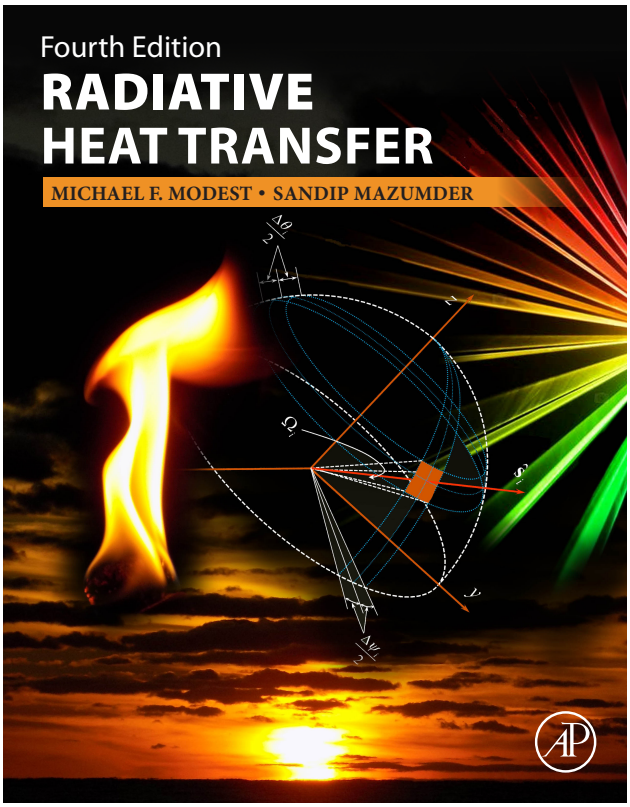
RADIATIVE HEAT TRANSFER



Fourth Edition

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COMPUTER CODES

(Brief Description)

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This manual/web page contains a listing and brief description of a number of computer programs that may be helpful to the reader of this book, and that can be downloaded from its dedicated website located at http://booksite.elsevier.com/9780123869449. Some of the codes are very basic and are entirely intended to aid the reader with the solution to the problems given at the end of the more basic chapters. Some of the codes were born out of research, but are basic enough to aid a graduate student with more complicated assignments or a semester project. And a few programs are so sophisticated in nature that they will be useful only to the practicing engineer conducting his or her own research. Finally, it is anticipated that the website will be kept up-to-date and augmented once in a while. Thus, there may be a few additional programs not described in this appendix.

It is a fact that most engineers have done, and still do, their programming in Fortran, and the author of this book is no exception. It is also true that computer scientists and most commercial programmers do their work in C++; more importantly, the younger generation of engineers at many universities across the U.S. are now also learning C++. Both compiled languages have in recent years been trumped by MATLAB® [1], which—while an interpreted rather than compiled language—has many convenient mathematical and graphical tools. Since all the programs in this listing were written by the author, either for research purposes or for the creation of this book, they all started their life in Fortran (older programs as Fortran77, and the later ones as Fortran90). However, as a gesture toward the C++ and MATLAB® communities, the most basic codes have all been converted to C++ as well as MATLAB®, as indicated below by the program suffixes `.cpp` and `.m`. If desired, all other programs are easily converted with freeware translators such as `f2c` (resulting in somewhat clumsy, but functional codes). Finally, self-contained programs that have been precompiled for Microsoft Windows have the suffix `.exe`.

The programs are listed in order by chapter in which they first appear. More detailed descriptions, sometimes with an example, can be found on the specific chapter's web page. Third-party codes that are also provided at the thus-labeled web site, and are listed at the end of this document.

Chapter 1

`bbfn.f`, `bbfn.cpp`, `bbfn.m`
Function `bbfn(x)` calculates the fractional blackbody emissive power, as defined by equation (1.24), where the argument is `x`= $n\lambda T$ with units of μmK.

`planck.f`, `planck.cpp`, `planck.m`, `planck.exe`
`planck` is a small stand-alone program that prompts the user for input (temperature and wavelength or wavenumber), then calculates the spectral blackbody emissive powers $E_{b\lambda}/T^5, E_{b\eta}/T^3$ and the fractional blackbody emissive power $f(\lambda T)$.

Chapters 2 and 3

`fresnel.f`, `fresnel.cpp`, `fresnel.m`
Subroutine `fresnel(n,k,th,rhos,rhop,rho)` calculates Fresnel reflectances from equation (2.113).
Input: `n` (= n) and `k` (= k) are real and imaginary parts of the complex index of refraction, and `th` (= θ) is the off-normal angle of incidence (in radians).
Output: `rhos` (= $\rho_\perp$) and `rhop` (= $\rho_\parallel$) are perpendicular and parallel-polarized reflectance, respectively, while `rho` (= ρ) is the unpolarized reflectance.

Chapter 3

`emdiel.f90`, `emdiel.cpp`, `emdiel.m`
Function `emdiel(n)` calculates the unpolarized, spectral, hemispherical emissivity of an optical surface of

a dielectric material from equation (3.82).
Input: `n` (= n) refractive index of dielectric.

`emmet.f90, emmet.cpp, emmet.m`
Function `emmet(n,k)` calculates the unpolarized, spectral, hemispherical emissivity of an optical surface of a metallic material from equation (3.77).
Input: `n` (= n) and `k` (= k) are the real and imaginary parts of the metal's complex index of refraction.

`callemdiel.f90, callemdiel.cpp, emmet.m, callemdiel.exe`
Program `callemdiel` is a stand-alone front end for function `emdiel`, prompting for input (refractive index n) and returning the unpolarized, spectral, hemispherical as well as normal emissivities.

`callemmet.f90, callemmet.cpp, callemmet.m, callemmet.exe`
Program `callemmet` is a stand-alone front end for function `emmet`, prompting for input (complex index of refraction n, k) and returning the unpolarized, spectral, hemispherical as well as normal emissivities.

`dirreflec.f, dirreflec.cpp, dirreflec.m, dirreflec.exe`
Program `dirrecflec` is a stand-alone front end for subroutine `fresnel`, calculating reflectivities for various incidence angles. The user is prompted to input the complex index of refraction, n and k, and the (equal) spacing of incidence angles $\Delta\theta$ (in degrees); the program then returns perpendicular polarized, parallel polarized, and unpolarized reflectivities, as well as unpolarized emissivities.

`totem.f90, totem.cpp, totem.m`
Program `totem` is a routine to evaluate the total, directional or hemispherical emittance or absorptance of an opaque material, based on an array of spectral data, by 10-point Gaussian quadrature.

Chapter 4 and Appendix D

`view.f90, view.cpp, view.m`
A function to evaluate any of the 51 view factors given in Appendix D.

`parlplates.f90, parlplates.cpp, parlplates.m`
A function to evaluate the view factor between two displaced parallel plates, as given by equation (4.42).

`perpplates.f90, perpplates.cpp, perpplates.m`
A function to evaluate the view factor between two displaced perpendicular plates, as given by equation (4.41).

`viewfactors.f90, viewfactors.cpp, viewfactors.m, viewfactors.exe`
A stand-alone front end to functions `view`, `parlplates` and `perpplates`. The user is prompted to input configuration number and arguments; the program then returns the requested view factor.

`vfplanepoly.f90:`
A program to compute the view factor between two planar polygons whose vertices are provided as inputs (Section 4.10). The program essentially performs the integration of equation (4.64) using a 10-point Gaussian quadrature formula. The number of vertices on the emitting and receiving surfaces are provided as inputs, and the program prints out the value of the computed view factor on screen.

Chapter 5

`graydiff.f90, graydiff.cpp, graydiff.m`:
Subroutine `graydiff` provides the solution to equation (5.38) for an enclosure consisting of N gray-diffuse surfaces.

graydiffxch.f90, graydiffxch.cpp, graydiffxch.m
Program graydiffxch is a front end for subroutine graydiff, generating the necessary input parameters for a three-dimensional variation to Example 5.4, primarily view factors calculated by calls to function view. This program may be used as a starting point for more involved radiative exchange problems.

Chapter 6

graydifspec.f90, graydifspec.cpp, graydifspec.m
Subroutine graydifspec provides the solution to equation (6.21) for an enclosure consisting of N diffusely emitting surfaces with diffuse and specular reflectance components.

grspecxch.f90, grspecxch.cpp
Program grspecxch is a front end for subroutine graydifspec, generating the necessary input parameters for a three-dimensional rectangular enclosure, primarily view factors calculated by calls to function view. This program may be used as a starting point for more involved radiative exchange problems.

semigray.f90, semigray.cpp, grspecxch.m
Subroutine semigray provides the solution to equations (6.41) for an enclosure consisting of N diffusely emitting surfaces with diffuse and specular reflectance components, considering two spectral ranges (one for external irradiation, one for emission).

semigraydf.f90, semigraydf.cpp
Subroutine semigraydf provides the solution to equations (6.41) for an enclosure consisting of N diffusely emitting and diffusely reflecting surfaces, considering two spectral ranges (one for external irradiation, one for emission).

semigrxch.f90, semigrxch.cpp, semigrxchdf.f90, semigrxchdf.cpp
Program semigrxch is a front end for subroutine semigray providing the necessary input for Example 6.7, primarily view factors calculated by calls to function view; similarly, program semigrxchdf is a front end for subroutine semigraydf. These programs may be used as a starting point for more involved radiative exchange problems.

bandapp.f90, bandapp.cpp
Subroutine bandapp provides the solution to equations (6.42) for an enclosure consisting of N diffusely emitting surfaces with diffuse and specular reflectance components, considering M spectral bands.

bandappdf.f90, bandappdf.cpp
Subroutine bandapp provides the solution to equations (6.42) for an enclosure consisting of N diffusely emitting and diffusely reflecting surfaces, considering M spectral bands.

bandmxch.f90, bandmxch.cpp, bandmxchdf.f90, bandmxchdf.cpp
Program bandmxch is a front end for subroutine bandapp providing the necessary input for Example 6.8, primarily view factors calculated by calls to function view; similarly, program bandmxchdf is a front end for subroutine bandappdf. These programs may be used as a starting point for more involved radiative exchange problems.

Chapter 7

MCintegral.f90
MCintegral is a little program that evaluates the integral $\int_a^b f(x)\,dx$ for any specified function by the Monte Carlo method, as outlined in equation (7.10).

Chapter 8

ExStoSEn1D.f90
A program to calculate the temperature distribution in a one-dimensional slab subjected to radiative heating from the top. The radiative fluxes are computed using the net radiation method. The program is specifically designed to solve Example 8.1. Radiative properties such as emittances of the slab surfaces, heater, and furnace walls, as well as heater temperature can be provided as inputs inside the code. This particular program uses the *explicit coupling procedure*, and the relaxation factor, ω, can also be provided as an input. The program outputs two files: `ExStoSEn1D.dat`, which contains the temperature distribution $T(x)$, and `ExStoSEn1D_residual.dat`, which contains residual versus number of iterations.

ImStoSEn1D.f90
A program to calculate the temperature distribution in a one-dimensional slab subjected to radiative heating from the top, which are computed using the net radiation method. The program is specifically designed to solve Example 8.1. Radiative properties such as emittances of the slab, heater, and furnace walls, as well as heater temperature can be provided as inputs inside the code. This particular program uses the *semi-implicit coupling procedure*. The program outputs two files: `ImStoSEn1D.dat`, which contains the temperature distribution $T(x)$, and `ImStoSEn1D_residual.dat`, which contains residual versus number of iterations.

Chapter 10

voigt.f
Fortran77 subroutine `voigt(S,bL,bD,deta,keta)` calculates the spectral absorption coefficient for a Voigt-shaped line based on the fast algorithm by Humlíček [2].

nbkdist.f90
Program `nbkdist` is a Fortran90 code to calculate narrow band k-distributions for a number of temperatures and a number of wavenumber ranges, for a gas mixture containing CO_2, H_2O, CH_4 and soot. The spectral absorption coefficient is either calculated directly from the HITRAN or HITEMP databases, or is supplied by the user.

wbmxxx.f, wbmxxxcl.f, wbmxxxcl.exe
Double precision Fortran77 subroutines `wbmxxx(T,PSIr,PHIr)`, where `xxx` stands for the different gases `h20`, `co2`, `ch4`, `co`, `no` and `so2`, calculate for a given temperature `T` the ratios `PSIr` = $\Psi^*(T)/\Psi^*(T_0)$ [from equations (10.156) and (10.160)] and `PHIr` = $\gamma/\gamma_0 = \sqrt{T_0/T}\Phi(T)/\Phi(T_0)$ [from equation (10.161)], i.e., the functions shown in Figs. 10-25 through 10-27, for all bands given in Table 10.4 in the order as listed (in order of decreasing band center wavelengths).

emwbm.f, ftwbm.f, wangwbm.f
Double precision Fortran77 functions to calculate the nondimensional total band absorptance A^* from the Edwards and Menard model, Table 10.3 (`emwbm(tau,beta)`), the Felske and Tien model, equation (10.168) (`ftwbm(tau,beta)`), and the Wang model, equation (10.170) (`wangwbm(tau,beta)`).

wbmodels.f, wbmodels.exe
Stand-alone double precision Fortran77 front end for the functions `emwbm`, `ftwbm` and `wangwbm`; the user is prompted to input `tau` (= τ_0, optical thickness at band center) and `beta` (= β, overlap parameter); the nondimensional total band absorptance A^* is printed to the screen, as calculated from three band models (Edwards and Menard, Felske and Tien, and Wang models).

wbkvsg.f
Double precision Fortran77 subroutine `wbkvsg(beta,kmax,kmin,n,k,g)` calculates the κ^* vs. g^* distribution of equation (10.182).

totemiss.f
Double precision Fortran77 subroutine `totemiss(ph2o,pco2,ptot,Tg,L,epsh2o,epsco2,epstot)` calculates the total emissivity of an isothermal gas mixture, using Leckner's model, equations (10.188) through (10.194).

totabsor.f
Double precision Fortran77 subroutine `totabsor(ph2o,pco2,ptot,Tg,Tw,L,absh2o,absco2,abstot)` calculates the total absorptivity of an isothermal gas mixture, using Leckner's model, equations (10.188) through (10.194).
Note: `totabsor` calls (i.e., requires) subroutine `totemiss`

Leckner.f, Leckner.exe
Stand-alone frontend for `totemiss(ph2o,pco2,ptot,Tg,L,epsh2o,epsco2,epstot)` and `totabsor (ph2o,pco2,ptot,Tg,Tw,L,absh2o,absco2,abstot)`. User is prompted for input, and the corresponding total emissivities and absorptivities are printed to the screen.

Chapter 11

mmmie.f, mmmiea.f
Fortran77 programs `mmmie` and `mmmiea` calculate Mie coefficients (scattering coefficients a_n and b_n, efficiencies $Q_{\text{sca}}, Q_{\text{ext}}$ and Q_{abs}, see Section 11.2 for definitions), and relate them to particle cloud properties (extinction coefficient β, absorption coefficient κ, scattering coefficient σ_s, scattering phase function Φ for specified scattering angles. In addition, program `mmmiea` also calculates the asymmetry factor g, and phase function expansion coefficients A_n, as defined in Section 11.3), but at a severe penalty in cpu time.

coalash.f90, coalash.exe
This Fortran90 program determines absorption and extinction coefficients κ^*, β^* for the Rayleigh limit, from the Buckius and Hwang [3] model, as well as from the Mengüç and Viskanta [4] model. The user is prompted for input; results are then printed to the screen.

Chapter 15

P1sor.f90, P1sor.cpp
Subroutine `P1sor` provides the solution to equation (15.38) with its boundary condition (15.48) for a two-dimensional (rectangular or axisymmetric cylinder) enclosure with reflecting walls and an absorbing, emitting, linear-anisotropically scattering medium.

Chapter 18

transPN.f90
Program `transPN` calculates energy from a pulsed collimated laser source transmitted through an absorbing, isotropically scattering slab as a function of time, using the P_1 and $P_{1/3}$ methods.

Chapter 19

wsggBrd.f90
Fortran subroutine to calculate the WSGG parameters for CO_2–H_2O–N_2 mixtures based on the Bordbar correlation given by equation (19.92) [5]. The routine is used with `call wsggBrd(T,p,pco2, ph2o,aa,kk)`, with input temperature (in K), total and partial pressures of CO_2 and H_2O (in atm). Output are the WSGG parameters `aa` = $a_n(0:4)$, and `kk` =$\kappa_n(0:4)$.

wsggKng.f90
Fortran subroutine to calculate the WSGG parameters for CO_2–H_2O–N_2 mixtures based on the Kangwanpongpan correlation given by equation (19.92) [6]. The routine is used with `call wsggKng(T,p,pco2, ph2o,aa,kk)`, with input temperature (in K), total and partial pressures of CO_2 and H_2O (in bar). Output are the WSGG parameters `aa` = $a_n(0:4)$, and `kk` =$\kappa_n(0:4)$.
wsggsoot.f90
Fortran subroutine to calculate the WSGG parameters for soot, for gray soot as well as with the Cassol correlation [7]. The routine is used with `call wsggsoot(ns,T,a,k)`, with input number-of-gray-gases and temperature (in K). Output are the WSGG parameters `aa` = $a_n(0:4)$, and `kk` =$\kappa_n(0:4)$. The values for $\kappa_n(0:4)$ are raw values, which still need to be multiplied by the soot volume fraction f_v and the index of refraction dependent C_0. The accuracy resulting from this routine has been found unsatisfactory except for the cases of `ns=1` (gray soot) and the highest order `ns=4`.
wsggex1D.f90
This Fortran program (written to compute data for Example 19.8) is included here to illustrate how the WSGG routines are used for gas–soot mixtures, and may be used as a starting point for more complicated problems.

fskdist.f90
Program `fskdist` is a Fortran90 code to calculate full spectrum k-distributions for a number of Planck function temperatures and a single gas property state (temperature, partial and total pressures), for a gas mixture containing CO_2, H_2O, CH_4 and soot; weight functions $a(T, T_{\text{ref}}, g)$ are calculated, as well. The spectral absorption coefficient is either calculated directly from the HITRAN or HITEMP databases, or is supplied by the user.

fskdco2.f90, fskdh2o.f90, fskdco2zm.f90
These subroutines determine single values of the cumulative k-distribution for CO_2 and H_2O, respectively. The first two use the correlations of Denison and Webb [8, 9], the last one the correlation by Zhang and Modest [10].

Chapter 20

mocacyl.f, rnarray.f
Program `mocacyl` is a Monte Carlo routine for a nongray, nonisothermal, isotropically scattering medium confined inside a two-dimensional, axisymmetric cylindrical enclosure bounded by gray, diffusely emitting and reflecting walls. Temperature and radiative properties are assumed known everywhere inside the enclosure and along the walls. Requires use of program `rnarray` to set up random number relationships (locations and wavenumbers of emission vs. random numbers). Calculates local radiative fluxes to the walls q_w^R.

FwdMCcs.f90, FwdMCck1.f90, FwdMCck2.f90
Program `FwdMCcs` is a standard forward Monte Carlo code for a narrow collimated beam penetrating through a nonabsorbing, isotropically scattering slab, calculating the flux onto a small, directionally-selective detector, as given in Example 20.3. `FwdMCck1` and `FwdMCck2` are forward Monte Carlo codes for the same problem, but also allow for absorption in the medium; `FwdMCck1` uses standard ray tracing, while `FwdMCck2` uses energy partitioning; see Example 20.4.

FwdMCps.f90
Program `FwdMCps` is a standard forward Monte Carlo code for a radiative energy emitted by a point source penetrating through a nonabsorbing, isotropically scattering slab, calculating the flux onto a small, directionally-selective detector.

RevMCcs.f90, RevMCck1.f90, RevMCck2.f90
These programs are backward Monte Carlo implementations of the equivalent FwdMCcs, FwdMCck1, and FwdMCck2, as also discussed in Examples 20.3 and 20.4.

RevMCps.f90
The backward Monte Carlo equivalent of FwdMCps.

Chapter 21

CpldP1En1D.f90
A program to calculate the nondimensional temperature distribution in a one-dimensional slab with coupled gray radiation (P_1-approximation) and conduction. The program is specifically designed to solve Example 21.2. The absorption coefficient of the slab, its thickness, and the temperatures of the two ends can be provided as inputs inside the code. This particular program implements both the *explicit* and the *semi-implicit coupling* procedures. The user can choose between one of the two options.
The program outputs two files:
CpldP1En1D.dat, which contains the nondimensional temperature distribution $\theta(x)$, and
CpldP1En1D_residual.dat, which contains residual versus number of iterations.

CpldP1En2D.f90
A program to calculate the nondimensional temperature distribution in a tube (two-dimensional axisymmetric) with coupled gray radiation (P_1-approximation) and forced convection. The program is specifically designed to solve Example 21.4. The optical thickness of the gas in the tube, the conduction-to-radiation parameter, and the Peclet number can be provided as inputs, along with the inlet and wall temperatures and emittances. This particular program implements the *semi-implicit coupling* procedure. The program outputs three files:
CpldP1En2D.dat, which contains the nondimensional temperature distribution $\theta(x)$,
CpldP1En2D_Nux.dat, which contains the local Nusselt number distribution $\mathrm{Nu}_x(x)$, and
CpldP1En2D_rsl.dat, which contains residual versus number of iterations.

Third-Party Codes

MONT3D
This code, developed at Colorado State University by Burns et al. [11–15], calculates radiative exchange factors for complicated, three-dimensional geometries by the Monte Carlo method, as given by equations (7.15) and (7.21). Diffuse and specular view factors may be calculated as special cases. We provide here only a link to the Colorado State University web site, where documentation and codes are kept up-to-date: http://www.colostate.edu/~pburns/monte.html

VIEW3D
This code, developed at National Institute of Standards and Technology (NIST) by Walton [16], calculates radiative view factors with obstructions by adaptive integration.

RADCAL
This code, developed at NIST by Grosshandler [17, 18] is a narrow band database for combustion gas properties, using tabulated values and theoretical approximations.

EM2C
This package contains a number of Fortran codes, developed at the Ecole Centrale de Paris by Soufiani and Taine [19], and updated and extended by Rivière and Soufiani [20], now based on CDSD-4000 [21] and

HITEMP 2010 [22]. The codes supply atmospheric pressure statistical narrow band properties for CO_2, H_2O, CO and CH_4, as well as narrow band k-distributions for CO_2 and H_2O.

FVM2D

This Fortran77 code, developed at the University of Minnesota and Nanyang Technological University by Chai and colleagues [23–25], calculates radiative transfer in participating media using the finite-volume method of Chapter 16 for a two-dimensional, rectangular enclosure with reflecting walls and an absorbing, emitting, anisotropically scattering medium. For each surface the emittance and blackbody intensities must be specified; for the medium spatial distributions of radiation properties and blackbody intensities must be input. Calculated are internal incident radiation (G) and wall flux (q) fields.

H2OEmissivity.xlsx, CO2Emissivity.xlsx, MixEmissivity.xlsx

Excel data sheets to calculate total emissivities of combustion gases CO_2 [26], H_2O [27], and CO_2–H_2O–CO–N_2 mixtures [28], with validity ranges equal to, or exceeding: temperature $300 \le T \le 3000$ K, total pressure $0.1 \le p \le 40$ bar, and pressure path length $0.05 \le p_a L \le 1000$ bar cm. Input and output are on the sheet INPUT-OUTPUT and are self-explanatory.

Software Packages at Repository

Some software packages developed by the first author's group are too large for the book's dedicated website and/or are occasionally updated, and are maintained in a repository at Marquette University, where additional documentation may also be found. They may be downloaded from
https://www.eng.mu.edu/ccl/software-data/radiation/.

NBKDIR

This package contains a number of Fortran codes, developed at the Pennsylvania State University and the University of California at Merced by the primary author and his students/postdocs A. Wang, G. Pal, and J. Cai, for the assembly of full spectrum k-distributions from a narrow band k-distributions database [29, 30]. At the time of printing `NBKDIR` contained data for five species ($CO_2, H_2O, CO, CH_4, C_2H_4$), as well as nongray soot [calculated from the Chang and Charalampopoulos correlation [31] given in equation (11.119)], for temperatures up to 3000 K and pressures up to 80 bar. Spectroscopic data are taken from the HITEMP 2010 database (CO_2, H_2O, CO) [22] and HITRAN 2008 database (CH_4, C_2H_4) [32].

FSK Databases

At present four different full-spectrum k-distribution databases created by Wang and coworkers are posted in the repository: the first contains distribution for 32 Gaussian quadrature points (i.e., without transformation or $\alpha = 1$) for all conditions given in Table 19.4 but without soot [33]. The second and third databases include soot while calculating the stretch factor a on-the-fly, the second using standard Gaussian quadrature points [34] and in the third the quadrature points are "optimized," i.e., transformed with $\alpha = 2$ as introduced in equation (19.143) [35]. Finally, a fourth was built specifically for the FSCK-4 scheme (atmospheric pressure only) [36].

LBL Monte Carlo Database

This database contains a lookup table to determine emission wavenumbers (plus corresponding absorption coefficients) as function of random number for mixtures of H_2O, CO_2, CO, CH_4, C_2H_4 and soot, for temperatures 300–3000 K and pressures 0.1 to 80 bar, assembled by Ren and Modest [37], as outlined in Section 20.4.

FSK–PMC Database

This database contains a lookup table to determine emission pseudo-wavenumbers g_0 as function of random number for mixtures of H_2O, CO_2, CO and soot for Monte Carlo calculations with the FSCK-4 spectral model, as outlined in Section 20.4. Assembled by Wang *et al.* [38].

LBL Absorption Coefficient Database

This database contains a lookup table of spectral absorption coefficients, for temperatures 300–3000 K and pressures 0.1 to 80 bar, obtained from the HITEMP 2010 (CO_2, H_2O, CO) [22] and HITRAN 2008 (CH_4, C_2H_4) [32] spectroscopic databases.

`1DRTEsolv`

This package contains a Fortran code that calculates the radiative transfer in a one-dimensional plane-parallel medium with specified temperature field bound by two gray walls, i.e., the solution to equations (13.46) and (13.47). The code takes in the physical size of the domain, temperature field, distribution of participating media and wall properties (temperature and emittance). Three spectral models may be chosen (Planck-mean gray, LBL, FSCK-2, or user-defined). Developed by Prof. Roy and his students at Marquette University.

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