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Performance Evaluation of Nexa Fuel Cell with Atmospheric Temperature and Humidity Data

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Abstract

Auxiliary power units are often installed on long-haul trucks, recreational vehicles, and military vehicles. Many of these vehicle applications prefer a robust system with low operation noise, low exhaust emissions, high specific energy, high energy density, and flexible fuel usage. One of the more promising technologies is that of the PEM fuel cell. The PEM fuel cell is one of six fuel cell technologies being developed by many areas of industry. The PEM fuel cell is a technology that potentially satisfies all of the requirements listed above. Nevertheless, demands on the balance of plant devices are well understood, but that knowledge is not always well implemented. Fuel cell engines are sensitive to changes of temperature, humidity inside the fuel cell , and the balance of plant devices must be well matched to ensure maximum efficiency. Furthermore, a properly programmed balance of plant control strategy must keep the operating conditions within the optimum operating range for the fuel cell. In the present study, changes in the Nexa's performance are investigated with respect to varying ambient temperature and relative humidity. It has been shown that ambient temperature directly affected heat exchanger fan power consumption and maximum power, and had a statistically significant effect on net efficiency. Ambient relative humidity played a statistically insignificant role in determining the net efficiency of the Nexa. Despite this, there was evidence that flooding was beginning to occur, indicated by the increased frequency and duration of the anode purges. This suggests that the Nexa's water management control strategy is not aggressive enough to deal with high-temperature and high-humidity conditions.

Keywords: PEM fuel cell(proton exchange membrane) , Efficiency, Environment, Power management

1 Introduction

Auxiliary power units are often installed on long-haul trucks, recreational vehicles, and military vehicles. Many of these vehicle applications prefer a robust system with low operation noise, low exhaust emissions, high specific energy, high energy density, and flexible fuel usage. One of the more promising technologies is that of the PEM fuel cell. The PEM FC is one of six FC technologies being developed by many areas of industry. The PEMFC is a technology that potentially satisfies all of the requirements listed above. The requirements presently lacking are overall system robustness and flexible fuel capabilities. With the steady improvement in these areas that come with continued product maturity, PEM FCs may soon enter the APU market[1-3]. There is a lot of interest in vehicle mounted FC APUs, particularly with the trucking industry and the military. Despite the high costs of fuel cells, many studies have been done in preparation for the day when FC costs become competitive with other energy conversion technologies. The trucking industry is primarily concerned with reducing idling time, fuel costs and engine wear while maintaining driver comfort when parked at rest stations. It was found that a significant amount of time, often 40% of the total time that the engine is running, is spent idling to power climate control devices and sleeper compartment accessories and to avoid start-up problems in cold weather[4]. There are general emission reductions, fuel cost savings, and economic benefits to using FC APUs over diesel APUs[5]. Majority of researches on FC APU development are based on paper studies and computer modeling[1-3], [6, 7]. While these are important tools in refining FC APU design, very few have focused on non-idealized systems. Such a methodology lacks connection with the real world. Products are not always used in a manner predicted in a paper study, or in the idealized conditions assumed in a computer model. Real world usage often involves operational validity, external perturbation, and application integration.

Furthermore, hardware testing is often invaluable as a means for improving the sophistication and validity of paper studies and computer models.

The demands on the balance of plant devices are well understood, but that knowledge is not always well implemented. FC engines are sensitive to changes of temperature and humidity inside the FC. Furthermore, a properly programmed balance of plant control strategy must keep the operating conditions within the optimum operating range for the FC. For the findings of this study to be immediately relevant, Nexa power module, commercial fuel cell engines manufactured by Ballard Power Systems, was selected. While the results of this study were obtained using Nexa FC, the results are by no means unique to the Nexa FC, and should applicable to other FC systems operated under similar conditions. In the present study, changes in the Nexa's performance with respect to varying ambient temperature and relative humidity are investigated experimentally. Special attention is given to the Nexa's thermal and water management control strategy, and the purge strategy. Finally, overall efficiency is calculated, and effects of ambient conditions are examined statistically.

2 Experimental facility and approach

The Nexa FC engine is rated by Ballard to produce 1200W, with a rated current of 46A at 26V. The operational voltage range was specified as 22V-50V, the operating temperature range as 3℃ to 30℃, and the operational humidity range as 0% to 95%. Because of the low volume of hydrogen purged during normal use, it is rated for both indoor and outdoor use[8].

Figure 1 shows a photograph of the Nexa power module. The Nexa is a self-contained FC engine, requiring only a hydrogen supply and a small external power source to facilitate start-up and shutdown. The Nexa uses low pressure reactant gas supply systems, and an air-cooled thermal management system. To accomplish this, the Nexa uses a non-adjustable hydrogen regulator, a cathode fan (CF) to supply the cathode reactant gas and facilitate cathode purges, and a heat exchanger fan (QXF) to provide active thermal management.

The Nexa uses two main types of purges for controlling stack voltage: an anode purge and the combined anode and cathode purge. The execution, duration, and type of purge performed are based on the Purge Cell Voltage (PCV), and on the net load. The PCV is the sum of the two cells in the stack located closest to the hydrogen purge valve.

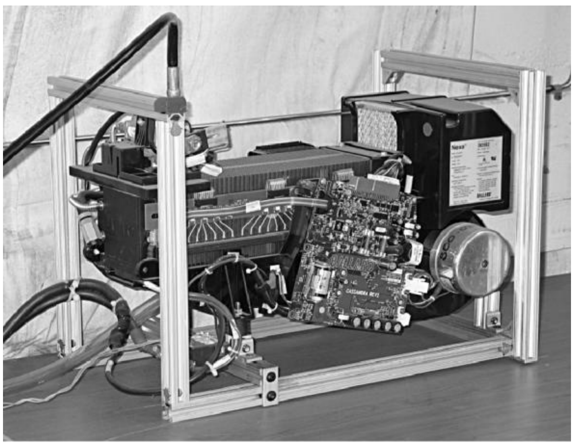

Figure1: The Nexa power module

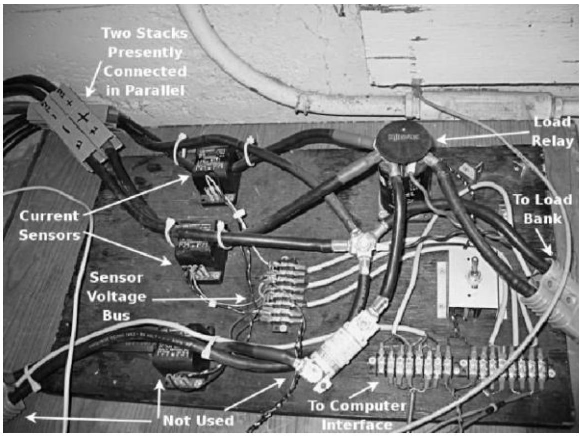

Figure2: Detail of a data acquisition board

The anode purge is the primary method of ensuring that the PCV remains above the apparent 1.1-volt minimum. Anode purges last between 1-to-3-seconds in duration. If the purge fails to raise the PCV above the minimum voltage, another anode purge will occur within a few seconds. This process will repeat until either the purge cell voltage does exceed the minimum voltage, or the stack shuts down due to a low-PCV failure.

The combined anode-cathode purge is the secondary method for raising the PCV above the minimum voltage, but it is only used if the gross current is in excess of 60A. This purge opens the hydrogen purge valve and sets the cathode fan duty-cycle to 100% for 10 seconds.

Fig. 2 shows that two Hall Effect sensors for measuring net stack currents, and two voltage dividers for measuring system and stack voltages were incorporated into a data acquisition board. Signals from these components were acquired using hardware and software from National Instruments. A PCI-MIO-16E-4 card was used in an x86 computer running LabVIEW 6.1.

The enclosure for controlling ambient conditions is made out of Plexiglas panels, and an aluminum frame. The height, width and length of the enclosure are 1.0m, 0.75m and 0.75m, respectively. Exhaust ports were cut into the lid to allow heated air from the heat exchanger to be vented out of the enclosure, and fresh air ports are located at the ends of the enclosure at the bottom edges to allow fresh air to enter the cathodes and the heat exchanger.

To provide as much of a realistic challenge for the Nexa as possible, it was that the atmospheric data for the month of July would be used to determine the values of the temperature and humidity variables used during testing. The National Oceanographic and Atmospheric Association (NOAA) publishes tabular data for many types of atmospheric properties for the largest 256 cities in the United States. The NOAA data for normal maximum temperatures and normal relative humidity for the years of 1971-2000 were used to determine the values for the temperature and relative humidity variables in this study[9, 10]. The factor values were designated using the following process:

- The averages and standard deviations of the temperatures and relative humidity data were calculated for the months of July.
- Two positive and negative standard deviations were added to the averages to find the target values.
- One standard deviation was added to each target value to find the upper and lower bounds for the acceptable range boundaries.

The resulting calculations for the targets and range boundary values are given in Table 1.

All of the tests conducted during this study were done when the local atmospheric conditions matched those of the Low-Temperature, Low-Humidity conditions. Particular environmental conditions for each run were then created by modifying these base-line conditions during the Nexa warm-up stage of each run. The process of data analysis was comprised of three phases. In the first phase, the matching net and gross data files were aligned by synchronizing all of the set-point transitions. In the next phase, net efficiency, maximum power and auxiliary power demand was calculated. Breaking-down the auxiliary power demand into individual component demand required the use of Regression Analysis. In the final phase, ANOVA analysis was used to test the effect of the control variables on net efficiency[11].

Table1: Summary of variable target temperatures and relative humidities

Environmental Targets				
	Low Temperature	High Temperature	Low Humidity	High Humidity
Target	25	40	25	81
Justification: Average value, plus or minus 2 standard deviations – except for the Low Temperature Target, which was chosen to be Room Temperature				
Acceptable Environmental Ranges Boundaries.				
	Low Temperature	High Temperature	Low Humidity	High Humidity
Upper Bound	30	40	39	95
Lower Bound	20	35	11	67
Justification: Target value, plus or minus one standard deviation.				

3 Results and discussion

3.1 Characterization of the Nexa power module

The load schedule for the Nexa FC testing was defined in terms of current loads, ranging from 0A to 60A in 2.5A increments. Each test step was set to have a duration of 20 sec. This relatively short time period was selected to allow the stack to reach a semi-steady state, yet be short enough to minimize excessive waste heat production. This step time was also double the length of the longest purge, but short enough that each step would contain only one purge. Table 2 shows that the test order was randomized to reduce any interrun history effects. Table 3 shows the environmental design for the Nexa testing whose run order was also randomized. In the table, a "+" designates that the variable is high, while a "-" designates that it is low.

At the time of testing, the Nexa used in this study was nearly two years old and had accumulated about 100 hours of actual use. Despite this, the Nexa was able to provide considerably more power than the rated power within the limits of the ambient conditions specified by the manufacturer as normal operation conditions of both LL and LH. The load schedule, which includes a maximum, sustained current of 60A to produce 1500W at 24V for 20sec, yielded only one operational stack failure in seven runs.

Under ambient conditions beyond those specified as normal operating conditions, the failure rate was 50%. All of the HL runs were completed successfully at 40℃ and less than 40% R.H.,

Table2: Load schedule for the Nexa testing

Step	1	2	3	4	5	6	7	8	9	10	11	12	13
Set Point (A)	30	15	35	50	45	5	52.5	2.5	40	20	37.5	17.5	27.5

Step	14	15	16	17	18	19	20	21	22	23	24	25
Set Point (A)	60	35	22.5	50	32.5	7.5	0	47.5	57.5	10	12.5	42.5

Table3: Type Environmental test design for the Nexa testing

Temperture	Relative Humidity	Testing Order
+	+	3, 4, 9
+	-	7, 10, 13
-	+	2, 5, 6
-	-	1, 8, 11, 12

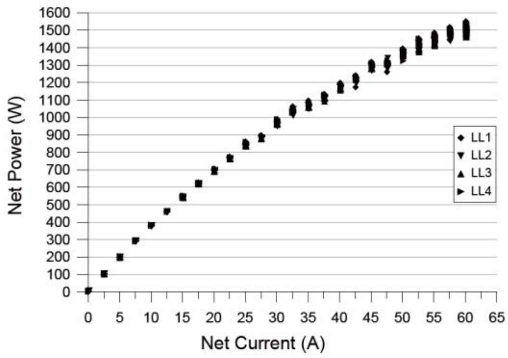

Figure3: Power curves of the low-temperature, low-humidity runs

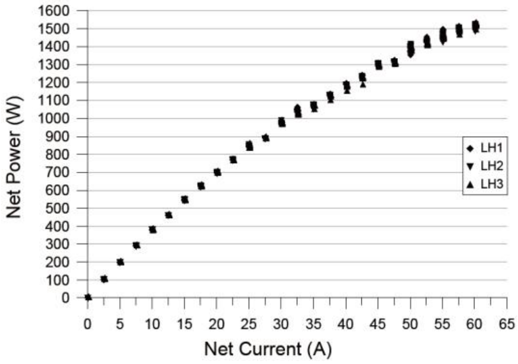

Figure4: Power curves of the low-temperature, high-humidity runs

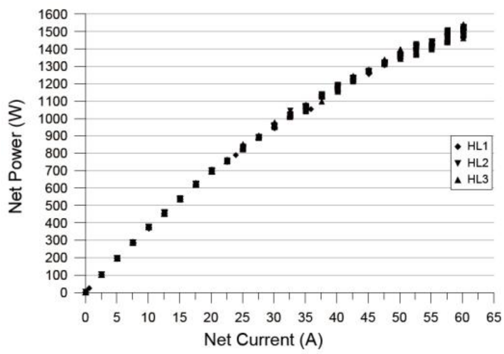

Figure5: Power curves of the high-temperature, low-humidity runs

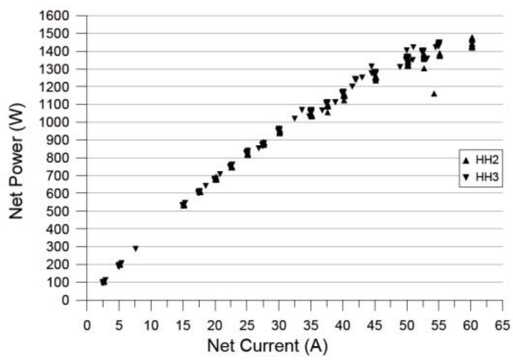

Figure6: Power curves of the high-temperature, high-humidity runs

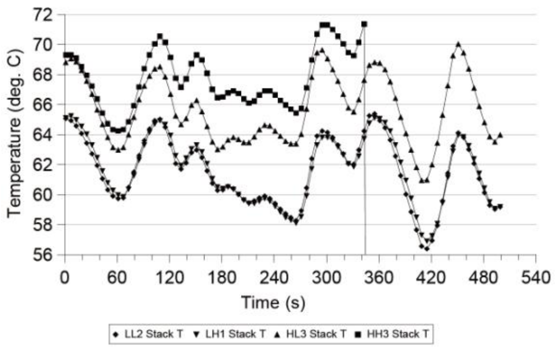

Figure7: Representative stack temperatures profiles

though the overall efficiency was somewhat reduced in comparison with the low temperature runs. Conversely, when the Nexa was tested under HH conditions at 40℃ and greater than 60% R.H., the Nexa failed on every run.

The performance data for all of the individual Nexa tests are given in Figure 3 through 6. Other than sorting the data by increasing values of net current, no mathematical operations have been performed on the data presented in these figures. For brevity, individual runs are referred to in a **#, where the first asterisk represents the temperature variable, the second one represents the humidity variable, and the pound symbol indicates the run number. As the partial pressure of hydrogen at the anodes fluctuates due to energy production, so does the stack voltage. This effect only partially explains the scatter of the net power data for a given current; furthermore, the remainder of the effect is due to fluctuations in auxiliary power demand.

The Nexa's balance of plant devices consists primarily of the cathode fan and heat exchanger fan. Examination of the auxiliary power demand data shows that the CF duty-cycle correlates very strongly with the gross current. Such a correlation is to be expected, as changes in gross current must be matched by changes in oxygen mass-flow in order to maintain the proper stoichiometry, typically 2.5:1. Deviations from the stoichiometry setting occurred during the execution of a cathode purge, at which time the duty-cycle of the CF was increased to 100% for a duration of 10sec. The CF power consumption was also affected by ambient temperature, but only slightly and in a roundabout way.

3.2 Effects of auxiliary power demand on net power

The amount of heat produced by a stack at any given time is dependent on the gross current and the stack efficiency at that current level. In order for the stack to maintain its temperature within a

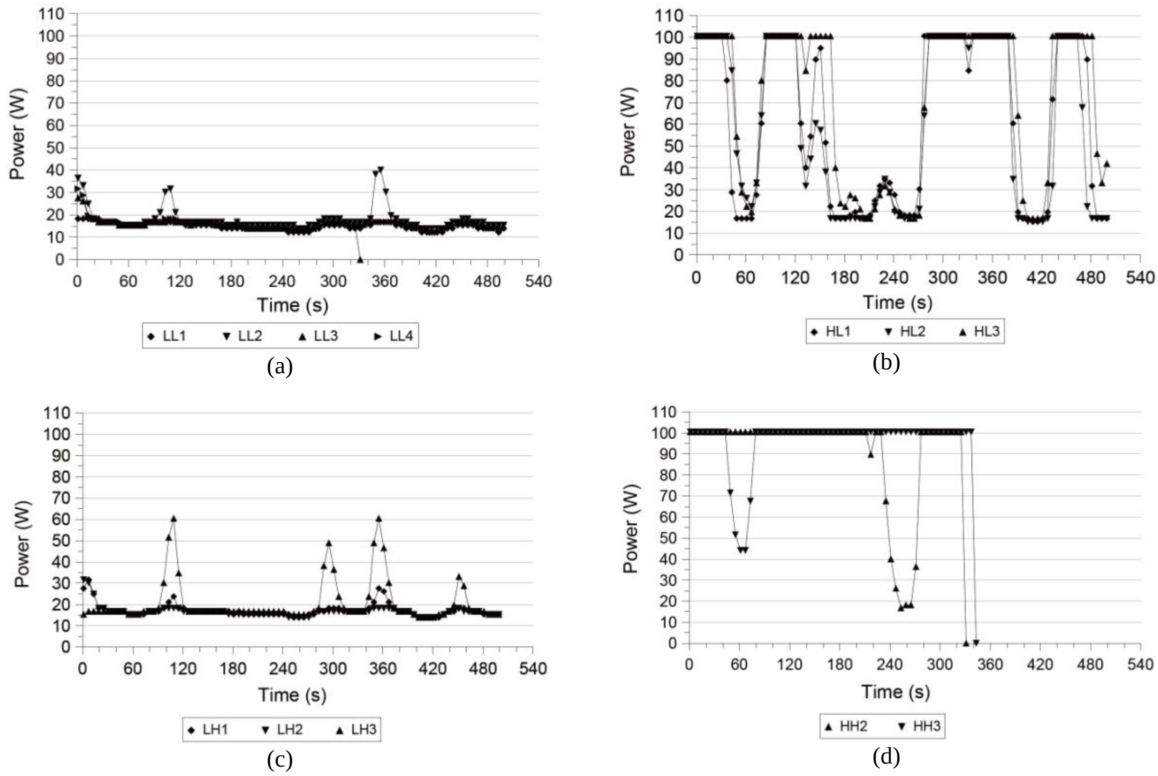

Figure8: Representative heat exchanger fan((a)Low Temperature, Low Humidity, (b)Low Temperature, High Humidity, (c)High Temperature, Low Humidity, (d)High Temperature, Low Humidity) power consumption profiles

particular range, the heat exchanger must expel excess heat. The target ambient air temperature settings of the high and low temperature ranges were 40℃ and 25℃, respectively. Figure 7 shows the representative stack operating temperatures while operating at those two ambient temperatures. As the figure shows, humidity appears to have no effect on the temperature of the stack at low ambient temperatures, and a visible effect at high ambient temperatures. Overall, the maximum difference in stack temperatures among the four runs for any given instance in time is about 8℃. Even though this difference is relatively small, the effects on the QXF power consumption are relatively large, as shown in Figure 8.

3.3 Net efficiency analysis

During the Nexa testing, the auxiliary power demand varied by run, by time within the run, and with ambient conditions. In effect, as the auxiliary loads changed, so did the net efficiency. To illustrate this effect, the average net efficiency is calculated as follows:

$$\frac{100\times\int_{run} VI_N\,dt}{\frac{n_{cells}\times HHV}{2F}\int_{run} I_G\,dt} \qquad (1)$$

Where I_N and I_G designate net and gross currents, respectively; V represents the net voltage; n_{cells} represents the number of cells in the Nexa stack; and HHV stands for the change in enthalpy of formation of hydrogen[12]. The results of the run net efficiency are given in Table 4. The net efficiency numbers in the table are given on a run basis. Ideally, the failed runs would be given a net efficiency of zero. However, in order to assign statically significance to the effect of ambient conditions on net efficiency, data from the failed runs up to the point of failure had to be included, and data thereafter had to be neglected.

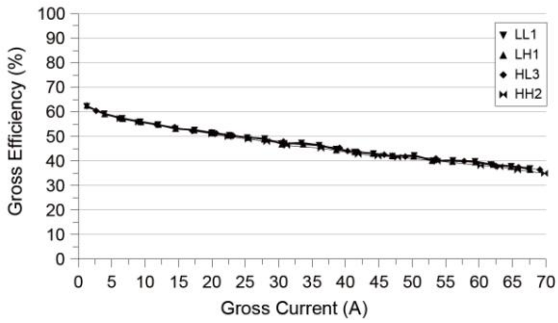

Figure9: Representative gross efficiency curves for runs LL1, LH1, HL3, HH2

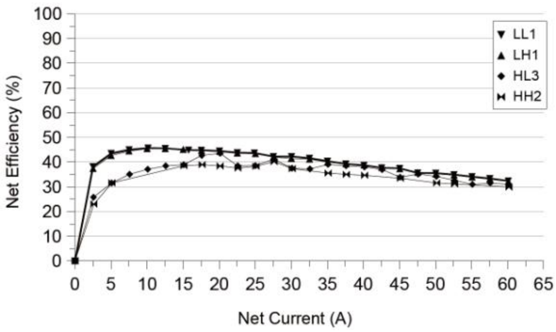

Figure10: Representative net efficiency curves for runs LL1, LH1, HL3, and HH2

The net efficiency data was evaluated using the ANOVA method. Along with the ANOVA method, effects from temperature, relative humidity, and their interactions were investigated using the Least Square Means method. Inspection of the Least Square Means in Table 5 shows that there is a statistically significant difference in net efficiency between the low and high temperature settings, while there is little difference in case of relative humidity settings. To that end, a graphical summary of both the gross and net efficiencies are given in Figure 9 and 10. Notice that in Figure 9, the curves overlap almost entirely, and that in Figure 10, only the curves for the low temperature runs overlap. The differences in net efficiency between the low temperature runs and the high

Table4: Net efficiency data by run type

Run	Successfully Completed Runs									Failed Runs		
	LL1	LL2	LL4	LH1	LH2	LH3	HL1	HL2	HL3	LL3	HH2	HH3
Gross Current Produced (A·s)	16,857	17,011	16,855	16,876	16,833	17,037	17,794	17,778	17,877	11,508	12,488	13,049
Net Current Produced (A·s)	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	10,415	10,305	10,865
QXF Current Usage(A·s)	309	374	331	358	345	429	1,288	1,234	1,470	220	1,255	1,379
CF Current Usage (A·s)	1,022	1,062	1,022	1,052	1,021	1,034	1,102	1,098	1,115	679	776	739
Runtime (s)	500	500	500	500	500	500	500	500	500	333	331	342
Gross H2 Usage (g)	72.33	72.99	72.32	72.41	72.23	73.1	76.35	76.28	76.71	49.38	53.58	55.99
Δh (kJ, HHV)	1,174	1,184	1,173	1,175	1,172	1,186	1,239	1,238	1,245	801	869	908
Net Energy (kJ)	448	438	445	446	445	446	440	441	442	303	299	318
Net Efficiency (%,HHV)	38.16	36.99	37.94	37.96	37.97	37.61	35.51	35.62	35.5	37.83	34.41	35.02

Table5: Least Squares Means analysis of effects from temperature and relative humidity

Least Squares Means(LSMEAN): Temperature				
Temp	Net Efficiency LSMEAN	Standard Error	H0 : LSMEAN = 0 Pr > |t|	H0 : LSMEAN1 = LSMEAN2 Pr > |t|
high	35.1291667	0.1665820	< .0001	< .0001
low	37.7883333	0.1393725	< .0001	
Least Squares Means(LSMEAN): Relative Humidity				
Relative Humidity	Net Efficiency LSMEAN	Standard Error	H0 : LSMEAN = 0 Pr > |t|	H0 : LSMEAN1 = LSMEAN2 Pr > |t|
high	36.2808333	0.1665820	< .0001	0.1400
low	36.6366667	0.1393725	< .0001	

temperature runs are due primarily to the associated heat exchanger fan power demand.

4 Conclusion

Changes in the Nexa's performance with respect to varying ambient temperature and relative humidity are investigated experimentally. The tests showed that ambient temperature directly affected the heat exchanger fan power consumption and the maximum power, and it has a statistically significant effect on net efficiency. On the other hand, the relative humidity played a statistically insignificant role in determining the net efficiency of the Nexa. Yet the increased frequency and duration of the anode purges indicate that flooding was evidently beginning to occur. One potential concern involves operating at near maximum powers under ambient temperatures above 35℃, which increases the probability of an operational stack failure occurring. Modification to the purge strategy upon start-up after an operational stack failure may be all that is needed to remedy the flooding problem. Water management control strategy must be able to differentiate between resuscitation after an operational stack failure and a normal start-up.

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