Enhanced water removal in a fuel cell stack by droplet atomization using structural and acoustic excitation

Vikrant Palan, W. Steve Shepard Jr. *

Department of Mechanical Engineering, The University of Alabama, 290 Hardaway Hall, Box 870276, Tuscaloosa, AL 35487, USA

Abstract

This work examines new methods for enhancing product water removal in fuel cell stacks. Vibration and acoustic based methods are proposed to atomize condensed water droplets in the channels of a bipolar plate or on a membrane electrode assembly (MEA). The vibration levels required to atomize water droplets of different sizes are first examined using two different approaches: (1) exciting the droplet at the same energy level required to form that droplet; and (2) by using a method called 'vibration induced droplet atomization', or VIDA. It is shown analytically that a 2 mm radius droplet resting on a bipolar-like plate can be atomized by inducing acceleration levels as low as 250 g at a certain frequency. By modeling the direct structural excitation of a simplified bipolar plate using a realistic source, the response levels that can be achieved are then compared with those required levels. Furthermore, a two-cell fuel cell finite element model and a boundary element model of the MEA were developed to demonstrate that the acceleration levels required for droplet atomization may be achieved in both the bipolar plate as well as the MEA through proper choice of excitation frequency and source strength.
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1. Introduction

Even though fuel cells have been around for a long time, significant progress towards their commercialization has not been made until recently. While the field has seen overwhelming progress, researchers are trying to make fuel cells more efficient and affordable. Presently, the cost of running a car entirely on fuel cells is estimated to be almost 10 times to that run on an internal combustion engine [1]. As a result, before the consumer invests in fuel cell technology, there are several issues that must be addressed with the goals of reducing costs and improving performance. One such issue is the process of product water removal in a PEM fuel cell. In the present study, the use of vibrational and acoustical principles to improve water removal is investigated. Effective water removal would result in smoother running of the fuel cell and hence improved performance. The result is that a smaller fuel cell stack may be required for the same power output, which would result in lower overall costs.

Polymer electrolyte membrane (PEM) fuel cells, which are considered here, are also known as solid polymer electrolyte and polymer electrolyte fuel cells. PEM cells operate at a temperature of around 80 °C, which makes it one of the most preferred fuel cells used in industry today [2]. In this type of fuel cell, the ion conducting medium or the electrolyte is a polymer membrane, such as Nafion®, that is permeable to protons but does not conduct electrons. The anode and cathode electrodes are typically made from carbon, catalyst, ionomer, and void space. The electrode/electrolyte assembly is called a membrane electrode assembly (MEA). The MEA is the smallest building block of a PEM fuel cell [3]. In a typical fuel cell, Hydrogen is fed continuously to the anode and oxidant (oxygen from air) is fed continuously to the cathode. The electrochemical reactions, which are described in detail in other works and therefore not shown here, take place at the electrodes to produce electric current.

The main products of electrochemical reactions in PEM fuel cells are electricity, heat, and water. The water often occurs in the form of condensation [4]. This water can accumulate on the cathode side of the stack. Besides this source of water, there are also various other sources of water in a fuel cell system.

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* Corresponding author. Tel.: +1 205 348 6419; fax: +1 205 348 0483/6419.
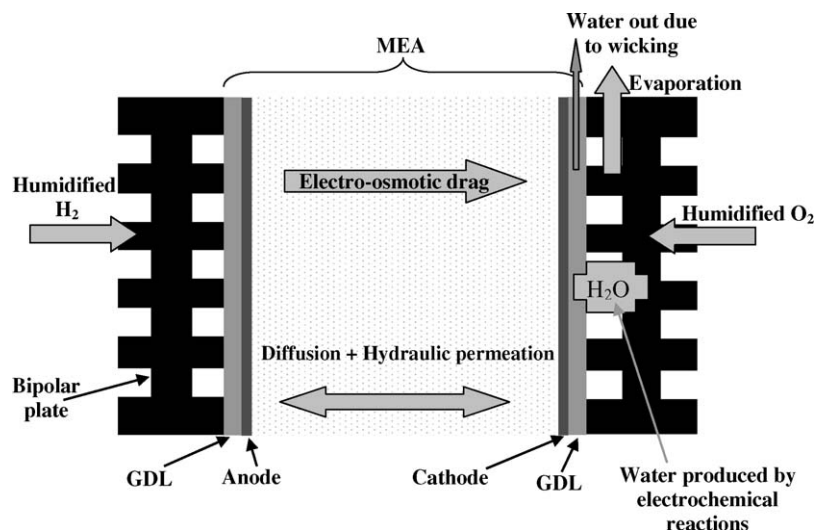 *E-mail address:* sshepard@eng.ua.edu (W.S. Shepard Jr.).

Fig. 1. Section of a single fuel cell showing various sources of water and components for removing that water.

Fig. 1 shows the location of various water sources in a single-cell system. The reactant gases are humidified for better ionic conductivity through the electrolyte [5]. Some of the water being used to humidify the reactant gases is carried by the H$^+$ ions from anode to cathode through the electrolyte membrane. This phenomenon is called electro-osmotic drag. Apart from this, water is also observed to diffuse from cathode to anode or vice versa due to concentration and pressure gradients across the membrane electrode assembly (MEA).

It should be emphasized that the presence of water is not necessarily detrimental to the fuel cell performance. In fact, maintaining the right amount of water improves the overall power output of the fuel cell. Excess water in the system, on the other hand, can cause a phenomenon called flooding [6]. Flooding in fuel cells results in water-clogging in the channels of the bipolar plates and hence reduces the amount of reactant gases being available for electrochemical reactions. Moreover, flooding causes some of the water to block the reaction sites, thus affecting the efficiency of chemical reactions. The excess water due to flooding is also found to affect the physical characteristics of MEA components. It should be noted here that flooding in a fuel cell system can occur separately in the bipolar plate channels, the diffusion media, as well as in the catalyst layers. In the present investigation, only the flooding in the bipolar plate channels is considered and investigated.

One of the conventional water removal methods is by capillary or wicking action [7] in the gas diffusion layer (GDL). The GDL is made out of a porous material and is located between the electrodes and the bipolar plates, as shown in Fig. 1. The pores in this material give rise to capillary-like structures, which results in water removal by capillary action. This capillary action causes the clogging water to rise and exit from the top of the GDL. Oxygen is generally supplied to the cathode via the introduction of air. This air is often pressurized to increase the efficiency of reaction. For better product water removal, air is supplied to the cathode at high stoichiometric ratios. The stoichiometric ratio, in case of fuel cells, is the ratio

of the amount of oxygen actually supplied to the amount of oxygen needed to operate the fuel cell. Typically, a stoichiometric ratio of 2 is used in an attempt to sweep out the excess water on the cathode side [8]. The purpose of higher stoichiometric ratio is also to overcome diffusion limitations to the catalyst layer given the low oxygen diffusivity and low mole fraction in the humidified air stream. Additionally, the electrodes are coated with a hydrophobic material, such as Teflon^{TM}, to reduce its affinity for water. These methods, although effective, increase the fuel cell costs in terms of production and parasitic losses.

Most of the conventional water removal methods are aimed at removing water at the cathode. This is certainly a logical approach as all of the water is produced on the cathode side. However, recently developed techniques work on the principle of transporting excess water to the anode side where it can then be removed. These research efforts assume that water removal from the anode side is easier and more efficient than from the cathode side. These methods work on the basis of creating gradients—pressure [9], concentration [10] and temperature [11] across the MEA and bipolar plates, thus inducing water accumulation on the anode side. The main disadvantage of using these methods is their detrimental effect on the ion transportation rate. Recall that H$^+$ ions are also transported through the electrolyte membrane when excess water is migrating through it (see Fig. 1). The excess water accumulating on the anode side, if not removed effectively, may result in reduction in active reaction sites. This reduction in sites will affect the rate of reaction and hence the fuel cell (FC) performance.

From the above discussion, it is evident that there still exists a need to investigate new methods to further improve the removal of excess water in fuel cells. The new methods to be considered here involve the use of vibro-acoustic energy to remove that water. Since there has been no effort to study the requirements for using vibro-acoustic means to enhance water removal, the present research examines the feasibility and potential requirements for such applications.

The objective of the present study is to investigate the possibility of disintegrating or atomizing the water droplets clogging the channels of the bipolar plates and the pores of the MEA. The atomization of water droplets as examined here may help in a couple of ways. First, with the water droplet atomized, the blocked channels can be cleared which results in more efficient flow of the oxidant on the cathode side. Consequently, the reaction rate and hence the overall FC performance may be enhanced. Second, when the droplets are disintegrated, it may be easier for the other water removal processes to sweep away that excess, unwanted water. This approach might result in lower parasitic loads and hence higher power output and better FC performance. After giving a brief introduction to atomization, the next section introduces two methods to estimate the vibration acceleration levels required to atomize a droplet resting on a plate. Then, the required vibration levels are estimated for a representative case at a few excitation frequencies. Next, the feasibility of generating the required acceleration levels in a fuel cell stack is discussed. This study is accomplished by first modeling a bipolar plate in order to predict the achievable vibration levels. It should be noted that the modeling does not include the surface tension effects that may exist with the presence of droplets in the diffusion media (gas diffusion layers). In other words, the water removal via vibro-acoustic means is studied only in the bipolar plate channels independent of the flooding in the diffusion media. The plate study is further extended to a two-cell fuel cell so that the achievable levels can be predicted for a more realistic configuration. In order to examine the acoustic excitation case, a boundary element model of a membrane resting across a channel is developed in order to predict the vibration levels that can be achieved via excitation by an acoustic source.

2. Theoretical background

Studies related to the atomization of liquids can be dated back to the early 20th century [12]. The atomization process has been studied for various applications such as increasing the efficiency of fuel atomization in IC engine cylinders and novel cooling methods in the microelectronics industry [13]. In the present study, two methods for droplet atomization are investigated in terms of applications in fuel cell stacks. The methods proposed may be employed to atomize or burst a water droplet resting on and/or blocking the bipolar plate channels in a fuel cell. If the droplet is atomized, some of the previously discussed methods are better able to remove the unwanted water. Removal of the water droplets would potentially result in higher power output and smoother running of the fuel cell system. The first method in this context, studies the droplet formation phenomenon in order to estimate the droplet atomization parameters. Once the atomization methods have been reviewed, their applications to a fuel cell will be examined through modeling.

2.1. Droplet atomization energy from droplet formation

One method of estimating the vibration energy required to atomize a droplet is to look at the energy required to form that droplet. This formation energy is a summation of viscous energy,

E_{vis} and surface tension energy, E_{st}. When this summation is equated to vibration energy, E_{vib} [14],

$$E_{\text{vib}} = E_{\text{vis}} + E_{\text{st}}, \tag{1}$$

the vibration amplitude and acceleration required to atomize or disintegrate a droplet may be estimated. The energy quantities in Eq. (1) are given by

$$E_{\text{vib}} = \frac{1}{2}\rho_{\text{w}}U^2 V_{\text{eff}}, \tag{2}$$

$$E_{\text{vis}} = 32\pi\mu_{\text{w}}R^3 f, \tag{3}$$

and

$$E_{\text{st}} = \sigma_{\text{w}}S_{\text{eff}}, \tag{4}$$

where U is the velocity amplitude of vibration; ρ_{w} is the water density $= 1000\,\text{kg m}^{-3}$; μ_{w} is the water viscosity $= 0.001\,\text{Pa s}$; R is the droplet radius; f is the excitation frequency; and σ_{w} is the liquid surface tension $= 0.072\,\text{N m}^{-1}$. The droplet cap volume V_{eff} and the droplet cap surface area S_{eff} are given by [15]

$$V_{\text{eff}} = \left(\frac{\pi R^3}{3}\right)(1 - \cos\varphi_0)^2(2 + \cos\varphi_0), \tag{5}$$

and

$$S_{\text{eff}} = 2\pi R^2(1 - \cos\varphi_0). \tag{6}$$

This droplet cap, as shown in Fig. 2, is the portion of the droplet resting on the surface. The contact angle, also shown in the figure, is a property of the surface. In Eqs. (5) and (6), φ_0 is the contact angle, which is the angle that the edge of the droplet makes with the horizontal surface.

Using Eqs. (2)–(4), the energy balance in Eq. (1) may be solved to determine the vibrational velocity amplitude and hence the corresponding displacement and acceleration amplitudes required to atomize a water droplet. Before presenting some representative cases, a very brief review of another method, called vibration induced droplet atomization (VIDA), is presented next.
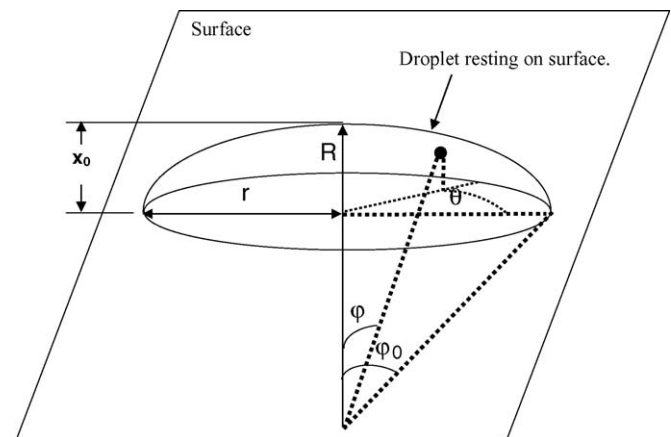

Fig. 2. Modeling of a water droplet cap resting on a surface.

2.2. Vibration induced droplet atomization

Vibration induced droplet atomization (VIDA) involves the vibration of the plate on which the droplet or liquid is resting. This vibration is induced at a particular excitation frequency and acceleration level [16]. This method becomes particularly attractive because of the wide range of droplet volumes it can potentially handle while consuming as little as a few milliwatts of power [17]. James et al. experimentally demonstrated the VIDA process in one of their papers [18]. They observed that there is a critical value of vibration amplitude and acceleration for the system under consideration above which atomization occurs. In spite of being able to atomize a droplet at relatively low frequencies, they observed that the corresponding critical acceleration levels were very high. The excitation frequency in their study was chosen such that it is close to the first natural frequency of the specimen under consideration. For the particular specimen that Smith et al. considered, the acceleration levels required for atomization were of the order on $2451 \, \text{m s}^{-2}$ (250 g). They concluded from their study that when the component under consideration is excited near its first natural frequency with vibration amplitudes corresponding to approximately $2451 \, \text{m s}^{-2}$, droplet atomization occurs. Since the VIDA method may prove to be promising for fuel cell applications, it will be considered in this study.

Smith et al. devised a simple model for VIDA in terms of the spring-mass-damper system. Nevertheless, some of the parameters needed to create that model, such as the nonlinear damping and stiffness terms, are based on fits to experimental data. Unlike the droplet atomization method discussed in the previous section, therefore, VIDA is experimental in nature. Also, the spring-mass-damper model does not account for the surface tension energy, which is considered in the previous method. Due to this reason, lower acceleration levels for atomization may be expected using VIDA as compared to the previous method. This will be clear from the results presented in the later sections. Furthermore, since formulation of VIDA requires accurate values for damping and stiffness of the vibrating system, it is not reasonable to analyze this method in great detail. Nonetheless, the feasibility of this method will be discussed with regards to whether the required $2451 \, \text{m s}^{-2}$ acceleration level can be achieved in a fuel cell system. This feasibility study is presented below.

3. Vibration levels based on formation energy approach

As discussed above, the vibration amplitudes required to atomize a water droplet resting on a bipolar plate may be predicted by considering the formation energies of that droplet. Fig. 3 shows the displacement and corresponding acceleration amplitudes required to atomize a droplet at several excitation frequencies for a range of droplet radii. Note that these parameters are estimated using the equations given in Section 2.1. Three different cases based on excitation frequency are presented in the figure. Note also that as the excitation frequency increases, the vibration amplitude needed to atomize a given sized droplet decreases significantly. Since the displacement and acceleration amplitudes are directly related by the excitation frequency, the corresponding acceleration level increases dramatically with
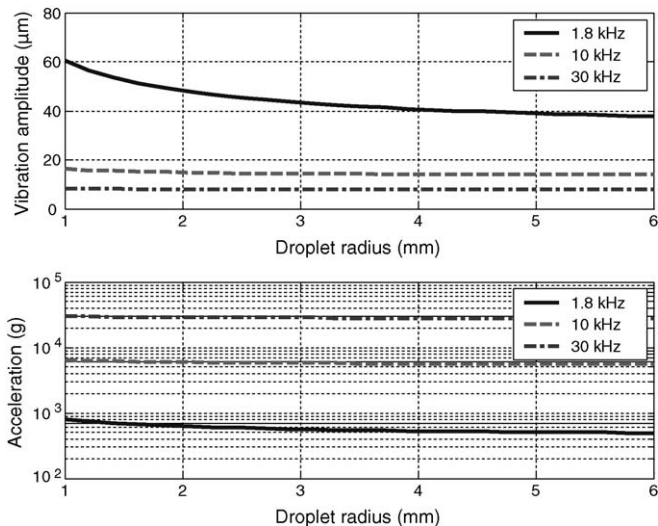

Fig. 3. Amplitude requirements for atomization considering droplet formation energies.

increasing frequency for the same size droplet. In order to disintegrate a droplet at lower vibration amplitudes, one needs to excite the plate at higher frequencies and anticipate the requirement for higher acceleration levels.

For the feasibility study presented next, a water droplet of 2 mm radius is assumed. From Fig. 3, it can be seen that acceleration levels of approximately $5884 \, \text{m s}^{-2}$ (600 g) would be required to atomize this drop using an excitation frequency around 1.8 kHz. Using these results and the deductions from the VIDA method, it can be concluded that acceleration levels between $2451 \, \text{m s}^{-2}$ (250 g) and $5884 \, \text{m s}^{-2}$ (600 g) may cause droplet atomization. Whether such high acceleration amplitudes can be achieved through various excitations will be examined next. To that end, a two-cell fuel cell stack was modeled using ANSYS® finite element software in order to predict achievable acceleration levels and determine the feasibility of atomizing the droplets. Furthermore, radiation characteristics of the MEA were modeled using COMET® boundary element software in order to determine if an acoustic source could be used to excite similar acceleration levels in the membrane. The purpose of these two studies was to determine the feasibility of exciting the required acceleration levels in a fuel cell given a reasonably sized source. The modeling approach is discussed in the next section.

4. Fuel cell plate and stack modeling

In this section, the components of a fuel cell (FC) stack were modeled in order to obtain an estimate of the acceleration levels that may be achieved for droplet atomization. After analyzing a single plate, a simplified two-cell FC stack model was considered. The following general assumptions were made in the analysis:

1. The bipolar plates were assumed to be made of steel. The density, Poisson's ratio and Young's modulus are given by $7700 \, \text{kg m}^{-3}$, 0.28 and 19.5E10 Pa, respectively.
2. The bipolar plates were assumed to be simple flat plates with no channels. Consequently, the effects of channels on the
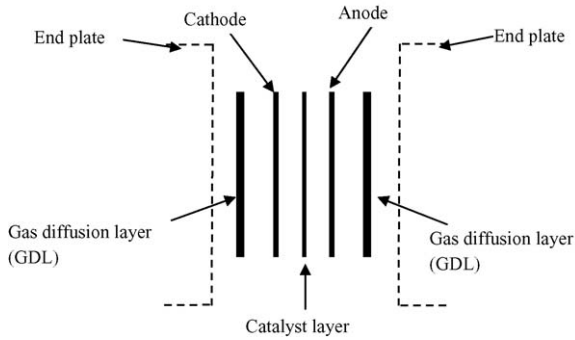
Fig. 4. Components of MEA shown in an exploded schematic. The five layers form one component.

problem examined here have been neglected. Future research will examine the more complicated geometry and its impact on the atomization problem.

3. The fuel cell membrane electrode assembly (MEA) was assumed to comprise of five layers as shown in Fig. 4. The two gas diffusion layers (GDL) shown in this figure are used to assist in uniform distribution of reactant gases. It should be noted that, for a single cell FC assembly, the bipolar plates will be placed on the exposed sides of the GDL, shown by dotted lines in the figure. In a FC stack, the two plates at the ends are called end plates since they enclose the entire stack and have channels cut only on one side. The relevant properties of various layers of MEA are given in a later section.

4. The stack is excited by exciting one of the end plates using a 10 lb shaker. Analysis results are also presented for a case utilizing four shakers. Also, the possibility of using a shaker (or shakers) with higher force output is acknowledged.

Instead of exciting the end plate at an arbitrarily chosen frequency, as discussed in Section 2.1, it was excited at a frequency in the vicinity of the first structural mode of a single plate simply supported along each edge. This plate may be considered to be analogous to an end plate in an actual stack.

The bipolar plates and the end plates have the dimensions 12.7 cm × 12.7 cm × 0.64 cm (5″ × 5″ × 1/4″) thick. The area over which the channels are cut form the active reaction sites for the plates. It is here that the water removal and hence droplet atomization becomes important. Therefore, this region was considered in evaluating the acceleration levels. An area of 6.9 cm × 6.9 cm (2.7″ × 2.7″) was considered as the active reaction site. These dimensions were obtained by assuming the ratio of the edge of the plate to the edge of the active reaction site to be 0.55.

The edges of the end plates were assumed to be simply supported. Since the exact boundary conditions of the plates as situated in a fuel cell are unknown, it was assumed that the realistic edge conditions lie between the plates being completely fixed and completely free. Since the membrane material that lies between the plates is relatively soft when compared to the plates, using the assumption of simply supported boundary conditions seems reasonable.

For the sake of completeness, the analyses presented in the following sections were also conducted using free boundary conditions at the edges of the bipolar plates. By using these conditions, the range of required levels can be estimated since the exact boundary conditions are not known. The levels for these conditions are discussed below. In future work, additional knowledge about the edge conditions in an actual FC stack may help in a better simulation of the exact boundary conditions.

5. System damping of 0.1% was assumed.

With these general assumptions, the modeling of the single plate is presented in the next section. After verifying the feasibility of inducing the required acceleration levels in this plate, a two-cell fuel stack was modeled. The details of this analysis are presented in a later section. Finally, the boundary element analysis of the MEA is presented.

4.1. Single plate modeling and results

This analysis was initiated by identifying the first natural frequency of a plate with simply supported edges. Once this frequency was identified, it was used as the excitation frequency with a 10 lb shaker. For the plate under consideration, the first natural frequency was found to be 1866 Hz. This FEM result was verified by comparing with closed-form analytical solutions [19]. A difference of less than 5% was found, which was considered acceptable. A contour plot of the average displacement levels in the transverse direction is shown in Fig. 5. The numbers indicate the FEM node numbers in the model. A ramped excitation frequency range of 1750–1950 Hz was specified in this analysis. The acceleration levels for two particular nodes, numbered 76 and 43, were estimated and the results shown in Fig. 6. These nodes were selected since they constitute the extreme displacement values in the active reaction site. As shown in the figure, acceleration levels as high as 20.6E3 m s^{-2} (2100 g) may be achieved by selecting the right shaker and excitation frequency for this simple plate. Of course, acceleration levels of 2100 g are neither necessary, nor realistic. These high levels are not necessary because atomization can potentially be caused by levels as low as 250 g, as discussed earlier. For such high acceleration levels, the resulting stresses in the components would be of particular interest. It was found that the resultant stress levels corresponding to acceleration levels of 20.6E3 m s^{-2} (2100 g) are much higher than a typical yield stress for steel. Therefore, these high acceleration levels are not realistic. Nonetheless, this study provides an extreme case with regards to the levels that may be achieved. Also, it should be noted that the stresses corresponding to acceleration levels of 2451 m s^{-2} (250 g) were below the yield stress values for steel. Specifically, stress values in the range of 3E6 N m^{-2} (435 psi) were obtained. The effect of the stresses produced on the plates and on the other components of fuel cell system as well as using more realistic material characterizations will be subjects of future work. The study presented here does not address these issues.

After analyzing a plate with simply supported edges, a similar study was conducted on a plate with free edges. However, very low acceleration levels were observed as compared to the required levels for droplet atomizations (≥250 g). Hence, the
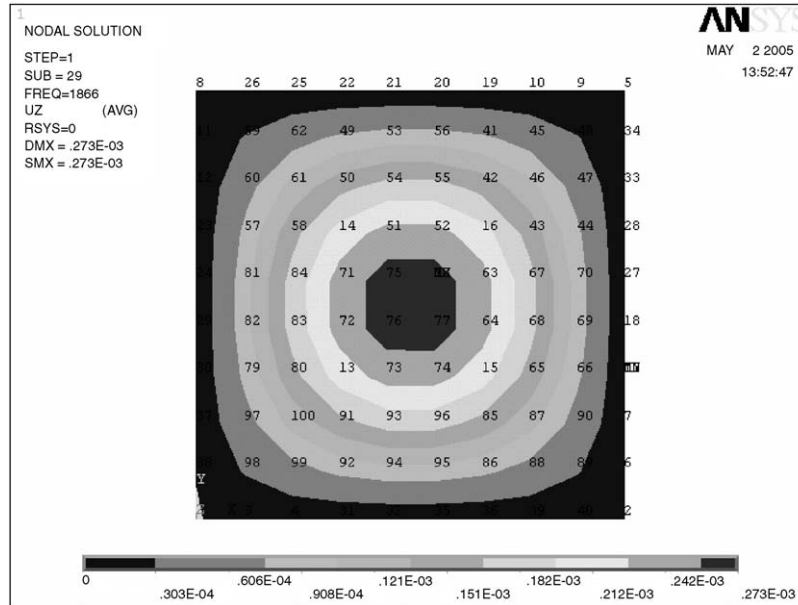
Fig. 5. Vibration response of a single plate with simply supported edges, in meters.

results of these analyses are not discussed here. Nevertheless, if the fuel cell boundary conditions are closer to free at the excitation frequency of interest, the vibration levels needed to achieve atomization cannot be achieved unless the excitation force is significantly increased. Generating such high forces may require a larger sized shaker, which may not be practical for a FC system. Therefore, other means of excitation such as a piezo-electric actuator may be considered. As a result, more work is needed in this area.

It should be reiterated that acceleration levels of approximately 2451 m s^{-2} (250 g) may potentially cause droplet atomization/disintegration according to VIDA. Whether such levels can be achieved in a FC stack is discussed next by considering a two-cell stack

4.2. Modeling and results for a two-cell FC stack

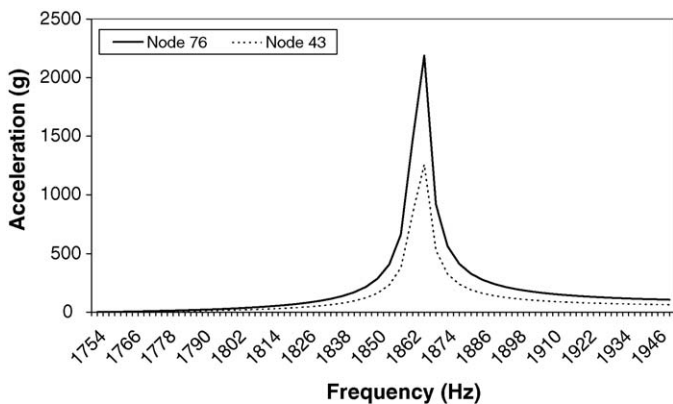As mentioned earlier, the main goal of the FE modeling was to estimate the acceleration levels at various locations on the active reaction sites of the end or bipolar plates. This analysis assumed that the stack is excited externally at one of the ends. This assumption was made to ensure that the addition of such an excitation source to an actual fuel cell unit can be accommodated with minimal space requirements and design changes. Other means for excitation are briefly discussed in Section 5. A 2D schematic of a two-cell stack is shown in Fig. 7. The proposed location of the shaker is also shown. The location of the shaker may be changed based on the constraints in the FC system. As shown in this figure, the MEA is modeled as a set of springs uniformly distributed over the channeled surface of the end and/or the bipolar plates. The representation of the MEA with springs as opposed to solid elements was done based on the vast differences in stiffness values for the bipolar plates and the MEA. It was assumed that due to the relatively low stiffness for the MEA, it behaves like a spring. For simplicity, the MEA is assumed to extend to the edges of the plates instead of being confined to the area of active reaction sites (Fig. 7(b)). The stiffness of the springs that represent the MEA is estimated using the equation for the axial stiffness of a rod. The properties and correspond-
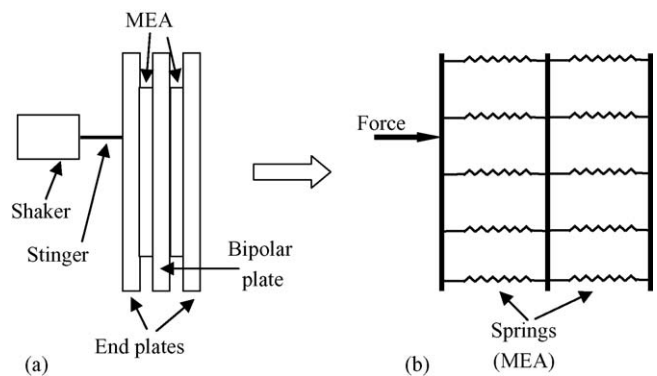

Fig. 6. Acceleration levels for nodes 76 and 43.

Fig. 7. Schematic of the (a) actual and (b) modeled two-cell FC stack.

Table 1
MEA properties and spring stiffness

MEA components	Thickness (μm)	Young's modulus (N m^{-2})	Stiffness (N m^{-1})	MEA stiffness (N m^{-1})	Spring stiffness (N m^{-1})
Membrane Nafion®, N-117 (water-soaked, 100° C)	183	6.4E7	1.64E9 (membrane spring)	1.2E9	4.79E7
Gas diffusion layer (GDL) lyflex, grade C494	300	5.65E8	8.85E9 (GDL spring)		

ing stiffness values assumed in this analysis are summarized in Table 1. In this table, the membrane refers to three layers: the catalytic layer, the cathode, and the anode. The stiffness k for a particular component is estimated using the relation $k = EA/L$, where E is the Young's modulus, A is the surface area and L is the thickness of the membrane or GDL. The properties for the MEA and the membrane were obtained from the technical specifications of these components provided by the vendor. The stiffness corresponding to the membrane is referred to as the membrane spring. This membrane, along with gas diffusion layers (GDL) attached to both its side forms the membrane electrode assembly (see Fig. 4). As shown in Table 1, the stiffness corresponding to the GDL is termed the GDL spring. The MEA stiffness is estimated by considering the membrane and GDL springs in series. The MEA stiffness is then distributed on the surface of the plates based on the number of nodes in the FEM model. Axial spring elements (COMBIN14 in ANSYS®) were used to model the MEA stiffness. In the case presented here, the total number of nodes on each plate was 25. Using the material properties given in Table 1, the stack was excited at one end and the acceleration values measured on active reaction sites of the three plates. Maximum acceleration levels were found at 1826 Hz as well as in the neighboring frequency range. The average displacement values in the transverse direction for the three plates at 1826 Hz are shown in Fig. 8. The lines connecting the three plates represent the spring elements with stiffnesses equivalent to that of

the MEA. It should be noted from the figure that the vibration response from the excited plate efficiently gets transmitted to the other plates. One of the reasons for this may be the relatively low stiffness of the MEA. The observation that exciting one plate excites all plates plays an important role because, for the proposed atomization methods to work, all the plates should be excited simultaneously by a single source or multiple sources on the same plate. Of course, multiple sources on multiple plates may be used, which would add to the complexity of the overall system. In the case discussed here, the shaker is attached to the end plate labeled as '1' in Fig. 8. The figure also shows the location of the shaker. From the FEM results, highest acceleration levels of approximately 120 g were obtained on all three plates. To further increase these levels, four shakers were assumed to be attached to the end plate being excited. With this change, acceleration levels as high as 460 g were obtained. The results are shown in Fig. 9, which shows three pairs of plots. Acceleration levels for two extreme nodal locations (on active reaction sites) for each plate are presented here for the frequency range of excitation. Using the plate numbering of Fig. 8, nodes 98, 95, nodes 62, 59 and nodes 26, 23 correspond to plates 1–3, respectively. Thus, it is analytically verified that the required acceleration levels of at least 250 g may be obtained with the right choice of shaker and excitation frequency. Additionally, it is worth mentioning that higher acceleration levels can be achieved by using an excitation source corresponding to a force greater than 10 lb.
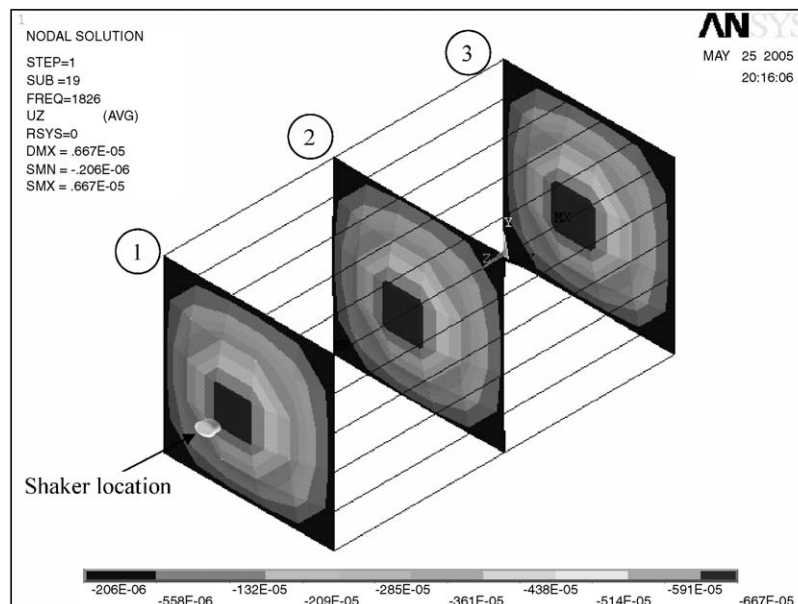

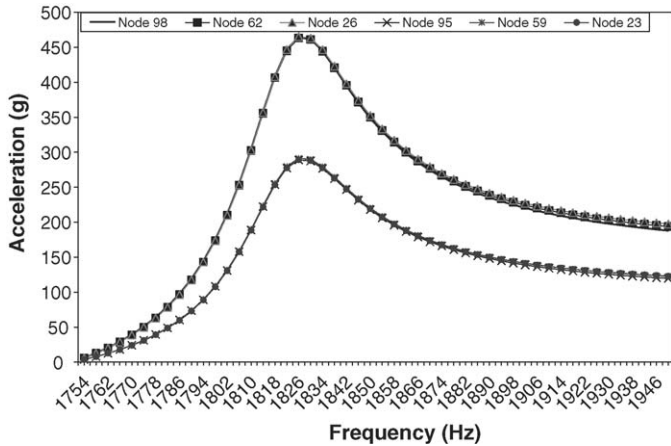Fig. 8. Vibration response for a two-cell FC stack at 1826 Hz, in meters.

Fig. 9. Acceleration levels on three plates using four 10 lb shakers.

Fig. 11. A bipolar plate channel with a portion of MEA resting on it.

Note that in the above discussion, structural excitation was used as the source. Moreover, this source was used to excite the bipolar/end plates. This type of excitation may potentially help remove product water in the clogged channels. But the method may not help in atomizing the water that clogs the membrane electrode assembly (MEA). Hence, the next section proposes methods to directly excite the membrane. Specifically, an acoustic source is used to excite the surface supporting the droplet.

4.3. Modeling and results of membrane excitation using an acoustic source

As mentioned earlier, the MEA forms an integral part of the fuel cell system, and can be broken down into a membrane and two gas diffusion layers (GDLs), as illustrated back in Fig. 4. The MEA is held firmly between two bipolar plates. The sketch in Fig. 10 shows an MEA embedded on a bipolar plate. A sealing gasket is generally placed over the uncovered area on the channeled side to prevent reactant gas leakage. These gaskets are not shown in the figure for clarity. Due to the pressures applied on the MEA by the two plates, it may be assumed that it is fixed to the 'channel side' of the plates. Note that the MEA rests only on a portion of the bipolar plate, which is referred to as the active reaction site. A combination of a channel and a portion of MEA resting on it may be seen as a waveguide with one flexible (MEA) and three rigid walls. For the case of this discussion, it is
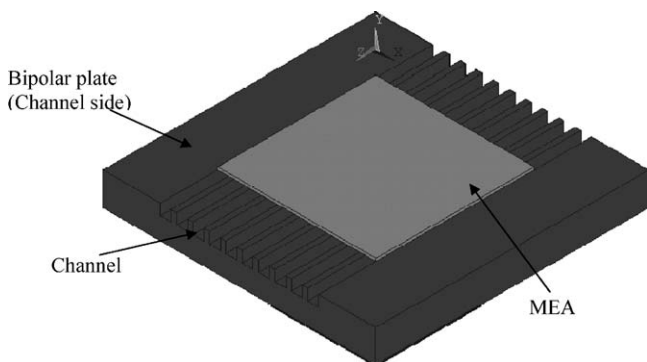
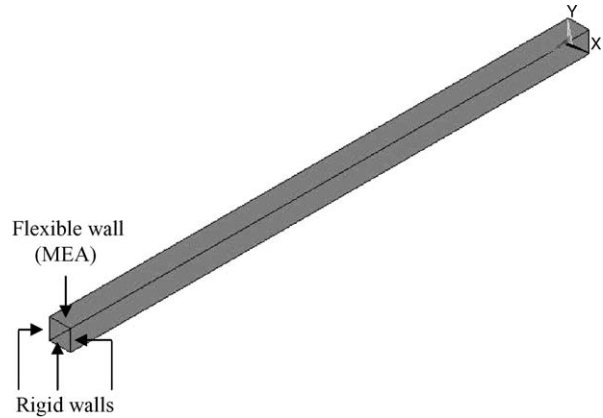assumed that the channels on the opposite side of the membrane are parallel to those shown. A single waveguide is shown in Fig. 11. The goal of this discussion is to examine the feasibility of exciting the top surface of this channel, which represents the MEA. Excitation of the MEA will potentially cause atomization of the clogging water droplets. This would in turn facilitate enhanced removal of the droplet by other methods, such as high air stoichiometric ratio.

An acoustic source, such as a point source and a plane wave, was considered as the source of excitation in the following study. A structural excitation (e.g. shaker) cannot be used in this case for two main reasons. First, the MEA is barely accessible; hence there is no room to attach a shaker. Secondly, the MEA is a very soft material and the attachment of a shaker would be difficult. Hence, the use of an acoustic source is a better approach.

Two types of excitations are considered in the present study—a plane wave (at a certain frequency and amplitude) incident on the MEA, and a line of point sources along the length of the channel. A schematic of both of these cases is shown in Fig. 12. The plane wave in the figure may be, for example, caused by a small loud speaker placed strategically at a certain distance from the bipolar plate. Of course, the angle of incidence of the plane wave becomes an important factor with regards to the wavelength and the dimensions of the channel cross section. Other factors, such as the source strength, location and number of sources were chosen arbitrarily since the goal of this exercise is to simply determine whether an acoustic source can induce the required acceleration levels. A more comprehensive parametric study is needed in order to understand the effects of each parameter.

A finite element model of a bipolar plate channel and MEA was created in ANSYS. For this analysis, only the MEA was flexible as the channel walls were modeled as rigid since their motion is not expected to significantly impact the MEA motion. The boundary conditions were set in ANSYS® and a modal analysis conducted. Then, the corresponding nodal displacements (eigenvectors) and natural frequencies (eigenvalues) were imported into COMET® in order to perform the acoustic analysis. COMET® was used to estimate the MEA structural displacements caused by an acoustic source. The excitation frequency,
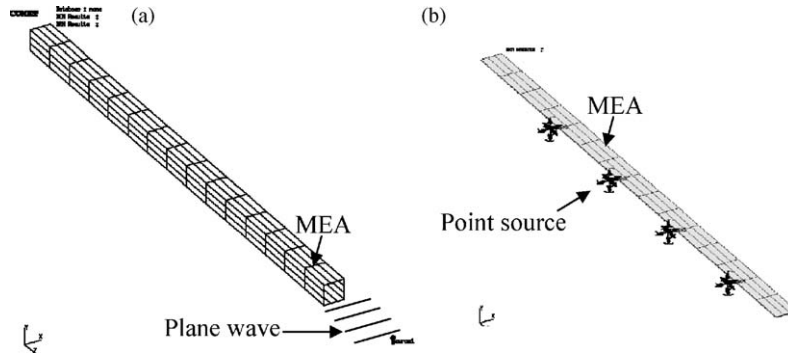

Fig. 10. MEA on a bipolar plate.

Fig. 12. MEA excitation using (a) a plane wave and (b) a line of point sources.

which in the illustrated case is 30 kHz, was chosen close to the first structural mode of the FE model of the channel. For simplicity, ambient air properties were assumed with density $\rho = 1.21 \, kg \, m^{-3}$ and sound speed of $c = 343 \, m \, s^{-1}$. The radiation characteristics of the MEA were determined in COMET® by coupling the MEA with the acoustic source. Fig. 13 shows the MEA acceleration levels obtained along the length of the channel considering a plane wave as well as a line of point sources for the excitation methods. In Fig. 13(b), even though just the MEA is shown, it should be assumed that this MEA rests on the rigid walls of the channel just like for Fig. 13(a). Note first, since the walls of the channel are assumed rigid, they have zero displacements. It is clear from the figure that the acceleration levels greater than 250 g are achieved due to the high excitation frequency considered in this case. As mentioned in the previous section, higher levels may be achieved by increasing the source strength.

In summary, this analysis demonstrates the feasibility of using an acoustic source for structural excitation of the MEA. However, future work is needed to experimentally verify whether such excitations can actually be achieved in a fuel cell stack. The current feasibility study was conducted in terms of implementation issues and also whether the accelerations levels required for atomization can be achieved practically. The excitation, as noted earlier, will potentially result in droplet atomization and hence easier product water removal in a fuel cell. Since water removal may be enhanced, there is a potential improvement in the overall fuel cell performance. Better performance correlates to smaller stacks and hence lower overall costs.

5. Summary

The main goal of the present study was to examine potential for new methods to enhance the removal of excess water from a fuel cell stack. These methods work on the principle of structural and acoustic excitation of the end plate and the MEA, respectively. The excitation causes a certain acceleration level on the plate surface and on the MEA, which would potentially result in droplet atomization. The atomized droplet may then be removed from the active reaction site by conventional water removal methods. The phenomenon of droplet atomization was explained and analyzed. The required acceleration levels were estimated using two approaches: (1) studying the energy required to form a droplet, and (2) using the levels associated with vibration induced droplet atomization (VIDA). Once these acceleration levels were estimated, a feasibility study was conducted to examine whether inducing these levels is possible in a fuel cell stack. For this, finite element and boundary element models of a fuel cell stack and the bipolar plate channel were created. In the study presented here, a shaker was assumed to be the source of structural excitation for the bipolar/end plate. This was mainly done because of the simplicity in simulating the shaker force in the FE model. Other means of structural excitation, such as through a piezo-electric actuator, may prove to be better suited for FC applications since compactness is a special asset for such a system. The modeling efforts in this direction may involve relating the force transmitted by the patch(es) to
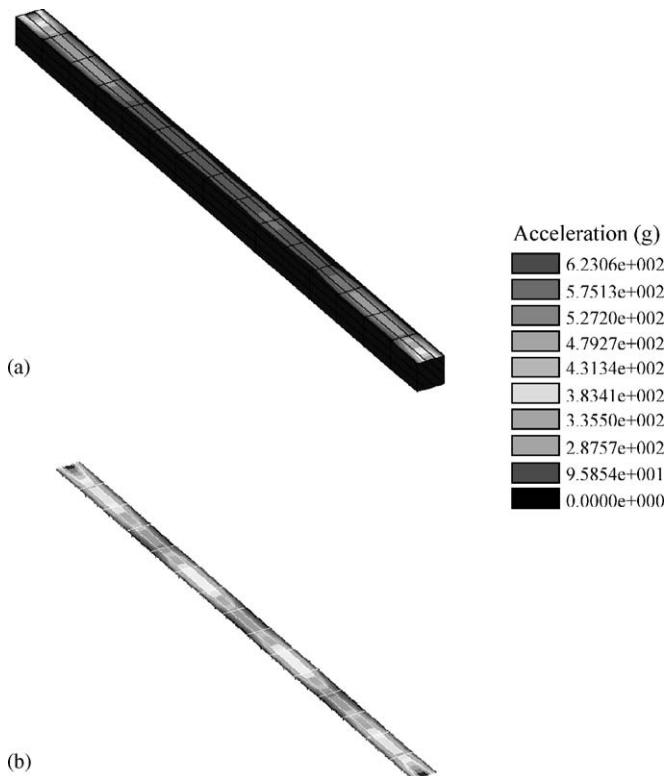

Fig. 13. Acceleration on MEA using (a) a plane wave and (b) a line of point sources with an excitation frequency of 30 kHz.

the moments generated by the same. Of course, the modeling analysis needs to be corroborated by the experiments. A plane wave and a line of point sources were the two cases considered for acoustic excitation of the MEA. It was shown that the acceleration levels of approximately 250 g may be achieved on both the plate as well as the MEA. Hence, it was shown that the implementation of the proposed droplet atomization methods is plausible. Further work into the types of sources and the magnitude of excitation forces is necessary to gain additional insight. If the proposed methods are shown to be effective, the enhanced fuel cell performance would potentially lead to smaller stacks and hence lower overall costs.

Acknowledgement

References

[1] GM unveils fuel cell car: http://money.cnn.com/2002/01/08/autos/auto_tech/, Jan 8, 2002.
[2] G. Hoogers, Fuel Cell Technology Handbook, CRC Press, New York, 2003, pp 1–4.
[3] http://www.generalhydrogen.com/tech_howfuel.shtml.
[4] P. Badrinarayanan, PEM fuel cell water and thermal management: a methodology to understand water and thermal management in an automotive fuel cell system, Master's thesis, University of California, Davis, CA, 1999.
[5] F. Chen, Y.-G. Su, C.-Y. Soong, W.-M. Yan, H.-S. Chu, J. Electroanal. Chem. 566 (2004) 85–93.
[6] D.P. Wilkison, H.H. Voss, D.S. Watkins, K. Prater, B., Solid polymer fuel cell systems incorporating water removal at the anode, US Patent number 5,366,818, 1994.
[7] U. Pasaogullari, C.Y. Wang, J. Electrochem. Soc. 151 (2004) A399–A406.
[8] K. Tuber, D. Pocza, C. Hebling, J. Power Sources 124 (2003) 403–414.
[9] H.H. Voss, D.P. Wilkison, D.S. Watkins, Method and apparatus for removing water from electrochemical fuel cells, US Patent number 5,260,143, 1993.
[10] H.H. Voss, D.P. Wilkison, P.G. Pickup, Electrochem. Acta 40 (1995) 321–328.
[11] H.H. Voss, D.P. Wilkison, D.S. Watkins, Method and apparatus for removing water from electrochemical fuel cells by controlling the temperature and pressure of the reactant streams, US Patent number 5,441,819, 1995.
[12] R.W. Wood, A.L. Loomis, Philosophical Magazine J. Sci. 4 (1927) 417–436.
[13] S.N. Heffington, A. Glezer, ITherm 2004—Ninth Intersociety Conference on Thermal and Thermo-mechanical Phenomena in Electronic Systems, vol 2, Institute of Electrical and Electronics Engineers Inc., Las Vegas, NV, 2004, pp. 90–94.
[14] S. Alzuaga, J.F. Manceau, F. Bastien, J. Sound Vibration 282 (2005) 151–162.
[15] R.J. Hunter, Foundations of Colloid Science, Oxford University Press, New York, 2001, pp 100–112.
[16] M.K. Smith, A. Glezer, Vibration induced atomizers, US Patent number 6,247,525, 2000.
[17] S.N. Heffington, W.Z. Black, A. Glezer, Eight Intersociety Conference on Thermal and Thermo-mechanical phenomena in Electronic Systems, Institute of Electrical and Electronics Engineers Inc., San Diego, CA, 2002, pp. 408–412.
[18] A.J. James, B. Vukasinovic, M.K. Smith, A. Glezer, J. Fluid Mechanics 476 (2003) 1–28.
[19] R.D. Blevins, Formulas for Natural Frequency and Mode Shape, Van Nostrand Reinhold Company, New York, 1979, pp 252–274.