# An experimental investigation on a single tubular SOFC for renewable energy based cogeneration system

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ABSTRACT

Having negative impacts on environment and the scarcity of resources of conventional fossil fuels, fuel cell technology draws more attention as an alternative for providing the electrical energy in parallel with thermal energy. In this study, a single tubular solid oxide fuel cell (SOFC) with an electrolyte of Yttria-Stabilized Zirconia 8 mol% ceramic powder was experimentally investigated. The investigation illustrated the effects of three different fuel flow-rates (175 ml/min, 250 ml/min and 325 ml/min) and two operating temperatures (650 °C and 750 °C) on the output electrical and thermal powers. The highest electrical voltage (open circuit) and overall output power of the cell were found to be 1.1 V and 5.30 W respectively for the fuel flow-rate of 250 ml/min at the operating temperature of 750 °C. The electrical power and efficiency were increased about 18.80% and 1.27% respectively for the increase of operating temperature from 650 °C to 750 °C for a constant fuel flow-rate of 250 ml/min, where; thermal power and efficiency were increased about 33.33% and 10.51% respectively for the same condition. The overall efficiencies of the fuel cell were obtained about 80.42%, 77.49% and 60.73% for the fuel flow-rates of 175 ml/min, 250 ml/min and 325 ml/min respectively for the operating temperatures of 650 °C. On the other hand, the overall efficiency of the cell was found to be 83.38% at the operating temperature of 750 °C and fuel flow-rate of 250 ml/min. The investigation recommends that for achieving higher efficiency, fuel flow-rate should be lower and operating temperature should be higher.



## 1. Introduction

In today's world, the development of a nation is completely dependent on the energy stored by that nation. Actually, the energy stored by a country reflects the economy, technological advancement and life style of the people of that country. Among all the energy sources, fossil fuels are widely used to handle the energy demand in industry, communication, transportations, educational institutes, offices as well as domestic appliances. But, during last few decades, the anxiety has been being arisen for not only the negative impact of fossil fuel on environment but also the scarcity of the resources of it. Hence, there are so many researchers around the world have been sweating to find out some environmentally friendly renewable energy technologies as the alternatives of fossil fuels [1,2]. The energy, having the characteristics of renewability, inexhaustibility and naturally replenished, is defined as renewable energy. Most of the renewable energy sources are pollution free and sometimes cheaper compared to the fossil fuels. Solar, wind, hydropower, biomass, tidal, wave and geothermal are considered the main sources of renewable energy [3]. Besides, now-a-days, fuel cell technology is also being adeptly introduced for using as a renewable energy source.

However, there are several amounts of heat energy exhausted and wasted out during the utilization of fossil fuels as well as renewable energies which cause the lower efficiency of the system. Hence, the term "cogeneration" is introduced to increase the system efficiency by using this wasted heat [4]. The term "cogeneration" indicates an energy system which is capable to produce the mechanical or electrical energy along with thermal energy in parallel. The International Energy Agency (IEA) has reported that more than 35% of total world energy is consumed in building sector of which domestic water heating as well as space heating accounts for 75% [5]. The report also mentioned that about 1.3 billion people from the developing countries are living far from the grid connection, where wood is used as prime energy source which causes

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deforestation [6]. Hence, a cogeneration energy system can play an important role to handle this huge thermal energy demand as well as to raise the overall efficiency over 85% compared to the conventional energy conversion efficiency (30–35%) [7].

Recently, there are several researches done related to the cogeneration system all over the world. For example, Raj et al. [5] have made a critical review on various renewable energy based cogeneration energy systems including biomass based, solar energy based waste-heat recovery based etc. Though the aforementioned cogeneration systems are widely practising, now-a-days, the cogeneration system with fuel cell technology has been extensively drawing the attention of the researchers for its higher efficiency compared to conventional cogeneration systems. Indeed, higher energy conversion efficiency, environmental compatibility and relatively independent of size are the main advantages of fuel cells compared to the traditional cogeneration system [8].

A fuel cell is an electrochemical device which generates electricity in parallel with thermal energy by an exothermic reaction occurred inside the fuel cell. The hydrogen (sometimes natural gases and/or hydrocarbons) is considered as fuel that reacts with air (oxygen) and produces water and heat [9]. There are many types of fuel cells which are recently used in cogeneration purposes. In our experimental investigation, we used a single tubular solid oxide fuel cell (TSOFC) because of having some additional features compared to other fuel cell technologies. For example, the fuel flexibility (usage of various types of fuels), higher energy conversion efficiency as well as the output gas (water and others) with higher temperature (600–1050 °C) which is suitably usable for cogeneration or combined heat and power (CHP) purpose. Besides, it has the capability internally to extract the hydrogen from the fuel; thus there is no additional hydrogen reformer is required. Moreover, the tubular SOFC has some additional features over planner SOFC which help to overcome some problems like sealing, cracking, thermo-cycling as well as fuel cell start-up time [10]. Hence, our experimental investigation was done with a TSOFC for the cogeneration purpose.

There are several research efforts have been made on the development, mathematical analysis and investigation of the TSOFC. For example, a simulation has been done by Zhang et al. [11] for a stack of tubular SOFC using AspenPlus™. Methane was considered as the fuel in their simulation. The result shows that the maximum electrical efficiency should be achieved about 52% if the fuel utilization factor is considered about 0.85. A module with some micro-tubular SOFCs was fabricated by Watanabe et al. [12]. The module was designed to handle the electrical load about 700 W. The investigation illustrates that the module would show 47% of low heat value (LHV) if the fuel utilization factor is considered about 0.75. A cone shaped tubular SOFC with ($Ni_{0.75}Fe_{0.25}$–5%MgO)/YSZ anode was investigated experimentally by Liu et al. [13]. The investigation confirmed that the output DC voltage of 2 V and power of 4 W were found by using the CO fuel in both moist and dry modes at the operating temperature of 800 °C. They summarized that CO or the fuels with CO increased the stability of operation and seemly applicable in the fuel cell with the anode made from ($Ni_{0.75}Fe_{0.25}$–5%MgO)/YSZ.

An experimental investigation was done by Guerra et al. [14] on an anode-supported tubular Ni/YSZ SOFC. The fuel cell fed by biogas was tested at an operating temperature of 800 °C which showed an output current of 17.5 A with the efficiency about 43.4%. A micro-tubular anode supported tubular SOFC was investigated experimentally by Calise et al. [15]. The investigation was performed by considering the thermodynamic as well as electrochemical performances of the fuel cell and the highest electrical efficiency was found about 37%. Their investigation concluded that the efficiency as well as the fuel utilization factor got higher for lower fuel flow-rate and the higher operating temperature showed the higher performance for both the electrical and thermal purposes.

Considering four different operating temperatures and pressures, an anode-supported tubular SOFC was investigated by Zhou et al. [16]. It was found that the performance of the cell increased significantly with the increase of operating pressure. Besides, the cell performance was more affected due to the lower operating temperature than the higher operating temperature. They concluded that at fuel utilization factor of 0.7 and operating temperature of 800 °C, the cell showed the output power of 25 W. Two cogeneration plants containing tubular SOFC have been installed in the TurboCare workshop at Italy which was investigated experimentally by Gariglio et al. [17]. The investigation consisted of a graphic comparison between the two fuel cells considering the fuel utilization factor and the setup temperature. With some optimization analysis and regression models, they concluded that both fuel cells showed the same manner for the result of stack voltage with respect to the fuel utilization factor, but the voltage sensitivity differed for different operating temperatures.

However, the above discussion and the literatures illustrate that there are many mathematical models; designs and experimental investigation have been done dealing with planner and tubular SOFC; where most efforts have been given to concern with the electrical performance of the cell [18–26]. But, among them, there are very few, especially the experimental efforts using tubular SOFC, concerning with the cogeneration purpose. Therefore, this experimental investigation deals with a single tubular SOFC for providing a cogeneration effort by generating electrical power in parallel with thermal energy. Also, the promising applications of high operating temperature the fuel cells like tubular SOFC have been highlighted at the end of the manuscript.

## 2. Methodology

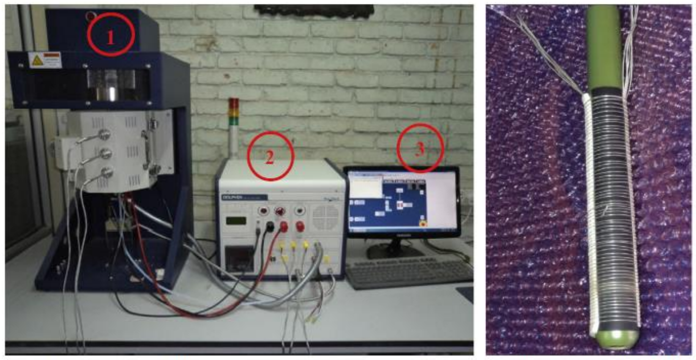
This section consists of some subsections containing the system description, operating principle and procedure of the experiment. Finally the mathematical procedure with required equations are described to calculate the various parameters like energy, power, efficiency, fuel utilization factor and uncertainties etc.

### *2.1. System description*

The experimental setup with a single tubular SOFC has been installed in the Chemical Laboratory of the Department of Chemical Engineering, Faculty of Engineering, University of Malaya, Malaysia. Fig. 1 shows the photograph of the arrangement of the experimental setup (in Fig. 1a) as well as the single fuel cell (in Fig. 1b) which has been investigated throughout the experiment. The total setup has been supplied by one of the renowned electrochemical products suppliers named "WonATech" from South Korea.

The system consists of the following four major parts:

i. The fuel cell with furnace: The furnace is red-marked as number 1 in the photo (Fig. 1a). The furnace contains the fuel cell inside it vertically. Actually a single tubular SOFC is wrapped by the furnace. The functions of furnace are to isolate the fuel cell thermally from the environment as well as to provide the required thermal power for heating up the fuel cell. It is also monitored and controlled by the fuel cell test system in terms of heating up/cooling down regularly, or to keep the operating temperature constant.
ii. The fuel cell test system: The fuel cell test system (product name: Dolphin™ SOFC test system) is red-marked as




(a) The arrangement of the equipment of the experimental setup (b) The single tubular SOFC

**Fig. 1.** The photograph of the experimental setup.

number 2 in the photo (Fig. 1a). It measures the required parameter like output voltage, output current, operating temperature etc. It is a testing unit which is directly connected with the furnace and provides the data to the data acquisition system.

iii. The data acquisition system: It is a spontaneous data stored system which is managed as well as connected with a computer. It collects the data from fuel cell test system and stores it to the memory of the computer. This part is marked as number 3 in the photograph (Fig. 1a).

iv. The cylinders with hydrogen and air: There are also a couple of cylinders in the system (not seen in the photograph). The cylinders are connected with the furnace. The cylinder-1 provides the fuel (hydrogen) to the anode surface of the fuel cell and the cylinder-2 delivers the air to the cathode surface of the cell tube. The flow-meter connected with the cylinder measures the fuel flow rates.

The specification of the fuel cell used in our experiment is given in Table 1.

*2.2. Operating principle of the fuel cell*

The tubular SOFC is fabricated with a pair of tubes (an inner tube and an outer tube). The outer tube is named as "cell-tube". The inner surface and the outer surface of the cell tube are regarded as the cathode and anode side respectively. The solid oxide electrolyte is kept between the anode and cathode surfaces. The cylinder-2 injects the air over the activated surface area of cathode and the cylinder-1 provides the fuel gas (hydrogen) to the activated area of anode surface. Each oxygen molecule gets negatively ionized by receiving four electrons from the cathode terminal and each hydrogen molecule gets positively ionized by donating two electrons to the anode side. Hence, a potential difference as well as the electromotive force (e.m.f) is arisen between anode and cathode terminal of the fuel cell.

On the other hand, the produced oxygen ions travel through electrolyte to reach into anode and react with hydrogen ions to produce water. Since, the production of water from hydrogen and oxygen is an exothermic chemical reaction; hence the reaction exhausts huge thermal energy around the cell. The chemical reaction is shown in the following equations [27]:

$$\text{Cathode reaction}: \; O_2(g) + 4e^- \rightarrow 2O^{2-}$$

$$\text{Anode reaction}: \; 2H_2(g) + 2O^{2-} \rightarrow 2H_2O + 4e^-$$

$$\text{Overall cell reaction}: \; 2H_2 + O_2 \rightarrow 2H_2O + \Delta H$$

where $\Delta H$ indicates the enthalpy exhausted in the reaction.

Thus the system provides the thermal energy in parallel with electrical energy which indicates a promising renewable energy solution for power and heat which is termed as "cogeneration" or "CHP (combined heat and power)" system.

**Table 1**
The specification of the tubular SOFC.

| Parameters | Specifications |
|---|---|
| Operating temperature | 600–800 °C |
| Cathode material | Lanthanum strontium manganite (LSM) |
| Anode material | Nickel (Ni) |
| Electrolyte material | Yttria-Stabilized Zirconia 8 mol% ceramic powder |
| Thickness of electrolyte | $3 \times 10^{-5}$ m |
| Cell length | 320 mm |
| Anode activation length | 100 mm |
| Cathode activation length | 100 mm |
| Cell outer diameter | 22 mm |
| Cell active area | 69.12 $cm^2$ |

*2.3. Working procedures and required equations*

The fuel cell was heated-up by the furnace until its operating temperature was achieved. In the fuel cell, 1 °C temperature increased within each 30 s. Hence, we needed to heat up the fuel cell about 5 and half hours as well as more than 6 h to reach the operating temperatures of 650 °C and 750 °C respectively. During the process, the fuel (hydrogen) and air were allowed to flow from the cylinders to the fuel cell. The pressure inside the fuel storage cylinder was 20 atm and operating pressure was 1 atm. The fuel flow rate was manually set and controlled. We investigated the performance of the fuel cell for three fuel flow rates (175 ml/min, 250 ml/min and 325 ml/min) at 650 °C operating temperature. Besides, a single fuel flow rate (250 ml/min) was also provided to investigate the cell performance at an operating temperature of 750 °C. Each flow rate was continued for 30 min and there was a 30 min time-interval to change the fuel flow rates. The following equations were used to calculate various parameters like fuel utilization factor, thermal and electrical power, thermal and electrical efficiency, overall efficiency etc.

The fuel utilization factor, $U_f$ was calculated by the following equation [28]:

$$U_f = \frac{J}{nF\dot{N}_{fuel}} \tag{1}$$

where $J$ is the electrical current density (in A/m$^2$) produced by the fuel cell, $\dot{N}_{fuel}$ is the fuel flow rate (in mole/s), $n$ is a constant (for hydrogen, $n = 2$) and $F$ is the Faraday's constant ($F = 96485$ C/mole).

The enthalpy (J/mole) provided by the fuel was calculated by the following equation [29]:

$$\Delta H_{fuel} = C_P \times \Delta T \tag{2}$$

where $\Delta T = T_{op} - T_{ref}$ (the difference between operating temperature, $T_{op}$ and reference temperature, $T_{ref}$) and $C_p$ is the specific heat capacity of the gas component which was calculated using the equation below [29]:

$$C_P = a + bT_{op} + cT_{op}^2 + dT_{op}^{-2} \tag{3}$$

where $a$, $b$, $c$ and $d$ are the constants and $273\ \text{K} \leqslant T \leqslant 1800\ \text{K}$ [29].

The Eq. (2) was also used to calculate the enthalpy provided by the air, $\Delta H_{air}$ (J/mole) and the enthalpy exhausted around the fuel cell, $\Delta H_{H_2O}$ (J/mole) for the exothermic reaction of producing steam.

Total thermal energy was calculated in terms of number of mole of fuel as well as oxygen utilized in the reaction. The equation could be shown as below:

$$\Delta H_{react} = n \times U_f \times \Delta H_{H_2O} \tag{4}$$

where $n \times U_f$ was the number of moles of steam produced by the electrochemical reaction ($n$ = number of hydrogen moles supplied). In this study, the sign of the enthalpy is neglected but the value is considered in calculations. Hence, we determined the thermal efficiency of the system using following equation:

$$\eta_{thermal} = \frac{\Delta H_{react}}{n\Delta H_{fuel} + \frac{n}{2}\Delta H_{air}} \times 100\% \tag{5}$$

It may be noted that all the enthalpies were calculated in terms of each second; hence this thermal energy can also be said as thermal power.

The electrical power generated by the fuel cell was calculated by the following equation:

$$P = VI = V \times (J \times A) = V \times (U_f nF\dot{N}_{fuel}) \times A \tag{6}$$

where $V$ (Volt) and $I$ (Ampere) are the voltage and current generated by the fuel cell across the anode and cathode terminal respectively (Eq. (6) has been simplified with the help of Eq. (1)). Besides; $A$ (m$^2$) denoted the cell active area. Hence, we calculated the electrical efficiency of the fuel cell by the equation below [30]:

$$\eta_{electrical} = \frac{P}{n\Delta H_{fuel} + \frac{n}{2}\Delta H_{air}} \times 100\% \tag{7}$$

Finally, the overall efficiency of the fuel cell was determined by summing up the electrical as well as thermal efficiency as below:

$$\eta_{overall} = \eta_{thermal} + \eta_{electrical} \tag{8}$$

The uncertainty analysis was also done throughout the calculation. All the equations modified and used to calculate the uncertainties are obtained from the literature [31]. The uncertainty of output electrical power was calculated by the following equation:

$$w_P = \left[\left(\frac{w_V}{V}\right)^2 + \left(\frac{w_I}{I}\right)^2\right]^{1/2} \times P \tag{9}$$

where $w_V$(=0.25% of measured voltage) and $w_I$ (=0.25% of measured current) are the uncertainties for the voltage and current measurement respectively. The uncertainty of fuel utilization factor was measured using the equation below:

$$w_{U_f} = \left[\left(\frac{w_I}{I}\right)^2 + \left(\frac{(-1)w_{\dot{N}_{fuel}}}{\dot{N}_{fuel}}\right)^2\right]^{1/2} \times U_f \tag{10}$$

where $w_{\dot{N}_{fuel}}$ (=1% of measured flow-rate) denotes the uncertainty of the fuel flow-rate meter. The uncertainty of the enthalpy exhausted by the cell reaction was calculated by following equation:

$$w_{\Delta H} = \left[\left(\frac{w_{C_P}}{C_P}\right)^2 + \left(\frac{w_{\Delta T}}{\Delta T}\right)^2\right]^{1/2} \times \Delta H_{react} \tag{11}$$

where uncertainty of specific heat of water, $w_{CP}$ and uncertainty of temperature difference, $w_{\Delta T}$ were calculated by following equations:

$$w_{C_P} = \left[\left(\frac{\partial C_P}{\partial T}\right)^2 \times (w_T)^2\right]^{1/2} \tag{12}$$

$$\frac{\partial C_P}{\partial T} = b + 2cT - 2dT^{-3} \tag{13}$$

$$w_{\Delta T} = \left[\left(\frac{\partial \Delta T}{\partial T_{op}}\right)^2 (w_{T_{op}})^2 + \left(\frac{\partial \Delta T}{\partial T_{ref}}\right)^2 (w_{T_{ref}})^2\right]^{1/2} \tag{14}$$

where $w_{T_{op}}$ and $w_{T_{ref}}$ are the uncertainties for the measurement of operating temperature and reference temperature respectively. (For K-thermocouple, $w_{T_{op}} = w_{T_{ref}}$ = 0.75% of measured temperature).

## 3. Result and discussion

This section illustrates the significant results found throughout the experimental investigation, the uncertainty analysis of experimental data, the comparison of present study with other works and finally a critical discussion on the performance of the fuel cell.

### 3.1. Result analysis

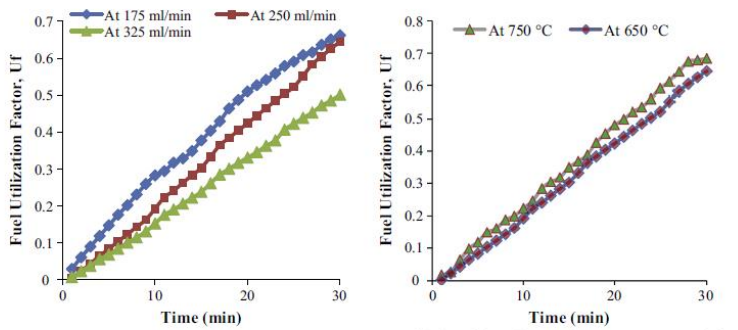
The cell goes in steady states and provides a stable electrical as well as thermal power after 25 min. Hence, all the data are taken and analyzed for 30 min. Besides, all the parameters (i.e. voltage, fuel utilization factor, electrical and thermal powers and all efficiencies) are discussed as well as compared at maximum output electrical power condition (at 28th minute).

Fig. 2(a) shows the variation of the fuel utilization factor for three different fuel flow-rates as the operating temperature of 650 °C and Fig. 2(b) illustrates the variation of the fuel utilization factor for two different operating temperatures for a constant fuel flow-rate of 250 ml/min.

It is observed form Fig. 2 that, for a constant operating temperature, the fuel utilization factor decreases with the increase of fuel flow rates. The $U_f$ were found to be 0.64, 0.60 and 0.47 for the fuel flow-rates of 175 ml/min, 250 ml/min and 325 ml/min respectively at 650 °C cell operating temperature. It happens due to having the inversely relationship between the fuel flow rate and fuel utilization factor (see Eq. (1)). Besides, for a constant fuel flow-rate (250 ml/min), the higher operating temperature (750 °C) ensures more reactions and hence shows the higher utilization factor (0.67) compared to the lower operating temperature (see Fig. 2(b)).

The Fig. 3 shows the relation between current density and output voltages of the fuel cell for various fuel flow-rates and operating temperatures.

It is seen from Fig. 3 that cell output voltage and current density maintain an inversely proportional relation for all flow-rates as




(a) The effect of fuel flow-rate on fuel utilization factor at operating temperature of 650 °C

(b) The effect of operating temperature on fuel utilization factor for a constant fuel flow-rate of 250 ml/min.

**Fig. 2.** The effect of fuel flow-rates and operating temperatures on fuel utilization factors.

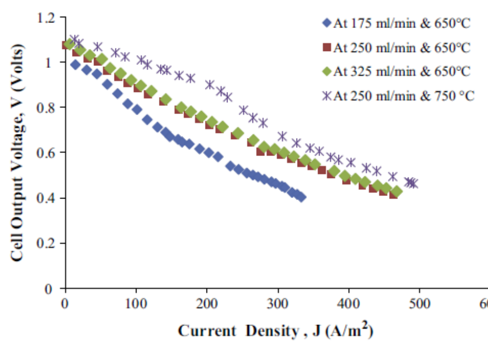



**Fig. 3.** The variation of cell voltages with output current density.

well as operating temperatures. Besides, for the same fuel flow-rate (250 ml/min), the higher operating temperature shows the higher current density. It happens due to the higher reaction rate in higher operating temperature. Besides, at constant temperature (650 °C), the higher fuel flow-rate ensures higher current density compared to others.

Fig. 4 shows the relation between the output cell voltage and fuel utilization factor. It is observed from figure that the fuel utilization factor, $U_f$ has a significant impact on output cell voltage. Actually, there is an inversely proportional relationship between the fuel utilization factor and the output cell voltages. Since, fuel utilization factor depends on the fuel flow-rate (inversely proportional relation) and output current (proportional relation) (see Eq. (1)), hence with the increase of fuel utilization factor, the output voltage decreases.

Fig. 5 exhibits the variation of voltages and currents of three different flow-rates for the same operating temperature (650 °C). It is shown from figure that the cell output voltage decreases and current increases with the time at different fuel flow-rates. It happens due to variation of the external electronic load (programed in fuel cell test system) connected across the anode and cathode terminals of the fuel cell. The figure also ensures that the higher flow-rate can provide the higher voltage and current at a constant operating temperature.

On the other hand, the increment of cell operating temperature ensures higher cell output voltage as well as current compared to lower operating temperature for a constant fuel flow rate (see Fig. 6).

The Fig. 6 shows a comparison between voltages and currents of two different operating temperatures (650 °C and 750 °C) at a constant fuel flow rate of 250 ml/min. Besides, Fig. 7 makes a comparison among various electrical powers for different operating temperatures as well as fuel flow rates.

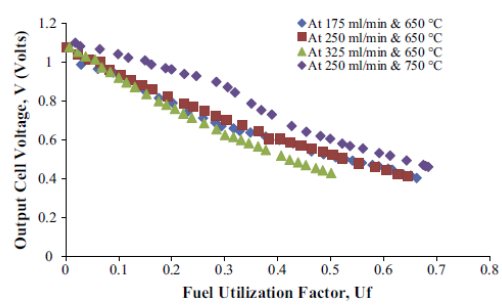



**Fig. 4.** The relation between the output cell voltage and the fuel utilization factor.

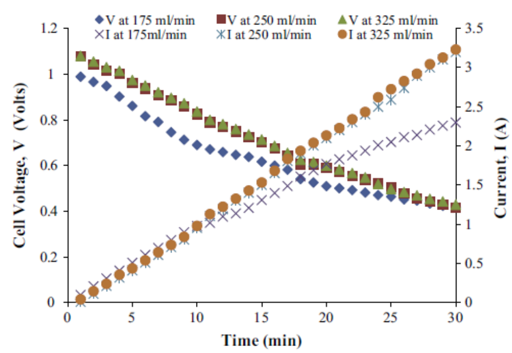



**Fig. 5.** The variation of currents and voltages with three different fuel flow-rates at the cell operating temperature of 650 °C.

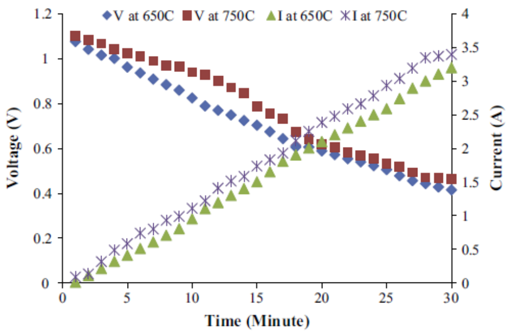



**Fig. 6.** The variation of currents with voltages with operating temperatures at same fuel flow-rate.

Fig. 7(a) illustrates that the electrical power goes higher with the increase of fuel flow-rate at constant operating temperature. The maximum electrical powers were found to be 0.96 W, 1.33 W and 1.38 W for the fuel flow-rates of 175 ml/min, 250 ml/min and 325 ml/min respectively at 650 °C cell operating temperature. It happens due to the more fuel flow which ensures more hydrogen to the anode surface, hence more reaction and more electrical power.

On the other hand, the higher operating temperature favors fuel cell to generate more electrical power compared to the lower operating temperature with same fuel flow-rate (see Fig. 7(b)). The maximum electrical power was found to be 1.58 W for the fuel flow-rate of 250 ml/min at 750 °C cell operating temperature which is 18.80% higher compared to the lower operating temperature for the same fuel flow-rate. Since temperature behaves as a catalyst to increase the electrochemical reaction, hence higher operating temperature ensures more reaction as well as electrical power compared to the lower operating temperature.

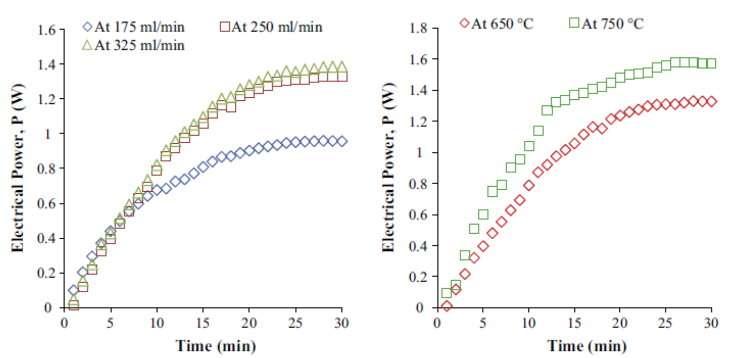
Though the electrical power increases with the increase of fuel flow-rate, consequently the electrical efficiency goes down with the increase of fuel flow-rate. The phenomenon is illustrated in the Fig. 8(a). It is seen that the lower fuel flow-rate (175 ml/min) exhibits the higher electrical efficiency compared to the larger fuel flow-rates. The maximum electrical efficiencies were found to be 25.19%, 24.41% and 19.57% for the fuel flow-rates of 175 ml/min, 250 ml/min and 325 ml/min respectively at 650 °C cell operating temperature.

On the other hand, Fig. 8 (b) illustrates that the increase of operating temperature aids to increase the electrical efficiency for a constant fuel flow-rate of 250 ml/min. The maximum electrical efficiency was found to be 24.72% for the fuel flow-rate of 250 ml/min at 750 °C cell operating temperature which is 1.27% higher compared to the lower operating temperature for the same fuel flow-rate.

The effect of fuel flow-rates and operating temperatures on output thermal power of the fuel cell is shown in Fig. 9. The results show that the thermal power generated during the exothermic reaction to produce water increases gradually with the increase of fuel flow rates which is shown in Fig. 9(a). The maximum thermal powers were found to be 2.06 W, 2.79 W and 2.83 W for the fuel flow-rates of 175 ml/min, 250 ml/min and 325 ml/min respectively at 650 °C cell operating temperature. Besides, the higher operating temperature raises the thermal power compared to the lower operating temperature for the constant fuel flow-rate of 250 ml/min which is shown in Fig. 9(b). The maximum thermal power was found to be 3.72 W for the fuel flow-rate of 250 ml/min at 650 °C cell operating temperature which is 33.33% higher compared to the lower operating temperature for the same fuel flow-rate. It happens due to the same reasons mentioned in results analysis for the electrical power.

In spite of increasing of thermal power, the thermal efficiency decreases with the increase of fuel flow-rates which is shown in the Fig. 10(a). It exhibits that the efficiency becomes greater if the fuel flow-rates become smaller. The maximum thermal efficiencies were found to be 55.23%, 53.08% and 41.16% for the fuel flow-rates of 175 ml/min, 250 ml/min and 325 ml/min respectively at 650 °C cell operating temperature. It is because; the electrochemical reaction does not increase as much as compared to the increase of fuel flow. Hence, the amount of exhausted output enthalpy increases slowly compared to the enthalpy provided as input.

Besides, the Fig. 10(b) shows the effect of operating temperature on the output thermal power. It illustrates that the higher operating temperature enables fuel cell to provide more thermal power as well as efficiency compared to the lower operating temperature at a constant fuel flow-rate of 250 ml/min. The maximum electrical efficiency was found to be 58.66% for the fuel flow-rate of 250 ml/min at 750 °C cell operating temperature which is 10.51% higher compared to the lower operating temperature for the same




(a) The variation of electrical power with fuel flow-rate at constant temperature

(b) The variation of electrical power with two different operating temperature at constant fuel flow-rate.

**Fig. 7.** The variation of electrical power with various fuel flow-rates and operating temperature.

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