3D-Printed Atmospheric-Pressure Plasma Reactors

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Abstract—Recently, the application of 3D-printing technology has opened a new frontier in industry, material science, chemistry, and medicine. In the field of plasma engineering, a plasma reactor is a key piece of equipment to successfully produce plasma. The aim of this research is to verify and evaluate the feasibility of a novel plasma reactor prototype prepared using a 3D printer. Essentially, a non-thermal plasma reactor operated at atmospheric pressure consists of electrodes (metals) and support parts (insulators). The insulating parts are usually made of glass, ceramics, or plastics. In this study, a new approach for the design and fabrication of non-thermal plasma reactors used at atmospheric pressure is presented. The reactor is based on a coaxial cylindrical configuration. The insulating parts of the reactor were prepared using a 3D printer. The performance of the prototypes was experimentally evaluated by comparison with that of a normal plasma reactor.

Keywords—3D printer, 3D data, plasma reactor, rapid prototyping, reactor optimization

I. Introduction

Three-dimensional (3D) printing is one of the key technologies in Maker movement [1]. 3D printers are widely used in the world, and as such, 3D printing technology is now expanding into many fields such as cellular engineering [2, 3], tissue and scaffold engineering [4, 5], anatomy [6], microfluidics [7, 8], electronics [9, 10], music [11], architectonics [12], and technics [13]. In contrast, the use of 3D printing in the field of plasma engineering has not yet been thoroughly explored. This research endeavor contends that as rapid prototyping of a 3D printer is suitable for the fabrication of a non-thermal plasma reactor with several geometries, it cannot be easily fabricated using conventional methods. From a historical perspective, the first development of a non-thermal plasma reactor operated at atmospheric pressure can be traced back to the ozonizer invented by Siemens in the 1850s [14]. To date, various types of plasma reactors have been developed and evaluated [15-23]. Essentially, the plasma reactor consists of electrodes (metals) and supporting parts (insulators). The insulating parts are usually made of glass, ceramics, or plastics. Therefore, there are limitations on the design and fabrication parameters of such a reactor.

In this study, a new approach for the design and fabrication of non-thermal plasma reactors used at atmospheric pressure is presented by using 3D printing technology. The aim of this research is to verify the feasibility of such an approach and to evaluate a novel plasma reactor prototype prepared using a 3D printer.

II. The 3D-printed plasma reactor

Fig. 1 shows a schematic diagram of the coaxial cylindrical plasma reactor used as the 3D prototype modeled in this study. The insulating parts of the plasma reactor were prepared using a 3D printer. In a practical fabrication process, the body of the reactor was first designed using computer-aided design (CAD) software (Rhinoceros Ver. 5, Robert McNeel & Associates), with the subject 3D CAD data being created as shown in Fig. 2. Subsequently, the 3D CAD data were converted to a Standard Tessellation Language (STL) file for printing. Finally, the main body (the insulating parts of the plasma reactor) was prepared with acrylonitrile butadiene styrene (ABS) plastic using the 3D printer (Value 3D MagiX MF-1000, Mutoh Engineering, Japan) on the basis of fused-deposition modeling. Fig. 3 depicts a typical fabrication process for the reactor. By printing with a resolution (i.e., the distance between layers) of 0.25 mm, it took approximately 3 hours to fully print. Only the metal electrodes, i.e., the threaded rod (used as a powered electrode) and the mesh (used as a grounded electrode), were added later. The reactor specifications and

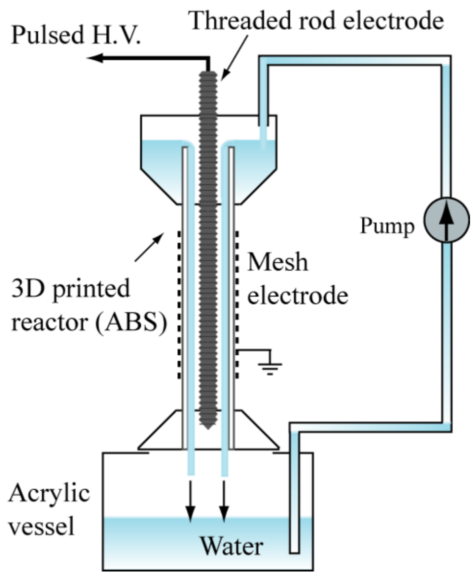

Fig. 1. 3D printing model reactor.
(DBD plasma reactor with running water film)

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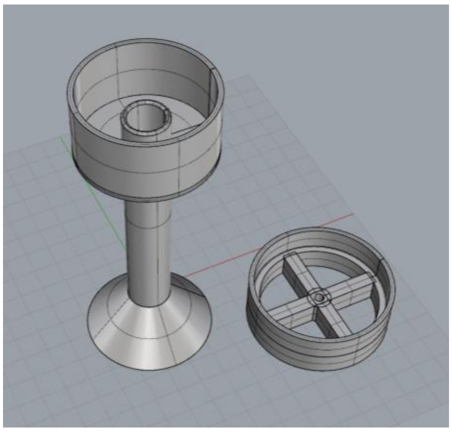


Fig. 2. 3D CAD data of the reactor body and its cap for the support of an inner electrode (perspective view).

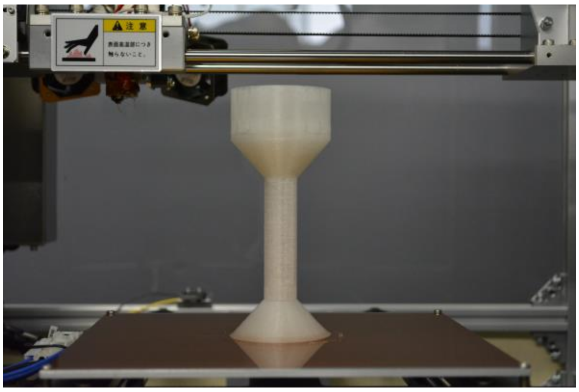


Fig. 3. 3D printing process of a prototype cylindrical plasma reactor using FDM technology.
A transparent ABS plastic was used as an insulating material.
(Printer: Value 3D MagiX MF-1000, Mutoh Engineering, Japan)

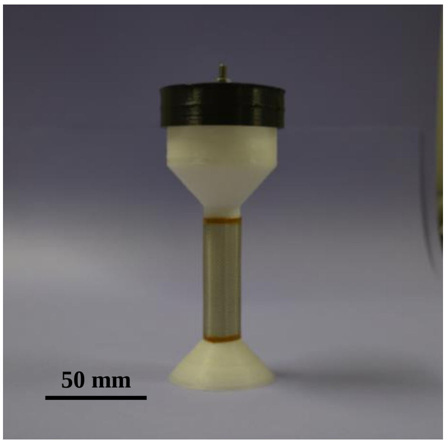


Fig. 4. 3D printed cylindrical plasma reactor.
STL files of the reactor are available at
http://elecls.cc.oita-u.ac.jp/plasma/download/3Dcad.html.

experimental conditions are summarized in Table I.

Fig. 4 shows a typical prototype of the reactor. Pulsed dielectric barrier discharge (DBD) was generated between the threaded metal rod electrode and running water film of the inner wall of the ABS plastic reactor.

TABLE I
REACTOR SPECIFICATIONS AND EXPERIMENTAL CONDITIONS

Reactor specifications
Cylindrical parts: Outer dia. 17.5 mm, Inner dia. 14.5 mm, ABS
Length for discharging region: 60 mm
Electrodes: High-voltage electrode: threaded rod (M4), Stainless steel
Grounded electrode: 30 mesh, Stainless steel
Gap distance for the discharge: 5 mm

Experimental conditions
Power source: Magnetic compression type pulse power system
(Suematsu, MPC3010S-50SP)
Applied voltage: 18–30 kV, Pulse width: 100 ns
Repetition rate: 100 pps

Liquid fluid: Running water film of the inner wall of the reactor
Tap water, Dyed water: 600 mL/min

TABLE II
COMPARISON OF ELECTRICAL PROPERTIES OF INSULATING MATERIALS USED FOR THE REACTORS IN THIS STUDY

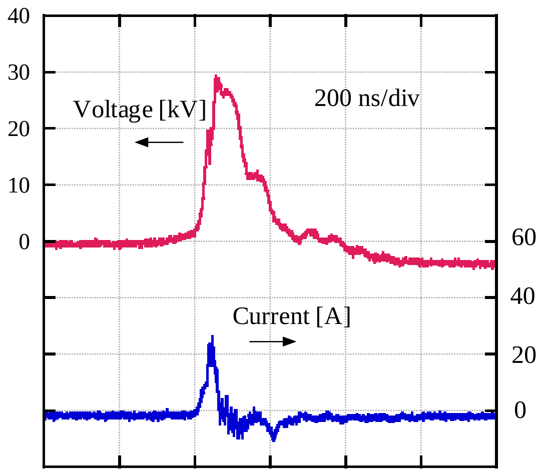
	ABS plastic	Silica glass
Volume resistivity [Ω・m]	10^{14}	10^{14}
Dielectric strength [MV/m]	12–16	43
Relative permittivity (1 kHz)	2.7–4.8	3.6
Dielectric loss tangent × 10^{-4} (1 kHz)	20–120	
× 10^{-4} (1 MHz)		1.2

The performance of the prototypes was experimentally evaluated by a comparison with a normal plasma reactor made by a silica glass tube.

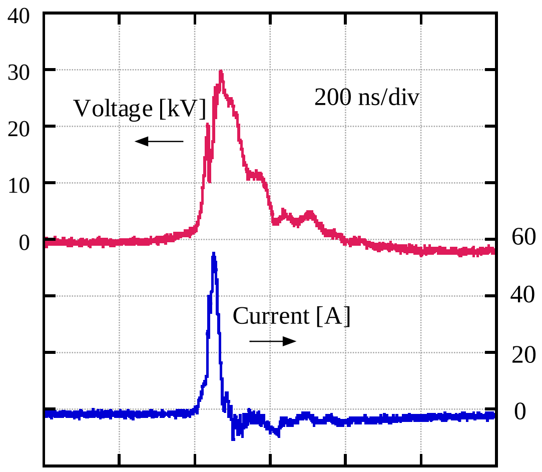
III. PERFORMANCE EVALUATION

Fig. 5 shows the typical applied pulse high voltage and current waveforms of the DBD-type pulsed discharges. Fig. 5 (a) shows the waveforms for the 3D printed reactor, while Fig. 5 (b) shows the waveforms for the normal silica glass reactor. Although the same applied voltages of 30 kV were applied to both reactors, the peak current of the 3D printed reactor was reduced to almost half. This is because of the difference in the electrical properties between the ABS plastic and silica glass (Table II, [24]). In the case of the 3D printed reactor, an infill density and irregularities (including void formation) in the printed material also affect the discharge performance.

Fig. 6 shows the typical discharge image captured by a digital camera (Nikon, D5200). The applied voltage was 24 kV, and its repetition rate was 100 pps. A noted bright, uniform illumination was because of the fact that many filamentary discharges were captured during the exposure time. The reactor proved itself strong and lightweight in comparison with the normal glass reactor. The 3D printed reactor could be operated without a spark transition up to 30 kV, which is the ceiling of the pulsed power system used in this study. However, when the water flow rate was decreased, subsequent breakdown occurred because the running water film became thin. Moreover, because the heatproof temperature of ABS is



(a)



(b)

Fig. 5. Typical applied voltage and discharge current waveforms (a) 3D printed reactor, (b) normal silica glass reactor.

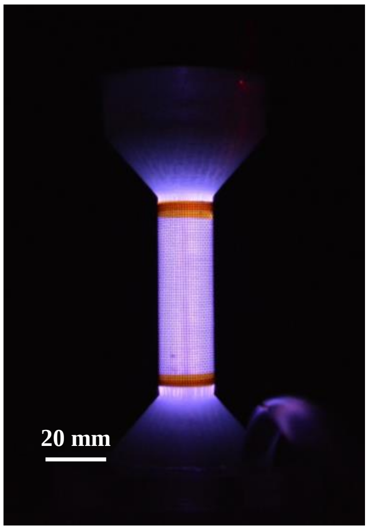


Fig. 6. Discharge image captured by the digital camera. (Applied pulse voltage: 24 kV, Tap water flow rate: 600 mL/min, Exposure time: 10 s)

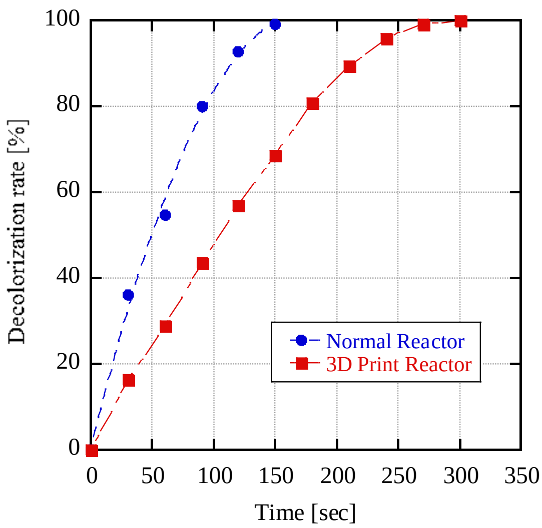


Fig. 7. Comparison of the decolorization process between 3D printed ABS plastic reactor and the normal silica glass reactor. (Dye type: Indigo carmine, Concentration of dye: 10 mg/L, Liquid volume: 200 mL, Applied voltage: 24 kV, Repetition rate: 100 pps)

100°C, a deterioration of the reactor (such as a surface deformation) occurs if the reactor is operated without the running water film, which has a function of cooling on the reactor wall. No water leakage was observed, however, via several operational trials. Furthermore, the 3D printed reactor's ability to be modified rapidly and easily using 3D CAD software is greatly advantageous.

Finally, the decolorization test for the treatment of simulated waste water was performed. Fig. 7 shows the test result of a comparison of the decolorization process between the normal silica glass reactor and the 3D printed ABS reactor. Although the decolorization speed of the glass reactor is a slightly faster than that of the 3D reactor, a degradation effect of the organic dye by the DBD plasma was confirmed using the 3D printed reactor. At present, the STL file of the reactor developed in this study is publicly available through a website via the following link: http://elecls.cc.oita-u.ac.jp/plasma/download/3Dcad.html. By introducing several modifications such as surface deformation of the reactor wall and incorporation of a catalyst, a novel plasma reactor with several functions can be successfully rendered. Consequently, 3D printing technology can be used for the conceptual design and optimization of a non-thermal plasma reactor.

IV. Conclusion

We found that 3D printing technology has opened a new door for the design and fabrication of a prototype non-thermal plasma reactor. In addition, such a technology can offer a variable, fast, and cost-efficient production process for the development of prototype plasma reactors.

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