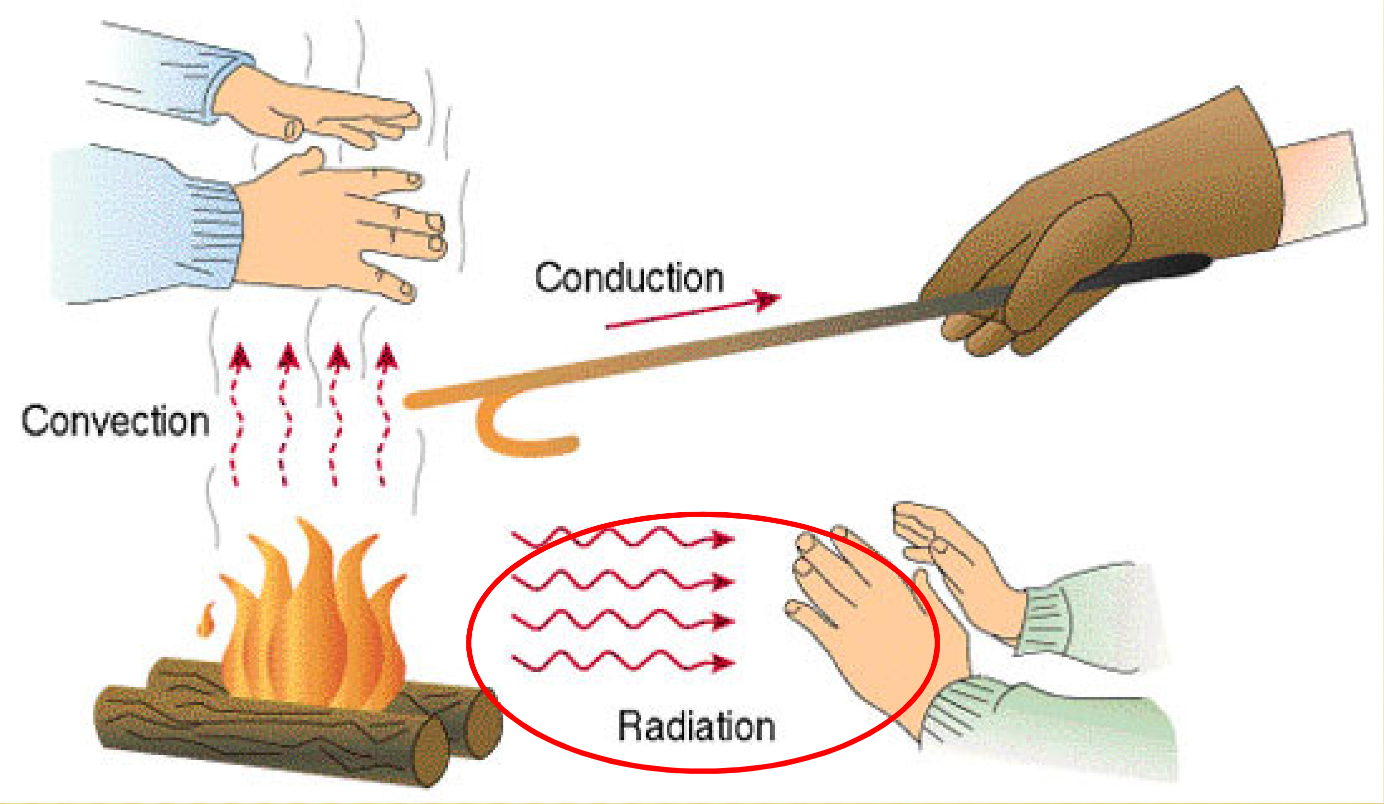
RADIAÇÃO



Transferência de Calor por Radiação

Radiation heat transfer occurs by electromagnetic waves, such as when the Sun warms the Earth.

Stefan-Boltzmann Law (simplificada):

$$E = \sigma T^4$$

Where E = Energy radiated per unit time per unit area for an *ideal* radiator kW / m2

σ = Stefan-Boltzman constant = 5.67 x 10^{-11} kW/m^2-K^4 (2.87 x 10^{-11} Btu/min/ft^2-°R^4)

T = absolute temperature, K

$$\frac{kW}{m^2 \, K^4} \, K^4 = \frac{kW}{m^2}$$

Transferência de Calor por Radiação

Radiation heat transfer occurs by electromagnetic waves, such as when the Sun warms the Earth.

Válido apenas para o caso ideal (blackbody) (ver próximo slide)

Stefan-Boltzmann Law

$$E = \sigma T^4$$

Onde "área" é a área superficial da chama

Where E = Energy radiated per unit time per unit area for an *ideal* radiator | kW / m2

σ = Stefan-Boltzman constant = 5.67×10^{-11} kW/m^2-K^4 (2.87×10^{-11} Btu/min/ft^2-°R^4)

T = absolute temperature, | K

$$\frac{kW}{m^2 \; K^4} \; K^4 = \frac{kW}{m^2}$$

Transferência de Calor por Radiação

Corpo cinza

Método Grey Body

Emissive Power (kW/m2)

$$E = \varepsilon \sigma T_f^4$$

Equação na sua forma mais geral.

ε **flame emissivity**

= 1 para caso ideal (blackbody)

Transferência de Calor por Radiação

Método Grey Body

$$E = \varepsilon \, \sigma \, Tf^{4}$$

Onde "área" é a área superficial da chama

E: radiant energy (per time per area) or **flame radiant emissive power** (kW/m2)

ε: flame emissivity

σ: Stefan Boltzman Constant ($5{,}67 \cdot 10^{-11}$ kW / (m^2 K^4))

Tf: radiantion flame temperature (K) **(tabela próximo slide)**

Table A.1. Effective flame emission/absorption coefficients, *k*, and radiation flame temperatures, T_f

Tf (K)

Material	k(m^{-1})	T_f(K)	Reference[a]
Benzene	2.6	1190	Mudan (1984), Drysdale (1985)
Butane	2.7	–	Mudan (1984)
Diesel Oil	0.43	–	Drysdale (1985)
Ethyl Alcohol	0.37	–	Mudan (1971)
Furniture (assorted)	1.13	–	Drysdale (1985)
Gasoline	2.0	1240	Mudan (1984)
Gasoline	–	1300	Drysdale (1985)
Hexane	1.9	–	Mudan (1984)
Hydrogen (liquid)	7.0	–	Mudan (1984)
JP-4	–	1200	Mudan (1984)
Kerosene	2.6	1600	Mudan (1984)
Kerosene	–	1260	Drysdale (1985)
LNG	3.0	1500	Mudan (1984)
Methanol	4.6	1500	Mudan (1984), Drysdale (1985)
PMMA	0.5	–	Drysdale (1985)
PMMA	1.3	1400	deRis (1979)
PMMA	1.5	1260	Orloff (1981)
Polypropylene	1.8	1350	deRis (1979)
Polystyrene	1.2	–	Drysdale (1985)
Polystyrene	5.23	1190	deRis (1979)
Wood Cribs	0.5, 0.8	–	Drysdale (1985)
Xylene	1.2	–	Mudan (1984)

[a]Data attributed to Mudan (1984) were compiled primarily by Attalah and Allan (1971). Data attributed to Drysdale (1985) were compiled from a variety of sources cited in his text

Table A.1. Effective flame emission/absorption coefficients, k, and radiation flame temperatures, T_f

Tf (K)

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Benzene	2.6	1190	Mudan (1984), Drysdale (1985)
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Methanol	4.6	1500	Mudan (1984), Drysdale (1985)
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Xylene	1.2	–	Mudan (1984)

[a]D… 984) were compiled primarily by Attalah and Allan (1971). Data attributed to … piled from a variety of sources cited in his text

K será explicado posteriormente.

Transferência de Calor por Radiação

Método Grey Body

$$E = \varepsilon \sigma Tf^4$$

E: radiant energy or flame radiant emissive power (kW/m2)

ε: flame emissivity

σ: Stefan Boltzman Constant (5,67 . 10^{-11} kW / (m^2 K^4))

Tf: radiation flame temperature (K)

Para grandes chamas considerar flame emissivity igual a 1.
Ver cálculo próximo slide.

Transferência de Calor por Radiação

Método Grey Body

$$E = \varepsilon \, \sigma \, \mathbf{Tf}^{4}$$

Ou:

$1 - e^{(-KL)}$

Onde:

ε: flame emissivity

$\varepsilon = 1 - \exp(-KL)$

Obs: através dessa equação é possível mostrar que a flame emissivity é aproximadamente igual a 1 para chamas grandes.

Onde:
K: effective emission/absorption coefficient (m^-1)
(**tabela no próximo slide**)

L: mean equivalent beam length of the flame (m)
(aproximadamente o raio da chama)

Transferência de Calor por Radiação

Método Grey Body

ε: flame emissivity

ε = 1 - exp (- K L)

Exemplo:

These parameters were recorded during the steady state —between 7 and 10 minutes— of 5 experimental tests which had different fuel loads. Temperature values between 650 ºC and 1300 ºC were obtained with flame thickness between 25 cm and 190 cm. Flame emissivities were also located in a wide range, between 0.1 and 0.6. A single expression for emissivity with thickness was developed from the data of all the tests:

$$\varepsilon_f = 1 - e^{-0.51x} \qquad (4)$$

where x = flame thickness, m.

http://upcommons.upc.edu/e-prints/bitstream/2117/7201/1/experimental.pdf

Transferência de Calor por Radiação

Método Grey Body

ε: flame emissivity

ε = 1 - exp (- K L)

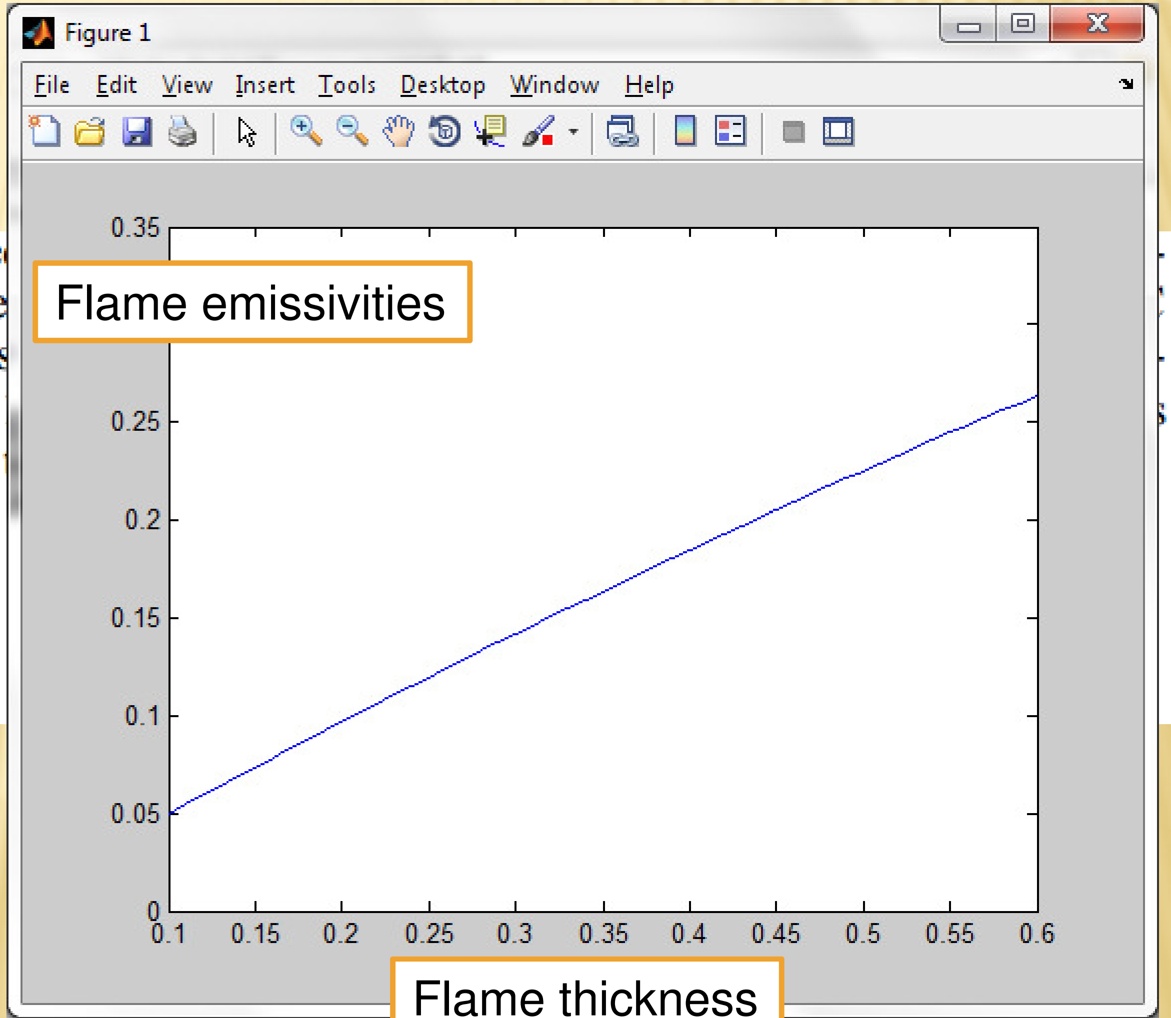
Exemplo:

These parameters were recorde
perimental tests which had differe
were obtained with flame thicknes
cated in a wide range, between 0.
developed from the data of all the

$$\varepsilon_f = 1 - e^{-0.51x}$$

where x = flame thickness, m.

```
>> x=0.1:0.01:0.60;
>> ef=1-(exp(-0.51.*x));
>> plot(x,ef)
```



Flame emissivities

Flame thickness

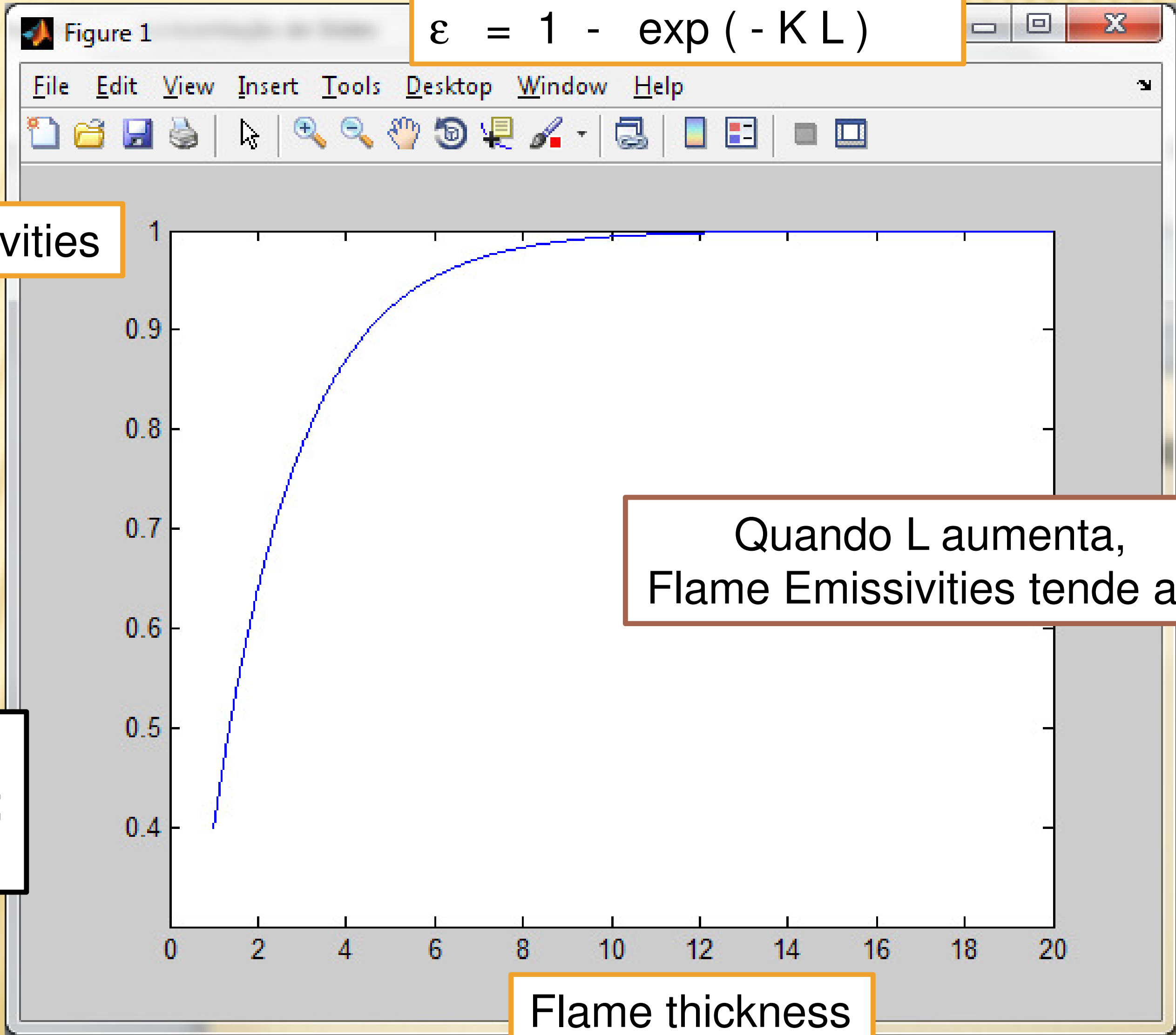
Transferência de Calor por Radiação

Método Grey Body

ε: flame emissivity

$$\varepsilon = 1 - \exp(-K L)$$

Flame emissivities



Flame thickness

Quando L aumenta,
Flame Emissivities tende a 1.

```
>> x=1:0.01:20;
>> ef=1-(exp(-0.51.*x));
>> plot(x,ef)
```

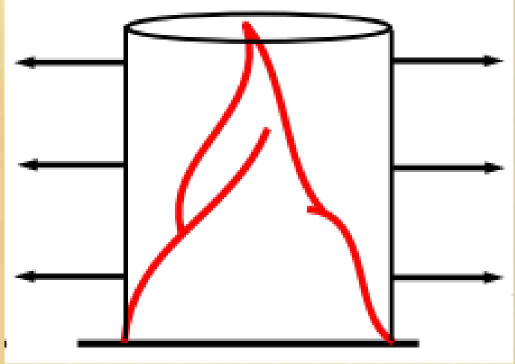
Transferência de Calor por Radiação

Método via área superficial de chama

kW / m2 = kW / m2

Emissive Power (kW/m2) → $E = Qr / Af$

E: flame radiant emissive power (kW/m2)
Qr: heat release rate (radiation only) (kW)
Af: flame surface area (m^2)



Transferência de Calor por Radiação

Método via área superficial de chama

kW / m2 = kW / m2

Emissive Power (kW/m2) → $E = Qr / Af$

Essa equação será aplicada nos cálculos de piscina. O próximo slide ilustra uma equação usada em piscina, equivalente a equação aqui apresentada.

Exemplo

Pool Fire

NIST

Heat Release Rate (HRR):

$$\chi_r \, \dot{Q} = P \, H \, E_f$$

Fração radiada (prox. slide)

HRR Total (kW)

Perímetro da chama (m)

Altura da Chama (m)

Emissive Power (kW/m2)

HRR radiado (Qr) (kW)

Área superficial da chama (m2)

Transferência de Calor por Radiação

Método via Q teórico (Q) ou Calor de Combustão (Hc)

$$Qr = Xrad \; Q = Xrad \; M \; Hc$$

Onde:

Qr: heat release rate (radiation only) (kW)

Xrad: fração radiada (fração emitida como radiação) (tabela A2)

Q: **theoretical** heat release rate (kW) (tabela A3 ou equação Q = M Hc)

M: mass burn rate (g/s) (tabela A4 ou A5)

Hc: theoretical heat of combustion (kJ / g) (tabela A2 ou A4 ou A5)

Transferência de Calor por Radiação

Método via Q teórico (Q) ou Calor de Co

Q é dado em kW:

Qr = Xrad Q
kW = 1 kW

Ou,

Q = M Hc
kW = g/s kJ/g
kW = kJ/s

Qr = Xrad Q =

Onde:
Qr: heat release rate (radiation only) (kW)
Xrad: fração radiada (fração emitida como radiação) (tabela A2)
Q: **theoretical** heat release rate (kW) (tabela A3 ou equação Q = M Hc)
M: mass burn rate (g/s) (tabela A4 ou A5)
Hc: theoretical heat of combustion (kJ / g) (tabela A3 ou A4 ou A5)

M pode ser obtido experimentalmente
ou
calculado através das equações acima
usando valores tabelados de Xrad, Q e Hc.

Transferência de Calor por Radiação

Método via Q teórico (Q) ou Calor de Combustão

Embora a unidade de M seja g/s, ele é tabelado em

$Kg / (m^2 s)$

para considerar a <u>área da piscina</u>.

Qr = Xrad Q = Xrad M Hc

Onde:

Qr: heat release rate (radiation only) (kW)

Xrad: fração radiada (fração emitida como radiação) (tabela A2)

Q: **<u>theoretical</u>** heat release rate (kW) (tabela A3 ou equação Q = M Hc)

M: mass burn rate (g/s) (tabela A4 ou A5)

Hc: theoretical heat of combustion (kJ / g) (tabela A2 ou A4 ou A5)

Eficiência Real (Combustion Efficiency)

Eficiência real (Combustion Efficiency):

$$X = X_{conv} + X_{rad}$$

(tabela A2)

A2

Table A.2. Chemical, convective and radiative combustion efficiencies (data from Chapter 3-4 of *SFPE Handbook*, 1995)

Material	H_c (kJ / g)	χ	χ_{conv}	χ_{rad}
Gases				
Ethane	47.5	0.99	0.79	0.20
Propane	46.4	0.95	0.68	0.27
Butane	45.7	0.95	0.68	0.27
Ethylene	47.2	0.91	0.59	0.32
Propylene	45.8	0.89	0.50	0.39
1,3-Butadiene	44.6	0.74	0.34	0.40
Acetylene	48.2	0.76	0.37	0.39
Liquids				
Heptane	44.6	0.93	0.59	0.34
Octane	44.4	0.92	0.61	0.31
Benzene	40.1	0.69	0.28	0.41
Styrene	40.5	0.67	0.27	0.40
Methanol	20.0	0.95	0.81	0.15
Ethanol	26.8	0.97	0.73	0.24
Isopropanol	30.2	0.97	0.73	0.24
Acetone	28.6	0.97	0.73	0.24
Methyl Ethyl Ketone	31.5	0.97	0.67	0.24
Polydimethyl Siloxane	25.1	0.61	0.51	0.10
High MW Hydrocarbons	43.9	0.84	0.56	0.28

A2

Solids				
Red Oak	17.7	0.70	0.44	0.26
Douglas Fir	16.4	0.79	0.49	0.30
Pine	17.9	0.69	0.49	0.21
Polyoxymethyene	15.4	0.94	0.73	0.21
Polymethylmethacrylate	25.2	0.96	0.66	0.30
Polyethylene	43.6	0.88	0.50	0.38
Polypropylene	43.4	0.89	0.52	0.37
Polystyrene	39.2	0.69	0.28	0.41
Silicone	21.7	0.49	0.34	0.15
Polyester	32.5	0.63	0.33	0.30
Epoxy	28.8	0.59	0.30	0.30
Nylon	30.8	0.88	0.53	0.35
Polyethylene-25%-Cl	31.6	0.72	0.32	0.40
Polyethylene-36%-Cl	26.3	0.40	0.24	0.16
Polyethylene-48%-Cl	20.6	0.35	0.19	0.16
Polyvinyl chloride	16.4	0.35	0.19	0.16
Fluoropolymers	5.3	0.32	0.17	0.15
Flexible Polyurethane Foams				
GM 21 (29 kg/m^3)	26.2	0.68	0.33	0.35
GM 23 (FR 29 kg/m^3)	27.2	0.70	0.38	0.32
GM 25 (44 kg/m^3)	24.6	0.69	0.29	0.40
GM 27 (FR 44 kg/m^3)	23.2	0.71	0.33	0.38

A2

Material	H_c	χ	χ_{conv}	χ_{rad}
Rigid Polyurethane Foams				
GM 29 (35 kg/m^3)	26.0	0.63	0.26	0.37
GM 31 (FR 32 kg/m^3)	25.0	0.63	0.28	0.35
GM 35 (64 kg/m^3)	28.0	0.63	0.28	0.35
GM 37 (320 kg/m^3)	28.0	0.64	0.31	0.33
GM 41 (36 kg/m^3)	26.2	0.60	0.22	0.38
GM 43 (33 kg/m^3)	22.2	0.67	0.29	0.38
Polystyrene Foams				
GM 47 (16 kg/m^3)	38.1	0.68	0.30	0.38
GM 49 (FR 16 kg/m^3)	38.2	0.67	0.26	0.41
GM 51 (34 kg/m^3)	35.6	0.69	0.29	0.40
GM 53 (29 kg/m^3)	37.6	0.69	0.30	0.39

A3

Table A.3. Theoretical unit heat release rates for fuels burning in the open

Commodity	Heat release rate (Btu/sec)
Flammable Liquid Pool	290/ft^2 of surface
Flammable Liquid Spray	2000/gpm of flow
Wood Pallets (Single Stack)	1000/ft of height
Wood or PMMA (Vertical)	
2 ft Height Burning	30/ft of width
4 ft Height Burning	70/ft of width
8 ft Height Burning	180/ft of width
12 ft Height Burning	300/ft of width
Wood of PMMA	
Top of Horizontal Surface	65/ft^2 of surface
Solid Polystyrene (Vertical)	
2 ft Height Burning	65/ft of width
4 ft Height Burning	150/ft of width
8 ft Height Burning	400/ft of width
12 ft Height Burning	680/ft of width
Solid Polystyrene (Horizontal)	120/ft^2 of surface
Solid Polystyrene (Vertical)	
2 ft Height Burning	45/ft of width
4 ft Height Burning	100/ft of width
8 ft Height Burning	280/ft of width
12 ft Height Burning	470/ft of width
Solid Polypropylene (Horizontal)	70/ft^2 of surface

A4

Liquid	Mass Burning Rate, $\dot{m}''$	Heat of Combustion	HRR Per Unit Area, $\dot{q}''_f$	Screen ASD		Reference
				Struct.	People	
	kg/m^2/s	kJ/kg	kW/m^2	m	m	
Acetic Acid	0.033	13,100	400	10	90	Ref. [10]
Acetone	0.041	25,800	1,100	10	250	Ref. [9]
Acrylonitrile	0.052	31,900	1,700	15	390	Ref. [10]
Amyl Acetate	0.102	32,400	3,300	30	750	Ref. [10]
Amyl Alcohol	0.069	34,500	2,400	20	550	Ref. [10]
Benzene	0.048	44,700	2,100	20	480	Ref. [9]
Butyl Acetate	0.100	37,700	3,800	35	860	Ref. [10]
Butyl Alcohol	0.054	35,900	1,900	15	430	Ref. [10]
m-Cresol	0.082	32,600	2,700	25	620	Ref. [10]
Crude Oil	0.045	42,600	1,900	15	430	Ref. [9]
Cumene	0.132	41,200	5,400	50	1220	Ref. [10]
Cyclohexane	0.122	43,500	5,300	45	1200	Ref. [10]
No. 2 Diesel Fuel	0.035	39,700	1,400	12	320	Ref. [9]
Ethyl Acetate	0.064	23,400	1,500	15	340	Ref. [10]
Ethyl Acrylate	0.089	25,700	2,300	20	530	Ref. [10]
Ethyl Alcohol	0.015	26,800	400	10	90	Ref. [9]
Ethyl Benzene	0.121	40,900	4,900	40	1100	Ref. [10]
Ethyl Ether	0.094	33,800	3,200	30	730	Ref. [10]
Gasoline	0.055	43,700	2,400	20	550	Ref. [9]
Hexane	0.074	44,700	3,300	30	750	Ref. [9]
Heptane	0.101	44,600	4,500	40	1000	Ref. [9]
Isobutyl Alcohol	0.054	35,900	1,900	15	430	Ref. [10]
Isopropyl Acetate	0.073	27,200	2,000	20	460	Ref. [10]
Isopropyl Alcohol	0.046	30,500	1,400	15	320	Ref. [10]
JP-4	0.051	43,500	2,200	20	500	Ref. [9]
JP-5	0.054	43,000	2,300	20	530	Ref. [9]
Kerosene	0.039	43,200	1,700	15	400	Ref. [9]
Methyl Alcohol	0.017	20,000	340	10	80	Ref. [9]
Methyl Ethyl Ketone	0.072	31,500	2,300	20	530	Ref. [10]
Pentane	0.126	45,000	5,700	50	1300	Ref. [10]
Toluene	0.112	40,500	4,500	40	1000	Ref. [10]
Vinyl Acetate	0.136	22,700	3,100	25	700	Ref. [10]
Xylene	0.090	40,800	3,700	30	850	Ref. [9]

Ver observações próximo slide

Kg / (m^2 s)

A4

Liquid	Mass Burning Rate, $\dot{m}''$	Heat of Combustion	HRR Per Unit Area, $\dot{q}''_f$	Screen ASD		Reference
				Struct.	People	
	kg/m²/s	kJ/kg	kW/m²	m	m	
Acetic Acid	0.033	13,100	400	10	90	Ref. [10]
Acetone	0.041	25,800	1,100	10	250	Ref. [9]
Cumene	0.132	41,200	5,400	50	1220	Ref. [10]
Cyclohexane	0.122	43,500	5,300	45	1200	Ref. [10]
No. 2 Diesel Fuel	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Heptane	0.101	44,600	4,500	40	1000	Ref. [9]
Isobutyl Alcohol	0.054	35,900	1,900	15	430	Ref. [10]
Isopropyl Ac						Ref. [10]
Isopropyl Al						Ref. [10]
JP-4						Ref. [9]
JP-5						Ref. [9]
Kerosene						Ref. [9]
Methyl Alcohol	0.017	20,000	340	10	80	Ref. [9]
Methyl Ethyl Ketone	0.072	31,500	2,300	20	530	Ref. [10]
Pentane	0.126	45,000	5,700	50	1300	Ref. [10]
Toluene	0.112	40,500	4,500	40	1000	Ref. [10]
Vinyl Acetate	0.136	22,700	3,100	25	700	Ref. [10]
Xylene	0.090	40,800	3,700	30	850	Ref. [9]

HRR e Mass Burning Rate para área da poça (base do fogo). E não para a área superficial da chama.

Atenção: aqui é **TAXA**, e não fluxo.
A divisão por metro quadrado apenas indica
a base de cálculo (tamanho da poça considerada)

HRR total e não apenas a fração radiada.

Liquid	Mass Burning Rate, $\dot{m}''$ kg/m²/s	Heat of Combustion kJ/kg	HRR Per Unit Area, $\dot{q}''_f$ kW/m²	Screen ASD Struct. m	Screen ASD People m	Reference
Acetic Acid	0.033	13,100	400	10	90	Ref. [10]
Acetone	0.041	25,800	1,100	10	250	Ref. [9]
Acrylonitrile	0.052	31,900	1,700	15	390	Ref. [10]
Amyl Acetate	0.102	32,400	3,300	30	750	Ref. [10]
Amyl Alcohol	0.069	34,500	2,400	20	550	Ref. [10]
Benzene	0.048	44,700	2,100	20	480	Ref. [9]
Butyl Acetate	0.100	37,700	3,800	35	860	Ref. [10]
Butyl Alcohol	0.054	35,900	1,900	15	430	Ref. [10]

0,100 kg/m^2.s x 37700 kJ/kg = 3800 kJ/m^2.s

Mass Burning Rate X ***Heat of Combustion*** = ***Heat Release Rate***

HRR Total (e não apenas em relação ao radiado)

Dados de M e Hc para piscinas grandes

A5

Data for Large Pool (D > 0.2 m) Burning Rate Estimates

Material	Density (kg/m³)	$\dot{m}''_{\infty}$ (kg/m²s)	ΔH_c (MJ/kg)	$k\beta$ (m⁻¹)
Cryogenics				
Liquid H_2	70	0.017	120.0	6.1
LNG (mostly CH_4)	415	0.078	50.0	1.1
LPG (mostly C_3H_8)	585	0.099	46.0	1.4
Alcohols				
Methanol (CH_3OH)	796	0.017	20.0	[a]
Ethanol (C_2H_5OH)	794	0.015	26.8	[b]
Simple organic fuels				
Butane (C_4H_{10})	573	0.078	45.7	2.7
Benzene (C_6H_6)	874	0.085	40.1	2.7
Hexane (C_6H_{14})	650	0.074	44.7	1.9
Heptane (C_7H_{16})	675	0.101	44.6	1.1
Xylene (C_8H_{10})	870	0.09	40.8	1.4
Acetone (C_3H_6O)	791	0.041	25.8	1.9
Dioxane ($C_4H_8O_2$)	1035	0.018	26.2	5.4[b]
Diethyl ether ($C_4H_{10}O$)	714	0.085	34.2	0.7
Petroleum products				
Benzine	740	0.048	44.7	3.6
Gasoline	740	0.055	43.7	2.1
Kerosine	820	0.039	43.2	3.5
JP-4	760	0.051	43.5	3.6
JP-5	810	0.054	43.0	1.6
Transformer oil, hydrocarbon	760	0.039[b]	46.4	0.7[b]
Fuel oil, heavy	940–1000	0.035	39.7	1.7
Crude oil	830–880	0.022–0.045	42.5–42.7	2.8

ftp://ftp.stru.polimi.it/corsi/Felicetti%20-%20Fire%20resistance%20of%20materials%20and%20structures/Books/Enclosure%20fire%20dynamics/1300_PDF_C03.pdf

Dados de M e Hc para piscinas grandes

A5

TABLE 3.3
Data for Large Pool ($D > 0.2$ m) Burning Rate Estimates

Material	Density (kg/m³)	$\dot{m}''_{\infty}$ (kg/m²s)	ΔH_c (MJ/kg)	$k\beta$ (m⁻¹)
Solids				
Polymethylmethacrylate $(C_5H_8O_2)_n$	1184	0.020	24.9	3.3
Polypropylene $(C_3H_6)_n$	905	0.018	43.2	
Polystyrene $(C_8H_8)_n$	1050	0.034	39.7	

[a] Value independent of diameter in turbulent regime.
[b] Estimate uncertain, since only two points available.

Source: Babrauskas, V., in *SFPE Handbook of Fire Protection Engineering*, 2nd ed., National Fire Protection Association, Quincy, MA, 1995. With permission.

ftp://ftp.stru.polimi.it/corsi/Felicetti%20-%20Fire%20resistance%20of%20materials%20and%20structures/Books/Enclosure%20fire%20dynamics/1300_PDF_C03.pdf

Transferência de Calor por Radiação

Método via HHR por unidade de área da base

$$Q = q_f'' \; A$$

heat release rate per unit area
Ver Tabela A4

Área da base
(m2)

For a given fuel, the heat release rate per unit area $\dot{q}_f''$ is relatively constant because the fuel mass burning rate per unit area is relatively constant

Em resumo...

Método Grey Body

$E = \varepsilon \sigma T_f^4$

ε: flame emissivity

$\varepsilon = 1 - \exp(-KL)$

Método via área superficial de chama

$E = Q_r / A_f$

Qrad = Xrad TeoricalHeatReleaseRate

Qrad = Xrad MassBurnRate TeoricalHeatOfComb

Eficiência real (Combustion Efficiency):

X = Xconv + Xrad

Método via HHR por unidade de área da base

$Q = q_f'' A$