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Non-thermal plasma dielectric barrier discharge reactor stability analysis using fiber bragg grating sensor

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Abstract. The main focus in this study is to determine the stability of the plasma generated by a Dielectric Barrier Discharge (DBD) reactor in the presence and without glass beads as dielectric enhancement. The stability of plasma was determined based on plasma temperature which measured within plasma stream. The DBD plasma reactor was designed, fabricated and being operated in an open air system. Fiber Bragg grating (FBG) was used to measure the plasma temperature. The applied voltage was increased up to 8 kV to determine breakdown voltage and evaluate plasma stability with and without the presence of glass beads as dielectric enhancement. Experimental results revealed that plasma started to generate at applied voltage about 3.0 kV. Plasma formation found generated with stable at applied voltage 8 kV for both with and without the presence of glass beads. With the presence of glass beads, the plasma temperature found much higher about 180 °C compare with without glass beads which is about 90 °C, and yet the plasma generation is still stable.

1. Introduction

Non-thermal plasma (NTP) is exist in non-thermal equilibrium state such that most of the kinetic energy absorbed by the electrons and only its temperature is much higher compare to ions and neutral gas temperature [1]. There are many different type of NTP such as corona discharges, gliding arc discharges, plasma jets, and dielectric barrier discharge (DBD) reactor. The DBD reactor is the most common utilization of NTP because of plasma formation that yield higher density of free electron and the reactor can be operated at atmospheric pressure [2]. The DBD reactor can be used for many applications such as air pollution control [3,4], wastewater treatment [5], food sterilization [6], and volatile organic compounds (VOCs) decomposition [7,8].

In NTP process, obtaining a stable NTP is important to avoid arc formation where NTP formation is no longer sustain. In addition, the formation of arc can result in dissipation of power due to current flow in high resistance environment thus can damage the NTP reactor. The stability of NTP can be categorised based on NTP discharge mode. The discharge mode of NTP can be in the form of glow, streamers or filamentary. Different applications of NTP utilize different discharge mode of plasma, for example, streamers discharge mode is used to treat cotton seed for improving plant growth [9] and glow discharge plasma is use to inactivate few bacteria on fruit [10].

Previous works have been done to examine the discharge mode of NTP at different NTP operational parameters. For instance, Feng et al. observe the beginning glow discharge on the alumina layer at the applied voltage of 22 kV for needle-plate corona discharge reactor. Increasing the applied voltage cause the glow discharge to become stable streamer corona [11]. Similarly, a study on NTP discharge mode at applied voltage range from 8 to 15 kV is carried out by Mohammadpour et al. using DBD plasma actuators under air condition. Based on their results, uniform plasma is observed at 8 kV. When increase applied voltage to 10 kV, uniform plasma with first appearance of streamers is formed. Then, filamentary discharge mode start to form at 10 kV applied voltage. When increase further the applied voltage to 15 kV, filamentary discharge mode is form [12]. Nijdam et al. stated that at even higher currents, at higher pressures, or with longer pulse durations, these discharges can transform into spark, arc, or leader discharges [13].

Previously, the discharge mode of plasma can be monitored based on the peak intensity on Optical Emission Spectroscopy (OES). For example, El-Zeer et al. observed the peak intensity and excited species of glow DBD and filamentary DBD NTP reactor at different discharge current by using OES in order to find the best discharge mode in treating the wool fabric. The result show that at discharge current 4 mA, peak intensities of nitrogen (N_2) is similar for both discharge mode. When increase discharge current to 7 mA, the peak intensity of N_2 show increasing for both discharge mode but, glow DBD are greater than filamentary DBD. Based on their OES result, they found that glow DBD show the best in treating the wool fabric due to the homogeneity and high intensity of N_2 excited species [14]. Hence, this show the importance to have a monitoring system to observe the plasma discharge mode so that not reached arc discharge. However, the OES fiber need to place from outside or near the wall of the plasma reactor in order to capture the light emission from plasma. This cause difficulty when detect the spectrum at low light emission intensity.

Other technique such as thermocouple can be used to measure reactor temperature for NTP. However, it is limited to the outer reactor wall [15,16]. This is because thermocouple can be affected by electromagnetic interference (EMI) when needed to operate at high voltage [17,18]. In addition, the temperature measurement at the wall outside plasma reactor does not represent the actual temperature inside plasma process [19].

Therefore, to overcome this problem, Fiber Bragg Grating (FBG) can be used as a real time monitoring sensor inside the plasma reactor for the temperature pattern measurement of the plasma generated. Recently, the temperature variation inside packed-bed NTP reactor have been studied by Musa et al. using FBG as temperature sensors via LabVIEW program. The germanium-doped fiber, FBG with center Bragg wavelength of 1552.5 nm was embedded in between dielectric beads, barium titanate ($BaTiO_3$) inside NTP reactor. The result prove that FBG is a suitable temperature sensor to measure inside a reactor. The spectrum from Optical Spectrum Analyzer (OSA) show that Bragg wavelength of FBG shifts as temperature increases when increasing applied voltage from power supply [19]. Significant wavelength shift occur when there is little change in temperature [20].

In this work, our aim in is to design and fabricate a DBD NTP reactor. Secondly, the applied voltage is varied to evaluate the breakdown voltage and the temperature for plasma formation using FBG. Lastly, the stability of the NTP generated by the DBD reactor at 8 kV applied voltage is determined for without and with the presence of glass beads as dielectric enhancement. The discharge mode of plasma in DBD reactor also observed in this study.

2. Methodology

2.1. Design and Fabrication of DBD Reactor

The design of DBD plasma reactor from side view are shown in Figure 1, respectively. The schematic diagram of DBD plasma reactor is illustrate in Figure 2(a) and the generation of plasma is shown in Figure 2(b).

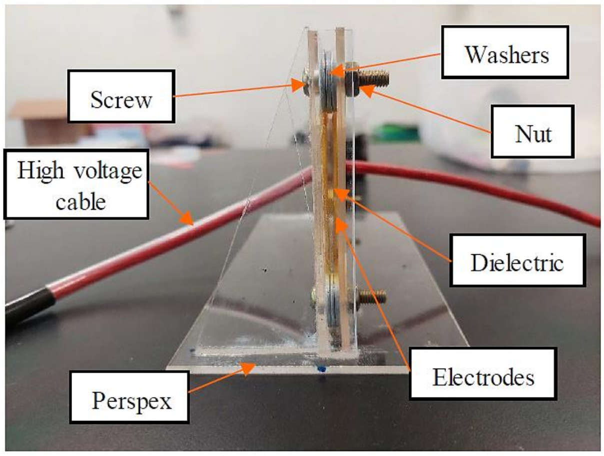

Figure 1. DBD plasma reactor from side view.

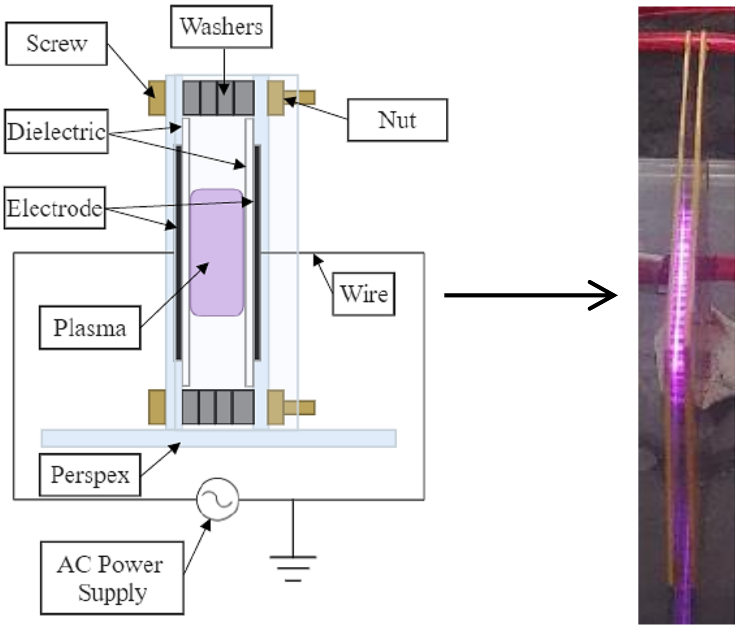

Figure 2. (a) Schematic diagram of DBD plasma reactor design (b) Plasma generation inside DBD reactor.

The DBD plasma reactor was designed and fabricated using two dielectric alumina plates in a parallel position with dimensions 14.0 cm x 6.0 cm x 0.1 cm. The two alumina plates was separated at a discharge gap distance of less than 1 cm. The alumina plates are chosen as dielectric layers due to their high melting point (T_m ~ 2000°C) and high dielectric constant (ε = 9.1). In the centre of the surfaces of the alumina plates, conductive paint is painted evenly in the shape of a rectangle with dimensions 11.0 cm x 3.0 cm and act as the electrodes to conduct electricity supplied by the copper wires. The electrode area needs to be symmetrical to each other when placing on the base. Two parallel rectangular Perspex are used to hold the plasma reactor. The alumina plates with electrodes are attached on the inner part of the Perspex body using Kapton tape. Four stainless steel screw and nuts with stainless steel flat washer were attached at each of the four sides on the corner of the Perspex. The purpose of the washers is to increase or decrease the plate separation by adding or removing the washers. Kapton tapes are used to cover and stick the copper wires to the electrodes. In addition, the insulating tapes act as a protective layer to prevent the formation of arcs. Two high performance high voltage cable were attached to the DBD reactor electrodes. Then, this high voltage cable were connected to the AC power supply.

2.2. Experimental Setup
The fiber Bragg grating (FBG) is made of a single mode fiber with operating wavelength at 1550 nm, reflectivity of 70%, grating length of 10 mm, and 3 dB bandwidth of less than 0.7 nm. FBG temperature sensitivity was 11.0 pm/°C. FBG was used as a temperature sensor to measure real plasma temperature inside the DBD reactor based on the Bragg wavelength shift. In this study, the plasma stability is monitored for without and with the presence of glass beads. For without and with the presence of glass beads, the FBG sensor is positioned in between the plates of the DBD reactor in the direction perpendicular to the direction of electrons' bombardment as shown in Figure 3. High performance high voltage cable was connected from DBD plasma reactor electrodes to the high voltage AC power supply to generate plasma. A high voltage probe (TT-HVP40, RS) and AC current probe (80i-400, Fluke) were used to monitor operating voltage and current, respectively. Both were connected to Picoscope (TDS2014, American Tektronix Co.) to record the voltage and current value.

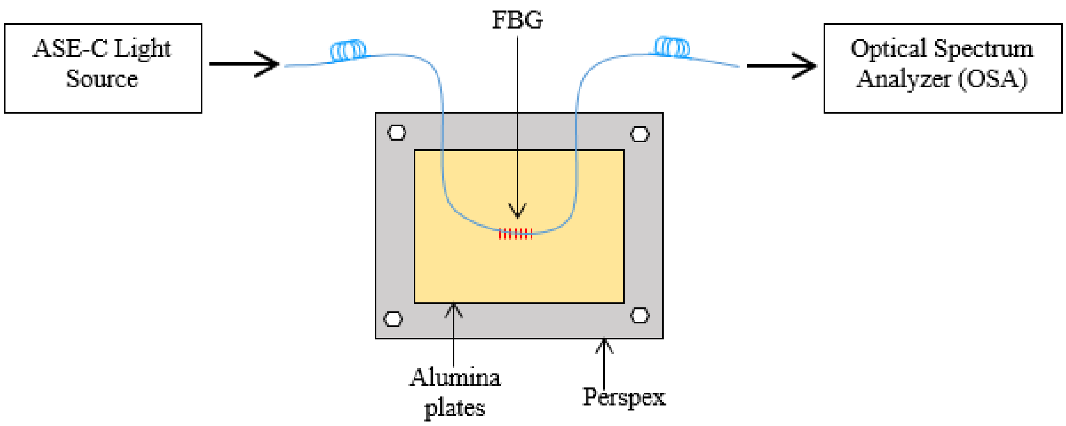

Figure 3. Position of FBG sensor inside the DBD reactor.

The FBG sensor was connected in between the external light source (ASE-C, Fiberer Global Tech Ltd.) and OSA (AQ6370D, Yokogawa) at both ends via optical connectors to obtain the Bragg wavelength shift based on the plasma temperature. The operating wavelength range for this light source is in the range of 1525 to 1607 nm. Experimental setup for DBD reactor is shown in Figure 4.

In this study, the experiment was divided into three parts. The first part is to operate the DBD reactor by varying the applied voltage from range 0 to 4 kV with increment of 0.5 kV to monitor the voltage and temperature that can generate the plasma. The formation of non-thermal plasma is monitored based on the plasma temperature via the Bragg wavelength shift for without the usage of glass beads. Second part is the comparison of non-thermal plasma stability for without and with the presence of glass beads at applied voltage, 8 kV. The fluctuation of plasma temperature is monitored via the Bragg wavelength shift. From this, stability of plasma formation can be determined. The plasma temperature was monitored for a total 10 minutes duration with time interval of 1 minute after the applied voltage is set to a desired value. Non-thermal plasma formation was captured using camera.

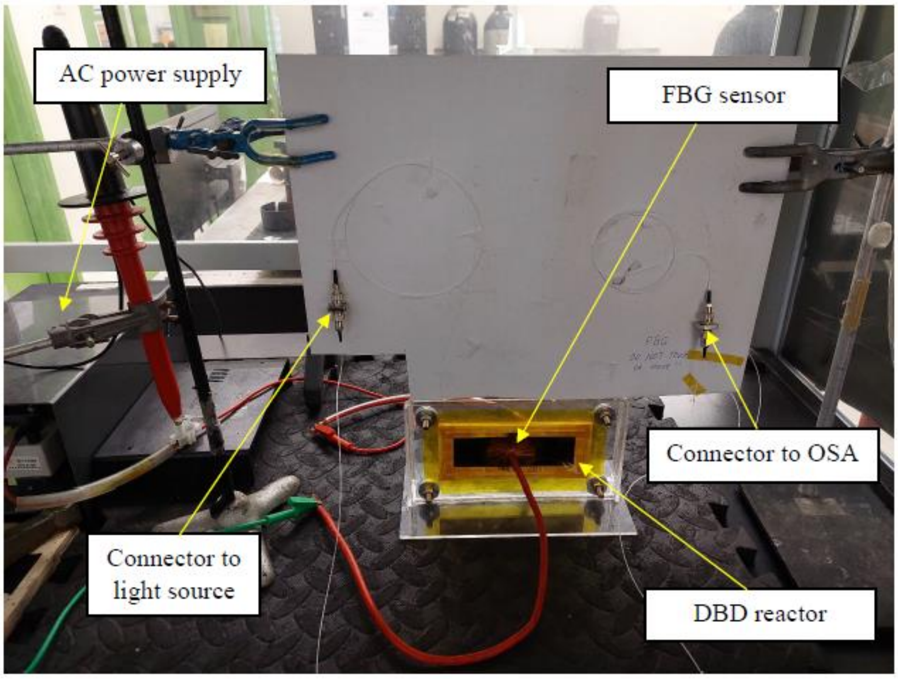

Figure 4. Experimental Setup of DBD Reactor with the fiber Bragg grating sensor embedded in the DBD reactor.

3. Results and Discussion

3.1. Non-Thermal Plasma Generation at Different Applied Voltage

Figure 5 shows the graph of temperature converted from Bragg wavelength against the applied voltage. Based on this graph, it is shown that the temperature remains the same from 0 until 3.0 kV. This indicate that no plasma is formed below 3.0 kV. When applied voltage is increased more than 3.0 kV, initial rise of plasma temperature starts to occur. At this stage, the plasma starts to generate when the initial temperature increment was detected. When increase further the applied voltage to 3.5 kV, the temperature of plasma is measured to be 54.0 °C. At this stage, plasma formation becomes stronger when the applied voltage increased further. The temperature is further increased to 65.6 °C at 4.0 kV of applied voltage.

Based on these results, the breakdown voltage of the gas molecules in DBD reactor are observed to be 3.5 kV or above in order to generate plasma. At lower energy, electrons excite slowly in vibrational form and released as heat energy causing an initial increment of plasma temperature. However, at higher applied voltage causing an increase in the electric field in the DBD reactor. So, by applying high electric field to the gas in the DBD reactor resulting in ionization of gases molecules where the outer shell electron is being ejected by strong electric fields thus producing free electrons. Then, electric field accelerates the free electrons causing collision between the energetic electrons and gas molecules or atoms which results in more outer shell electrons of atoms and molecules being ejected and accelerated. This process produced high energetic electrons and ions. The gas is ionized and plasma is generated. In addition, the high collision of energetic electrons and gas molecules releases high heat energy which causes the temperature of the plasma to increase.

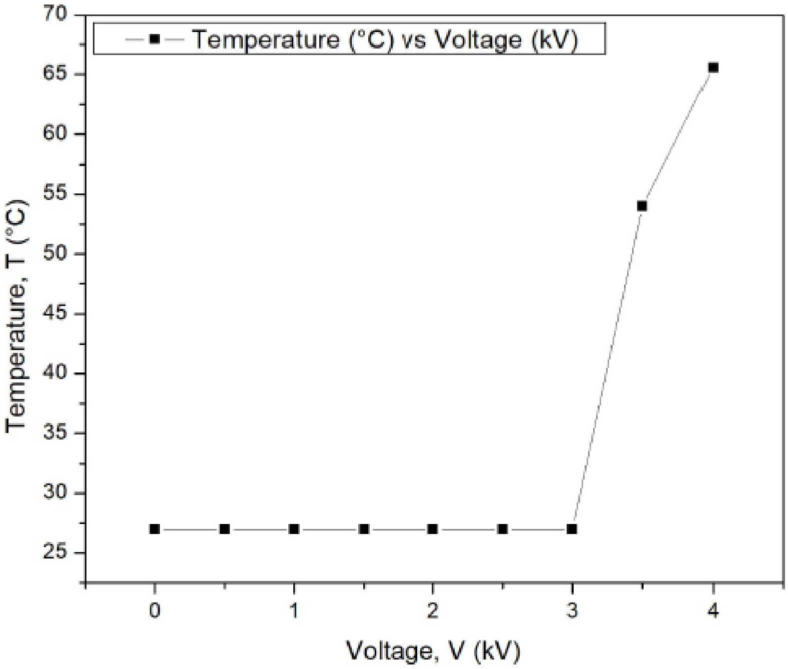

Figure 5. Graph of temperature against voltage.

3.2. Non-Thermal Plasma Stability for Without and With the Presence of Glass Beads

Figure 6 shows the comparison graph of the plasma temperature against time at 8 kV applied voltage for without and with usage of glass beads as dielectric. From this graph, it can be seen that after the plasma is generated, it still requires some time to warm up, which is found to be 5 minutes before the temperature of the plasma maintains its stability for without and with presence of glass beads. The graphs for the usage of glass beads show a high fluctuate within the first one minute from room temperature 23.1 to 123.4 °C compare to without the usage of glass beads which is from 23.1 to 57.9 °C. The increase in temperature show that the plasma is formed inside the DBD reactor. After 5 minutes, the temperature of plasma formed inside DBD reactor increase to 181.3 °C with presence of glass beads compare to without presence of glass beads which is 87.9 °C. Then, the plasma temperature reaches plateau for the presence of glass beads. The temperature is stabilized after 5 minutes of plasma formation is 182.8 °C with the usage of glass beads whereas the plasma temperature show very slightly increasing for without the presence of glass beads

According to this graph, it is found that for the setup with glass beads inside the DBD reactor at high applied voltage, the temperature of the plasma is the highest compared to without glass beads. The graph show no fluctuation in the temperature after 5 minutes of plasma generation for with the presence of glass beads. This means that the plasma has reached steady state. The presence of glass beads at high applied voltage affect the DBD reactor to achieve a higher temperature. The result show plateau and the plasma have a good stability under high temperature conditions. Therefore, the result suggests that by using higher applied voltage and increasing the dielectric constant, the DBD reactor can be enhanced to form stable plasma under high temperature.

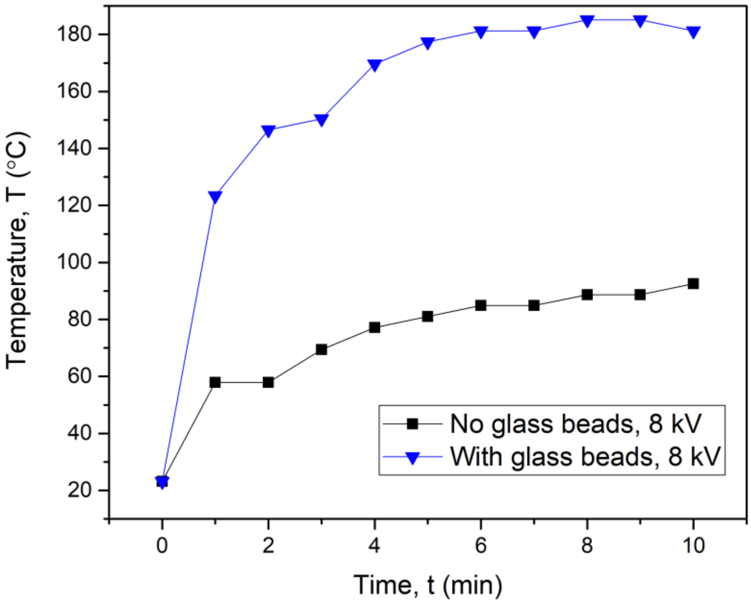

Figure 6. Graph of temperature vs time with and without beads at 8 kV applied voltage.

Based on result illustrate in Figure 6, by applying 8 kV applied voltage to the DBD reactor for both without and with presence of glass beads, the electric field is further enhanced. Hence, the rate of collision between high energetic electrons and gas molecules will increase further. Thus, the high collision then releases high heat energy which causes the temperature of the plasma to increase further for both without and with presence of glass beads. Strong plasma is generated as there is now gas of ions with high energy in between the reactor. Interestingly, the plasma temperature for addition of glass beads in DBD reactor is found to be higher than without addition of glass beads. This is because by having dielectric beads as an enhancement to the dielectric plates, the dielectric constant is increased which causes more accumulation of the charge carriers on the dielectric surface. More accumulation of charge will generate higher electric field. So, high energetic electrons are generated and collide with gas molecule. Then, releases heat energy. Hence, the plasma temperature increase much higher than that without addition of glass beads.

As can be seen in Figure 6, for without addition of glass beads, plasma temperature pattern shows a very slight increasing whereas when there is an addition of glass beads, the plasma temperature pattern shows plateau after 5 minutes. The plateau pattern indicate that with presence of dielectric beads in between the DBD reactor, DBD reactor can be enhanced to form stable discharge plasma under high temperature due to increasing of dielectric constant compare to without presence of glass beads. The slightly increasing of the plasma temperature show that the DBD without addition of glass beads still not reached stable plasma at 8 kV applied voltage.

3.3. Image for Generation of Plasma in Non-Thermal Plasma DBD Reactor

The non-thermal plasma generated by the DBD reactor without addition of glass beads can be seen in Figure 7. From the image, streamers discharge mode of plasma is considered formed inside the discharge gap of DBD reactor. This is because the plasma temperature in Figure 6 in Section 3.2 for without presence of glass beads shows a very slight increase and not reached plateau.

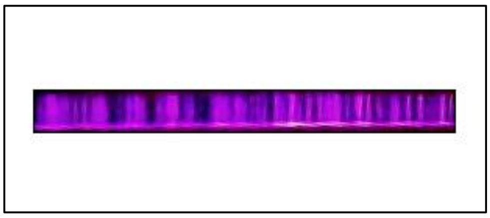

Figure 7. Non-thermal plasma generated by the DBD reactor at high applied voltage.

4. Conclusion

The DBD reactor was designed and fabricated successfully using alumina plates as dielectric barrier, conductive paint as electrodes and glass beads as dielectric enhancement. The plasma reactor can generate plasma when sufficient voltage is supplied to the electrodes and the discharge gap of less than 1 cm is set.

Plasma starts to generate when the applied voltage is more than 3.0 kV. The temperature inside the DBD reactor increase as the plasma formation increase. Plasma temperature for the presence of glass beads is higher than without the presence of glass beads. With the presence of dielectric beads in between the DBD reactor, DBD reactor can be enhanced to form stable plasma under high temperature due to increasing of dielectric constant compare to without addition of glass beads. The addition of glass beads produce a plateau graph which indicate the stable plasma temperature formed inside DBD reactor at 8 kV applied voltage. On the other hand, the plasma temperature for without the presence of glass beads show very slightly increasing and not reached plateau at 8 kV applied voltage. This can be seen from the formation of streamers discharge mode inside the DBD reactor when not using glass beads. This shows that FBG can be used as a real time monitoring temperature sensor to determine the plasma stability inside DBD reactor.

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