SEMI-ANALYTICAL DERIVATION OF HEATING MATERIAL DISTRIBUTION FOR HOMOGENIZING HEAT GENERATION OF CYLINDRICAL CATALYST

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ABSTRACT. This paper investigates the homogeneous induction heating of cylindrical catalysts with fine micropores for promoting chemical reactions of the fluid material flowing through the micropores. These catalysts are made of a ceramic base with micropores some of which are stuffed with lossy magnetic materials, which generate heat under ac magnetization by the heating coil. For stabilizing the reaction condition, these catalysts should be heated uniformly, although the optimal distribution of stuffed micropores for uniform heating has been difficult to be derived. This paper addresses this issue by proposing a simple calculation method for stuffed micropore distribution. The proposed method is a semi-analytical method, which utilizes the FEM analysis to construct the magnetic circuit model and then analyzes the model to determine the stuffed micropore distribution. The appropriateness of the proposed method was supported by the simulation, which exhibited remarkable improvement in uniform heat generation.

INTRODUCTION

Cylindrical catalysts with fine micropore channels [1]-[3] are widely utilized in industry to promote chemical reactions of the fluid materials flowing through the micropores. These catalysts are commonly made of ceramic bodies with micropores, whose surface is coated with the catalyst material. Thereby, this catalyst can have a large contact surface with the fluid material to have effective chemical reactions.

As many catalyst materials have a functioning temperature, these catalysts commonly need a heating system to keep the catalyst's micropore channels heated at an appropriate temperature. However, the conductive heating from the periphery of the catalyst tends to cause severe inhomogeneity of the local temperature inside the catalyst, as the heat transfer from the outer periphery to the center tends to have large thermal resistance due to the long distance of heat conduction through the porous geometry of the catalyst.

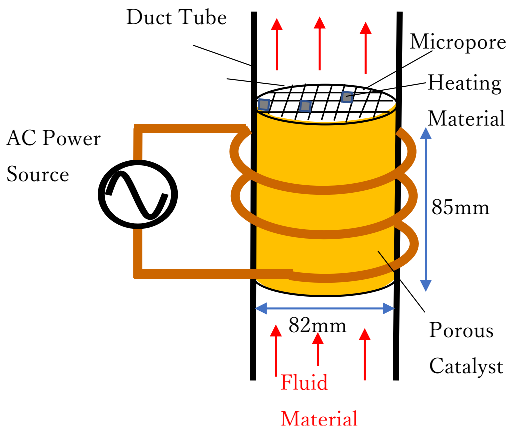

Figure1. Induction heating system for porous catalyst for fluid material

Induction heating can be a promising remedy to solve this problem because induction heating can generate heat without thermal conduction [4]-[6]. Figure 1 illustrates one of the typical systems [3]. In this system, the outer periphery of the cylindrical catalyst is covered with the heating coil, which carries the ac current. Additionally, some of the micropores are stuffed with heating material, i.e. lossy magnetic material, which generates heat due to the ac magnetic field induced by the heating coil. This heat is conducted to the neighboring micropores to heat up the catalyst material to an appropriate temperature.

Conventionally, the stuffed micropores were designed to be uniformly distributed in the cylinder cross-section so that the heat is generated homogeneously under the assumption of the homogeneous ac magnetic field parallel to the axis of the catalyst. This assumption is approximately valid if the catalyst diameter is far smaller than the catalyst axial length. Nonetheless, this induction heating system for the cylindrical catalyst is still adopted in many practical applications with large-diameter catalysts, which cannot accept this requirement, although they tend to suffer from inhomogeneous temperature distribution due to the weak magnetic field at the center of the cylinder horizontal cross-section.

The inhomogeneity in heat generation occurs both in the axial and radial directions. However, the axial inhomogeneity in the heat generation scarcely results in the inhomogeneous temperature because the fluid flows in the axial direction and therefore the heat can be effectively transferred in this direction. Hence, the temperature inhomogeneity in the axial direction can be naturally solved even under inhomogeneous heat generation. Meanwhile, the radial inhomogeneity in heat generation should be solved because it results in the inhomogeneous temperature distribution.

The solution to this radial inhomogeneity may lie in the optimization of the stuffed micropore distribution. However, the calculation of the optimal distribution is complicated because the micropore distribution simultaneously affects both the magnetic field distribution and the heat amount per unit volume generated by the unit magnetic field intensity. This makes the FEM-analysis-based optimization impractical because the FEM analysis needs trial-and-error searching for optimization and therefore needs enormous calculation time.

The purpose of this paper is to propose a practical calculation method to derive the optimal stuffed micropore distribution. For reducing the calculation burden, the proposed method adopts a semi-analytical approach, which is mainly based on analytical calculation but partly contains the FEM analysis. Specifically, the proposed method calculates the ac magnetic field distribution as well as heat distribution based on the analytical magnetic circuit model, which is constructed by partly utilizing the FEM analysis. Along with the theoretical discussion of the proposed method, this paper also presents an example of deriving the optimal stuffed micropore distribution, which was successfully supported to improve the homogeneity of the heat generation by the FEM-based simulation.

PROPOSED DERIVATION METHOD OF STUFFED MICROPORE DISTRIBUTION

Overview

The stuffed micropore distribution may need to be varied continuously in the radial direction if the solution for precisely homogeneous heat generation is to be obtained. However, this needs enormous effort and does not accept the analytical approach. Therefore, the proposed method simplifies the problem. Specifically, the proposed method divides the catalyst into two regions with the same cross-section area, i.e. the inner and outer regions, as shown in Fig. 2. These two regions are assumed to have different but constant stuffed micropore densities. Then, the proposed method derives the micropore densities that generate the same heat in these two regions.

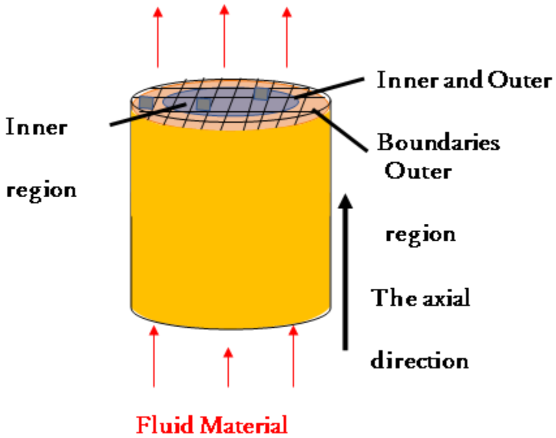

Figure 2. Inner and outer regions defined in horizontal cross-section of catalyst

Additionally, the proposed method neglects the fine structures of the micropores but simply regards the catalyst with stuffed micropore as the uniform magnetic material, whose equivalent permeability is dependent only on the stuffed micropore density A. In this paper, the stuffed micropore density A is defined as the local areal ratio of micropores in the catalyst in the horizontal cross-section.

The magnetic and eddy current losses of the many magnetic materials are approximately proportional to the square of the magnetic field in the material. Therefore, the heat amount per unit volume can be regarded to be proportional to AH_m^2, where H_m is the magnetic field in the stuffed micropores. Hereafter, this paper refers to the value of AH_m^2 as the heating index. The proposed method calculates A of these regions so that they have an equal heating index.

For this purpose, this method takes the following three steps: 1. The equivalent permeability of the catalyst is determined as a function of A using the FEM analysis, 2. A magnetic circuit model is constructed to calculate H_m inside each region, 3. The heating index is determined for the two regions as functions of A. Finally, values of A for these regions are determined to equalize the heating index between these regions. Below, each of these three steps is discussed in detail.

Step 1: Determination of Equivalent Permeability of Catalyst

The FEM analysis is performed to determine the equivalent permeability μ as a function of A. This simulation calculates the magnetic field and magnetic flux density distribution of the catalyst with uniformly distributed stuffed micropores. Then, the average magnetic flux density B_{ave} and the magnetic field $H_{//}$ in parallel to the micropore were evaluated in the small area near the center of the catalyst. The equivalent permeability was calculated according to $\mu = B_{ave} / H_{//}$. This procedure was repeated with various stuffed micropore densities A to determine μ as a function of A.

Step 2: Magnetic Circuit Modelling

This step constructs the magnetic circuit model that represents the magnetic field in the catalyst. Firstly, the magnetic circuit topology is determined according to the electromagnetic field simulation results of the FEM analysis, which is performed in the first step.

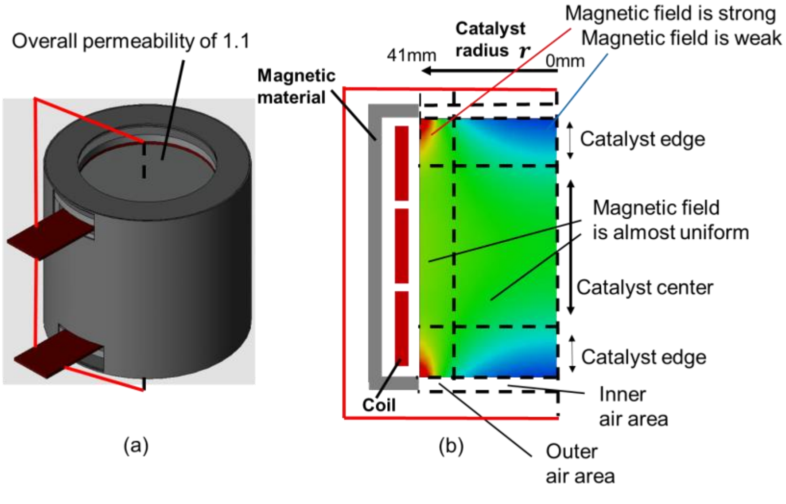

Figure 3. FEM analysis model (a) and analysis result of square of magnetic field in catalyst vertical cross-section (b).

Figure 3 illustrates the simulation result of the square of the magnetic field inside the catalyst with uniformly distributed stuffed micropores. The equivalent permeability for this catalyst was 1.1. The simulation conditions for Fig. 3 are listed in Table 1.

As can be seen in the figure, the catalyst can be distinguished into 6 segments. In the proposed method, the catalyst was divided into two regions, i.e. the inner and outer regions. However, each inner and outer region can be further divided into 3 segments in the vertical direction according to the vertical and

Table 1: Simulation conditions of FEM analysis

RMS current	229[A]
Frequency	100[kHz]
Magnetic permeability	1.1

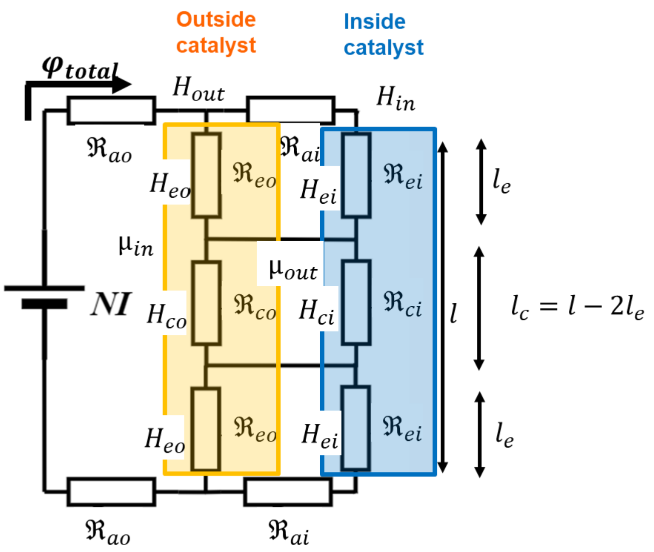

Figure 4. Magnetic circuit model. I is the current and N is the number of turns of heating coil wound on catalyst.

horizontal differences in the magnetic field.

The catalyst's top and bottom edges exhibited an intense difference in the magnetic field between the inner and outer regions. However, the central body of the catalyst has a small difference between these two regions. The reason for the intense difference at the catalyst edge is that the catalyst edge has a small vertical height compared with the horizontal dimension and therefore horizontal flow of the magnetic flux in the open space above and beneath the catalyst experiences far greater magnetic resistance than the vertical flow through the catalyst edge. Meanwhile, the central body of the catalyst has a greater height than the horizontal dimension, and therefore the horizontal flow of the magnetic flux experiences smaller magnetic resistance than the vertical flow.

Regarding vertical and horizontal magnetic flux flow in each segment as a magnetic resistance, the magnetic circuit model can be derived. Figure 4 illustrates the magnetic circuit model constructed in this step. The magnetic resistances R_{eo}, R_{co}, R_{ei}, and R_{ci} correspond to those for the vertical magnetic flux flow through each segment; R_{ai} corresponds to the magnetic resistance of the open space above and beneath the catalyst openings from the outer region to inner region; R_{ao} corresponds to the magnetic resistance of the open space around the heating coil. The magnetic resistance representing the horizontal magnetic flux flow in the central body was simply approximated as short-circuit in Fig. 4.

The magnetic resistances R_{eo}, R_{co}, R_{ei}, and R_{ci} were determined according to

$$R=l_m/\mu S, \tag{1}$$

where R is one of R_{eo}, R_{co}, R_{ei}, and R_{ci}, l_m, and S are the length and the horizontal area of the segment corresponding to R. Meanwhile, R_{ai} and R_{ao} are determined so that the magnetic circuit model can best fit with the magnetic flux distribution of the simulation result, i.e. Fig. 4, based on the values of R_{eo}, R_{co}, R_{ei}, and R_{ci} determined according to (1).

Step 3: Calculation of Heating Index

This step derives the heating index as a function of the stuffed micropore density based on the relation between the equivalent permeability and the stuffed micropore density, derived in step 1, as well as the magnetic circuit model, derived in step 2. For this purpose, the magnetic field through the 6 segments, represented by the magnetic resistance R_{eo}, R_{co}, R_{ei}, and R_{ci}, is calculated as a function of the equivalent permeability using the magnetic circuit model.

The proposed method assumes different equivalent permeability between the inner and outer regions. Therefore, R_{eo} and R_{co} are regarded to be functions of the equivalent permeability of the outer region μ_{out}; R_{ei}, and R_{ci} are regarded to be functions of the equivalent permeability of the inner region μ_{in}. Meanwhile, R_{ai} and R_{ao} are assumed to be constant because they represent the open space outside the catalyst. Consequently, the magnetic field is calculated as a function of μ_{in} and μ_{out}.

Then, the heating index of the inner and outer regions is calculated. If H_{eo}, H_{co}, H_{ei}, and H_{ci} denote the calculation result of the magnetic field at R_{eo}, R_{co}, R_{ei}, and R_{ci} based on Fig. 4, the heating indices Q_{in} and Q_{out} of the inner and outer regions can be formulated respectively as

$$Q_{in}=A_{in}\{2H_{ei}^2l_e+ H_{ci}^2(l-2l_e)\}/l, \quad (2)$$
$$Q_{out}=A_{out}\{2H_{eo}^2l_e+ H_{co}^2(l-2l_e)\}/l, \quad (3)$$

where A_{in} and A_{out} are the stuffed micropore densities of the inner and outer regions, respectively; l_e is the height of the catalyst edge; and l is the height of the catalyst.

The calculated results of Q_{in} and Q_{out} according to (2) and (3) yield functions A_{in}, A_{out}, μ_{in}, and μ_{out}. However, by utilizing the result of step 1, Q_{in} and Q_{out} can be rewritten as functions only of A_{in} and A_{out}. Therefore, adjusting the values of A_{in} and A_{out} can change Q_{in} and Q_{out}. Finally, A_{in} and A_{out} that satisfy $Q_{in}=Q_{out}$ are sought to achieve homogeneous heating.

SIMULATION

The effectiveness of the proposed method is tested by determining stuffed micropore densities A for Fig. 1. The permeability and resistivity of the stuffed heating material are 250 and 2.29×10-5[Ωm].

Firstly, the relation between the stuffed micropore densities and the equivalent permeability was investigated by the FEM analysis according to the procedure described in the previous section. Figure 5 shows the result. This figure plots the equivalent permeability when one micropore is stuffed for every region of 3×3 micropores, 5×5 micropores, 7×7 micropores, and 9×9 micropores, respectively. (The stuffed micropore is located at the center of the region.) The results exhibited linear relation, which is utilized in step 3.

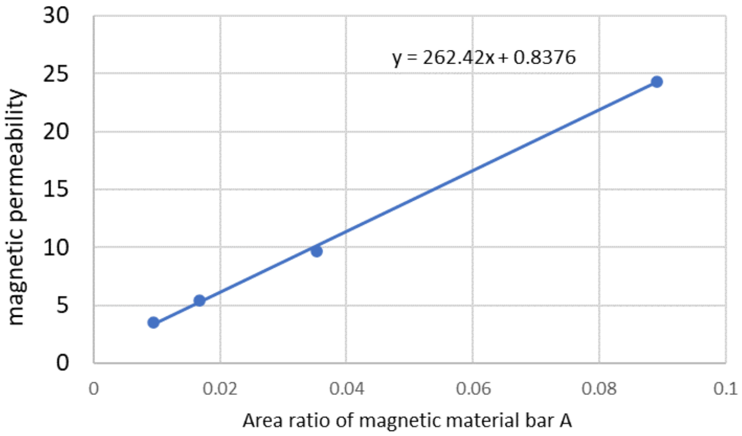

Figure 5. Relation between stuffed micropore density A and equivalent permeability μ.

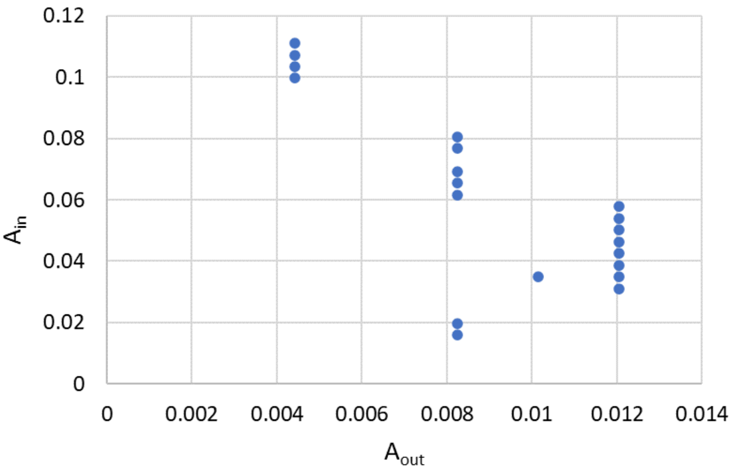

Figure 6. Calculated combinations of A_{in} and A_{out} that can generate same heat in inner and outer regions.

Finally, in step 3, the optimal combination of A_{in} and A_{out} was obtained. Figure 6 shows some of the results, which predicted similar heating indices Q_{in} and Q_{out} for the inner and outer regions. The result revealed plural optimal combinations of A for the two regions.

Among them, we chose the case of A_{in}=3.48×10^{-2} and A_{out}=1.01×10^{-2}, and performed the FEM analysis of the heat generation in the catalyst. In this simulation, the rms value and the frequency of the heating coil current were set at 229Arms and 100kHz, respectively. Furthermore, the conventional case of uniformly stuffed micropore distribution between the inner and outer regions was also performed to elucidate the effectiveness of the proposed method. (The conventional case has one stuffed micropore per every 5×5 micropores.)

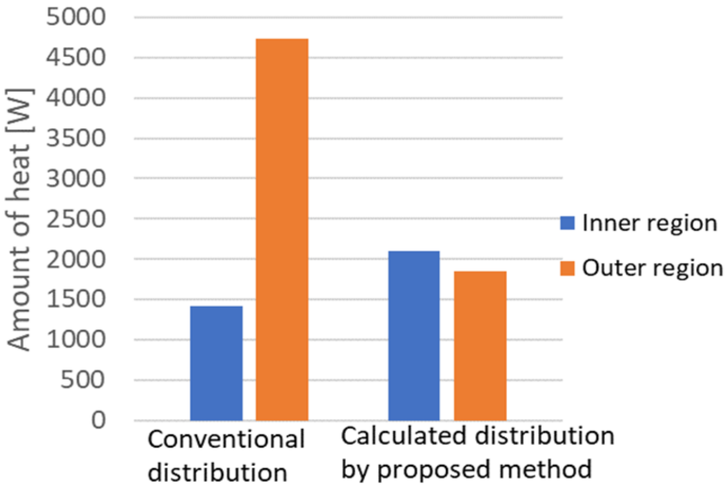

Figure 7. Simulated total heat generation in inner and outer regions of conventional stuffed micropore distribution and proposed stuffed micropore distribution.

Figure 7 shows the result of the total heat generation in the inner and outer regions, respectively. The result revealed that the proposed calculation method succeeded to mitigate the radial inhomogeneity of the heat generation compared to the conventional case.

EXPERIMENT

An experiment was carried out to evaluate homogeneous heating by the proposed method. For this purpose, the prototype catalyst with stuffed micropores at A_{in}=3.48×10^{-2} and A_{out}=1.01×10^{-2} was constructed, as presented in Fig. 8. This prototype catalyst was wound with 3 turns coils, supplied with the ac current at 100 kHz. The dry air flows through the catalyst micropores at the ground air pressure with the airflow amount of 7.5×10^{-3} m^3/sec.

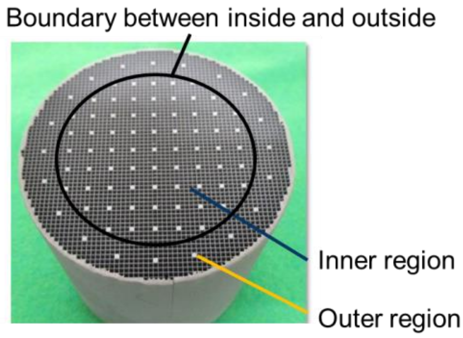

Figure 8. Experimental catalyst with open and stuffed micropores.

Figure 9 illustrates the temperature distribution observed using the radiation thermometer. The results revealed strong temperature inhomogeneity in the outer region due to the too-sparse distribution of the stuffed micropore, which declined the effective experimental evaluation of the proposed method. In future research, we will work on the experiment with denser stuffed micropore distribution.

CONCLUSIONS

This paper proposed a calculation method of the stuffed micropore distribution for uniform heating of the cylindrical catalyst. The proposed method is a semi-analytical calculation method with the magnetic circuit model, which is constructed utilizing the FEM analysis method. By avoiding the trial-and-search approach using the full FEM analysis, the proposed method can derive the optimal stuffed micropore distribution with straightforward calculation, although the proposed method simplifies this problem by dividing the catalyst horizontal cross-section into the inner and outer regions with uniform stuffed micropore densities.

The simulation successfully revealed effective homogenization of the heat generation betewen the inner and outer regions. However, the experimental validation exhibited a

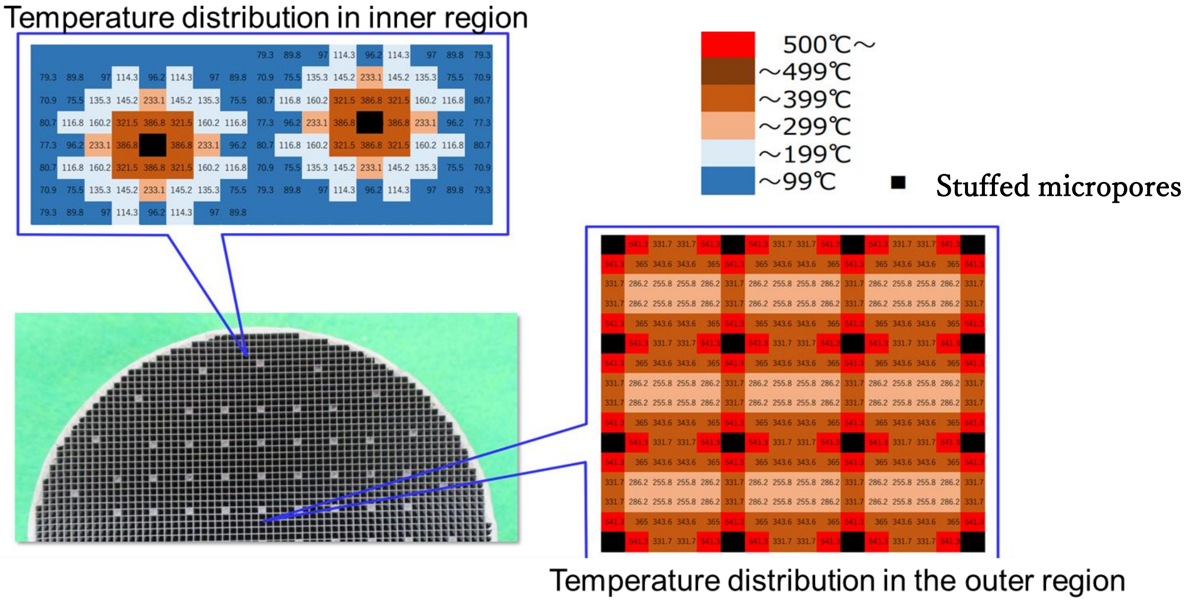

Figure 9. Experiment result of temperature distribution in outer and inner regions.

problem of significant temperature inhomogeneity due to the extremely sparse stuffed micropore distirbution in the outer region, which will be addressed in the future study.

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