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An emissive power correlation for solid fuel packages

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Abstract
The most commonly used emissive power correlations were developed for pool fires. A literature search has been conducted to identify available empirical data sets that could be used to benchmark these correlations and to predict emissive power of fires involving wood and similar materials. Using the benchmark data, it has been demonstrated that pool-fire correlations underpredict the flame emissive power. With the identified data, a new emissive power correlation has been developed for solid fuel fires. The new correlation permits a more realistic representation of the flames associated with burning solid fuel packages.

Keywords
Cribs, emissive power, flame, forest, fuel package

Introduction

The commonly used techniques to estimate the heat flux (kW/m^2) imparted on a target by a fire typically combine three basic terms:

$$\dot{q}'' = F_{\mathrm{f-t}} E_{\mathrm{f}} \tau \tag{1}$$

The view factor between the fire and the target, $F_{\mathrm{f-t}}$, is typically accomplished using standard shape factors and an assumption of the fire shape (e.g., right cylinder). The atmospheric transmissivity, τ (dimensionless), accounts for water vapor absorption of radiation. For most problems, this effect is small and the value is taken as unity. The emissive power, E_{f}, is normally estimated empirically. The most commonly used emissive power correlations [1,2] were developed using pool-fire data. The techniques have been successfully benchmarked for pool fires [3,4] and are usually accepted for predictions of solid fuel fires [1].

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Currently used emissive power correlations

Two commonly used emissive power correlations are [1,2]:

$$E_{\mathrm{f}} = E_{\mathrm{m}}e^{-\mathrm{SD}} + E_{\mathrm{s}}\left(1 - e^{-\mathrm{SD}}\right) \tag{2}$$

$$E_{\mathrm{f}} = 58 \times 10^{-0.00823D} \tag{3}$$

where E_{f} is the effective emissive power of the fire (not just the emissive power of the luminous flames) [kW/m^2], E_{m} the maximum emissive power of the luminous spots [140 kW/m^2], E_{s} the emissive power of smoke [20 kW/m^2], S an empirical constant [0.12 m^{-1}], and D the pool diameter [m].

Both of these correlations were derived from pool-fire data and predict lower emissive powers as the fire diameter increases. Such behavior is expected because during hydrocarbon fires a thick black smoke will be present along the periphery of the fire. This smoke will absorb a significant part of the radiation and reduce the effective emissive power from the fire [2]. While both correlations were developed for hydrocarbon fires, NFPA 555 [1] suggests that they may be applied to other fuel packages.

Emissive power data

Direct emissive power measurements for non-pool fires are sparse. Typically, published emissive power data have been estimated from flame temperature measurements or derived from heat flux measurements using configuration factor estimates. Two empirical data sets have been identified where the measurement of emissive power was an experiential objective.

Hägglund and Persson [5] measured the emissive power of flames generated by the burning of wood cribs. The measurements were made at 0.15 or 0.5 m above the crib. The cribs were 1.2 m wide and varied from 0.25 to 2.0 m deep. Emissive powers were calculated from spectrophotometer measurements and varied from 20 to 152 kW/m^2, with the higher powers occurring for the greater flame depths. Maximum flame temperatures varied from 600 to 1030°C, again with the higher temperatures occurring for greater flame depths. These temperatures were measured with thermocouples spaced 0.1 m apart at the elevation of the spectrophotometer. Data from these tests are presented in Table 1. For comparison, these data are presented with Equations (1) and (2) in Figure 1.

Butler et al. [6] measured the emissive power and flame temperature in burning timber stands. These stands averaged 13 m high, with widths that varied from 75 to 150 m. The test instrumentation was installed on towers near the downwind edge of each test plot and the fire was ignited on the opposite side of the test plot. Radiant heat fluxes were measured with narrow angle radiometers viewing horizontally at the approaching flame front [6]. Their view field had a half-angle of 4.1°. Bare-wire 0.13-mm diameter type-K (chromel alumel) thermocouples [6] were used to measure temperature. Six tests were conducted during this program.

Table 1. Test results from Hägglund and Persson [5].

Test	Elevation meters	Flame depth meters	Maximum flame temperature (°C)	Emissive power (kW/m^2)
1	0.30	0.15	600	20
2	0.30	0.60	980	80
3	0.30	0.90	1020	101
4	0.30	1.20	1020	122
5	0.30	1.30	1000	120
6	0.30	2.00	1030	152
7	0.30	1.10	980	116
8	0.30	0.70	950	89
9	0.30	0.40	800	40
10	0.30	0.30	800	31
11	0.30	0.20	740	19
12	0.50	1.10	960	109
13	0.50	0.80	980	90
14	0.50	0.25	750	20
15	0.50	1.20	960	110
16	0.50	1.60	1020	136

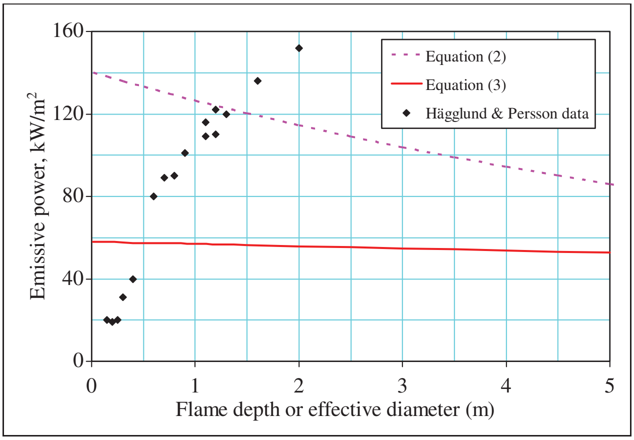

Figure 1. Emissive power correlation comparison with Hägglund and Persson data.

Table 2. Test data details for Butler [7].

		Heat flux gage elevation (m)				
		13.8	12.3	9.2	6.2	3.1
Test plot	Tower	Emissive power (kW/m^2)				
1	4	122	139	170	109	189
1	5	175	219	219	163	205
4	1	231	186	...	88	140
4	4	161	180	183	...	...
5	3	166	150	134	...	...
6	1	...	277	260	268	253
6	2	156	229	178	290	280
9	2	220	243	259	238	160
9	3	243	199	289	178	258

The published results pooled the data from the six tests by instrument elevation with a goal of understanding the vertical heat flux and temperature profiles. Average emissive powers were 190 kW/m^2 with a standard deviation of 90 kW/m^2. The peak emissive power observed during the six tests was 290 kW/m^2. There was no significant variation in the vertical heat flux profile for the pooled results. Average temperatures varied from 550°C to 1000°C, with the lower values occurring 3.1 m above the ground. Peak flame temperatures were 1330°C. The standard deviation for the average flame temperatures in the upper elevations (9.2, 12.3, and 13.8 m) was approximately 100°C. For consistency with the Hägglund and Persson tests, the currently available test-specific data were obtained and presented in Table 2.

Data for Test Plot A were derived from the plots in [6] since these were not provided along with the data from the other five tests [7]. The derived Test Plot A data are presented in Table 3.

The average rate of fire spread for the tests in [6] ranged from 0.48 to 1.16 m/s. Since the intense burning period was approximately 30 s in duration, the effective flame depth has been estimated as the product of the fire spread rate and the burn period. These values are provided in Table 4.

Predictive emissive power correlation

A correlation was derived based on a blend of the two available data sets. The correlation form was taken from that for an isothermal radiating gas [8].

$$E_f = \alpha\left(1 - e^{-\beta D_f}\right) \tag{4}$$

Table 3. Test data details derived for Test Plot A from Ref. [6].

		Heat flux gage elevation (m)				
		13.8	12.3	9.2	6.2	3.1
Test plot	Tower	Emissive power (kW/m^2)				
A	4	120	135	170	105	185
A	5	175	215	215	160	205

Table 4. Test results from [6] consolidated by test plot.

Test plot	Calculated flame depth (m)	Calculated from Table 2 (kW/m^2) Emissive power	SD
A	28.2	169*	39*
1	17.7	171	39
4	22.2	167	45
5	14.4	150	16
6	18.0	243	47
9	34.8	229	40

*From Table 3.

where E_f is the effective emissive power of the fire [kW/m^2], D_f the effective flame depth [m], α an empirical coefficient [kW/m^2], and β an empirical coefficient [m^{-1}].

The coefficients were estimated using a non-linear least square fit of the data presented in Tables 1 and 4. The α-coefficient has been calculated as $189 \pm 16\,\mathrm{kW/m^2}$, and the β-coefficient as $0.80 \pm 0.18\,\mathrm{m^{-1}}$. These values are best rounded to 190 and 0.8, respectively. The new correlation is shown in Figure 2 with the data from Tables 1 and 2. Also, presented in the figure are the correlations discussed earlier. These results are the same as the correlation proposed by Babrauskas [9], who developed the following with just the Hägglund and Persson data:

$$E_f = 190\left(1 - e^{-0.8D_f}\right) \tag{5}$$

Since the flame depth was limited to 2 m during the Hägglund and Persson tests, the emissive powers for larger fires required significant extrapolation.

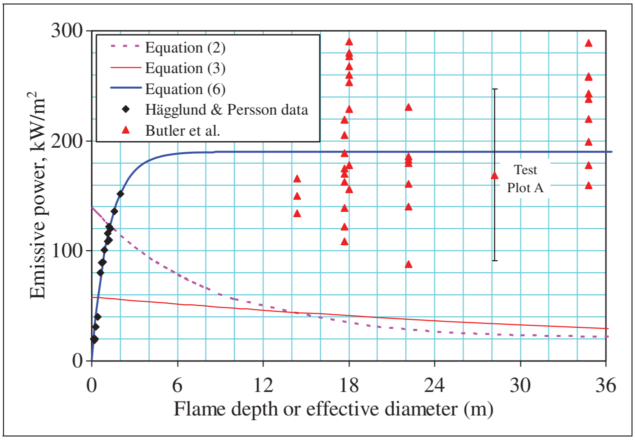

Figure 2. Emissive power correlation comparisons.

Conclusions

An empirically derived emissive power correlation, which is specific to fires involving wood and similar cellulose material, has been demonstrated to satisfactorily predict the experimental data for flame depths from 0.15 to 35 m.

$$E_f = 190\left(1 - e^{-0.80D_f}\right) \tag{6}$$

This equation was published [9] in 2003, but at that time the demonstrated validity was limited to flame depths of 0.15–2 m. In addition to extending the validity of Equation (6) over a wider range, it has now been demonstrated that for flame depths greater than 2 m, the current NFPA 555 correlations underpredict the emissive power for fires involving wood or similar materials. NFPA 555 should be updated to include Equation (6) for fires involving wood and similar materials.

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