High Efficiency TM_{01}-mode Cylindrical Waveguide Microwave Reactor for Microwave Material Continuing Processing

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Abstract— A cylindrical waveguide microwave reactor is proposed for microwave material continuing processing. This traveling-wave type chemical reactor could be used in food processing, microwave chemistry, coal desulfurization, etc.. The new structure is designed in order to support the reactants at the central of the reactor to achieve the highest efficiency. Compared with the existing microwave reactors, such as rectangular waveguide types and ridge waveguide types, our structure has considerable advantages in the distribution of the field strength, reaction effect, lack and energy consumption on processing reactants.

1. INTRODUCTION

Nowadays, more microwave energy has been used in different areas of its unique effects such as food processing, machining, environmental protection, development of new materials, chemical synthesis, etc. [1]. The industrial application of microwave energy for continuous high-power microwave reactor raised higher requirements while the traditional box-type reaction chambers are not suitable to the assembly line in the factory anymore [2]. Previous researchers have done fruitful research in the continuous microwave reactor and various forms were invented [2, 3], such as rectangular waveguide types, ridge waveguide types, and folded waveguide types. They focused mainly in the distribution of the field strength, reaction effect, and energy consumption but it has not been satisfactorily resolved [4].

However, the application of the circular waveguide type microwave reactor is relatively uncommon while circular waveguide is widely used in other fields [2]. Because 1) it is difficult to transport sample in a circular waveguide reactants without wheels, which would seriously destroy the original distribution of field inside so that the efficiency and power capacity would drastically reduce [4]. 2) The dominant mode of circular waveguide (TE_{11} mode) has polarization degeneracy phenomenon, which will greatly reduce the microwave absorption efficiency. Therefore, high-order mode circular waveguide reactor is needed to improve the efficiency of it. In this paper, a cylindrical waveguide microwave reactor, as shown in Fig. 1, is proposed for microwave material continuing processing. This traveling-wave type chemical reactor compared with the existing microwave reactor, such as rectangular waveguide types, ridge waveguide types, has obvious advantages in the distribution of the field strength, reaction effect, and energy consumption.

2. MICROWAVE REACTOR DESIGN

As shown in Fig. 1, a cylindrical waveguide microwave reactor with two axial slits is demonstrated in this paper. It operates with TM_{01} mode, i.e., the first high-order mode. In this configuration, the electric field is concentrated on the axis of the cylindrical waveguide as shown in Fig. 2, which indicates that the field reduces significantly due to the strong interaction between the microwave and samples. Thus the sample is located in this region and carried by the low-loss conveyor belt. In this case, the electric field sufficiently react with the samples, thereby enhancing the absorption of the microwave power of the sample to accelerate the reaction (the absorbed power $P = 56.62 \times 10^{-12} f E^2 \varepsilon''$ is proportional to electric field strength) [5]. Two axial slits are cut out from the conductor wall of the cylindrical waveguide in order to fix the conveyor belt, which goes through the two slits, is connected to the wheels outside to support the sample and the absorbing materials are placed around the slots. However, the two axial slits will not influence the field in the reactor because currents on the wall of circular waveguide only have axial component, which means only a very small part of the electromagnetic waves will radiate from the slot [6]. We use the simulation software Ansoft HFSS 13.0 for modeling & simulation while C8 standard circular waveguide, which was shown in Fig. 3 with $L = 30\,\mathrm{mm}$, was chosen to find out the radiation loss ratio of TM_{01} mode at 915 MHz. The result is shown in Fig. 4 and it indicates that the width of slots should be no more than 20 mm, which is wide enough to fix a thicker conveyor belt [7]. The total radiation loss of a reactor within one meter long will be less than 0.06% of the power being inputted, which is less enough to be absorbed by absorbing materials.

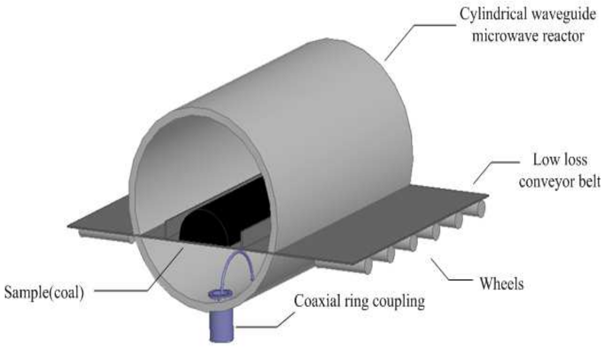

Figure 1: Pulverized coal desulfurization reaction.

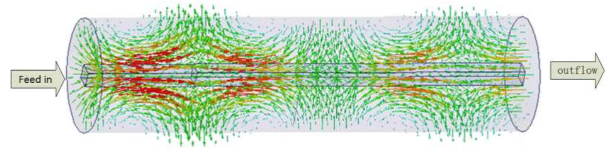

Figure 2: Distribution of electric fields in part of reactor.

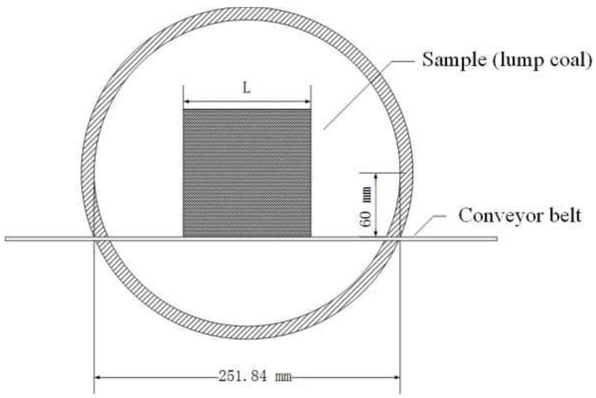

Figure 3: Axial view of the reactor.

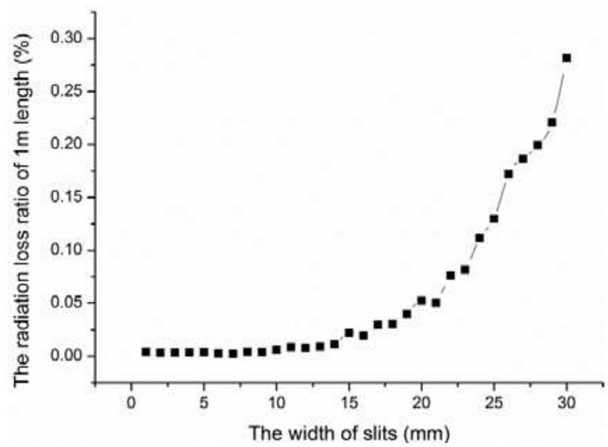

Figure 4: Radiation loss ratio.

However, the TM_{01} mode microwave in the reactor may be converted into the TE_{11} mode [6], i.e., the dominant mode of cylindrical waveguide, due to the discontinuity of the waveguide and the sample. It should be noted that the conversion will no always happen due to the orthogonally between the electric fields of these two mode [6]. Furthermore, the slits that wrapped by absorbing material outside could inhibit the appearance of the TE_{11} mode by cutting radially current on the inner surface.

The coaxial ring coupling feeding method is employed to excite the TM_{01} mode. Depending on the size of sample, reactor can be fed from beneath, as shown in Fig. 2, or above of the conveyor belt. Considering the versatility and power capacity, coaxial line Model 50-16 was chosen to feed the reactor. The feeding method is to connect the outer conductor of the coaxial line with the inner wall of the reactor, then wound the inner conductor into a semi-circle, the radius of 89.07 cm, and connect it to the inner wall too. Considering the impedance of microwave reactor is depending on type and quantity of samples, it is necessary to change the depth of insertion depending on reflection coefficient of the coaxial to get the best match. As shown in Fig. 5, twice small rectangular waveguides at both sides of reactor are used to transmit the reactant and block the microwave from leaking. Simulation results show that the ratio of power been leaked from both sides will be less than 0.02%.

3. COMPARISON AND RESULTS

Before compared with the other widely used reactors [3, 8], we must first establish a unified criteria. Although there have many different criteria for different types of samples and needs, we still can find some common standards such as efficiency, processing speed, uniformity of field, cost, etc. [9]. We selected others and ignored speed and cost because they are hard to compare between different reactors for different materials and applications. Two kinds of standard reactors which are widely used: rectangular waveguide reactor and ridge waveguide reactor working at 915 MHz will be compared with the reactor shown in this paper. They will be modeled and simulated in Ansoft

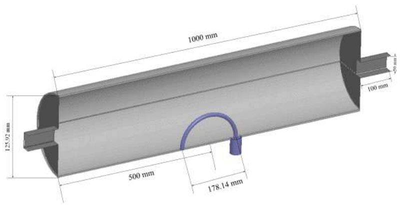

Figure 5: Feed and baffles of the reactor.

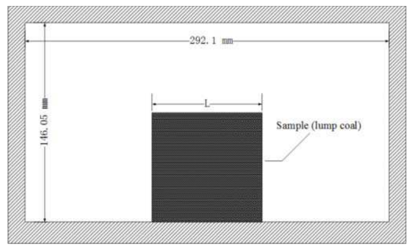

Figure 6: Rectangular type reactor.

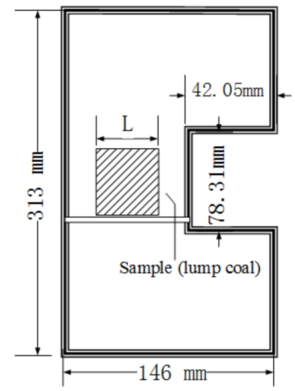

Figure 7: Single ridge type reactor.

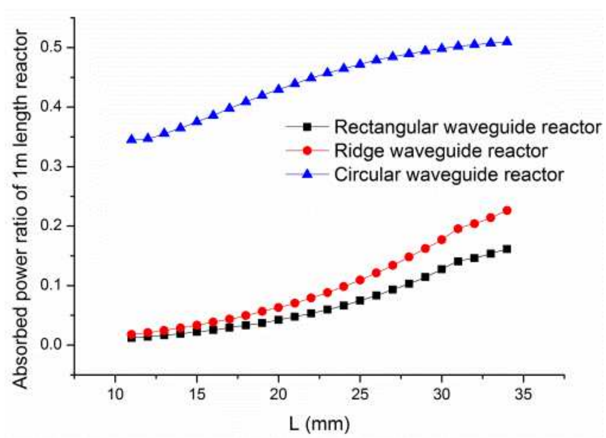

Figure 8: Absorbed power ratio of the three reactors.

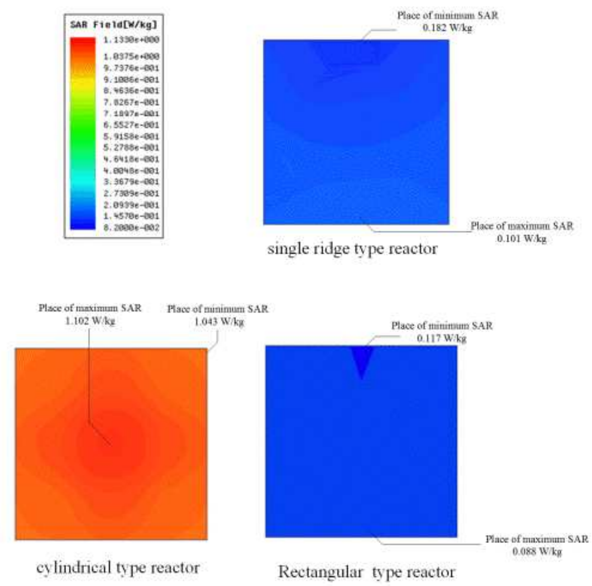

Figure 9: SAR of cross section of the three reactors.

HFSS 13.0 and the mismatch loss of feed will not be considered due to fair comparison.

The standard rectangular waveguide R8 and single ridge waveguide 24JD420 were selected as two comparison microwave reactors which are shown in Fig. 5 and Fig. 6. They are widely used as TE_{10} mode chemical reactor at 915 MHz for microwave material continuing processing [3]. The sample was put on the moving conveyor which goes along the central axis of the rectangular waveguide and the ridge waveguide reactors. We used square coal ($\varepsilon' = 4.88$, $\tan\delta = 0.3$) in long strip as samples because the thermal effects of microwave energy is widely used in removing sulfur of the coal [10], which is becoming an increasingly important environmental issues in China [10, 12].

Efficiency is nearly the most important factors to consider in microwave reactors [3, 12]. We compared the efficiency of these three kinds of reactor by putting the same sides of square coal in long strip into reactors continuously. The results shown in Fig. 8 indicated that more power will be absorbed if the bigger reactants were inputted [13] and the absorption efficiency of cylinder type reactor is considerable higher than the other twice with the same sides of reactants inputted. Specific Absorption Rate (SRA) is a measure of the rate at which energy is absorbed by the human body or the materials. We measured the SAR of the cross section of the square coal to compare the effect and uniformity of microwave heating. Fig. 9 shows the SARs (W/kg) of the cross sections of the square coal ($L = 20$ mm) which were in three different reactors feeding by coaxial line of 1 W inputted. The result indicates that compared with some traditional reactors, the reactor designed in this paper has much higher SAR ($6 \sim 12$ times) in reactants, which means the microwave energy has been fully utilized and the heating efficiency has been greatly improved.

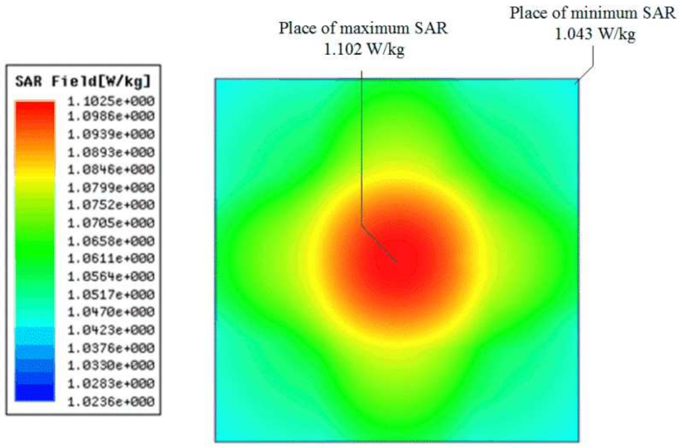

Figure 10: SAR of cross section of cylindrical reactor.

Another important factor of reactors is the uniformity of SAR, which means the inner and surface of the reactants should be uniformly heated at the same time. The picture of cylindrical type reactor in Fig. 9 was redrawn in Fig. 10 with a sparser scale to illustrate the SAR in the different parts of coal clearly. Fig. 10 indicates that the minimum SAR takes place at the corner of the square sample and it is just 5.45% lower than maximum SAR at the center. Compared with other reactors in Fig. 10, the cylindrical type reactor has the best uniformity of SAR.

4. CONCLUSION

A traveling-wave cylindrical waveguide microwave reactor is proposed for microwave material continuing processing. The new structure was designed in order to support the reactants at the central of the reactor to achieve the highest efficiency. Simulation results show that only very few microwave energy could be lacks from slots and both ends of reactor and it will be absorbed by the absorbing material. Compared with the existing microwave reactor, such as rectangular waveguide type reactor and ridge waveguide type reactor; our structure has considerable advantages in the distribution of the field strength, reaction effect, and energy consumption on processing reactants.

ACKNOWLEDGMENT

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REFERENCES

1. Ford, J. D. and D. C. T. Pei, "High temperature chemical processing via microwave absorption," *Journal of Microwave Power and Electromagnetic Energy*, 61–64, 1967.
2. Jing, Q. H., *Microwave Chemistry*, Science Press, Beijing, 2001.
3. Yu, V. B., K. I. Rybakov, and E. Semenov, "High-temperature microwave processing materials," *Journal of Physics D: Applied Physics*, Vol. 34, No. 13, 55–75, 2001.
4. Tinga, W. R. and W. A. G. Voss, *Microwave Power Engineering*, Vol. 2, Academic, New York, 1968.
5. Kappe, C. O., A. Stadler, and D. Dallinger, *Microwaves in Organic and Medicinal Chemistry*, 2nd Edition, Wiley-VCH, Weinheim, 2012.
6. Pozar, D. M., *Microwave Engineering*, John Wiley & Sons, 2009.
7. Larhed, M. and K. Olofsson, *Microwave Methods in Organic Synthesis*, Springer, Berlin, 2006.
8. Haque, K. Z., "Microwave energy for mineral treatment processes: A brief review," *International Journal of Mineral Processing*, Vol. 57, No. 1, 1–24, 1999.
9. Kingman, S. W. and N. A. Rowoson, "Microwave treatment of minerals: A review," *Minerals Engineering*, Vol. 11, No. 11, 1081–1087, 1998.
10. Cheng, Y. J., Z. X. Xia, and Y. Fan, "A frequency reconfigurable experimental microwave device of coal desulfurization," *Journal of University of Electronic Science and Technology of China*, Vol. 41, No. 1, 31–35, 2014.
11. Yi, Y. B., "Microwave desulfurization in coal," *Coal Technology*, Vol. 4, 54–55, 2003.

12. Xia, Z. X., Y. J. Cheng, and Y. Fan, "Frequency-reconfigurable TM_{010}-mode reentrant cylindrical cavity for microwave material processing," *Journal of Electromagnetic Waves and Applications*, Vol. 27, No. 5, 605–614, 2013.
13. Wang, L., Z. X. Xia, Y. J. Cheng, and Y. Fan, "A frequency reconfigurable microwave reaction cavity based on a quarter-wave coaxial cavity resonator," *10th International Symposium on Antennas, Propagation, and EM Theory*, Xi'an, China, Oct. 2012.