

LARGE-SCALE POOL FIRES

by

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Review paper

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A review of research into the burning behaviour of large pool fires and fuel spill fires is presented. The features which distinguish such fires from smaller pool fires are mainly associated with the fire dynamics at low source Froude numbers and the radiative interaction with the fire source. In hydrocarbon fires, higher soot levels at increased diameters result in radiation blockage effects around the perimeter of large fire plumes; this yields lower emissive powers and a drastic reduction in the radiative loss fraction; whilst there are simplifying factors with these phenomena, arising from the fact that soot yield can saturate, there are other complications deriving from the intermittency of the behaviour, with luminous regions of efficient combustion appearing randomly in the outer surface of the fire according to the turbulent fluctuations in the fire plume. Knowledge of the fluid flow instabilities, which lead to the formation of large eddies, is also key to understanding the behaviour of large-scale fires. Here modelling tools can be effectively exploited in order to investigate the fluid flow phenomena, including RANS- and LES-based computational fluid dynamics codes. The latter are well-suited to representation of the turbulent motions, but a number of challenges remain with their practical application. Massively-parallel computational resources are likely to be necessary in order to be able to adequately address the complex coupled phenomena to the level of detail that is necessary.

Key words: *pool fires, spill fires, large-scale, radiation, soot, modelling*

Introduction

Pool fires concern flames developed over horizontal fuel surfaces (as opposed to wall fires which involve vertical fuel surfaces) [1-4]. Generally, these surfaces have defined boundaries and if a liquid fuel is involved its depth is established through the accumulation of fuel in the prescribed area. If there is no fuel confinement then a spill fire may result, with the fuel layer thickness being determined by the equilibrium of forces affecting the motion of the fluid flow. These fires are often large and shallow, requiring specific considerations [4-6]. Intensive research has been carried over decades on these subjects [1-4, 6], though only a small proportion of the work has looked specifically at large-scale pool fires [1].

For confined liquid pool fires, the area of the fuel surface is usually limited by the physical barrier providing fuel containment. They can burn for long periods if fuel remains available and often at high burning rates (guaranteed by the effective limit on heat losses to the substrate) [1, 2]. Spill fires move along the surface, the dimensions of the spread being controlled both by the physical properties of the fuel and the nature of the substrate, and thus are more difficult to precisely define. Nevertheless, local accumulation of fuel tends to be small (layers are thinner) and heat losses to the substrate are correspondingly larger. They therefore tend to be large, and of shorter duration. Large surface areas also imply poorer air entrainment, therefore enhanced soot production [7, 8].

Considering fires occurring after fuel releases more generally, it may be appreciated that pool fires are simply a part of a wider continuum of possible burning regimes [1, 2]. For example, a pool fire may be a consequence of a major fuel release in the absence of an ignition source, which allows fuel to build up before being ignited. However, liquid fuels may also be volatilised to form a cloud of combustible mixture, with subsequent gas-phase ignition and establishment of a vapour-cloud fire; if the burning region then moves back towards the spilt fuel a pool fire is established, or alternatively if the spill is relatively small a jet flame issuing from the release location might ensue. Fuel releases in the presence of ignition sources can lead directly to jet fires, or if the release is very large, to the development of a fireball.

The present paper provides a discussion of the different physical factors affecting the behaviour of large pool fires. Special attention is given to large pool fires ensuing from spills.

Pool fires

Pool fire dynamics

For the purpose of description the structure of most pool fires may be split into a number of fairly well-defined zones:

- the liquid fuel itself; in deep pools there may be significant convective flow within the fuel which can affect the fuel vaporisation rate and hence influence the “external” characteristics of the fire; the interaction between the fuel and the vessel which surrounds it (if any) may also have a big impact on the burning behaviour,
- a zone of unburnt fuel vapours above the fuel, which is usually a good approximation to a constant conical shape,
- a zone of luminous flame surrounds the cone of vapour, also with a fairly constant shape,
- a further combustion region above this zone, but here there is intermittency and obvious turbulence in the flaming, and
- the non-reacting buoyant plume, which is generally fully turbulent in nature and is characterised by decreasing velocity and temperature with height and lateral position.

Each individual zone has been extensively described in the literature and numerous studies have investigated the different parameters controlling the behaviour in each

regime and their interactions [3]. The resulting fire is then quantified via a number of “measurable quantities”, of which the main ones are [9]:

- burning rate or mass loss rate: these are closely related to the heat release rate; historically, burning rate has been expressed in terms of a “regression rate” given as an effective depth of fuel consumed per unit time,
- heat release rate (HRR): the total amount of heat energy released by the fire per unit time (*e. g.* kW); the heat release rate per unit area is also often used for pool fires [kW/m^2]; occasionally these values are taken to mean the convected energy only, but this convention is best avoided as it can be a source of confusion,
- flame height: the distance from the burning surface to the flame “tip”, which is often taken to be the point of 50% intermittency [10],
- flame temperature: most usefully, some characterisation of the distribution of temperatures; often given as mean centreline values, with radial variations [11],
- smoke production rate: may be expressed volumetrically [m^3/s] or gravimetrically [kg/s],
- radiation: described either as the emissive power at a given point in space [kW/m^2] or as the sum of all heat lost by radiation [kW]; the latter is often normalised by the total heat release rate, the “radiative loss fraction” [12], and
- puffing frequency: the quasi-regular formation of toroidal vortices at the base of the fire [10].

These measurable quantities are controlled by a number of “physical characteristics” associated with the pool, ranging from simple parameters to highly complex phenomena, including:

- pool geometry (diameter, depth, substrate),
- fuel composition,
- ventilation conditions (wind, forced or restricted ventilation, *etc.*),
- surrounding geometry (open air, compartment height, proximity to walls, *etc.*), and
- nature of the bounding materials, *i. e.* those used to construct the lip of liquid pool fire trays.

These physical characteristics affect the burning behaviour of the pool and are assessed by the measurable quantities. The fundamental underlying phenomena are now discussed in more detail.

Early experiments with pools of liquid fuels showed that there are two basic burning regimes for pool fires: radiatively-dominated burning for pools with “large” surface areas, and convectively-dominated burning for “small” pools [13, 14]. Other ways of defining large pools are discussed in the next section. Nevertheless, diameters smaller than ca. 0.2 m will always fall into the category of “small” pool fires and this paper will not discuss these any further.

The burning rate per unit area (and hence most other characteristics) of a pool fire increases with tray diameter up to a limit of about 2-3 m, beyond which it becomes largely independent of diameter or may decrease slightly [15, 16]. This dependence is related to the burning regime which becomes increasingly dominated by radiation as soot levels rise, up to a value where the fire is effectively optically thick and saturated. Several studies indicate a slight decrease in burning rate at very large

pool diameters (~ 10 m), but there is not enough data to accurately describe this for general cases [15].

To estimate the mass loss rate, \dot{m} , (the " symbol indicates a value "per unit area" and the dot above the quantity indicates a rate) of a pool fire in the open air, the following equation may be used [9, 15]:

$$\dot{m} = \dot{m}_{\infty} (1 - e^{-\kappa\beta D})$$

where \dot{m}_{∞} is the mass loss rate per unit area for a very large pool, κ – the absorption-extinction coefficient of the flame, β – the "mean beam length corrector", and D – the pool diameter. The HRR of a pool fire may be estimated from this expression if the heat of combustion (Δh_c) of the fuel is known and a value for the combustion efficiency, χ , can be determined:

$$\dot{q} = \dot{m} \Delta h_c A \chi$$

where A is the surface area of the pool. Tables of values of \dot{m}_{∞} , $\kappa\beta$, and Δh_c for most common liquid fuels can be found in the literature (*e. g.* ref. 15). It should be noted that the burning behaviour of alcohol pools is different from most other hydrocarbon fuels as the burning rate does not vary significantly with diameter, with generally $\dot{m} = \dot{m}_{\infty}$; this is due to the fact that alcohols burn very cleanly, producing little soot.

Principal factors influencing the "measurable quantities" associated with pool fires are given in next several subsections. This summary is largely based on refs. [3, 15].

Ventilation effects

The effects of wind or other applied ventilation on a pool fire are complex. Depending on the ventilation rate, there may be an effect of convective enhancement. The ventilation may also bring about improved mixing and more efficient combustion which will tend to increase the flame temperature [17]. Furthermore, the plume will be displaced which will bring about a significant change to the radiation profile, and hence the rate of vaporisation of the fuel. Several studies (*e. g.* [18]) show strong increases in the burning rates of large open-air pools with increased wind.

The influence of ventilation is further complicated if the fire is confined within a compartment, corridor or tunnel. Under these circumstances a pool fire, particularly a large one, may well be significantly under-ventilated in "natural ventilation" conditions and any applied ventilation may therefore enhance the burning rate. This is particularly common in tunnel fires at the onset of forced ventilation [19]. The combination of ventilation and a confining geometry tends to produce a much larger deflection of the flames than ventilation will on its own. Much of the recent research into these phenomena relates to the flame behaviour in tunnels [20-22], but some of the trends observed here are applicable to forced ventilation in any restricted geometry conditions.

Bounding materials

Most “pool fires” discussed in the literature are, essentially, “tray fires” or “pan fires” – that is, they are fires of liquid fuel contained within a vessel with walls of a finite height, allowing the fuel to exist as a layer of sufficient depth. As noted above, the burning behaviour of such fires is different to that of unconfined “spill fires” which are discussed separately in subsection *Spill fires and layer thickness effects*. Studies of reasonably small pools [17] have shown substantial variation in burning behaviour with changes in the materials used to construct the pan, primarily through differences in heat losses. There are a number of edge effects due to the “lip” of a pan, which exists where the pan extends above the fuel surface to confine the liquid. These include greater turbulence near the base of the flame (which leads to higher convective heat transfer), a shorter flame height, higher gas emissivity, and changes in the gas-phase temperature distribution (hotter near the surface) [23]. These changes are consistent with an enhancement in the burning rate, as noted by Orloff [24]. However, in certain circumstances, the lip may also cause a decrease in the burning rate [25], a result which might be expected if the additional heat losses are important. Thus, the overall effect may vary from case to case, and Babrauskas [15] noted that there was insufficient data on lip height effects. This is currently still the case.

Boilover

Some fuels, especially hydrocarbons with significant moisture content, do not exhibit steady burning behaviour but, on attaining a certain temperature will start to boil rapidly, possibly causing overflow of the pan and expanding the fuel surface area. This phenomenon has been discussed in detail in early pool fire literature [26] and in subsequent papers and reviews [27, 28].

Pulsation

Turbulent flames exhibit a pulsing behaviour. This has been studied in detail by many researchers, and reviewed by Pagni [29], Malalasekera *et. al.* [30], and Joulain [3]. In general, the oscillation frequency is well-correlated by a Strouhal-Froude number relationship (where $St = fD/V$, $Fr = V/(gD)^{1/2}$ which gives frequency as a function of the inverse root of the source diameter, D , and the square root of the acceleration due to gravity, *i. e.* $f \propto (g/D)^{1/2}$. Thus, frequencies become lower in large pool fires, but at a reducing rate as source diameter increases. Pulsations can have a large effect on air entrainment, and thus on the completeness of combustion and soot production, so this issue has a wider significance.

Transient effects

Most analyses of pool fires consider steady-state burning. However, in the initial stages of a fire there are a number of non-steady effects, due to heat losses to the sides of the pan, heating of the fuel itself and heat losses to the base of the pan. These are particu-

larly important in shallow pools and are all consistent with a steady increase in the burning rate. Another transient effect in the “steady-state” burning phase may become evident if the increase in effective lip height becomes significant as the fuel level diminishes. Ultimately, there is often a change in the nature of burning as the layer thickness diminishes, with consequently greatly enhanced heat transfer and reduced combustion rates. Furthermore, many fuels, such as crude-oils, may vary strongly in composition during burning, leading to a complete absence of a steady burning regime [31].

Spill fires and layer thickness effects

As indicated above, the fuel thickness may not be sufficient to achieve steady-state burning in thin layers, *e. g.* shallow pans or spill fires. Even if the initial volume of fuel spilled is known, it is still necessary to estimate the spillage area, how much fuel is consumed in the first stages of the fire and, hence, how much fuel remains for the “fully involved” phase. There are a number of uncertainties with these fires which have not been adequately investigated to date, for example, the effects of slope of the substrate or interaction with winds [4]. Nevertheless, many other dependencies have already been clarified in a range of experimental studies [4].

Most previous research on spill fires has concentrated on establishing the burning rate and the potential size of the spill, which together determine the overall heat release rate of the fire. The size of the spill, *i. e.* the surface area, is clearly of great importance but it is also very difficult to define given the many variables involved in the spill process, including the initial momentum of the fluid, the fluid surface tension, and the porosity and roughness of the substrate materials [4]. Fuel depths are typically in the range 0.7 to 4 mm but any uncertainty in this parameter corresponds directly to a difference in surface area, and hence fire size. More fundamentally, the size and conditions in a spill fire depend on whether it is “continuously flowing” or “instantaneous (static)”. In the former case, the spill area will be determined by the balance between the supply rate and the rate of consumption of the fuel whilst for the latter it will be necessary to determine the rate of change of the surface area. It has also been demonstrated that spill thickness can decrease after ignition, due purely to the change in fuel properties, with a potential increase in surface area, and hence fire size, of approximately 50%. Comparisons with deeper pools have shown that the burning rate in shallow spills is depressed by the drastic reduction in convective currents within the fuel and by enhanced heat losses to the substrate [31]. Typically this results in a five-fold reduction in burning rates between unconfined spills and deeper liquid pool fires of identical area.

Efforts have also been devoted to analyzing flame spread rates [4-6] which may be controlled by effects in the liquid-phase or gas-phase, depending on fuel temperature. For the former case, it seems that reduction of internal convective transport and enhanced heat losses in shallow spills lead to slower spread rates of the order 0.01-0.12 m/s, compared with the 1.3-2.2 m/s for gas-phase controlled flame. For very shallow pools (depth ≤ 2.0 mm), a point may be reached at which flames no longer spread away from the ignition location [5]. Flames can also spread over porous surfaces, typically at very low velocities [6].

Non-spread of flames due to heat losses has not been studied in great detail. Nevertheless, it is of great importance in some specific cases of large pool fires. One of the most relevant applications where non-spread is a critical issue is *in-situ* burning of oil spills for remediation purposes. In this case non-spread represents the main limitation for the use of the technique. While the conclusions presented by Gottuk and White [4] still apply, for spills on water there are a number of further complexities associated with the relative motion of the fuel and the water substrate. A detailed review of the effects of fuel layer, weathering and emulsification of the fuel on flame spread rates is presented by Wu *et al.* [5].

Soot production

Soot production in fire plumes is a highly complex subject due to the spatially-varying formation and oxidation processes, the influence of turbulent fluctuations and strong temperature- and fuel-dependent effects. Nevertheless, a number of researchers, notably Faeth and co-workers [32], have had some success in identifying factors which allow simplified analysis [33, 34]. Their reviews [32, 33, 35] provide generalised state relationships for major gas species and soot; it was established that soot in the overfire (fuel lean) regions of the plume varies with fuel type but is relatively independent of position in the plume and that beyond a certain flame residence time the yield reaches an asymptotic value (and thereafter depends only on mixing levels). In the underfire (fuel rich) region, there are strong correlations between soot volume fractions and temperature, and the soot is largely confined to a narrow region of mixture fraction and temperature, *i. e.* exists in nearly constant temperature layers. Furthermore, despite the difficulty in correlating soot yields to mixture fraction, there has been some success in predicting soot yields using global kinetics models [*e. g.* 36, 37]. The latter, for example, is a multi-step model including nucleation, coagulation, and surface growth processes, using flamelet representations of each to accommodate the influence of variations in mixture state (for a number of hydrocarbon fuels). This approach successfully overcomes the limitations which are present in correlations to mean mixture fraction, but there remain some approximations due to turbulence interactions. In particular, radiation calculations are typically based on mean properties, and Gore and Faeth [35] have shown that spectral intensities might be increased by 40-100% from estimates based on mean properties.

Other workers have developed methods for relating the emissivity and/or extinction coefficient of the fire gases to the soot concentration. Modak [12] proposed a simple grey gas model (*i. e.* with no spectral resolution) and Yuen and Tien [38] generalised this by considering data from flames of gaseous, polymer and wood fuels [1]. de Ris [39] and Lallemand *et al.* [40] have reviewed more advanced models, which do include spectral resolution in a finite number of bands (*i. e.* weighted sum of grey gas models and narrow band models, *etc.*). The results of Shaddix *et al.* [41] suggest that the absorptivity of agglomerating soot shows only minor variations with different fuels and flame types. A different approach is followed by Lautenberger *et al.* [42] who use the classic principle

of the smoke point to relate soot production to material properties [43] and produce a generalised numerical methodology to establish soot volume fractions.

Heat transfer

At laboratory scale, experimental studies have shown that the mass-burning rate of a solid fuel in a horizontal oxidizing stream flowing parallel to its surface is dominated by the convective heat transfer to the gas-solid interface, with a negligible contribution from radiation [44]. The same is true of liquid pool fires which are sufficiently small (<0.3 m) [13, 14]. However, radiation will be the dominant mode of heat transfer in most practical fire scenarios involving liquid fuels [1, 3, 44, 45].

The thermal radiation hazard from a pool fire is related mainly to the fuel type and the fire size, *i. e.*, pool diameter and flame height [46]. More specifically, radiative heat loss is directly related to the quantities of the major combustion products (CO₂, H₂O, and CO) and soot in the flames and plume. Soot may often be the dominant influence on the optical properties in large fires, and it has been established that the majority of the radiation in fire plumes (>90%) is derived from the visible part of the flame, where soot particles are radiating heat [47]. In moderate-sized liquid pool fires a strong correlation has been demonstrated between radiative flux near the plume and the fuel-dependent rates of soot and combustion product generation [16]. For larger hydrocarbon fires, beyond about 3 m in diameter, the fire gases become optically thick, such that the effective emissivity of the fire tends to unity and the emissive power saturates [1, 48-51]. This can also happen at smaller diameters with strongly sooting fuels. Beyond this point, radiative loss to the environment will tend to be dominated by the fire temperatures and soot concentrations towards the outside of the plume, underpinned by an effective fire gas emissivity of unity. However, empirical evidence shows that in sooty fires of still larger diameter the emissive power is substantially reduced, by a factor of up to 6 [1, 49, 50]. This is thought to occur due to the presence of thick black smoke on the outer periphery of the fire, which acts as a blockage for radiation release [1, 50]. In turn, this effect compounds the reduction in optical thickness so that the effective radiative loss fraction for the fire can drop to very low values. This issue is complicated by the fact that there is strong intermittency in the appearance of hotter luminous zones on the external surface of the fire, associated with turbulent mixing, such that averaging approaches are no longer valid; this is discussed in the next section.

The transition from convective to radiative dominance in the heat transfer is of special importance in the spread characteristics of spill fires and in the ultimate size of these flames. A summary of the existing work is presented in refs. [4, 5].

Large pool fires

A number of phenomena which become apparent as we progress towards larger fires have been mentioned in the context of the general pool fire review, including:

- decrease in the frequency of the pulsation, or regular eddy shedding, according to the inverse square root of the source diameter,
- optically-thick conditions are typically approached for source diameters of 3 m and more in hydrocarbon pool fires,
- beyond the optically-thick limit, there is a progressive decrease of the radiative loss fraction from a fire, with very low values reached in extensive pools due to the radiation shielding effect of the cooler soot clouds in the external surfaces of the plume, and
- the intermittency of radiative exposures once radiation shielding comes into play.

These issues are discussed in more detail below together with other key features of large pool fires. First of all, it is necessary to define precisely what is meant by “large” in this context. The terms large and small were initially introduced in distinguishing between radiatively- and convectively-dominated fires, respectively. However, the term “large pool fires” also has another meaning in the literature, or more colloquially, as pertaining to fires with sources which are physically of great extent, exemplified by liquid storage tank fires of diameter perhaps 10-100 m. To be more specific here, we shall distinguish these fires as any which are optically thick, *i. e.* typically from a diameter of 3 m or so upwards.

Such “large” pool fires, as distinct from general pool fires described, have been a subject of research for many years; nevertheless, the understanding of the different processes involved has not yet reached a level of maturity. The main efforts being currently undertaken can be divided into experimental and modelling; both are needed to further advance the field. The review of Howell *et al.* [45] on international efforts towards gathering radiation validation data for fire applications includes most of the large-scale experiments of interest. There has also been ongoing work at Sandia National Laboratories, USA [52-54], where detailed measurements have been conducted to identify soot production, flow fields and heat transfer mechanisms in large-scale liquid pool fires. Different sets of fire tests have also been conducted as part of oil spill mitigation programmes in the USA and Japan [55-57]. These experiments have been used to support the development of some aspects of the Fire Dynamics Simulator, developed at National Institute of Standards and Technology, USA [58-60].

Considering fundamental aspects of fluid flow in large-scale fires, it can easily be appreciated that Froude numbers ($Fr = V/(gD)^{1/2}$) tend to reach very low levels, since roughly constant velocities will arise if burning rates are approximately constant, but the source length-scale, D , continues to increase. Thus a key feature of *large-scale* pool fires is a relatively low initial velocity of the vaporised combustibles leaving the fuel surface. This low velocity, combined with the effects of buoyancy and low Reynolds number flow, presents a number of theoretical and experimental difficulties [3]. These are intrinsic to the behaviour of the fire since they control the interaction between fuel and oxidizer, the production of soot and heat feedback to the fuel. In particular, knowledge of the structure of such flows can be seen to be essential, since the vertical entrainment in the near-field is the dominant entrainment mechanism. Phenomenological models of entrainment based on large-scale vortex dynamics are required as a basis for scaling the near-field entrainment data.

The pulsation phenomenon in fire plumes is intimately related to the behaviour in the near-field. The unsteadiness leading to periodic oscillation is connected with the Rayleigh-Taylor instability due to the density stratification in the region where the flow necks above the fuel source. Experimental evidence and modelling results reveal strong acceleration along the plume axis within one burner diameter of the source. The formation of the toroidal vortex structure, which controls the eddy shedding, occurs at a height of around half a diameter, *i. e.* at the point where the streamwise velocity reaches zero. Following the work of Hamins [61], the review of Malalasekera *et al.* confirms the resultant Strouhal-Froude number correlations [30]. However, Joulain [3] comments that the mechanism involved in the instability is not yet completely understood, and highlights the role that Particle Imaging Velocimetry (PIV) measurements at larger scales might play in providing an improved understanding of these phenomena.

Recent research on large pool fires [62, 63] has identified the increased production of soot in large-scale fires as a key factor controlling their behaviour. Unlike in smaller fires, where flames are relatively clean-burning and soot emerges only at the flame tip, as we move towards increasingly large source diameters soot is produced in large quantities lower in the fire plume [3]. This requires breaking-down the core region of the pool fire into two well-defined sections:

- (1) the “luminous band” of the flame just above the surface of the pool, and
- (2) the upper parts of the plume, where the smoke generally obscures the flames.

Soot yields have been found to increase with source diameter, reaching approximately constant values (0.15 mass fraction) at source diameters beyond 2-3 m [64]. Despite extensive work on soot modelling, as above-mentioned, more still needs to be done before we are able to reliably characterise smoke concentrations in large-scale fires [3].

Radiative heat transfer in large pool fires has been studied extensively since the 1980's [1, 3, 65]. First of all, it is clear that radiative feedback to the pool surface controls the rate of burning for fire sizes beyond a metre or so [51]; this feedback is fuel dependent, with significant structural differences between low-sooting (*e. g.* alcohol) fires compared to hydrocarbon pool fires. Babrauskas presented a review for the purpose of estimating the burning rates of free-burning fires [15]. The inhomogeneity of fluxes across the surface of large pools has been confirmed both experimentally and numerically, as has the great influence of crosswinds [7, 8].

The fuel-rich region near the pool surface can greatly attenuate radiative feedback to the fuel thereby depressing the mass burning rate. This is the phenomena of “radiative energy blockage” and has been estimated at 25-35% in large-scale polymethyl methacrylate (PMMA) pool fires [3]. A similar phenomenon applies to external radiation with a significant decrease of the average emissive powers from the outside of large fire plumes, and a consequent decrease in the radiative loss fraction (which can fall as low as 3% at source diameters beyond 30 m [3]). However, more reliable methods for predicting radiative heat loss, accounting for the effects of radiation blockage, are still required (see next section).

The latter phenomenon is commonly seen in large hydrocarbon fires with a carbon-to-hydrogen ratio greater than about 0.3, where a substantial proportion of the external surface of the fire can be seen to be cloaked in an envelope of thick black smoke.

However, this smoke shield is not complete, and it opens up at intervals in random locations, according to the influence of the turbulent nature of the flow, bringing fuel to the outside where it can be combusted more efficiently, to release pulses of much more powerful radiation from the flames. Data from kerosine fires on land and gasoline fires on water indicates that the proportion of the external fire surface which is luminous is approximately 20%, on average. The intermittency of the “hot spots” makes computation of the radiation field around such fires problematic, though equivalent area approaches have been used [1].

Modelling of pool fires

Fire models have been developed and used for many years. They range from simple correlations, applied for specific purposes, to extremely complex simulation tools with many sub-models for different aspects of the problem. Which model is used in any particular scenario depends on the nature of the fire, the outputs required and the desired accuracy of the prediction. Important interests in pool fires typically include air entrainment, dispersion of combustion products, and heat transfer to adjacent objects; the latter is often the required output for risk analyses, *etc.* [3, 66].

Modelling pool fires presents a number of significant challenges derived from the fundamentally complex and highly coupled nature of the problem. In common with turbulent diffusion flames, the coupled turbulence-combustion-radiation processes control the behaviour of the fire plume; however, for pools, the additional complexity is that the volatilisation rate of the fuel is controlled mainly by the radiative feedback from the unsteady fire plume. This in turn is enhanced by the evolving soot loading and partially mitigated via absorption by fuel vapours above the fuel surface, both of which are very challenging to predict. The time- and length-scales associated with these processes span a broad range, and the behaviour of pool fires does not generally scale; therefore, despite great advances in computer technology in recent years, a compromise is generally required between the desired complexity (model resolution, number of sub-models, *etc.*) and the computational time required for the simulations. Nevertheless, some modern simulation tools are able to represent pool fires with a sufficient accuracy for certain applications, though only a small number of codes have thus far been validated against measurements for these cases.

The basis of any comprehensive model of a pool fire is the discretised form of the Navier-Stokes equations used for general fluid flow phenomena. These are known as Computational Fluid Dynamics (CFD) simulation tools. Different techniques for representation of turbulence are available [67], including RANS (Reynolds Averaged Navier Stokes) and LES (Large Eddy Simulation). A useful, though not critical, feature of the latter for pool fires is the explicit representation of the turbulent fluctuations in the fire plume; these are approximated in RANS codes using turbulence models, *e. g.* the buoyancy-modified $k-\varepsilon$ model. Direct representation of the major turbulent eddies provides a good basis for prediction of entrainment rates, provided the numerical grid is sufficiently resolved [68].

Most early work was based on RANS modelling, though with various restrictions or assumptions which limited the generality of the models [3]. The ability of these codes to predict the fire plume behaviour above pool fires in cross-winds was clearly demonstrated [69]. However, in this scenario, the computation is simplified by the fact that turbulence is convected into the combustion zone from the surroundings; far more challenging is the prediction of plume evolution in quiescent conditions, which demands simulation of the transition to self-generated turbulence. This too was demonstrated in further work [70], with successful prediction of the cyclic appearance of large vortical structures originating from the Rayleigh-Taylor instabilities at the base of the fire, and their subsequent evolution. Initial validation was performed with respect to experimental studies of a 20 m diameter kerosine pool fire in a stagnant atmosphere, though it was noted that more work was still needed [70]. More recently, RANS simulations of a 20 m kerosine fire were used as a basis for demonstrating that the mean surface emissive power from large-scale pool fires could be effectively modelled [71].

A number of other pool fire models have exploited the LES method. For example, the Isis-3D model [72] was developed as a dedicated LES code for simulation of heat transfer from large fires to engulfed packages for transportation risk studies. It employs semi-empirical models for fuel combustion/soot and radiation heat transfer models that are designed to provide reasonably accurate estimates of the total heat transfer to objects engulfed in the fire or nearby but of limited generality. A number of validation exercises have been described, comparing the model outputs with experimental data from several large pool fire experiments, up to 19 m diameter. Isis-3D accurately calculated the time-dependent temperatures in each case, with limited computational demands [72].

Another LES code developed specifically for fire applications is NIST's Fire Dynamics Simulator (FDS) [60, 73]. The code is based on a simplified form of the Navier-Stokes equations relevant to low-speed flows [74] and has since been parallelised [75]. Validation has been performed for a range of fire problems, including the characteristics of medium-scale [76] and large-scale pool fires [77, 78]. Of the latter studies, the first [77] examined radiative transfer for experiments with jet fuel in 15 m diameter trays; despite use of very large CFD cells reasonable predictions of radiative fluxes to remote objects were achieved. The second [78] relates to atmospheric dispersal of the fire plume from a pool of area ca. 100 m²; the focus here was the representation of far-field behaviour and favourable comparisons were obtained over distances of several kilometres.

Advanced LES simulations of pool fires are also being developed by the CSAFE group in Utah, USA [79]. Simulations on highly-resolved grids are achieved using massively-parallel computations, towards an end goal of prediction of detailed heat transfer to engulfed objects. Computationally efficient methods have been developed to incorporate detailed soot mechanisms and the sensitivity of the radiant heat transfer to the soot processes has been studied. For the case of a 20 m diameter pool fire, it has been shown that the simulation tool sufficiently captures global plume characteristics, including the puffing frequency and the qualitative trends in the velocity profiles close to the base of the fire.

Conclusions and areas for further research

Large-scale pool fires have been studied in great detail for several decades. The phenomenology behind them has been qualitatively characterized and many of the specific processes described to great extent. A series of well-defined parameters have been established to classify pool fires in a quantitative manner. Quantitative predictions of temperatures, air entrainment and species concentrations can be currently conducted but their precision is still unclear, especially for the more complex scenarios.

This review has clearly shown that despite the enormous body of work on large-scale pool fires there are still significant uncertainties in our understanding of such fires and capabilities to predict their behaviour. There is a critical need for more well-instrumented experimental studies, as well as further development and validation of detailed numerical models.

A particular application where knowledge is still in its infancy is the area of spill fires. Due to the nature of these fires, there are a large number of unknown factors that make such an event difficult to assess, predict or model. Uncertainties generally exist in the volume of fuel that has been spilled, the distribution of the fuel, the nature of the surfaces and the effects of the environmental conditions such as wind, temperature, as well as many other factors.

A challenge with all large-scale liquid hydrocarbon pool fires is the difficulty of undertaking experimental analysis due to the sheer scale of the fire. Also, great complexity is presented by a number of interrelated factors. Firstly, these fires are predominantly turbulent, meaning that dynamic vortical structures are present; secondly, the fire size is self-regulated, with the rate of heat release being controlled by heat transfer, mainly radiative, back to the fuel source; thirdly, heat loss from the fire plume is fundamentally controlled by the impact of complex sooting processes on radiative heat transfer. The latter problem, in particular, does not scale with fire size, with radiation blockage becoming increasingly important in larger fires and significantly depressing the effective emissive power of the fire plume; furthermore, radiative loss from the external fire envelope is spatially extremely variable, with intermittent pulses of energy from high temperature parts of the plume where fuel comes into contact with oxidizers. This is important if the interest is assessment or prediction of heat transfer to objects engulfed in a fire. Further detailed measurements are required, encompassing soot sampling and temperature characterization of the whole volume of the fire plume [65].

All of the above-mentioned aspects have to be properly accounted for if one wants to understand or model the performance of large pool fires. The intimate couplings, in particular, present severe challenges for simulation tools and there is a fundamental lack of knowledge on other aspects, such as the details of the sooting processes. Nevertheless, realistic models have been developed and demonstrated based on the comprehensive methodologies provided by CFD, including both RANS and LES approaches. The challenge of representing the complex coupled combustion/soot and radiation heat transfer processes within an environment fundamentally governed by turbulent fluctuations, over a large range of length-scales, is being effectively overcome by exploitation of advanced simulation tools. Simplifications have also been adopted to reduce the calculation

time, but these generally decrease the accuracy of the outputs. Massively-parallel computing may ultimately offer a vehicle to deliver robust analysis of these large problems, but the simulations will nevertheless remain very expensive and have other residual uncertainties.

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