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Numerical investigation of the influence of operating conditions on the performance of PEMFC powered Unmanned Aerial Vehicle (UAV): a statistical approach

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ABSTRACT: In this research, the effect of various operating conditions on the performance of an Unmanned Aerial Vehicle (UAV) with a PEMFC propulsion system is surveyed using a statistical approach, namely the Design of Experiment technique (DOE). Results indicate that increasing operating pressure improves the efficiency parameter for both the PEMFC and the system 3.5% and 14.5% respectively. Although increasing cathode stoichiometry augments the PEMFC efficiency, it plummets the system efficiency up to 30.6%. In addition, the influence of operating altitude on the PEMFC efficiency is negligible, while it causes a substantial decline in the system efficiency (more than 30%). As proved, at any desired operating altitude, maximum efficiency for the system obtains when the operating pressure and cathode stoichiometry are set at their maximum and minimum bound, respectively.

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1- Introduction

An unmanned aircraft (UAV) is a flying robot capable of performing defined operations automatically or remotely controlled. Nowadays, the application of polymer membranes and solid oxide fuel cells in the propulsion system of UAVs is expanding. Using each of these types of electrochemical cells in drones has some advantages and disadvantages. For example, polymer membrane fuel cells have low start-up time, operating temperature, and noise. However, the issue of water management in them is always a big operational challenge [1]. Unlike polymer membrane fuel cells, the high operating temperature of solid oxide fuel cells has caused the evaporation of water produced in them and no need for water management. It is also possible to benefit from the thermal waste of solid oxide fuel cells in gas turbines and thus increase the overall efficiency of the system. In addition, systems that benefit from solid oxide batteries in their propulsion are more stable and durable. But it should be noted that high operating temperature means a long start-up time, the need for special materials, and slower system dynamics [2]. In this research, a thermodynamic cycle based on a polymer membrane fuel cell is designed for the UAV propulsion system. In the following, while implementing the thermodynamic equations of conservation of mass and energy, the efficiency of the fuel cell and the system is calculated. After that, the test design method is used to know the effective parameters and check the effect of different performance conditions. Finally, by using the numerical model obtained from the experimental design method, the performance of the system is optimized at three operating heights.

2- Methodology

In this research, a thermodynamic cycle has been designed and analyzed to supply the required power of the UAV. In this system, a polymer membrane fuel cell is used to provide power. Figure 1 shows the overview of the cycle studied in this research. As can be seen, this cycle includes four main units:

• Fuel supply unit: This unit includes a hydrogen tank, pressure valve, ejector, heat exchanger, distributor, and hydrogen storage tank at the inlet and outlet side of the anode stack.

• Air supply unit: This unit includes a heat exchanger, air compressor, control valve, distributor, and air collector at the inlet and outlet side of the cathode stack. In this unit, first, the temperature of the incoming air in the heat exchanger increases. Then, while passing through the compressor and control valve, the desired temperature and pressure are provided to enter the fuel cell stack.

• Power supply unit: this system includes 3 stacks of

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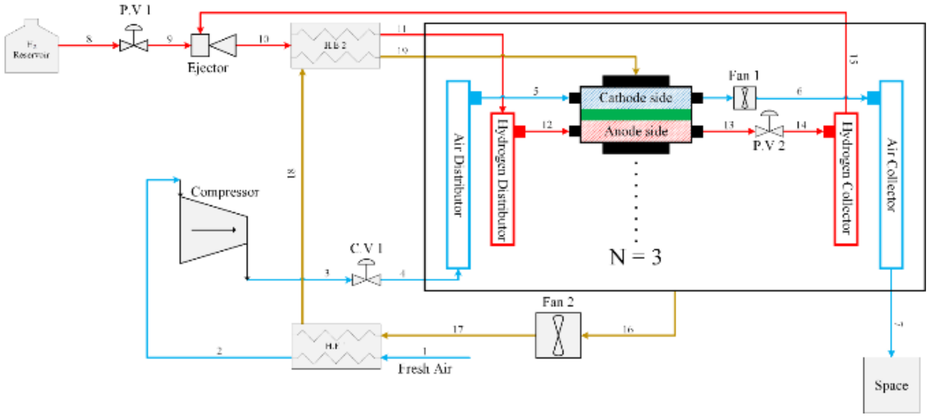

Fig. 1. Schematic of the proposed cycle in the present research.

polymer membrane fuel cells manufactured by Horizon company. This stack is considered a self-moistening fuel cell and includes 72 mono cells with an active surface of 80 cm^2. Based on the contents of the stack guide, this battery can produce 1 kW of power at a voltage of 2.43 V and a corresponding current of 24 A, and a maximum operating temperature of 65 °C.

• Heat recovery unit: In polymer membrane fuel cells, electricity, heat, and water are known as reaction products. During this process, the air temperature decreases and cool air enters the power supply unit again to cool the stacks.

The design assumptions used are summarized as follows:

• The system is simulated in a steady state,

• Gases in the fuel cell stack behave similarly to ideal gas,

• The pressure drop on the anode side of the battery is ignored. But the pressure drop on the cathode side is calculated based on the values determined in the stack guide,

• The relative humidity of the reactants when entering the stack is zero.

In the present study, the efficiency of the fuel cell and the efficiency of the system have been analyzed simultaneously. The thermal efficiency of the fuel cell stack is calculated by dividing the generated power of the cell by the maximum available power according to equation (1) [3]:

$$\eta_{fc} = \frac{\dot{W}_{fc}}{\dot{n}_{H_2}^{Cons} \times HHV} \quad (1)$$

To calculate the efficiency of the system, its network should be calculated according to equation (2):

$$\dot{W}_{net} = \dot{W}_{fc} - \dot{W}_{comp} - \sum \dot{W}_{fan} \quad (2)$$

In the above relationship, they represent the production power of the fuel cell stack, the power consumption of the compressor, and the power consumption of the fan. Finally, the efficiency of the system is determined using equation (3):

$$\eta_{sys} = \frac{\dot{W}_{net}}{\dot{Q}_H} \quad (3)$$

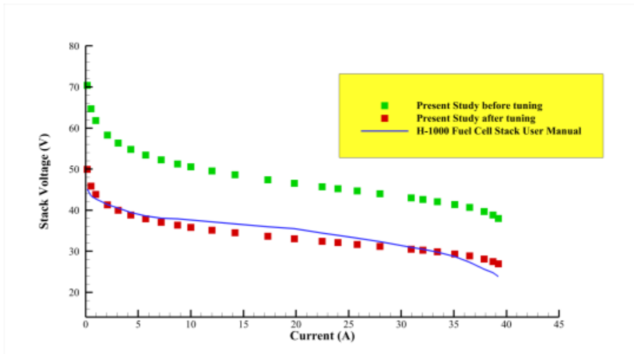

Fig. 2. Validation of the numerical model.

3- Results and discussion

As mentioned earlier, present study uses the zero-dimensional model to simulate the performance of the fuel cell stack. In this model, several parameters such as the geometry of the flow channels, the porosity of the gas infiltration layer and the catalyst, and the formation and transfer of water between the two sides of the anode and the cathode are neglected. Therefore, one should not expect complete agreement between the numerical model and the one provided by the manufacturing company. Figure 2 shows the polarity curve for the studied fuel cell stack in three states before applying the correction factor, after applying the factor, and the curve provided by the manufacturer. To calculate the correction factor, first, the error between the numerical model and the polarity diagram provided by the manufacturing company is calculated at several points. Next, the average of these errors is calculated (~0.28) and then

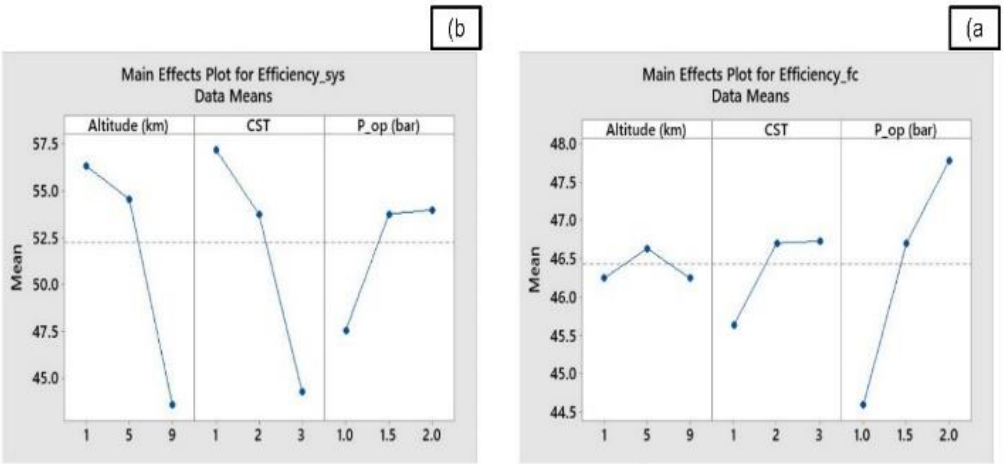

Fig. 3. Diagram of the main effects of fuel cell stack and system efficiencies.

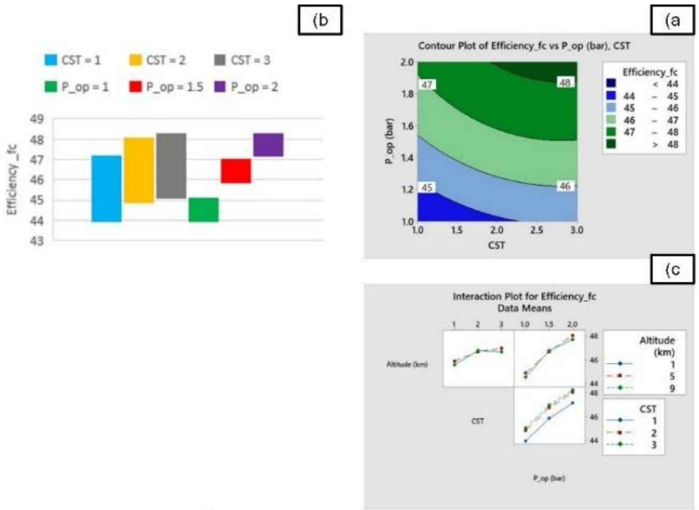

Fig. 4. (a) the contour of fuel cell stack efficiency versus cathode stoichiometry and working pressure, (b) sensitivity analysis of fuel cell stack efficiency, (c) The effects of independent input parameters on fuel cell stack efficiency

correction factor parameter was calculated (~0.72). Based on the calculations, the numerical model error is equal to 4.72%, which is an acceptable error.

The main effects diagram is obtained by averaging the values at each level. Therefore, in this diagram, the simultaneous effects of the parameters on the response variable are not considered. Studying the results of the diagram in Figure 3a shows that on average, the efficiency of the fuel cell stack increases with the increase in working pressure. Examining the graphs extracted for the system efficiency values shows (Figure 3b) the increase in working pressure from the low limit (= 1) to the average (= 1.5) improves the performance of the system, while increasing it again from the middle limit (= 1.5) to the upper limit (= 2) does not affect the efficiency. On the other hand, increasing the stoichiometry of the cathode and operating height always reduces the efficiency of the system.

According to Figure 4a, fuel cell efficiency always increases with increasing cathode stoichiometry and working pressure. Therefore, the best performance is obtained at the stoichiometric rate and high working pressure. However, battery operation in low cathode stoichiometry and low-pressure results in a sharp drop in efficiency. Examining the sensitivity of fuel cell efficiency for fixed values of cathode stoichiometry and working pressure in Figure 4b shows that always with increasing cathode stoichiometry, the minimum, and maximum fuel cell efficiency increases slowly. The same is true for the work pressure. But this increase in efficiency occurs with a greater gradient for working pressure. Examining the parameter interaction diagram in Figure 4c also shows that the effect of operating height on fuel cell stack efficiency can be neglected. On the other hand, increasing the stoichiometry of the cathode from the lower limit value (=1) to the middle limit value (=2) causes a jump in the efficiency of the fuel cell, although increasing it again to the upper limit value (=3) does not have much effect on the stack efficiency. Also, increasing the working pressure always results in improving the efficiency of the fuel cell stack.

4- Conclusion

In the current research, the effect of different operating conditions on the efficiency of a UAV with a polymer membrane fuel cell propulsion system has been studied using the test design method. The obtained results are summarized as follows:

- Based on the results of the Pareto chart, cathode stoichiometry, working pressure, and their squared values can be considered as parameters affecting the fuel cell and system efficiencies, and the effects of operating height can be ignored.
- By increasing the stoichiometry of the cathode, the efficiency of the fuel cell increases, but due to the increase in the power consumption of the compressor, this results in a decrease in the overall efficiency of the system.
- Increasing the operational height does not affect the efficiency of the fuel cell.
- At all operating heights, the highest system efficiency is achieved when the stoichiometric rate of the cathode is at the minimum value (=1.2) and the working pressure is at the upper limit (=2).

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