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Performance of Methane Steam Reforming in Internal Spiral Finned Tube

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ABSTRACT

Methane steam reforming is an important method of hydrogen production. In this study, the performance of methane steam reforming in internal spiral fin structure reactors through the equivalent medium method has been investigated. The efficiencies of different structure reactors have been compared in same boundary conditions. It is found that internal spiral fin structure reactors can improve the efficiency of methane steam reforming. Methane conversion rate of the structure S40 increased by up to 2% compared with the structure Normal. Hydrogen production rate of the structure S40 increased by up to 0.3% compared with the structure Normal.

Keywords: Hydrogen, Methane steam reforming, Internal spiral finned tube, Methane conversion efficiency

NOMENCLATURE

Abbreviations	
H120	Screw pith 120mm structure
H80	Screw pith 80mm structure
H60	Screw pith 60mm structure
H40	Screw pith 40mm structure
Fin	Tube with straight fin
Normal	Normal tube
UDF	User-Defined Function
Symbols	
h_m	Formation standard enthalpy of substance *m*
J_{mj}	Substance material *m* flux in direction *j*
k_1	Reaction rate constant of reaction (1), kmol·bar$^{1/2}$/ (kg cat·h)
k_2	Reaction rate constant of reaction (2), kmol·bar$^{1/2}$/ (kg cat·h)
k_3	Reaction rate constant of reaction (2), kmol/ (kg cat·h·bar)
K_{CH_4}	Adsorption coefficient of CH_4, bar^{-1}
K_{CO}	Adsorption coefficient of CO, bar^{-1}
K_{H_2}	Adsorption coefficient of H_2, bar^{-1}
K_{H_2O}	Adsorption coefficient of H_2O
k_{eff}	Effective thermal conductivity of porous media, W/(m·K)
k_f	Thermal conductivity of fluid, W/(m·K)
k_s	Thermal conductivity of solid particle, W/(m·K)
K_1 K_3	Equilibrium constant of reaction (1) and (3), Bar^2
K_2	Equilibrium constant of reaction (2)
K_{CH_4}	Adsorption coefficient of CH_4, bar^{-1}
S_h	Energy source term, W/m^{-3}
S_i	Momentum source term, Pa/m
Y_{CH_4}	Mass fraction of methane
Y_{CO}	Mass fraction of carbon monoxide
Y_{CO_2}	Mass fraction of carbon dioxide
Y_{H_2}	Mass fraction of hydrogen

1. INTRODUCTION

Recent years hydrogen has been the focus of researchers. Methane steam reforming is main methods of hydrogen production. According to the reference [1], methane steam reforming accounts for over 40% in hydrogen supply worldwide. Methane steam reforming that is high temperature endothermic reaction proceed in packed bed reactor. It is important for improve the efficiency of reactor. Jurtz [2] et al. proposed the method that could enhance thermal performance of packed bed through internal heat fins. The author pointed that an increase of 25% to 35% in wall heat transfer coefficient was found for the internal spiral finned tube. Therefore, the internal spiral fin is worth studying in methane steam reforming reactor.

In methane steam reforming research, scholars use different methods for studying. Pashchenko [3] studied the performance of methane reforming with flue gases for different operating parameters through experiments. Mokheimer et al. [4] adopted the equivalent medium method to study the methane steam reforming and compared the results with experiments. The author pointed that the equivalent medium method can give accurate results. Dixon et al. [5] numerically studied the effects of cylindrical catalyst particles with through-hole on the methane steam reforming with using the solid particle method. Among these methods, the equivalent medium method has advantages of less calculation time and accurate results.

To the authors' best knowledge, currently no study is conducted to investigate methane steam reforming in the internal spiral fin tube reactor. In the present paper, the performance of methane steam reforming has been studied in internal spiral fin structure reactors with the equivalent medium method. Besides, the efficiencies of different structure reactors have been compared in same boundary conditions.

2. PHYSICAL MODEL AND COMPUTATIONAL METHOD

2.1 Physical model

As shown in Fig. 1, with catalyst particles are packed in an internal spiral finned tube with velocity inlet and pressure outlet. In the study, there are 6 different structures with same round tubes for compared performance. Two groups of internal spiral fin are set in the internal spiral finned tube as shown in Fig. 2. Different internal spiral finned tube structures have different screw pitch spiral fins. Meanwhile, there are a common tube and a tube with straight fin set as control groups as shown in Fig.3 and Fig. 4. The diameter of catalyst particle is 7 mm. The detailed information is shown in the Table 1.

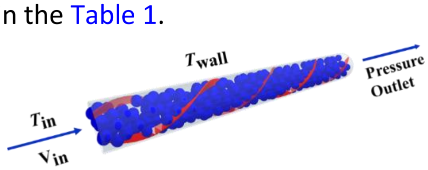

Fig. 1. Physical model

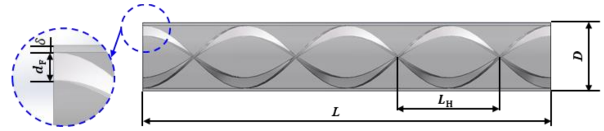

Fig. 2. Detailed information for internal spiral finned tube

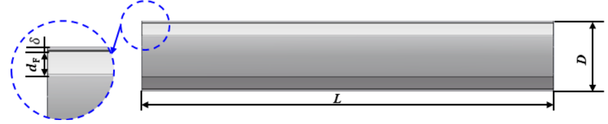

Fig. 3. Detailed information for straight fin tube

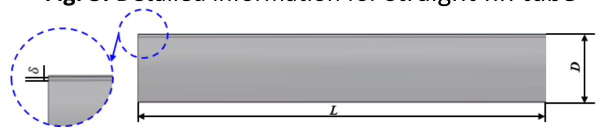

Fig. 4. Detailed information for normal tube

Table 1

Typical geometrical parameters for different structures

Structure	*L* (mm)	*D*(mm)	d_F(mm)	δ(mm)	L_H(mm)
S120					120
S80					80
S60	240	27.4	4.7	1	60
S40					40
Fin					0
Normal			0		0

2.2 Governing equations and computational methods

The equivalent medium method was used in this research for numerical simulation of methane steam reforming. The reaction area where catalyst particles pack is treated as equivalent medium. The laminar model was chosen to simulate the flow. The simulation is solved by SIMPLE algorithm. Momentum term, energy term and species term are calculated by second-order upwind iteration. Conservation equations for mass, momentum and energy are as follows:

Continuity:

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

Momentum:

$$\rho_f \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\frac{\partial u_i}{\partial x_j} I\right] + S_i \tag{2}$$

Energy:

$$\rho_f \frac{\partial u_i T}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\frac{k_{eff}}{c_p}\frac{\partial T}{\partial x_j}\right) - \frac{\partial}{\partial x_j}\left(\sum_m h_m J_{mj}\right) + S_h \tag{3}$$

Species:

$$\frac{\partial}{\partial x_j}\left(\rho_f u_j Y_m\right) = -\frac{\partial}{\partial x_j}\left(J_{mj}\right) + R_m \tag{4}$$

Where S_i is momentum source term, S_h represents the energy source term and R_m represents generation

Table 3
Properties for fluid and catalyst particle

$\rho_f(\mathrm{kg/m^3})$	$c_{p,f}(\mathrm{J/kg \cdot K})$	$k_f(\mathrm{W/m \cdot K})$	$\mu_s(\mathrm{Pa \cdot s})$	$\rho_s(\mathrm{kg/m^3})$	$c_{p,s}(\mathrm{J/kg \cdot K})$	$k_s(\mathrm{W/m \cdot K})$
6.1616	2395.38	0.0876	3×10^{-5}	1947	1000	1

or consumption rate of substance m . S_h and R_m were used through the UDF program.
The kinetics model of Xu et al. [6] is used. Rate formulas of different reactions are listed below.

$$r_1 = \frac{k_1\left(p_{\mathrm{CH_4}} p_{\mathrm{H_2O}} - \dfrac{p_{\mathrm{H_2}}^3 p_{\mathrm{CO}}}{K_1}\right)}{p_{\mathrm{H_2}}^{2.5}(\mathrm{DEN})^2} \quad (5)$$

$$r_2 = \frac{k_2\left(p_{\mathrm{CO}} p_{\mathrm{H_2O}} - \dfrac{p_{\mathrm{H_2}} p_{\mathrm{CO_2}}}{K_2}\right)}{p_{\mathrm{H_2}}(\mathrm{DEN})^2} \quad (6)$$

$$r_3 = \frac{k_3\left(p_{\mathrm{CH_4}} p_{\mathrm{H_2O}}^2 - \dfrac{p_{\mathrm{H_2}}^4 p_{\mathrm{CO_2}}}{K_3}\right)}{p_{\mathrm{H_2}}^{3.5}(\mathrm{DEN})^2} \quad (7)$$

$$\mathrm{DEN} = 1 + K_{\mathrm{CO}} p_{\mathrm{CO}} + K_{\mathrm{H_2}} p_{\mathrm{H_2}} + K_{\mathrm{CH_4}} p_{\mathrm{CH_4}} + K_{\mathrm{H_2O}} p_{\mathrm{H_2O}} / p_{\mathrm{H_2}} \quad (8)$$

2.3 Boundary conditions

There are four groups of simulation that set inlet and wall temperature as variables. The details of boundary condition are shown in Table 2. Meanwhile, the properties for fluid and catalyst particle are shown in Table 3.

Table 2
Boundary conditions for different cases

<table>
<tr><th>Case</th><th>V_{in} (m/s)</th><th>T_{in} (K)</th><th>T_{wall}(K)</th><th>Y_{CH_4}</th><th>Y_{H_2}</th><th>Y_{CO}</th><th>Y_{CO_2}</th></tr>
<tr><td>1</td><td rowspan="4">0.069</td><td>750</td><td>750</td><td rowspan="4">0.1966</td><td rowspan="4">0.0005</td><td rowspan="4">0.0007</td><td rowspan="4">0.1753</td></tr>
<tr><td>2</td><td>824.15</td><td>824.15</td></tr>
<tr><td>3</td><td>880</td><td>880</td></tr>
<tr><td>4</td><td>950</td><td>950</td></tr>
</table>

3. COMPUTATIONAL GRID AND MODEL VALIDATION

In this calculation, the structures S80 was selected for grid independence. Unstructured grid mesh was used in this simulation. By changing the maximum grid size, four grids ranging from 3×10^7 to 1.1×10^8 were used. Finally, the average deviations of the outlet methane mass fraction and hydrogen mass fraction are 0.01% and 0.06% respectively. Therefore, the grid independent solution is considered to be obtained.

The model validation is compared with the work of Mokheimer et al. [4]. For the validation, the operating pressure set as 1000000 Pa, the inlet temperature and wall temperature are set as 848 K, 838 K and 798 K respectively. Through the validation, the results were compared. The maximum deviations of methane conversion are 10.92%, 9.20% and 12.60% respectively for 848 K, 838 K and 798 K. The average deviations are 6.23%, 6.08% and 2.36% respectively for three cases.

4. RESULTS AND DISCUSSIONS

In this section, methane conversion and hydrogen production of different structures in four groups cases are compared respectively. Besides, for comparing efficiency of production better, the results of per 100 catalyst particles are used in the figures.

In Fig. 5 with temperature rising, methane conversion rate per 100 catalyst particles increase. Meanwhile, the difference between six structures gradually increase. The structures with internal spiral finned have better performance than other structures. Besides, the structure S40 has best performance which is internal spiral finned tube with 40 mm screw pitch. Methane conversion rate of the structure S40 increased by up to 2% compared with the structure Normal.

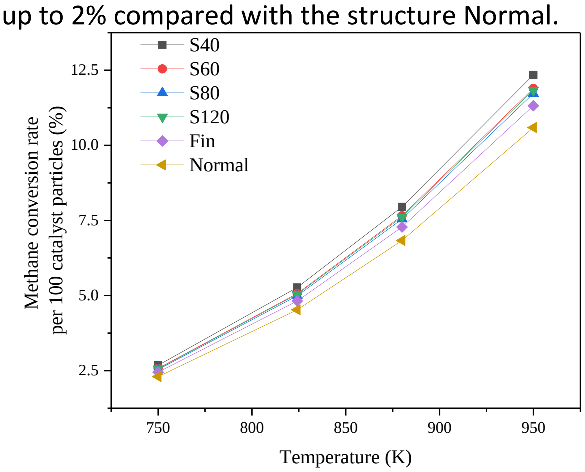

Fig. 5. Methane conversion rate per 100 catalyst particles for different temperature

There is a same tendency presenting in Fig. 6. Hydrogen production rate per 100 catalyst particles increase when temperature rises. The structures with internal spiral finned have better performance than other structures. Moreover, the structure S40 has best performance. Hydrogen production rate of the structure S40 increased by up to 0.3% compared with the structure Normal.

According to the analyzing, the results of average cross section temperature along axial distance were organized into Fig. 7. From the figure, the temperature drops sharply near inlet and then increases gradually. Besides, in the Fig. 8, the temperature contours present a zone of lower temperature. This indicates that there is a zone that chemical reactions proceed quickly. Meanwhile, in the Fig. 8, the internal spiral finned tube could make heat transfer efficiency and flow uniformly. It leads to that the performance of chemical reaction for per 100 catalyst particles improves.

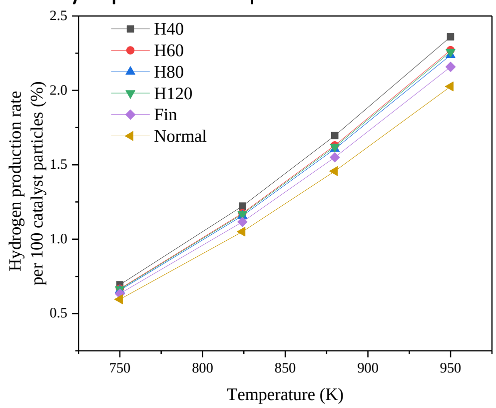

Fig. 6. Hydrogen production rate per 100 catalyst particles for different temperature

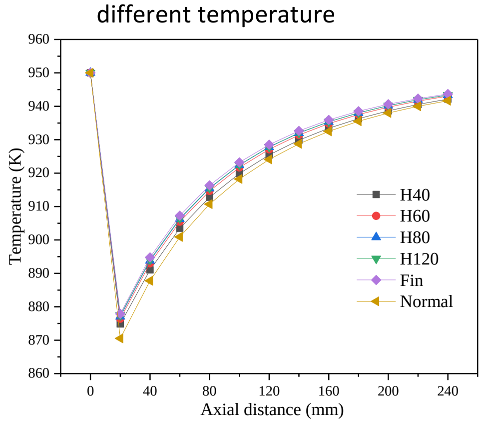

Fig. 7. Average temperature of cross section along axial distance

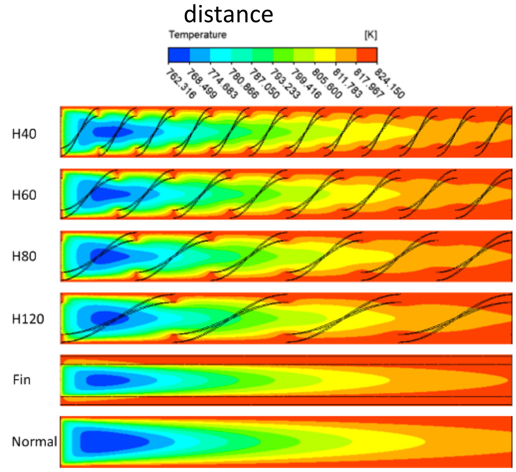

Fig. 7. Temperature contour in Longitudinal section of different structures

5. CONCLUSIONS

In the present study, the performance of methane steam reforming in different structures have been investigated and compared. The internal spiral finned tube can improve the performance of reactor compared with traditional reactor. The main results are as follows:

(1) Under same boundary condition, the internal spiral finned tube could make heat transfer efficiency and flow uniformly. It leads to that the performance of chemical reaction for per 100 catalyst particles improves. Methane conversion rate of the structure S40 increased by up to 2% compared with the structure Normal. Hydrogen production rate of the structure S40 increased by up to 0.3% compared with the structure Normal.

(2) The temperature drops sharply near inlet and then increases gradually. There is a zone near inlet which has lower temperature and higher reaction speed. Enhancing performance of heat transfer near reactor inlet is necessary.

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