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Minimum Safe Distance from Pool Fires

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Radiation heat transfer is a primary reason for fire growth. Experimental data are needed to clarify the ignition potential and time required to ignite a particular target second item. The concepts of critical heat flux and thermal response parameter are important to the material ignition problem. The objective of the present contribution is to clarify these important radiant ignition concepts and to exemplify a range of realistic calculations related to real-world situations.

Introduction

FIRE dynamicists have a need to appreciate technical/scientific understanding of fire development phenomena and its applicability to real-world practical situations. In fire development, radiation heat transfer is a primary reason for fire growth. Uninvolved items become involved in a fire (and fire growth thus proceeds) via conduction, convection, and radiation heat transfer and/or direct flame contact (which is actually a combination of the three modes of heat transfer). Simple rules of thumb are available for 1) the heat release rate Q (kilowatt) of the first burning item, 2) the radiant heat flux $\dot{q}''$ (kilowatt per square meter) being received on the surface of an item R meters distant, and 3) the level of $\dot{q}''$ being required for ignition of the as-yet uninvolved subsequent item, typically taken as 10, 20, and 40 kW/m^2 being required for easy, normal, and difficult to ignite items, respectively.

The initial burning item in a fire is characterized in terms of its heat release rate (heat energy evolving on a per unit time basis) $\dot{Q}$ changing as the size of the fire changes, as a function of time t (second) after fire ignition. That is, the variation of $\dot{Q}$ vs t is extremely important in characterizing the rate of growth of a fire, and data are available for many items, (for example, see Refs. 1–3). Furniture calorimeter and cone calorimeter measurements are available. In the special case of liquid hydrocarbon pool fires, a systematic study over a wide range of pool diameters was conducted by Blinov and Khudiakov[4] and plotted by Hottel[5] with results available in tables and figures in Ref. 2.

With regard to the ignition of the second target item and its possible ignition from the radiant heat flux arriving on its surface, in actuality, even direct flame contact requires time to pyrolyze the fuel and time to heat the gases produced to their ignition temperature. Of course, a portion of the heat being received on the surface is transported away into the material by conduction and reradiated at the surface. Experimental data are needed to clarify the ignition potential and time required to ignite a particular target second item. The objective of the present contribution is to clarify these important radiant ignition concepts and to exemplify realistic calculations related to real-world situations.

Minimum Safe Distance from Flames

Theory

For many enclosure fires, it is of interest to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire to determine if secondary ignitions are likely. The radiant heat flux received from a flame depends on a number of factors, including flame temperature and thickness, concentration of emitting species, and the geometric relationship between the flame and the receiver. Although considerable progress is being made toward developing a reliable method for calculating flame radiation, a high degree of accuracy is seldom required in real-world fire engineering problems, such as estimating what level of radiant flux a plant item might receive from a nearby fire so that a water spray system might be designed to keep the item cool. Two approximate methods are now considered.

Considerations of inverse square distance lead to

$$\dot{q}''_0 = P/4\pi R_0^2 = x_r \dot{Q}/4\pi R_0^2$$

where

$\dot{q}''_0$ = incident radiation on the target, kW/m^2
R_0 = distance (radius) to target fuel, m
P = total radiative power of the flame, kW
x_r = fraction of total radiated from flame
Q = total heat release rate, kJ/s or kW

Usually, the radiative fraction x_r ranges from 20 to 60% (Ref. 2), depending on the fuel type (Table 1). The distance R_0 should be measured from the center of the flame. Experimental measurements indicate that this equation has good accuracy for values of R_0/R greater than 4, where R is the flame radius. The point-source nature of the heat from the flame is then a reasonable assumption.

In a second approximate method, the flame is approximated as a vertical rectangle and the radiant flux is calculated using view factor information. This takes into account the large size of the flame, with angles and orientations being accounted for appropriately. Flux levels close to the flame are then more accurately handled.[6,7]

Sample Calculations

Useful related calculations are now given in Table 2. The heat flux (in kilowatt per square meter) landing on a target is given as a function of total heat release rate $\dot{Q}$ (in megawatt) and distance away (in meters). A radiative fraction x_r of 0.4 is used in these calculations, typical of liquid hydrocarbon pool fires.

Radiant Ignition

Theory

In actuality, ignition is not immediate when the particular level of incident radiant heat flux reaches 10, 20, or 40 kW/m^2, respectively, for easy, normal, and difficult to ignite items. These values are used as simple rules of thumb in applied calculations (see Lilley[8] and Karlsson and Quintiere[9]). Fundamental ignition principles, for example, outlined in Ref. 2, suggest that for fire initiation a material has to be heated above its critical heat flux CHF value (CHF value is related to the fire point). The CHF value can be determined in one of several heat release rate apparatuses, including the so-called flammability apparatus and cone calorimeter. The design features, test conditions, and types of measurements vary as described in

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Table 1 Radiation fraction of combustion energy for hydrocarbon pool fires

Hydrocarbon	Pool size, m	% Radiative output/ combustion output
Methanol	1.2	17.0
LNG on land	18.0	16.4
	0.4–3.05	15.0–34.0
	1.8–6.1	20.0–25.0
	20.0	36.0
LNG on water	8.5–15.0	12.0–31.0[a]
LPG on land	20.0	7.0
Butane	0.3–0.76	19.9–26.9
Gasoline	1.22–3.05	40.0–13.0[a]
	1.0–10.0	60.1–10.0[a]
Benzene	1.22	36.0–38.0
Hexane	——	40
Ethylene	——	38

[a]In these cases, the smaller diameter fires were associated with higher radiative ouputs.

Table 2 Heat flux $\dot{q}''$ (kW/m^2) on target

Source total heat release $\dot{Q}$, MW	Distance of target from source, m 1	2	5	10
1	31.8	7.96	1.27	0.32
5	159.0	39.80	6.37	1.59
10	318.0	79.60	12.70	3.18

Ref. 2. Typically, the CHF values are determined by exposing the horizontal sample (for example, about 100 mm diameter or about 100×100 mm^2 and up to about 100 mm in thickness with blackened surface in the flammability apparatus) to various external heat flux values until a value is found at which there is no ignition for about 15 min.

It was found that, as the surface is exposed to heat flux, initially most of the heat is transferred to the interior of the material. The ignition principles suggest that the rate with which heat is transferred depends on the ignition temperature T_{ig}, ambient temperature T_a, material thermal conductivity k, material specific heat c_p, and the material density ρ. The combined effects are expressed by a parameter defined at the thermal response parameter (TRP) of the material

$$\text{TRP} = \Delta T_{\text{ig}}\sqrt{k\rho c_p}$$

where $\Delta T_{\text{ig}} (= T_{\text{ig}} - T_a)$ is the ignition temperature above ambient in degree Kelvin, k is in kilowatt per meter Kelvin, ρ is in kilogram per cubic meter, c_p is in kilojoule per kilogram degree Kelvin, and TRP is in kilowatt second$^{1/2}$ per square meter. TRP is a very useful parameter for engineering calculations to assess resistance of ignition and fire propagation in as-yet uninvolved items.

The ignition principles suggest that, for thermally thick materials, the inverse of the square root of time to ignition is expected to be a linear function of the difference between the external heat flux and the CHF value

$$\sqrt{1/t_{\text{ig}}} = \frac{\sqrt{4/\pi}(\dot{q}_e'' - \text{CHF})}{\text{TRP}}$$

where t_{ig} (s) is time to ignition $\dot{q}_e''$ is the external heat flux, and CHF is in kilowatt per square meter. Most commonly used materials behave as thermally thick materials and satisfy this equation. Tables 3–5 give the ignition times deduced from this equation, using CHF and TRP data from Table 6.

The TRP for a surface that is not blackened is higher than the value for a blackened surface. For example, for nonblackened and blackened surfaces of polymethylmethacrylate PMMA, TRP = 383 and 274 kW-s$^{1/2}$/m^2, respectively, from the flammability apparatus. The value for the TRP for a blackened surface of PMMA is close to the value calculated from the known T_{ig}, k, ρ, and c_p values for

Table 3 Ignition time t_{ig} (seconds) for CHF = 10 kW/m^2

External heat flux $\dot{q}_e''$, kW/m^2	TRP, kW-s$^{\frac{1}{2}}$/m^2 100	200	400	800
15	314.2	1,256.6	5,026.5	20,106.2
20	78.5	314.2	1,256.6	5,026.5
30	19.6	78.5	314.2	1,256.6
40	8.7	34.9	139.6	558.5
50	4.9	19.6	78.5	314.2
100	1.0	3.9	15.5	62.1
150	0.4	1.6	6.4	25.6

Table 4 Ignition time t_{ig} (seconds) for CHF = 20 kW/m^2

External heat flux $\dot{q}_e''$, kW/m^2	TRP, kW-s$^{\frac{1}{2}}$/m^2 100	200	400	800
25	314.2	1,256.6	5,026.5	20,106.2
30	78.5	314.2	1,256.6	5,026.5
40	19.6	78.5	314.2	1,256.6
50	8.7	34.9	139.6	558.5
60	4.9	19.6	78.5	314.2
100	1.2	4.9	19.6	78.5
150	0.5	1.9	7.4	29.7

Table 5 Ignition time t_{ig} (seconds) for CHF = 40 kW/m^2

External heat flux $\dot{q}_e''$, kW/m^2	TRP, kW-s$^{\frac{1}{2}}$/m^2 100	200	400	800
45	314.2	1,256.6	5,026.5	20,106.2
50	78.5	314.2	1,256.6	5,026.5
60	19.6	78.5	314.2	1,256.6
70	8.7	34.9	139.6	558.5
80	4.9	19.6	78.5	314.2
100	2.2	8.7	34.9	139.6
150	0.6	2.6	10.4	41.5

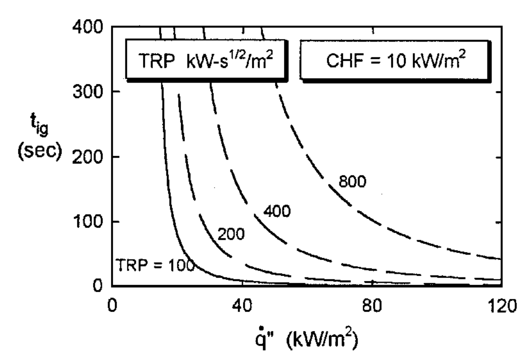

Fig. 1 Ignition time for materials with CHF = 10 kW/m^2.

PMMA. The TRP depends on the chemical as well as the physical properties of materials, such as the chemical structure, fire retardants, thickness, etc. For example, the TRP increases with sample thickness and increases in the amount of passive fire protection agent used, such as provided by a surface coating to a heavy corrugated paper sheet.

The CHF and the TRP values for materials derived from the ignition data measured by Scudamore et al.[10] are listed in Table 6. In the cone calorimeter, the surface was not blackened, and thus the values of the TRP may be somewhat higher than expected from the T_{ig}, k, ρ, and c_p values.

Sample Calculations

Computations with the preceding equations may be done for a variety of CHFs and TRPs. Figures 1–3 show the effect of CHF and

Table 6 CHF and TRP of materials

Materials	CHF, kW/m^2, flammability apparatus	TRP, kW-s$^{\frac{1}{2}}$/m^2 Flammability apparatus	TRP, kW-s$^{\frac{1}{2}}$/m^2 Cone calorimeter
Natural materials			
Flour	10	218	—
Sugar	10	255	—
Tissue paper	10	95	—
Newspaper	10	108	—
Wood (red oak)	10	134	—
Wood (Douglas fir)	10	138	—
Corrugated paper (light)	10	152	—
Corrugated paper (heavy)			
No coating	10	189	—
Coating (10% by weight)	15	435	—
Coating (15% by weight)	15	526	—
Coating (20% by weight)	15	714	—
Wood (hemlock)	—	—	175
Wool 100%	—	—	252
Wood (Douglas fir/fire retardant, FR)	10	251	—
Synthetic materials			
Epoxy resin	—	—	457
Polystyrene (PS)	13	162	—
Acrylic fiber 100%	—	—	180
Polypropylene (PP)	15	193	—
PP/FR panel	15	315	291
Styrene-butadiene (SB)	10	198	—
Crosslinked polyethylenes (XLPE)	15	224–301	—
Polyvinyl ester	13	—	263
Polyoxymethylene	—	269	—
Nylon	15	270	—
Polyamide-6	—	—	379
Polymethylmethacrylate (PMMA)	11	274	—
lsophthalic polyester	—	—	296
Acrylonitrile-butadiene-styrene (ABS)	—	—	317
Polyethylene (high density) (PE)	15	321	364
PE/nonhalogenated fire retardants	15	652–705	—
Polyvinyl ester panels	13–15	440–700	—
Modified acrylic (FR)	—	—	526
Polycarbonate	15	331	—
Polycarbonate panel	16	420	—
Halogenated materials			
Isoprene	10	174	—
Polyvinylchloride (PVC)	10	194	—
Plasticized PVC, LOI = 0.20	—	—	285
Plasticized PVC, LOI = 0.25	—	—	401
Plasticized PVC, LOI = 0.30	—	—	397
Plasticized PVC, LOI = 0.35	—	—	345
Rigid PVC, LOI = 0.50	—	—	388
Rigid PVC1	15	406	—
Rigid PVC2	15	418	—
PVC panel	17	321	—
PVC fabric	26	217	—
PVC sheets	15	446–590	—
Ethylene tetrafluoroethylene (ETFE), Tefzel™	27	356	—
Fluorinated ethylene-propylene (FEP), Teflon™	38	682	—
Teflon fabric	50	299	—
Teflon coated on metal	20	488	—
Composite and fiberglass-reinforced materials			
Polyether ether ketone–30% fiberglass	—	—	301
lsophthalic polyester–77% fiberglass	—	—	426
Polyethersulfone–30% fiberglass	—	—	256
Polyester 1–fiberglass	—	—	430
Polyester 2–fiberglass	10	275	—
Polyester 3–fiberglass	10	382	—
Polyester 4–fiberglass	15	406	—
Polyester 5–fiberglass	10	338	—
Epoxy Kevlar (thin sheet)	—	—	120
Epoxy fiberglass (thin sheet)	10	156	198
Epoxy graphite	15	395	—
Epoxy 1–fiberglass	10	420	—
Epoxy 2–fiberglass	15	540	—
Epoxy 3–fiberglass	15	500	—
Epoxy 4–fiberglass	10	388	—
Epoxy resin–69% fiberglass	—	—	688
Epoxy-graphite 1	—	481	—
Epoxy-graphite 1/ceramic coating (CC)	—	2273	—
Epoxy-graphite 1/intumescent coating (IC)	—	962	—
Epoxy-graphite 1/IC-CC	—	1786	—
Polyvinyl ester 1–69% fiberglass	—	—	444
Polyvinyl ester 2–fiberglass	—	281	—
Polyvinyl ester 2–fiberglass/CC	—	676	—
Polyvinyl ester 2–fiberglass/IC	—	1471	—
Polyvinyl ester 2–fiberglass/IC-CC	—	1923	—
Graphite composite	40	400	—
Phenolic fiberglass (thin sheet)	33	105	172
Phenolic fiberglass (thick sheet)	20	610	—
Phenolic-graphite 1	20	333	—
Phenolic-graphite 2	—	—	400
Phenolic kevlar (thin sheet)	20	185	258
Phenolic kevlar (thick sheet)	15	403	—
Phenolic-graphite 1/CC	—	807	—
Phenolic-graphite 1/IC	—	1563	—
Foams (wall-ceiling insulation materials, etc)			
Polyurethane foams	13–40	55–221	—
Polystyrene foams	10–15	111–317	—
Phenolic	20	610	—
Phenolic laminate-45% glass	—	—	683
Latex foams	16	113–172	—
Materials with Fiberweb, Netlike and multiplex structures			
Polypropylenes	8–15	108–417	—
Polyester-polypropylene	10	139	—
Wood pulp-polypropylene	8	90	—
Polyester	8–18	94–383	—
Rayon	14–17	161–227	—
Polyester-rayon	13–17	119–286	—
Wool-nylon	15	293	—
Nylon	15	264	—
Cellulose	13	159	—
Cellulose-polyester	13–16	149–217	—
Electrical cables: power			
PVC/PVC	13–25	156–341	—
PE/PVC	15	221–244	—
PVC/PE	15	263	—
Silicone/PVC	19	212	—
Silicone/cross linked polyolefin (XLPO)	25–30	435–457	—
EPR (ethylene-propylene rubber/EPR)	20–23	467–567	—
XLPE/XLPE	20–25	273–386	—
XLPE/EVA (ethyl-vinyl acetate)	12–22	442–503	—
XLPE/Neoprene	15	291	—
XLPQ/XLPO	16–25	461–535	—
XLPO. PVF (polyvinylidine fluoride)/XLPQ	14–17	413–639	—
EpR/Chlorosulfonated PE	14–19	283–416	—
EPR/FR	14–28	289–448	—
Electrical cables: communications			
PVC/PVC	15	131	—
PE/PVC	20	183	—
XLPE/XLPO	20	461–535	—
Si/XLPC	20	457	—
EPR-FR	19	295	—
Chlorinated PE	12	217	—
ETFE/EVA	22	454	—
PVC/PVF	30	264	—
FEP/FEP	36	638–652	—
Conveyor belts			
Styrene-butadiene rubber (SBR)	10–15	336–429	—
Chioroprene rubber (CR)	20	760	—
CR/SBR	15	400	—
PVC	15–20	343–640	—

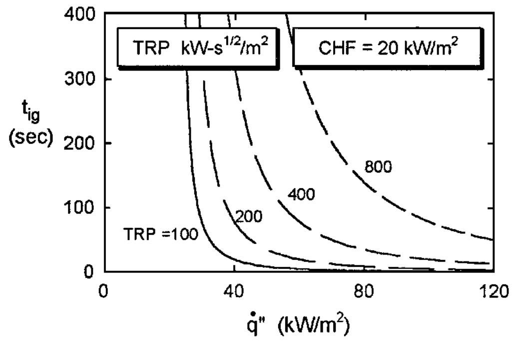

Fig. 2 Ignition time for materials with CHF = 20 kW/m^2.

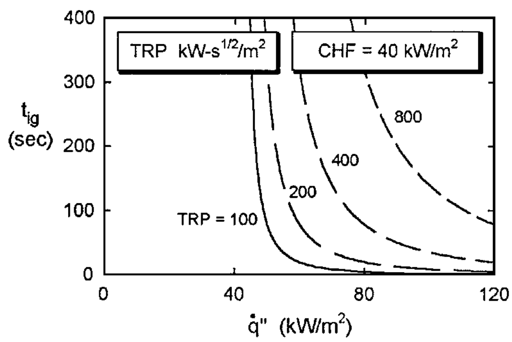

Fig. 3 Ignition time for materials with CHF = 40 kW/m^2.

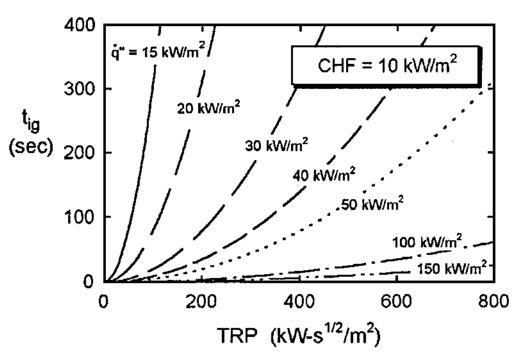

Fig. 4 Ignition time for materials with CHF = 10 kW/m^2.

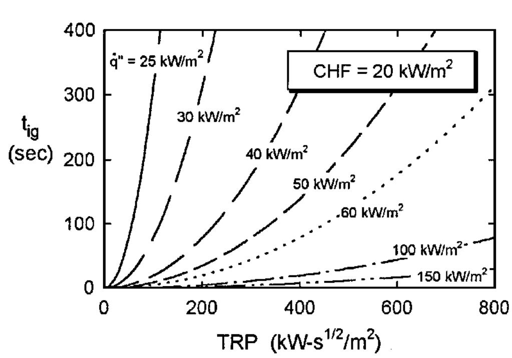

Fig. 5 Ignition time for materials with CHF = 20 kW/m^2.

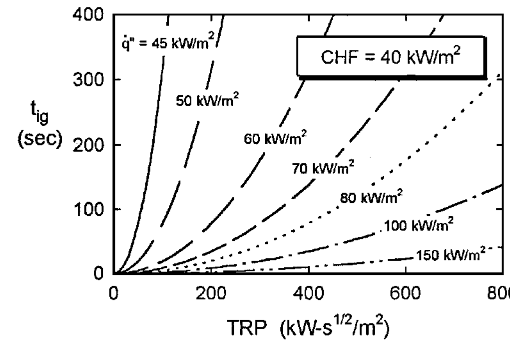

Fig. 6 Ignition time for materials with CHF = 40 kW/m^2.

TRP on the time required to reach ignition t_{ig} of the material, for different incident heat fluxes $\dot{q}''$. As expected, the time to ignition decreases substantially as the incident heat flux becomes greater than the CHF. Figures 4–6 give similar data in a slightly different form. Tables 3–5 give the same results of a range of calculations involving CHF, TRP, and $\dot{q}''$. The actual values of CHF and TRP used here are typical of many materials of practical interest.

Conclusions

A fire may spread because of radiant heat flux levels becoming high enough for ignition to take place. Critical heat flux (CHF) and thermal response parameter (TRP) are needed to clarify the thermal ignition potential of any material. Typical values were given for an extensive range of materials, and corresponding ignition times were presented for a range of realistic situations.

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