

LARGE-SCALE POOL FIRES

by

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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 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, and LES codes, in particular, provide an avenue for further research.

Keywords: *Large-scale pool fires, Spill fires, Radiation, Soot production.*

1. Introduction

Pool fires are defined as flames established over horizontal fuel surfaces (as opposed to wall fires which involve vertical fuel surfaces). 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. Intensive research has been carried over decades on this subject [1-4], though only a small proportion of the work has looked specifically at large-scale pool fires [4].

An important variant on the pool fire problem is the liquid spill, where confinement of the fuel does not exist, with the fuel layer thickness being established by the equilibrium of forces affecting the motion of the fluid flow. In many such cases the fuel layer is thin, thus different considerations are necessary since the relative importance of heat transfer to the substrate is enhanced while convective currents tend to be suppressed. Furthermore, due to the lack of confinement the overall size of spill fires tends to be large. Thus, when addressing spills, specific considerations have to be made [4-6].

In general terms, liquid pool fires are confined in size by the physical barrier providing fuel containment. Nevertheless, 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 spread 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 losses to the substrate are correspondingly larger. Therefore, spill fires are expected to be shorter in height and duration and larger in effective diameter. Large diameters also imply poor 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 volatilise 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 will provide a detailed discussion of the different physical factors affecting the behaviour of large pool fires. Especial attention will be given to large pool fires ensuing from spills.

2. Pool fires

2.1 Pool Fire Dynamics

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 may affect the fuel vapourisation 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 significant influence over the burning behaviour.
- Above the fuel there is a reasonably constantly-shaped conical zone, rich in unburned fuel vapours.
- Surrounding the cone of vapour is a zone of luminous flame, also with a reasonably constant shape.
- Above this zone is a further combustion region, but here there is intermittency and obvious turbulence in the flaming.
- Finally there is the non-reacting buoyant plume, which is generally 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 described the different parameters controlling the behaviour of each zone and their interactions [3]. The resulting pool is then quantified via a number of "measurable quantities." The main "measurable quantities" associated to a pool fire are [9]:

- Burning rate or mass loss rate: these are closely related to the HRR. Mass loss rate is generally expressed in terms of kg/s. Historically, burning rate has been expressed in terms of a 'regression rate' given in mm/min (i.e. the surface is lowered by a number of mm per minute as the fuel is consumed in the fire).
- Heat release rate (HRR): the total amount of heat energy released by the fire, generally expressed in kilowatts (kW) or megawatts (MW). For pool fires this is sometimes expressed in terms of HRR per unit area (i.e. kW/m²). Occasionally this is taken to mean the convective HRR only, but this convention is best avoided as it can be a source of confusion.
- Flame height: generally expressed in metres (m). The flame tip is often taken to be the point of 50% intermittency [10].
- Flame temperature: actually a distribution of temperatures, often given as mean centreline values, with radial variations [11].
- Smoke production rate: may be expressed in m³/s or kg/s.
- Radiation: described either as the emissive power at a given point in space (kW/m²) or as the sum of all heat lost by radiation (kW), the latter often expressed as a percentage of the HRR [12].

A number of physical characteristics of the pool then control these “measurable quantities”. These physical characteristics vary from the very simple to the complex. A simple abbreviated list will include:

- 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.)
- Nature of the bounding materials, i.e. those used to construct the lip of liquid pool fire trays

In summary, physical characteristics associated with the pool fire will have a direct impact on the different zones and this impact is generally defined by means of “measurable quantities.” It is important to note that “zones” and “measurable quantities” are a practical way to describe a pool fire that has been found useful to breakdown a very complex problem but do not correspond to the fundamental physical parameters controlling the combustion and different transport processes. These will be discussed as follows.

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” diameters and convectively dominated burning for pools with ‘small’ diameters [13,14]. “Large” pool fires are difficult to define and potential definitions will be discussed throughout this paper. Nevertheless, diameters smaller than 0.2 m will always fall in the category of “small” pool fires and this paper will not discuss them any further.

The burning rate per unit area (and hence most other characteristics) of a pool fire increases with tray diameter up to about 2-3 m, beyond which limit 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 (~10m), but there is not enough reliable data to accurately describe this for general cases [15].

To estimate the mass loss rate (\dot{m}'')[†] of a pool fire in the open air, the following equation may be used [9, 15]:

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

[†] The '' symbol indicates a measurement ‘per unit area’, similarly ‘ indicates ‘per unit length’ and ''' ‘per unit volume’. The dot above the quantity indicates a flux.

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

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

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 [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, generally $\dot{m}'' = \dot{m}''_{\infty}$; this is due to that fact that alcohols burn very cleanly, producing little soot.

Joulain [3] presents much of the current (as of 1998) knowledge of flow structure in pool fires, as well as discussing air entrainment, soot production and radiation, pulsation phenomena and factors affecting the mass burning rate. An addition of particular importance is the study by Quintiere and Grove [11] which attempts to unify all entrainment correlations by means of basic scaling principles.

A summary of the principal factors influencing the “measurable quantities” associated with pool fires is given below. This summary is largely based on references [3,15].

2.2 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 (i.e. [18]) show significant 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 pool fire, may well be significantly under-ventilated in “natural ventilation” conditions and any applied ventilation may therefore increase the burning rate greatly. 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 from a pool fire 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.

2.3 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 significant height, allowing the fuel to exist as a layer of sufficient depth. The burning behaviour of such fires is different to that of “spill fires” which are discussed separately below. 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 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.

2.4 Boil-over

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 has been discussed in detail in early pool fire literature [26] and in subsequent papers and reviews [27,28].

2.5 Pulsation

Turbulent flames exhibit a pulsing behaviour. This has been studied in detail by many researchers and reviewed by Pagni [29], Malalasekera [30] and Joulain [3]. In general, the oscillation frequency is well-correlated by a Strouhal-Froude number relationship (where $St=fD/V$, $Fr=V/\sqrt{gD}$) 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, $f \propto (g/D)^{0.5}$. Thus, frequencies become lower in large pool fires, but at a reducing rate as source diameter increases. Pulsations have a significant effect on air entrainment, and thus on the completeness of combustion and soot production, therefore this issue will be further addressed in later sections.

2.6 Transient effects

Most analyses of pool fire burning 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, especially in shallow pools. These tend to produce 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. Finally, there is often change in the nature of burning as the fuel is consumed, with the layer thickness becoming very thin and consequently greatly enhanced heat transfer and reduced burning rates. Many fuels, such as crude oils, will strongly vary in composition during burning leading to complete absence of steady burning [31].

2.7 Spill fires and layer thickness effects

In shallow pans or in spill fires, the fuel thickness may not be sufficient to achieve ‘steady-state’ burning. 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’ fire. 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, main other dependencies have already been clarified in a range of experimental studies [4].

This 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 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 diameter.

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, c.f. 1.3-2.2 m/s for the latter). For very shallow pools (≤ 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 this technique. While the conclusions presented by Gottuk and White still apply, in this case 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].

2.8 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 & co-workers [32], have had some success in identifying factors which allow simplified analysis [33,34]. Their reviews [32,33,35] provided 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 & 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 & Tien [38] generalised this by considering data from flames of gaseous, polymer and wood fuels [1]. de Ris [39] and Lallemand [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 smoke point to relate soot production

to material properties [43] and produce a numerical methodology to establish soot volume fractions.

2.9 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 ($<0.3\text{m}$) [13,14]. However, in most practical fire scenarios involving liquid fuels radiation will be the dominant mode of heat transfer [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 (CO_2 , H_2O and CO) and soot in the flames and plume. Soot may often be the dominant influence on the absorption coefficient 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 products production [16]. For larger hydrocarbon fires, beyond about 3m 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 [1,50]. This effect compounds the reduction in optical thickness so that the 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 further in section 3 below.

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 references [4] and [5].

3 Large Pool Fires

A number of phenomena which are exhibited as we progress towards larger fires have been mentioned in the context of the general pool fire review section above, 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 reached in hydrocarbon pool fires at source diameters of about 3m,
- 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,
- 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 above 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 10-100m. To be more specific here, we shall distinguish these fires as any which are optically thick, i.e. often from a diameter of 3m or so upwards.

Such “large” pool fires, as distinct from general pool fires as described above, 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 on 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 in Albuquerque, New Mexico [52-54]. Here 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 extensively to support the development of some aspects of the Fire Dynamics Simulator [58-60].

Considering fundamental aspects of fluid flow in large-scale fires, it can easily be appreciated that Froude numbers ($Fr=V/\sqrt{gD}$) tend to reach very low levels, since roughly constant velocities will arise if burning rates are approximately constant, but the source lengthscale, 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 difficulties 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 needed as a basis for scaling the near field entrainment data. Modelling has an important role to play here, and the continuing development of LES codes should be strongly supported [3]. Furthermore, the pulsation phenomenon in fire plumes is intimately related to the behaviour in the near field. The instability 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 diameter of the source. The formation of the toroidal vortex structure, which controls the eddy shedding, occurs at a height of around half the nozzle or source diameter, i.e. at the point where the streamwise velocity reaches zero. Following the work of Hamins, [61], the review of Malalasekera 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 the behaviour of these fires. 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 2-3m [64]. Despite extensive work on soot modelling, as mentioned above, 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]. 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 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 30m [3]). However, more reliable methods for predicting radiative heat loss, accounting for the effects of radiation blockage, are still required, see section 4 below.

The latter phenomenon can commonly be 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, which brings fuel to the outside where it can be combusted more efficiently, to release pulses of much more powerful radiation from the flames. Data from kerosene 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 very problematic, though equivalent area approaches have been used [1].

4 Modelling of pool fires

Fire models have been developed and used for many years. These range from very simple models, for specific tasks, to extremely complex simulation tools with many sub-models used to predict different aspects of fire behaviour. Which fire model is used in any particular scenario depends on the scenario itself, the outputs required and the desired accuracy of the prediction. Current models are well adapted to study a number of large-scale effects including plume characteristics, dispersion of combustion products and heat transfer to adjacent objects; the latter is often the required output for risk analyses, etc [3,65].

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. Modern models are also still limited by a lack of detailed knowledge of the processes going on in the flames of a fire, e.g. soot formation, and chemistry/radiation-turbulence interactions. Nevertheless, modern models are able to simulate pool fires with sufficient accuracy to be useful. Some recent pool fire models are discussed below.

The Isis-3D model [66] employs fuel evaporation reaction rate and radiation heat transfer models that were designed to provide reasonably accurate estimates of the total heat transfer from large fires to objects engulfed in the flames or nearby. The model is able to reproduce the general characteristics of the object temperature and requires a fairly short computer turnaround time. In the cited paper [66] a number of ‘validation’ exercises are described, comparing the model outputs with experimental data from large pool fire experiments. Isis-3D accurately calculated the time-dependent temperatures in all three experiments.

The Navier-Stokes equations describe a rich variety of physical processes, many of which have nothing to do with fires. The complete solution of these equations is mathematically complex and computationally intensive. In order to use these equations in practical numerical simulation it is necessary to introduce simplifications. The observed zones described in section 1 provide the basis for simplifications to the Navier-Stokes equations that have enabled the development of useful numerical codes, known as Computational Fluid Dynamics (CFD). For example, the Fire Dynamics Simulator (FDS) [60,67] uses the simplified equations developed by Rehm & Baum [68]. These equations describe the low-speed motion of a gas driven by chemical heat release and buoyancy forces. The combustion research community generally refers to these as the “low Mach number” combustion equations. FDS uses the Large Eddy Simulation (LES) method to predict large-scale fire and plume behaviour that includes plume characteristics, combustion product dispersion, and heat effects to adjacent objects. The code was developed by the US National Institute of Standards and Technology (NIST). The model has been validated against fires of several types, including many pool fires [67,69].

LES models offer the opportunity for realistic fire modelling simulations to be performed that take into account the detailed behaviour of the fire plume, which is approximated in RANS codes using buoyancy modified k - ϵ turbulence models. In particular, the transient nature of the model allows the effects of entrainment to be modelled in detail. Accurate, time-dependent entrainment modelling is very important in fire scenarios as the time-scales are frequently short and the conditions may change rapidly, details which may be overlooked by a model employing an averaging technique. Although, LES modelling appears as the most promising technique, currently there are still many limitations to its precise application to large pool fires [70].

State-of-the-art methods for modelling pool fires on massively parallel computers are being advanced by the CSAFE group in Utah, USA [71]. A 20m heptane pool fire has been used as an archetypal fire for demonstrating the use of high performance computers to integrate multi-scale phenomena. Kinetic Monte Carlo methods have been combined with Molecular Dynamics to compute chemical structural growth of soot. A detailed soot mechanism has been incorporated in an LES fire simulation using the “Intrinsic Lower Dimensional Manifolds” (ILDm) method to reduce the degrees of freedom in the system from however many steps there may be in the soot formation reaction scheme (in this case, several hundred) down to just the mixture fraction, enthalpy, and extent of reaction. Preliminary soot volume fraction data from a 3-D fire simulation using the soot reaction model showed that soot appears throughout the flame and post-flame zones similar to what is observed in real pool fires. The sensitivity of the radiant heat transfer to the soot formation mechanism in these large-scale fires has also been studied. Simulations have reproduced features of large-scale fires such as initial roll-up of vortices and subsequent break-up from the continuous flame zone [71]. In the cited paper it is shown that the simulation tool captures global characteristics of large-scale pool fires, including the puffing frequency and the qualitative trends in the

velocity profiles close to the base of the pool fire. Despite the complexity of these simulations and the enormous computational cost, there are still many features associated with radiative heat transfer and species generation that can not be reproduced. Work on modelling pool fires thus continues [72-75].

5 Conclusions and Further work

Large-scale pool fires have been characterized 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.

The above sections have clearly shown that despite the enormous body of work on large-scale pool fires there are still significant uncertainties in our capability to predict the behaviour of such fires. There is a critical need for more well instrumented experimental studies as well as further development of numerical models.

A particular application where knowledge is still in its infancy is the area of spill fires. Due to the nature of spill 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 wind conditions, the initial temperature, the roughness of the surfaces and many other factors.

Large-scale (diameters $> 10\text{m}$) liquid hydrocarbon pool fires are difficult to analyze experimentally because of the sheer scale of the fire. Attempts to model large-scale pool fires are hindered by that lack of either:

- a mathematical closed form solution of the fundamental equations (mass, force, energy and transport), or,
- computational power that is able to simulate all the required lengthscales directly, or,
- models describing the nature of the chemistry and physics that provide filtered equations and closures of the fundamental equations in the range of length and time scales which can be resolved numerically.

Massively parallel computing may offer a vehicle to deliver simulation-science based analysis of such large-scale events, but these analyses are nevertheless very time consuming and have remaining uncertainties. Simplification models can reduce the calculation time significantly, but generally decrease the accuracy of the outputs.

Large-scale fires are turbulent, meaning that dynamic vortical structures are present. The fire chemistry requires reaction mechanisms that allow for soot formation, growth and oxidation. Radiation is the dominant mode of heat transfer in large pool fires and this is strongly affected

by the presence of soot. All these aspects have to be taken account if one wants to understand or model the behaviour of large pool fire, because they change the results – however, they are intimately coupled and hence very challenging to model.

Heat transfer from large-scale pool fires to adjacent objects remains a challenging and relevant problem. Important unknowns still remain when addressing radiative and convective heat transfer.

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