The Use of CFD for Modeling Pool Fires

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INTRODUCTION

When an analysis is performed of the thermal response of a transport flask to a pool fire test it is usual for the analysis to concentrate upon heat transfer within the flask, with the fire being represented by specified boundary conditions. These boundary conditions usually represent heat transfer by both radiation and convection and are normally based upon the parameters specified in the IAEA Regulations (e.g. a temperature of 800°C) (IAEA 1990).

Computational Fluid Dynamics (CFD) codes potentially have the ability to model the flames of a pool fire from a knowledge only of the size and nature of the fuel pool and the atmospheric conditions. Such codes are being increasingly used to model fires as part of fire engineering studies in unusual geometries such as tunnels, offshore oil rigs, and large open buildings. Although modeling the flames of a fire is currently not necessary for demonstrating the compliance of a package with the IAEA Regulations, it could be useful in investigating the behavior of various postulated fire accidents, in the planning of some pool fire tests (e.g. on unusually large containers), and in investigating the likely heat fluxes to containers of unusual geometries in a pool fire test. Any analytical method which can help reduce the number of pool fire tests which are required, and hence the costs involved and the smoke pollution which is produced, is worthy of consideration. A program of work has therefore been carried out to test the ability of a CFD code to produce realistic estimates of the flame size, shape and temperature in a pool fire test, and the resulting heat fluxes to objects within the flames.

After selecting a suitable CFD code a series of two-dimensional calculations was first performed to test and develop its pool fire modeling capability. The code was then validated by modeling, in three-dimensions, a practical pool fire test performed on an instrumented, cuboid, steel vessel. Other calculations were performed using this model to test the ability of the code to correctly predict the experimentally observed effects of vessel thermal capacity, wind, and flame guides. Finally two calculations were

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performed modeling a pool fire test on a large container, to investigate problems that performing a test on such a size of container may present.

DESCRIPTION OF THE MODEL

After considering several possible candidate CFD codes, the code CFDS-FLOW3D (CFDS 1991) was selected as the most suitable for the purpose since it was efficient, had good geometric flexibility, had an accurate and flexible radiation model, and included several combustion models as standard options.

When the standard code was first used to model, in two dimensions, a 5m wide pool fire engulfing a cuboid vessel of side 1m, the results were disappointing with no flames being predicted below the vessel. This was attributed to a lack of turbulence to mix the fuel and air and produce combustion. It is observed in practical tests that the burning of the fuel produces localized turbulence, and this was not being represented. A small source of turbulence proportional to the rate of combustion was therefore added to the model. This was found to produce far more realistic results. Other workers (Sinai 1995), using a later release of the code, have been able to produce realistic pool fire simulations, for wind blown situations, without this additional turbulence.

To model radiation it is necessary to attribute an emission coefficient to each cell within the flames. Because the flames are optically thick the calculated heat fluxes to engulfed objects are relatively insensitive to the assumed emission coefficient. A simple linear function relating the absorption coefficient to the fuel mixture fraction was therefore used. This linear function varied from zero for a mixture fraction of zero (i.e. no radiation absorption or emission in the clear air) to 2.0 at the stoichiometric mixture (i.e. undiluted combustion products). This function gave an average absorption coefficient of 1.0, the typical value observed experimentally in pool fires.

The model used the standard k-ε turbulence model and the Eddy Break-Up combustion model. The three-dimensional model contained over 83,000 cells. The calculations reported in this paper were performed using release 2.3.3 of the CFDS-FLOW3D code.

VALIDATION OF THE MODEL

To validate the CFD model a pool fire test on a 1m x 1m x 1m cube, carried out in AEA Technology's Pool Fire Test Facility (Fry 1992), was modeled. The experimental test vessel was constructed from 90mm thick mild steel plates which each acted as a calorimeter. The transient temperature of each plate was measured from which the absorbed heat flux on each surface was determined. The incident radiation flux onto each surface was also measured using Direction Flame Thermometers. These simple instruments, developed at Winfrith, have been described previously (Fry 1989 and Burgess & Fry 1990). The fuel source in the test was a pool of kerosene, 5m x 5m. The pool thus extended 2m beyond the vessel in each direction and satisfied the geometrical arrangements for a pool fire test specified in the IAEA Regulations. The particular test which was modeled (test TSV-1) was performed in light wind conditions (1.5m/s average). Flame guides constructed from thin steel plates were placed below the test vessel to promote more uniform flame cover.

In the test, which lasted for 15 minutes, the incident and absorbed heat flux both varied significantly with time, largely due to fluctuations in the wind conditions. The calculation, however, modeled only a steady state situation. This needs to be constantly borne in mind when comparing measured average temperatures against predicted values.

Calculation 1 - No Wind

A calculation was first performed modeling a pool fire test upon the test vessel in perfectly calm conditions (a condition which is seldom achieved experimentally). The predicted temperatures in the vertical plane through the center of the vessel are shown in Figure 1. The flame shape, thickness, and temperature is predicted to be identical on either side of the vessel. The flame shape is similar to that observed in practical tests. The peak temperature of 1259°C is, however, greater than that measured in the tests. It is important to remember, that this is a localized, peak gas temperature, while the heat flux to temperature instruments in practical tests is dominated by radiation rather than convection. Experimental measurements are therefore more a measure of the local radiation flux than the thermodynamic gas temperature.

To enable a more meaningful comparison with the experimental measurements, the results from the calculation have been post-processed to determine, from the calculated radiation fluxes, the temperature that would be measured by Directional Flame Thermometers mounted on each of the vessel faces. These temperatures are shown in Table 1. The highest temperature, 1078°C, is measured on the top of the vessel. This temperature is significantly lower than the peak gas temperature of 1259°C and much more realistic of temperatures typically measured in pool fire tests. This example serves to demonstrate the importance of considering the design of instruments and what they are actually measuring when comparing experimental results against theoretical predictions.

Calculation 2 - With Wind

The second calculation which was performed with this model was identical to that previously described except that a light wind of 1.5m/s was imposed blowing directly onto one of the faces of the test vessel. Imposing a light wind is complicated by the fact that the fire itself produces air flows of a similar magnitude because of the buoyant plume. A fixed air velocity was therefore only imposed over the upper part of the upwind boundary in the model so that the fire could draw in air freely over the lower part of the boundary at a greater velocity if desired. The predicted temperatures in the vertical plane through the center of the vessel are shown in Figure 2. This plane is parallel to the imposed wind.

Comparison with Figure 1 shows that the imposed wind has only a fairly small effect upon the predicted flame temperatures but has a significant effect on the location of the flames. These are predicted to be blown under the bottom of the box and rise up on its downwind side. The upwind side and top of the box are therefore almost completely bare of any flame cover. This result illustrates well the sensitivity of flame cover to the wind conditions and is typical of the behavior observed in early experimental test at Winfrith. These tests led to the development and recommendation of the use of flame guides below the test vessel to help promote more uniform flame cover (Burgess and Fry 1990).

The temperatures which the model predicted that Directional Flame Thermometers on the vessel faces would measure are shown in Table 1. As would be expected from the observed changes in flame cover, the temperatures on the upwind and top faces are significantly lower than that predicted in the absence of wind. The temperatures predicted on the bottom and downwind faces are increased only moderately because the flame cover was already fairly optically thick in these directions even in the absence of any wind.

Calculation 3 - Wind and Flame Guides

In the final calculation which was performed using this model, a thin wall, representing the flame guides, was placed below the test vessel. The imposed wind conditions were identical to those in the previous calculations. The predicted temperatures in the vertical plane through the center of the vessel are shown in Figure 3. The wind still has a significant effect upon the flame cover around the vessel, but the cover on the upwind face and the top is significantly better than that which was predicted without the flame guides.

The temperatures which it was predicted would be measured in a test are again shown in Table 1. The increased flame cover to the upwind and top faces of the vessel can be seen to result in significant increases in measured temperature compared to the previous case.

The average temperatures measured by the Directional Flame Thermometers on each face of the vessel in test TSV-1 are also shown in Table 1. Since the test was performed in the presence of wind, and with flame guides below the vessel, the experimental results should only be compared against the predicted temperatures from the wind and flame guides calculation. To help in the judgment of how well the experimental results are reproduced, the standard deviation in the experimental measurements is also shown as an indication of the magnitude of the fluctuation in measured temperatures with time.

The model correctly predicts that the DFTs on the bottom face will measure higher temperatures than those on the top face and, considering the magnitude of the measured fluctuations, produces a reasonable estimate of the measured temperatures. The model somewhat overpredicts the difference between temperatures measured on the upwind and downwind faces. This may be due, in part, to the calculation being performed for the average wind conditions and then compared against average measured temperatures. It is probable that the effect of wind speed upon predicted temperature is highly non-linear and the short periods of almost calm wind conditions in the test have a disproportionate effect upon the average measured temperatures.

On the two side faces parallel to the wind, the average temperature is predicted reasonably well, especially considering the magnitude of the fluctuations in measured temperature. It can be seen that there is a difference between the temperatures measured on either side. This is due to the direction of the wind in the test not being exactly parallel to the sides, as was assumed in the calculations. This difference in wind direction in the test and calculation may also have contributed to the observed difference between measured and predicted temperature on other faces (e.g. on the downwind side).

In the above calculations the test vessel was modeled as having cold walls. This is a reasonable approximation to the conditions in the test where the thick steel walls remained effectively cold (relative to the flames) during the short test. Experimentally, it had previously been observed that lower flame temperatures are measured during tests on vessels which have a large thermal capacity and hence remain effectively cold (Fry 1992). This was postulated to be due to the heat absorbed by the vessel cooling the flames. A test was performed, using the CFD model, to determine whether this effect could be confirmed theoretically. A calculation was performed, with no applied wind, with the surface of the test vessel represented as being adiabatic, rather than at a fixed cold temperature. The results did indeed show an increase in the temperatures which it was predicted a DFT on the surface of the vessel would measure. This increase ranged from 71°C on the sides to 153°C on the top.

MODELING A FIRE TEST ON A LARGE VESSEL

AEA Technology is currently developing a type 'B' container, for transporting drums of waste, based on a 6.1m long, 2.4m wide and 2.6m high ISO container. As a demonstration of a possible application of the CFD pool fire model, a regulatory pool fire test upon this container has been modeled. Little information is available on the practicality of subjecting such a size of container to the regulatory IAEA pool fire test and, if it proved necessary to perform a practical test upon the package, as part of its safety submission, the results of the CFD calculation could be used to determine the most effective arrangement of flame guides and size of pool and the degree of flame cover that might be expected.

A three-dimensional model was used similar to that described above for the small cuboid test vessel. Two calculations were performed, one with the pool of kerosene extending 2m beyond each side of the container and one with the pool extending 3m, the maximum size permitted under the IAEA regulations. In both calculations a light wind of 1.0m/s was assumed blowing perpendicular to the long faces of the container. A flame guide was represented below the container running, in the center, along its length. This model contained 121,000 cells. The container was assumed to have insulating walls and so its surfaces were modeled as being adiabatic.

With the smaller pool of fuel reasonable flame cover was predicted on the upwind side, bottom and ends of the container but very poor flame cover on both the top and downwind side. The poor flame cover on the top was caused by the flames not being high enough to cover the top. The poor flame cover on the downwind side was a result of large vortices which were generated, at the downwind vertical edges, by a combination of the wind and buoyant flames. These vortices had the effect of drawing the flames on the downwind side towards the ends of the container, leaving most of the side of the container without any flame cover.

The average temperatures which it was predicted that Directional Flame Thermometers on the surface of the container would reach were locally as low as 317°C. It was predicted that while almost all of the bottom face would experience effective flame temperatures of over 800°C, only a small fraction of the top and downwind face would get this hot. Overall only 51% of the surface of the container would be exposed to flame temperatures of 800°C or over.

With the larger pool the same behavior was observed but the flame cover was somewhat improved, particularly on the downwind side. The predicted temperatures which would be measured by a DFT on the surface only went as low as 434°C. Overall still only 62% of the surface of the container was predicted to experience flame temperatures in excess of 800°C, even though the pool of fuel was the maximum size permitted under the IAEA regulations.

CONCLUSIONS

It is concluded that the CFD code CFDS-FLOW3D can make a reasonable prediction of flame shape and temperature in a pool fire and has been able to reproduce several phenomena which were observed in experimental tests. CFD codes should therefore be considered as a practical tool for modeling pool fires upon transport flasks. This may be required, for example, in order to investigate particular postulated fire accidents or in support of practical pool fire tests.

The turbulence, combustion, and soot formation models in CFD codes are continuing to be developed. This will, in principle, make the codes more accurate. However, because of the large fluctuations in temperatures and flame shape which occur, mainly as a result of fluctuations in wind conditions, these improvements will be of only limited benefit to the modeling of practical pool fire tests.

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TABLE 1 CALCULATED DFT TEMPERATURES

CASE	CALCULATED TEMPERATURE OF DFT (°C)					
LOCATION	TOP	BOTTOM	EAST FACE (UP-WIND)	WEST FACE (DOWN-WIND)	NORTH FACE	SOUTH FACE
NO WIND	1078	979	995	991	992	992
WIND	692	1037	414	1079	840	840
WIND AND FLAME GUIDES	788	1056	583	1072	931	931
EXPERIMENT (TEST TSV-1) - AVERAGE	716	803	719	804	888	843
EXPERIMENT - STANDARD DEVIATION	135	157	115	74	77	135

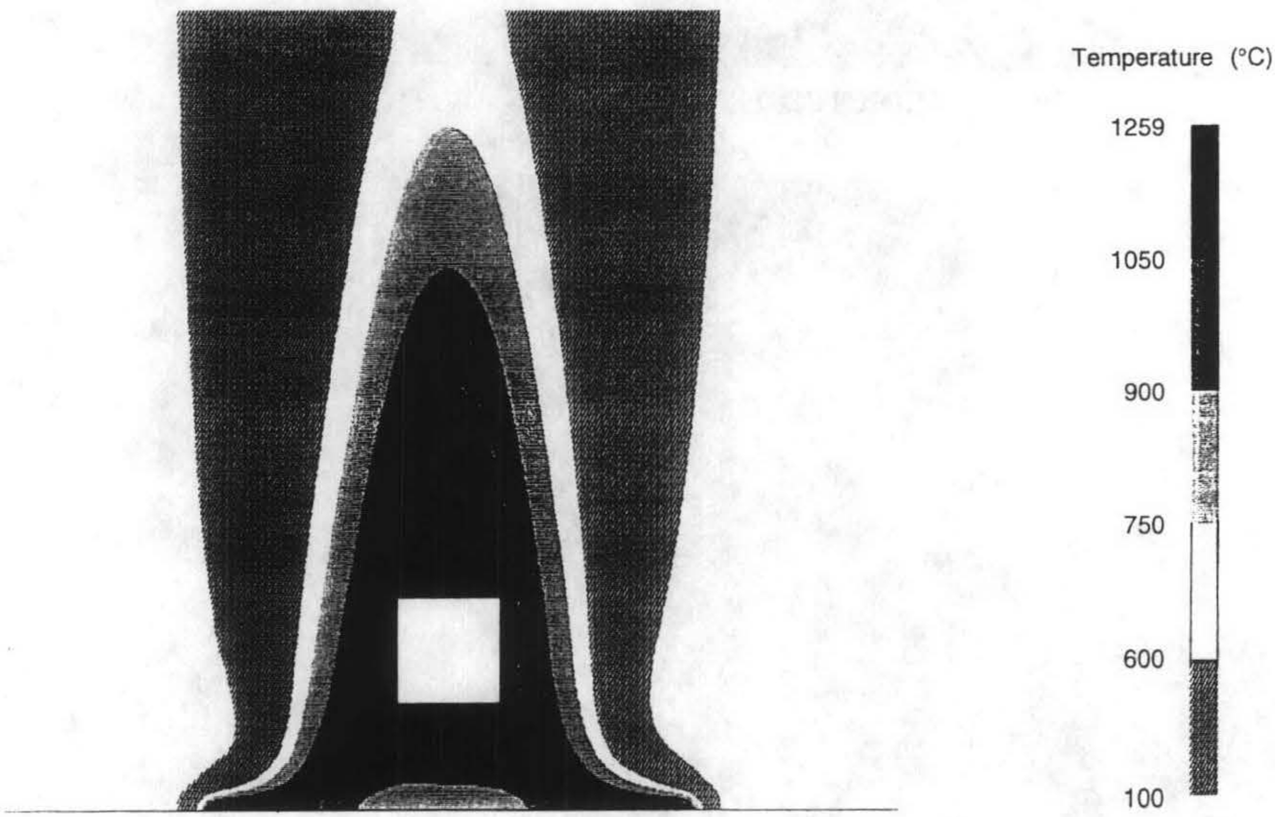

FIG.1 PREDICTED TEMPERATURES - NO WIND

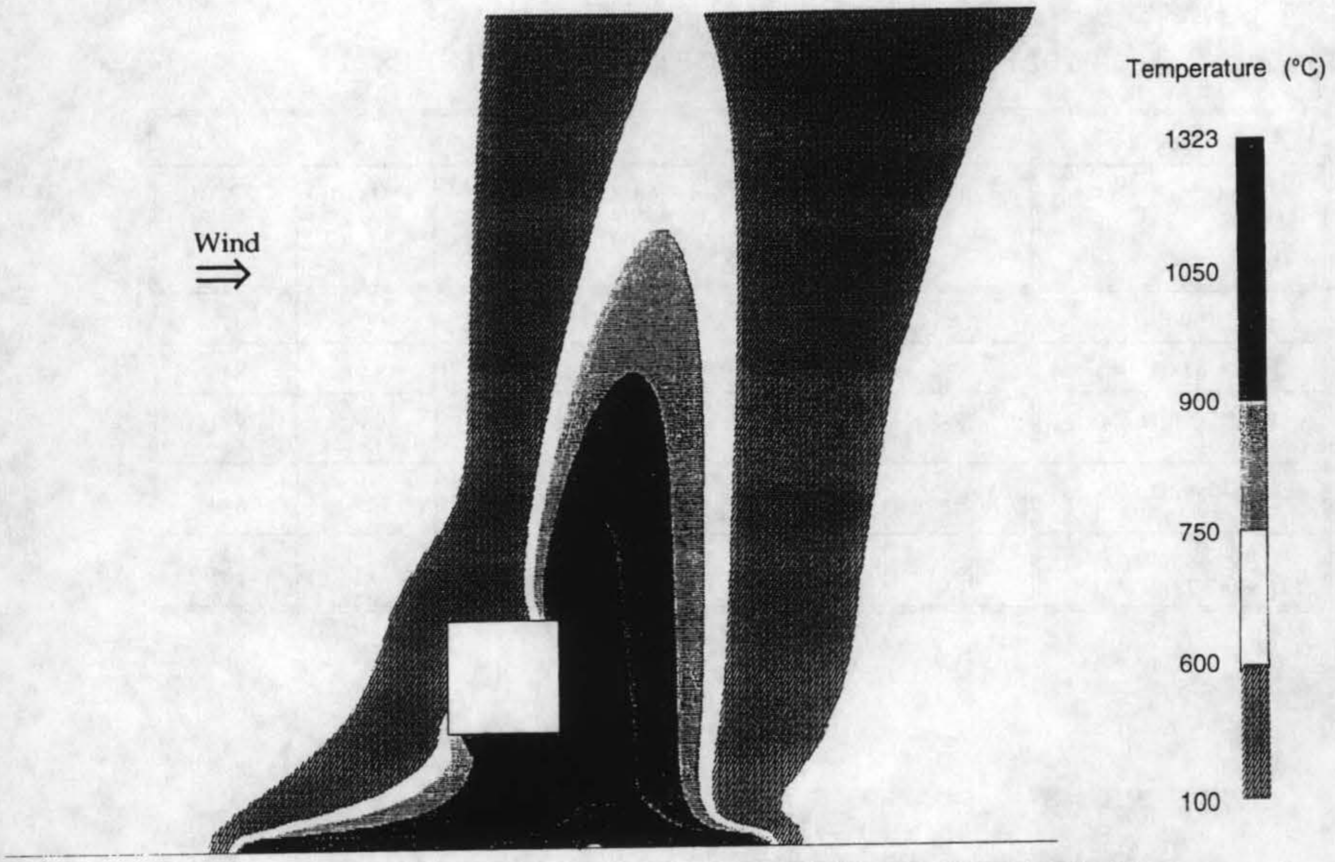

FIG.2 PREDICTED TEMPERATURES - WITH WIND

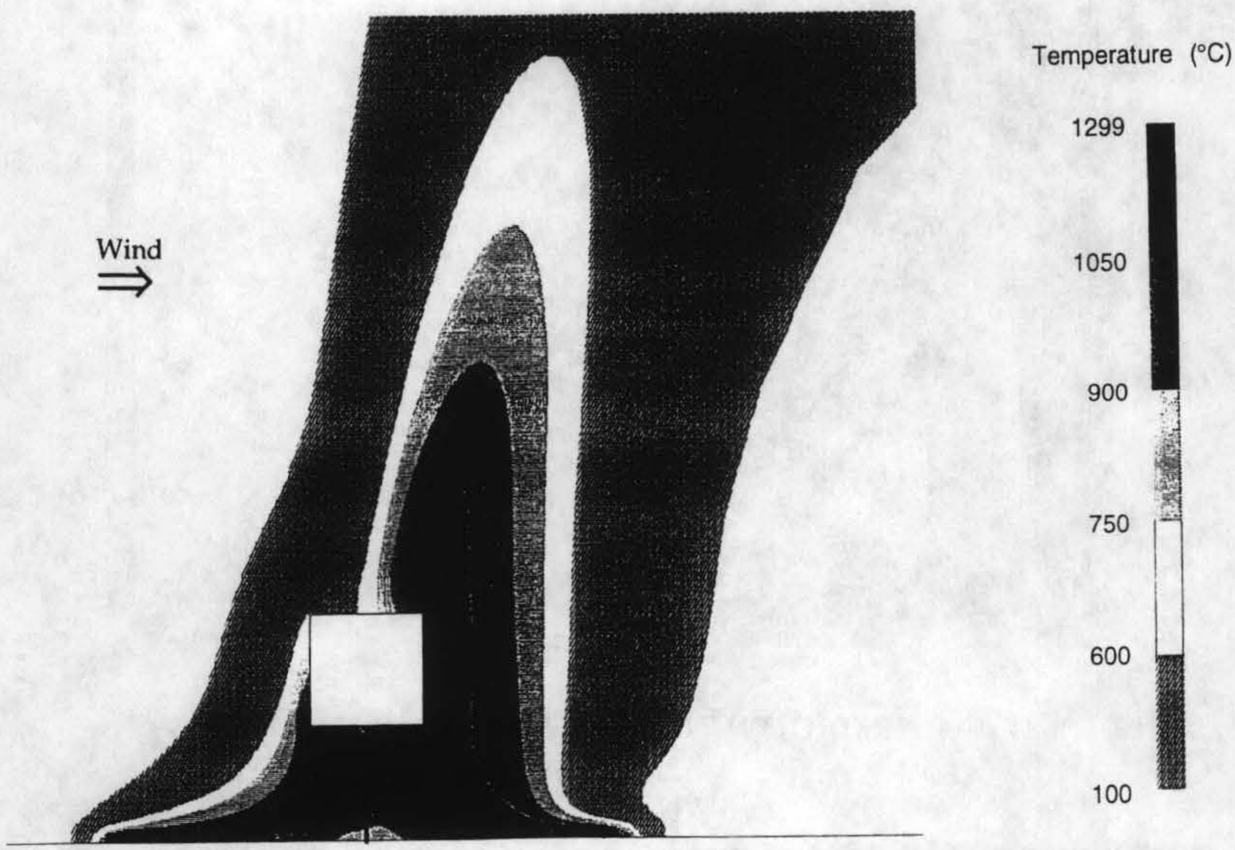

FIG.3 PREDICTED TEMPERATURES - WITH WIND AND FLAME GUIDES