Midterm Take Home Exam, Spring Semester 2017
CEE 546: Air Quality Control

This is an open book, note, and library exam. The exam is to be taken without the exchange of information that is relevant to this exam between you and anyone else. If you have questions about the exam (e.g., difficulty understanding the questions or the calculations appear to be inappropriate), then please call me, send me an e-mail message, or stop by my office. My office phone number is 217-333-6963, my cell number is 217-390-2237, my e-mail address is mrood@illinois.edu, and my office address is 3230E NCEL.

Your solutions to this exam shall be submitted electronically to mrood@illinois.edu within 48.00 hr of receiving the exam. Show all of your calculations. Include an interpretation of your results for problem 4. A paragraph of 10-15 sentences for the interpretation is sufficient. If all the information is not given in the problem statements, then make the necessary assumptions to solve the problems and indicate what assumptions you made with justifications. Good luck!

1) (10 pt) Provide a critical review (critical yet constructive) of Table 2.3 “Property of Selected Solid Fuels” that was discussed during lecture in the underlined area provided below.
   Critical Review: ___discuss: use of LHV vs HHV, typographical errors for proximate/ultimate analyses, include standard deviations to describe variability, mention relationship between fuel composition and HHV

2) (10 pt) Discuss Figure 2.6 “Equilibrium Composition and Temperature for Adiabatic Combustion of Kerosene, CH1.8, as a Function of Equivalence Ratio” for fuel lean conditions in the underlined area provided below.
   Discussion: ___discuss: lean vs rich equivalence ration for product composition, dashed vs continuous lines (CO formation), N2 vs NO concentration dependence on equivalence ratio
3) (16 pt) Describe in the area below the following terms when trying to reduce the emissions of an air pollutant. Then provide two examples of each term when trying to reduce the emissions of sulfur dioxide (SO₂) into the atmosphere in the underlined areas provided below.

3a) Modify feed stream:
(4 pt) Description: _modify composition of feed stream

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

(4 pt) Two examples: _low sulfur content fuel, use natural gas_______________
_____________________________________________________________________
_____________________________________________________________________
_____________________________________________________________________

3b) Demand Side management:
(4 pt) Description: _modify products to meet demands while consuming less resources

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

(4 pt) Two examples: _provide high efficiency refrigerators, provide hybrid vehicles__________________________________________________
_____________________________________________________________________
_____________________________________________________________________
_____________________________________________________________________

4) (75 pt) An electrical-power production facility burns coal to produce 500 MW\textsubscript{e}. The combustion air enters at 400 K and 101 kPa and coal enters at 320 K and 101 kPa. The thermal to electrical energy conversion efficiency is 32\% when using the higher heating value (HHV) of the coal to determine the thermal to electrical conversion efficiency. Assume (1) complete (no CO formation) and adiabatic combustion, (2) all nitrogen in the fuel and air forms N\textsubscript{2} (no NO\textsubscript{x} formation), (3) all Cl forms HCl (no Cl\textsubscript{2} formation), (4) all S forms SO\textsubscript{2} (no SO\textsubscript{3} formation), and (5) all ash becomes flyash. Standard temperature and pressure are 0\,\degree C and 1 atm, respectively. The coal is high-volatile bituminous coal from Kentucky. The ash melts at 1,363 K and its enthalpy of fusion is 0.2 J/g. The specific heats for the coal and ash are 1.5 J/g-K and 1.8 J/g-K, respectively.

4a) (20 pt) Calculate and provide a plot (using linear scales) of adiabatic flame temperature (in unit of K) on the ordinate (vertical axis) vs. equivalence ratio ranging from 0.7 to 0.95 on the abscissa (horizontal axis).

4b) (15 pt) Calculate the concentrations of gaseous end-products and provide a plot of concentrations (in unit of \% by volume) on the ordinate (vertical axis) using log scale vs. equivalence ratio ranging from 0.5 to 0.9 on the abscissa (horizontal axis) using a linear scale.

4c) (15 pt) Provide a plot (using log scale) for the chlorine (Cl) and sulfur (S) containing species (in unit of ppmv) on the ordinate (vertical axis) vs. equivalence ratio (using linear scale) for equivalence ratios ranging from 0.5 to 0.9 on the abscissa (horizontal axis).

4d) (15 pt) Compare the moles of CO\textsubscript{2} generated per MJ of fuel burned for the coal case described above and for No. 4 natural gas case at an equivalence ratio of 0.9. Assume a thermal to electrical conversion efficiency value for the natural gas of 38\%.
1: (CEE 546 midterm exam)

2: (This computer code calculates adiabatic flame temperature versus equivalence ratio when taking into consideration the C, H, N, Cl, O, S, and H2O content of coal, heat content of coal, and thermal to electrical efficiency of the combustor when considering the HHV of the fuel. The facility generates 500 MWe of power for this facility. Complete combustion, no NOx formation, and Cl and S equilibrium constraints are assumed. High volatility Kentucky coal from Table 2.3 is to be used to determine composition of the coal and its higher heating value.)

4: 
5: (Initial conditions and constants)

6: Function AshMelt(T)

7:  Heat of melting for ash at T > 1363K, J/g

8:  If (T < 1363) Then

9:   Hma: = 0

10:  Else

11:   Hma: = 0.2

12:  Endif

13:  AshMelt: = Hma

14:  End

15:  Hma = Ashmelt(T)

16:  (Initial conditions and constants)

17:  Po = 101.325 {reference pressure, kPa}

18:  Ps = 101.325 {standard pressure, kPa}

19:  Pg = 101 {actual total pressure, kPa}

20:  Pg_atm = Pg/101.325 {total pressure, atm}

21:  Pg_atms = 1 {total pressure, atm}

22:  To = 298 {reference temperature, K}

23:  Ts = 273 {standard temperature, K}

24:  Ta = 400 {air temperature, K}

25:  Tf = 320 {fuel temperature, K}

26:  Tm = 1363 {estimated temperature that ash melts from fuel analysis, K}

27:  phi = 0.8 {equivalence ratio varying from 0.5-0.9}

28:  (MWe = 500) {700 MWe electrical generating capacity}

29:  eta = 0.32 {thermal to electrical conversion efficiency, assuming efficiency is based on HHV of fuel}

30:  Rc = 0.0821 {ideal gas law constant = atm-l/g-mole K, ideal gas law constant, Rc= 8.3144 KJ/kmol K}

31:  HvH2O = 44000 {heat of vaporization for water, J/g-mole K}

32:  HHVi = 28.1 {HHV = higher heating value for fuel=28.1x10^6 J/kg, using value in Table 2.3; needs to be converted to J/g coal}

33:  HHV = 28100000/1000 {HHV = higher heating value for fuel as J/g coal}

34:  Cpc = 1.5 {specific heat of coal, J/g K}

35:  Cpa = 1.8 {specific heat for ash, J/g K}

46:  MWC = 12

47:  MWCO2 = 44

48:  MWH = 1

49:  MWH2O = 18
50: MWN = 14
51: MWN2 = 28
52: MWCl = 35.5
53: MWHCl = 36.5
54: MWO = 16
55: MWO2 = 32
56: MWS = 32
57: MWSO2 = 64
58:
59: (mass of constituents in coal, per 100 g sample)
60: (If using values in Table 2.)
61:
62: mTOT = mc + mH + mN + mCl + mO + mS + mash
63: mC = 66.9 (% mass of each constituent as received)
64: mH = 4.8
65: mN = 1.4
66: mCl = 0 (Cl is not included in table 2.3, assume zero, but unlikely)
67: mO = 6.4
68: mS = 3.5
69: mH2O = 7.5
70: mash = 9.5
71: m_coal = mC + mH + mN + mCl + mO + mS + mH2O (check fuel analysis to see if 100%)
72:
73: (constants for specific heat terms)
74:
75: aiCO2 = 44.3191 (CO2)
76: biCO2 = 0.00730
77: aiH2O = 32.4766 (H2O)
78: biH2O = 0.00862
79: aiN2 = 29.2313 (N2)
80: biN2 = 0.00307
81: aiO2 = 30.5041 (O2)
82: biO2 = 0.00394
83: aiHCl = 6.27 (HCl)
84: biHCl = 0.00124
85: aiSO2 = 45.8869 (SO2)
86: biSO2 = 0.00574
87:
88: (Problem 2a)
89:
90: (coefficients to determine composition of fuel)
91:
92: n = (mC/MWC)/(mC/MWC) (g-mole C/g-mole C)
93: m = (mH/MWH)/(mC/MWC) (g-mole H/g-mole C)
94: (check that H moles is > Cl mole in fuel for stoichiometry assumption)
95: p = (mN/MWN)/(mC/MWC) (g-mole N/g-mole C)
96: q = (mCl/MWCl)/(mC/MWC) (g-mole Cl/g-mole C)
97: r = (mO/MWO)/(mC/MWC) (g-mole O/g-mole C)
98: s = (mS/MWS)/(mC/MWC) (g-mole S/g-mole C)
99: u = (mH2O/MWH2O)/(mC/MWC) (g-mole H2O in coal/g-mole C)
100: nash = mash/(mC/MWC) (normalized ash content, g ash/g-mole C)
101:
102: (formula weight SUM(ni/nc)(MWi))
103:
104: FW = 100/(mC/MWC) (100 g coal/(g-mole C/100 g sample))
105: \[ FW_2 = n^*MWC + m^*MWH + p^*MWN + q^*MWCl + r^*MWO + s^*MWH_2O + \text{ ash} \] \{calculate FW2 to check value for FW\}

106:

107: \{balance stoichiometry for incoming CnHmNpClqOrSs plus moisture content\}

108: \{reactants = CnHmNpClqOrSs + uH_2O(l) + (alpha/phi)*(O_2 + 3.78*N_2) = \}

109: \{products = n^*CO_2 + (u+m(m-q)/2)^*H_2O + ((3.78*alpha/phi) + p/2)^*N_2 + alpha^*(1/phi -1)^*O_2 + q^*HCl + s^*SO_2\}

110: \{where alpha = n+(m-q)/4-r/2+s\}

111:

112: \text{niCHNClOS} = 1 \quad \text{inlet CnHmNpClqOrSs}\n
113: \text{niO_2} = \alpha/\phi \quad \text{inlet O_2}\n
114: \text{niH_2O} = u \quad \text{inlet moisture content of fuel}\n
115: \text{niN_2} = (\alpha/\phi)^*3.78 + p/2 \quad \text{inlet N_2}\n
116: \text{noCO}_2 = n \quad \text{outlet CO}_2\n
117: \text{noH}_2O = u+(m-q)/2 \quad \text{outlet H}_2O\n
118: \text{noN}_2 = (3.78*\alpha/\phi) + p/2 \quad \text{outlet N}_2\n
119: \text{noO}_2 = \alpha^*(1/\phi -1) \quad \text{outlet O}_2\n
120: \text{noHCl} = q \quad \text{outlet HCl}\n
121: \text{noSO}_2 = s \quad \text{outlet SO}_2\n
122: \alpha = n + (m - q)/4 - r/2 + s \quad \text{stoichiometry coefficient}\n
123: \text{nototal} = \text{noCO}_2 + \text{noH}_2O + \text{noN}_2 + \text{noO}_2 + \text{noHCl} + \text{noSO}_2 \quad \text{total moles of gas generated}\n
124:

125: \{calculate heating values of the fuel\}

126:

127: \text{HHV}_c = \text{HHV}^*\text{FW} \quad \{\text{HHV, J/g-mole C}\}

128: \text{LHV}_c = \text{HHV}_c - \text{noH}_2O^*\text{HvH}_2O \quad \{\text{LHV, J/g-mole C}\}

129: \text{LHV} = (\text{LHV}_c/\text{FW}) \quad \{\text{LHV, J/g coal}\}

130:

131: \{energy considerations for ash : Hash = (h(T) - h(To))_ash = (g \text{ ash/g coal})^*(g \text{ coal/g-mole C})^*(C_p(T_m - T_f) + H_m + C_p(T - T_m))\}

132: \text{Hash} = (\text{mash}/100)^*\text{FW}^*(C_p(T_m - T_f) + H_m + C_p(T - T_m))

133:

134: \{energy considerations for coal, H_coal = (h(T) - h(To))_coal^*(g \text{ coal/g-mole C})^*(C_p(T_f - T_o))\}

135: \text{H_coal} = \text{FW}^*C_p(T_f - T_o)

136:

137: \{determine adiabatic flame temperature\}

138: \{enthalpy of products = enthalpy of reactants, T = final temperature\}

139: \text{hprod1} = \text{noCO}_2^*(a_i\text{CO}_2^*(T - To) + (b_i\text{CO}_2/2)^*(T^2 - To^2))

140: \text{hprod2} = \text{noH}_2O^*(a_i\text{H}_2O^*(T - To) + (b_i\text{H}_2O/2)^*(T^2 - To^2))

141: \text{hprod3} = \text{noN}_2^*(a_i\text{N}_2^*(T - To) + (b_i\text{N}_2/2)^*(T^2 - To^2))

142: \text{hprod4} = \text{noHCl}^*(a_i\text{HCl}^*(T - To) + (b_i\text{HCl}/2)^*(T^2 - To^2))

143: \text{hprod5} = \text{noSO}_2^*(a_i\text{SO}_2^*(T - To) + (b_i\text{SO}_2/2)^*(T^2 - To^2))

144: \text{hprod6} = \text{noSO}_2^*(a_i\text{SO}_2^*(T - To) + (b_i\text{SO}_2/2)^*(T^2 - To^2))

145: \text{hprod7} = \text{Hash}

146: \text{hract1} = \text{LHV}_c + \text{H_coal}

147: \text{hract2} = \text{niO}_2^*(a_i\text{O}_2^*(T_a - To) + (b_i\text{O}_2/2)^*(T_a^2 - To^2))

148: \text{hract3} = \text{niN}_2^*(a_i\text{N}_2^*(T_a - To) + (b_i\text{N}_2/2)^*(T_a^2 - To^2))

149: \text{hprod1} + \text{hprod2} + \text{hprod3} + \text{hprod4} + \text{hprod5} + \text{hprod6} + \text{hprod7} = \text{hract1} + \text{hract2} + \text{hract3}

150:

151: \{Problem 2b\}

152:

153: \{mole fraction concentrations of gases at outlet, [-]\}

154:

155: \text{yoCO}_2 = \text{noCO}_2/\text{nototal}

156: \text{yoN}_2 = \text{noN}_2/\text{nototal}

157: \text{yoSO}_2 = \text{noSO}_2/\text{nototal}

158: \text{yoO}_2 = \text{noO}_2/\text{nototal}

159: \{\text{yoHCl} = \text{noHCl}/\text{nototal}\}
160: yoH2O = noH2O/nototal

162: \( \text{(calculate concentrations, in \% by volume, of SO2, SO3, HCl, and Cl2)} \)

163:

164: C1_CO2=yoCO2*100
165: C1_N2=yoN2*100
166: C1_SO2=yoSO2*100
167: C1_SO3=yoSO3
168: C1_O2=yoO2*100
169: \( \{C1_HCl=yoHCl*100\} \)
170: C1_H2O=yoH2O*100

172: \( \text{(Problem 2c)} \)

174: \( \text{(calculate equilibrium coefficients for the reactions to SO3 and Cl2)} \)

175: \( \{\text{SO2+0.5O2 \to SO3}\} \)
176: \( \{\text{2HCl+0.5O2 \to Cl2+H2O}\} \)

178: a1_SO3=11995.06
179: a2_SO3=-0.36231
180: a3_SO3=0.000936
181: a4_SO3=-29690
182: a5_SO3=-9.88104
183: \( \{a1_Cl2=7058.862\} \)
184: \( \{a2_Cl2=0.015097\} \)
185: \( \{a3_Cl2=-0.00009\} \)
186: \( \{a4_Cl2=-27173.9\} \)
187: \( \{a5_Cl2=-8.10913\} \)

189: ln(K_SO3)=a1_SO3/T+a2_SO3*ln(T)+a3_SO3*T+a4_SO3/T^2+a5_SO3
190: \( \{ln(K_Cl2)=a1_Cl2/T+a2_Cl2*ln(T)+a3_Cl2*T+a4_Cl2/T^2+a5_Cl2\} \)

192: \( \text{(calculate equilibrium concentrations of SO3 and Cl2, assuming SO3 and Cl2 concentrations are much smaller than SO2 and HCl concentrations)} \)

193:

194: K_SO3=yoSO3/(yoSO2^2*yoO2^0.5)
195: \( \{K_Cl2=(yoCl2*yoH2O)/(yoHCl^2*yoO2^0.5)\} \)

197: \( \text{(calculate concentrations, in ppmv, of SO2, SO3, HCl, and Cl2)} \)

199: C2_SO2=yoSO2*10^6
200: C2_SO3=yoSO3*10^6
201: \( \{C2_HCl=yoHCl*10^6\} \)
202: \( \{C2_Cl2=yoCl2*10^6\} \)

Function \textbf{AshMelt} (T)

If \( \{T < 1363 \} \) Then

\[ \text{Hma} := 0 \]

Else

\[ \text{Hma} := 0.2 \]
EndIf

AshMelt := Hma

End AshMelt

Hma = \textit{AshMelt} \left( T \right)

Po = 101.325

Ps = 101.325

Pg = 101

\[ P_{\text{atm}} = \frac{Pg}{101.325} \]

\[ P_{\text{atms}} = 1 \]

To = 298

Ts = 273

Ta = 400

Tf = 320

Tm = 1363

\[ \eta = 0.32 \]

Rc = 0.0821

\[ \text{HvH}_2\text{O} = 44000 \]

\[ \text{HHV}_i = 28.1 \]

\[ \text{HHV} = \frac{2.81 \times 10^7}{1000} \]

Cpc = 1.5

Cpa = 1.8

MWC = 12

MWCO2 = 44

MWH = 1

MWH2O = 18

MWN = 14
MWN2  =  28
MWCl  =  35.5
MWHCl =  36.5
MWO   =  16
MWO2  =  32
MWS   =  32
MWSO2 =  64

mTOT  =  mc  +  mH  +  mN  +  mCl  +  mO  +  mS  +  mash
mc    =  66.9
mH    =  4.8
mN    =  1.4
mCl   =  0
mO    =  6.4
mS    =  3.5
mH2O  =  7.5
mash  =  9.5

m_{coal}  =  mc  +  mH  +  mN  +  mCl  +  mO  +  mS  +  mS  +  mH2O
aiCO2   =  44.3191
biCO2   =  0.0073
aiH2O   =  32.4766
biH2O   =  0.00862
aiN2    =  29.2313
biN2    =  0.00307
aiO2    =  30.5041
biO2    =  0.00394
aiHCl   =  6.27
biHCl   =  0.00124
aiSO2   =  45.8869
biSO2 = 0.00574

\[ n = \frac{mc}{MWC} \]

\[ m = \frac{mH}{MWH} \]

\[ p = \frac{mN}{MWN} \]

\[ q = \frac{mCl}{MWCl} \]

\[ r = \frac{mO}{MWO} \]

\[ s = \frac{mS}{MWS} \]

\[ u = \frac{mH2O}{MWH2O} \]

\[ nash = \frac{mash}{mc} \]

\[ FW = \frac{100}{mc} \]

\[ FW2 = n \cdot MWC + m \cdot MWH + p \cdot MWN + q \cdot MWCl + r \cdot MWO + s \cdot MWS + u \cdot MWH2O + nash \]

\[ niCHNClOS = 1 \]

\[ niO2 = \frac{\alpha}{\phi} \]
\[ \text{niH}_2\text{O} = u \]
\[ \text{niN}_2 = \frac{\alpha}{\phi} \cdot 3.78 + \frac{p}{2} \]
\[ \text{noCO}_2 = n \]
\[ \text{noH}_2\text{O} = u + \frac{m - q}{2} \]
\[ \text{noN}_2 = \frac{3.78 \cdot \alpha}{\phi} + \frac{p}{2} \]
\[ \text{noO}_2 = \alpha \cdot \left[ \frac{1}{\phi} - 1 \right] \]
\[ \text{noHCl} = q \]
\[ \text{noSO}_2 = s \]
\[ \alpha = n + \frac{m - q}{4} - \frac{r}{2} + s \]
\[ \text{nototal} = \text{noCO}_2 + \text{noH}_2\text{O} + \text{noN}_2 + \text{noO}_2 + \text{noHCl} + \text{noSO}_2 \]
\[ \text{HHV}_c = \text{HHV} \cdot \text{FW} \]
\[ \text{LHV}_c = \text{HHV}_c - \text{noH}_2\text{O} \cdot \text{HvH}_2\text{O} \]
\[ \text{LHV} = \frac{\text{LHV}_c}{\text{FW}} \]
\[ \text{Hash} = \frac{\text{mash}}{100} \cdot \text{FW} \cdot \left( \text{Cpa} \cdot \left( T_m - T_f \right) + \text{Hma} + \text{Cpa} \cdot \left( T - T_m \right) \right) \]
\[ \text{Hcoal} = \text{FW} \cdot \text{Cpc} \cdot \left( T_f - T_o \right) \]
\[ \text{hprod1} = \text{noCO}_2 \cdot \left[ \text{aiCO}_2 \cdot \left( T - T_o \right) + \frac{\text{biCO}_2}{2} \cdot \left( T^2 - T_o^2 \right) \right] \]
\[ \text{hprod2} = \text{noH}_2\text{O} \cdot \left[ \text{aiH}_2\text{O} \cdot \left( T - T_o \right) + \frac{\text{biH}_2\text{O}}{2} \cdot \left( T^2 - T_o^2 \right) \right] \]
\[ \text{hprod3} = \text{noN}_2 \cdot \left[ \text{aiN}_2 \cdot \left( T - T_o \right) + \frac{\text{biN}_2}{2} \cdot \left( T^2 - T_o^2 \right) \right] \]
\[ \text{hprod4} = \text{noHCl} \cdot \left[ \text{aiHCl} \cdot \left( T - T_o \right) + \frac{\text{biHCl}}{2} \cdot \left( T^2 - T_o^2 \right) \right] \]
\[ \text{hprod5} = \text{noO}_2 \cdot \left[ \text{aiO}_2 \cdot \left( T - T_o \right) + \frac{\text{biO}_2}{2} \cdot \left( T^2 - T_o^2 \right) \right] \]
\[ \text{hprod6} = \text{noSO}_2 \cdot \left[ \text{aiSO}_2 \cdot \left( T - T_o \right) + \frac{\text{biSO}_2}{2} \cdot \left( T^2 - T_o^2 \right) \right] \]
hprod7 = Hash
hreact1 = LHVc + Hcoal
hreact2 = \( \frac{aiO2 \cdot (Ta - To)}{2} \cdot (Ta^2 - To^2) \)
hreact3 = \( \frac{aiN2 \cdot (Ta - To)}{2} \cdot (Ta^2 - To^2) \)
hprod1 + hprod2 + hprod3 + hprod4 + hprod5 + hprod6 + hprod7 = hreact1 + hreact2 + hreact3

\( \frac{yoCO2}{nototal} = \frac{noCO2}{nototal} \)
\( \frac{yoN2}{nototal} = \frac{noN2}{nototal} \)
\( \frac{yoSO2}{nototal} = \frac{noSO2}{nototal} \)
\( \frac{yoO2}{nototal} = \frac{noO2}{nototal} \)
\( \frac{yoH2O}{nototal} = \frac{noH2O}{nototal} \)

C_{1CO2} = yoCO2 \cdot 100
C_{1N2} = yoN2 \cdot 100
C_{1SO2} = yoSO2 \cdot 100
C_{1SO3} = yoSO3
C_{1O2} = yoO2 \cdot 100
C_{1H2O} = yoH2O \cdot 100

a_{1SO3} = 11995.06
a_{2SO3} = -0.36231
a_{3SO3} = 0.000936
a_{4SO3} = -29690
a_{5SO3} = -9.88104

\( \ln(K_{SO3}) = \frac{a_{1SO3}}{T} + a_{2SO3} \cdot \ln(T) + a_{3SO3} \cdot T + \frac{a_{4SO3}}{T^2} + a_{5SO3} \)

\( K_{SO3} = \frac{yoSO3}{yoSO2 \cdot yoO2^{0.5}} \)
\[ C_{2\text{SO}_2} = y_{\text{SO}_2} \cdot 10^6 \]

\[ C_{2\text{SO}_3} = y_{\text{SO}_3} \cdot 10^6 \]

**Parametric Table: Table 4**

<table>
<thead>
<tr>
<th>Run</th>
<th>( C_{2\text{SO}_2} ) [ppmv]</th>
<th>( C_{2\text{SO}_3} ) [ppmv]</th>
<th>( \phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>1663</td>
<td>16.93</td>
<td>0.5000</td>
</tr>
<tr>
<td>Run 2</td>
<td>1806</td>
<td>12.44</td>
<td>0.5444</td>
</tr>
<tr>
<td>Run 3</td>
<td>1949</td>
<td>9.489</td>
<td>0.5889</td>
</tr>
<tr>
<td>Run 4</td>
<td>2091</td>
<td>7.45</td>
<td>0.6333</td>
</tr>
<tr>
<td>Run 5</td>
<td>2232</td>
<td>5.974</td>
<td>0.6778</td>
</tr>
<tr>
<td>Run 6</td>
<td>2372</td>
<td>4.86</td>
<td>0.7222</td>
</tr>
<tr>
<td>Run 7</td>
<td>2512</td>
<td>3.981</td>
<td>0.7667</td>
</tr>
<tr>
<td>Run 8</td>
<td>2651</td>
<td>3.257</td>
<td>0.8111</td>
</tr>
<tr>
<td>Run 9</td>
<td>2789</td>
<td>2.628</td>
<td>0.8556</td>
</tr>
<tr>
<td>Run 10</td>
<td>2927</td>
<td>2.042</td>
<td>0.9000</td>
</tr>
</tbody>
</table>
CO₂, H₂O, N₂, O₂, SO₂, and SO₃ Concentrations (% by volume)

$\phi$, equivalence ratio
The figure shows two graphs. The upper graph plots temperature (T) in Kelvin (K) against the equivalence ratio (φ) ranging from 0.5 to 0.9. The relationship is linear and increases as φ increases.

The lower graph plots the concentrations of SO2 and SO3 in parts per million (ppmv) against φ. The SO2 concentration is represented by black triangles and increases with φ, while the SO3 concentration, represented by blue squares, decreases with φ.

Black triangle = SO2 concentration
Blue square = SO3 concentration
4d) (15 pt) Compare the moles of CO$_2$ generated per MJ of fuel burned for the coal case described above and for No. 4 natural gas case at an equivalence ratio of 0.9. Assume a thermal to electrical conversion efficiency value for the natural gas of 38%.

**Solution**

Coal combustion:

\[
\left( \frac{66.9 \text{ g C}}{100 \text{ g fuel}} \right) \left( \frac{1 \text{ g-mole C}}{12 \text{ g C}} \right) \left( \frac{1 \text{ g-mole CO}_2}{1 \text{ g-mole C}} \right) \left( \frac{1 \text{ kg}}{28.1 \text{ MJ}} \right) \left( \frac{1000 \text{ g/kg}}{0.32} \right) = \frac{6.20 \text{ g-mole CO}_2}{\text{MJ}}
\]

Natural gas combustion:

\[
\left( \frac{99.2 \text{ g-mole CH}_4}{100 \text{ g-mole fuel}} \right) \left( \frac{1 \text{ g-mole CO}_2}{1 \text{ g-mole CH}_4} \right) + \left( \frac{0.2 \text{ g-mole CO}_2}{100 \text{ g-mole fuel}} \right) \left( \frac{1 \text{ g-mole}}{17.8 \text{ g}} \right) \left( \frac{0.656 \text{ g}}{1 \text{ m}^3} \right) \left( \frac{1 \text{ m}^3}{36.3 \text{ MJ}} \right) \left( \frac{1000 \text{ l/m}^3}{0.38} \right) = \frac{2.66 \text{ g-mole CO}_2}{\text{MJ}}
\]