DEVELOPMENT OF ULTRASONIC GAS HUMIDIFICATION SYSTEMS FOR FUEL CELL STACKS

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ABSTRACT

The development of efficient and cost economical gas humidifiers is of main interest for the fuel cells industry. Water balance in operating proton exchange membrane (PEM) fuel cells is critical to increase performance and durability of the cell´s components. An approach in fuel cells water management refers to gases humidification in order to keep the optimum moisture of the membrane without blocking the gas pathways with excess water. The challenges on humidification systems are related to the parasitic power required to operate them, the response time and the extra volume and weight they add to the power plant. This work presents the design and implementation of an ultrasonic humidification system for fuel cells based on the water requirements for a 1 kW PEM fuel cell. The humidification system prototype was manufactured including an ultrasonic mist generator. The attained results are presented in conjunction with a proposed methodology to characterize the performance of a gas humidification system.

Key words: ultrasound, gas humidification, PEM fuel cells

1. INTRODUCTION

Proton exchange membrane fuel cells (PEMFCs) are electrical power generators with no emissions of contaminants when pure hydrogen is fed as fuel. The high performance efficiency of this technology makes them attractive power generators from portable to transportation applications. In spite of these advantages, their mass commercialization is in hold until technical challenges, mainly depending on improving their lifetime and reducing fabrication costs, can be overcome. Failures related to a bad water management are one of the main limitations for an optimum performance and longer life time of PEFC stacks [1] [2]. Decreasing failure occurrences helps extending the lifetime of PEMFCs. Conventionally, the water requirement in the PEMFC is usually supplied by external means, although internal humidification is also an approach for low power systems [2].

External humidification in PEMFCs relies either on adiabatic or heat based systems to evaporate or simply by gas bubbling in a water volume to saturate a gas flow before entering the cell [1], [3]. Although the use of heat improves the efficiency of these systems, as the saturation pressure of water is increased helping to keep more vapor in the gas phase (i.e. higher relative humidity), the power required can be considerably high, rising the parasitic losses in the whole system. Among other challenges, volume and weight contribute to make a voluminous power plant without mentioning the drawback of the response time from a heating depending humidifier.

Considering these challenges, this work focused on the development of an ultrasonic gas humidifier to provide moisture in an instantaneous way with a low power requirement and minimal dimensions and weight for a 1 kW PEMFC.

An ultrasonic generator, nebulizer unit, was selected to convert water into fine particles. The unit is a compact and low power nebulizer based on a piezo ceramic resonator. The piezo resonator is fixed to the base of a water receptacle built into the nebulizer. The frequency of the resonator is 1,65 MHz and corresponds to the piezo resonator´s own resonant frequency. The resonator apply mechanical energy generated from a 48 VAC supplied by drive circuits directly into the water [4].

Once the voltage is applied, the mechanical energy is transmitted in a direction that is perpendicular to the resonance surface of the resonator. By modifying efficiently the water depth, it is possible to produce a water column where the energy is concentrated; this is, above the axis of the transmission on the water´s surface. This yields a surface tension that is reduced and the water surface is divided into minute regions that match the length of the surface tension waves. Each of these areas became individual particles that are lifted and distributed into the air. This is the principle to convert water into cloud-like particles. The average particle size, d_h, is related to the surface tension (*T*), density (*p*) and the frequency (f_a) as determined by the following formula [5].

$$d_h = 0.73\sqrt[3]{\frac{T}{\rho f_a^2}} \qquad (1)$$

In the case of water, where *T*=.0729N/m, *p*=1000kgm^{-3}, and f_a=1.65 MHz, the size of the particles centers around 2 microns. The ultrasonic device produces a mist cloud through which a flowing gas is humidified. The gas flow besides acting as a mist carrier goes through a saturation process itself as it is bubbled through a liquid water column before crossing the mist cloud. Some of the questions to solve are how much mist is produced as a result of the applied voltage? And how much vapor can this mist cloud provide to humidify the gas flow? The research expectation is to define the humidification efficiency of the ultrasonic nebulizer identifying the effect from the operating parameters over the amount of vapor transported by the carrying gas. Thus, this work focused on the characterization of the ultrasonic humidifier by keeping a steady state process while temperature, air gas flow rate and applied voltage were varied separately.

2. EXPERIMENTAL

2.1 Description of the set up

The humidifier was formed by an acrylic cylinder partially filled with liquid water with a gas inlet that allowed an air flow to be bubbled from the bottom of the water column. The cylinder's base was the piezoelectric device itself, from where the ultrasound wave is freed through the water to the surface. The cylinder was kept at atmospheric pressure but closed with an acrylic lid from where tubing could transport air and vapor out of the cylinder to a sensing point for temperature (T) and relative humidity (RH).

The ultrasonic device consisted of a nebulizer board and piezo crystal (APC™ Mod. # 50-1011) specified to work with a maximum power input for the electronics of 29 Watts with a rated input voltage of 48 VAC and a resonant frequency of 1.65 MHz, which in average formed water droplets of 2μm size. The electronic board was attached to the piezo crystal and this to the cylinder´s base, as observed in the photos of Figure 1.

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Figure 1. Piezoelectric board (left), humidification system with piezoelectric integrated (right).

The dimensions of the acrylic cylinder were 19 x 8 x 0.3 cm (h x d x w) and the water column height was maintained constant at 4.65 cm. A *K* type thermocouple immersed in the water bulk recorded water temperature changes. The air flow was regulated with a mass flow controller (Sierra Mod. 100). The gas flow temperature and relative humidity were measured before and after entering the saturator with two RH and T sensors (Vaisala™ HMP 45AC), both connected to a data logger (21X Campbell Sci. Inc.) to record on line.

The liquid water column was manually replenished to keep its height constant, and the bulk water temperature (T_w) was monitored with the thermocouple. The data obtained with the mass flow meter and thermocouple were recorded into a PC with data logging software and hardware (National Instrument™).

The RH and T sensors were fixed up-and-down-stream to the gas pipe line with acrylic T´ connectors to ensure the monitoring of the air flow before and after entering the humidifier. The compressor fed a constant air flow in the range of 10 to 20 LPM. The data showed a low RH and temperature ranging 15% and 25.3^{o}C on average, respectively, and changing with daily environmental conditions.

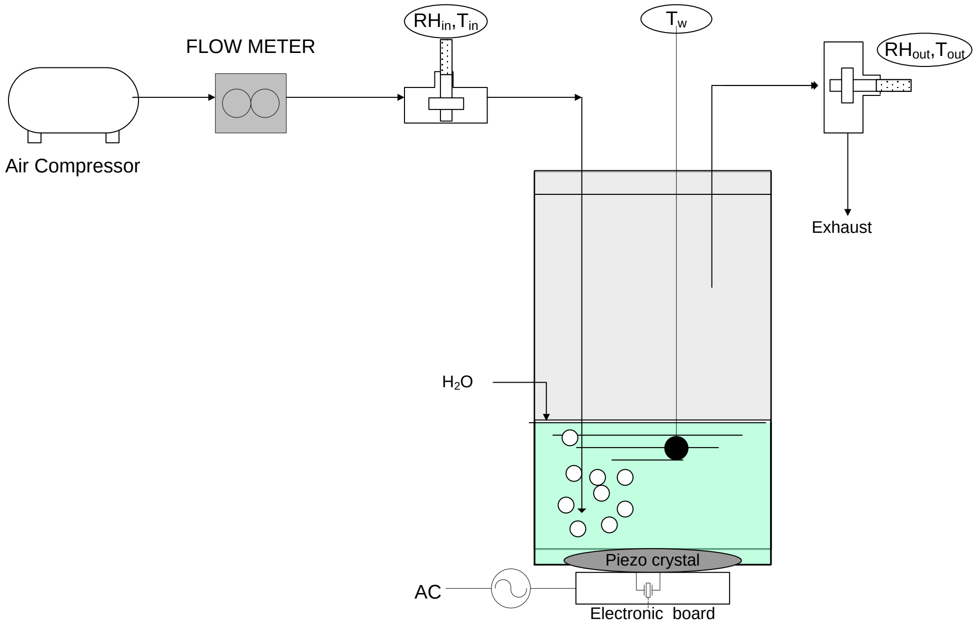

Figure 2. Experimental setup for characterization of ultrasonic humidifier

2.2 Methodology

The experiment consisted on flowing a dry air stream from a compressor through the mass flow meter to the humidifier where it was bubbled into the liquid water column, first, and through the mist cloud generated by the piezoelectric. The piezoelectric was kept working within a voltage range from 26 VAC to 30 VAC, as the signal to noise ratio of the acquired signals increased after 30 VAC, and below 26 VAC there was no visible mist produced.

The RH data gathered from measurements were converted into water flow (LPM) based on a mass balance considering the humidifier as the control volume, where the exhaust flow is composed by the gas flow ($\dot{m}_{air,out}$) and the carried water flow ($\dot{m}_{w,out}$) from the humidifier:

$$\dot{m}_{T,out} = \dot{m}_{air,out} + \dot{m}_{w,out} \qquad (2)$$

where,

$$\dot{m}_{air,in} = \dot{m}_{air,out} \quad (3)$$

where,

$$\dot{m}_{w,out} = \frac{X_w}{1 - X_w} \dot{m}_{air,in} \quad (4)$$

where

$$X_{w,out} = \frac{P_{w,out}}{P_{Total}} \quad (5)$$

and assuming $P_{total} = P_{atm}$.

3. RESULTS

The air temperature and relative humidity at the inlet (T_{in}, RH_{in}) and outlet (T_{out}, RH_{out}) ports were collected every two seconds. The inlet data showed intermittent variation apparently dominated by the operating cycles of the compressor, which limited the analysis of data to a smaller range than the original experimental design proposed. The selected data for the analysis was chosen from the operational regions where the signal to noise ratio allowed to observe a steady state. As explained in the previous section, the mass balance around the humidifier let to the calculation of the amount of water driven out (grams of water per minute, g min^{-1}) by the carrying gas in the vapor phase, and it is shown in the next graphs as the outlet water flow in grams per minute.

During the measurements it was also identified a fast temperature increase of the water bulk that impacted negatively to the steady state requirement. Even though it was expected a temperature gradient produced by the ultrasonic wave, the piezoelectric's frequency was high enough to generate excess heat from cavitation. From the piezoelectric effect only, the water bulk temperature observed a fast increment that was offset by the convective effect of the flowing gas. From this experience it is believed that dimensions of the water recipient (or the water volume itself) and the voltage frequency applied to the piezoelectric need to be studied as impacting factors for the next design of the humidifier.

The rising of bulk water temperature (T_w), resulted from the piezoelectric and convective effects, can be observed in Figure 3. For this graph, the input voltage was kept constant, and the increment of T_w can be observed from 28 to 34°C, for 26 VAC; and from 32 to 36°C, for 28 VAC. Due to this temperature increase, the amount of water vapor leaving the humidifier with the carrying gas increased for both voltage values. In the plot, the two different data sets also differ in the rate of the air flow at 14 and 20 LPM. It was expected that increasing the input voltage, the outlet water flow would increase; contrarily, a decrease on the water flow was observed at higher voltages, presumably attributed to the effect of lowering the gas flow rate. Thus, from this plot, it is assumed that the input voltage has minor influence on the rate of evaporation than the carrying gas flow rate. Considering that the input voltage is directly related to the amount of mist produced by the piezoelectric, it can be assumed that a small mist cloud provides enough vapor to humidify the gas flow rate in the selected range, which confirms that evaporation in the cloud is enhanced as the tiny droplets in the mist provide larger contact surface for the gas to evaporate faster and providing enough vapor to humidify large air flows [5].

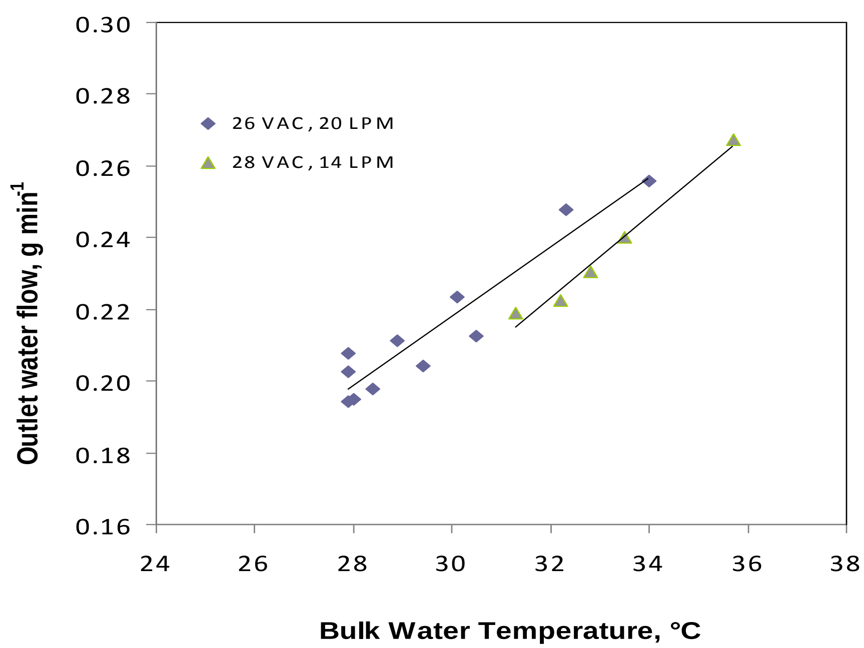

Figure 3. The outlet water flow as a function of the water temperature (Tw) for an air flow of 14 LPM and 2 VAC input and 20 LPM and 26 VAC input.

The effect of the air flow rate on the outlet water flow is shown in Figure 4, in the 10 to 20 LPM range, for 26 VAC and 28 VAC. As seen, the water flow increases with air flow rate, which was expected from convective mass transport. Yet, the effect of T_w can be observed as well. The three data series differ in T_w, with one degree difference between each other. Even though the temperature difference is apparently minimum, a visible effect is shown in the outlet water flow, increasing with increasing T_w. From linear fitting applied to each data series, it was found that the line slopes depend on voltage, which explains that at a constant air flow, the outlet water stream can be varied with the input voltage applied to the piezoelectric.

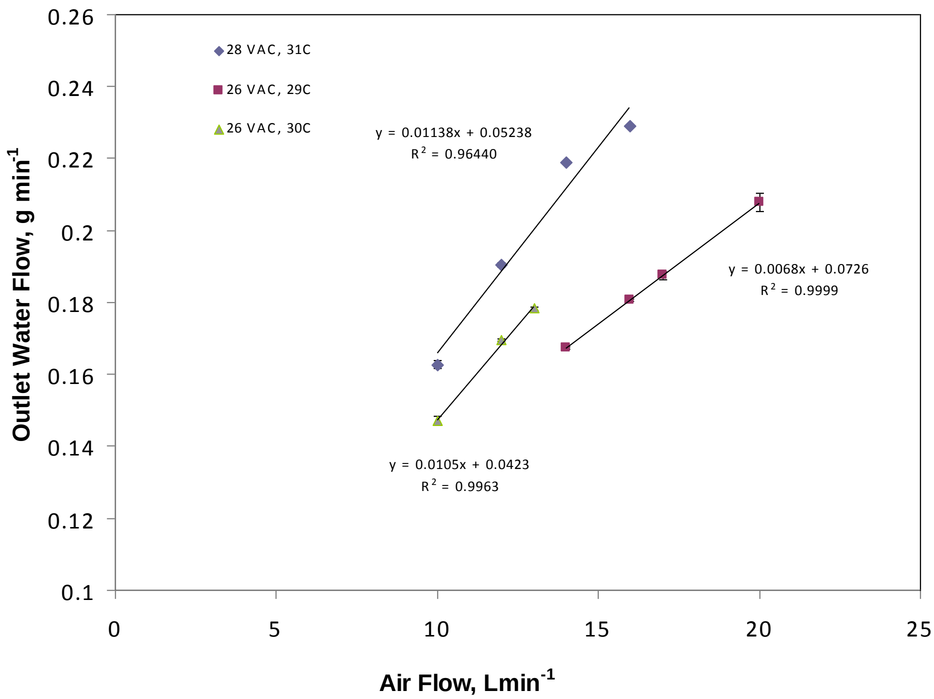

Figure 4. The outlet water flow as a function of the air flow. The input voltage and T_w were kept constant

This same final idea was confirmed with the graph of Figure 5. In this, the air flow rate was kept constant, and the outlet water flow was measured against the input voltage. The voltage could only be tested in the 26 VAC – 30 VAC range due to the sensibility of the humidity sensors. Within this range, the grams of water leaving per minute increased with increasing voltage, and as shown in both data series, the rate of change was similar in both scenarios although the absolute values increased with a higher T_w.

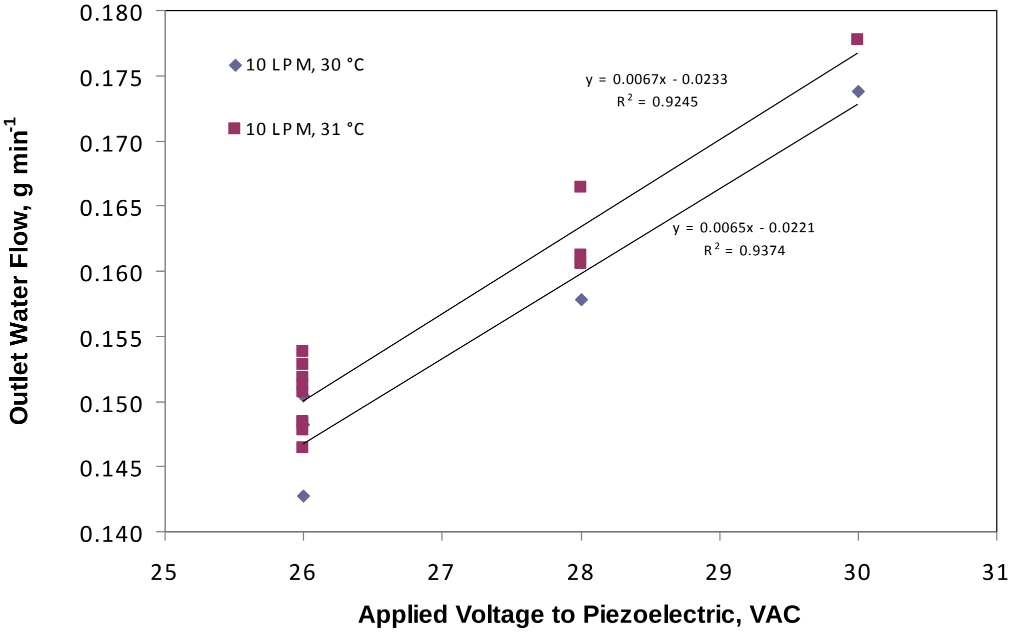

Figure 5. The outlet water flow as a function of the input voltage to the piezoelectric board.

It is observed from these data, that the effect from T_w in the amount of water leaving the humidifier is probably the factor with the largest impact in the process. It is clear that a higher T_w results in an enhanced evaporation inside the cylinder. Whether this enhancement is a mixed result from a faster evaporation of the water surface and or from the heat transported by air convection and radiation from the liquid water to the mist cloud, is not clearly understood. In any case, the application for this humidification system on PEMFCS does not attempt a dependency on T_w; instead, the interest is to reduce energy requirements for gas humidification. Hence, a subsequent objective is to find the optimum gas-to-vapor ratio with the aim to control the relative humidity of the gas fed to the fuel cell. In the following experiments, it is planned to include variations from the recipient dimensions, the voltage, the frequency and the possibility to keep T_w constant.

4. CONCLUSIONS

An ultrasonic humidifier was built using an ultrasonic wave generator to humidify an air flow to be fed into a 1 kW PEMFC. The air flow was bubbled through a liquid water volume and the mist cloud generated by the ultrasonic wave in an acrylic cylinder. The air flow acted as a carrier gas dragging out vapor water. Keeping steady state conditions, operating variables such as input voltage (applied to the piezoelectric), air flow rate and water temperature were varied for characterization of the humidification system. It was found that the temperature in the liquid water, T_w, generated by the piezoelectric effect, has a larger impact on the water evaporation rate than the input voltage itself. The data showed that the humidification process using ultrasound is more efficient than typical bubbler humidifiers, as evaporation in the mist cloud is enhanced by the tiny droplets created by the piezoelectric effect providing a larger contact surface for the gas, which improves the gas humidification.

5. REFERENCES

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