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Novel Gas-Driven Fuel Cell HVAC and Dehumidification Prototype

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ABSTRACT
Performance of a novel gas-driven, electricity-producing heating, ventilation, and air conditioning (HVAC) system with no vapor compression and no hydrofluorocarbon (HFC) refrigerant shall be discussed in the paper. The prototype was evaluated at ORNL under a Small Business Voucher (SBV) Cooperative Research and Development (CRADA) program. The target market is commercial buildings in the United States. The goal is to mitigate or eliminate grid-power for building air conditioning, coincident peak demand and associated spinning reserves, aiding in flattening of the "duck curve". The technical goal is to transform the common packaged rooftop unit into a cost-effective distributed energy resource, opening a new range of small applications and broad markets for micro-combined cycle cooling, heating, and power with integral thermal energy storage. The test results indicate the prototype would be competitive with natural gas distributed power plants with average electrical production ranging from 45% to 60% natural gas to electricity conversion efficiency. The technology has a Primary Energy Savings Potential of 4.4 Quads, higher than any other air conditioning and heating technology.

KEYWORDS: Fuel Cell, Distributed Generation, Heating, Cooling, Dehumidification

INTRODUCTION

The first integrated electricity-producing heating, ventilation, dehumidification, and air conditioning (HVAC) system using a non-vapor compression cycle (VCC), packaged rooftop unit that also produces base-load electricity was evaluated[1]. For convenience throughout this document we will call this integrated system Electricity-Production HVAC or EP-HVAC. The EP-HVAC unit represents a distributed energy resource with energy storage that eliminates the tremendous peak electricity demand associated with commonly used electricity-powered vapor compression air conditioning systems.

The objective is to enable the proliferation of renewable resources into the electric grid, reduce greenhouse gas emissions, eliminate the use of refrigerants used for air conditioning, and provide significant cost savings for utilities and ratepayers. This technology eliminates grid-powered electricity for building air conditioning, coincident peak demand and associated spinning reserves, aiding in the flattening of the "duck curve." The technology is scalable from 2 to 20 tons and is applicable to 98% of US commercial buildings.

The results of the evaluation indicated that the technology, as tested would be competitive with natural gas distributed powerplants with average electrical power efficiency ranging from 45% to 60%. Test results indicate that the technology has a Primary Energy Savings Potential of 1.3 x 10^{12} kWh (4.4 Quads); higher than any other air conditioning and heating technology.

[1] Natural Gas Powered HVAC System for Commercial and Residential Buildings, ORNL/TM-2017/211, CRADA/NFE-16-016126, https://resolution.ornl.gov/pub/preview/74419

The project goal was to test and evaluate the performance metrics of a unit that provided 5 kW cooling capacity and generates electricity from burning natural gas using a commercially available solid oxide fuel cell (SOFC).

TECHNOLOGY DESCRIPTION

Principle of operation of the prototype:

A simplified description of the prototype is shown in Figure 1 and consists of three main sections: natural gas driven fuel cell for producing electricity; liquid desiccant regeneration; and dehumidification and air conditioning.

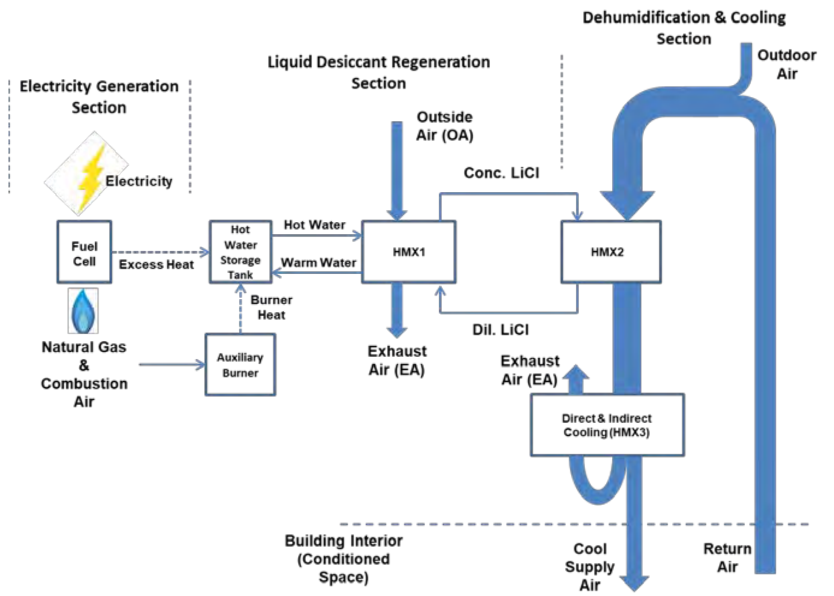

Figure 1 Schematic of the prototype EP-HVAC with three discrete sections: electricity Generation; LD regeneration; and Cooling and Dehumidification.

The prototype operates using a fuel cell and a burner to transform natural gas into electricity and heat. The heat generated is used to increase the concentration of a LiCl solution to 42% (mass fraction). This process occurs within a heat and mass exchanger (HMX) for liquid desiccant regeneration (HMX1). The concentrated LiCl is stored in a tank. When air conditioning is required, the concentrated LiCl is used to dehumidify process air (PA) within a dehumidifier (HMX2). PA for this prototype system is generally composed of a mixture of 30%–40% outdoor air (OA) with the remainder being return air (RA). The HMX2 is composed of a series of plates designed so that PA and high concentration LiCl flow on one surface. The LiCl is separated from the PA by a selectively permeable membrane that enables the interaction of water (in vapor form) with the air but prevents the flow of LiCl into the air. Because the liquid desiccant is at a high concentration, it will remove water from the air to reach water vapor pressure equilibrium with the air. This process, if adiabatic, would be isenthalpic dehumidification, resulting in a significant temperature increase of the process air. To mitigate this temperature rise, OA flows on the opposite side of the HMX2 plates, in cross-flow to the PA. The plate prevents both streams from mixing but enables heat transfer between the two flows. Water is also flown on the surface of the OA side of the plate. The OA in HMX2 absorbs the water, and this evaporation process (as well as sensible heat exchange with the air) cools the liquid desiccant dehumidification process on the other side of the plate. Consequently, the PA leaving HMX2 has a humidity that corresponds to a design dew point temperature, and a dry bulb temperature that is sometimes higher than the inlet air temperature but far lower than it would be if the dehumidification was isenthalpic (the exit temperature can be slightly lower than inlet temperature if the outdoor conditions are very dry, which yields high-powered evaporative cooling).

To reduce the temperature of the PA down to supply air (SA) conditions, the stream is subjected to dew point-style indirect evaporative cooling (IEC) in a heat and mass exchanger (HMX3). HMX3 is composed of a series of plates. The entire PA flows over the plate's surface. However, at the exit of the plate approximately 30%–40% of the PA is redirected to flow counter to the bulk PA flow through HMX3, on the opposite side of the plates as the bulk PA flow. On this side of the plate water is flown, causing the redirected flow to cool to its wet bulb temperature. The redirected air flow leaves at close to 100% relative humidity (RH) and is exhausted. This reverse flow both cools the bulk flow, and is derived from the bulk flow, which means the lowest temperature achievable is the incoming air's dew point temperature, instead of its wet bulb temperature. At the outlet end of HMX3 plates, where a portion of the flow reverses its path, the exhaust air will indirectly cool the bulk air toward the exhaust air's wet bulb temperature. The cooler bulk air now has a lower wet bulb temperature, and it subsequently becomes the next batch of exhaust air, lowering the achievable temperature further. This continues until it cannot continue further, which (in theory) is when the dry bulb temperature of the bulk air equals the wet bulb temperature of the exhaust air, which, since they are the same stream, occurs when the bulk process air is exiting at its dew point. The bulk PA exiting HMX3 is the supply air (SA) to the building.

A more effective cooling process:
The air conditioning/dehumidification process is referred to as enhanced liquid desiccant air conditioning (ELD-AC). ELD-AC typically removes the latent heat duty of the air prior to cooling it down to as near the theoretical limit of the dew point temperature as possible. Compared to conventional VCC, the ELD-AC process is more energy efficient.

The ELD-AC process removes the more energy intensive latent first, followed by sensible indirect evaporative cooling using water extracted from the air. The change in enthalpy is typically roughly 30% lower than vapor compression (Figure 2). Most VCC systems introduce air into the space at near 100% RH and at a temperature much lower than for human comfort. VCC systems rely on heat from occupants and from building equipment (and sometimes supply their own reheat) to heat the air up to a comfortable temperature. Consequently, the prevailing method of air conditioning, VCC, is energy intensive.

In contrast, the ELD-AC dehumidification process is achieved through diffusion of water vapor from humid air across a semipermeable membrane into a flowing concentrated liquid desiccant. Liquids cannot penetrate the membrane, keeping the desiccant isolated from the conditioned air stream. This process of dehumidification is actively cooled using outside air so that it does not increase the DA temperature (however, even if it did, this would not increase the overall maximum enthalpy change, as long is the dehumidification process remains close to being isothermal). Air dehumidification, due to latent loads, is energy intensive and its removal by the above technique is more efficient than a VCC process. After removal of sufficient latent loads, further cooling in the ELD-AC process is achieved with indirect evaporative cooling.

RESULTS
The evaluation consisted of 29 data sets with varying conditions in the outdoor air chamber (Figure 3 and **Error! Reference source not found.**). The test showed a 1st law efficiency that ranged from 0.6 to 1.2. The average 1st law efficiency for all runs was 0.9, with a standard deviation of ±0.15. Supply air temperature varied from 15.4°C to 19.4°C, with an average SA temperature of 17.3°C and a standard deviation of ±0.9°C. SA average RH was 55%, and it ranged from 48% to 62%. Note that the 1st law efficiency in this case can be greater than 1 because the heat of water vaporization is not included in this calculation.

The first law efficiency is defined in Eq.(1) as,

$$\eta_{1st\ Law} = \frac{C+E}{F} \quad (1)$$

C is the air cooling is instantaneous steady state rate of enthalpy removed from air, corrected to eliminate liquid desiccant energy storage effects; E is the electrical power produced by the system; and F is the rate of chemical energy of the fuel provided to the system during a day. In this report, F is calculated using the lower heating value of the fuel.

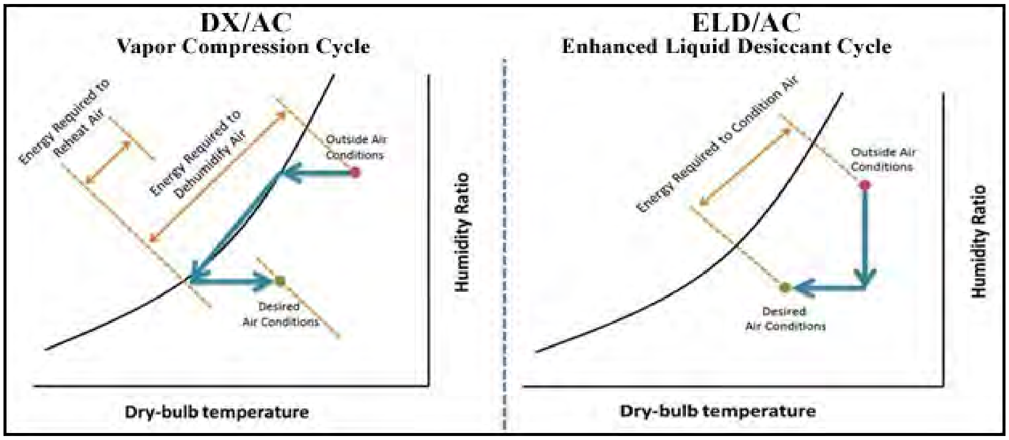

Figure 2 Difference in air conditioning and dehumidification processes between conventional vapor compression cycle (VCC) and the enhanced liquid desiccant evaporative cooling air conditioner (ELD/AC) cycle.

The testing was conducted at constant simulated outdoor and indoor air conditions. In other words, it did not take into account the daily varying requirements for air conditioning, which might have resulted in the air conditioning not being operated while the fuel cell continued to provide electrical power and regenerating liquid desiccant for later use. Under these test conditions, the heat supplied by the fuel cell was not sufficient to provide the heat required to sustain the air conditioning process, since these isolated tests could not rely on storage from daily continuous regeneration. For this reason, the supplemental natural gas burner was used to supply the extra heat required. Fuel cell performance was very predictable and repeatable. On average the fuel cell electrochemical efficiency was 47% (lower heating value based) with a combined heat and power efficiency of 90%, when producing 2.5 kW_e. Certain tests were performed without the fuel cell (burner only), in which case, for consistency, the expected power output and total natural gas input were calculated via the stable observed fuel cell electrical and combined heat and power efficiencies and included in the 1st law efficiency.

To provide a more insightful and comparative evaluation of the performance of the EP-HVAC, we define a distributed power efficiency (η_{DG}), as shown in Equation (2), where $\dot{E}$ is the electrical power produced by the fuel cell system as a function of time, $\dot{C}$ is the rate of cooling provided by the system as a function of time, COP_{VCC} is the coefficient of performance of an equivalent vapor compression system, $\dot{F}_{FC}$ is the rate of fuel energy consumed by the fuel cell system as a function of time on a lower heating value basis, and $\dot{F}_B$ is the rate of fuel energy consumed by the auxiliary burner as a function of time on a lower heating value basis. Note that $\dot{F}_B$ is only required when the fuel cell is unable to produce enough excess heat to drive the air conditioning process. The heat required to run the air conditioning process can be calculated using the quantified $\eta_{1st\ Law}$ in Equation 1. τ is the operating time period under which the efficiency is calculated, and t is time. Equation 2 converts the air cooling produced into an electrical equivalent output of the system. This efficiency definition enables the comparison of the EP-HVAC with a power plant that is providing both electrical power to the building and to run an air conditioning unit with equivalent output performance as the EP-HVAC.

$$\eta_{DG} = \frac{\int_0^\tau \dot{E}dt + \int_0^\tau \frac{\dot{C}}{COP_{VCC}}dt}{\int_0^\tau \dot{F}_{FC}dt + \int_0^\tau \dot{F}_B dt} \tag{2}$$

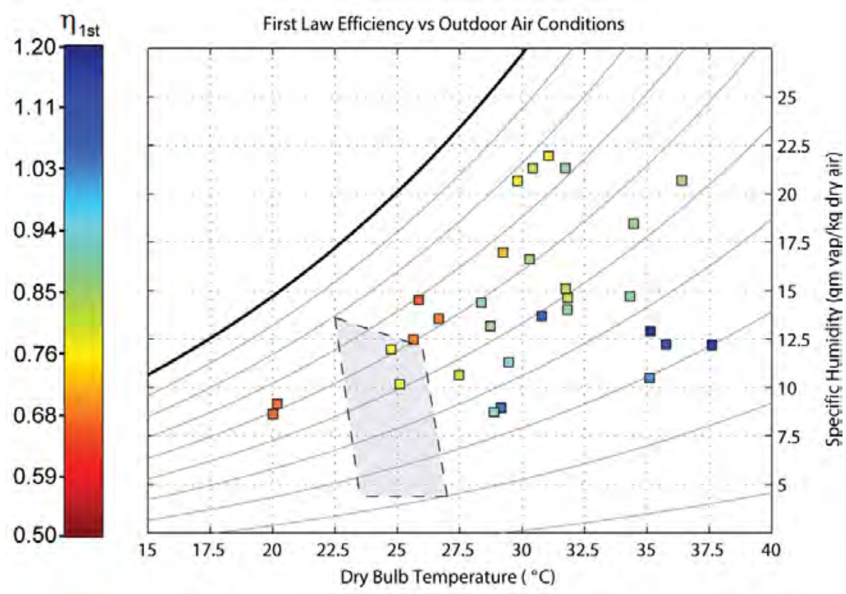

Figure 3. Psychrometric chart showing summary of outdoor air test points and $\eta_{1st\ Law}$ achieved (represented by point color and referenced to color bar on left) with the prototype unit. Comfort zone region is shown in dashed line polygon.

For illustration and simplicity, we have evaluated η_{DG} assuming the outdoor and indoor air conditions do not change during a day and that the air conditioning portion of the system operates in on/off operation (as most air conditioners do). Given this, a duty cycle can be defined as a ratio of the time the system spent cooling (air conditioner on) and the time the system produced electrical power. Also, for simplicity, we maintained the fuel cell power output constant during the day.

The tested conditions had two extremes: hot and humid (H&H), and hot and dry (H&D) conditions. These conditions are summarized in Table 1. Using the collected data and the simplifying assumptions previously described, where the power to cooling capacity ratio of the EP-HVAC is 1kW/RT, and a COP_{VCC} of 4.1 (EER = 14), which would correspond to a very high efficiency vapor compression cycle system, η_{DG} as a function of duty cycle was evaluated and the result is shown in Figure .

The results indicate that initially, η_{DG} increases as duty cycle increases, as the excess heat generated by the fuel cell is more than the heat required to drive the increasing air conditioning loads. In this regime, the excess heat from the fuel cell is better utilized and efficiency increases. As the duty cycle increases further, the fuel cell excess heat becomes insufficient to drive the cooling load, leading to increasing use of the auxiliary burner. This increases fuel consumption and decreases η_{DG}. For both H&H and H&D cases η_{DG} is higher than most distributed generation systems, ranging between 65% and 52% for the H&D case, and between 59% and 37% for the H&H case.

Table 1. Hot and Humid (H&H), and Hot and Dry (H&D) conditions tested

Hot and Humid Conditions			
First Law Efficiency:	90%	DG Efficiency Range:	37% to 57%
	Dry Bulb Temp. (°C)	**Relative Humidity (%)**	
Outdoor Air	31.8	72%	
Return Air	25.2	56%	
Hot and Dry Conditions			
First Law Efficiency	126%	DG Efficiency Range:	52% to 65%
	Dry Bulb Temp. (°C)	**Relative Humidity (%)**	
Outdoor Air	37.4	30%	
Return Air	25.5	55%	

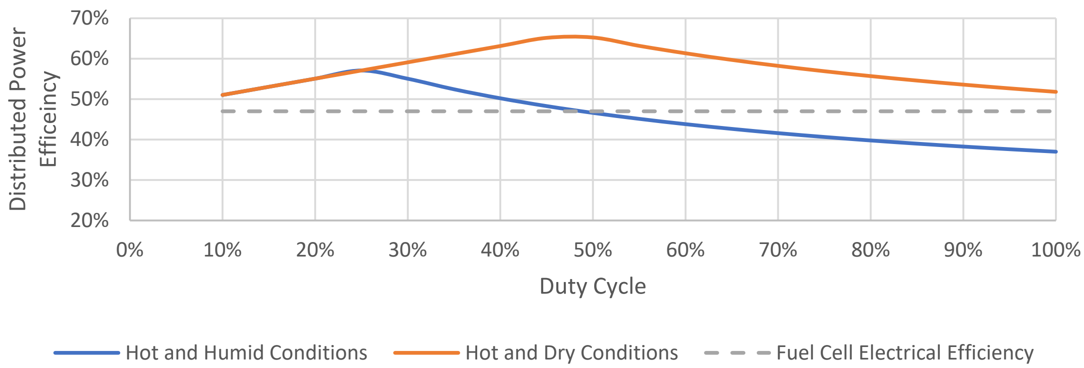

Figure 4. Distributed power efficiency of tested EP-HVAC as a function of duty cycle for constant return air and outdoor air conditions H&H and H&D. The COP_{VCC} is 4.1 and fuel cell power to air conditioner cooling capacity is 1kW/RT.

DISCUSSIONS

The EP-HVAC tested was the first prototype of its kind tested under varying outdoor air conditions. While the performance of the system measured in terms of $\eta_{1sr\ Law}$ is generally high, with improvements to the design it could be significantly higher.

EP-HVAC is an enhanced power generator and the most relevant comparative performance indicator is η_{DG}. The analysis of η_{DG} presented is sensitive to the assumptions made. In particular, COP_{VCC} and the power to cooling ratio. COP_{VCC} depends on outdoor air conditions and humidity, an effect that is not captured in the results presented. A COP_{VCC} of 4.1, the value used in our analysis, corresponds to the peak value found in the literature for high efficiency roof-top units.

Fuel cell electrical efficiency and CHP efficiency also play an important role and affect the optimization of the power to cooling design point in different weather conditions.

Further work is needed to complete a full evaluation of the EP-HVAC. This includes improving design of the system to reduce size and increase $\eta_{1sr\ Law}$ in all weather conditions. Additionally, there is a lot of room for system optimization for a particular building and weather conditions. To explore this, further dynamic, yearlong, location specific models should be developed.

CONCLUSIONS

The building and testing of this 1st EP-HVAC demonstrates that this is a technology with enormous potential to reduce energy consumption associated with electricity generation and powering air conditioners in buildings.