AIAA JOURNAL
Vol. 43, No. 11, November 2005

Effect of Uniform Magnetic Field on Equilibrium Combustion Composition: Constant Volume

A. Gupta* and J. Baker†
University of Alabama, Tuscaloosa, Alabama 35401-2079

The impact of a uniform magnetic field on equilibrium combustion characteristics under constant volume conditions has been explored. An expression for Helmholtz free energy in terms of Gibbs free energy, which includes a magnetic field contribution, has been developed. With use of the method of Lagrange multipliers, changes in the Helmholtz free energy for a mixture of paramagnetic and diamagnetic ideal gases are minimized. The magnetic susceptibility of paramagnetic ideal gases has been calculated using the Curie–Weiss law. A model reaction of methane in air is used to examine quantitatively the changes in mole fractions as a function of temperature and magnetic induction for all product species. Equilibrium mole fractions have been plotted as a function of temperature and magnetic field strength for all product species. The variation of equilibrium pressure as a function of temperature and magnetic field strength has also been examined. As expected, the results indicate that the equilibrium pressure increases with increasing temperature. At a specified temperature, the equilibrium pressure decreases with increasing magnetic field strength. The results indicate that within the temperature range considered, the magnetic field decreases the mole fraction of most of the product species except for CO_2, N_2, H_2O, and CH_4. For an increase in magnetic induction of 0.00–0.04 T, the maximum equilibrium mole fraction of NO was observed to decrease considerably.

Nomenclature

A = Helmholtz free energy
a_{ij} = atoms of element j in product i
B = magnetic induction
b_j = atoms of element j in reaction
C = damping constant
E = iteration error
G = Gibbs free energy
g_L = Lande's g factor
$\bar{g}^0$ = molar specific reference Gibbs free energy
H = magnetic field strength
k = Boltzmann constant
M = intensity of magnetization
m_i = molecular weight of species i
n = number of moles
N_A = Avogadro's number
p = pressure
p_i = partial pressure of species i
R_u = universal gas constant
S = entropy
S_i = total electron spin of species i
T = absolute temperature
U = internal energy
V = volume
W = work
y_i = mole fraction of species i
λ_i = Lagrange multiplier of species i
μ_B = Bohr magneton
μ_0 = magnetic permeability of vacuum
χ_i = magnetic susceptibility per unit mass of species i

Subscripts

i = species i
T = total; also isothermal conditions
v = isometric conditions

Superscripts

m = step number
0 = reference conditions; also no applied magnetic field

Introduction

THE impact of magnetic fields on combustion processes is a well-known fact. The application of a magnetic field is known to change diffusion flame shape, emission intensities, and temperature profiles.[1–3] Because of the paramagnetic and diamagnetic behavior of gases involved in the combustion process, the application of magnetic fields also affects equilibrium combustion characteristics. The magnetic susceptibility is defined as the degree to which a substance will be magnetized when placed in a given magnetic field. The magnetic susceptibility of paramagnetic species can be specified by the Curie–Weiss law given as

$$\chi_i = \frac{N_A g_L^2 \mu_B^2 S_i (S_i + 1)\mu_0}{3kTm_i} \tag{1}$$

As can be deduced from Eq. (1), the magnetic susceptibility decreases with increasing temperature. It was observed that the magnetic susceptibility for paramagnetic species decreases rapidly for temperatures less than 1500 K and then slowly reaches an asymptotic value as the temperature increases. On the other hand, diamagnetic susceptibility is independent of the temperature. The magnitude of the magnetic susceptibility of paramagnetic substances varies in the range of 10^{-3}–10^{-6} cgs units and is positive. Among the product species considered for a model reaction of methane in air, NO (nitric oxide), O_2 (oxygen), and OH (hydroxyl) are paramagnetic gases.

Previous research has examined the effect of gradient magnetic fields on gas flows.[4,5] and the effect of magnetic field on flames.[1–2,6–10] Akoi[1] investigated the quenching characteristics of butane flames under the influence of magnetic gradient fields. Quenching of flames was also studied by Ueno.[2] Ueno[2] introduced the theory of "magnetic curtain" to explain the phenomena of flame quenching. Wakayama[3] experimentally studied the effect of

---

Received 15 June 2004; revision received 19 May 2005; accepted for publication 6 July 2005. Copyright © 2005 by the American Institute of Aeronautics and Astronautics, Inc. All rights reserved. Copies of this paper may be made for personal or internal use, on condition that the copier pay the $10.00 per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923; include the code 0001-1452/05 $10.00 in correspondence with the CCC.

*Associate Professor, Department of Mechanical Engineering. Senior Member AIAA.

†Graduate Student, Department of Mechanical Engineering.

gradient magnetic fields on the combustion reaction of methane in air. Akoi[6] examined the effect of a uniform magnetic field on emission intensities arising from particle cloud radiation. Wakayama et al.[8] experimentally investigated the generation of convective airflows with the application of magnetic fields and showed that an applied magnetic field can be used to support combustion under microgravity conditions. It was found that a diffusion flame became more brilliant and shorter when a nonuniform magnetic field was applied.[8] Yamada et al.[11] numerically studied the effect of an applied magnetic field on OH radical distribution in a hydrogen–oxygen diffusion flame. Kajimoto et al.[12] explored possibility of controlling combustion using magnetic field. It was found that the equivalence ratio greatly affects the OH fluorescence intensity distribution.[12] Ueno et al.[13] studied the effects of magnetic fields on the combustion velocities of gasoline and alcohol with platinum catalysis. The variation of combustion velocities as function of homogeneous magnetic field was found to be undulant.[13] Braithwaite et al.[14] showed that strong magnetic fields available from superconducting magnets can be used to induce magnetic convection in normal paramagnetic fluids.

The present study is a continuation of the work done by Baker and Saito.[15] In that study, the impact that an applied uniform magnetic field has on constant pressure equilibrium combustion composition was examined. It was shown that significant changes in equilibrium combustion characteristics could be achieved with an applied magnetic field. Constant volume equilibrium combustion characteristics were not examined. Such characteristics are of interest given the importance of constant volume combustion in applications such as diesel engines. The specific objectives of this study can be outlined as follows: 1) to model a reaction of methane in air and quantitatively study the effect of a uniform magnetic field on equilibrium combustion compositions under constant volume condition and 2) to study the impact of a uniform magnetic field on equilibrium pressure.

Mathematical Formulation

Consider a closed, constant volume, homogeneous, isotropic, stationary system subjected to constant uniform magnetic field. For a reversible process, the first law of thermodynamics states that

$$T\,\mathrm{d}S + \delta W = \mathrm{d}U \tag{2}$$

Because there is no boundary work, the work contribution due to magnetic field, may be written as[16]

$$\delta W = -H\,\mathrm{d}B \tag{3}$$

Note that Eq. (3) is referred from Rosenweig[16] by taking into account the sign convention. The change in Helmholtz free energy per unit volume is given by

$$-\mathrm{d}A = \delta W = -H\,\mathrm{d}B \tag{4}$$

Integrating Eq. (4) at constant temperature gives

$$A(v, T, B) = v\left(\int_0^{B_{\mathrm{NET}}} H\,\mathrm{d}B\right)_{v,T} + A_0(v, T) \tag{5}$$

Equation (5) can be equivalently written as

$$A(v, T, H) = A(v, T) + vHB - \left(\int B\,\mathrm{d}H\right)_{v,T} \tag{6}$$

Equation (6) can be simplified by noting that the magnitude of magnetic field is constant, that is, $\mathrm{d}H = 0$. It has been assumed that the system consists of paramagnetic and diamagnetic ideal gases, and thus, the relation $B = \mu_0(H + M)$ is used to further simplify Eq. (6). The magnetization is related through magnetic intensity and magnetic susceptibility as $M = \chi H$. Hence, the relation $B = \mu_0(H + M)$ changes to $B = \mu_0 H(1 + \chi)$. Under constant volume conditions, thermodynamic equilibrium is achieved by minimizing the Helmholtz free energy, given by the expression

$$A(v, T) = G - pV \tag{7}$$

When Eq. (7) is divided by $R_u T$ and substituted in Eq. (6), Eq. (6) for any species i can be written as

$$A/R_u T = G/R_u T - p_i V/R_u T + v_i HB/R_u T \tag{8}$$

When $G/R_u T$ is substituted as $(g_i^0/R_u T + \ln y_i + \ln p)$ in Eq. (8), the pressure term is replaced by $n_T RT/V$, Eq. (8) is incorporated in equation (6), and Eq. (6) is simplified as per the preceding discussion and summing over all species, Eq. (6) can be written as

$$\frac{A}{R_u T} = \sum_{i=1}^{n_s} n_i \left[\frac{g_i^0}{R_u T} + \ln y_i + \ln\left(\frac{\bar{n}_T R_u T}{V}\right)\right] - \sum_{i=1}^{n_s} \frac{p_i V}{R_u T} + \sum_{i=1}^{n_s} \frac{H^2 \mu_0 (1 + \chi_i) y_i V}{R_u T} \tag{9}$$

Equation (9) is an expression for Helmholtz free energy of a mixture of ideal paramagnetic and diamagnetic gases. Note that, because magnetic susceptibility of any species can be positive or negative depending on whether the respective species is paramagnetic or diamagnetic, the sign of the last term will vary accordingly. The effect of magnetic field is inversely proportional to temperature.

Equilibrium combustion composition characteristics under constant volume conditions have been computed using equilibrium constant method[17] or by minimizing the changes in Helmholtz free energy (see Ref. 17). This paper deals with computing of equilibrium combustion compositions by minimizing Helmholtz free energy and using Lagrange multiplier method. Recall that, at a specified temperature and volume, equilibrium will be achieved by $(\mathrm{d}A)_{T,V} = 0$. The conservation of mass for each of the constituent elements involved in the chemical reaction is given as

$$\sum_{i=1}^{n_s} a_{ij} n_i - b_j = 0 \tag{10}$$

Equation (10) is system of n_e equations. To compute equilibrium combustion composition for a given reaction at a specified temperature and pressure, minimization of Helmholtz free energy should be done in addition to mass conservation as specified by Eq. (10).

Note that the method of Lagrange multiplier was used to obtain the solution of the preceding system of equations. Following the algorithm outlined by Baker and Saito,[15] the following pseudoalgorithm was used to determine equilibrium compositions:

1) Initialize the number of moles for each of the product species to 0.1, calculate various constants, populate the mass conservation matrix, read in the thermochemical data, and evaluate the normalized reference Helmholtz free energy for each of the product species.

2) Calculate magnetic susceptibility for paramagnetic species and populate magnetic susceptibility for diamagnetic species.

3) Calculate the magnetic field contribution for all of the species using the earlier described calculated magnetic susceptibilities.

4) Solve the following system of equations:

$$\sum_{i=1}^{n_s} M_i = \sum_{j=1}^{n_e} \lambda_j \sum_{i=1}^{n_s} \bar{n}_i a_{ij} \tag{11}$$

$$\sum_{k=1}^{n_e} \lambda_k \sum_{i=1}^{n_s} a_{ij} a_{ik} \bar{n}_i + \frac{n_T}{\tilde{n}_T} \sum_{i=1}^{n_s} a_{ij} \bar{n}_i + \sum_{i=1}^{n_s} (-a_{ij} M_i) - b_j = 0 \tag{12}$$

where

$$M_i = n_i \left[\frac{\bar{g}_i^0}{R_u T} + \ln\left(\frac{\bar{n}_i}{\tilde{n}_T}\right) + \ln\left(\frac{\tilde{n}_T R_u T}{V}\right) + \frac{H^2 \mu_0 \chi_i V}{\tilde{n}_T R_u T} - \sum_{m=1}^{n_s} \frac{H^2 \mu_0 \chi_m V}{\tilde{n}_T^2 R_u T}\right] \tag{13}$$

Note that Eq. (12) provides n_e equations and Eq. (11) provides a single equation. The unknowns for the system are $n_T/\tilde{n}_T$ and n_e

values of λ_k. This system of equations is solved by using standard Gaussian elimination with pivoting.

5) Calculate a new temporary estimate of the number of moles of each component by using

$$\tilde{n}_i^{m+1} = \tilde{n}_i^m \left(\frac{n_T}{\tilde{n}_T} - \sum_{j=1}^{n_e} \lambda_j a_{ij} \right) - M_i \tag{14}$$

The new estimate of the equilibrium number of moles is calculated by using

$$\tilde{n}_i^{m+1} = \tilde{n}_i^{m+1} + C\left(\tilde{n}_i^{m+1} - \tilde{n}_i^m\right) \tag{15}$$

where C is adjusted to ensure convergence.

6) Calculate the normalized maximum norm of the solution

$$E = \max{}_i \left(\left| n_i^{m+1} - n_i^m \right| \Big/ n_i^{m+1} \right) \tag{16}$$

If $E < 10^{-15}$, the solution is taken to be converged, the results are written to a file, and the program stops. If $E \geq 10^{-15}$, then $n_i^m = n_i^{m+1}$, and the program proceeds to step 3.

Results and Discussion

Model Chemical Reaction and Validation

The equilibrium composition of a model reaction of methane in air was used to investigate the impact of a uniform magnetic field on combustion compositions under constant volume conditions. The model reaction of combustion of methane in air is represented as

$$\begin{aligned} CH_4 + n_{\mathrm{air}}(O_2 + 3.76N_2) &\rightarrow n_{CO_2}CO_2 + n_{CO}CO \\ &+ n_{H_2O}H_2O + n_H H + n_{H_2}H_2 + n_{O_2}O_2 + n_{OH}OH \\ &+ n_O O + n_{N_2}N_2 + n_{NO}NO + n_{CH_4}CH_4 \end{aligned} \tag{17}$$

The validation of the equilibrium composition model developed was done by comparing the results with GASEQ. GASEQ uses the same technique for calculating equilibrium composition as used in this study to generate results. Comparison between the results generated from the code and GASEQ was made for temperature ranging from 1000 to 5000 K. Setting the magnetic induction to zero produced results that exactly (a maximum of 0.1% at a temperature of 2500 K) match to the results from GASEQ for the same conditions.

Effect of Magnetic Field on Equilibrium Pressure as Function of Temperature

The magnetic susceptibility values[17] for diamagnetic species are listed in Table 1. As discussed earlier, the magnetic susceptibilities for paramagnetic elements have been calculated using the Curie–Weiss law. To calculate magnetic susceptibility, the value of Lande's g factor is taken as constant 2.0 for all paramagnetic species considered, that is, O_2, NO, and OH. The value of total electron spin is taken as 1.0, 0.5, and 0.5 for O_2, NO, and OH, respectively. An equivalence ratio of unity was used for all of the test cases considered. The range of the magnetic induction considered in this paper is 0.00–0.04 T. The decision to examine this range was an ad hoc decision based solely on the fact that the impact of a magnetic field on equilibrium characteristics was easily observable in this range. Also note that the results presented are only of qualitative value above temperatures on the order of 4000 K. The reason for this is that the dissociation of nitrogen becomes significant above this value and such a reaction is not included in the model problem.

Table 1 Magnetic susceptibility of diamagnetic species

Species	Magnetic susceptibility, cgs units
N_2	-12.00×10^{-6}
H_2O	-12.63×10^{-6}
CO	-9.80×10^{-6}
CO_2	-21.00×10^{-6}
H	-2.93×10^{-6}
O	-4.61×10^{-6}
H_2	-3.99×10^{-6}
CH_4	-17.4×10^{-6}

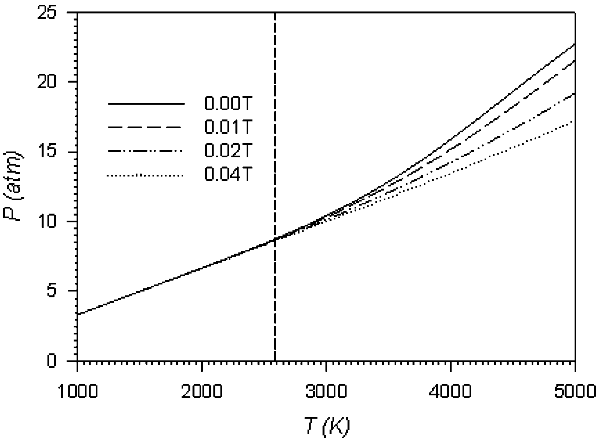

Fig. 1 Equilibrium pressure.

Figure 1 shows equilibrium pressure as a function of temperature with varying magnetic field strengths. From Fig. 1, one can see that as the temperature increases, the equilibrium pressure increases for all values of magnetic field strengths. At constant volume, the increase in pressure with increase in temperature is due to the combined effect of increase in temperature, as well as due to increase in total number of moles of products. At low temperatures below 2000 K, there was no significant effect of increasing magnetic field strength on equilibrium pressure. As the temperature increases, the equilibrium pressure drop becomes more evident with increase in magnetic induction. Because of the paramagnetic and diamagnetic nature of the gases involved in the chemical reaction, application of magnetic field exerts selective pressure on different species, which tends to change the composition of each of the product species. According to Le Châtelier's principle, if the conditions of a chemical reaction at equilibrium are changed, then the composition of the system will tend to change until the new equilibrium state is attained. The change in condition can be either through change in pressure or temperature, or change in the composition of the components. In present study, when magnetic field is applied, the selective pressures due to magnetic field on different species increases. As the pressure on the product species increases, according to Le Châtelier's principle, increase in pressure will cause the reaction to shift in the direction that reduces the pressure. In other words, the equilibrium shifts to the side with fewer total numbers of moles. Hence, at a constant temperature with the application of magnetic field, the equilibrium reaction shifts to the left, thereby reducing total number of moles of product species. As the temperature and volume are kept constant, the effect of change of composition will tend to decrease the equilibrium pressure with increase in magnetic induction. The degree of change of pressure depends on the difference in the total number of moles of products and total number of moles of reactants. As the temperature increases, the difference between the total number of moles of products and total number of moles of reactants increases. Hence, the effect of pressure drop is more evident at higher temperatures.

Effect of Magnetic Field on Mole Fractions as Function of Temperature

Figure 2 shows the equilibrium mole fraction for carbon dioxide as a function of temperature and magnetic field strength. From Fig. 2, one can see that the mole fraction of CO_2 decreases nonlinearly in a temperature range of approximately 2500–4500 K for all values of magnetic induction. At temperatures below 1500 K, no effect of magnetic field strength was observed on the equilibrium mole fraction of CO_2. As the temperature increases, the effect of magnetic field becomes evident. As explained earlier, according to Le Châtelier's principle the effect of magnetic field increases with increase in temperature. At a fixed temperature, the mole fraction

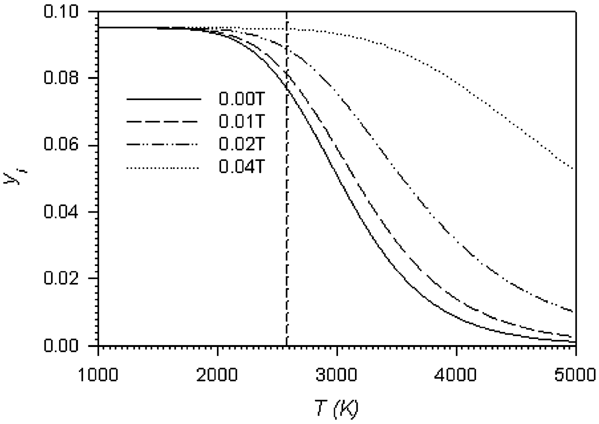

Fig. 2 Equilibrium mole fraction of CO_2.

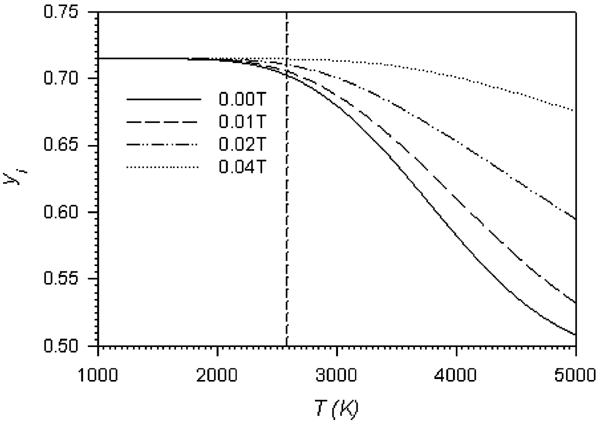

Fig. 3 Equilibrium mole fraction of N_2.

of CO_2 increases with increase in magnetic field strength. As the magnetic field strength increases, the initial period of constant mole fraction of CO_2 increases. In the case of no magnetic induction, the equilibrium mole fraction of CO_2 goes below 0.001 at a temperature close to 4000 K, whereas with increase in magnetic induction the same value of mole fraction is attained at higher temperature value. Under constant volume conditions and zero magnetic field strength, the adiabatic flame temperature of the stoichiometric mixture of methane–air combustion is 2587.50 K. A vertical dashed line is used in all mole fractions vs temperature plots to represent adiabatic flame temperature for stoichiometric mixture of methane–air combustion under constant volume condition and zero magnetic field strength. It is obvious that there will be a shift in equilibrium flame temperature due to the application of magnetic field. The effect of magnetic field on adiabatic flame temperature is beyond the scope of this paper. Based on this fundamental study on equilibrium combustion compositions under constant volume conditions and within the temperature range considered, one can see that the equilibrium mole fraction of CO_2 increases significantly because of the application of magnetic field.

Figure 3 shows the equilibrium mole fraction for nitrogen as a function of temperature and magnetic field strengths. As with CO_2, the mole fraction of N_2 also increases with increase in magnetic field within certain temperature range. The change in the mole fraction of N_2 with the magnetic field starts at a temperature close to 1800 K. As the temperature increases, the effect of the magnetic field starts becoming more evident. Within the temperature range considered, no asymptotic value of N_2 mole fraction of observed. At higher values of magnetic field, the minimum value of N_2 mole fraction shifts to a higher temperature. For a case of zero magnetic induction, the equilibrium mole fraction of N_2 goes below 0.60 at a temperature of approximately 4000 K, whereas for a magnetic induction of 0.02 T the same value is attained at 5000 K, and for 0.04 T the mole fraction of N_2 remains well below 0.60 within the temperature range considered.

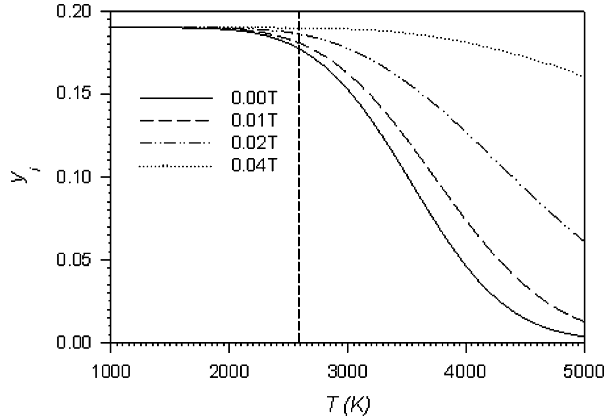

Fig. 4 Equilibrium mole fraction of H_2O.

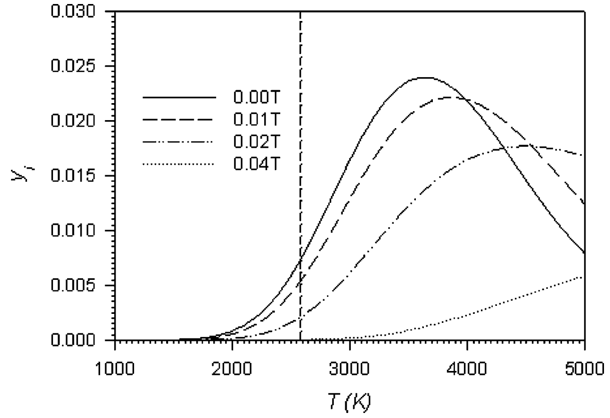

Fig. 5 Equilibrium mole fraction of O_2.

Figure 4 shows the equilibrium mole fraction for water as a function of temperature and magnetic field strengths. Similar to Figs. 2 and 3, the trend of increasing mole fraction of water with increases in magnetic field strength was observed. The change in mole fraction of H_2O with magnetic field starts at a temperature close to 1900 K. As the temperature increases, the effect of magnetic field becomes more evident. For a case of zero magnetic induction, the equilibrium mole fraction of H_2O goes below 0.001 close to 4700 K, whereas for higher values of magnetic induction the equilibrium mole fraction of H_2O does not go below 0.001 within the temperature range considered. No asymptotic behavior of H_2O mole fraction as a function of temperature was observed, even for zero magnetic induction and in the temperature range considered. At higher values of magnetic field, the minimum value of H_2O equilibrium mole fraction shifts to a higher temperature.

Figure 5 shows the equilibrium mole fraction for oxygen as a function of temperature and magnetic field strengths. It is evident from Fig. 5 that as the temperature increases the mole fraction of O_2 increases to a maximum and then steadily decreases. At temperatures below 1700 K, the mole fraction of O_2 is less than 1.0×10^{-6} for all magnetic field strengths. The mole fraction of O_2 reaches maximum close to 3600 K and then again decreases steadily for zero magnetic field strength. As magnetic field strength increases, the maximum value of equilibrium mole fraction of O_2 decreases and shifts at a higher temperature. For magnetic field strength of 0.01 T, the maximum was observed close to 3900 K; for 0.02 T, the maximum was observed close to 4500 K; and for 0.04 T, the maximum was not observed within the temperature range considered. At temperatures below 4000 K, the mole fraction of O_2 decreases with increases in magnetic field, but as the temperature increases, the equilibrium mole fraction of O_2 for increasing magnetic field crosses the zero magnetic field values.

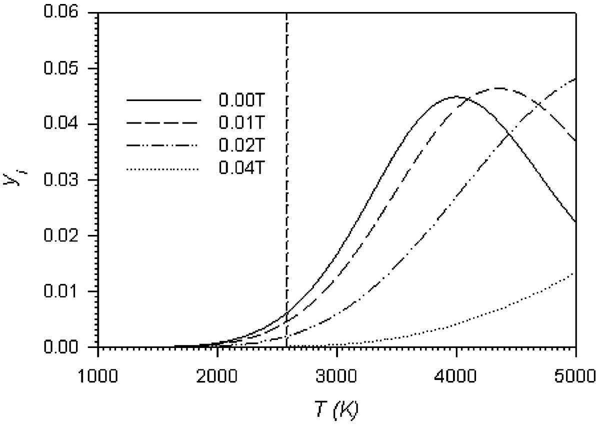

Fig. 6 Equilibrium mole fraction of H_2.

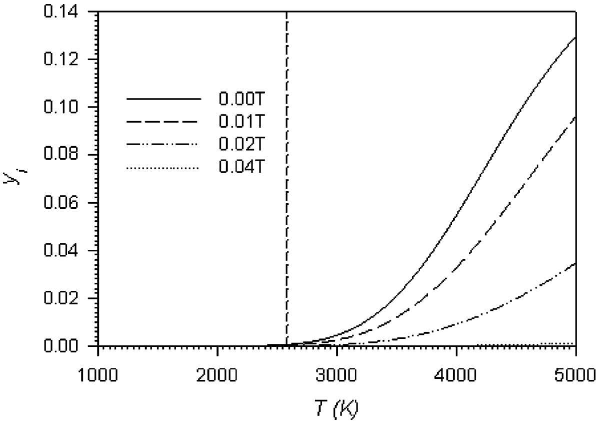

Fig. 7 Equilibrium mole fraction of O.

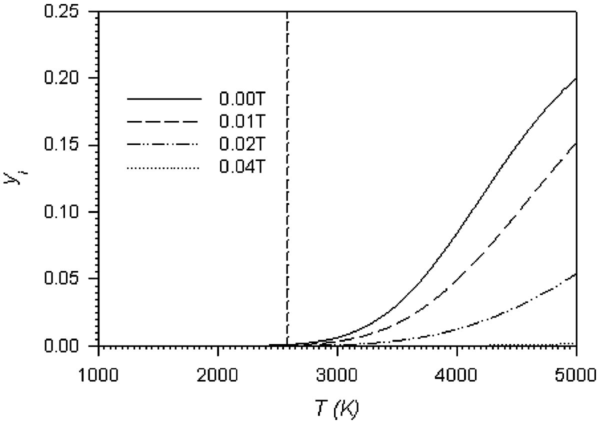

Fig. 8 Equilibrium mole fraction of H.

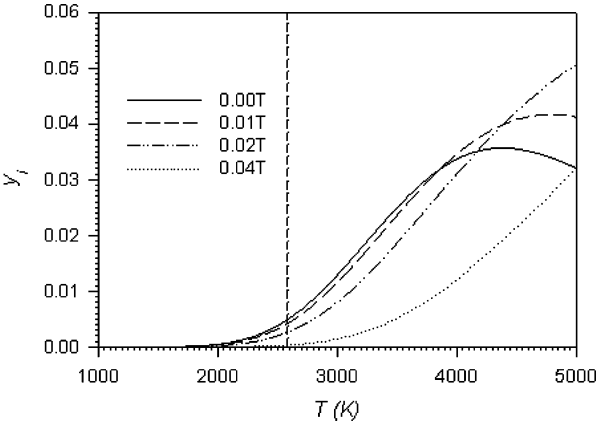

Fig. 9 Equilibrium mole fraction of NO.

Figure 6 shows the equilibrium mole fraction for diatomic hydrogen as a function of temperature and magnetic field strengths. Diatomic hydrogen exhibited similar behavior as diatomic oxygen. At low temperatures below 1700 K, the equilibrium mole fraction of H_2 is less than 1.0×10^{-6} for all magnetic field strengths. The equilibrium mole fraction of H_2 increases with increase in temperature and then steadily decreases. Within the temperature range considered, the maximum has not been observed for magnetic induction of 0.02 and 0.04 T. The maximum equilibrium mole fraction of H_2 for magnetic field strengths of 0.00 and 0.01 T was observed close to 4000 and 4400 K, respectively. The distinction between the behavior of mole fraction variation of O_2 and H_2 is that in case of O_2 the magnitude of maximum value of mole fraction of O_2 decreases with increase in magnetic field strength, whereas the maximum value of equilibrium mole fraction of H_2 increases with increase in magnetic field strength.

Figure 7 shows the equilibrium mole fraction for monatomic oxygen as a function of temperature and magnetic field strengths. From Fig. 7, one can see that the equilibrium mole fraction of monatomic oxygen increases with increase in temperature for all values of magnetic field. For temperatures below 2100 K, the equilibrium mole fraction of O was less than 1.0×10^{-6} for all magnetic inductions. At higher temperatures, the effect of an applied magnetic field becomes more evident. As explained earlier, according to Le Châtelier's principle the effect of magnetic field increases with increase in the difference of total number of moles of products and reactants, which in present study increases with increase in temperature. Within the temperature range considered, the mole fraction of O never reached an asymptotic value or a maximum value for all magnetic inductions. At a temperature of 2587.5 K (adiabatic flame temperature under constant volume), Fig. 7 shows that an increase in magnetic induction decreases the equilibrium mole fraction of monatomic oxygen.

Figure 8 shows the equilibrium mole fraction for monatomic hydrogen as a function of temperature and magnetic field strengths. As for monatomic oxygen, the equilibrium mole fraction of H increases with increase in temperature for all values of magnetic field strengths. At a specified temperature, the effect of increases in the magnetic field strength decreases the equilibrium mole fraction of monatomic hydrogen. The temperature at which the effect of an applied magnetic field on equilibrium mole fraction of H was found to be significant was approximately 2250 K. At a temperature of 2587.5 K, the effect of magnetic field was to decrease the equilibrium mole fraction of H with increasing magnetic induction. With the increase in temperature, the equilibrium mole fraction of H keeps on increasing, that is, no asymptotic value was observed for all values of magnetic field strengths within the temperature range considered.

Figure 9 shows the equilibrium mole fraction for nitric oxide as a function of temperature and magnetic field strengths. As can be seen from Fig. 9, above a temperature of 1600 K the equilibrium mole fraction of NO was observed to increase to a maximum and then steadily decreases. At a temperature of 2587.5 K (the adiabatic temperature with no applied magnetic field), the NO mole fraction was found to decrease by approximately 20% for 0.01-T magnetic induction and approximately 90% for 0.04-T magnetic induction. Because the analysis is a thermodynamic analysis, the equilibrium compositions shown here do not take into account the time duration to achieve those mole fractions. With the present study, a fundamental understanding of the trends of equilibrium combustion compositions under the influence of uniform magnetic field can be achieved. The maximum value of NO mole fraction continues increasing with increasing magnetic induction and also shifts at a higher temperature. Within the temperature range considered, the maximum value of the NO mole fraction was not observed for magnetic field strengths of 0.02 and 0.04 T. Because the maximum NO mole fractions shift to a higher temperature with increasing

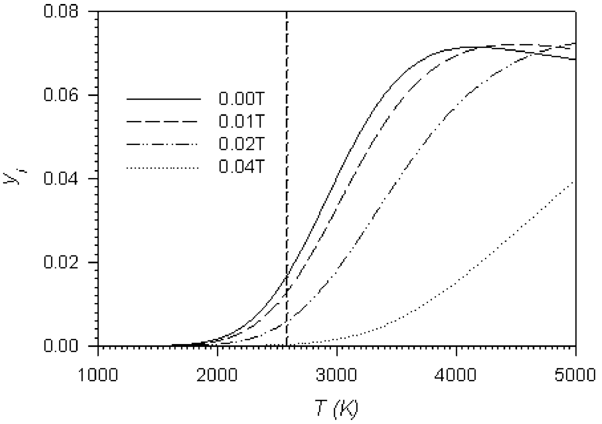

Fig. 10 Equilibrium mole fraction of CO.

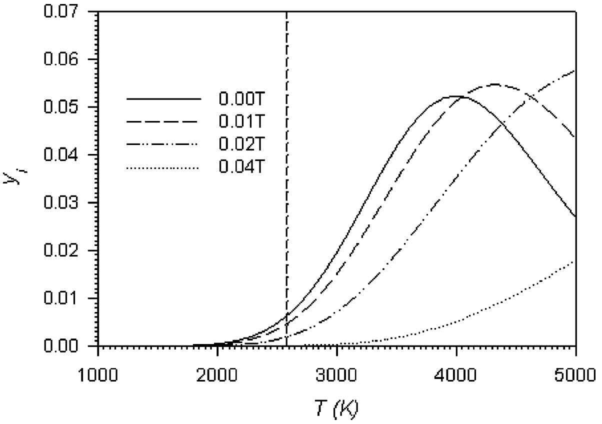

Fig. 11 Equilibrium mole fraction of OH.

magnetic field strength, the NO mole fraction for 0.01 T crosses the zero magnetic field mole fraction at about 3900 K, and for 0.02 T it crosses at approximately 4200 K.

Figure 10 shows the equilibrium mole fraction for carbon monoxide as a function of temperature and magnetic field strengths. As can be seen from Fig. 10, at a temperature above 1500 K the equilibrium mole fraction of CO was observed to increase to a maximum and then decrease slightly for no magnetic field within the temperature range considered. As observed for the NO mole fraction, an increase in the magnetic field strength increased the temperature at which the maximum equilibrium mole fraction occurred. The maximum mole fraction of CO was observed at 4200 K for 0.00-T magnetic induction and 4500 K for 0.01-T magnetic induction. The maximum for 0.02- and 0.04-T magnetic induction was not observed within the temperature range considered. The magnitude of the maximum value of CO mole fraction was observed to increase with increasing magnetic induction. Again, Fig. 10 shows that, at 2587.5 K, an increasing magnetic induction increases the predicted mole fraction of CO.

Figure 11 shows the equilibrium mole fraction for hydroxyl radical as a function of temperature and magnetic field strengths. Above a temperature of 1650 K, OH was observed to increase to a maximum and then steadily decrease. As with NO and CO, the magnitude of the maximum value of the OH mole fraction was observed to increase with increasing magnetic induction. The maximum value of OH mole fraction was observed at approximately 4000 K for 0.00-T magnetic induction and 4300 K for 0.01-T magnetic induction. Again, the maximum for 0.02- and 0.04-T magnetic induction was not observed within the temperature range considered. Note that the decrease in values of mole fractions may not be same as those in practical engineering applications because the time duration of the reaction is not considered. However, a fundamental understanding of the trends of the mole fractions can be achieved under the impact of uniform magnetic field using an equilibrium composition analysis.

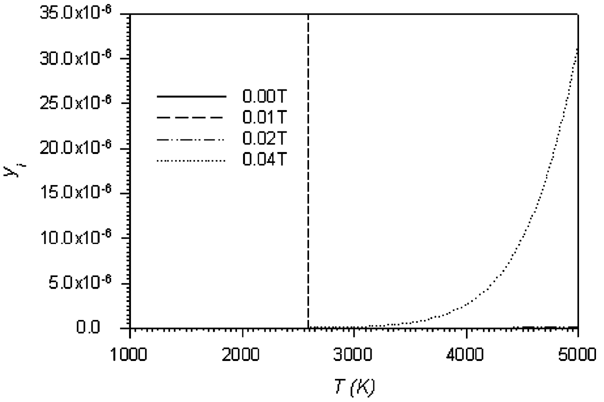

Fig. 12 Equilibrium mole fraction of CH_4.

Figure 12 shows the equilibrium mole fraction of methane as a function of temperature and magnetic field strengths. As can be seen from Fig. 12, as the temperature increases the mole fraction of CH_4 increases for all magnetic inductions. At a temperature close to 2600 K, the equilibrium mole fraction of CH_4 increases sharply for magnetic induction of 0.04 T. The nonlinear increase in equilibrium mole fraction of CH_4 for magnetic induction of 0.04 T above 2600 K is much significant as compared to other magnetic inductions. At a temperature of 2587.5 K, Fig. 12 indicates that there no significant effect of magnetic field strength on equilibrium mole fraction of CH_4.

Conclusions

Results are presented for the effect of uniform magnetic field on equilibrium combustion compositions under constant volume conditions. A model reaction of combustion of methane in air is considered that include 11 product species including methane. An expression for Helmholtz free energy as a function of Gibbs free energy was developed. The change in Helmholtz free energy was minimized using the method of Lagrange multiplier. The effect of uniform magnetic field on equilibrium pressure was also investigated. Results are presented in the form of plots of equilibrium pressure and equilibrium mole fractions of different species as a function of temperature and magnetic induction. Based on the analysis done from these plots, the following qualitative conclusions may be drawn:

1) The effect of magnetic field on equilibrium pressure and equilibrium mole fraction of species increases with increases in temperature.

2) The equilibrium pressure decreases with increase in magnetic induction at a particular temperature. The effect is more evident at higher temperatures.

3) At the stoichiometric equilibrium flame temperature for zero applied magnetic field strength, the application of magnetic field decreases equilibrium mole fraction of CO, H, O, H_2, O_2, OH, and NO product species and increases for CO_2, N_2, H_2O, and CH_4.

4) The equilibrium combustion composition of NO was greatly reduced with the application of magnetic field. When NO mole fraction at stoichiometric equilibrium flame temperature was compared for methane–air combustion under zero magnetic induction, the NO mole fraction reduced considerably when largest magnetic field that is, 0.04 T, was applied. It was observed that NO equilibrium combustion composition was reduced by the impact of a uniform magnetic field at temperatures close to those occurring in practical engineering applications. Additional research is needed to predict the exact impact of magnetic fields on NO production for different engineering applications.

References

[1] Aoki, T., "Radical Emissions and Butane Diffusion Flames Exposed to Uniform Magnetic Fields Encircled by Magnetic Gradient Fields," *Japanese Journal of Applied Physics*, Pt. 2, Vol. 29, No. 5, 1990, pp. 952–957.

[2] Ueno, S., "Quenching of Flames by Magnetic Fields," *Journal of Applied Physics*, Vol. 65, No. 3, 1988, pp. 1243–1245.

[3] Wakayama, N. I., "Effect of a Gradient Magnetic Field on the Combustion Reaction of Methane in Air," *Chemical Physics Letters*, Vol. 188, No. 3, 4, 1992, pp. 279–281.

[4] Wakayama, N. I., "Behavior of Gas Flow Under Gradient Magnetic Fields," *Journal of Applied Physics*, Vol. 64, No. 4, 1991, pp. 2734–2736.

[5] Wakayama, N. I., "Magnetic Acceleration and Deceleration of O_2 Gas Streams Injected into Air," *IEEE Transactions on Magnetics*, Vol. 31, No. 1, 1995, pp. 897–901.

[6] Aoki, T., "A Magnetically Induced Anomalous Ring Flame and Quenching Characteristics of Butane Flames," *Japanese Journal of Applied Physics*, Pt. 2, Vol. 29, No. 5, 1990, pp. 864–867.

[7] Ueno, S., and Harada, K., "Effects of Magnetic Fields on Flames and Gas Flow," *IEEE Transactions of Magnetics*, Vol. MAG-23, No. 5, 1987, pp. 2752–2754.

[8] Wakayama, N. I., Ito, H., Kuroda, Y., Fujita, O., and Ito, K., "Magnetic Support of Combustion in Diffusion Flames Under Microgravity," *Combustion and Flame*, Vol. 107, No. 1–2, 1996, pp. 187–192.

[9] Wakayama, N. I., and Sugie, M., "Magnetic Promotion of Combustion in Diffusion Flames," *Physica B*, Vol. 216, No. 3–4, 1996, pp. 403–405.

[10] Wakayama, N. I., "Magnetic Promotion of Combustion in Diffusion Flames," *Combustion and Flame*, Vol. 93, No. 3, 1993, pp. 207–214.

[11] Yamada, E., Shinoda, M., Yamashita, H., and Kitagawa, K., "Numerical Analysis of Hydrogen Oxygen Diffusion Flame in Vertical or Horizontal Gradient of Magnetic Field," *Combustion Science and Technology*, Vol. 174, No. 9, 2002, pp. 131–146.

[12] Kajimoto, T., Yamada, E., Shinoda, M., and Kitagawa, K., "Dependence of Magnetically Induced Change in OH Distribution in a Methane–Air Premixed Flame on Equivalence Ratio," *Combustion Science and Technology*, Vol. 175, No. 9, 2003, pp. 1611–1623.

[13] Ueno, S., Esaki, H., and Harada, H., "Combustion Processes Under Strong DC Magnetic Fields," *IEEE Transactions on Magnetics*, Vol. MAG-21, No. 5, 1985, pp. 2077–2079.

[14] Braithwaite, D., Beaugnon, E., and Tourneir, R., "Magnetically Controlled Convection in a Paramagnetic Fluid," *Nature*, Vol. 354, 1991, pp. 134–136.

[15] Baker, J., and Saito, K., "Magnetocombustion: A Thermodynamic Analysis," *Journal of Propulsion and Power*, Vol. 16, No. 2, 2000, pp. 263–268.

[16] Rosenweig, R. E., *Ferrohydrodynamics*, Cambridge Univ. Press, New York, 1985, pp. 103, 104.

[17] *CRC Handbook of Chemistry and Physics*, 67th ed., edited by R. C. Weast, CRC Press, Boca Raton, FL, 1986, pp. E119–E132.

S. Mahalingam
Associate Editor