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Article

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Study of the reactor temperature effect on H₂ production from steam decomposition using DBD plasma

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Abstract

Heat transfer data for the effect of the reactor and surrounding temperature on the hydrogen production from water vapour decomposition using Dielectric-Barrier Discharge (DBD) plasma are reported. The water vapour was injected into the plate micro channel reactor (PMCR) where the PMCR and its surrounding temperatures were raised using an insulated constant temperature heater type in a range of 20–130 °C. This experiment was run at the following steam inlet conditions: pressure 100 kPa, temperature 300 °C and flow rates of 100–200 ml/h, while the plasma applied voltage was in a range of 14–18 kV. In particular, the concentrations of hydrogen and oxygen species were analysed using gas phase chromatography (GC). It was observed that the hydrogen concentration percent increased with the reactor and surrounding temperature increased at all tested steam flow rates. Also, it was seen that the maximum obtained H₂ concentrations were at high reactor temperature 130 °C and plasma applied voltage of 18 kV. The effect of reactor temperature on the total heat transfer resistances at different steam flow rates was investigated. The trend behaviour of these resistances reveals interesting information about how these resistances interact and distribute according to the reactor heating temperature. Also, it was found that the total heat transfer rate decreased with the reactor temperature increased while the overall heat transfer rate increased with plasma voltage and reactor heating temperature. It can be concluded that the DBD plasma effect improved by decreasing the temperature difference between input steam and the PMCR temperatures. Further, it was clear that the steam dissociation processes not mainly depending on the plasma applied voltage but also the reactor heating temperature.

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Keywords: DBD plasma; Hydrogen production; Steam decomposition

1. Introduction

Hydrogen production from water decomposition is considered one of the attractive chemical processes to generate pure hydrogen and oxygen gas. Hydrogen production technologies such as biomass, thermolysis, steam reforming etc. have been studied by Barelli et al. [1], El-Shafie et al. [2,3], and Holladay et al. [4]. Water electrolysis is

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considered the most classical one which hydrogen was produced at ordinary or intermediate temperature by Turner et al. [5]. The steam reforming process with plasma has been studied in different plasma modes using different types of feedstock such as water, natural gas, and ethanol. Hydrogen production using plasma electrolysis has been studied by Chaffin et al. [6], El-Shafie et al. [2,3], Jasinski et al. [7], Khojaa et al. [8], and Wang et al. [9]. Hydrocarbons have also been studied as a feedstock including methanol, ethanol etc. by Babaritskii et al. [10], Czyrkowski et al. [11], Paulmier and Fulcheri [12], Sarmiento et al. [13], Xi Zhen et al. [14], and Yan et al. [15]. The prediction of heat transfer between fluids and the surrounding walls are considered the most important roles in the design of hydrogen production by plasma devices like, gaseous fuel reactors, etc., the heat transfer from plasma in tube flow has been studied by Schmidt and Leppert [16]. Heat transfer measurements were developed for different plasma reactor types by Acayanka et al. [17], and Daviet and Peccoud [18]. These studies declared the importance of heat transfer information for plasma devices design and the operating temperatures. In this study, the effects of the PMCR heating and surrounding temperatures on the steam decomposition using DBD plasma were investigated. The PMCR temperature was raised by constant temperature heater type and tested at a temperatures range of 20–130 °C. The plasma was generated at atmospheric pressure and applied voltage range of 14–18 kV. The water vapour was fed into the PMCR at a temperature of 300 °C, pressure of 100 kPa and flow rates of 100–200 ml/h. The outlet gases were cooled down using ice trap and the hydrogen concentrations were measured using gas phase chromatography (GC). The total thermal resistances and overall heat transfer coefficient were determined and compared at different input steam flow rates and PMCR temperatures range of 20–130 °C.

2. Experimental

Experiment was done to focus on the effect of the reactor and surrounding temperature on the steam dissociations processes. The DBD plasma was generated in the gap between the Dielectric glass quartz type (70 mm × 70 mm × 2 mm) and the flow channel part. The dielectric glass part was installed between the high voltage electrode and ground electrode part. The PMCR was installed inside the insulated constant temperature heater type of Yamato DVS-402, the PMCR and its surrounding temperatures are heated to the same temperature before starting experiment for 1hr. The heating temperature range of 20 °C–130 °C and steam flow rates 100–200 ml/h were studied at the plasma applied voltage range of 14–18 kV. Water was fed into the reactor through the insulated pipes as a superheated steam at a temperature of 300 °C and pressure 100 kPa. The plasma applied voltage was controlled by the high voltage regulator; additionally the plasma power consumption was measured using digital power metre. Through the PMCR flow channels, the temperature of injected steam increased due to the plasma effect and steam dissociated in to hydrogen and oxygen. To avoid the recombination between hydrogen and oxygen molecules, the outlet gases were quickly cooled down in the ice trap. The outlet species samples were collected using 0.5 ml syringe and analysed using the gas chromatography instrument (GC) (see Fig. 1).

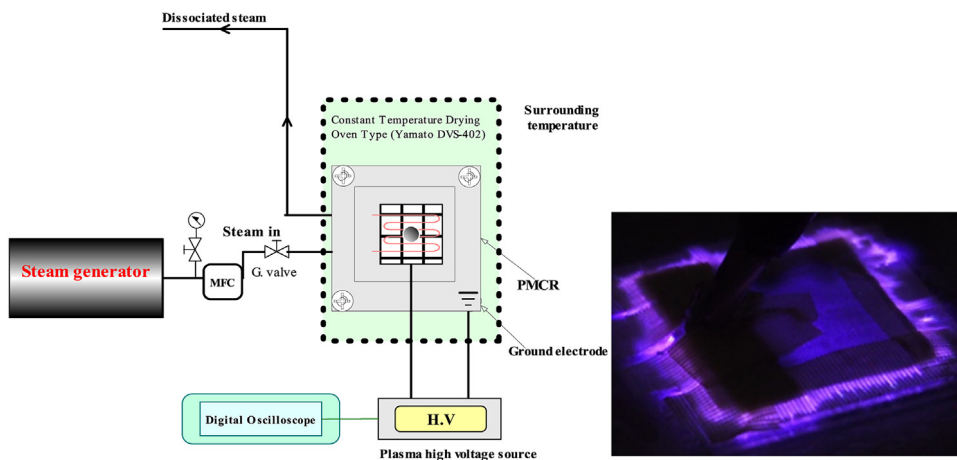


Fig. 1. Schematic diagram of the experimental setup and plasma firing photo.

3. Results & discussion

The effect of PMCR heating and surrounding temperature on the steam decomposition using DBD plasma was studied at different input steam flow rates and plasma applied voltage. The sample time collection was 2 min that for each steam decomposition experiment after starting the plasma firing. In this experiment, the outlet species concentrations were measured by GC, it is remarked that the hydrogen concentrations values were low because of the low density of hydrogen gas. To clarify the reactor and surrounding heating temperature effect, the PMCR was tested at heating temperature range of 20–130 °C. The change of H₂ concentrations versus the PMCR heating temperatures at different plasma applied voltage are shown in Fig. 2. The temperature and flow rates of steam were 300 °C and 100–200 ml/h respectively, while the applied plasma voltage was in range of 14–18 kV. It was observed that the hydrogen concentration % increased with the reactor temperature increased at all tested steam flow rates. Also, it was seen that the maximum obtained H₂ concentration at steam flow rates 200 ml/h was 2.3% at reactor heating temperature 130 °C and plasma applied voltage of 18kV, While the maximum H₂ concentration at steam flow rate 150 ml/h was 1.7151% at plasma applied voltage 16 kV. For instance, at steam input flow rate of 100 ml/h the highest value of H₂ concentration was 0.6965% at reactor temperature of 110 °C while at reactor temperature 130 °C the H₂ concentration value was 0.6288%, this difference in H₂ concentration data indicates that some of dissociated species were still remained inside the ice trap.

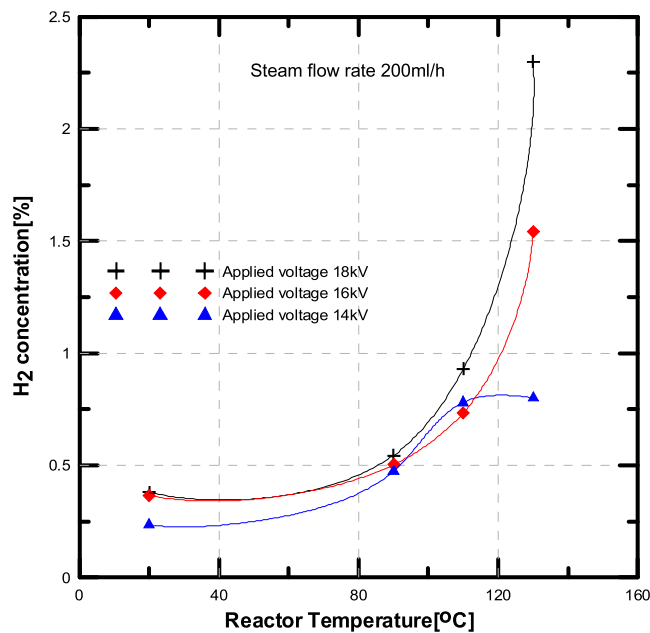


Fig. 2. The effect of surrounding temperature at steam inlet flow rate 200 ml/h.

The analysis showed the importance and effect of the reactor heating temperature on the steam decomposition process, therefore the heat transfer processes through the PMCR were investigated. The heat was transferred from steam to the quartz glass by forced convection heat transfer then by conduction through the quartz glass thickness and finally the heat was transferred by convection to the ambient. The total heat transfer rate can be written according to Incropera et al. [19] as follow:

$$dQ = n \cdot U (T_s - T_a) dA \text{ [W]} \quad (1)$$

where n is the number of flow channels in the PMCR, U the overall heat transfer coefficient ($\text{W/m}^2 \text{K}$), A the total heat transfer area (m^2), T_s and T_a the steam temperature and the PMCR surrounding temperature (K) respectively.

In this reactor, the overall heat transfer coefficient was determined according to three distinct thermal heat transfer resistances as given in Fig. 3 as follow: The forced convection heat transfer resistance from inside PMCR flow channel to reactor wall (R_{in}), the conduction resistance through the reactor wall (R_{wall}) and the convection resistance between the reactor wall and surrounding air (R_{out}).

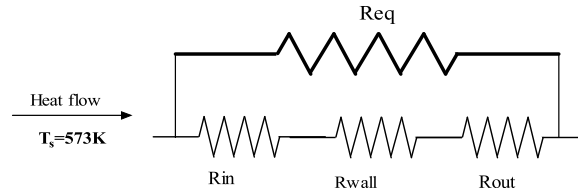


Fig. 3. Heat transfer resistances from flow channels to outside.

The total heat transfer resistances (Req) are incorporated from the sum of the previous resistances ($Req = Rin + Rwall + Rout$) and the overall heat transfer coefficient can be calculated as from the following expression: ($U = 1/Req \times Ai$) [W/m^2].

For internal heat transfer resistance calculations, the heat is transferred from steam to the quartz glass by forced convection, additionally the PMCR flow channels length was too short, and it can be considered that the flow inside the reactor channels is laminar flow. The Nusselt number values cannot be used with its limiting value of $Nu = 3.66$, the relationship proposed by Kays [20] can be used for unestablished laminar flow regime and ($0.7 < Pr < 1$) as follows:

$$Nu = 3.66 + \frac{0.104 (d/L) Re \times Pr}{1 + 0.016[(d/L) Re \times Pr]^{0.8}} \quad (2)$$

where, Re is the Reynolds number determined from the flow channel diameter d [m], L [m] is the flow channel length and Pr is the Prandtl number. The thermodynamic properties of steam were obtained from superheated stream tables at steam temperature $300^\circ C$ and pressure 100 kPa. The forced convection heat transfer coefficient h_i [W/m^2] obtained from the Nusselt number relation of $Nu = h_i d_i / k_s$, where k_s [$W/m K$] is the thermal conductivity of steam.

For the conduction and outside heat transfer resistance calculations, it was calculated using the thermal conductivity of the glass quartz and its thickness. The outside heat transfer coefficient was determined from the Nusselt number relation $Nu = h_o l / k_{air}$, while the Nusselt number was determined from [21] relation as a function of Rayleigh and Prandtl number as follows:

$$Nu = 0.68 + \frac{0.670 Ra^{1/4}}{[1 + (0.492/Pr)^{9/16}]^{4/9}} \quad (3)$$

where Ra is the Rayleigh number determined from ($Ra = Gr Pr$). While the Grashof number was estimated using,

$$Gr = \frac{g \beta (T_w - T_a) L^3}{\nu^2} \quad (4)$$

where β [K^{-1}] was thermal expansion coefficient, ν [m^2/s] was kinematic viscosity, L [m] was the flow channel length, and the reactor wall and outside air temperatures were T_w and T_a [K] respectively. The effect of reactor heating temperature on the total heat transfer resistances at different steam inlet flow rates are shown in Fig. 4. These plots indicate the influence of reactor and surrounding temperature on the total heat transfer resistances at different applied voltage, it was clear that the total heat transfer resistance decreased with the PMCR reactor and surrounding temperature increased. Also, each of the total heat transfer resistances plot represents a specific steam inlet flow rate which it depends on the reactor temperature and operational conditions. The behaviour of these resistances as the reactor temperature changes reveals interesting information about how these resistances interact and distribute according to the reactor heating temperature.

The overall heat transfer coefficient was determined based on Eq. (1). The change of overall heat transfer coefficient at different PMCR heating temperatures and steam flow rates 200 ml/h, 150 ml/h, and 100 ml/h are shown in Fig. 5. It was found that the overall heat transfer coefficient increased by the PMCR heating temperature and plasma applied voltage increased. Therefore, the steam decomposition into their constituent's molecular elements is affected by the PMCR heating temperature and its surrounding temperature. Also, it was observed that the plasma effect increased by decreasing the temperature difference between input steam and reactor temperature. It was concluded from this study that the steam decomposition using DBD plasma was influenced by the reactor and surrounding temperature.

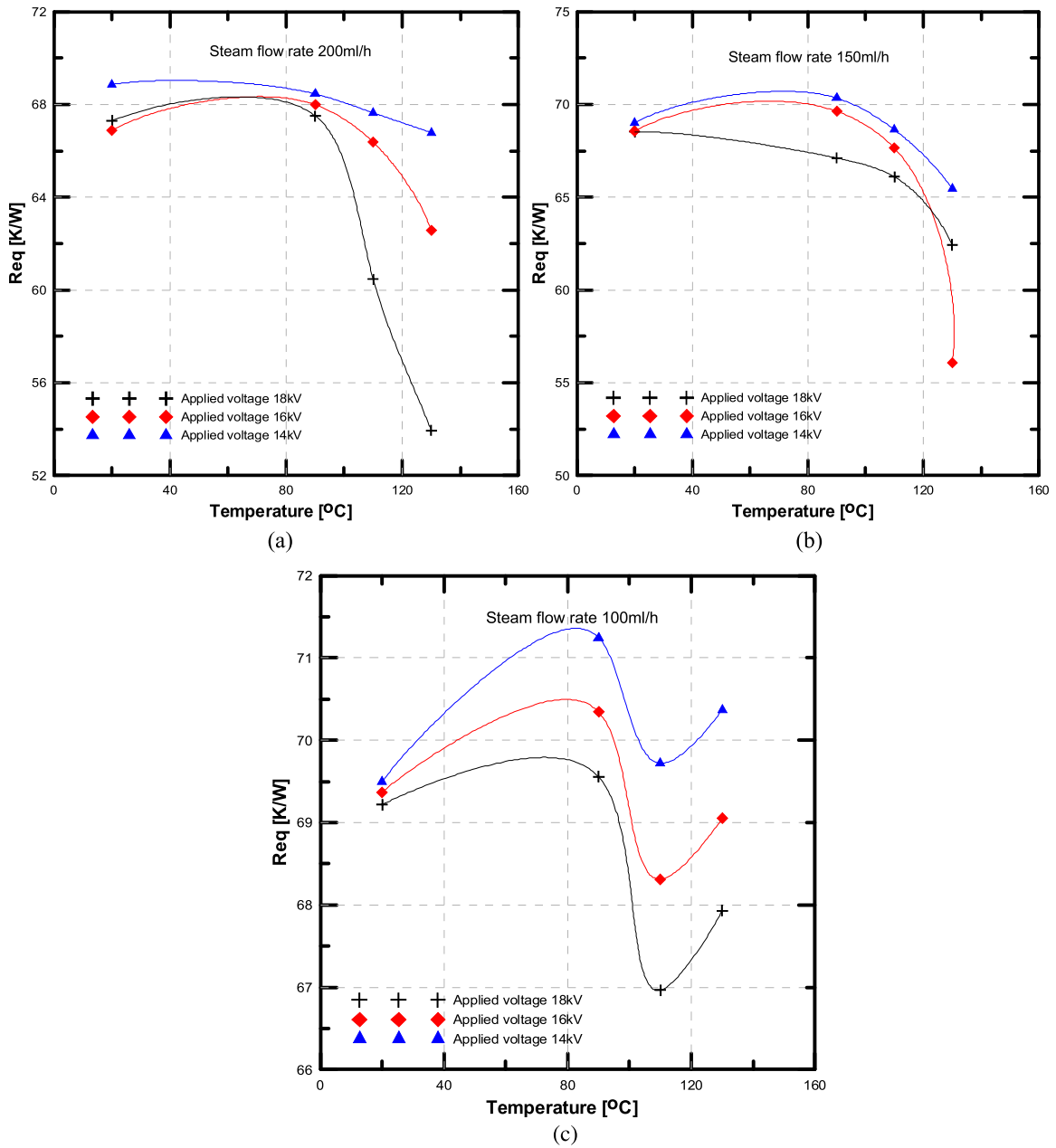


Fig. 4. Heat transfer resistances from flow channels to outside.

4. Conclusion

The effects of PMCR and surrounding and PMCR temperature on the steam decomposition processes using plasma were studied. This experiment was tested the PMCR heating temperature in a range of 20–130 °C, while the steam temperature and flow rates were 300 °C and 100–200 ml/h respectively. It is observed that the hydrogen concentration percent increased with the reactor and surrounding temperature, additionally, the maximum H₂ concentration was obtained at steam flow rate 200 ml/h, reactor temperature 130 °C and plasma applied voltage of 18kV. The effect of the PMCR reactor temperature on the total heat transfer resistances and overall heat transfer coefficient were investigated. It is showed that the total heat transfer resistances decreased with the reactor

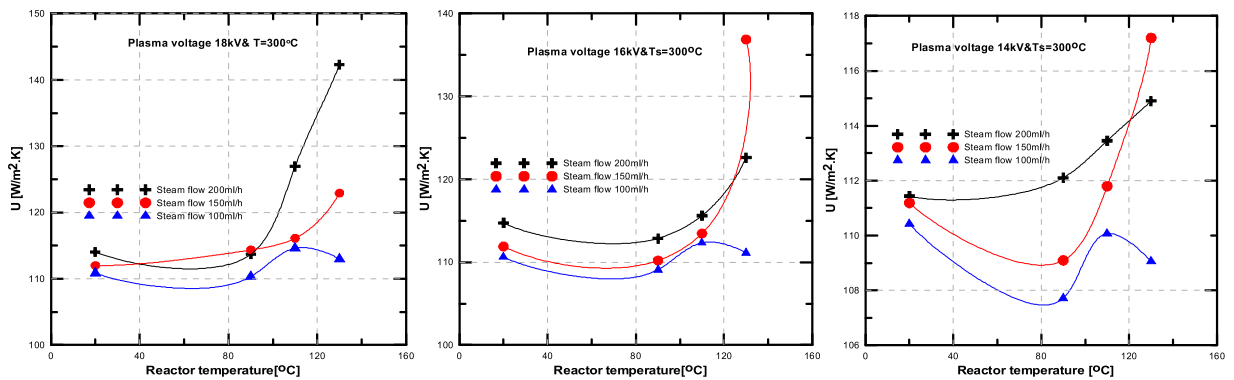


Fig. 5. Overall heat transfer coefficient at different steam flow rates.

temperature increased, further the trend of these resistances showed how these resistances interact and distribute according to the PMCR temperature. Also, the most interesting thing was that the DBD plasma effect increased by decreasing the temperature difference between input steam and the PMCR temperature. Furthermore, it was found that the steam dissociation processes not mainly depend on the plasma applied voltage but also the surrounding and reactor temperature.

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