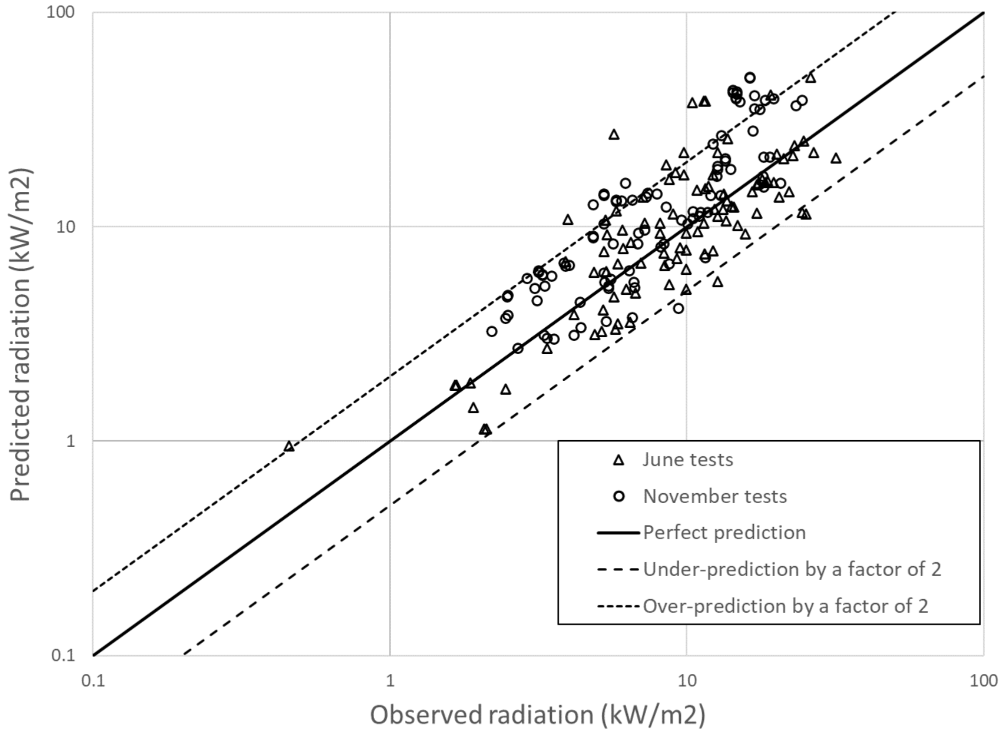

Figure 7 Comparing predicted radiation against measured max radiation for all tests by LASTFIRE in 2021

LNG trench fires by Croce, Mudan & Wiersma (1986)

To ensure the thermal radiation model was accurately predicting incident radiation from LNG trench fires, tests of LNG trench fires were carried out by former British Gas Corporation at the Spadeadam test facility for the Gas Research Institute (GRI) USA. The tests were conducted to understand fire behaviours and thermal radiation from large-scale LNG trench (elongated pool) fires. Thirteen tests were performed with nominal trench sizes ranging from 0.82m x 4.4m to 3.9m x 52.1m, and aspect ratios ranging from approximately 5 to 30. Table 3 summaries the setup and ambient conditions of the tests. Incident radiation were measured at downwind, upwind and crosswind locations with wide-angle thermopile radiometers.

Figure 8 compares the model predictions against measurements of all tests of the LNG trench fires (Test 5 was excluded from the validation due to incomplete data on ambient conditions from the report received). As for the LASTFIRE tests, most of the predictions are within a factor of 2 of the measurements. On average, there is an overprediction of 5.9% comparing with the measurements of all tests included. However, consistent under-predictions are observed at the crosswind locations.

Table 3 Test conditions of the LNG trench fires

Test No.	Trench Length (m)	Trench width(m)	Ambient temperature	Ambient humidity	Wind speed	Wind direction
Test 1	23.53	1.81	4.5	94	3.8	-3.6
Test 2	15.52	1.81	2.0	92	1.5	12.9
Test 3	9.23	1.83	2.1	91	1.0	47.0
Test 4	23.50	1.83	6.6	90	8.36	3.0
Test 5*	9.05	1.82	--	--	9.31	--
Test 6	23.45	3.94	15.8	68	4.98	-177.0
Test 7	23.45	0.82	21.8	69	3.80	1.0
Test 8	11.82	0.82	20.0	95	2.05	9.0
Test 9	9.10	0.82	13.0	83	5.40	157.7
Test 10	52.05	3.89	16.1	88	7.05	5.6
Test 11	4.37	0.81	17.0	73	5.90	173.0
Test 12	52.15	1.82	13.9	72	8.60	-10.5
Test 13	23.10	0.77	14.5	85	3.69	-14.5

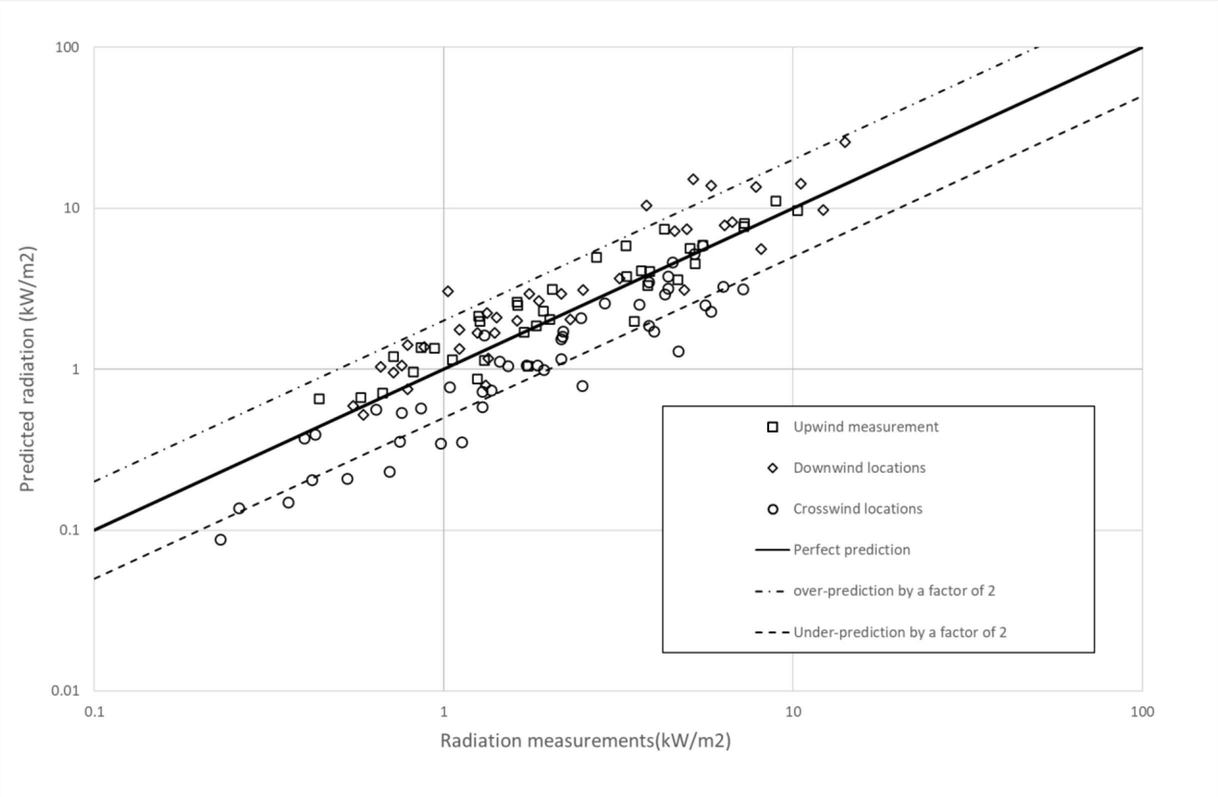

Figure 8 Comparing predicted radiation against measurement of all tests by Croce, Mudan & Wiersma (1986)

5. Conclusions

A new solid-flame model is developed based on empirical relationships as well as correlations derived from CFD simulations of a series of designed cases using KFX (a CFD tool) for large-scale rectangular pool fires and trench fires. The model is validated against measurements of LNG trench fires by Croce, Mudan & Wiersma (1986) and rectangular pool fires of gasoline by LASTFIRE (2021). The predictions are generally conservative and are within factor of 2 of the measurements.

Initially this model was developed for rectangular pool and trench fires with modest aspect ratios and the CFD simulations that form the basis of the model have aspect ratios up to 4. However, a lot of the test cases have higher aspect ratios up to the highest AR of about 30. The validation results are generally reasonable as presented in this paper. This validation seems to indicate the method used to estimate correction factors in the model works adequately for pool fires up to an AR of 30. For pool fires with AR higher than 30, we can't recommend the model as it is outside the validation range and possibly a single flame representation of the fire may still give reasonable results. More validation is required to test its capability for pool fires of mixtures and heavy hydrocarbons.

As part of the ongoing research into foam effectiveness, LASTFIRE have carried out some similar large-scale tests with ethanol in 2022. Measurements of these tests will be used to provide further validation of this model in due course.

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