Modeling, Application and Economic Feasibility Analysis of SOFC Combined Heat and Power System for Apartment in Wuhan Area

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***Abstract*- Abstract:** Solid fuel cells combined heat and power is one of the most promising technologies for reducing energy consumption in stationary area (commercial building and residential environmental). This paper is aim to studies the model, applications and economic feasibility of an model of Solid Oxide Fuel Cell micro combined Heat and Power (SOFC mCHP) for single-family apartment in Wuhan area. A model of Solid Oxide Fuel Cell micro combined Heat and Power (SOFC mCHP) system is presented to estimate the energy required to meet the average of electricity and heating demand of a 120 m^2 of single-family apartment in Wuhan area. Several simulation are conducted in Matlab-Simulink® environment in order to archive the aim of this paper. The model can be modified for any SOFC micro-CHP system. SOFC micro-CHP for stationary area has a higher potential to becoming cost-competitive in the worldwide. Based on the economic feasibility analyzes presented, the results indicated that it is feasible to introduce the SOFC micro-CHP system in Wuhan area from the economic viewpoint. However, fuel cell are still a non-mature technology aiming to reach the market in the coming years. Due to the constant development of fuel cell technology and recent commercial production, the available information about its performance in real applications is currently limited to date, and the cost information is not well established.

***Index Terms*-** Model, application, economic analyze, SOFC, co-generation Heat and Power, Wuhan area.

I. INTRODUCTION

In many reaching Solid oxide fuel cells (SOFC) has defined as energy technology conversation system, that in recent years shown many advantages friendly for the environmental, such as low emission.

Stationary fuel cells applications have been successfully spreaded at a number of commercial buildings including supermarkets [1]. A typical apartment has a relatively low-level of energy consumptions during the day/month/year when high power devices are operated and higher heating loads when is required, [2].

The size of a SOFC micro-CHP system is dependent on climate conditions, which directly determine the thermal and electrical demands of the residents. It is therefore, important to evaluate the performance of the SOFC micro-CHP system to ensure that it matches well with the local area heat-to-power load ratio, [3]. For the performance assessment of building integrated SOFC micro-CHP system, the interaction between the cogenerations system and building loads is considered using dynamic building simulations tools.

This study aims to create a model of SOFC combining Heat-Power generations system, applications, using gas methane (CH_4) as a fuel, for a single-family apartment located in Wuhan area, and economic feasible analyze. The system created is to caver the heat and electricity demand of a 120 m^2 [4], of single-family apartment with an average of two (2) occupant. The proposed methodology have been conducted in different researching for different residence with different load profiles. Alternatively, the model parameters could also be derived using a detailed fuel cell system model including a detailed cell and stack fuel cell model

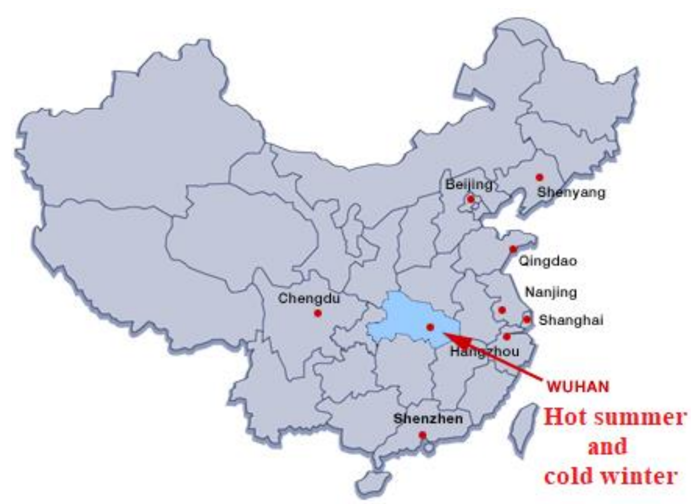

Figure.1- Map of climate zone in Wuhan area (by Corel photo)

II. CLIMATE REGION AND ENERGY DEMAND PROFILE IN WUHAN AREA

In the present study Wuhan area have been chosen for the analysis and applications of the SOFC micro-CHP system, as shown in figure 1. According to the Annual Weather Averages [1985-2015], Wuhan climate is humid subtropical with abundant rainfall and four (4) distinctive seasons. The summer it's oppressively humid, and the dew-points can reach 26 °C (79°F) or more. While the winter is cool with occasional snow, spring and autumn are generally mild. The monthly 24 hour average temperature ranges 4 °C (39.2°F) in January to 29.1°C (84.4 °F) in July, with 1320 mm of annual precipitation (majority of which falls from April to July). Based on the Microsoft Excel Database [5], the annual temperature of Wuhan area are plotted, as shown in figure 2.

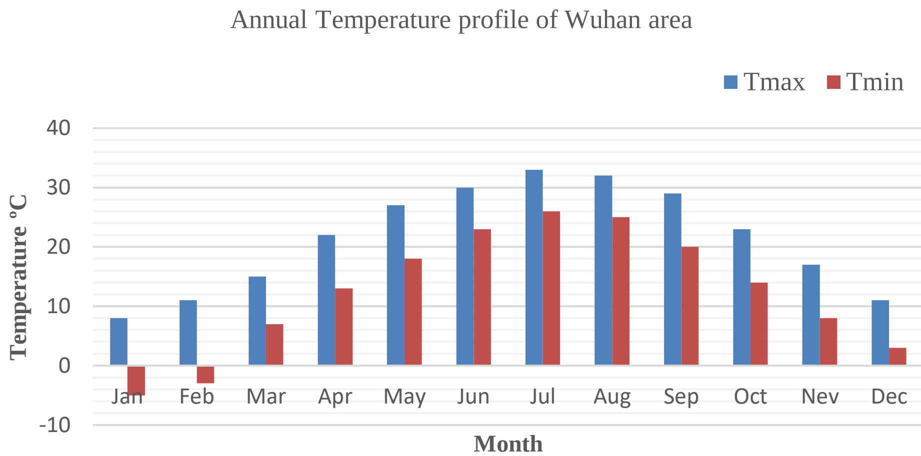

Figure.2-Annual Temperature profile of Wuhan area

In the present study the energy demand for space heating of a single-family apartment with 120 m^2, and with an average of two (2) occupant are plotted according with the equations bellows. The energy demand is shown in figure 3, [6].

2.1 Heating demand

$$Q_{Demand} = c_p \Delta T - (Q_r + Q_{in}) \quad (1)$$

Where:
C_p - Heat capacity;
Q_r - Solar energy gains through windows;
Q_{in} - Internal energy.

Where:

$$Q_r = T_s w_c w_f S_w I_{sol} * 0.65 \quad (2)$$

Where:
T_s - Coefficient of solar transmission of the windows;
w_c - shading coefficient of the windows;
S_w - Total surface of the windows of the building (m^2); and
I_{sol} - Global irradiation on horizontal surface (w/m^2).

$$Q_{in} = Q_{lig} + Q_{app} + Q_{occ} \quad (3)$$

Where:
Q_{lig} - Heat generate by light sources (w);
Q_{app} - Heat generate by appliances (w); and
Q_{occ} - Heat generate by occupants.

$$Q_{lig} = L_c A \quad (4)$$

$$Q_{app} = A_c A \quad (5)$$

$$Q_{occ} = O_c A \quad (6)$$

Where:
L_c - Average specific heat gain due the light in the building (w/m^2);
A_c - Average specific heat gain due to domestic appliances in the building; and
O_c - Average specific heat gain due to people in the building (w/m^2)

2.2. Hot water demand

$$Q_{Hotw} = m H_w \Delta T \quad (7)$$

Where H_w is the average specific heat demand for hot water production (w/m^2).

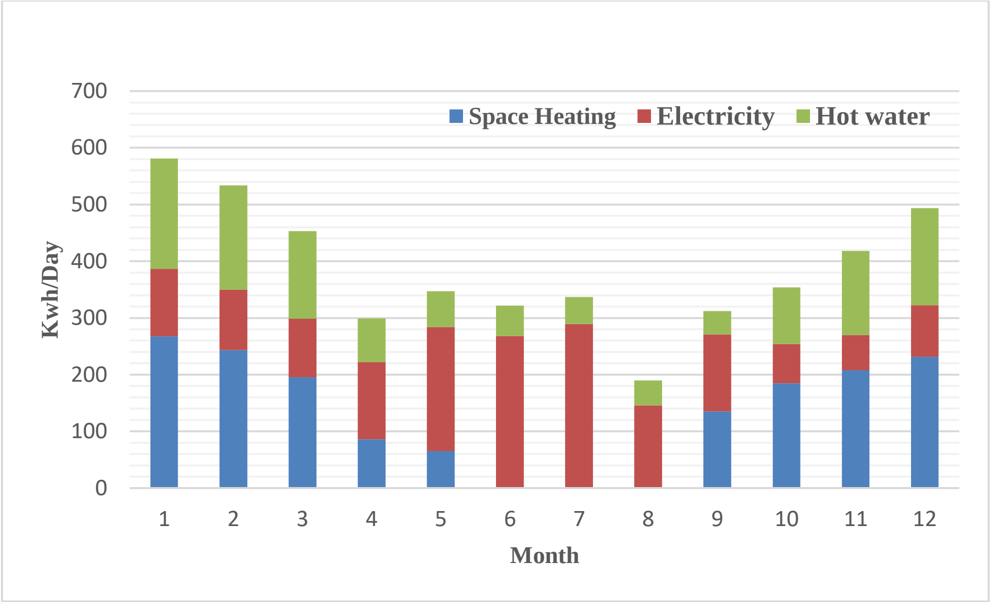

Figure.3-Energy demand for a 120 m^2 of Single-family apartment in Wuhan Area

III. SYSTEM CONFIGURATION AND MODEL ASSUMPTIONS

A dynamic SOFC micro-CHP system has been developed in a Matlab-Simulink® environment, considering mass balance, energy balance, chemical and electrochemical reactions, electrochemical losses and heat transfer. Several assumptions and simplifications were made when developing the model of electrochemical and thermodynamic of the SOFC micro-CHP system:

- **a)** The fuel cell reactions are assumed to be in equilibrium;
- **b)** The fuel cell is assumed to be operated under the steady-state conditions;
- **c)** The air that enter the fuel cell consists of 79% of N_2 and 21% of O_2;
- **d)** All gases behave as ideal gases; and
- **e)** The cathode and anode exit temperature of the fuel cell are assumed to be equal;

Each of the components are modelled individually and integrated to form the overall SOFC micro-CHP system.

3.1 Modelling of SOFC micro-CHP system

A process flowsheet for a natural gas (CH_4) fueled SOFC is shown in Figure 4, the dished lines indicate process flow diagrams for the system. In the system the fuel (natural gas- CH_4) enter a fuel heat exchanger (state 2), where the cleaned natural gas is mixed with super-heating steam provided by gas exhaust (state 11) to archive the necessary steam-to-carbon without carbon deposition. The mixture of the fuel gas (state 3) is then passed through an external pre-reformer before entering to the anode cell-stack (state 4), were his pre-reformed and converted to hydrogen and carbon monoxide. The air from the ambient enter to the system by compressor (state 7) to cool the SOFC, and a portion of airflow is preheated by the burner exhaust gas in the air heat exchange (state 8), and then enter to the stack (state 9). After the electrochemical oxidation process on the anode, the residual combustible are mixed with excess air from the cathode exhaust and catalytically oxidized in the tail-gas burner. The highest temperature (850-1000 ºC) on the system is verified in the burner exhaust (state 11), that are used for downstream process gas reactors and heat exchange. The SOFC stack produce only direct current (DC) power that must be converted into alternating current (AC) power (single or three phase, 50 or 60 Hz) for use by building power demands or for export to the electric grid.

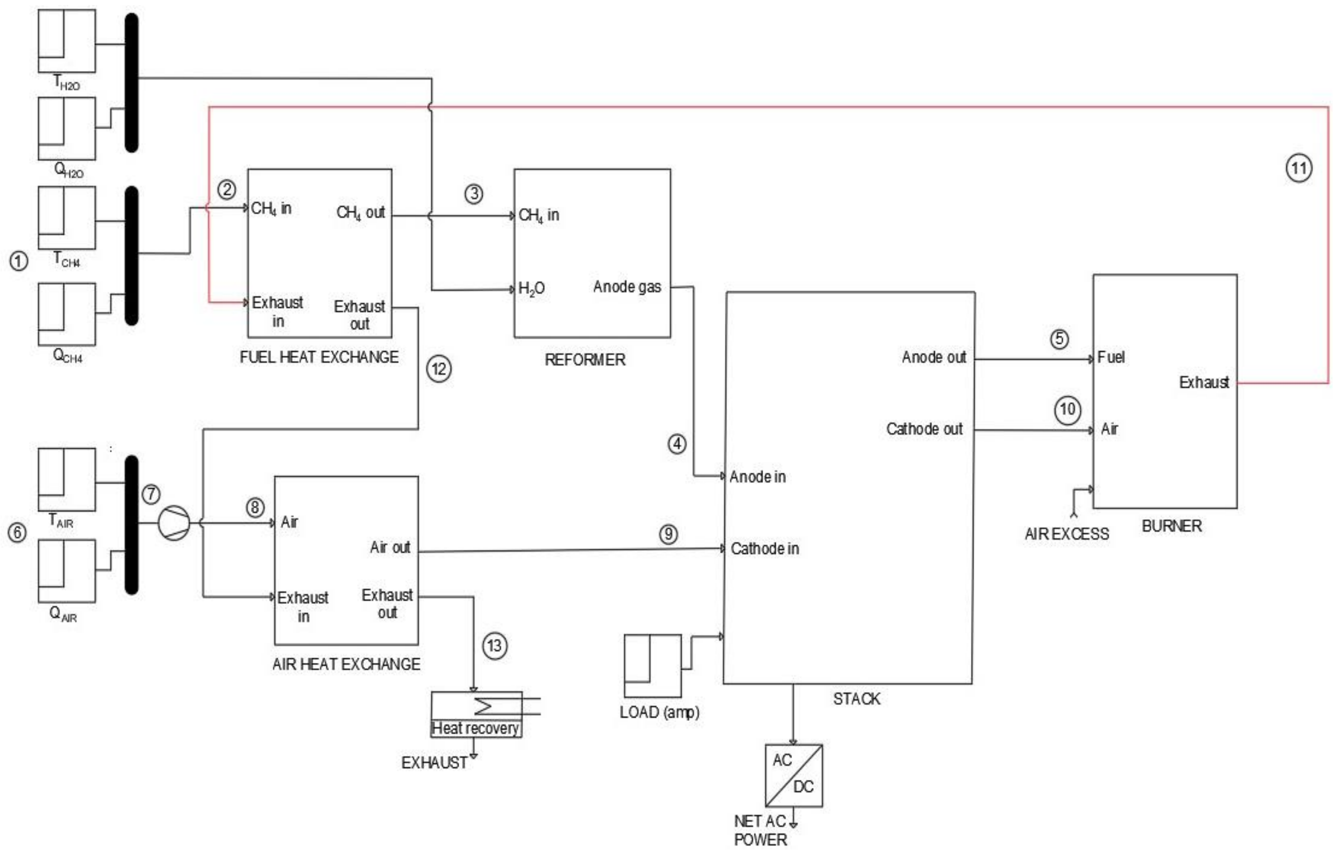

Figure.4- Flowsheet for SOFC micro-CHP System

The mathematical description of the system is formulated in terms of governing equations that are established from:

- **a)** Conservations laws;
- **b)** Interface and boundary conditions;
- **c)** Performance characteristics of the components.

The mass balance and energy balances written for each component in the system, [7].

3.1.1 SOFC stack
Mass

$$\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e \quad (8)$$

3.1.2 Reforming process

$CH_4 + H_2O \rightarrow CO + 3H_2$ (Stream reforming) (9)
$CO + H_2O \rightarrow CO_2 + H_2$ (Water gas shift) (10)
$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ (Overall cell reaction) (11)

3.1.3 Energy conservation

$$k_{sofc}\frac{dT_{SOFC,out}}{dt} = \dot{E}_{sofc,in}T_{sofc.in} - \dot{E}_{sofc,out}T_{sofc,out} - iAV_{sofc}$$
(12)

$\dot{E}_{sofc,in}$ and $\dot{E}_{sofc,out}$ are the energy flows in and out of the stack, respectively, and V_{sofc} is the SOFC voltage evaluated through the following black box.

$$V_{sofc} = 26.66 - 12.28 * U_f - 185.28 * J + 0.6204 * \lambda\frac{T_{sofc,out}}{1000} + 128.91 * J\frac{T_{sofc,out}}{1000} + 107.3\frac{T_{sofc,in}}{1000}$$
(13)

3.1.4 Air compressor

The air compression system has an important role in the design and control of SOFC systems. The parasitic required by the air compressor, which serve to supplying the total amount of air needed for electroxidation reaction and stack cooling requirements, is calculated by the following equations, [7]:

$$P_{cp} = \dot{m}\frac{C_pT_a}{\eta_{EM}\eta_{cp}}\left[\beta^{(k-1)/k} - 1\right] \quad (14)$$
$$P_{gross} = V * J * I \quad (15)$$
$$P_{net} = P_{gross} - P_{cp} \quad (16)$$

Where:

P_{cp}	Compressor power (kW)
P_{net}	Net SOFC power (kW)
P_{gross}	Gross SOFC power (kW)
$\dot{m}$	Compressor air flow (kgs^{-1})
J	Current density (A/cm^2)
η_{cp}	Compressor efficiency
β	Compressor ratio
C_p	Specific heat at constant pressure (Jk^{-1}k^{-1})
T_a	Temperature ambient

3.1.5 Post-burner

This sub-model is aim to evaluate exist post-burner temperature after combustion of residual H_2 and CO molecules held by the anodic exhaust stream. Another important function of the post-burner is in recovery, although in a thermal form, which is the chemical energy held by the residual hydrogen existing the SOFC. The T_{pb} is estimated solving the following energy balance, [7]:

$$\dot{E}_{pb,in}(T_{sofc,\ out}) = \dot{E}_{pb,out}(T_{sofc,out}) \quad (17)$$

3.1.6 Air pre-heater and pre-reformer

The heat exchange is required to pre-heat the feed gases before entering cell stack, because the SOFC system runs at relatively high temperature. The dynamic equations of hot and cold fluid temperatures in the pre-heater and reformer is presented below, [8]:

a) Hot fluid:

$$(K + C_h)\frac{dT_h}{dt} = \dot{E}_{h,in}T_{h.in} - \dot{E}_{h,out}T_{h,out} - UA(T_h - T_c) \quad (18)$$

b) Cold fluid:

$$C_c\frac{dT_c}{dt} = \dot{E}_{c,in}T_{h.in} - \dot{E}_{c,out}T_{h,out} + UA(T_h - T_c) \quad (19)$$

Where

k	Heat capacity (J/K);
C_h	Heat capacity of hot fluid ;
$T_{h,in}$, $T_{h,out}$	Hot and cold fluid mean temperature (K), respectively;
$\dot{E}_{h,in}$, $\dot{E}_{h,out}$	Energy rate flow in and flow out (W), respectively ;
U	Lumped heat coefficient transfer (W/m^2/K);
A	Heat area transfer (m^2);
C_c	Heat capacity of cold fluid (JK^{-1});

3.1.7 Electric stack power

The activation polarization is described as the energy barrier that should be overcome by the reacting species. Is calculated by using the Bulter-Volmer equation, [8]:

$$I = I_o\left[exp\left(\alpha_a n_e \frac{FU_{act}}{RT}\right) - exp\left(-\alpha_c n_e \frac{FU_{act}}{RT}\right)\right] \quad (20)$$

$$I_o = K_{O_2} exp\left(-\frac{E_{O_2}}{RT}\right)\frac{\left(\frac{P_{O_2}}{P_{O_2}^*}\right)^{1/4}}{1+\left(\frac{P_{O_2}}{P_{O_2}^*}\right)^{1/2}} \quad (21)$$

Where

$$P_{O_2}^* = A_{O_2} exp\left(-\frac{E_{O_2}}{RT}\right) \quad (22)$$

The electric stack power P_{sofc} is defined by the equations bellow, [9]:

$$P_{sofc} = I * U_t = A_{vecel} * N * I \quad (23)$$

Where $A_{vecel} = \frac{U_{stack}}{N}$ in the average single cell voltage.

IV. SIMULATIONS AND RESULT

The dynamic and detailed model presented in this paper can be useful to simulating fuel cell behavior under different operating conditions. The model was implemented in Matlab-Simulink environment, where in order to speed up computation time, the parameters of the balance of plant components was estimated and assumed based on the averages gas species of specific heat. Table 1 shown the parameters and operating conditions for the system.

Table 1-Parameter and operating conditions [2, 8]

Parameter	Symbol	Value
Configurations		Planar
Electroactive area		100
Anode thickness(μm)	L_a	500
Cathode thickness (μm)	L_c	50
Electrolyte conductivity constants	$C_{1e}; C_{2e}$	3.34x10^4;-10,300
Anode exchange current density (Am^{-2})	$i_{0,a}$	6500
Cathode exchange current density (Am^{-2})	$i_{0,c}$	2500
Heat capacity	C_p	4186
Pressure	P_0	1
Ambient Temperature (k)	T_0	298
Number of cells	n	5
Fuel utilization	U_f	0.025
Air utilization	U_a	0.023
Fuel composition, reformate		x_{H_2}=0.273 x_{H_2O}=0.483 x_{CH_4}=0.171 x_{CO}=0.019 x_N=0.28
Heat area	A_h	0.5
Air blower power consumption factor	η_{ab}	10%

Based on the equations (8 to 30) and the parameter presented in table 1, the SOFC micro-CHP system fueled by 0.025 kg/h of methane (CH_4), 298 k as initial temperature, was simulated and produce around 1.67 kw of power output and an exhaust of 602.7 k. Figure 5 shown the plant schematic of SOFC with description of energy and mass flows at the nominal operating point.

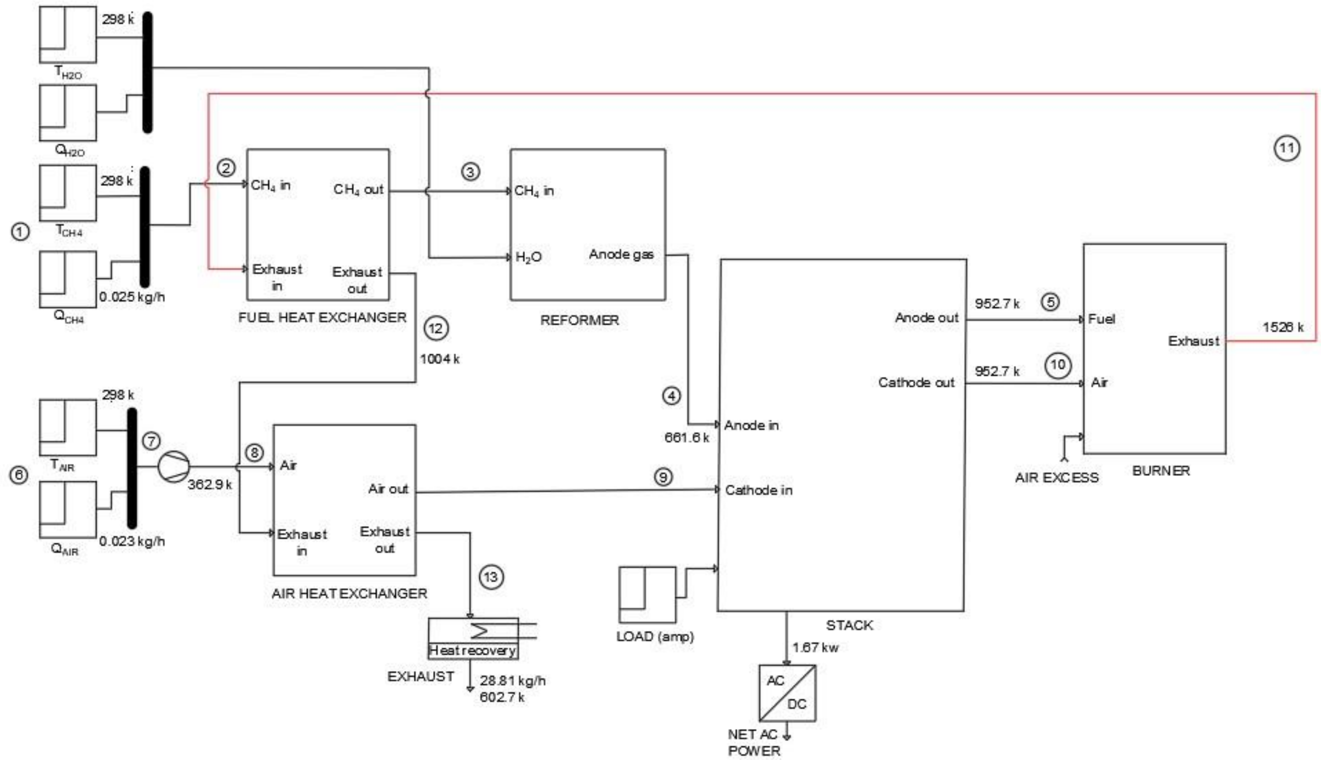

Figure.5- SOFC micro-CHP system with description of energy and mass flows

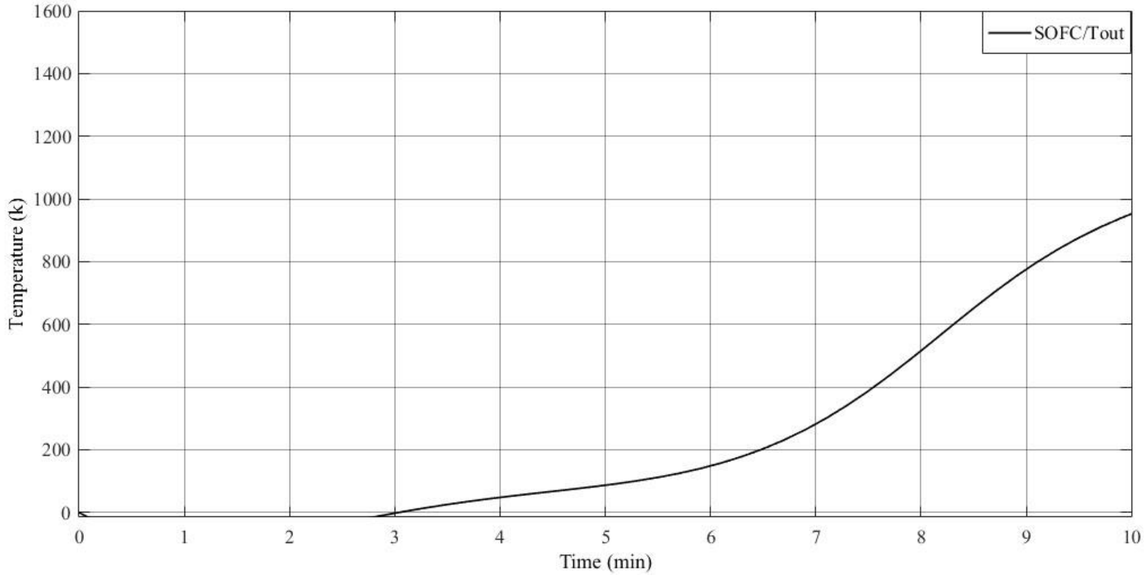

Figure.6- SOFC micro-CHP Tout

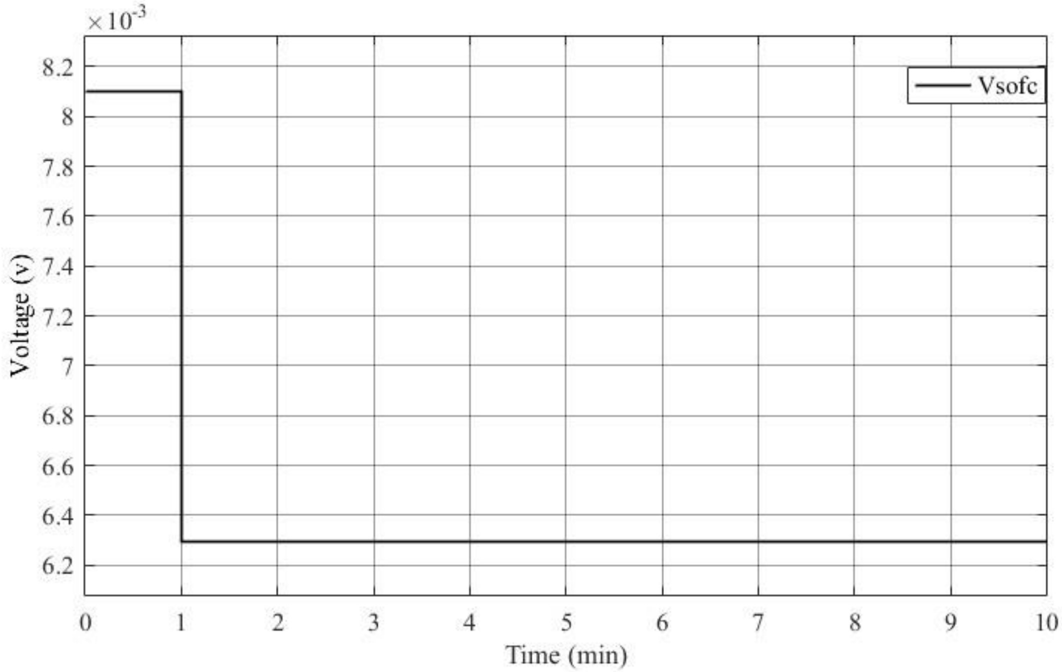

Figure.7- SOFC micro-CHP voltage

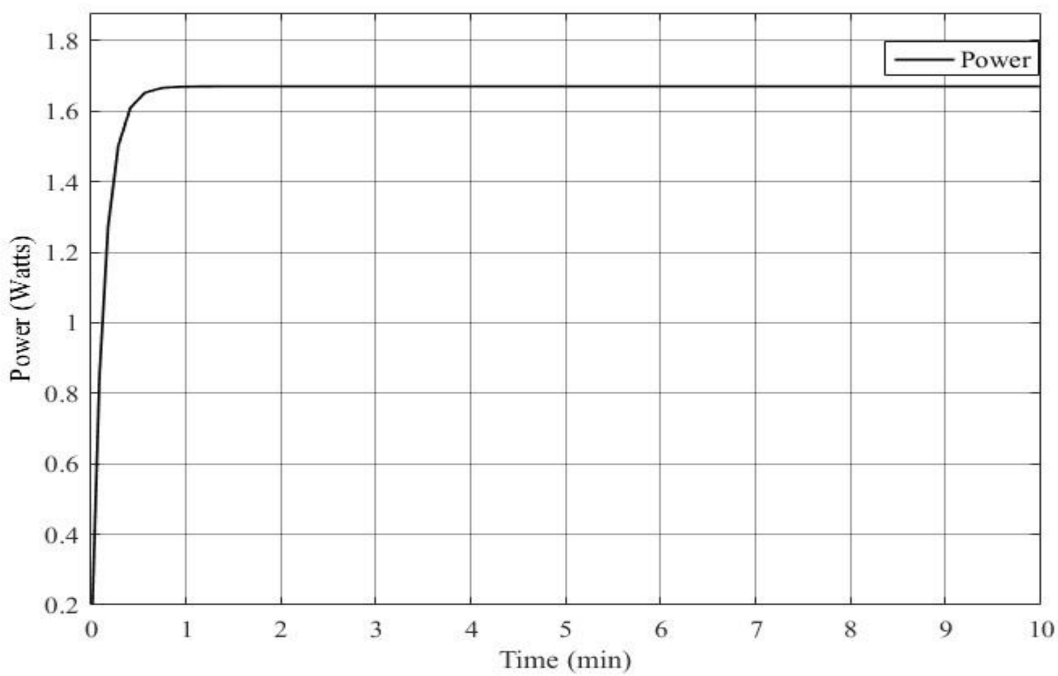

Figure.8- SOFC micro-CHP power output

V. APPLICATIONS OF SOFC MCHP SYSTEM

Fuel cells can be applied for transport, portable and stationary energy generations. Stationary fuel cell systems is the most used finding applications in all scales: micro-scale CHP for residential use, to off-grid back-up power system, to power prime power for buildings and even to megawatt-scale power stations, (Fuel Cell Today, 2013).

5.1 Economic feasibility Analysis

Energy crisis has become an undeniable global issue. The energy reform is also an important part of the Chinese government's plan to go green because the reform will bring out a more efficient power network and allow more interactive matching of supply and demand through intelligent energy networks.

Fuel cells are still relatively immature in commercial markets, however, there are two major markets where fuel cells have moved from the laboratory to the company:

a) Portable units;
b) Large stationary combined heat and power (CHP); and
c) Domestic micro-CHP.

SOFC technology is currently at the stage of development, thus its cost information is not well established and very little data are available from the open literature. According to (U.S. Department of Energy -DOE, 2017), [10] , the current capital cost of a SOFC is estimated about $335.89-$1385.69/kW for 1-5 kW CHP System, and for 10-25 kW CHP System is about $516.58-$1109.42 kW. To calculate the cost and the maintenance cost for the system proposed has to be defined, due the fuel cost is variable. For this reason in this paper, it has been calculated the operating of the system, based on the prices of fuel (CH_4- natural gas) and the electricity. The following value have been assumed (based on the Key China Energy Statistics, 2016):

a) Natural gas = $0.41/m^3
b) Electricity = $0.09/kWh

Based on the model created, it has been simulated 0.025 kg of fuel and 1.67 kW as result, which was not enough to evaluate the electricity demand from the single-family apartment. To evaluate the electricity demand, the quantity of fuel necessary to supply the electricity demand for each month, has been calculated as shown in table 2:

Table 2-Annual electricity demand

Electricity consumption (kw/Month)	Fuel (kg/Month)	Electricity cost ($/Month)	Fuel cost ($/Month)
119.188	1.781052002	10.72692	1.0178859
106.238	1.587537358	9.56142	0.9072907
103.122	1.540974298	9.28098	0.8806795
136.203	2.035310819	12.25827	1.1631969
219.132	3.27453676	19.72188	1.8714247
268.108	4.006395696	24.12972	2.2896881
289.324	4.323430962	26.03916	2.4708764
146.134	2.183711895	13.15206	1.2480093
136.142	2.034399283	12.25278	1.1626759
69.241	1.034683204	6.23169	0.59133
62.208	0.929587567	5.59872	0.5312669
90.698	1.355319785	8.16282	0.7745764

According with the result in table 2 the electricity and fuel cost has plotted

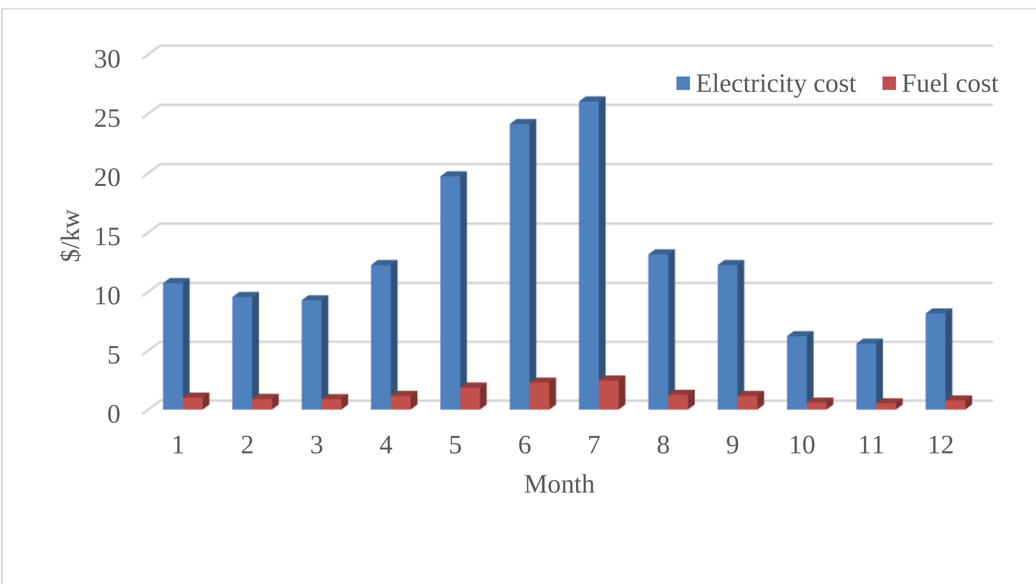

Figure.9- Electricity and fuel cost

According with the graphic, the cost variable during the year, according with the variation of demand from the apartment.

VI. Discussion

The model SOFC mCHP system has been designed based on the Wuhan area weather conditions and Energy demand from a 120 m^2 of Single-family apartment, as shown in figures 3 and 4. Based on the model created in Matlab-Simulink environmental, it has been simulated 0.025 kg/h of methane (CH_4) as fuel, 298 k as initial temperature and produced around 1.67 kW of power output and an exhaust of 602.7 k. It has noted that, the power output was not enough to evaluate the electricity demand from the single-family apartment. Therefore, in order to evaluate the electricity demand, the quantity of fuel necessary to supply the electricity demand for each month, has been recalculated as shown in table 2. An economic analysis has been conducted in this paper considering the costs values of electricity and fuel in order to have an economic viewpoint to introduce this system in our study area.

VII. CONCLUSION

In the present work was aim to investigated a model of SOFC micro-CHP system to cover the heat and electricity demand of an 120 m^2 of single-family apartment with an average number of two (2) occupants, located in Wuhan area. In order to understand the system operating limits, a dynamic model of SOFC micro-CHP system has been developed and analyzed. Numeral simulation are conducted in Matlab-Simulink® environment, to determine the optimal match between the energy demand from the apartment and the energy supply from the SOFC micro-CHP during the whole year. Finally, the cost operating are calculated. From these results, it's possible to see that the total cost variable during the year according with the variation of the demand of electricity, and the analysis result indicate that it is feasible to introduce the SOFC micro-CHP system in Wuhan area from the economic viewpoint. An economic analysis including the installation and the maintenance cost of the fuel has to be made in order to calculate the total savings that can be achieved installing a fuel cell micro-CHP system. Promising applications were looked into during this work to find the applications that will give fuel cells the opportunity of market penetration.

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