

Estimating Large Pool Fire Burning Rates

VYTENIS BABRAUSKAS
*Center for Fire Research
National Bureau of Standards*

Data for estimating the burning rate and heat output of large pool fires (diameter \gtrsim 0.2 m) are compiled and computational equations presented. Since a large scatter in the reported data is noted, attention is also focused on areas where further research is most needed in order to improve predictability.

POOB BURNING is probably the simplest form of combustion applicable to a wide range of industrial fire protection concerns. Typically, this is conceived of as a fire in an open-topped, circular flammable liquid tank or as a bounded spill of combustible liquid. More generally, both liquefied gases and melting plastics materials, horizontally placed, conform to the same pattern. Somewhat related, but computationally different are problems of pools burning in enclosed spaces. The solutions of Reference 2 consider the limit where the enclosure effects dominate the fire. Here we will only consider "free" pools, not inside an enclosure nor in the vicinity of another fire. The burning of pool fires presents a rich field for inquiry into flame chemistry, radiation, fluid mechanics and other aspects. To a fire protection engineer, however, two questions are primary: How fast is the fire burning? And, what is its temperature (or heat flux) distribution?

In this article an attempt is made to systematically summarize the available information only to the first question. Furthermore, the fires of greatest practical concern are the larger ones. A fire of 100 kW can be typically produced by a fuel pool \sim 0.2 m in diameter. As will be shown, such a restriction to "large" pools simplifies the data analysis considerably.

Thus, except where otherwise specified, all the discussion will pertain to pools with $D \gtrsim 0.2$ m.

Hottel¹⁹ was probably the first to suggest how to systematically analyze pool burning data according to basic heat transfer principles. By conservation of energy for the liquid we have

$$\dot{m}'' \Delta h_g = \dot{q}_r'' + \dot{q}_c'' - \dot{q}_{rr}'' - \dot{q}_{misc}'' \quad (1)$$

where \dot{m}'' is the mass loss rate per unit area (assumed identical to the burning rate) in units of kilograms per square meter per second; Δh_g is the total heat of gasification, i.e., the heat to bring a liquid fuel at 298 K to its boiling temperature and then to change it to vapor; \dot{q}_r'' is the radiant flux absorbed by the pool; \dot{q}_c'' is the heat received convectively; \dot{q}_{rr}'' is the re-radiant heat loss, due to the surface of the pool being at an elevated temperature; and into \dot{q}_{misc}'' are lumped wall conduction losses and non-steady terms. (Units for all are given in Nomenclature.) Quantitative expressions for \dot{q}_{misc}'' are usually not available, while \dot{q}_{rr}'' is usually small. For simple analysis both are customarily dropped. Hottel's analysis of Blinov and Khudiakov's³ data showed two basic regimes are possible: radiatively dominated burning for large D and convectively dominated burning for small D . Furthermore, in the convective regime the flow can be either laminar or turbulent (being always turbulent for radiatively driven pools), while in the radiative regime the flames can be optically thin or thick. These distinctions can, in the simplest analysis, be made solely on the basis of pool diameter. Thus:

<u>$D(m)$</u>	<u>Burning Mode</u>
< 0.05	convective, laminar
0.05 to 0.2	convective, turbulent
0.2 to 1.0	radiative, optically thin
> 1.0	radiative, optically thick

In the convective limit (small pools) then we would expect that

$$\dot{m}'' \approx \dot{q}_c'' / \Delta h_g \quad (2)$$

Behavior in the convective laminar mode has not been fully correlated although Blinov³ and Corlett and Fu⁹ indicate functional relations of the form

$$\dot{m}'' = aD^{-n} + b \quad (3)$$

with $\frac{1}{2} \lesssim n \leq \frac{3}{2}$. For the convective turbulent mode, the \dot{m}'' values are independent of D and at their lowest. DeRis and Orloff¹¹ have provided a dimensionless correlation, based on fuel thermochemical properties.

In the radiative mode both the optically thick and thin regimes might be modeled if we let

$$\dot{m}'' = \frac{\sigma T_f^4 (1 - e^{-k\beta D})}{\Delta h_g} \quad (4)$$

Here σ is the Stefan-Boltzmann constant and Δh_g is easily determinable, at least for pure liquids. T_f is an effective equivalent grey-gas flame temperature. It should be related to the measured temperatures in the hottest zone, but a predictive relationship is not available. The effective flame volume emissivity is represented by $(1 - e^{-k\beta D})$, where k is the absorption-extinction coefficient of the flame, D is pool diameter and β is a "mean-beam-length corrector."

For most fuels, reliable measurements exist only for \dot{m}'' as a function of D and not for T_f , k , or β separately. The data can be presented in predictive form as

$$\dot{m}'' = \dot{m}_\infty'' (1 - e^{-k\beta D}) \quad (5)$$

This form was first recommended by Zabetakis and Burgess⁴⁰ and requires determining two empirical factors: \dot{m}_∞'' and $(k\beta)$, not separated into k and β . For a few fuels, independent measurements of T_f , k , and β are reported. In those cases one could examine the quantity

$$\frac{\dot{m}_\infty'' \Delta h_g}{\sigma T_f^4}$$

which should go to 1.0. Instead values of 0.05 to 0.25 can be computed, based on data in the table. This computation illustrates some pitfalls:

1. The assumption of grey-gas radiation, while fruitful as a functional form for correlation, is too simplified when computed from fundamental constants.

2. The flame volume should not, in fact, be represented as being at a mixed mean temperature. The volume right above the pool surface, in fact, contains mostly low-temperature pyrolysis gases.

If \dot{m}_∞'' has to be determined experimentally, instead of from theory, how about β ? Can values of k measured through flames, in a laboratory fire, be used with a fixed β to produce $k\beta$? Polymethylmethacrylate is a material for which adequate values of $k\beta$ and of k exist.^{12,26} These imply $\beta = 2.6$. For other fuels, the tabulated data range over $0.7 \leq \beta \leq 3.8$. This probably can be attributed to widely differing measurement techniques for k . Nonetheless, a common β does not emerge.

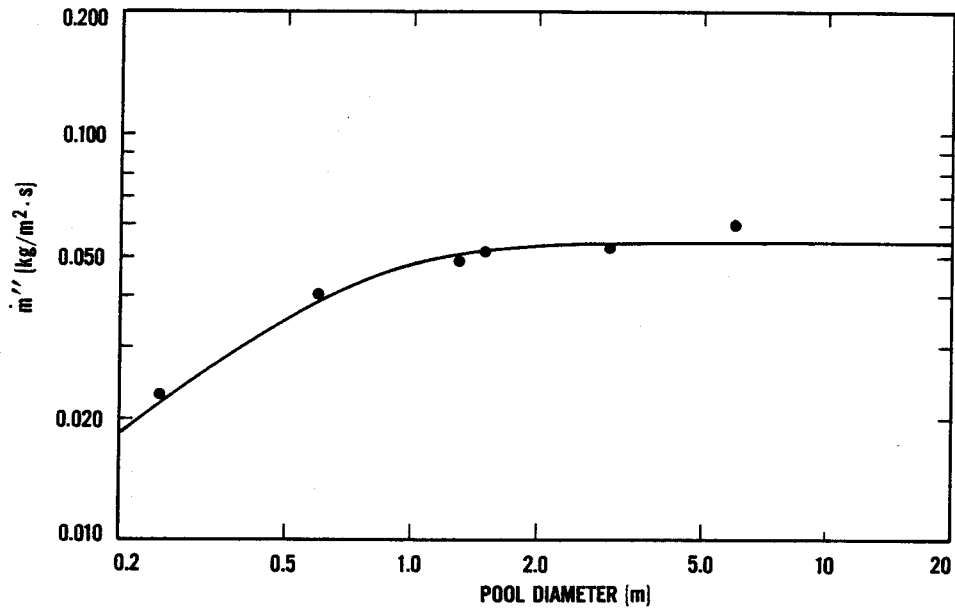


Figure 1. Gasoline pool burning rates.

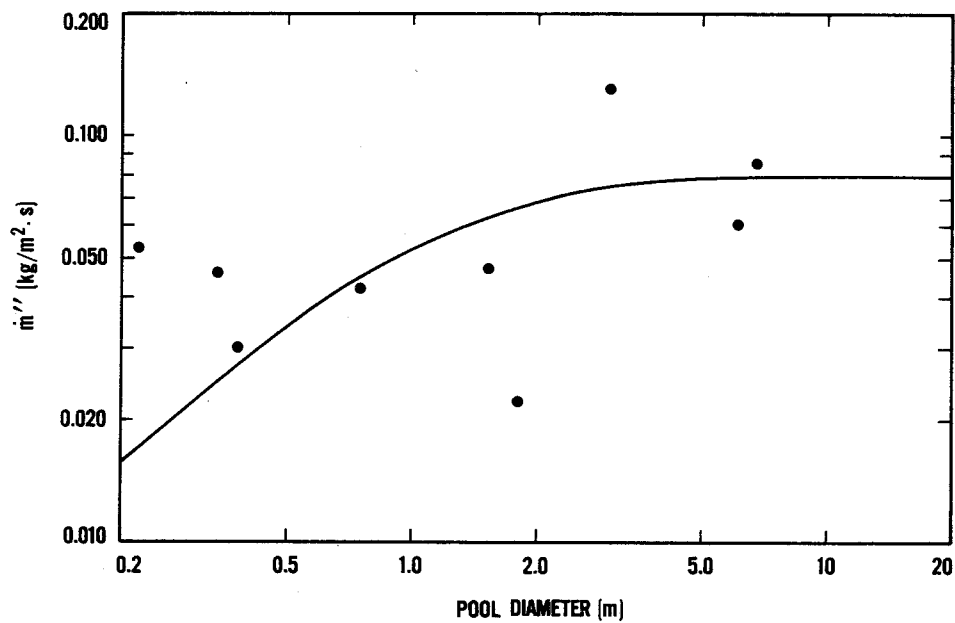


Figure 2. LNG pool burning rates.

ANALYSIS OF DATA

Experimental data are tabulated in the Appendix. From these data points values of $k\beta$ and \dot{m}''_0 were determined by using a numerical algorithm for nonlinear curve-fitting. In each case, Equation (5) was used for fitting, with the exception of the alcohols. For alcohols a functional form of

$$\dot{m}'' = \dot{m}''_0, \quad D \geq 0.2 \text{ m} \tag{6}$$

is appropriate. The results are listed in the table, along with values of some relevant thermochemical properties, taken from Cragoe¹⁰ and NFPA *Fire Protection Handbook*.²⁷ For illustration, the experimental data points and the curve fit are shown for three fuels in Figures 1, 2, and 3. Figure 1 shows the results for gasoline, a typical fuel. Figure 2 gives results for LNG, chosen to illustrate the larger degree of scatter associated with cryogenic fuel measurements. Finally, Figure 3 illustrates the behavior of alcohol fuels. The fit in these curves, along with the standard deviations indicated in the table can be used to gauge the expected uncertainty of predictions.

Use of Tabulated Data: The data in the table can be used directly to estimate the burning rates of pools with $D \gtrsim 0.2$ m. The values pertain to steady-state burning, in a wind-free environment and in a vessel without excessive lip height (freeboard height). When these assumptions are not met, weaker predictions are to be expected. We will discuss briefly some of these complications.

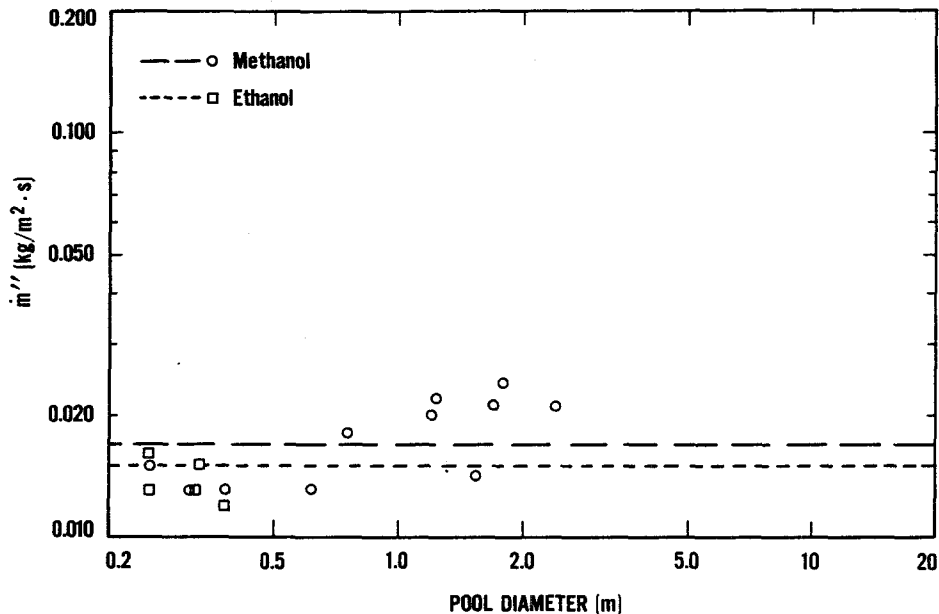


Figure 3. Alcohol pool burning rates.

Boil-Over: A few fuels do not show steady burning properties. Instead, at a certain temperature they start to boil rapidly. This results in a significant expansion and may cause overflow of the vessel, with attendant flame spread hazards. This problem has been associated primarily with certain crude oils and with petroleum products with a significant amount of moisture. Burgoyne and Katan⁶ have discussed boil-over in detail.

Transient Effects: Systematic burning rate data are available only for steady-state burning. A pool fire, however, does not reach a steady state immediately after ignition for several reasons:

1. The heat conduction losses into the liquid are still changing.
2. Edge heating effects may still be present.
3. The bottom of the vessel may be progressively heated if the fuel layer is thin.
4. Lip effects on convective and radiative fluxes may progressively change if the liquid level is allowed to run down in the vessel significantly.

In some short-burning fires there may indeed not be a steady state. Others, however, do show eventually a fairly steady burning rate. Some experimenters have reported transient periods as short as one minute. On the whole, however, 10 or more minutes may be expected before fully steady-state burning results. A general model of the various losses which could predict these transient effects in large pool fires has not been developed.

Bounding Materials and Layer Thickness Effects: Pool fires in vessels made of different materials can be expected to show different burning rates, primarily due to conduction losses. Blinov³ has shown quite substantial effects for small pools. For large pools, systematic studies are not available. Burgess⁴ and Zabetakis⁴⁰ have studied some aspects of special relevance to cryogenic fuels.

The layer thickness for a pool has an effect if it is less than that required to reach steady-state burning conditions. A fuel spilled in relatively small volume on a surface is a problem often encountered. Modak²⁶ provides some experimental guidance on expected thicknesses.

For thin, diathermanous layers, the boundary materials present under the pool can show radiative differences, depending on their reflectivity. The practical effects of this have not been explored.

Lip Height Effects: The effects of having a nonzero freeboard height, d , are significant for all pool fires and involve numerous phenomena. Hall¹⁷ has summarized some findings for small pools. For large pools, there are convective, conductive, and radiative effects:

1. A lip of significant height can initiate turbulence closer to the pool edge, and thereby raise convective heat transfer.
2. It can change the temperature distribution of the vessel walls, and thereby change conduction heat terms.
3. It tends to promote a stubbier, more emissive flame volume.

Orloff²⁸ has studied the combined effects of this heat redistribution on one fuel, PMMA, and finds that between $d/D = 0$ and $d/D = 0.07$ the burning rate is roughly raised by 60 percent, then slowly rises to twice the zero-lip rate at $d/D = 0.20$, and then slowly falls. Earlier data by Blinov³ and by Magnus²⁴ are available for liquid fuels burned at large freeboard heights. These do not show burning rate increasing with lip height, but rather, monotonically decreasing, down to as low as 12 percent of the zero-lip condition. It is unfortunate that further data do not exist on the lip height effects. Orloff's findings, however, could explain up to a factor of 2, inconsistencies among reported experimental data.

Effects of Wind: The effects of wind on a pool fire are complex. In the small-diameter limit, the main effect could be taken simply as convective heat transfer enhancement. Here, however, we are concerned with the effects at large diameters. Here, there still is an effect of convective enhancement, but two other phenomena also appear. The flame temperature is raised due to improved mixing and combustion,³ and the radiant heat fluxes are

TABLE 1. Data for Large Pool Burning Rate Estimates

Material	Density (kg/m ³)	Δh_c (kJ/kg)	Δh_v (MJ/kg)	\dot{m}_{∞} (kg/m ² -s)	$k\beta$ (m ⁻¹)	h (m ⁻¹)	T_f (K)	References
<i>Cryogenics</i>								
Liquid H ₂	700	442	120.0	0.169 (±0.006)	6.1 (±0.4)	—	1600	4,5
LNG (mostly CH ₄)	415	619	50.0	0.078 (±0.018)	1.1 (±0.8)	0.5	1500	1,4,30
LPG (mostly C ₃ H ₈)	585	426	46.0	0.099 (±0.009)	1.4 (±0.5)	0.4	—	20,35
<i>Alcohols</i>								
Methanol (CH ₃ OH)	796	1230	20.0	0.017 (±0.001)	*	—	1300	5,22,37
Ethanol (C ₂ H ₅ OH)	794	1000	26.8	0.015 (±0.001)	*	0.4	1490	7,9,24,31
<i>Simple Organic Fuels</i>								
Butane (C ₄ H ₁₀)	573	370	45.7	0.078 (±0.003)	2.7 (±0.3)	—	—	5
Benzene (C ₆ H ₆)	874	500	40.1	0.085 (±0.002)	2.7 (±0.3)	4.0	1460	5,31,38
Hexane (C ₆ H ₁₄)	650	450	44.7	0.074 (±0.005)	1.9 (±0.4)	—	1300	5,38,39
Heptane (C ₇ H ₁₆)	675	505	44.6	0.101 (±0.009)	1.1 (±0.3)	—	—	22,33
Xylene (C ₈ H ₁₀)	870	555	40.8	0.090 (±0.007)	1.4 (±0.3)	—	—	5
Acetone (C ₃ H ₆ O)	791	570	25.8	0.041 (±0.003)	1.9 (±0.3)	0.8	—	9,29,37
Dioxane (C ₄ H ₈ O ₂)	1035	530	26.2	0.018 ^a	5.4 ^a	—	—	33
Diethyl ether (C ₄ H ₁₀ O)	714	385	34.2	0.085 (±0.018)	0.7 (±0.3)	—	—	3
<i>Petroleum Products</i>								
Benzine	740	—	44.7	0.048 (±0.002)	3.6 (±0.4)	—	—	3
Gasoline	740	330	43.7	0.055 (±0.002)	2.1 (±0.3)	2.0	1450	3,18,24,31,38,39
Kerosene	820	670	43.2	0.039 (±0.003)	3.5 (±0.8)	2.6	1480	3,21
JP-4	760	—	43.5	0.051 (±0.002)	3.6 (±0.1) ^c	—	1220	3,16,21,34
JP-5	810	700	43.0	0.054 (±0.002)	1.6 (±0.3)	0.5	1250	8,14,15,32
Transformer oil, hydrocarbon	760	—	46.4	0.039 ^b	0.7 ^b	—	1500	22
Fuel oil, heavy	940-1000	—	39.7	0.035 (±0.003)	1.7 (±0.6)	—	—	3,6
Crude oil	830-880	—	42.5-42.7	0.022-0.045	2.8 (±0.4)	—	—	3,38
<i>Solids</i>								
Polymethyl- methacrylate	1184	1611	24.9	0.020 (±0.002)	3.3 (±0.8)	1.3	1260	12,26

* Value independent of diameter in turbulent regime

^b Only two data points available

^c Data from [14] excluded; otherwise $\dot{m}_{\infty} = 0.064$ (±0.010) and $k\beta = 5.3$ (±6.0)

redistributed. It would seem that the flux change would be such as to make the flame volume smaller and less well-centered, and thereby lower the radiative heating. Capener and Alger⁸ did indeed find such an effect for 1 and 3 m JP-5 pools. In their data the burning rate of a 1 m pool in a 6 meter per second wind drops to about half of its still-air value.

Unfortunately, there is somewhat more documentation showing an increased burning rate for large-diameter pools in wind. Lois and Swithenbank²³ observe a doubling of the burning rate of a hexane pool in a 4 meter per second wind, with no further increase for greater velocities. Blinov and Khudiakov³ give some equations which can be expressed as

$$\frac{\dot{m}''_{windy}}{\dot{m}''_{still}} = 1 + 0.15 \frac{u}{D} \quad (7)$$

The above appears to be the best formula available for use, with the restriction that it is not appropriate for alcohol fuels, nor for wind velocities sufficient to lead to blow-off. Beyond about 5 meter per second some fuels can be blown out, but the exact value depends on whether a flameholder action can be obtained.

Effects at Very Large Diameters: Some experimental data show a slight decrease in the burning rate of very large pools ($D \gtrsim 5$ or 10 m). Not enough systematic, precise data exist to provide a numeric model here beyond assuming independence of \dot{m}'' on D in this regime. Qualitatively this is presumed to be due to poorer mixing, leading to a larger cool vapor zone, lower flame temperatures, and cooler smoke (which can act to shield a fire base from its flames). In any case, this effect is not likely to be larger than about 20 percent.

RECOMMENDATIONS

Burning rates for pools with $D > 0.2$ m can be estimated on the basis of the equations

$$\dot{m}'' = \dot{m}''_{\infty} (1 - e^{-k_B D}) \quad (5)$$

and

$$\dot{q} = \Delta h_c \cdot \dot{m}'' \cdot A \quad (8)$$

with appropriate values taken from the table. The largest causes of uncertainty are believed to stem from effects of wind and of lip height. In the worst case this can introduce an uncertainty of the order of a factor of 2. Additional investigations are needed to provide better estimates in these areas.

NOMENCLATURE

A	= pool area (m ²)
d	= lip height (m)
D	= pool diameter (m), = $\sqrt{4A/\pi}$ for noncircular pools
Δh_c	= lower heat of combustion (kJ per kg)
Δh_s	= total heat of vaporization or gasification (kJ per kg)
k	= extinction coefficient (m ⁻¹)
\dot{m}''	= pool mass loss rate (kg per m ² per s)
\dot{m}''_{∞}	= infinite-diameter pool mass loss rate (kg per m ² per s)
\dot{q}''_c	= convective heat flux (kW per m ²)
\dot{q}''_{misc}	= miscellaneous heat loss flux (kW per cm ²)
\dot{q}''_r	= re-radiant heat flux (kW per m ²)
T_f	= flame temperature (K)
u	= wind speed (meters per second)
s	= second
β	= mean beam length corrector (-)
σ	= Stefan-Boltzmann constant (5.67×10^{-11} kW per m ² K ⁴)

APPENDIX

Data for Burning Rates

For each entry, measured burning rates (kg per m² per s) are listed, along with pool diameter D (m).

- Ref. 1* LNG: 0.053 (D=0.22), 0.046 (D=0.34), 0.042 (D=0.75), 0.022 (D=1.8), 0.13 (D=3.0), 0.060 (D=6.1), 0.085 (D=6.8).
- Ref. 3* Diethyl ether: 0.025 (D=0.3), 0.032 (D=0.8), 0.056 (D=1.4), 0.073 (D=2.6).
Benzene: 0.026 (D=0.2), 0.026 (D=0.25), 0.029 to 0.032 (D=0.3), 0.046 (D=0.5), 0.043 (D=0.8), 0.049 (D=1.3), 0.048 (D=1.4), 0.054 (D=2.6), 0.046 (D=8.6), 0.044 (D=22.9).
Gasoline: 0.048 (D=1.3).
Kerosene: 0.022 (D=0.2), 0.022 (D=0.25), 0.022 to 0.024 (D=0.3), 0.031 (D=0.8), 0.035 (D=1.4), 0.037 (D=2.6), 0.049 (D=22.9).
Fuel oil, heavy: 0.025 (D=1.3), 0.038 (D=2.6), 0.037 (D=22.9).
Crude oil: 0.012 (D=0.3), 0.021 (D=0.8), 0.021 (D=1.4), 0.022 (D=2.6).
- Ref. 4* LNG: 0.030 (D=0.38), 0.042 (D=0.75), 0.047 (D=1.52).
- Ref. 5* Liquid H₂: 0.064 (D=0.075), 0.101 (D=0.15), 0.147 (D=0.33).
Methanol: 0.013 (D=0.31), 0.018 (D=0.75), 0.022 (D=1.22), 0.024 (D=1.8).
Butane: 0.044 (D=0.31), 0.064 (D=0.61), 0.067 (D=0.75).
Benzene: 0.047 (D=0.31), 0.054 (D=0.38), 0.077 (D=0.75), 0.076 to 0.083 (D=1.22).
Hexane: 0.037 (D=0.31), 0.050 (D=0.50), 0.063 (D=0.75), 0.073 (D=1.22).
Xylenes: 0.027 (D=0.31), 0.053 (D=0.75), 0.067 (D=1.22).
- Ref. 6* Fuel oil, heavy: 0.025 (D=0.56), 0.032 (D=2.7).
- Ref. 7* Ethanol: 0.015 (D=0.33).
- Ref. 8* JP-5: 0.042 (D=0.92), 0.054 (D=3.1), 0.054 (D=17.).
- Ref. 9* Methanol: 0.015 (D=0.25), 0.013 (D=0.32), 0.013 (D=0.38).
Ethanol: 0.013 (D=0.25), 0.013 (D=0.32), 0.012 (D=0.38).
Acetone: 0.019 (D=0.25), 0.019 (D=0.3).
- Ref. 13* Cyclohexane: 0.110 (D=0.2), 0.165 (D=0.3).
- Ref. 14* Avgas: 0.106 (D=0.6 to 2.4).
JP-4: 0.106 (D=0.6 to 2.4).
JP-5: 0.071 (D=0.6 to 2.4).
- Ref. 16* JP-4: 0.051 (D=1.0, 1.5, 2.0, 3.0, 5.0, 10.).
- Ref. 20* LPG: 0.053 (D=0.34), 0.066 (D=0.77), 0.067 (D=1.7), 0.102 (D=3.4), 0.099 (D=6.9), 0.111 (D=14).

- Ref. 21 Kerosene: 0.026 (D=0.2).
JP-4: 0.026 (D=0.2).
- Ref. 22 Methanol: 0.020 (D=1.2), 0.021 (D=1.7), 0.021 (D=2.4).
Heptane: 0.067 (D=1.2), 0.073 (D=1.7).
Transformer oil, hydrocarbon: 0.022 (D=1.2), 0.027 (D=1.7).
- Ref. 24 Ethanol: 0.016 (D=0.25).
Gasoline: 0.023 (D=0.25).
- Ref. 26 PMMA: 0.009 (D=0.26), 0.016 (D=0.34), 0.017 (D=0.52), 0.018 (D=0.69),
0.018 (D=0.86), 0.020 (D=1.4).
- Ref. 33 Heptane: 0.028 (D=0.25), 0.062 (D=0.5).
Dioxane: 0.0131 (D=0.25), 0.0165 (D=0.5).
- Ref. 34 JP-4: 0.045 (D=1.22, 2.4, 3.9, 5.3).
- Ref. 37 Methanol: 0.013 (D=0.61), 0.014 (D=1.52).
Acetone: 0.025 (D=0.61), 0.038 (D=1.52).
- Ref. 38 Benzene: 0.087 (D=6.0).
Hexane: 0.077 (D=6.0).
Gasoline: 0.059 (D=6.0).
Crude oil: 0.045 (D=6.0).
- Ref. 39 Hexane: 0.036 (D=0.6), 0.060 (D=1.5), 0.074 (D=3.0).
Gasoline: 0.040 (D=0.6), 0.051 (D=1.5), 0.052 (D=3.0).

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