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Analysis of Catalytic Reaction Systems under Microwaves to Save Energy

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Abstract−Effects of microwaves on catalytic reaction systems are analyzed theoretically in this work. Use of microwaves is encouraged to save energy. The effects of microwave heating are analyzed theoretically by assuming that the catalyst pellet is homogeneous. The temperature and concentration profiles within the catalyst pellet were obtained by numerical simulations for the cases of microwave heating and conventional heating. In the modeling the catalyst pellet is regarded as a continuum. When a chemical reaction was conducted in a heterogeneous medium with microwave heating, the reaction rate and the yield were found to be increased compared to conventional heating under the same reaction conditions. This is due to hot spots generated by selective heating of the catalyst pellet, resulting in an increased reaction rate.

Key words: Microwave Heating, Catalyst Pellet, Numerical Analysis, Heat Transfer, Porous Media, Simulation

INTRODUCTION

Microwave heating has attracted the attention of many researchers as a new tool for saving energy in various chemical operations. Recent reviews, especially in the field of chemical reactions [Mingos and Baghurst, 1991; Toma, 1993], clearly show that increased reaction rate, higher yield and improved selectivity could be achieved via reactions accompanied by microwave heating compared to reactions with conventional heating. To the authors knowledge, more than 300 research papers have been published in the area of microwave chemistry since the last decade. The issue of a specific non-thermal effect by microwaves has also been addressed [Sun et al., 1988; Berlan et al., 1991]. Quantum mechanics clearly indicate that microwave irradiation does not have sufficient energy enough to trigger any chemical changes such as breaking bonds and transferring electrons. Non-thermal effect by microwaves is hard to identify due to the difficulty in measuring the temperature within the microwave field and partly to the local superheating which can give rise to overall faster reaction rates than those estimated by using the average temperature [Jahngen et al., 1990; Pollington et al., 1991; Raner and Strauss, 1992; Chemat et al., 1998]. Some researchers advocate that there is no need to postulate non-thermal microwave effects and that accurate measurements of temperature within samples heated by the microwave are crucial. However, many of the works reported so far have been empirical and qualitative. Identification of temperature effects is very important for a quantitative description on the effects of microwave heating.

The primary objective of the present work is to propose mathematical models to describe temperature profiles and to predict conversions in heterogeneous chemical reactions occurring in catalyst pellets under microwave heating. In general, the catalyst involved in a chemical reaction has a significantly higher dielectric loss than the surrounding solvent, and the chemical reagents flow through the catalyst at a low bulk temperature. However, the reaction is conducted in the active site of the catalyst which is continuously heated by microwaves, resulting in a higher local temperature and increased reaction rates. This selective increase of reaction rates cannot be achieved by conventional heating since the catalysts and reagents will be both at the same temperature. Plazl et al. [1997] and Pipus et al. [2000] investigated a heterogeneous chemical reaction heated by microwaves. But they neglected the microwave effects on each catalyst pellet and used a pseudo-homogeneous model of the packed bed reactor.

It is obvious that there is a fundamental difference between microwave and conventional heating. Microwave heating results from the interaction of the electromagnetic wave with the irradiated medium provided its loss factor is not too low. In conventional heating, the rate of heat transfer from the heating device to the medium depends on thermal conductivity, on the temperature difference across the material and on the convection current. For this reason the temperature increase is rather slow. Under microwave heating, heat is dissipated inside the irradiated medium and heat transfer occurs from the treated medium to the outside, and much faster increase of temperature can be achieved depending on the microwave power and the loss factor of the material being irradiated. The strong tendency of microwave dielectric heating to create superheating in the centers of samples makes it difficult to compare microwave-assisted reactions with conventional reactions directly [Berlan, 1995].

The efficiency of conversion of microwave energy into thermal energy depends upon both the dielectric and thermal properties of the medium being heated. If the magnetic effects are negligible, which

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is true for most materials used under microwave heating applications, the heat absorbed per unit volume by microwave power, Q_{MW}, is determined by the following relation as given by Metaxas and Meredith [1983]:

$$Q_{MW}=\frac{1}{2}\omega\varepsilon_0\varepsilon''_{ei}E^2_{rms} \tag{1}$$

where E_{rms} is the root-mean-squared value of the electric field intensity in the medium, ω is the angular frequency of the microwave applicator, ε_0 is the free space dielectric constant and ε''_{ei} is the dielectric loss factor for the dielectric medium being heated which is a function of the temperature at a given frequency. The power absorbed depends on the intensity of the electric field and on dielectric properties of the medium. As a result of dielectric losses, microwaves penetrating a dielectric material act as a volumetrically distributed heat source. The power absorbed by cylindrical and spherical medium can be represented by Lambert's law [Datta and Liu, 1992]:

$$Q_{MW}(r, T)=Q_{MW,0}(T)e^{-(R-r)/\delta} \tag{2}$$

where r is the location from the center and δ is the penetration depth based on decay of heating rate. According to Lambert's law the microwave power is attenuated exponentially as a function of distance of penetration into the sample. For material with small minimum thickness-to-penetration depth ratio such as catalyst pellet and seed, $(R-r)/\delta\rightarrow 0$ and we have

$$Q_{MW}(r, T)\cong Q_{MW,0}(T) \tag{3}$$

In this case the power absorbed at various locations in the medium is not significantly different from each other and uniform heat generation may be assumed. This consideration was reported by Hill and Marchant [1994], Adu and Otten [1996] and Le Bail et al. [1999]. In the simulations, the temperature-dependence of dielectric property on the medium should be taken into account to solve the temporal and spatial evolution of the non-uniform temperature profile, since temperature has a significant effect on dielectric properties. Metaxas and Meredith [1983] considered the case in which dielectric properties increased as the temperature increased and employed the following relation to give the dependence of ε''_{ei} on the temperature:

$$\varepsilon''_{ei}(T)=\varepsilon''_{ei}(T_0)+\varepsilon''_{Bi}\left\{1-\exp\left(1-\frac{\chi_i(T-T_0)}{T_0}\right)\right\} \tag{4}$$

where ε''_{Bi} andare χ_i constants.

If the above equation for dielectric property is used and exponential attenuation of the microwave energy is not taken into account because of the small dimension of the volume exposed to waves, we can use the simplified relation given by

$$Q_{MW}=A(1-\exp(-BT)) \tag{5}$$

where A and B are constants.

Pipus et al. [2000] investigated microwave heating in the packed bed reactor and modeled the volumetric power by using the relation given by

$$Q_{MW}=A\exp(-BT) \tag{6}$$

They assumed that the dielectric properties of the reacting system decreased with temperature. In this work we will consider these two relations of dielectric properties in modeling of a catalyst pellet under microwave heating. The catalyst pellet is assumed to be homogeneous.

In this work, the model of a catalyst pellet being heated by microwave is proposed and temperature profiles of active sites which absorb microwaves and are dispersed on the support material are discussed. The model can be effectively used to interpret the increase of the reaction rate by microwave heating in terms of the "hot spots" related to active sites as well as the type of the temperature profile within the porous body of each catalyst pellet.

MODELING

When pellets move in the gas phase, it is necessary to differentiate the overall porosity of the system from porosity inside catalyst pellets [Thomas and Thomas, 1997]. The flow regimes of gas flow inside and outside the pellet should be distinguished and treated separately. Moreover, the low thermal conductivity of porous pellets and uniform absorption of microwaves by porous pellets lead to non-uniform temperature distribution inside the catalyst pellets (the temperature in the center will be higher). These facts are not taken into account in the result of Thomas and Thomas [1997]. The so-called "hot spots" can appear in the case of non-uniform heating of catalyst pellets.

In modeling of catalyst pellets, the catalyst pellets are regarded as a continuum. Heat and mass transfer rates are described according to the Fourier law and the Ficks law, respectively. Energy and mass balances in a spherical pellet of radius R_p are given by the following relations for 1st order reaction:

$$\frac{\partial C_p}{\partial t}=\frac{D_{eff,p}}{r_p^2}\frac{\partial}{\partial r_p}\left(r_p^2\frac{\partial C_p}{\partial r_p}\right)-\rho_p s_m(k_{r0}\exp(-E_a/RT_p))C_p \tag{7}$$

$$\rho_p c_{p,p}\frac{\partial T_p}{\partial t}=\frac{\lambda_{eff,p}}{r_p^2}\frac{\partial}{\partial r_p}\left(r_p^2\frac{\partial T_p}{\partial r_p}\right)+Q_{MW,p}$$
$$+(-\Delta H_{rxn})\rho_p s_m(k_{r0}\exp(-E_a/RT_p))C_P \tag{8}$$

The effective diffusivity ($D_{eff,p}$) and the effective conductivity ($\lambda_{eff,p}$) are not physical quantities and can be expressed in terms of the molecular diffusivity, the molecular conductivity and the porosity of the porous catalyst pellet. $Q_{MW,p}$ represents the volumetric power deposition in the pellet, r_p is the radial distance, ρ_p is the apparent density of the catalyst pellet and s_m is the specific surface area per unit mass of the catalyst pellet.

COMPARISON OF MICROWAVE AND SURFACE RADIATION

When microwave radiation is used as a heat source, we assume that the dielectric property of the catalyst pellet decreases as the temperature increases as shown in (6): $Q_{MW,p}=A\exp(-BT_p)$. If the heat effect due to the chemical reaction is neglected, we have

$$\frac{\partial T_p}{\partial t}=\beta_{hom,1}\frac{1}{\bar{r}_p^2}\frac{\partial}{\partial\bar{r}_p}\left(\bar{r}_p^2\frac{\partial T_p}{\partial\bar{r}_p}\right)+\beta_{hom,2}\exp(-BT_p) \tag{9}$$

where $\beta_{hom,1}=\frac{\lambda_{eff,p}}{\rho_p c_{p,p}R_p^2}$, $\beta_{hom,2}=\frac{A}{\rho_p c_{p,p}}$

Boundary conditions are given by

$$\text{at } \bar{r}_p=0:\ \left.\frac{\partial T_p}{\partial \bar{r}_p}\right|_{\bar{r}_p=0}=0 \tag{10a}$$

$$\text{at } \bar{r}_p=1:\ \left.\frac{\partial T_p}{\partial \bar{r}_p}\right|_{\bar{r}_p=1}=Bi_H(T_b-T_p|_{\bar{r}_p=1}) \tag{10b}$$

where $Bi_H=\frac{h_{b,H}R_p}{\lambda_{eff,p}}$

Now we investigate the effects of heating of the pellet by microwave radiation and by conventional surface radiation. We assume that the radiation is uniform throughout the surface and that the flux density of conventional surface radiation is equal to Q_{SH}. It is also assumed that deposited power is equal for both cases (microwave and surface radiations), i.e.,

$$\frac{4}{3}\pi R_p^3 Q_{MW}=4\pi R_p^2 Q_{SH} \tag{11}$$

In the case of the conventional surface radiation on the pellet surface, the temperature of the pellet and the boundary conditions is given by

$$\frac{\partial T_p}{\partial t}=\beta_{hom,1}\frac{1}{\bar{r}_p^2}\frac{\partial}{\partial \bar{r}_p}\left(\bar{r}_p^2\frac{\partial T_p}{\partial \bar{r}_p}\right) \tag{12}$$

$$\text{at } \bar{r}_p=0:\ \left.\frac{\partial T_p}{\partial \bar{r}_p}\right|_{\bar{r}_p=0}=0 \tag{13a}$$

$$\text{at } \bar{r}_p=1:\ \left.\frac{\partial T_p}{\partial \bar{r}_p}\right|_{\bar{r}_p=1}=Bi_H(T_b-T_p|_{\bar{r}_p=1})+\frac{R_pQ_{SH}}{\lambda_{eff,p}} \tag{13b}$$

Temperature profiles were obtained by solving the partial differential equations using the finite difference method. In the case of microwave radiation, the parameter values used in modeling and correlations are: $\beta_{hom,1}=0.8$, $\beta_{hom,2}=700.0$, $B=0.032$, $Bi_H=100.0$, $T_b=80$ °C. In the case of surface radiation, the parameter values used are: $\beta_{hom,1}=0.8$, $Q_{SH}=7.0\times\exp(-0.032\times T_b)$, $Bi_H=100.0$, $R_p=3.0$ mm, $\lambda_{eff,p}=80.0$ W/mK, $T_b=80$ °C.

Fig. 1 shows the temperature increase in a catalyst pellet by microwave and surface radiation without considering the heat effects due to chemical reactions, and Fig. 2 shows steady-state temperature profiles in a catalyst pellet for both cases. It can be seen from Fig. 1 and Fig. 2 that with the same power deposition the temperatures of the pellet at $r_p=R_p$ are equal to each other for both cases compared to the large discrepancy in the temperatures inside the pellet. The higher steady-state temperature for microwave radiation indicates that uniform volumetric heating by microwave radiation is more efficient to transfer heat than conventional surface radiation with the same power deposition.

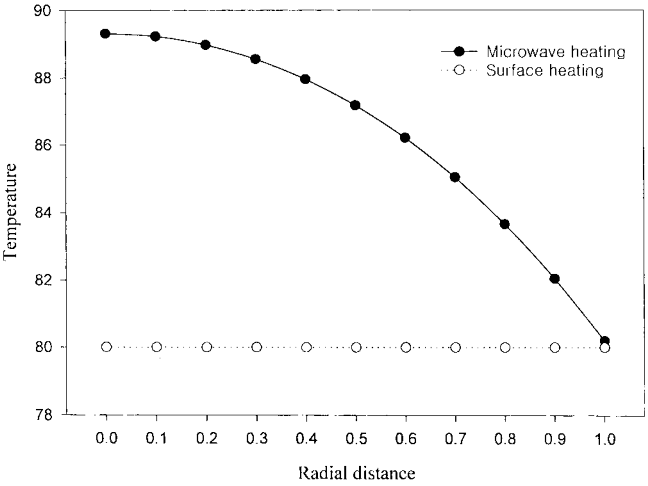
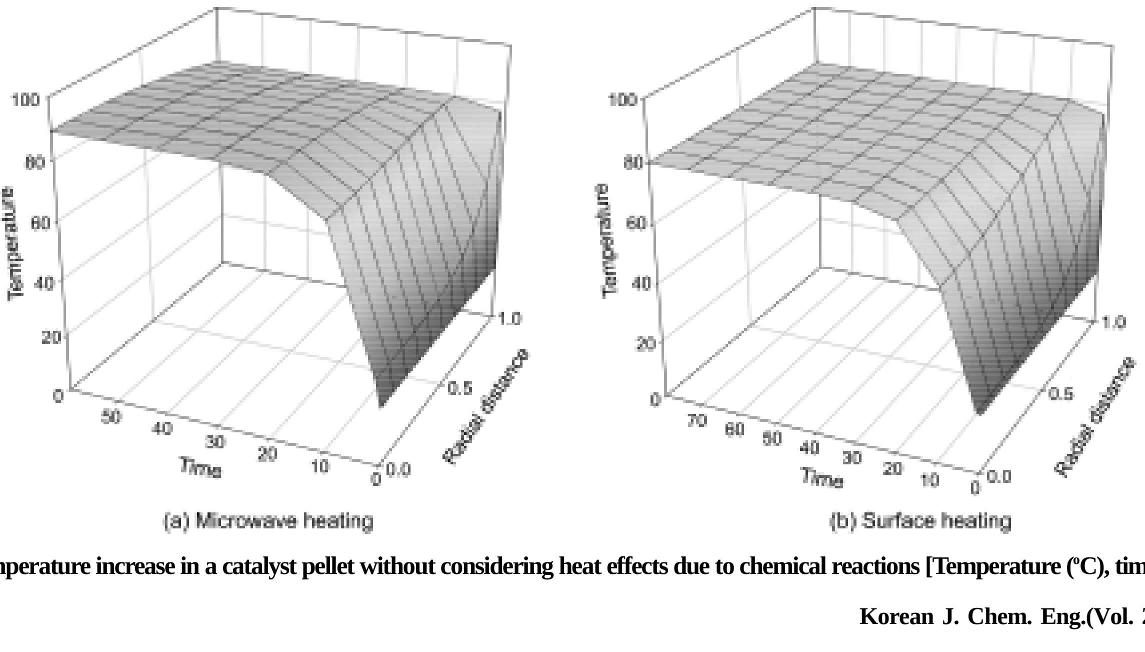


Fig. 2. Steady-state temperature profiles in a catalyst pellet without considering heat effects due to chemical reactions [Temperature (°C)].

COMPARISON OF MICROWAVE AND CONVENTIONAL HEATING

In this section, microwave heating and conventional heating in a catalyst pellet under chemical reactions are compared. As the chemical reaction proceeds in a catalyst pellet the mass balance in the catalyst pellet must be considered. In both cases of microwave heat-



(a) Microwave heating

(b) Surface heating

Fig. 1. Temperature increase in a catalyst pellet without considering heat effects due to chemical reactions [Temperature (°C), time (sec)].

ing and conventional heating, it is assumed that the bulk fluid has been heated up to 80 °C by microwave heating and conventional heating, respectively. The mass balance and energy balance in the spherical catalyst pellet with 1st order reaction are expressed by (7) and (8). When the microwave is used as a heat source we assume that the dielectric property of the catalyst pellet increases as the temperature increases, i.e., $Q_{MW}=A(1-\exp(-BT_p))$. The simplified model equations and boundary conditions are given by

$$\frac{\partial \overline{C}_p}{\partial t}=\alpha_p\frac{1}{\bar{r}_p^2}\frac{\partial}{\partial \bar{r}_p}\left(\bar{r}_p^2\frac{\partial \overline{C}_p}{\partial \bar{r}_p}\right)-\mathrm{Da}\overline{C}_p\exp(-E_a/RT_p) \tag{14}$$

$$\frac{\partial T_p}{\partial t}=\beta_{hom,1}\frac{1}{\bar{r}_p^2}\frac{\partial}{\partial \bar{r}_p}\left(\bar{r}_p^2\frac{\partial T_p}{\partial \bar{r}_p}\right)+\beta_{hom,2}(1-\exp(-BT_p))$$
$$+\beta_{hom,3}\mathrm{Da}\exp(-E_a/RT_p)\overline{C}_P \tag{15}$$

where $\overline{C}_p\equiv\frac{C_p}{C_b}$, $\bar{r}_p\equiv\frac{r_p}{R_p}$, $\alpha_p=\frac{D_{eff,p}}{R_p^2}$, $\mathrm{Da}\equiv k_{r0}\rho_p s_m$,

$$\beta_{hom,1}=\frac{\lambda_{eff,p}}{\rho_p c_{p,p} R_p^2},\quad \beta_{hom,2}=\frac{A}{\rho_p c_{p,p}}$$

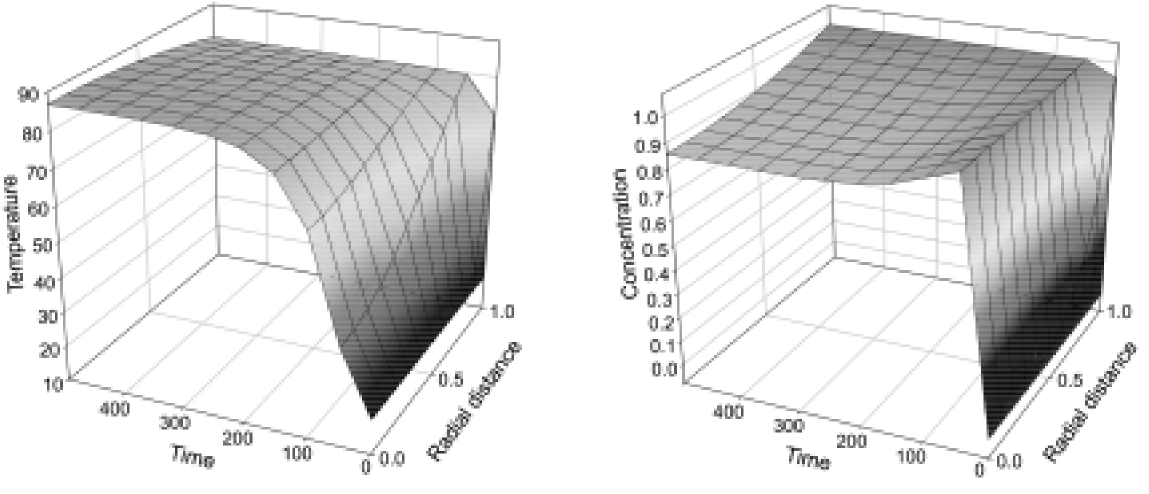
and $\beta_{hom,3}=\frac{(-\Delta H_{rxn})C_b}{\rho_p c_{p,p}}$

$$\text{at } \bar{r}_p=0:\ \left.\frac{\partial \overline{C}_p}{\partial \bar{r}_p}\right|_{\bar{r}_p=0}=0,\ \left.\frac{\partial T_p}{\partial \bar{r}_p}\right|_{\bar{r}_p=0} \tag{16a}$$

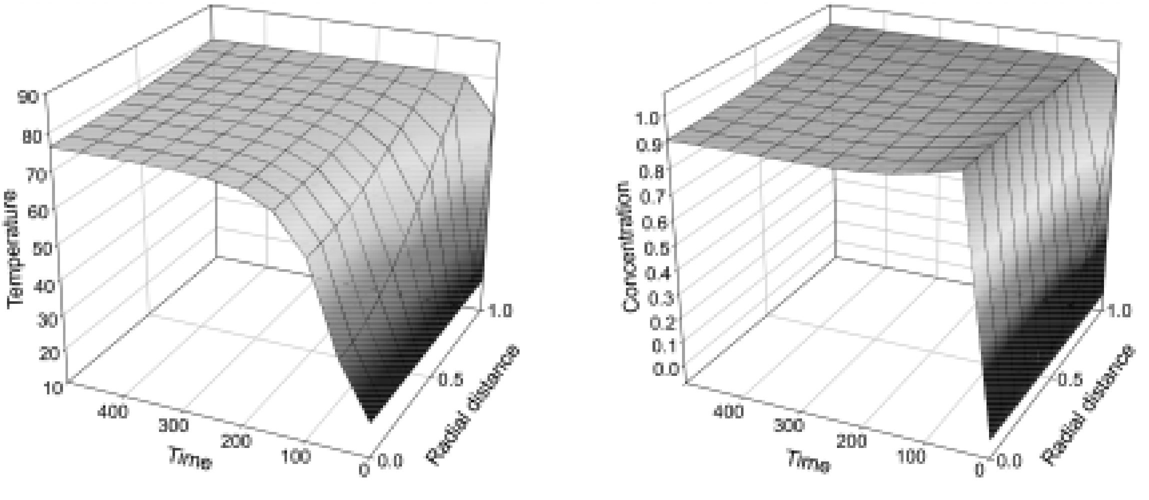
$$\text{at } \bar{r}_p=1:\ \left.\frac{\partial \overline{C}_p}{\partial \bar{r}_p}\right|_{\bar{r}_p=1}=\mathrm{Bi}_M(1-\overline{C}_p|_{\bar{r}_p=1}),\ \left.\frac{\partial T_p}{\partial \bar{r}_p}\right|_{\bar{r}_p=1}=\mathrm{Bi}_H(T_b-T_p|_{\bar{r}_p=1}) \tag{16b}$$

where $\mathrm{Bi}_M\equiv\frac{k_{b,M}R_p}{D_{eff,p}}$ and $\mathrm{Bi}_H\equiv\frac{h_{b,H}R_p}{\lambda_{eff,p}}$

The 1st order endothermic reaction and the 1st order exothermic reaction in a catalyst pellet are considered in the present work. We will compare microwave heating and conventional heating based on these two models. First, we consider the 1st order endothermic reaction in the catalyst pellet under microwave heating and under conventional heating. In the case of microwave heating the parameter values for model and correlations are: $\alpha_p=0.8$, $\beta_{hom,1}=0.08$, $\beta_{hom,2}=7\times10^{10}$, $\beta_{hom,3}=-4.0$, $B=10^{-12}$, $E_a=69{,}100.0$ J/mol, $\mathrm{Da}=9\times10^9$, $\mathrm{Bi}_M=100.0$, $\mathrm{Bi}_H=100.0$. The dimensionless concentration and the tem-

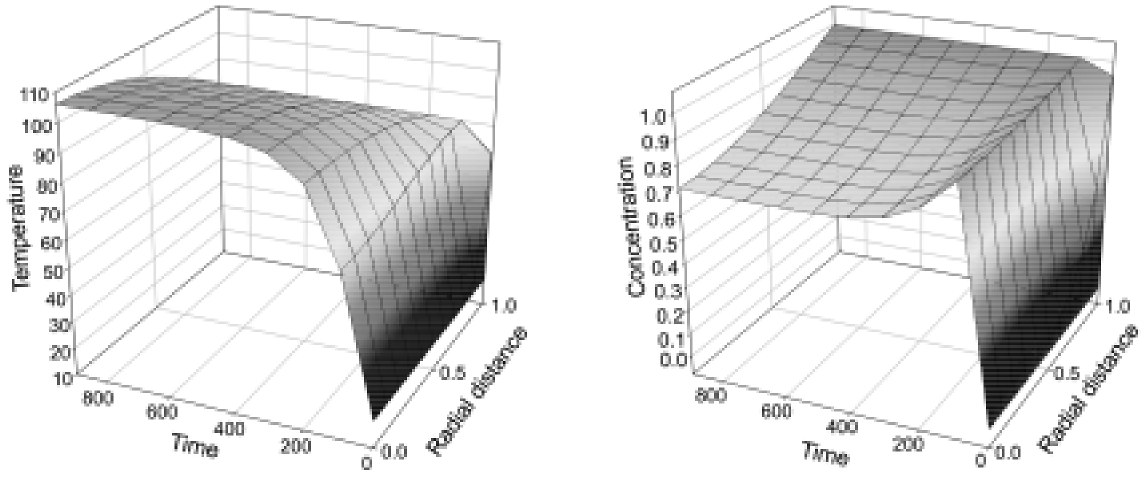


(a) Temperature - microwave heating (b) Concentration - microwave heating



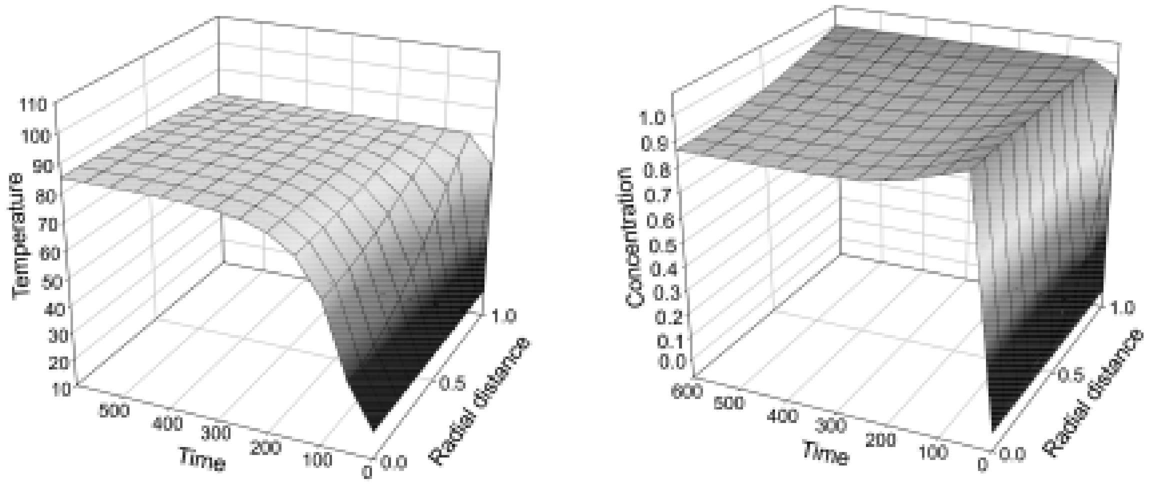
(c) Temperature - conventional heating (d) Concentration - conventional heating

Fig. 3. Profiles of temperature and concentration in a catalyst pellet with 1st order endothermic reaction [Temperature (°C), Concentration (mol/m³)].



(a) Temperature - microwave heating

(b) Concentration - microwave heating



(c) Temperature - conventional heating

(d) Concentration - conventional heating

Fig. 4. Profiles of temperature and concentration in a catalyst pellet with 1st order exothermic reaction [Temperature (°C), Concentration (mol/m^3)].

perature of bulk fluid outside the catalyst pellet are 1 and 80 °C, respectively. The initial dimensionless concentration and the initial temperature of the catalyst pellet are 0 and 20 °C, respectively. In the case of conventional heating, the parameter values used are the same as above except that the heat source term of microwave power in the catalyst pellet is 0, i.e., $\beta_{hom,2}$=0.0. The same conditions and parameters were used in the analysis of the 1st order exothermic reaction in the catalyst pellet under microwave heating and under conventional heating except for $\beta_{hom,3}$=4.0.

Fig. 3 shows the profiles of temperature and concentration in a catalyst pellet with the 1st order endothermic reaction under microwave and conventional heating, and Fig. 4 shows those with the 1st order exothermic reaction. Fig. 5 and Fig. 6 show steady-state profiles of both temperature and concentration in a catalyst pellet with the 1st order reaction. Because the dielectric property considered in the present study increases with temperature, the absorbed power by microwave heating at high temperature is larger than that at low temperature. Thus the temperature difference between microwave and conventional heating at the center of the catalyst pellet for exothermic reaction is larger than that for endothermic reaction. The difference between the temperature at the center of the spherical catalyst pellet and the temperature of the bulk fluid phase outside the catalyst pellet is in the range of 7-27 °C under microwave heating and −3-5 °C under conventional heating. Thus we can see that hot spots at the center of the catalyst pellet appear in the microwave heating for exothermic reaction. Microwave heating in exothermic reaction must be done carefully because possible hot spots may cause sintering and shrinkage of the catalyst pellet. If the catalyst pellet is not harmed by hot spots (i.e., no sintering and shrinkage of the catalyst pellet), hot spots increase the reaction rate in the catalyst pellet.

Table 1 shows the yield and the rate of the reaction under microwave and conventional heating of a catalyst pellet at the steady-state. When the catalyst is introduced in solid granular form, the yield and the rate of the heterogeneous reaction increase under microwave heating compared to conventional heating at the same reaction conditions (temperature, concentration and pressure). In Fig. 3 and Fig. 4, it is assumed that reagent reaches saturated concentra-

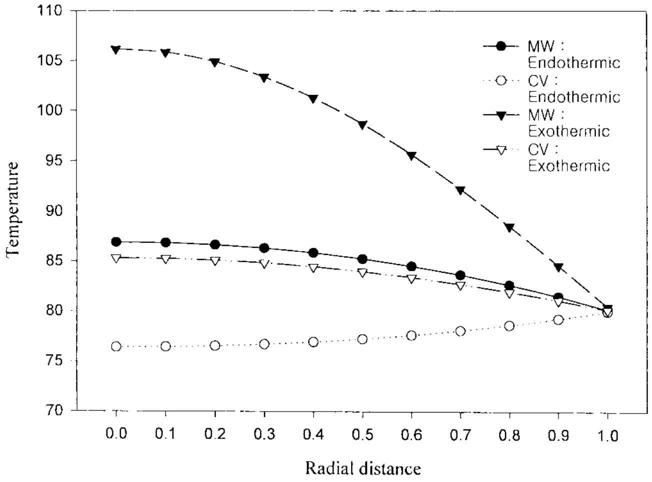


Fig. 5. Steady-state temperature profile in a catalyst pellet for 1st order reaction [Temperature (°C)].

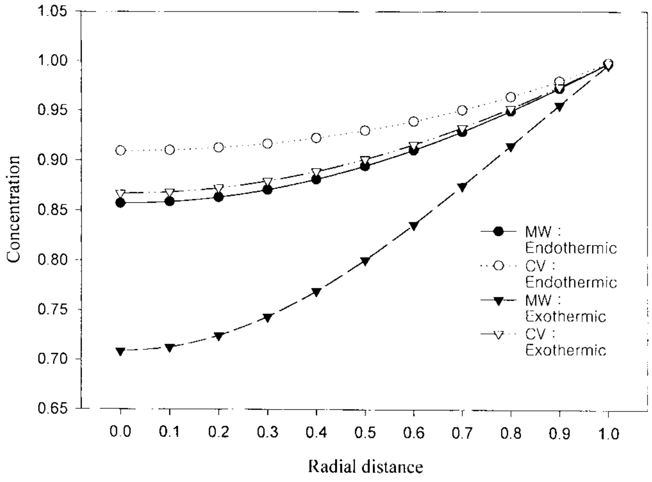


Fig. 6. Steady-state concentration profile in a catalyst pellet for 1st order reaction [Concentration (mol/m^3)].

tion uniformly in the catalyst pellet and is consumed as a result of chemical reaction. Thus the product yield can be calculated from the reagent concentration in the catalyst pellet at steady-state. If non-thermal microwave effects are ruled out, the increase in the reaction rate must be due to a difference in reaction temperatures. The reaction rate is related to the temperature of the catalyst pellet via the Arrhenius equation: $k_r=k_0\exp(-E_a/RT)$. In the present study, the frequency factor of 9×10^{12} m/s was used in the heterogeneous chemical reaction. We can see a relatively large amount of increase both in product yield and in the average reaction rate by microwave heating. The higher increase rate for exothermic reaction compared to endothermic is due to larger absorbed power at high temperature as stated before. This factor is true when the reaction is conducted in a heterogeneous medium and under microwave heating. Selective heating of the catalyst pellet creates hot spots, resulting in an increased reaction rate.

CONCLUSIONS

From modeling and simulations we could see that the temperature at the center of the pellet under microwave heating is higher than that under surface radiation. Thus we can see that uniform volumetric heating by microwave is more efficient than surface radiation with the same power deposition. When the heterogeneous chemical reaction under microwave heating is compared with that under conventional heating of the same bulk fluid conditions, the difference in the temperature at the center of pellet and the bulk fluid phase under microwave heating is larger than that under conventional heating. The difference depends on the temperature dependence of the dielectric property of the catalyst. In the model used in the present work, the difference in the temperature under microwave heating and under conventional heating for exothermic reaction is larger than that for endothermic reaction. With microwave heating, the reaction rate and the product yield increase compared to conventional heating under the same conditions. This is due to selective heating of the catalyst pellet creating hot spots, resulting in an increased reaction rate. In short, direct heating of catalysts by microwaves was found to be effective to enhance the reaction rate and the production yield.

ACKNOWLEDGEMENT

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NOMENCLATURE

A : constant in Eq. (5) and (6) [W/m^3]
B : constant in Eq. (5) and (6) [°C^{-1}]
Bi_H : Biot modulus of pellet for heat ($=h_{b,H}R_p/\lambda_{eff,p}$)
Bi_M : Biot modulus of pellet for mass ($=k_{b,M}R_p/D_{eff,p}$)
$c_{p,p}$: specific heat of catalyst pellet [J/kg K]
C_A : concentration of reactant molecules [mol/m^3]
C_b : concentration of reactant molecules in bulk fluid phase outside catalyst [mol/m^3]
C_p : concentration of reactant molecules in spherical catalyst pellet [mol/m^3]
$\overline{C}_p$: dimensionless concentration of reactant molecules in spher-

Table 1. Effect of the heating mode on the rate and the yield of the reaction under microwave (MW) and conventional (CV) heating of a catalyst pellet at steady-state

Reaction type	Product yield (%)			Average reaction rate k (10^{3}m/s)		
	MW heating	CV heating	Increase (%)	MW heating	CV heating	Increase (%)
1st order endo-thermic	9.2	6.1	52	0.73	0.46	59
1st order exo-thermic	17.9	8.6	107	1.55	0.68	128

ical catalyst particle (=C_p/C_b)
Da : parameter defined in Eq. (14) and (15) (=$k_{r0}\rho_p s_m$) [sec^{-1}]
$D_{eff,\,p}$: effective diffusivity in catalyst pellet [m^2/s]
E_a : activation energy of chemical reaction [J/mol]
$h_{b,\,H}$: heat transfer coefficient between catalyst pellet and bulk fluid [W/m^2 K]
($-\Delta H_{rxn}$) : heat of chemical reaction [J/mol]
$k_{b,\,M}$: mass transfer coefficient between pellet and bulk fluid outside catalyst [m/s]
k_{r0} : frequency factor for reaction [m/s]
Q_{MW} : absorbed heat per unit volume by microwave power [W/m^3]
$Q_{MW,\,p}$: absorbed heat per unit volume at catalyst pellet by microwave power [W/m^3]
Q_{SH} : flux density of radiation under surface radiation [W/m^2]
r_p : radial distance from the center of spherical particle [mm]
$\bar{r}_p$: dimensionless radial distance in spherical particle (=r_p/R_p)
R : gas constant [J/mol K]
R_p : radius of spherical catalyst pellet [mm]
s_m : specific surface area per unit mass of the solid [m^2/kg]
t : time [sec]
T_0 : reference temperature in equation (1.4) [°C]
T_b : temperature of bulk fluid phase outside catalyst [°C]
T_p : temperature of spherical catalyst pellet [°C]

Greek Letters
α_p : parameter defined in Eq. (14) (=$D_{eff,\,p}/R_p^2$) [sec^{-1}]
$\beta_{hom,\,1}$: parameter defined in Eq. (9) and (12) (=$\lambda_{eff,\,p}/\rho_p c_{p,\,p} R_p 2$) [°C/sec]
$\beta_{hom,\,2}$: parameter defined in Eq. (9) and (15) (=$A/\rho_p c_{p,\,p}$), [°C/sec]
$\beta_{hom,\,3}$: parameter defined in Eq. (15) (=$(-\Delta H_{rxn})C_b/\rho_p c_{p,\,p}$) [°C]
δ : penetration depth based on decay of heating rate [cm]
ε_0 : free space dielectric constant
ε''_{ei} : dielectric loss factor for the dielectric medium being heated
ε''_{Bi} : constant in Eq. (4)
$\lambda_{eff,\,p}$: effective conductivity in catalyst pellet [W/m K]
ρ_p : apparent density of the catalyst pellet [kg/m^3]
σ : Stefan-Boltzmann constant [$W/m^2\ K^4$]
τ : residence time of fluid in pore of catalyst pellet [sec]
χ_i : constant in Eq. (4)
ω : angular frequency for microwave applicator

Subscripts
a : active site phase
b : bulk
eff : effective
g : gas
hom : homogeneous mode
H : heat transfer
m : per mass
M : mass transfer
MW : microwave
p : pellet
rxn : reaction
RD : radiation
s : support-fluid phase
SH : surface radiation

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