ELSEVIER

Characteristics of surface reaction and heat transfer in a catalytic heat exchanger

Yong-Seog Seo*, Nam-Jo Jeong, Kwang-Sup Song

Korea Institute of Energy Research, 71-2 Jang-dong Yusung-gu, Taejon 305-343, South Korea

Abstract

The characteristics of a catalytic heat exchanger which can integrate heat generation and heat exchange were numerically investigated. The catalytic heat exchanger was modeled in a three-dimensional, steady state and laminar flow system, including the surface reaction on catalytic fins. The surface reaction was modeled with one-step reaction incorporating the diffusion effect on the catalysts. The surface reaction on catalytic fins was significantly influenced by the heat transfer rate in fin tubes. In order to achieve both the complete conversion of the mixture and the efficient recovery of heat generated, the results suggest that the surface reaction should be completed in the first stage of the catalytic heat exchanger and the second stage should function only as a heat recovery. The effects of the catalytic fin configuration on the catalytic combustion performance were also investigated at a variety of operating conditions.
© 2003 Elsevier Science B.V. All rights reserved.

Keywords: Catalytic fin; Catalytic heat exchanger; Surface reaction; Kinetics; Numerical simulation

1. Introduction

To supply hot water or air at various places, a boiler and a heat exchanger are basically required. These two facilities are essential to obtain the necessary heat energy from the primary fuel. The catalytic heat exchanger can, however, integrate heat generation and heat exchange into one equipment and can replace the boiler and heat exchanger. For instance, the catalytic fin tube that is a key component in the catalytic heat exchanger can play roles of the heat generation as well as the heat exchange. The mixture of fuel-air reacts on the surface of catalytic fin tubes and then the generated heat is transferred from the catalytic surface to air or water inside catalytic fin tubes. Accordingly, the catalytic heat exchanger can be more compact and cost-effective compared to the conventional boiler and heat exchanger system. It is also expected that the catalytic heat exchanger barely emits pollutants because the catalytic combustion has the advantage of ultra-low NO_x emission [1–4].

The catalytic heat exchanger can be fabricated into several types of configurations. One is shown in the early patent [5], which is very similar with a shell-and-tube heat exchanger except employing the catalyst bed. As an example, a shell side is packed with catalytic pellets or spheres through which catalytic combustion occurs, and the generated heat is transferred to the working fluid in the tube side. Other type is the one employing form-type catalysts in a double piped heat exchanger. To increase the rate of heat transfer in this type of catalytic heat exchanger, metal form catalysts are mostly preferred. Ismagilov et al. [6] have developed the metal form catalyst and used it to fabricate a compact catalytic heat exchanger.

Another type of the catalytic heat exchanger is the one comprised of fin tubes whose fin surfaces are catalyzed. The work done by Seo et al. [7] is a typical example of the catalytic heat exchanger using catalytic fin tubes. They have developed the catalytic heat exchanger adopting high fin tubes made of SUH 409 (11.0 Cr, 1.0 Ti, 0.06 C, Fe balance). One of the core technologies in developing catalytic fin tubes is to select the metal suitable to coat catalysts on its surface, and to catalyze its surface. Once the fin tube is successfully catalyzed, then the appropriate design technology for the catalytic heat exchanger is required to obtain the best performance in both the heat generation and the heat transfer. To investigate the characteristics of heat generation and heat transfer in catalytic fin tubes, the catalytic fin has been studied by some researchers [8–12].

Griffin and Wood [8] investigated experimentally the heat and mass transfer over a catalytic plate surface, where there is no heat extract. They classified the kinetic control and mass transfer control regions at a variety of operation

* Corresponding author. Tel.: +82-42-860-3612; fax: +82-42-860-3134.
E-mail address: ysseo@kier.re.kr (Y.-S. Seo).

conditions by analyzing the temperature distribution at the catalytic plate. Recently, they extended the investigation to a catalytic fin from whose one side the heat is extracted by attaching a cooling pipe [11]. They found that the heat flux from the fin edge to the cooling pipe was sensitive to the fuel concentration, free stream temperature, sink temperature and free stream velocity, and all these parameters must be considered in the design of an industrial catalytic heater.

Another research group [12] investigated numerically on gas-phase ignition over a wedge-type catalytic plate, whose temperatures were assumed to be adiabatic or external cooling. They derived an explicit criterion of ignition including the properties of working fluid and flow system, and showed that the ignition region for an adiabatic wall is greater than that for external cooling. Their results imply that the external cooling is an influential parameter for catalytic ignition and catalytic combustion performance, which stimulates one to investigate in more depth about the effect of heat transfer from the catalytic fin where surface reaction occurs.

The objective of the present study is to numerically investigate the characteristics of the catalytic heat exchanger fabricated with catalytic fin tubes. Most of previous works on catalytic fin tubes have treated only a single fin tube, but the present study handles a multi-fin tube system. As described above, the catalytic heat exchanger may have quite different features from the conventional heat exchanger because the heat transfer is coupled with the surface reaction. When designing the conventional heat exchanger without surface reaction, the heat transfer and the mechanical strength are important factors. However, when designing the catalytic heat exchanger, besides the heat transfer and the mechanical strength, the surface reaction should be carefully considered.

In the present study, the numerical simulation were conducted to investigate the characteristics of the surface reaction and the heat transfer in the catalytic heat exchanger. Because the heat generation and the heat transfer are coupled each other, the influence of the rate of heat transfer on the catalytic combustion is investigated in detail. The effects on the catalytic combustion performance of the catalytic fin configuration such as fin thickness and fin number are also analyzed. For the numerical calculation a commercial software FLUENT [13] is employed and the surface reaction on catalytic surface is treated by means of its user-defined function.

2. Mathematical model of the fin tube

The numerical simulation of the catalytic heat exchanger is performed in a three-dimensional, steady state and laminar flow system, including the surface reaction on the catalytic fin. The numerical model handles the coupling of the mixture flow in gas phase and the surface reaction on the fin tube. The governing equations for the mixture flow are written as follows.

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i \tag{2}$$

Energy equation:

$$\frac{\partial}{\partial x_i}(\rho u_i(\rho E + p))$$
$$= -\frac{\partial}{\partial x_i}\left(c\frac{\partial T}{\partial x_i} + \sum_k h_k J_k + u_j(\tau_{ij})\right) + \sum_k h_k R_{g,k} \tag{3}$$

Species equation:

$$\frac{\partial}{\partial x_i}(\rho u_i m_k) = -\frac{\partial}{\partial x_i}J_{k,i} + R_{g,k} \tag{4}$$

State equation:

$$p = \rho R T \sum_k \frac{Y_k}{W_k} \tag{5}$$

In Eqs. (1)–(5), ρ is density, u_i velocity, p pressure, τ_{ij} stress tensor, g_i gravitational force, E internal energy, c thermal conductivity, T temperature, h_k the enthalpy of species k, J_k the diffusion flux of species k, m_k the mass fraction of species k, $R_{g,k}$ the gas reaction rate of species k, R universal gas constant, Y_k the mole fraction of species k, and W_k the molecular weight of species k.

In Eq. (3), the stress tensor τ_{ij} is given by

$$\tau_{ij} = \left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - \frac{2}{3}\mu\frac{\partial u_l}{\partial x_l}\delta_{ij} \tag{6}$$

where μ is the molecular viscosity and the second term on the right hand side is the effect of volume dilation.

In Eq. (3), the internal energy E is given by

$$E = h - \frac{p}{\rho} + \frac{u_i^2}{2} \tag{7}$$

In Eq. (4), the diffusion flux $J_{k,i}$ is given by

$$J_{k,i} = -\rho D_{k,i}\frac{\partial m_k}{\partial x_i} \tag{8}$$

where $D_{k,m}$ is the diffusion coefficient for species k in the mixture.

Boundary conditions are given by the followings.
Inlet conditions:

$$T = T_o, \quad u_i = u_{i,o}, \quad m_k = m_{k,o}$$

where the subscript 'o' refers to the initial condition.
Outlet conditions:

$$\frac{\partial T}{\partial x} = 0, \quad \frac{\partial u_i}{\partial x} = 0, \quad \frac{\partial m_k}{\partial x} = 0$$

Conditions at the catalytic surface:

$$J_k \cdot \boldsymbol{n} = R_{w,k} \tag{9}$$

$$k \left(\frac{\partial T}{\partial x_i} \cdot \boldsymbol{n} \right) + \sum_k h_k (J_k \cdot \boldsymbol{n}) = \sum_k h_k R_{w,k} \tag{10}$$

where $\boldsymbol{n}$ is a unit vector normal to the catalytic surface and $R_{w,k}$ the surface reaction rate of species k.

The surface reaction of CH_4 can be written as the following one-step reaction (Eq. (11)). The surface reaction rate of CH_4 over the catalytic surface deposited with Pd catalyst is calculated with Eq. (12), proposed by Hayes and Kolaczkowski [14]:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{11}$$
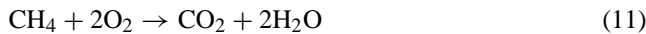
$$R_w = \eta A_w \exp \left(-\frac{E_w}{RT} \right) [Y_{CH_4}]^{0.72} \tag{12}$$

where η is the effectiveness factor, R_w the surface reaction rate of CH_4 (kg/m^{2}s), A_w the pre-exponential coefficient (2.84×10^5 kmol/m^{2}s), E_w the activation energy (1.31×10^8 J/kmol), R the universal gas constant and Y_{CH_4} the mole fraction of CH_4.

The effectiveness factor in Eq. (12), η, addresses the diffusion effect of reactants in the washcoat, which can be calculated by Eqs. (13) and (14), as derived by Leung and Hayes [15]:

$$\eta = (1 + 0.87\phi^{1.33})^{-0.75} \tag{13}$$

$$\phi = \left(\frac{L_c k_s RT}{D_{eff} p Y_{CH_4}^{0.28}} \right)^{0.5} \tag{14}$$

where L_c is the thickness of the washcoat (20.0×10^{-6} m), p the pressure, R the universal gas constant, k_s the rate constant based on catalyst surface area (Eq. (15)) and D_{eff} is the effective diffusion coefficient in the washcoat (Eq. (16)):

$$k_s = A_w \exp \left(-\frac{E_w}{RT} \right) \tag{15}$$

$$D_{eff} = 0.125 \left(\frac{1}{D_{ab}} + \frac{1}{D_k} \right)^{-1} \tag{16}$$

In Eq. (15), A_w and E_w are the same as those used in Eq. (12). D_{ab} and D_k in Eq. (16) are the bulk diffusion coefficient ($9.87 \times 10^{-10} T^{1.75}$) and the Knudsen diffusion coefficient ($6.0625 \times 10^{-8} T^{0.5}$) in the washcoat.

The computational domain and grid system for the catalytic heat exchanger are shown in Fig. 1(a) and (b). In the domain, x-coordinate corresponds to the stream-wise of the mixture, y- and z-coordinate along the height and width of the catalytic heat exchanger. A grid system is composed of hexahedron and triangular prism cells, whose number amounts to about 85,000. To solve governing Eqs. (1)–(5), FLUENT software [13] was used. The stream-wise velocity and temperature at the inlet boundary of the computational
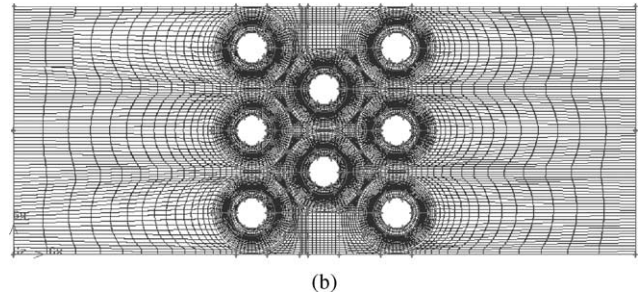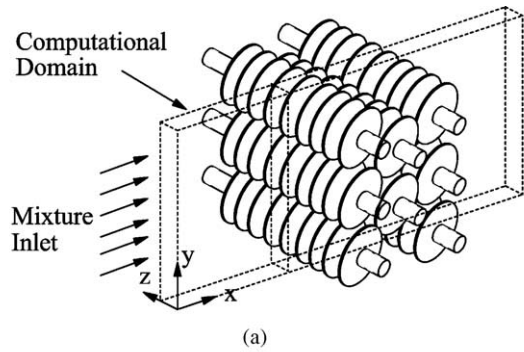

Fig. 1. (a) Computational domain used to model the catalytic heat exchanger and (b) grid system shown in xy-plane. Only one fin array is selected to model the catalytic heat exchanger of which the x-coordinate is along the main stream-wise.

domain are assumed to be uniform. The velocity components in the y and z directions at the inlet boundary are assumed to be zero. It is also assumed that the radiation heat transfer from the catalytic surface is negligible.

The surface reaction is initiated when the temperature of the fin surface reaches the ignition temperature of the surface reaction. Thus, the mixture of air and fuel supplied at the room temperature should be heated to the ignition temperature of catalytic reaction by means of an external heating device. Once the surface reaction starts, the mixture flowing over the catalytic fin surface is heated by the heat generated from the surface reaction. If the mixture is heated higher than its flame ignition temperature, the gas reaction is initiated. In this case, the gas reaction and the surface reaction coexist in the flow. However, if most of the mixture is burned by the surface reaction before the gas reaction starts, the gas reaction can be neglected. The present numerical calculation treats only the surface reaction as the gas reaction can be negligible.

3. Results and discussion

Before proceeding with the analysis, we checked the validation of model predictions with the experimental data, which is provided elsewhere [16]. Fig. 2(a) shows the comparison between the calculation and the experiment about the catalytic combustion performance as a function of the inlet velocity. Comparing the predicted values with the
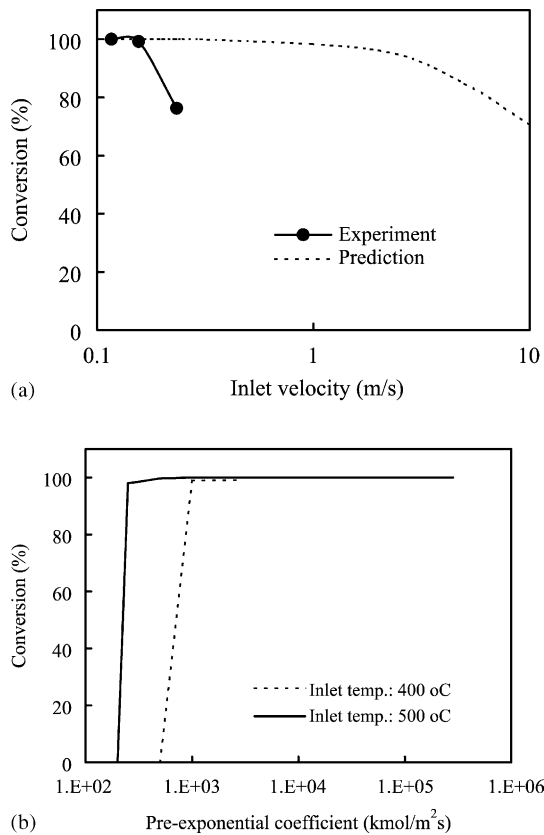
Fig. 2. (a) Comparison between the predicted and experimental conversions as a function of the inlet velocity at an inlet temperature of 500 °C and an equivalence ratio of 0.267 and (b) predicted conversions with regard to pre-exponential coefficient at an equivalence ratio of 0.267 and an inlet velocity of 0.19 m/s.

measured data shows quite a lot of discrepancy except for the agreement only in their trends. The measured conversions decrease drastically at an inlet velocity >0.2 m/s, whereas the calculated data maintain 100% until an inlet velocity of 1.0 m/s, followed by gradual decrease. The calculation shows much higher catalytic combustion performance at the inlet velocity of over 0.2 m/s than the experiment. Many parameters can be regarded as the reason for this discrepancy. However, the present study checked only the effects of the pre-exponential coefficient in Eq. (12) on the catalytic combustion performance, since previous studies reported very different values for the pre-exponential coefficient. For example, Lyubovsky and Pfefferle [17] reviewed that the pre-exponential coefficient varied by orders of magnitude, while the activation energy for the reaction varied by a factor of 3.

Fig. 2(b) shows the predicted conversions as a function of the pre-exponential coefficient. The pre-exponential coefficient has a significant effect on the conversions. Especially, the conversion is very sensitive to the pre-exponential coefficient in the range of 200–1000 kmol/m²s. These suggest that to obtain the reliable results in the numerical calculation including surface reaction, the appropriate empirical formula

on the rate of surface reaction is one of critical factors. The analysis hereafter uses Eq. (12) in calculating the rate of surface reaction, since no kinetic data is provided for the Pd catalyst related with the experimental data in Fig. 2(a). Eq. (12) was derived from the Pd catalyst deposited on the ceramic honeycomb, whereas the catalyst related with the experimental data in Fig. 2(a) is the Pd catalyst deposited on the metal surface.

The catalytic combustion performance was first investigated with respect to the heat transfer rate in the fin tube. Figs. 3 and 4 show the mass fraction distribution of methane on the catalytic fin surface at each heat transfer rate. The heat transfer rate is set to the internal surface of fin tubes in convective heat transfer rate (W/(m² K)), which is a part of the boundaries in the computation domain. The calculation is performed in the range of 0.0–200.0 W/(m² K), which corresponds to the heat transfer rate for the air or water flow inside the fin tubes as a working fluid.

In the case of 0.0 W/(m² K), (a) in Figs. 3 and 4, the conversion is calculated to be 99.3% and most of the mixture is burned in the front part of fin tubes as shown in the figures. It means that only the front part is functioned as a catalytic surface to generate heat, whereas the rear part participates only in heat transfer with no surface reaction. This is not desirable from the point of view that the catalytic fins should be fully used for catalytic reaction without any redundant part. On the other hand, (b) and (c) in Figs. 3 and 4 refer to the cases of 100.0 and 200.0 W/(m² K) in heat transfer rate, respectively. The mass fraction of methane at the rear part rises with increasing heat transfer rate. The reason for this is that as the rate of heat transfer increases, the rate of surface reaction on fin surface is suppressed due to the lower surface temperature dropped by more heat removal. Thus, the excessive heat removal from catalytic surface may cause the mixture to be incompletely burned, resulting in unburned hydrocarbons and the low conversion of mixture. This fact is clearly shown in Fig. 4(c), where the last catalytic fin tube (Fin #5) has some degree of methane on its surface. As a result, in the case of (c) where the rate of heat transfer is set to 200.0 W/(m² K), the conversion declines to 93.6%, not reaching the complete conversion. Through the analysis for three different rates of the heat transfer, it can be known that there is an optimal condition satisfying both of the complete conversion of the mixture and the efficient recovery of the generated heat.

Fig. 5 shows the predicted conversions at a variety of operating conditions. As seen in the Fig. 5(a), the conversion declines with increasing heat transfer rate at each inlet temperature. At the lower inlet temperature, the conversion is more significantly affected by the heat transfer rate. This is because when the heat removal from the catalytic fin at each inlet temperature is assumed to be the same for a fixed heat transfer rate, the case of lower inlet temperature has lower surface temperature, so that the rate of surface reaction drops more significantly with lower inlet temperature. Fig. 5(b) represents the influence of the heat transfer
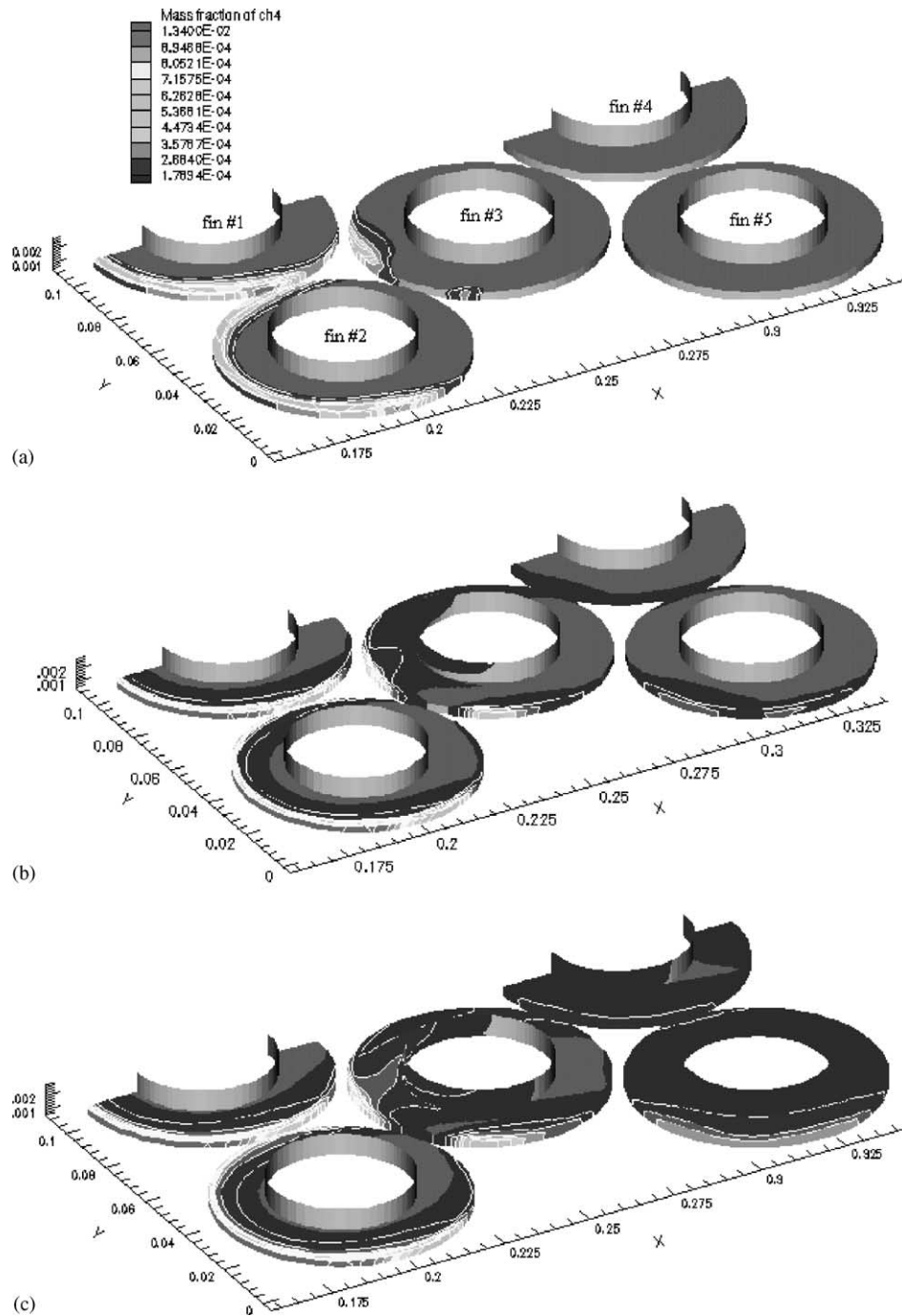
Fig. 3. Mass fraction distributions of methane on the catalytic fin surface at each heat transfer rate. The inlet temperature, inlet velocity and equivalence ratio are set to 500 °C, 1.0 m/s and 0.267, respectively. (a) heat transfer rate, $h = 0.0$ W/(m^2 K); (b) $h = 100.0$ W/(m^2 K) and (c) $h = 200.0$ W/(m^2 K).

rate on the conversion of the mixture at each inlet velocity. In the case of an inlet velocity of 0.19 m/s, the conversion reaches a maximum, ca. 100%, at the low heat transfer rate of 0.0–50.0 W/(m^2 K), but it decreases steeply with the heat transfer rate of more than 50 W/(m^2 K), and finally it drops to zero, the extinction of the surface reaction. The cases of an inlet velocity of 1.0 and 5.0 m/s show different pattern in the conversion from the previous one, 0.19 m/s. For these two cases, even if the heat transfer rate affects the conversion, its influence is very slight. The inlet velocity is a parameter determining the quantity of mixture flow to which the chemical reaction energy is proposal, so the higher inlet velocity contains larger chemical reaction energy. Therefore, the case of higher inlet velocity is less affected by the heat transfer rate, which leads to nearly constant conversion as shown in the Fig. 5(b).
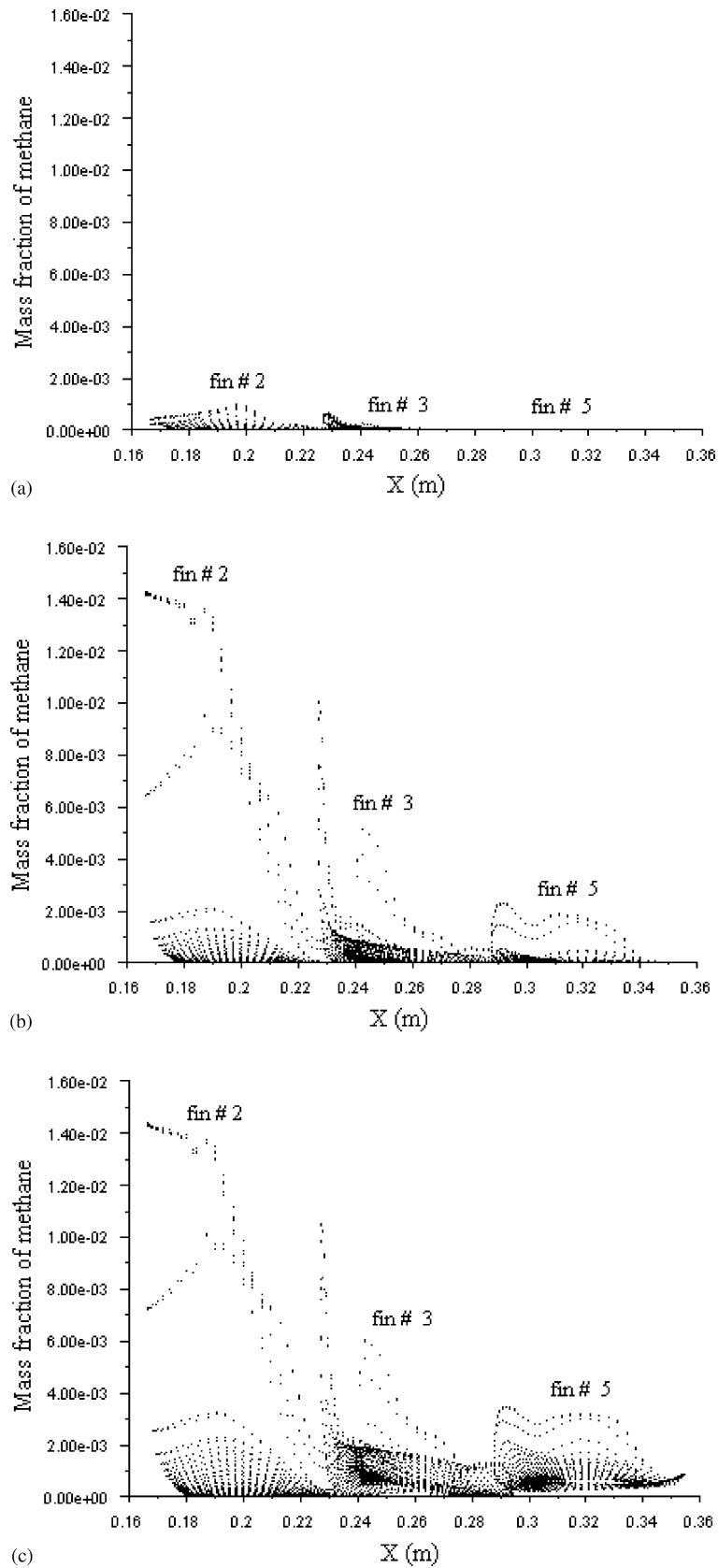
Fig. 4. Mass fraction distribution of methane plotted with scattered data at each heat transfer rate. The inlet conditions for the calculation are the same as those in Fig. 3, (a) heat transfer rate, $h = 0.0\,\mathrm{W/(m^2\,K)}$; (b) $h = 100.0\,\mathrm{W/(m^2\,K)}$ and (c) $h = 200.0\,\mathrm{W/(m^2\,K)}$.
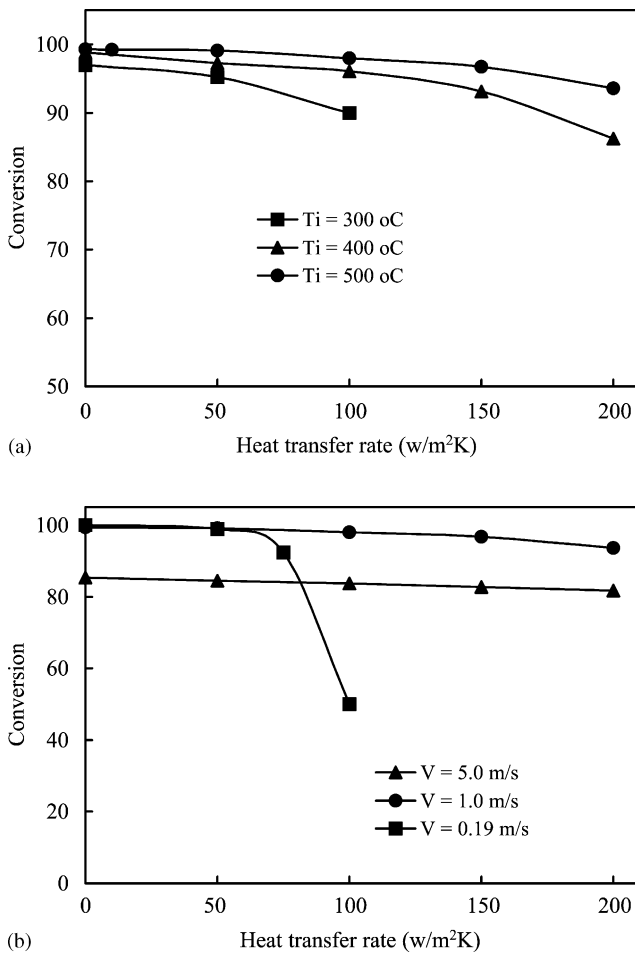
Fig. 5. Effects on the conversion of the heat transfer rate which is set to the fin tube as a boundary condition.

The temperature of catalytic surface is one of important factors in designing the catalytic heat exchanger, because the surface temperature determines directly the thermal stability of catalysts coated on fin surfaces. Fig. 6 shows the temperature distributions on the fin surface at each heat transfer rate, where (a) corresponds to the adiabatic condition, that is, no heat transfer through fin tubes. In the case (a), temperatures are the same all over the catalytic fins except for the starting point of catalytic reaction that is located at the front of the first catalytic fin, Fins #1 and #2. The constant temperature distribution in the adiabatic condition would be easily expected. Its maximum temperature reaches up to 1426 K, which agrees with the adiabatic flame temperature for the mixture of methane and air at an equivalence ratio of 0.267. Such a high temperature is likely to damage the catalysts by sintering catalytic material, so that an alternative to reduce the high temperature on catalytic surface is required.

Fig. 6(b) and (c) represent the temperature distributions on the fin surface for 100.0 and 200.0 W/(m^2 K) in heat transfer rate, respectively. The surface temperatures drop significantly compared to Fig. 6(a). Maximum temperature appears at the first catalytic fins, Fins #1 and #2, and mini-

mum temperature does at the last catalytic fin, Fins #4 and #5. Surface temperatures range 837–1269 K for the case (b) and 606–1171 K for the case (c). When the maximum temperature suitable to the Pd catalyst is assumed to be <800 °C (1073 K), the case (b) seems to be too high in surface temperature and the case (c) to be some reasonable even though its maximum temperature is slightly higher than 800 °C. Another thing to consider here is about a minimum surface temperature. If the surface temperature drops lower than the temperature to sustain the catalytic reaction, the catalytic combustion comes to extinguish. When investigating whether or not the catalytic combustion is maintained on the fin surface, the case (c) reveals to have catalytic fins where the catalytic combustion is almost extinguished, which can be confirmed from Fig. 4(c).

Fig. 7 shows the scattered plot of surface temperatures at each heat transfer rate. The figure shows the overall view of the temperature distribution at each operating condition. It is shown that the larger heat transfer rate causes the wider distribution of the surface temperature. When comparing the temperature distributions in the Fin #2 between the cases (a) and (b), it is revealed that the case (b) with the larger heat transfer rate has the wider distribution in the surface temperature. The same trend appears in other fins between two cases. It implies that the excessive heat transfer rate can decrease the surface temperature at such a low level that the surface reaction is extinguished. This is found in the rear part of the fin tubes in the case (b), where the surface temperature drops to 606 K. Accordingly, the appropriate heat transfer rate should be cautiously selected in order to achieve both the complete conversion of the mixture and the efficient recovery of the generated heat.

As a result of investigating the characteristics of the surface reaction coupled with the heat transfer, it is found that the previous design concept of the catalytic heat exchanger, which was suggested by Seo et al. [7], should be modified so that the surface reaction can be integrated successfully with the heat transfer. The previous system was designed in such a way that it was composed of two stages and the surface reaction was maintained even at the second stage. But this design is likely to bear the drawback in the heat recovery even though the mixture is completely combusted, because the surface temperature on fin tubes of the second stage should be maintained at more than the minimum temperature to sustain the surface reaction. Thus, it is recommended that the catalytic combustion should be completed in the first stage and the second stage be only in charge of the heat recovery. In other words, the first stage is used for the surface reaction coupled with the heat transfer and the second one only recovers the heat produced in the first stage, which can achieve effectively the complete combustion of the mixture and the efficient heat recovery.

As the next step, the influence of the catalytic fin configuration on the catalytic combustion is analyzed, for which only one fin tube in the computational domain shown in Fig. 1, which is composed of eight fin tubes, is modeled. As
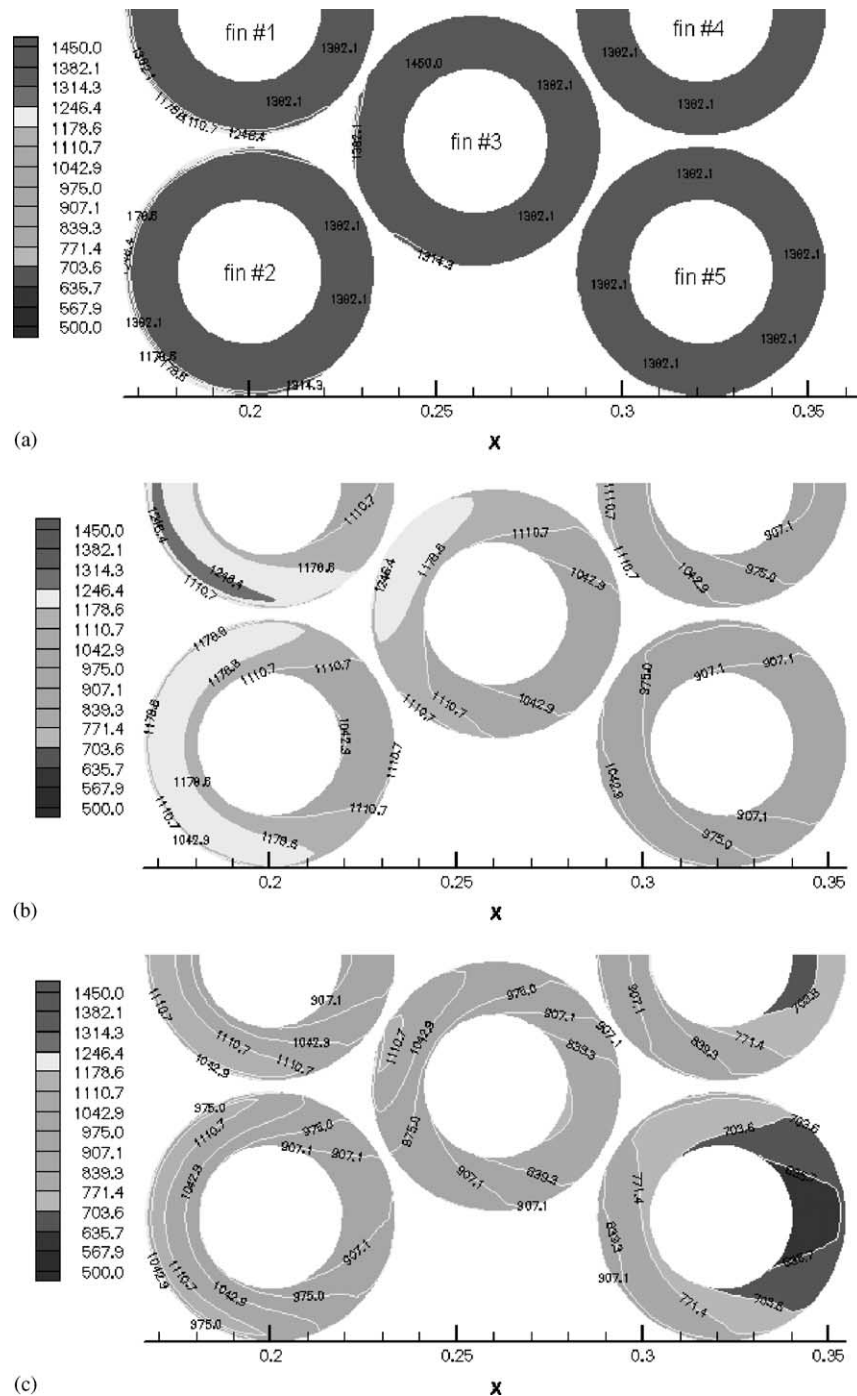
Fig. 6. Temperature distributions on the catalytic fin surface at each heat transfer rate. The inlet conditions for the calculation are the same as those in Fig. 3, (a) heat transfer rate, $h = 0.0\,W/(m^2\,K)$; (b) $h = 100.0\,W/(m^2\,K)$ and (c) $h = 200.0\,W/(m^2\,K)$.

important factors in the configuration of the fin tube, there are fin thickness and fin number. In the case of conventional fin tubes without catalytic reaction, there are a lot of design data on its fin configuration. For the catalytic fin tube, however, few design data is reported. Thus, we analyze the effects of fin thickness on the catalytic combustion in the catalytic heat exchanger. The calculated results about the conversion of the mixture and the exit temperature are shown

in Fig. 8. As the fin thickness is raised while the fin number is fixed to 6 pieces/in., the conversion appears to decrease. For example, the conversion diminishes from 88 to 70% as the fin thickness increases from 1.0 to 3.0 mm. If the thickness becomes over 2.0 mm, the conversion diminishes more steeply. From the point of view in designing the catalytic heat exchanger, the results recommend that the fin thickness should be as thin as possible within the allowable mechanical
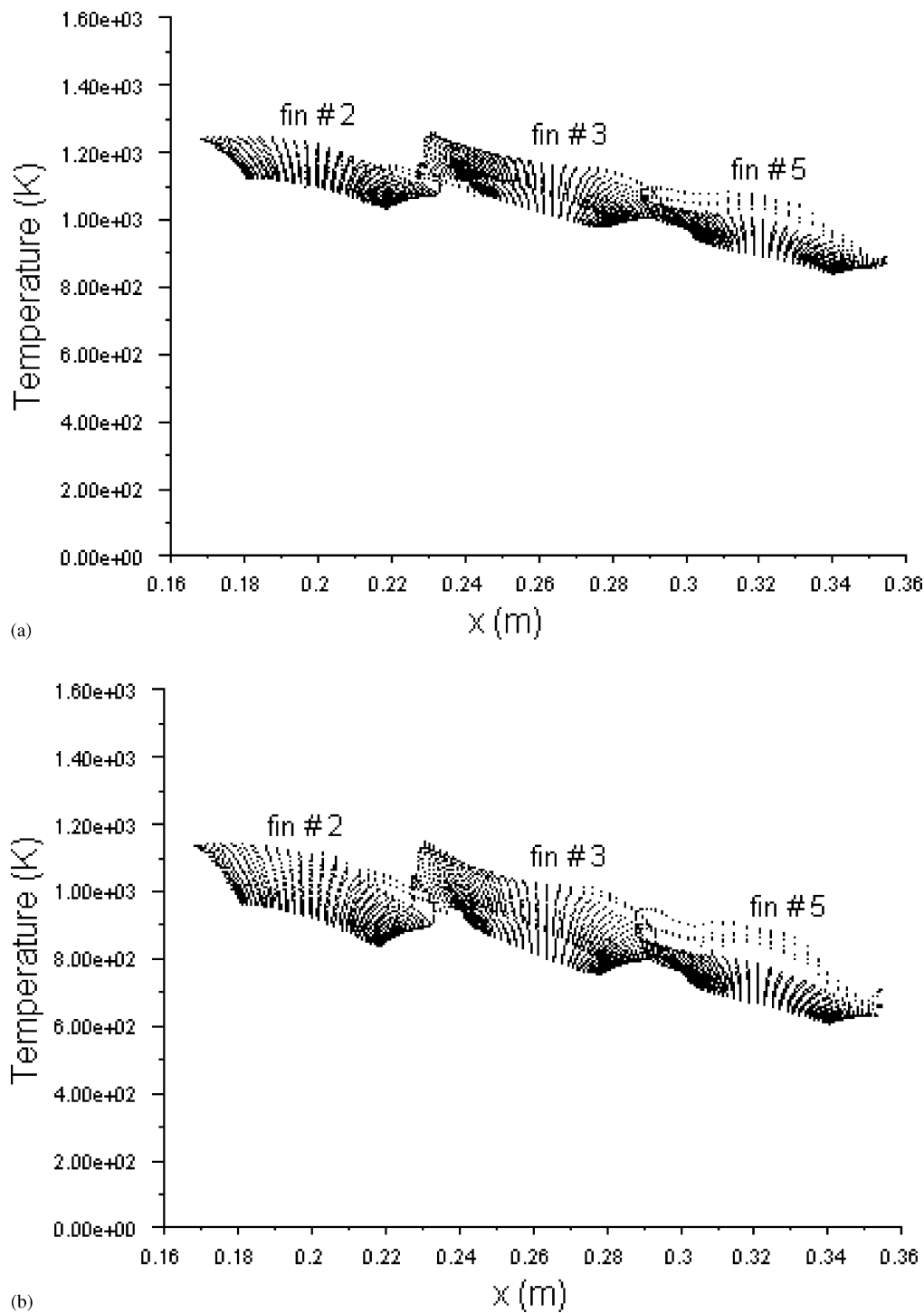
Fig. 7. Temperature distributions plotted with scattered data at each heat transfer rate. The inlet conditions for the calculation are the same as those in Fig. 3, (a) heat transfer rate, $h = 100.0\,\text{W/(m}^2\,\text{K)}$ and (b) $h = 200.0\,\text{W/(m}^2\,\text{K)}$.

strength of the catalytic fin. The mixture temperature at the exit also decreases with the increase of the fin thickness, which agrees well with the trend of the conversion.

The influence of fin number on catalytic reaction is investigated with a fin thickness of 1.0 mm as shown in Fig. 9. The calculated results show that the conversion rises steeply with increasing fin number in the range of 4–6 fin numbers. However, in the fin number of over 6 pieces, the conversion reaches a maximum and stays constant regardless of the further increase of fin number. The exit temperatures also show a similar trend with the conversion of the mixture. As a result of these investigations on the catalytic fin configuration, the
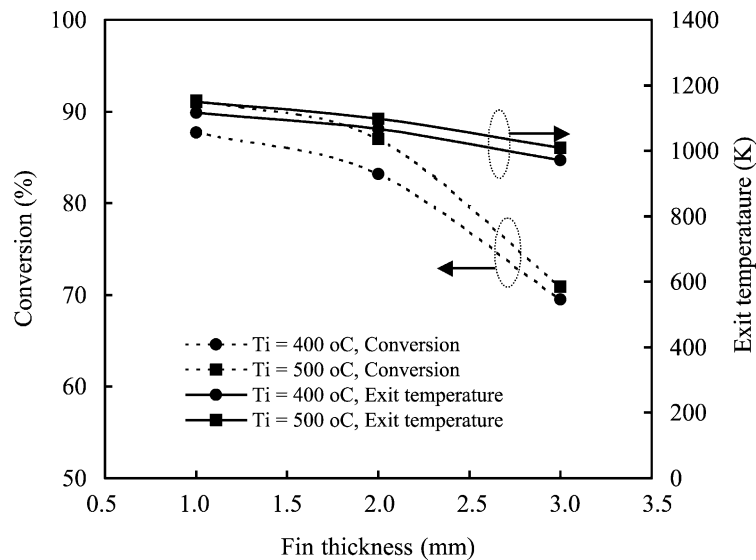
Fig. 8. The effects of the catalytic fin thickness on the conversion and the exit temperature of the catalytic heat exchanger. The fin number is fixed to 6 pieces/in., and the inlet conditions for the calculation are set to a velocity of 0.19 m/s, an equivalence ratio of 0.267 and a heat transfer rate of 20.0 W/(m^2 K).
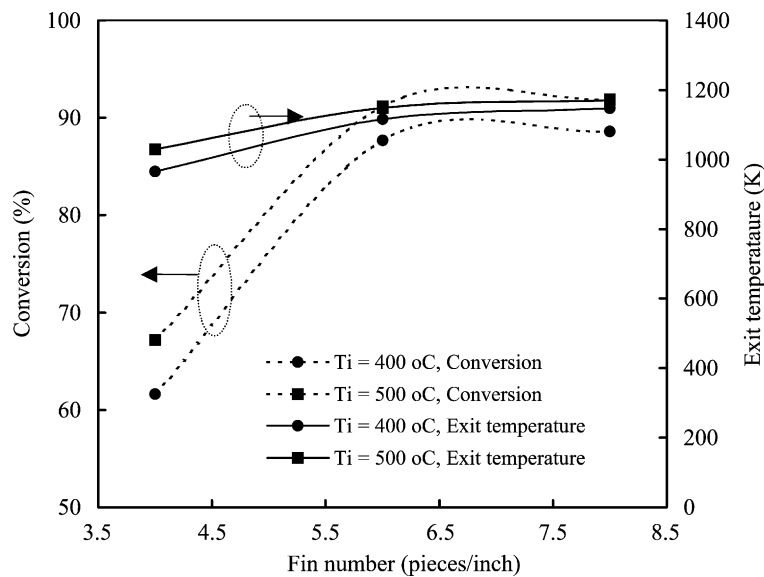

Fig. 9. The effects of the catalytic fin number on the conversion and the exit temperature of the catalytic heat exchanger. The fin thickness is fixed to 1.0 mm, and the inlet conditions for the calculation are set to a velocity of 0.19 m/s, an equivalence ratio of 0.267 and a heat transfer rate of 20.0 W/(m^2 K).

fin number and the fin thickness are revealed to be parameters affecting significantly the catalytic combustion performance. In order to achieve the best performance in the catalytic heat exchanger, the results of Figs. 8 and 9 recommend that the fin number and the fin thickness should be designed to be over 6 pieces/in. and less than 1.0 mm, respectively.

4. Conclusions

The characteristics of the catalytic heat exchanger which can integrate the heat generation and the heat exchange into

one equipment have been numerically investigated. The catalytic heat exchanger was modeled in a three-dimensional, steady state and laminar flow system, including the surface reaction on catalytic fins. The rate of surface reaction was calculated with one-step reaction considering the effectiveness within the catalytic washcoat.

The surface reaction on catalytic fins was significantly influenced by the heat transfer rate in fin tubes. The higher rate of the heat transfer in the fin tubes causes more heat removal from the catalytic fins, which suppresses the surface reaction, resulting in the lower conversion of the mixture. In order to achieve both the complete conversion of the mixture

and the efficient recovery of heat energy generated, the results suggest that the surface reaction should be completed in the first stage of the catalytic heat exchanger and the second stage should function only as a heat recovery. The effects of the catalytic fin configuration on the catalytic combustion performance have also been investigated at a variety of operating conditions. The results show that the conversion rises with increasing fin number and decreasing fin thickness.

Acknowledgements

References

[1] J. Saint-Just, J. Kinderen, Catalytic combustion: from reaction mechanism to commercial application, Catal. Today 29 (1997) 387–395.

[2] Y.S. Seo, S.K. Kang, H.D. Shin, Catalytic combustion of lean premixed mixture in catalytically stabilized thermal combustion, Combust. Sci. Technol. 145 (1999) 17–35.

[3] K.W. Beebe, K.D. Cairns, V.K. Pareek, S.G. Nickolas, J.C. Schlatter, T. Tsuchiya, Development of catalytic combustion technology for single-digit emissions from industrial gas turbines, Catal. Today 59 (2000) 95–115.

[4] A. Schlegel, P. Benz, T. Griffin, W. Weisenstein, W. Bockhorn, Catalytic stabilization of lean premixed combustion: method for improving NO_x emissions, Combust. Flame 105 (1996) 332–340.

[5] R.A. Clyde, Catalytic heat exchanger, US Patent No. 4420462 (1983).

[6] A.R. Ismagilov, V.V. Pushkarev, O.Y. Podyacheva, N.A. Korabkina, H. Veringa, A catalytic heat-exchanging tubular rector for combining of high temperature exothermic and endothermic reactions, Chem. Eng. J. 82 (2001) 355–360.

[7] Y.S. Seo, K.S. Song, S.K. Kang, S.J. Cho, H.J. Jung, I.S. Ryu, S.P. Ryu, Development of the hybrid heat exchanger using catalytic combustion, Research report KIER-A03917, Korea Institute of Energy Research, 2001.

[8] G.J. Griffin, D.G. Wood, Combustion of a gas flowing over a catalytic flat surface: experimental investigation of heat and mass transfer, Appl. Catal. A: Gen. 138 (1996) 235–244.

[9] G.J. Griffin, D.G. Wood, Investigation of catalytic combustion within a fin boundary layer, Combust. Flame 118 (1999) 3–12.

[10] G.J. Griffin, D.G. Wood, Modeling of the catalytic combustion of lean fuel flowing over a fin with heat extraction from the trailing edge, Catal. Today 63 (2000) 387–395.

[11] G.J. Griffin, D.G. Wood, Non-adiabatic catalytic combustion at a fin surface involving heat extraction from the fin edge, Combust. Flame 125 (2001) 1230–1238.

[12] W.J. Sheu, M.C. Lin, Gas-phase ignition of accelerated boundary-layer flows on strongly catalytic surfaces, Combust. Flame 103 (1995) 161–170.

[13] Fluent software, FLUENT User's guide, Fluent Incorporated, http://www.fluent.com, 2002.

[14] R.E. Hayes, S.T. Kolaczkowski, Introduction to Catalytic Combustion, Gordon and Breach, London, NY, 1997, pp. 169–170.

[15] D. Leung, R.E. Hayes, Diffusion limitation effects in the washcoat of a catalytic monolith reactor, Can. J. Chem. Eng. 74 (1966) 94–103.

[16] Y.S. Seo, S.P. Yu, S.J. Cho, K.S. Song, The catalytic heat exchanger using catalytic fin tubes, Chem. Eng. Sci. 58 (2002) 43–53.

[17] M. Lyubovsky, L. Pfefferle, Complete methane oxidation over Pd catalyst supported on α-alumina, Catal. Today 47 (1999) 29–44.