User Guides and Example Cases for Use of OpenSC

1.1 Evaluation of Radiative Properties

To demonstrate the operational procedure of OpenSC, the total emissivity/absorptivity for mixture in various conditions is determined in this section. Fig. 1a shows the user interface for OpenSC and there are two options for the radiation calculations. Given with mixture conditions, which includes a source temperature (T_w), a gas temperature (T_g), a total absorptive optical thickness ($P_g L$), an absorptive mole fraction of CO_2 (X_{CO_2}), and a soot concentration thickness ($f_v L$), the total emissivity/absorptivity can be obtained from a single-value calculation. It should be noted that even though the path-length L is not required as an input parameter, the user is asked to provide a value for L. This input is to remind the user that the absorptive optical thickness divided by the path-length does not exceed 1 atm (~100 kPa). Otherwise, there will be errors and the calculation will not be able to start. For single-value calculations, the computation is efficient and results can be obtained in less than a fraction of a second.

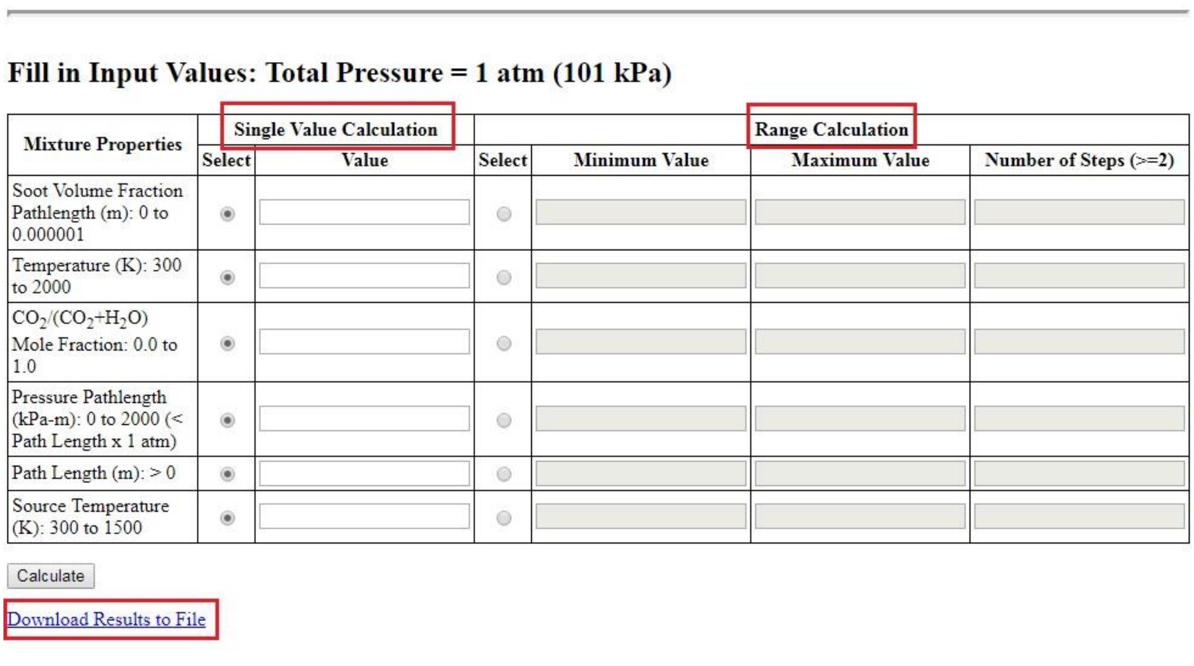
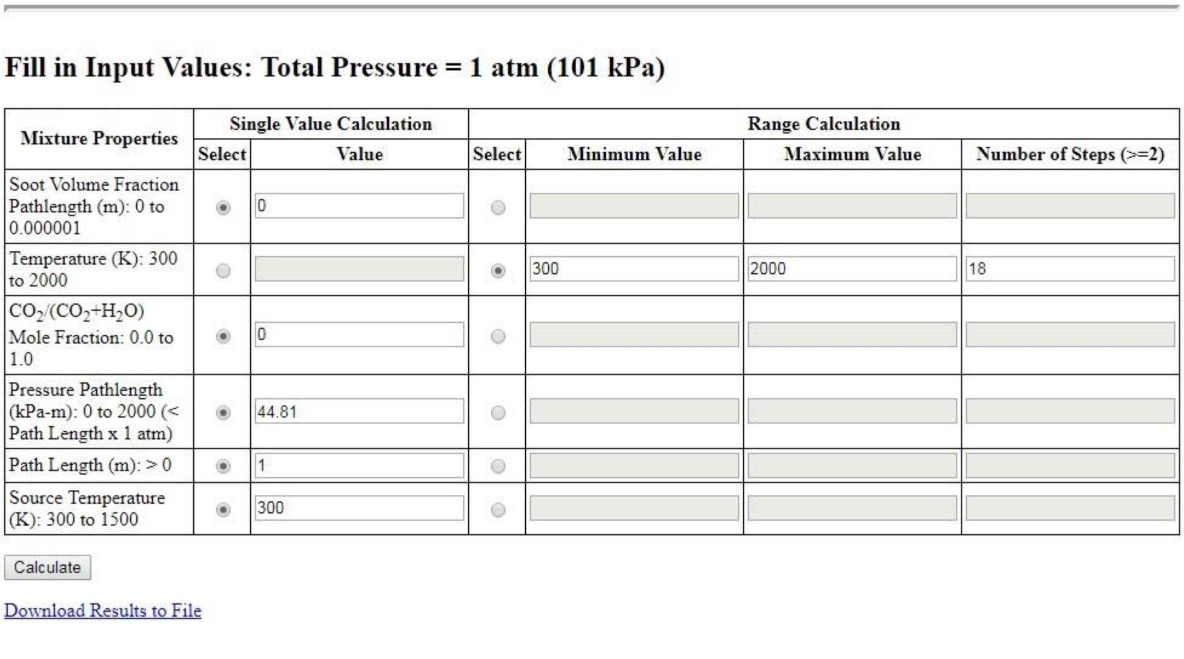


Fig. 1a. User interface of OpenSC.

The second option is a range calculation. The range calculation offers a capability to carry out parametric studies to understand the effect for different mixture conditions. An example for the determination of total emissivity for pure H_2O at different gas temperature is provided in Fig. 1b. Since the total emissivity of H_2O is of interest in this example, soot volume fraction and absorptive mole fraction of CO_2 are set to be zero. Source temperature is set to be the same as the gas temperature. By clicking the *Calculate* button, the calculation will execute and results for total emissivity will be displayed in the user interface. In order to facilitate further analysis on the radiative properties, the results obtained from either single-value or range calculation can be saved in an Excel spreadsheet by simply clicking the *Download Results to File* button. Generally, input parameters such as partial pressure for gaseous species and volume fraction of soot are not typically being obtained directly from fire design/protection engineering calculations. Therefore, a simple algorithm is included in Appendix A to provide the relevant expressions for the conversion of species/soot mass into appropriate variables with correct units.



Fill in Input Values: Total Pressure = 1 atm (101 kPa)

Mixture Properties	Single Value Calculation		Range Calculation			
	Select	Value	Select	Minimum Value	Maximum Value	Number of Steps (>=2)
Soot Volume Fraction Pathlength (m): 0 to 0.000001	◉	0	○			
Temperature (K): 300 to 2000	○		◉	300	2000	18
$CO_2/(CO_2+H_2O)$ Mole Fraction: 0.0 to 1.0	◉	0	○			
Pressure Pathlength (kPa-m): 0 to 2000 (< Path Length x 1 atm)	◉	44.81	○			
Path Length (m): > 0	◉	1	○			
Source Temperature (K): 300 to 1500	◉	300	○			

Calculate

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Fig. 1b. Inputs for the evaluation of pure H_2O emissivity at different gas temperature (since the optical thickness is not evenly distributed, manual input is needed to handle calculations for 10 different optical thicknesses).

1.1.1 Emissivity

A total emissivity chart for pure H_2O generated by OpenSC is presented in Fig. 2 for different optical thicknesses and with gas temperature ranging from 300 K to 2000 K. The relevant inputs for generating the numerical data for a specific absorptive optical thickness are provided in above (refer to Fig. 1b). In Fig. 2, it can be noticed that the total emissivity is a monotonic decreasing function of increasing gas temperature for small optical thickness. When the optical thickness becomes larger, the total emissivity first increases with increasing gas temperature in low temperature region and then decreases from its peak value with increasing gas temperature. The physical mechanism corresponding to the increase or decrease for the total emissivity can be attributed to the unique absorption characteristics associated with H_2O at a specified gas temperature and pressure.

A total emissivity chart for pure CO_2 and the relevant input file for a specific absorptive optical thickness are presented in Fig. 3a and 3b, respectively[1]. The total emissivity of CO_2 is plotted for different absorptive optical thicknesses with gas temperature ranging from 300 K to 2000 K. The slight nonlinearity in the region of 700 K corresponds to the effect of the strong CO_2 absorption band at 4.3 μm. In comparison to the results shown in Fig. 2, the CO_2 emissivity is lower than the H_2O emissivity and this is generally due to the weaker CO_2 absorption bands.

[1] Completed list of data are provided in Appendix A in this documentation for all example cases and the raw data can be downloaded from Verification folder.

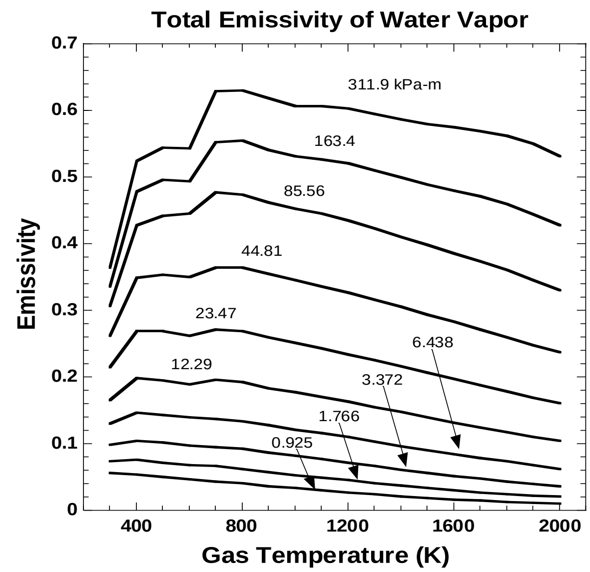

Fig. 2. Calculated total emissivity of H_2O using OpenSC.

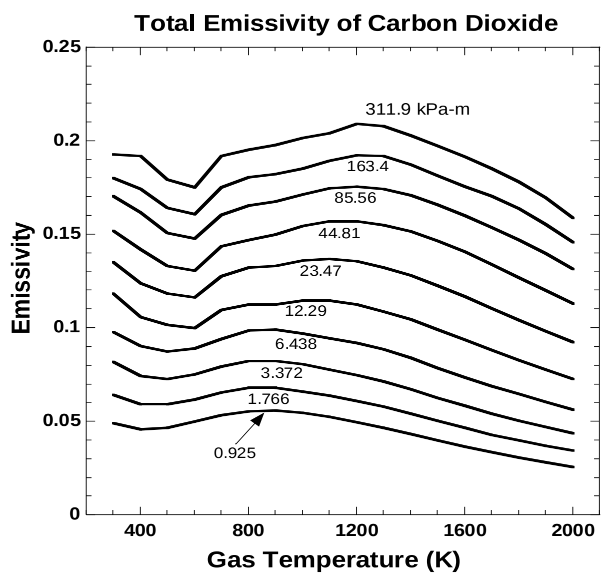

Fig. 3a. Calculated total emissivity of CO_2 using OpenSC.

A total emissivity chart for pure soot is shown in Fig. 4a and the relevant input file is shown in Fig. 4b. The soot emissivity is plotted for different soot concentration thicknesses, f_vL, ranging from 10^{-9} m to 10^{-6} m for a wide range of gas temperature. As shown in the Fig. 4a, in contrast to the emissivity behavior of pure H_2O and pure CO_2, soot emissivity is a monotonic increasing function of increasing gas temperature and this is because of the inverse wavelength dependence of the soot's absorption coefficient. A high emissivity can thus be obtained with either larger value of soot concentration or larger gas temperature. As expected, when the soot concentration is high (i.e., $f_vL > 10^{-6}$ m), the soot emissivity approaches unity.

Fill in Input Values: Total Pressure = 1 atm (101 kPa)

Mixture Properties	Single Value Calculation		Range Calculation			
	Select	Value	Select	Minimum Value	Maximum Value	Number of Steps (>=2)
Soot Volume Fraction Pathlength (m): 0 to 0.000001	◉	0	○			
Temperature (K): 300 to 2000	○		◉	300	2000	18
$CO_2/(CO_2+H_2O)$ Mole Fraction: 0.0 to 1.0	◉	1	○			
Pressure Pathlength (kPa-m): 0 to 2000 (< Path Length x 1 atm)	◉	44.81	○			
Path Length (m): > 0	◉	1	○			
Source Temperature (K): 300 to 1500	◉	300	○			

Calculate

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Fig. 3b. Inputs for the evaluation of pure CO_2 emissivity at different gas temperature (since the optical thickness is not evenly distributed, manual input is needed to handle calculations for 10 different optical thicknesses).

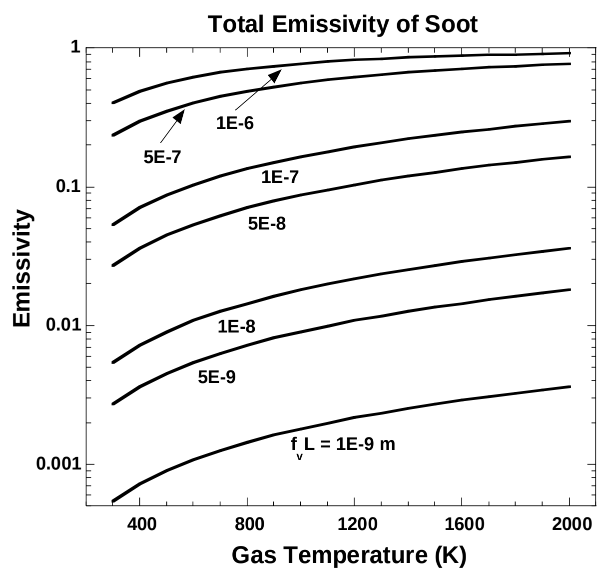
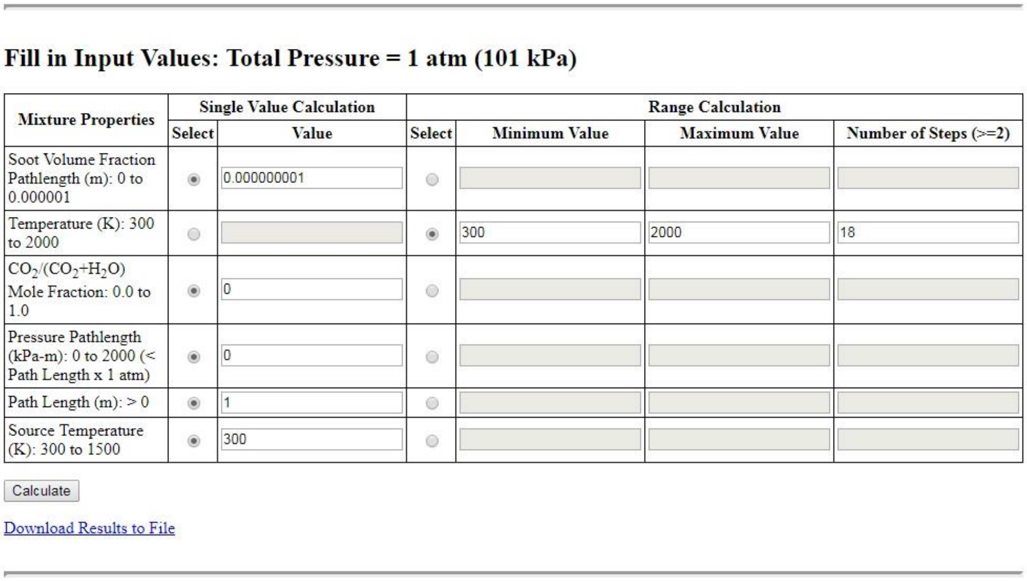


Fig. 4a. Calculated total emissivity of soot particulates using OpenSC.

In practical engineering calculations, H_2O, CO_2, and/or soot particulates can simultaneously exist in a mixture. The total emissivity behavior associated with such mixture along a line of sight is limited in currently available literature except for those found in [13]. In order to provide a more comprehensive overview of mixture emissivity behavior to the reader, examples are generated by OpenSC to demonstrate the effect of different combination of gaseous species and soot particulates.



Fill in Input Values: Total Pressure = 1 atm (101 kPa)

Mixture Properties	Single Value Calculation		Range Calculation			
	Select	Value	Select	Minimum Value	Maximum Value	Number of Steps (>=2)
Soot Volume Fraction Pathlength (m): 0 to 0.000001	●	0.000000001	○			
Temperature (K): 300 to 2000	○		●	300	2000	18
$CO_2/(CO_2+H_2O)$ Mole Fraction: 0.0 to 1.0	●	0	○			
Pressure Pathlength (kPa-m): 0 to 2000 (< Path Length x 1 atm)	●	0	○			
Path Length (m): > 0	●	1	○			
Source Temperature (K): 300 to 1500	●	300	○			

Calculate

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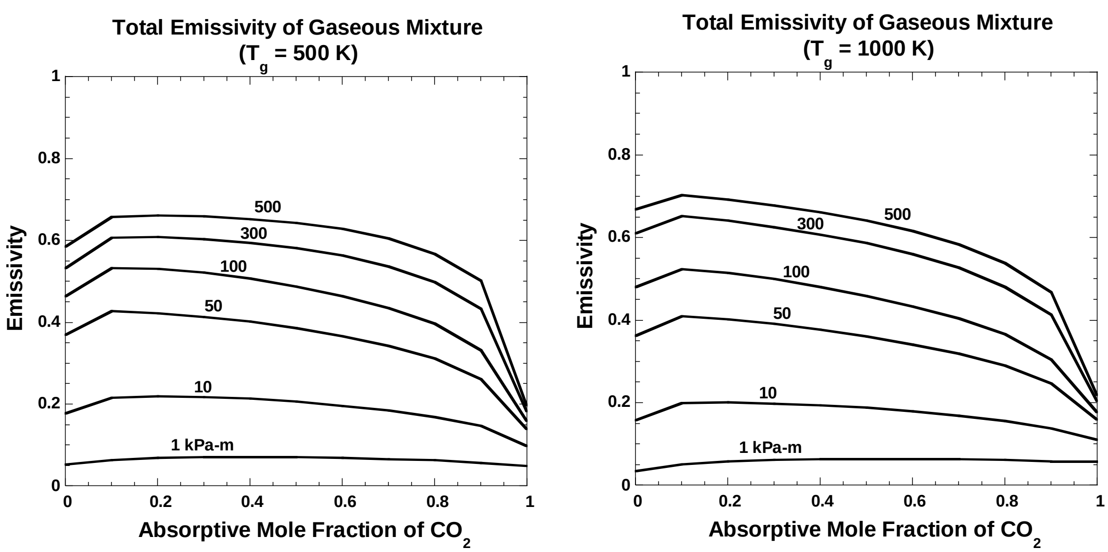
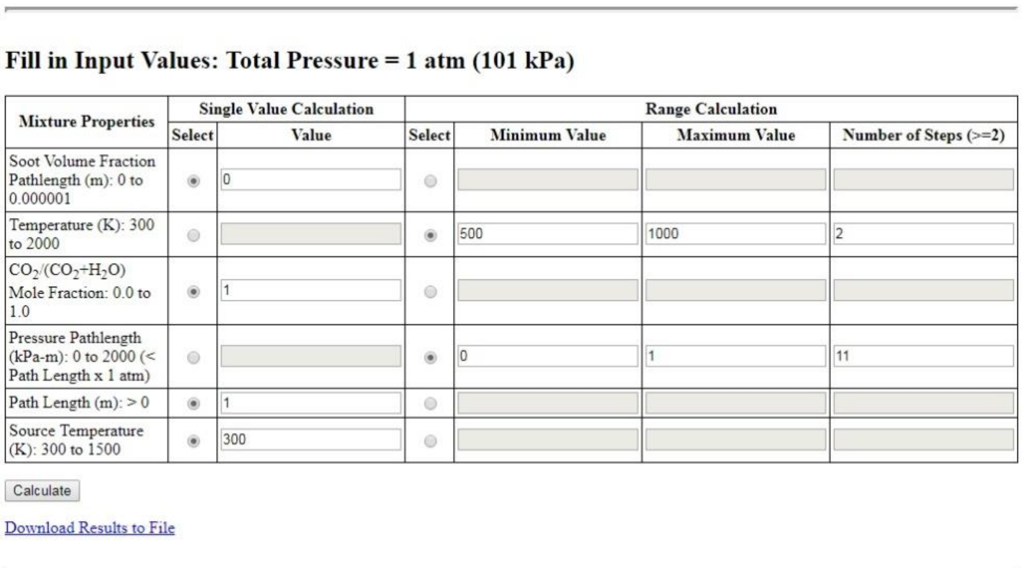
Fig. 4b. Inputs for the evaluation of pure soot emissivity at different gas temperature (since the soot concentration is not evenly distributed, manual input is needed to handle calculations for 7 different soot concentrations).



Figs 5a. Calculated total emissivity of mixture consisted of water vapor and carbon dioxide with gas temperature evaluated at 500 K (left) and 1000 K (right) using OpenSC.

In Figs. 5a, the total emissivity of a mixture of H_2O and CO_2 is plotted as a function of the absorptive mole fraction of CO_2 with different absorptive optical thicknesses. A typical input file for the generation of the numerical data is shown in Fig. 5b. Two gas temperatures, 500 K and 1000 K, are considered in this example. In general, the mixture emissivity increases with increasing absorptive optical thickness and this emissivity behavior is independent of gas temperature. For different fraction of CO_2, it is interesting to see that CO_2 addition to the mixture first increases and then decreases the mixture emissivity. The initial increases of the mixture emissivity in the region of low CO_2 fraction is primarily due to the strong absorption effect from the fundamental band CO_2 (4.3 μm) and the overlapping effect associated with the absortion band of H_2O (2.7 μm) and CO_2 (2.7 μm) near the peak of Planck function for 1000 K (2.9 μm)[2]. A "small" amount of CO_2 added to the mixture thus increase the mixture emissivity. However, as the CO_2 concentration increases, the H_2O contribution to the mixture emissivity decreases and the mixture emissivity decreases toward the total emissivity of pure CO_2 (refer to Fig. 3a). Fig. 6 shows the emissivity of mixture consisted of H_2O, CO_2, and soot particulates and, as expected, the mixture emissivity generally increases with increasing soot concentration.



Fill in Input Values: Total Pressure = 1 atm (101 kPa)

Mixture Properties	Single Value Calculation		Range Calculation			
	Select	Value	Select	Minimum Value	Maximum Value	Number of Steps (>=2)
Soot Volume Fraction Pathlength (m): 0 to 0.000001	◉	0	○			
Temperature (K): 300 to 2000	○		◉	500	1000	2
$CO_2/(CO_2+H_2O)$ Mole Fraction: 0.0 to 1.0	◉	1	○			
Pressure Pathlength (kPa-m): 0 to 2000 (< Path Length x 1 atm)	○		◉	0	1	11
Path Length (m): > 0	◉	1	○			
Source Temperature (K): 300 to 1500	◉	300	○			

Calculate

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Fig. 5b. Inputs for the evaluation of mixture emissivity with different absorptive mole fraction of CO_2 as a function of gas temperature.

1.1.2 Absorptivity

Total absorptivity is an important parameter that characterizes the total amount of energy being absorbed by a medium due to emission from another source. Fundamentally, the total absorptivity from non-gray gases can have a completely different behavior as compared to the total emissivity if the source temperature differs from the gas temperature. However, if the mixture is assumed to be gray, the total absorptivity is constrained to be equal to the total emissivity, an assumption generally invoked without any mathematical verification in many fire applications (for example, this practice is found in one of the most commonly used fire simulation codes[3] [25] certified by the U.S. Department of Energy). Since the effect of radiation is known to be not only important, but dominant in combustion/fire calculations. OpenSC can be used to obtain the total absorptivity of a mixture consisting of H_2O, CO_2, and/or soot particulates for different conditions and the obtained results can be used to assess the accuracy of the gray assumption of equal total absorptivity and total emissivity.

[2] The peak of Planck function is determined from solving the Wien's displacement law with a gas temperature.

[3] The fire simulation code is typically being used to predict the environment in a multi-compartment structure subjected to a fire and/or to simulate the impact of past or potential fires and smoke in a specific building environment by fire investigators, safety officials, engineers, architects, and builders.

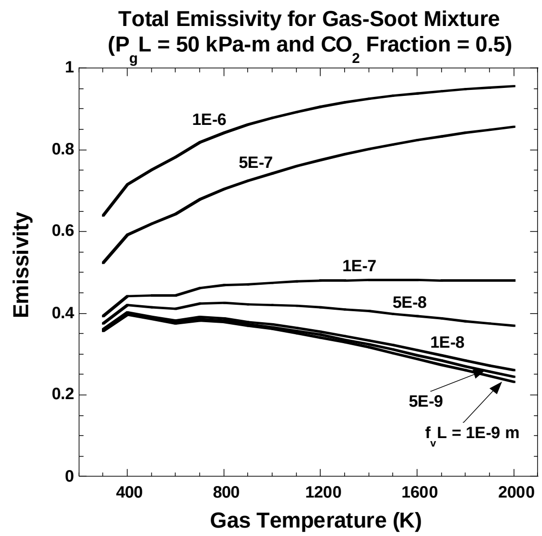

Fig. 6. Calculated total emissivity of soot-gas mixture using OpenSC.

Fill in Input Values: Total Pressure = 1 atm (101 kPa)

Mixture Properties	Single Value Calculation		Range Calculation			
	Select	Value	Select	Minimum Value	Maximum Value	Number of Steps (>=2)
Soot Volume Fraction Pathlength (m): 0 to 0.000001	○		◉	0	0.0000001	2
Temperature (K): 300 to 2000	○		◉	300	2000	18
$CO_2/(CO_2+H_2O)$ Mole Fraction: 0.0 to 1.0	◉	10	○			
Pressure Pathlength (kPa-m): 0 to 2000 (< Path Length x 1 atm)	◉	0.5	○			
Path Length (m): > 0	◉	1	○			
Source Temperature (K): 300 to 1500	○		◉	500	1500	3

Calculate

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Fig. 7. Inputs for the evaluation of mixture emissivity and absorptivity as a function of gas temperature with 3 different source temperatures for 2 soot conditions.

1.1.3 Comparison between absorptivity and emissivity

Fig. 7 shows a typical input file for the determination of absorptivity and emissivity of mixture consisted of H_2O, CO_2, and/or soot particulates. In contrast to the evaluation of total emissivity, the source temperature is now important. For a gas mixture, the total emissivity and the total absorptivity as a function of gas temperature are plotted in Fig. 8. Three different source temperatures (500 K, 1000 K, and 1500 K) for the total absorptivity are considered in the example. Since the total emissivity is independent of source temperature, there is only one curve for the total emissivity. As shown in the figure, the total absorptivity is significantly different than the total emissivity both in terms of its numerical value and its dependence on the gas temperature. In general, the total absorptivity is an increasing function of gas temperature, which is completely opposite to the trend for the total emissivity. For the effect of source temperature, it can be noticed that lower source temperature typically leads to overall higher total absorptivity. Physically, this trend is expected because the peak of the Planck function for lower source temperature is shifted to the more active absorption band for H_2O in the long wavelength region (4.7 μm and 6.3 μm). The total absorptivity for a soot-gas mixture is presented in Fig. 9. Note that the gas temperature has an effect on the total absorptivity only for a gas-soot mixture with a finite absorptive optical thickness (P_gL = 10 kPa-m in Fig. 9). In the limit of a pure soot mixture, the total absorptivity is only a function of the source temperature.

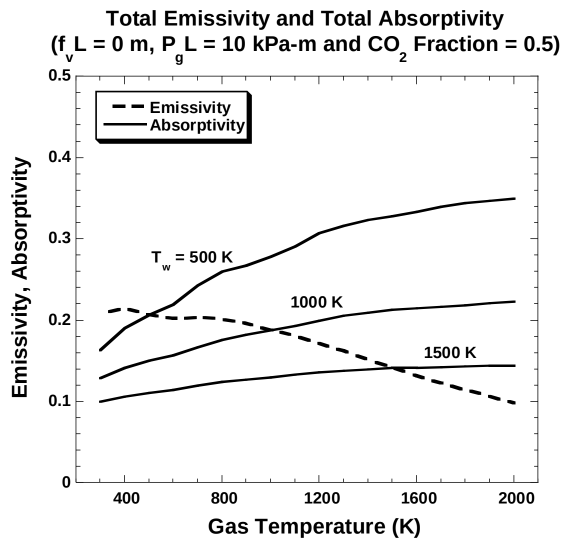

Fig. 8. Absorptivity of gas mixture (no soot) at different source temperature (Emissivity of the same mixture is also plotted for comparison).

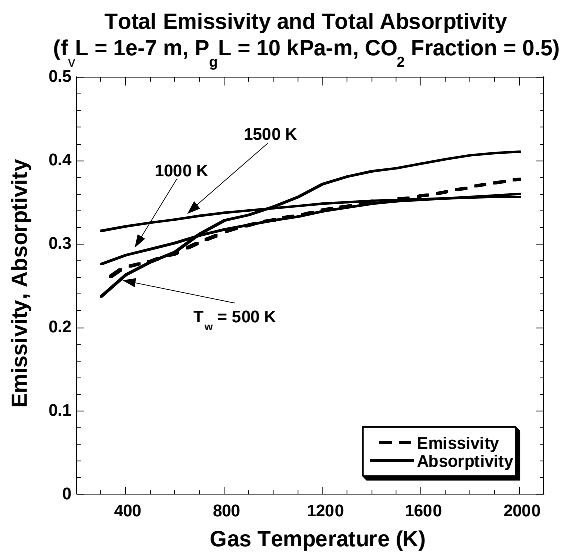

Fig. 9. Absorptivity of soot-gas mixture at different source temperature (Emissivity of the same mixture is also plotted for comparison).

Quantitatively, comparison between the total emissivity and the total absorptivity as shown in Fig. 8 and 9 demonstrates clearly that the two properties are different and have different dependence on mixture parameters. Therefore, the assumption of a gray medium with equal emissivity and absorptivity for the combustion products is not supported by fundamental physics and should not be applied for the evaluation of radiation effect for non-gray medium in fire design/safety protection calculations.

Appendix A: Expressions for Mass Conversion

The authors notice that mass for species and soot are typically being provided in fire safety/design calculations. In order to facilitate the radiation calculation, three expressions are presented below to convert 1) species mass for H_2O and CO_2 into partial pressure and 2) soot mass into soot volume fraction.

Assuming the total pressure of gaseous species to be 101.325 kPa, the partial pressure of H_2O can be obtained from the ideal gas law

$$P_{H_2O} = \frac{n_{H_2O} R T_g}{V}$$

where R is the universal gas constant (8.3143 J/mol/K or 8.20562e-5 atm·m^3/mol/K), T_g is the gas temperature (K), V is the volume of the mixture, and n_{H_2O} is the mole number of H_2O that can be evaluated by dividing the mass of H_2O by mole mass of H_2O

$$n_{H_2O} = \frac{m_{H_2O}}{M_{H_2O}}$$

for which the unit of m_{H_2O} and M_{H_2O} is kg and kg/mol, respectively. For H_2O, the mole mass is taken to be 18.0153e-3 kg/mol.Similarly, the partial pressure of CO_2 is given by

$$P_{CO_2} = \frac{m_{CO_2} R T_g}{M_{CO_2} V}$$

where the mole mass of CO_2 is taken to be 44.0088e-3 kg/mol. The soot volume fraction can be obtained from

$$f_v = \frac{m_{soot}}{V \rho_{soot}}$$

where m_{soot} is the mass of the soot and ρ_{soot} is the density of the soot that is taken to be 1800 kg/m^3.

Appendix B – List of data for all cases

1) Data for Figure 2 (total emissivity for pure H_2O):

Gas Temperature	0.925	1.766	3.372	6.438	12.29	23.47	44.81	85.56	163.4	311.9
K	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m
300	0.056221	0.074237	0.099141	0.13036	0.16582	0.21568	0.26187	0.30659	0.3365	0.36479
400	0.053881	0.076432	0.10489	0.14728	0.19935	0.26937	0.34916	0.42843	0.47856	0.52462
500	0.050864	0.072532	0.10264	0.14328	0.19587	0.26926	0.35468	0.44252	0.49636	0.54506
600	0.047591	0.068424	0.097892	0.1397	0.18924	0.26217	0.35062	0.44561	0.49346	0.54358
700	0.044196	0.066657	0.096038	0.13808	0.19667	0.27155	0.36425	0.47724	0.55216	0.62857
800	0.040771	0.062957	0.092884	0.13422	0.19247	0.26941	0.36464	0.47362	0.55477	0.63054
900	0.037287	0.058036	0.087625	0.128	0.18424	0.25981	0.35502	0.46178	0.54065	0.61855
1000	0.033811	0.053517	0.082401	0.12174	0.17763	0.25154	0.34594	0.45329	0.53163	0.60645
1100	0.030462	0.049503	0.077521	0.11618	0.1707	0.24322	0.33649	0.44581	0.52659	0.60718
1200	0.027288	0.045509	0.072468	0.11054	0.16338	0.23461	0.32658	0.43566	0.52048	0.60303
1300	0.024322	0.041375	0.067072	0.10412	0.15573	0.22566	0.31626	0.42347	0.51099	0.59451
1400	0.021603	0.037377	0.061682	0.097171	0.14781	0.21639	0.30556	0.41069	0.49943	0.58629
1500	0.01916	0.033792	0.056667	0.090493	0.1398	0.2069	0.29455	0.39818	0.48873	0.57976
1600	0.017004	0.030668	0.052118	0.084497	0.13189	0.19732	0.28328	0.38603	0.48023	0.57448
1700	0.015135	0.027909	0.047933	0.079051	0.12428	0.18785	0.27185	0.37374	0.47172	0.56917
1800	0.013539	0.025411	0.043988	0.073788	0.11714	0.17863	0.26033	0.36067	0.46009	0.56192
1900	0.012197	0.023109	0.040221	0.068345	0.11058	0.16981	0.24883	0.34624	0.44503	0.55018
2000	0.011084	0.020981	0.036635	0.062476	0.10464	0.16146	0.23745	0.33015	0.42818	0.53108

2) Data for Figure 3a (total emissivity for pure CO_2):

Gas Temperature	0.925	1.766	3.372	6.438	12.29	23.47	44.81	85.56	163.4	311.9
K	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m
300	0.049394	0.064503	0.081808	0.098032	0.11846	0.1353	0.15193	0.17065	0.18007	0.19282
400	0.045798	0.059345	0.074573	0.090302	0.10599	0.12378	0.14216	0.16177	0.17438	0.19194
500	0.046668	0.059137	0.072684	0.087199	0.10181	0.11839	0.13331	0.1508	0.16413	0.17931
600	0.04999	0.061967	0.07506	0.089064	0.10008	0.11633	0.13066	0.14803	0.16086	0.175
700	0.053462	0.0658	0.079628	0.094225	0.10968	0.12782	0.14356	0.16046	0.17529	0.19205
800	0.055604	0.068065	0.082579	0.098565	0.11249	0.13214	0.14721	0.16549	0.18064	0.19516
900	0.055997	0.06789	0.082487	0.099086	0.11268	0.1331	0.14981	0.16767	0.18235	0.1977
1000	0.054826	0.066175	0.080559	0.096901	0.11485	0.13621	0.15478	0.17136	0.18512	0.20163
1100	0.052575	0.063795	0.077903	0.094402	0.11459	0.13693	0.15713	0.17456	0.1893	0.20425
1200	0.049707	0.061075	0.074884	0.092125	0.11241	0.1355	0.1571	0.17571	0.19246	0.20927
1300	0.04654	0.057962	0.071389	0.088866	0.10891	0.13244	0.15512	0.1744	0.19186	0.20785
1400	0.043263	0.054371	0.0673	0.084005	0.10444	0.12808	0.15151	0.17092	0.1874	0.20295
1500	0.039989	0.050474	0.062824	0.078526	0.099334	0.12277	0.14656	0.16591	0.18128	0.19727
1600	0.036794	0.046617	0.058361	0.073474	0.093881	0.11685	0.14062	0.16	0.17562	0.1915
1700	0.033734	0.043054	0.054192	0.069016	0.088331	0.11062	0.13401	0.15362	0.17041	0.18535
1800	0.03085	0.039864	0.050406	0.064864	0.082876	0.10433	0.12706	0.14694	0.16399	0.17823
1900	0.02817	0.037014	0.046978	0.060699	0.07765	0.098185	0.12001	0.13976	0.15549	0.16952
2000	0.025705	0.034438	0.043847	0.056337	0.072741	0.092311	0.11307	0.13151	0.14568	0.15867

3) Data for Figure 4a (total emissivity for pure soot):

Gas Temperature	1.00E-09	5.00E-09	1.00E-08	5.00E-08	1.00E-07	5.00E-07	1.00E-06
K	--	--	--	--	--	--	--
300	0.0005459	0.0027293	0.0054586	0.027293	0.053773	0.2359	0.405
400	0.0007278	0.0036391	0.0072782	0.036391	0.071107	0.29843	0.49165
500	0.0009098	0.0045489	0.0090977	0.045106	0.087717	0.35458	0.56271
600	0.0010917	0.0054586	0.010917	0.053773	0.10424	0.405	0.62148
700	0.0012737	0.0063684	0.012737	0.06244	0.12012	0.4506	0.67044
800	0.0014556	0.0072782	0.014556	0.071107	0.13587	0.49165	0.71149
900	0.0016376	0.008188	0.016376	0.079457	0.15106	0.52894	0.74616
1000	0.0018195	0.0090977	0.018195	0.087717	0.16609	0.56271	0.77562
1100	0.0020015	0.010008	0.020015	0.095977	0.18062	0.59346	0.8008
1200	0.0021835	0.010917	0.021835	0.10424	0.19496	0.62148	0.82243
1300	0.0023654	0.011827	0.023654	0.11224	0.20888	0.64703	0.84111
1400	0.0025474	0.012737	0.025474	0.12012	0.22257	0.67044	0.85731
1500	0.0027293	0.013647	0.027293	0.12799	0.2359	0.69182	0.87142
1600	0.0029113	0.014556	0.029113	0.13587	0.24898	0.71149	0.88377
1700	0.0030932	0.015466	0.030932	0.14354	0.26174	0.72953	0.89461
1800	0.0032752	0.016376	0.032752	0.15106	0.27425	0.74616	0.90417
1900	0.0034571	0.017286	0.034571	0.15857	0.28648	0.76148	0.91263
2000	0.0036391	0.018195	0.036391	0.16609	0.29843	0.77562	0.92013

4) Data for Figure 5a (total emissivity for mixture of H_2O and CO_2 for fixed gas temperature at 500 K):

Mole Absorptive Fraction of CO2	**1**	**10**	**50**	**100**	**300**	**500**
--	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m
0	0.053385	0.17901	0.36959	0.46354	0.5332	0.58508
0.1	0.064849	0.2165	0.42824	0.53369	0.6072	0.65849
0.2	0.069523	0.22045	0.42354	0.53145	0.6098	0.66241
0.3	0.071243	0.21858	0.41473	0.52207	0.604	0.65934
0.4	0.071501	0.21402	0.40244	0.5078	0.5948	0.65337
0.5	0.07081	0.20703	0.38645	0.48861	0.5821	0.64396
0.6	0.069286	0.19738	0.36687	0.4646	0.564	0.62914
0.7	0.066848	0.18492	0.34323	0.43563	0.5367	0.6057
0.8	0.063273	0.16933	0.31195	0.39824	0.4982	0.56854
0.9	0.057907	0.14835	0.26203	0.33289	0.4343	0.50319
1	0.048105	0.097631	0.13642	0.15569	0.1775	0.19296

5) Data for Figure 5a (total emissivity for mixture of H_2O and CO_2 for fixed gas temperature at 1000 K):

Mole Absorptive Fraction of CO2	**1**	**10**	**50**	**100**	**300**	**500**
--	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m	kPa-m
0	0.035942	0.15741	0.364	0.48014	0.61203	0.66983
0.1	0.051684	0.20028	0.40998	0.52488	0.6521	0.7039
0.2	0.05916	0.20177	0.403	0.51467	0.64142	0.69338
0.3	0.062686	0.19904	0.39227	0.50007	0.62605	0.67889
0.4	0.064289	0.19443	0.37811	0.48145	0.60805	0.66197
0.5	0.064778	0.18818	0.36086	0.45927	0.58701	0.64201
0.6	0.064425	0.18004	0.34105	0.43344	0.5611	0.61717
0.7	0.063324	0.1697	0.31856	0.40401	0.52733	0.5844
0.8	0.061561	0.15665	0.29048	0.36688	0.48134	0.53892
0.9	0.059214	0.13933	0.24646	0.30502	0.41315	0.46854
1	0.056172	0.1097	0.15762	0.17543	0.201	0.21414

6) Data for Figure 6 (total emissivity for mixture consisted of H_2O, CO_2, and soot):

Gas Temperature	**1.00E-09**	**5.00E-09**	**1.00E-08**	**5.00E-08**	**1.00E-07**	**5.00E-07**	**1.00E-06**
K	--	--	--	--	--	--	--
300	0.35802	0.35947	0.3613	0.37614	0.39438	0.52338	0.64106
400	0.39795	0.39981	0.40214	0.42106	0.44364	0.59286	0.71687
500	0.38705	0.38944	0.39243	0.41633	0.44452	0.61979	0.75314
600	0.37578	0.3787	0.38236	0.41121	0.44507	0.64317	0.78258
700	0.3835	0.38692	0.3912	0.42474	0.46337	0.67964	0.81861
800	0.37913	0.38307	0.38802	0.42655	0.4703	0.70501	0.84367
900	0.37006	0.37454	0.38017	0.42356	0.4724	0.72435	0.86237
1000	0.36212	0.36718	0.37352	0.42197	0.47618	0.7437	0.87966
1100	0.35255	0.35822	0.36534	0.4192	0.4787	0.76117	0.89435
1200	0.34165	0.34797	0.35589	0.41551	0.48045	0.77679	0.90673
1300	0.32971	0.3367	0.34548	0.41089	0.48144	0.79074	0.91712
1400	0.31689	0.3246	0.33426	0.40564	0.48201	0.80328	0.92587
1500	0.30336	0.31181	0.3224	0.39999	0.48208	0.81447	0.93325
1600	0.28932	0.29853	0.31008	0.39411	0.48192	0.8246	0.93955
1700	0.27499	0.28498	0.29751	0.38798	0.48159	0.83374	0.94498
1800	0.26061	0.27141	0.28494	0.38182	0.48129	0.8421	0.94972
1900	0.24643	0.25804	0.27259	0.376	0.48115	0.84978	0.95393
2000	0.23265	0.24508	0.26066	0.37067	0.48131	0.85688	0.95771

7) Data for Figure 8 (total emissivity and absorptivity for a H_2O and CO_2 mixture):

Gas Temperature	Emissivity	Absorptivity 500K	Absorptivity 1000K	Absorptivity 1500K
K	--	--	--	--
300	0.20837	0.16306	0.12899	0.099572
400	0.21433	0.19031	0.14128	0.10603
500	0.20703	0.20703	0.15031	0.11098
600	0.20265	0.21946	0.15749	0.11468
700	0.20321	0.24296	0.16718	0.11984
800	0.20172	0.26028	0.17638	0.12409
900	0.19589	0.26765	0.18258	0.12724
1000	0.18818	0.27801	0.18818	0.13021
1100	0.18027	0.29104	0.19373	0.1333
1200	0.17182	0.30757	0.20013	0.13616
1300	0.16228	0.31651	0.20564	0.13829
1400	0.15185	0.32376	0.2098	0.13976
1500	0.1414	0.32821	0.2129	0.1414
1600	0.13163	0.33388	0.21528	0.14194
1700	0.12268	0.33971	0.21724	0.14285
1800	0.11432	0.34427	0.21906	0.14359
1900	0.10624	0.34742	0.22094	0.14412
2000	0.098286	0.34962	0.22304	0.14438

8) Data for Figure 9 ((total emissivity and absorptivity for a H_2O, CO_2, and soot mixture):

Gas Temperature	Emissivity	Absorptivity 500K	Absorptivity 1000K	Absorptivity 1500K
K	--	--	--	--
300	0.19995	0.23781	0.27641	0.31638
400	0.20214	0.26353	0.28702	0.32217
500	0.1916	0.27931	0.29507	0.32655
600	0.18442	0.29082	0.30177	0.32982
700	0.1823	0.3129	0.31062	0.3345
800	0.17863	0.32918	0.31867	0.33827
900	0.17128	0.33581	0.32383	0.34104
1000	0.16266	0.34536	0.32875	0.3437
1100	0.15439	0.35749	0.33401	0.34651
1200	0.14604	0.37293	0.33975	0.3491
1300	0.13696	0.38121	0.34468	0.35104
1400	0.1273	0.38788	0.34855	0.35241
1500	0.11782	0.39194	0.35154	0.35372
1600	0.1091	0.39721	0.35386	0.35458
1700	0.1012	0.40264	0.35574	0.35552
1800	0.093859	0.40688	0.35738	0.35633
1900	0.086828	0.40979	0.35899	0.35693
2000	0.08004	0.41182	0.36075	0.3573