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Study on Performance Improvement of Low Temperature Proton Exchange Membrane Fuel Cell System by Stack Modification Using Simulation Tool

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Abstract

The low-temperature proton exchange membrane fuel cell (LT-PEMFC) is the leading contender and has been developed intensively over the past decades. On top of that, the challenges associated with the development of PEM fuel cell systems have also increased many times due to the complexity of various technological interactions such as mechanical (hydration systems, compressors, heat exchangers), electrical/electronic (pumps, motors, sensors, power electronics), catalysts, etc. Consequently, this hinders their commercialization and competence with present automotive engines. Nevertheless, to accomplish higher power from the fuel cell system study on optimized performance behavior between balance of plant (BoP) and fuel cell system is significant. For this reason, the AVL CRUISE M Simulation software is deployed as a critical tool to simulate the performance of LT-PEM fuel cell systems. Based on the above discussion, the overall aim of this paper is to study the LT-PEM fuel cell system performance characteristics by modifying the fuel cell stack surface area for optimized hydrogen, air and cooling system management to achieve system power of 70–80 kW to use in commercial vehicle applications.

Keywords: Fuel cell; PEM; Stack area; BoP; Simulation.

Research Article

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1. Introduction

Nowadays, nonrenewable fossil based fuels continue to be the major energy source for most-mobility applications, contributing adversely to the CO_2 emission [1]. Therefore, it is appropriate to study the use of renewable fuel (hydrogen) for transition of automobiles to green energy through the research and development of various strategies [1,2]. To support green energy transition, high power fuel cell system performance behavior for commercial vehicles are now being studied and developed extensively for commercial vehicles. The fuel cell is a power generating system that uses electrochemical reaction of hydrogen and oxygen (air) to generate electric power and water. Though proton exchange membrane fuel cell (PEMFC) has significantly improved over the past decades in terms of performance, reliability and stability the cost continues to be significantly higher. The key part in the fuel cell system is the central stack housing and it is comprised of set of reactive membranes [3-10].

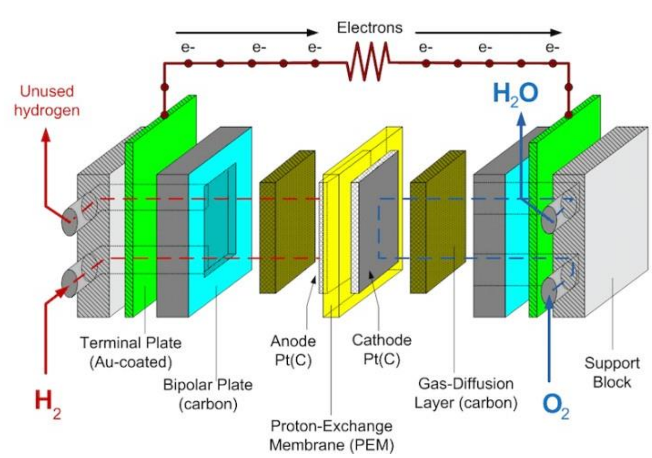


Fig. 1. Schematic structure of PEM fuel cell

Nevertheless, the proton exchange membrane fuel cell (PEMFC) is most appropriate for automotive applications. It is due to relatively low operation temperature (< 100 °C) as well as higher efficiency. This system consists of two electrodes - the anode (AN) and cathode (CL), the catalyst layer, the gas diffusion layer (GDL), and the proton exchange membrane (PEM). The schematic structure of PEM fuel cell is shown in Figure 1. For this reason, fuel cell system performance study using simulation tool to understand the interactions of BoP and fuel cell system for the selection of system parameters and stack area to meet the power demand is further discussed.

In addition, the fuel cell system is a multi-domain system and hence modeling the same is also difficult. Some of the major issues in modeling a PEM fuel cell system for further simulation include: (i) finalizing the trade-off between model complexity (and hence the computing time) with the system required to represent the reality of the application; (ii) a methodology to verify the model for its correctness; (iii) availability of intrusive and non-intrusive measurement techniques; and (iv) a lack of performance data on an existing fuel cell systems. Due to the above scenario, validation of the model becomes the most challenging and critical [11]. However, considering the right trade-off in modeling can facilitate simulation of the critical performance. Furthermore, there are also various research studies carried out for fuel cell polarization curve improvements based on stack area optimization [12–14]. The distribution of current density and temperature over the surface area of fuel cell models are also studied [14–18]. In this paper, the AVL CRUISE M software is used to simulate fuel cell performance. This simulation software typically includes all fuel cell associated components. Hence, this simulation software has become one of the indispensable tools for the development of fuel cell systems in the automotive industry. Moreover, the use of this simulation tool significantly reduces development time and cost [19–24]. Besides, modeling of a fuel cell system, it is also important to specify the dynamic state and environmental conditions for the operation of the fuel cell system using this software. The defined environment condition for validations includes energy interfaces such as hydrogen concentration, ambient temperature, and pressure.

The fuel cell components used for this simulation model study is developed using AVL CRUISE M software is shown in Figure 2. Based on this simulation study, the effort required to optimize the parameters is significantly reduced. Overall, in this paper, fuel cell stack area performance simulation is carried out using the inputs from actual test measurements using for the existing stack area. Further, to enhance the fuel cell stack performance, fuel cell stack area is increased. In this regard, performance parameters such as system power, stack power, efficiency, hydrogen consumption, air pressure ratio, compressor speed, and radiator cooling temperature performances are compared for various stack areas.

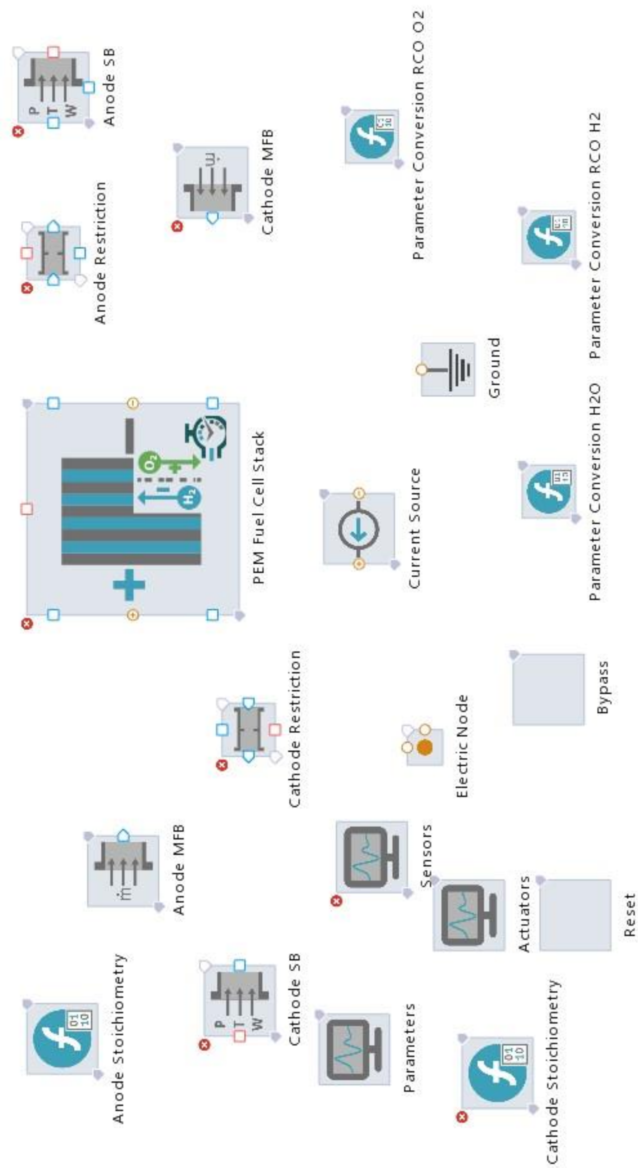


Fig. 2. Fuel cell components in AVL CRUISE M

1.1 AVL CRUISE M Simulation

AVL CRUISE M is a dynamic simulation software with multi-function capabilities and pre-installed library templates for several automobile applications. This software is an effective tool to conceptualize and design systems to simulate conditions as close to the real world as possible. This software is also used to identify design flaws and determine the root cause of several problems. AVL CRUISE M is basically a multi-physics software to create models and systems based on the following libraries:

- Thermal parameters for various heat transfer
- Flow of any fluid, gas, liquid, or mixture
- The electric and electromagnetic curves of circuits and electromechanical devices
- Chemical kinetics
- Signal processing and control

This software, with its productivity tools and multi-physical modeling capabilities, it is observed to be suitable for optimizing, analyzing, and simulating fuel cells and their various subsystems. In addition, this AVL CRUISE M is also capable of simulating the performance capabilities of the cooling system, the gas supply system to the cathode and anode, the humidification system, the hydrogen tank storage system, and the amount of H_2 fuel consumed by the fuel cell. The aforementioned system's effectiveness can also be simulated across various dynamic-state and transient driving cycles [24]. This software is competent not only for designing the fuel cell system; however, it is also used for integrating with various interfacing systems for heat management, water management, air management, fuel management systems, etc. Hence, AVL CRUISE M software is identified as a one of the suitable tool for simulating fuel cell performance.

1.2 Fuel Cell Simulation Model

To study the fuel cell system performance using AVLCRUISE M software simulation, the primary objective is to have quick component selection and sizing based on the requirements. After accomplishing the required sizing for the components (mechanical and electrical) the flow paths for coolant, gas, air, and hydrogen to be developed. For this study developed simulation model of PEM fuel cell is shown in Figure 3. The key parameters that affect fuel cell performance are the current, voltage, generated power, efficiency, and various temperatures [25]. Based on the simulation results, power performance characteristics are compared and discussed below to identify the right stack area for vehicle applications. Besides the above, using this AVL CRUISE M the list of fuel cell system performance characteristics that can be simulated is shown in Table 1.

Accordingly, the fuel cell is initially simulated with the existing test data of 330 cm^2 (base model) stack area, and further studies, are carried out by increasing the stack areas from 360 cm^2 to 420 cm^2. However, for meeting 70–80 kW of fuel cell system power, about 98 kW of fuel cell stack power with a stack current of around 450 A and 330 stack cells are required. The fuel cell stack design parameters used for this study are shown in Table 2.

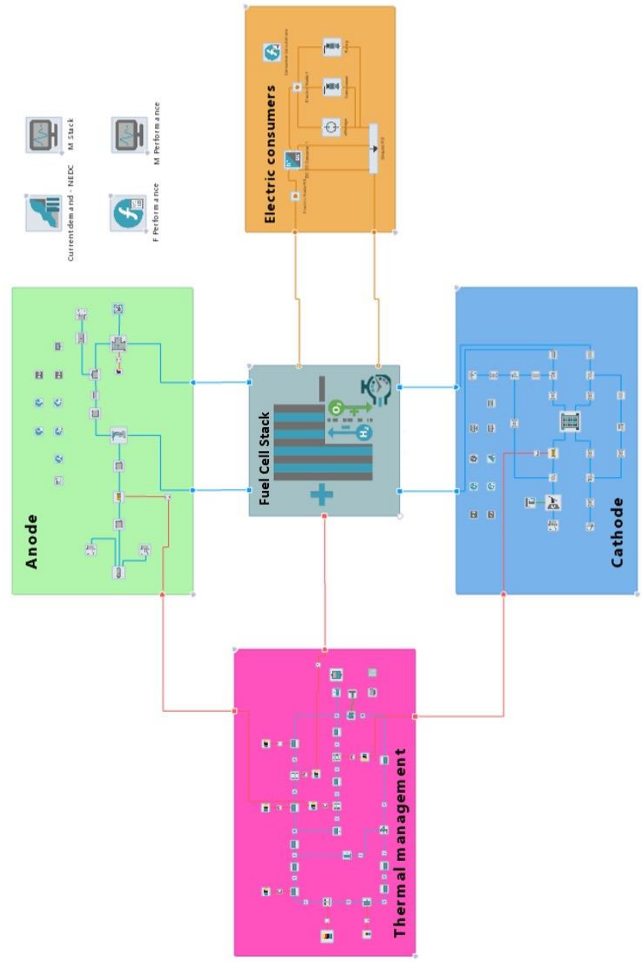
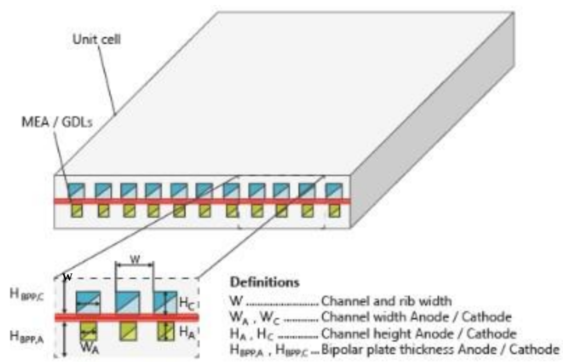


Fig. 3. Simulation model of PEM fuel cell

Table 1. Fuel cell performance characteristics

1	Stack power vs Time
2	System power vs Time
3	Hydrogen fuel consumption vs Time
4	Stack & System power efficiency
5	Stack voltage
6	Stack current
7	Stack cooling temperature
8	Radiator cooling temperature
9	Compressor before temperature
10	Intercooler after temperature
11	Relative humidity
12	Air compressor speed
13	Air compressor pressure ratio

Table 2. Fuel cell stack design parameters



Structure		
Number of cells in a stack:	330	
Active cell area:	420	cm^2
Bipolar plate design:	Machined	
Channel length:	300	mm
Channel and rib width (W):	0.4	mm
Anode Geometry		
Channel width:	0.25	mm
Channel height:	0.3	mm
Bipolar plate thickness:	0.5	mm
Scaling factor gas volume:	1	[-]
Cathode Geometry		
Channel width:	0.25	mm
Channel height:	0.3	mm
Bipolar plate thickness:	0.5	mm
Scaling factor gas volume:	1	[-]
Membrane Assembly		
Membrane thickness:	0.025	mm
Scaling factor active membrane area:	1	[-]
Catalyst layer thickness:	Automatic	

2. Research Methodology

Fig. 4. Research methodology

In this paper, the research methodology followed for fuel cell performance simulation is shown in Figure 4. The overall activity is categorized as a preliminary study based on literature, followed by a simulation model development phase and an experimental study for input generations using base stack area. Further, the current density distribution is one of the most important parameters to characterize fuel cell performance, which provides local reaction activity and electrochemical consequence resulting from local reactant concentrations, temperature, liquid water, and materials. Hence, for this study, input boundary condition for stack current is kept as 440 A and 40% reduction in current density from base stack condition. Based on the above mentioned condition, finally, the stack area is modified (330 cm^2 to 420 cm^2) and performance simulated for the optimized BoP as well as with operating environmental conditions to meet the required fuel cell power output.

3. Results and Discussion

The fuel cell stack cell voltage is shown in Figure 5. For this simulation study, 330 cells kept common and the stack area is varied from 330 to 420 cm^2. With 420 cm^2 stack area cell voltage of around 0.9 V is initially observed, however it is reduced to 0.6 V. Overall, 16% improvement in continuous cell voltage observed compared to other stack areas. The Nernst equation demonstrates how the cell potential changes as the reaction progresses. This is due to the effect of temperature and partial pressures of reactants and products on cell potential.

Nernst's equation for fuel cells:

E_{cell}=E^0 + (RT/nF). In (π_r/ π_p)

E_{cell}= Cell potential, E^o= Standard Cell Potential, R=Universal gas constant, T= Temperature in K, F= Faraday's constant, N= Number of moles of electrons transferred. π_r = partial pressure of reactants $\pi_{p=}$ partial pressure of products.

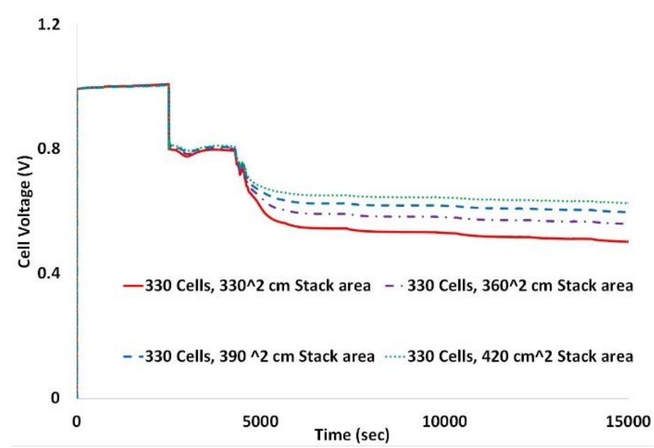


Fig. 5. Cell voltage vs Time

So a moderate cell potential is ideal if its coupled with a decent current density, to meet the required power and efficiency, along with an optimized fuel cell temperature ranges along with sufficient electrons transfer, for the better the flow of current. Furthermore, a higher partial pressure of the reactants in the fuel cell (by increasing the flow rate of the reactants) will lead to an increase in the open circuit voltage. However, partial pressure of both hydrogen and oxygen decreases when temperature increases for PEMFCs (decreases exponentially after 80ºC), which increases activation losses and reduces cell performance. So a good balance between both partial pressure and temperature is needed, which will probably be around the 80ºC for PEMFCs. Another most important parameter for the fuel cell performance improvement at higher temperatures is mainly due to increased membrane proton conductivity, enhanced electrode kinetics for the oxygen reduction reaction (ORR) and the hydrogen oxidation reaction (HOR), and improved mass transfer of the reactants. In addition, increasing the temperature can also increase the tolerance of electro catalysts to contaminants, especially for the sensitive PEMFCs. However, higher operating temperatures can lead to membrane dehydration, increased hydrogen crossover rate, and the degradation of components such as bipolar plates, resulting in a shortened fuel cell lifetime.

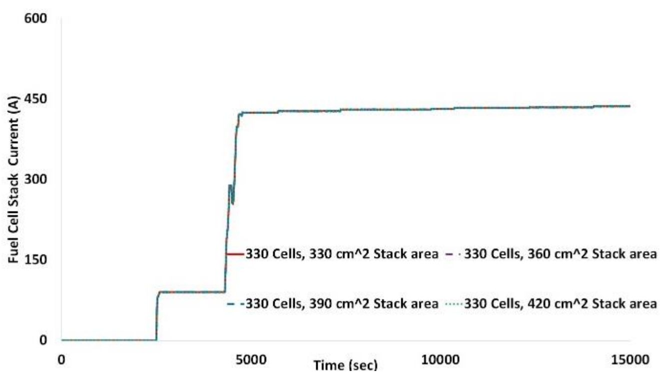


Fig. 6. Fuel cell stack current vs Time.

The fuel cell stack current is shown in Figure 6. Based on the simulation results, an increase in the cell surface area increased the stack current marginally, reaching a maximum of 450 A for the all the stack area from 330 cm^2 to 420 cm^2.

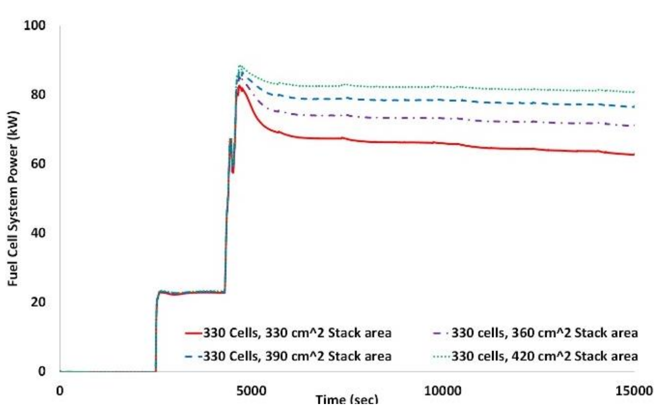


Fig. 7. Fuel cell system power vs Time

The fuel cell system power is shown in Figure 7. Based on the simulation study, with 330 cells and a 420 cm^2 stack area, peak power of 88 kW and continuous rated power of 81 kW are achieved. However, compared to other cell surface areas like 330-390 cm^2, the lowest power range of 82 kW and continuous rated power of 62 kW is observed with a 330 cm^2 stack area. This could be due to an increase in surface area stack current increased along with optimized cell voltage. Overall, the achieved continuous fuel cell power output is 24% according to the vehicle applications.

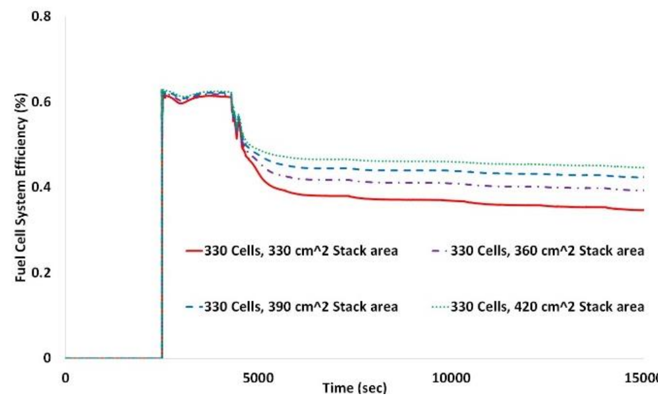


Fig. 8. Fuel cell stack efficiency vs Time

The efficiency of the fuel cell stack is shown in Figure 8. Stack efficiency is typically measured as the ratio of electrical energy output to chemical energy input. This is calculated by measuring and comparing the electrical power output of the stack, as well as the flow rate and energy content of the fuel and oxidant inputs. $\eta_{el} = P_{el} / P_{fuel}$, consumed P_{el} is the stack electric (gross) power and P_{fuel}, consumed is the consumed fuel power. Overall, the electric efficiency is expressed as $\eta_{el, LHV}$ = AveCell /1.253 V or $\eta_{el, HHV}$ = AveCell /1.481 V. The efficiency of a fuel cell stack can vary depending on a number of factors, including the fuel cell stack technology, the operating conditions of the stack, and the quality and purity of the fuel and oxidant. Compared to 330 cm^2, 360 cm^2, 390 cm^2, and 420 cm^2 stack area, about 60% efficiency is achieved in lower power regions for all the surface area. However, at continuous power, 50% efficiency is accomplished for the 420 cm^2 surface area and 40% for the lower surface area of 330 cm^2. In general, hydrogen fuel cell stacks are efficient when operating at their rated power output and at optimal temperatures and pressures.

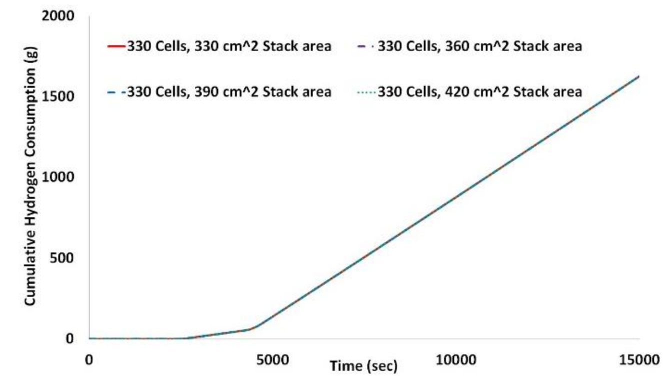


Fig. 9. Cumulative hydrogen consumption vs Time

The cumulative hydrogen consumption for the fuel cell system is shown in Figure 9. Based on the simulation results, cumulative fuel consumption is almost common and about 1600 gms of fuel is consumed for all the stack areas from 330 cm^2 to 420 cm^2.

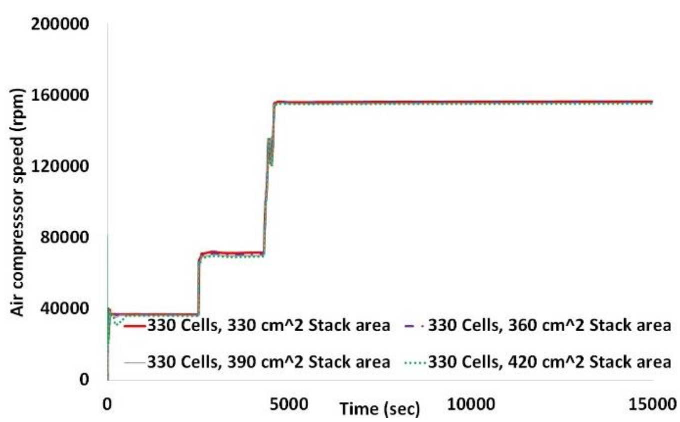


Fig. 10. Air compressor speed vs Time

The air compressor speed is shown in Figure 10. The primary function of the air compressor is to supply oxygen from air for the fuel cell. Therefore, performance of the compressor has a direct effect on complete system efficiency. Based on the simulation study, a compressor speed of around 150000 rpm can supply the required air quantity. Hence, this speed condition is kept common across all stack surface area conditions. This compressor is also capable of responding dynamically according to the power requirements. In addition, about 20-30% power is required to operate this compressor. This can affect the overall efficiency of the fuel cell system. Therefore, selection of an optimized compressor design for the fuel cell system is significant.

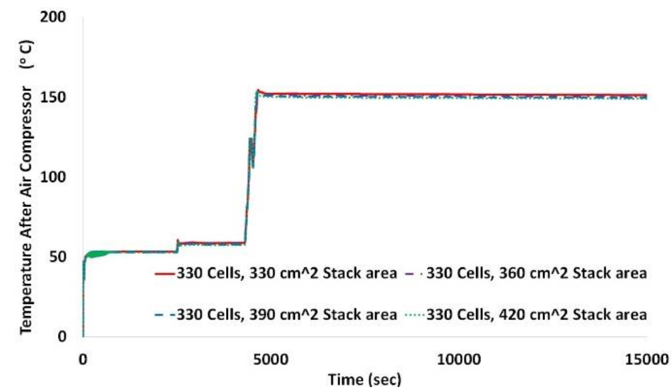


Fig. 11. Air Compressor outlet temperature vs Time

The air compressor outlet temperature is shown in Figure 11. For the selected compressor design, an air outlet temperature of around 150° C is attained.

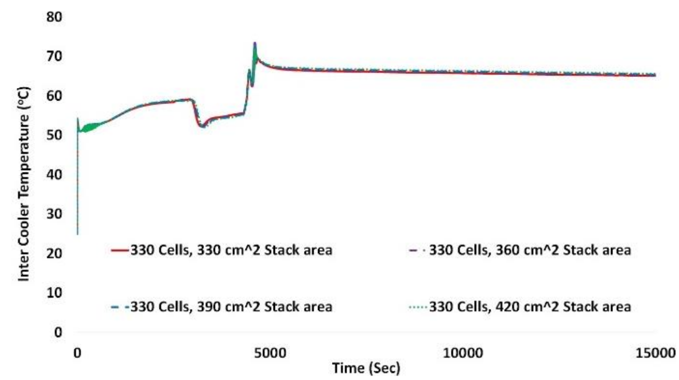


Fig. 12. Inter cooler outlet temperature vs Time

The intercooler outlet air temperature is shown in Figure 12. However, with the use of the intercooler system, the air outlet temperature is further reduced to 65°C. Overall, about 56% of the intercooler efficiency accomplished for all surface area conditions based on the simulation studies for enhanced performance of fuel cell system.

3. Conclusions

Overall, by using this AVL CRUISE M simulation technique, a PEM fuel cell model is developed and fuel cell system performance characteristics are studied expeditiously. Further, the continuous fuel cell system peak power output of 88 kW is accomplished with 20% increase of the stack area from 330 cm^2 to 420 cm^2. Compared to 330 cm^2, and 420 cm^2 stack area, about 60% efficiency is achieved in lower power regions for all the surface area. However, at continuous power, 50% efficiency is accomplished for the 420 cm^2 surface area Based on this simulation performance study, the capabilities of selected fuel cell system, cooling system and BoP performance characteristics are verified according to operating temperature and pressure considerations. In addition, due to this simulation study the number of preliminary tests required for selecting optimized performance for fuel cell system is also accomplished. This study also provided an overview of 81kW fuel cell system and its operating capabilities in real-world scenarios in lesser time and at a lower cost.

Nomenclature

BoP	:	Balance of plant
PEM	:	Proton exchange membrane
MEA	:	Membrane electrode assembly
GDL	:	Gas diffusion layer
HHV	:	Higher heating value
LHV	:	Lower heating value

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Gopi Sankar Mariappan: Conceptualization, Formal analysis
Karthikeyan Subramanian: Writing-original draft, Validation
Rajavel Rangasamy: Supervision

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