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Evaluation of Model and Performance of Fuel Cell Hybrid Electric Vehicle in Different Drive Cycles

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Abstract**—**In recent years fuel cell vehicles are rapidly appearing all over the globe. In less than 10 years, fuel cell vehicles have gone from mere research novelties to operating prototypes and demonstration models. At the same time, government and industry in development countries have teamed up to invest billions of dollars in partnerships intended to commercialize fuel cell vehicles within the early years of the 21st century.

The purpose of this study is evaluation of model and performance of fuel cell hybrid electric vehicle in different drive cycles. A fuel cell system model developed in this work is a semi-experimental model that allows users to use the theory and experimental relationships in a fuel cell system. The model can be used as part of a complex fuel cell vehicle model in advanced vehicle simulator (ADVISOR).

This work reveals that the fuel consumption and energy efficiency vary in different drive cycles. Arising acceleration and speed in a drive cycle leads to Fuel consumption increase. In addition, energy losses in drive cycle relates to fuel cell system power request. Parasitic power in different parts of fuel cell system will increase when power request increases. Finally, most of energy losses in drive cycle occur in fuel cell system because of producing a lot of energy by fuel cell stack.

Keywords**—**Drive cycle, Energy efficiency, energy consumption, Fuel cell system.

I. INTRODUCTION

IN a fuel cell, electricity generated from chemical reaction is transformed to mechanical energy via an eclectic motor [1], [2]. Nowadays, there are several kinds of fuel cells in which PEM and SOFC can be pointed out as the most important ones. High power density and low operating temperature in addition to quick start capability of PEM fuel cells make them attractive for automobile manufacturing company [3], [4] so that in 1970', General Motors in the USA developed the first automobile using fuel cell, which was an unsuccessful project regarding the low efficiently and huge volume of its fuel cell.

However, huge founding provided by Department of Energy after Persian Gulf War and additional investment provided by the United State Ministry of Interior in 1990 create a serious revolution in fuel cell technology in automobile industry. This policy is continued to the present time. Nowadays, billon dollars spend in fund by these two ministries and private sectors to accelerate the development of the fuel cell components and its related infrastructures.

Ever increasing concentration in fuel cell research and its application in automobile industry provide an appropriate background for tremendous research in this field, especially in PEM fuel cells. For instance, Doss and his colleague in 1998 created a model for fuel cell systems to demonstrate power generation in which the temperature of the fuel cell was below than 300 k [5].

Quyang and his co-workers in 1999 studied five different fuels like liquefied natural gas, liquefied oil gas, methanol, hydrogen, de ethyl ether, fixture tropes diesel and electricity in five different vehicle as spark, diesel, hybrid electric, electric, and fuel cell vehicle. The results revealed that fuel cell could be recognized as high performance and low pollutions system [4]. In 2000, Ogburn and his colleague examined the design and structure of a vehicle using fuel cell system. This device was consists of a small fuel cell stack for producing a requested average power and a battery for providing power in different moving conditions [6]. Boettner and his colleague in 2001 proposed a fuel cell model for using in a vehicle. In this model, auxiliary system like air compressor and cooling system are investigated [7].

At the same year, a model for proton exchange membrane fuel cell was presented in which Ceraaolo and his colleague studied fuel cell stack reactions using physical chemistry relationships [8]. In 2004, a mathematical model for simulating the transient phenomena in fuel cell PEM system was presented by Pathapati and his colleague [9]. In 2006, Kim and his colleague submitted a strategy for power management to optimize fuel consumption in a fuel cell hybrid vehicle in which different component in various scales are modeled [10]. They also investigated the operating point for each part and proposed an effective procedure to optimize the fuel consumption. In the same year, Swanson studied the performance of several hybrid battery-fuel cell vehicles with ADVISOE software and declared an effective method for computing the energy efficiency. In addition to the above mentioned researches, in 2007, Paldani and his associates reviewed a vehicle with optimized structure which two reservoirs are embedded in the system. They not only developed software with Matlab but also studied different methods to reduce fuel cell consumption [11].

To continue previous study and optimizing energy consumption, in this paper, operating of an ordinary hybrid auto-

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mobile using fuel cell with PEM technology is investigated. This model and its fuel cell systems are a semi empirical model, which uses different experimental and theoretical relations to simulate a stack of a fuel cell and different equipments similar to compressors, condensers, radiators and fans. Using numerical results of this semi empirical model as an input for ADVISOR software, it is possible to study various effects in an automobile like energy efficiency, consumption, power, pollution, and automobile operations in different moving cycle.

II. MODELING OF AN AUTOMOBILE

A small hybrid automobile using fuel cell is simulated by the Advisor software, which its characteristics are shown in Table I. The automobile is consists of three main systems as follow: electric locomotion, fuel cell and battery systems.

TABLE I
FUEL CELL VEHICLE SPECIFICATION

Specification	value	unit
Glider mass	592.4218	Kg
Vehicle mass	1335	Kg
Frontal area	2	M2
Coefficient of aerodynamic drag	0.335	-
MC_AC75	75	KW
Fuel cell system power	50	KW
Lead acid battery	26	Ampere

In this model a 50 KW, fuel cell accompanied by a 26-Ampere phosphoric acid battery is used. To simulate an automobile, it is necessary to implement an appropriate model and strategy for proper controlling of the fuel cell system and automobile. It is also required to provide a proper set of inputs to the software, which will be described in details accordingly.

A. Demonstrating Different Models for Simulating Fuel Cells

As it is shown in Fig. 1, fuel cell systems in automobile is consists of a stack, reservoir, compressor, radiator, humidifier, pump and other devices which are used to optimized the stack operations [12].

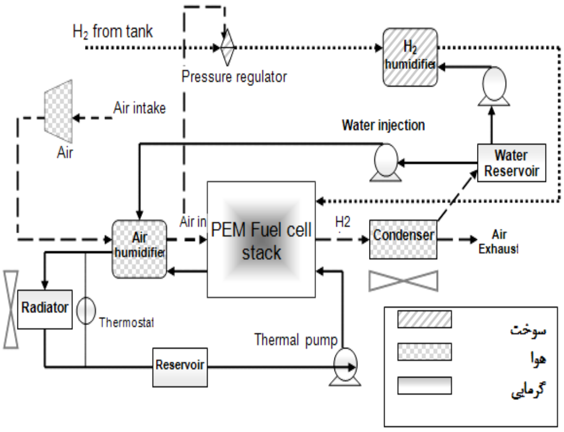


Fig. 1 Fuel cell system in vehicle

This paper divides fuel cell system into three subsystems including fuel, air and heating.

For the fuel system, it is now possible for all components to be embedded in the automobile. In this system, before hydrogen enters into the stack, water is used to humidify this reactant in the humidifier. Then additional hydrogen is returned to the stack inlet to reuse. A pressure regulator also synchronized the pressure of hydrogen and air in the system.

Air system consists of air compressor, humidifier and condenser. To increase stack efficiency, it is necessary to soar the operating pressure. Increasing the difference between surrounding and system air pressure can result in improving fuel cell operation. Therefore, it is imperative to pressurized air before entering to the steak by an air compressor. In this paper, a screw compressor is used. According to the design of the model, air pressure will rise by increasing the cell load. There is always a simple linear relationship between the current of fuel cell stack and operating pressure of the cathode as shown in Fig. 2.

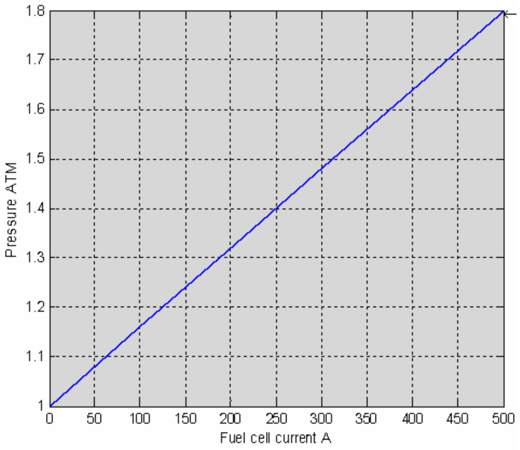


Fig. 2 Strategy control of operating pressure

Compressor operating fluctuation is also dependent on the moving cycle and controlling strategy of the model.

Due to the specific characteristic of PEM fuel cell, before air entrance to the stack, water is used to humidify it. A pump to the air going into the humidifier directly sprays it. A condenser also is utilized to balance the water in the air system.

Water vapor exited from the stack with the exhaust air stream is compacted by a compressor and used due to the system requirement. Compressor fan is utilized to reject additional heat from the compressor. Finally, heating system is consisted of a reservoir and radiator. Radiator is used to maintain fuel cell stack temperature by rejecting additional heat to the surrounding.

Radiator fan is act similar to the condenser fan. A simple thermostat as a part of radiator inhibits wasting of heat in the proper operating system temperature. A refrigerant is pumped from a reservoir and enters to the system. Additional heat of stack is rejected by cooling system; hence, heating operation of the system is controlled.

In order to simulate the model shown in Fig. 1, mass, energy and momentum conservation as lumped equations [12] are applied for each parts. Then, these codes are written by Matlab and entered as an input to Advisor software. It is notable that in extended model in order to investigate the electrochemical behavior of fuel cell, all wasting effects like ohm, density and activation [13] are considered. Besides, in this model operating pressure is corrected with the temperature. This correction can reduced cold activation effects. The correction factor, a constant value dependent on temperature, is added to the operating pressure. Temperature interval is assumed between 0 and 100 degree Celsius. Correction interval, act like pressure, is added using operation pressure strategy.

The most essential part in fuel cells is the stack. If low heat value is used for hydrogen (LHV) in energy conservation equation, it is assumed that all generated water in the fuel cell exists in vapor phase. Therefore, water produced in cathode is saturated and is converted to liquid in the stack. During this process, heat is generated. In this model, there are three kinds of inlet flow and two kinds of outlet from the stack. Simplifying the model, water vapor flow accompanied by the air and hydrogen in the stack are analyzed separately. Hence, there are five inlet flow (air, water vapor plus air, hydrogen, water vapor plus hydrogen and refrigerant) and three outlet flows (air, water vapor plus air and refrigerant).

Inlet and outlet flows from the stack are shown in Fig. 3 which outlet hydrogen is excluded. It is also considered that all the water vapor in the hydrogen flow is diffused in the membrane and extracted by the cathode [8]. Generally, this model assumed that hydrogen would not transport high amount of energy. Therefore, heat generated by hydrogen is ignored. Assuming a stack as a good exchanger for mass and heat, the entire outlet flow and heat mass of a stack are at the same temperature.

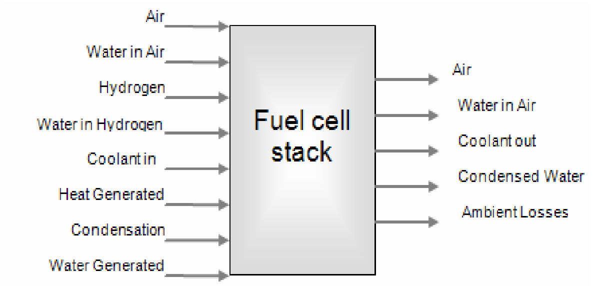


Fig. 3 Block diagram simulation of fuel cell

B. *Battery Selection Strategy*

In the hybrid automobiles, various kinds of battery were observed. These batteries include Phosphoric Acid, Nickel Metal Hydride, Lithium Polymer, Sodium Nickel Chloride and Nickel Cadmium. In Table II, different characteristic of batters are presented. The biggest number in each parts of the table indicates the best operation for that specification.

TABLE II
THE CHARACTERISTIC OF RECHARGEABLE BATTERIES

Power density		Energy density		Kind of Battery
Wh/l	Wh/kg	Wh/l	Wh/kg	
955	412	71	35	Phosphoric Acid
600	220	200	80	Nickel Metal Hydride
445	310	220	155	Lithium Polymer
200	100	150	90	Sodium Nickel Chloride
-	-	150	50	Nickel Cadmium

Due to poisonous characteristic of Cadmium in Nickel Cadmium batteries and heavy and giant volume of Nickel Chloride batteries in addition to rare use of lithium polymer batteries in automobile industries, they are not studied in the present paper. Power density (w/kg) is an important factor in hybrid vehicles inasmuch as a great amount of power should be generated in them. Although Energy and power density in Nickel Metal Hydride batteries are suitable for the vehicles, they are very expensive in the market and are not considered in this paper. Finally, Phosphoric acid batteries have the highest power density among all batteries. They are also accessible in the market and cheaper in the price. Their charging and discharging efficiency are suitable as well. Therefore, this kind of battery is used in the present work.

C. *Describing Control Strategy*

Operation of the model in receiving power from fuel cell system is described as follow: At first, power is requested from moving cycle of a vehicle, the amount of necessary power which should be received from the fuel cell and batteries is determined by the controlling strategy which is written by a code in Matlab Simulink and applied as an input to the Adviser software.

In the present model, a repetitive methodology is implemented and for simplicity a single input variable, input power, is defined. Controlling strategy is worked based on the requested current form stack of fuel cell. In the present model, a simple linear relation between stack current and operating pressure of the cathode is assumed. Therefore, this strategy is qualified adequately to control an air compressor velocity and pressure. In fact, the increase in the load of the fuel cell system leads to the rise of the pressure outlet of the compressor. After performing the necessary computation, similar to polarization curve calculation, power density, voltage and partial pressure, the outlet of the electrochemical model that is heat, gross power, and parasitic power is obtained. Due to the existing losses and parasitic power, the calculated gross power from electrochemical model is more than the requested net power. Hence, it is imperative to subtract parasite power from gross power to obtain the desirable net power.

Using an iterative methodology, the computations related to the electrochemical model and heat are repeated until the desirable net power is acquired. In the present model, some restrictions like voltage and minimum power of fuel cell is applied.

D. *Moving Cycle*

Operation of a fuel cell vehicle like fuel consumption, efficiency and pollutions depends on moving cycle types. Therefore, in this model five different types of moving cycle are considered which their characteristics are described as follow:

Japanese moving cycle 1015: this cycle is proposed by NREL in 1998. The maximum velocity of this cycle is 69.97 km/hr and its maximum acceleration is 0.79 m/s2. Average velocity and pressure are also 22.68 km/hr and 0.57 m/s2.

NEDC moving cycle: this cycle is an urban cycle, which builds from a combination of ECE and EUDC. The maximum velocity is 120 km/hr and maximum acceleration is 1.06 m/s2. Average velocity and acceleration are 33.21 km/hr and 0.54 m/s2 respectively.

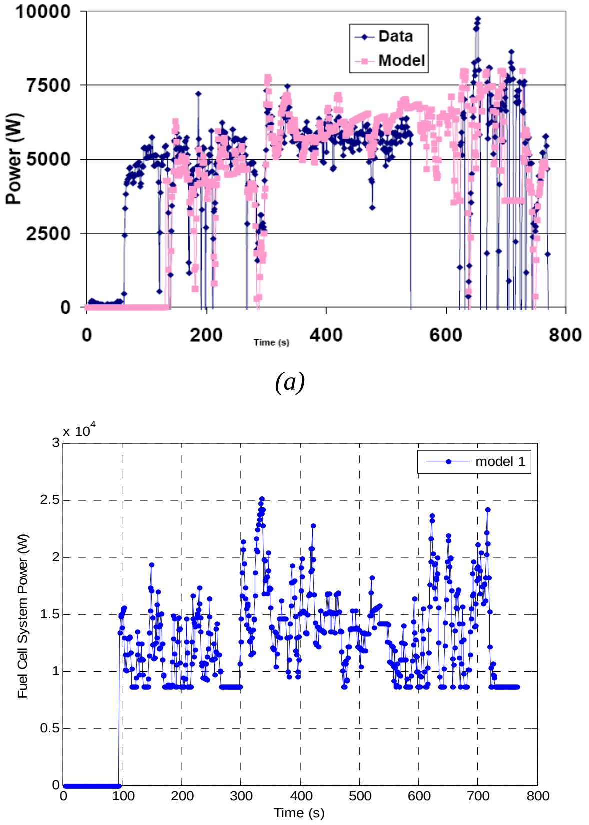
FTP moving cycle: this cycle is used by US EPA standard for the acknowledgment of the pollution of passenger vehicle in the united state, which is the longest cycle among the various moving cycles investigated in the present paper. The maximum velocity in this cycle is 91.25 km/hr and maximum acceleration is 1.48 m/s2. Average velocity and acceleration are 25.82 km/hr and 0.51 m/s2 respectively.

HWFET cycle: this cycle is implemented by US EPA standard for acknowledgment of fuel economy of passenger vehicle in the united state. The maximum velocity is 96.4 km/hr and maximum acceleration is 1.43 m/s2. Average velocity and acceleration are 77.58 km/hr and 0.19 m/s2 respectively.

US06 moving cycle: this is a cycle having high velocity and acceleration. The maximum acceleration in this cycle is 3.76 m/s2, maximum velocity is 129.23 km/hr. Average velocity, and acceleration is 77.2 km/hr and 0.67 m/s2 respectively [14].

III. VALIDATION

Before proceeding further, in order to verify the model and Advisor software, the outcomes of the model are compared with the results in reference [15]. In this reference, a hybrid fuel cell vehicle is simulated and the results are compared with the experimental data. In Fig. 4, the results of the power variations for a fuel cell system versus time assuming HWFET moving cycle is plotted considering the present investigation and reference 14 results. As it is indicated in the figure, the trends are essentially the same and the discrepancy is emerged from different model implemented in the two analyses. Because the fuel cell system used in the reference 15 is a 20 KW system, and in addition to use a 16 Ampere phosphoric battery, a 100 KW electric motor power is also assumed. It is important to note that all outlet parameter from two models are compared with each other and the experimental data, which are not mention here.



(a)

(b)

Fig. 4 Comparing power system variation of the fuel cell versus time regarding moving cycle HWFET, in the reference 14 figure (a) and the present paper figure (b)

IV. VEHICLE OPERATION

By developing the models presented in the previous section and writing, the required code in Matlab and Simulink. This information is applied to the Advisor software. At first, for initial assessment of the designed vehicle using software capabilities, acceleration and inclined running test are performed on the vehicle. The results are shown in Table III. As it can be seen, the results of acceleration and inclined running test are the same for various moving cycle. According to Table III, the vehicle can increase its speed from 0 to 96.6 km/hr in 1.07 second, from 64.4 to 96.6 km/hr in 21.2 sec and from 96.6 to 130 km/hr in 21.2 sec. it is also capable to maintain its speed at 88.5 km/hr in a 11.1% inclination.

TABLE III

Time (s)	acceleration test (velocity km/h)
10.7	0 - 96.6
5.5	64.4 – 96.6
21.2	0 – 137
VELOCITY (km/h)	Inclined running test (inclination %)
88.5	11.1

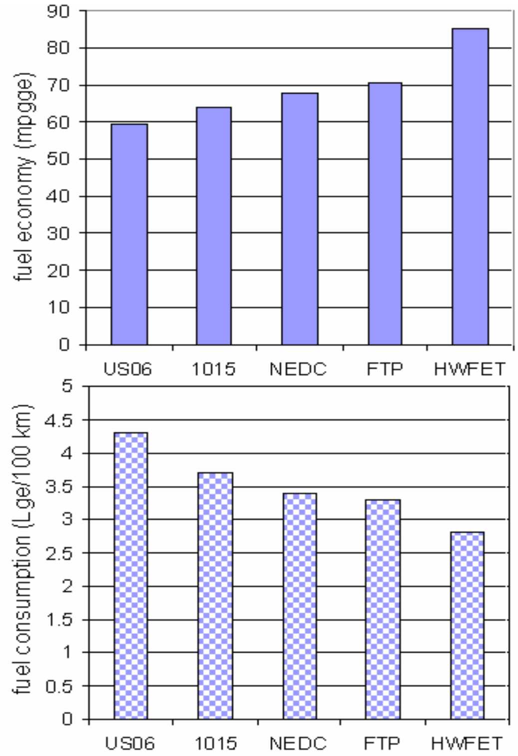


Fig. 5 Comparing the fuel consumption and economy in different moving cycle

The results of comparison between fuel economy and consumption are presented in Fig. 5. In this paper, the amount of fuel economy in advanced vehicle and a percentage of Miles per Gallon for reference vehicle are presented. According to the figure, by decreasing fuel consumption, fuel economy will increase. It is also apparent that the amounts of these parameters vary from changing in the moving cycle.

By rising in average velocity and acceleration of the vehicle in a moving cycle, fuel consumption also, increase. Therefore US06 cycle which has high velocity and acceleration consumes more fuel than other moving cycle. In addition to the moving cycle, fuel consumption in a vehicle is dependent on various factors like weight, design, division of power between fuel cell system and battery and power of moving system.

Each indicated parts in Fig. 6, denotes the energy wasting generated from different parts of the system of a vehicle during the simulation in various moving cycle, which is originated from incompetence in different parts of a vehicle during moving cycle. As it is apparent, the most energy wasting in a moving cycle is generated in fuel cell system, which is a result of high amount of heat produced in fuel cell stack. Among all kinds of moving cycle, energy wasting in battery for US06 cycle is the most because this cycle has high acceleration, therefore, SOC battery decreases.

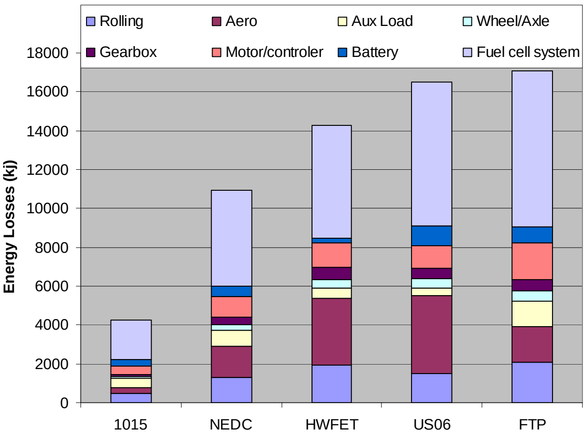


Fig. 6 Energy wasting in various part of a vehicle for different moving cycle

According to the Fig. 7, at low charging state, battery resistance for discharging is more than charging state. On the other hand, battery power and low SOC decrease sharply. Since US06 moving cycle has high acceleration, more power will be used from battery which leads to decrease in SOC and increase in wasting for a battery. Besides, aerodynamics waste is dependent on average velocity of a vehicle. Average velocity of US06 and HWFET moving cycle are more than the others. Hence, it increases aerodynamics waste in a vehicle. Generally, energy wasting in long run moving cycle like FTP is more other cycles.

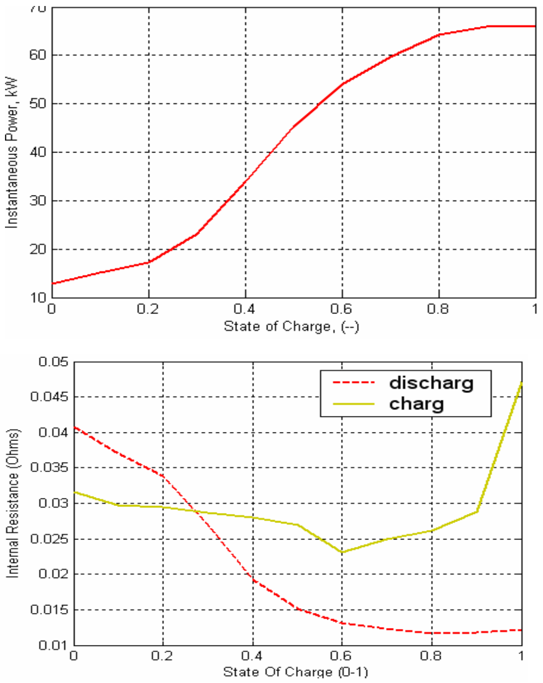


Fig. 7 Variation of internal resistance and power of a battery versus charging states [16]

In Fig. 8, efficiency variation versus power of a fuel cell system in different moving cycle is presented.

By decreasing, the power necessary for moving cycle, efficiency of fuel cell system increases. By rising in requested system power, the load of auxiliary system specially air compressor increase because more air flow rates is required. Therefore, more parasite power is used and the power generated from stack of fuel cell decreases more and more. Hence, for generating required power, it is necessary to consume more fuel which leads to decrease in net system efficiency of the fuel cell. Obviously, the behavior of a fuel cell system in different moving cycle is dependent on the cycle characteristic like time, moving distance of the cycle, velocity and acceleration of the vehicle.

V. CONCLUSION

In this paper, a hybrid vehicle using fuel cell is investigated. A control strategy for the fuel cell system is designed in such a way that by increasing the load of the system, air compressor performance increases. Therefore, a suitable operating pressure is prevailed during the system operation.

Since one of the substantial factors in energy efficiency and consumption is the type of moving cycle in the vehicle, in this paper various kinds of moving cycle are studied. Energy efficiency in different components and battery charge and discharge procedure are also analyzed.

The results revealed that by increasing average velocity and acceleration, fuel consumption increases. Therefore, US06 moving cycle, a cycle with high velocity and acceleration, consume more energy than other cycles.

It is also concluded that the total energy wasting in various moving cycle is different. Decreasing required power of a moving cycle results in increasing system efficiency. Rising requested system power leads to intensifying the load of auxiliary system specially compressors, because it demands for more airflow rate. Therefore, more parasite power is used and net generated power from the stack of fuel cell decreases accordingly. Hence, producing the required power, more fuel should be consumed which can diminish the fuel cell system efficiency. Comparing wasting in various components, it is concluded that wasting energy in long run moving cycle like FTP is more than the other cycles.

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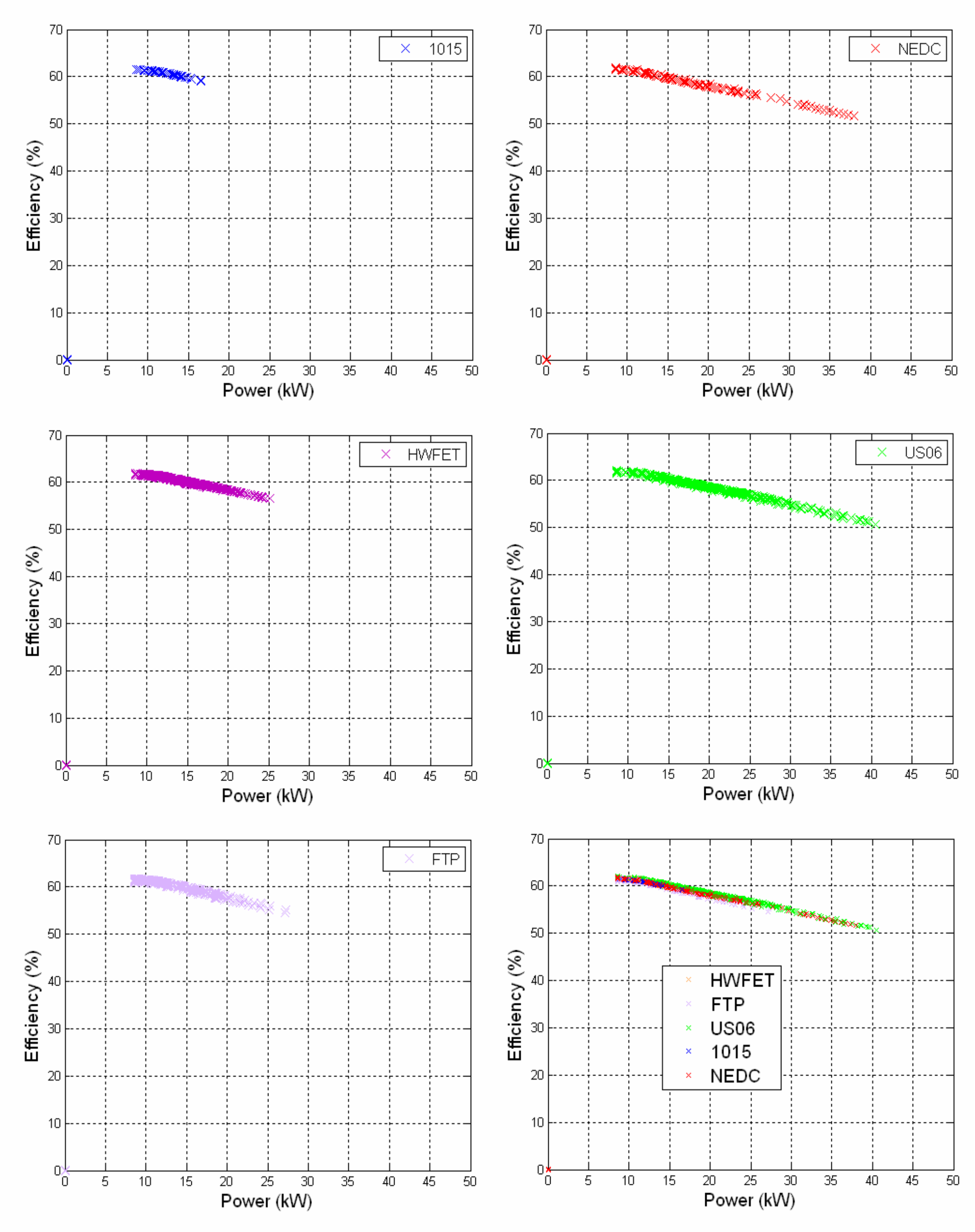

Fig. 8 Efficiency versus power in different moving cycle