A Study on the Flow of Air and Water Vapor in the Fuel Cells

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Abstract

In recent years, there has been a renewed interest in finding alternative energy sources. Among the possibilities currently being explored are hydrogen fuel cells, which produce electrical energy from hydrogen and oxygen gas. Hydrogen fuel cells have already been proven useful in applications ranging from automobiles to space exploration. However, hydrogen fuel cells are currently hindered by water management issues. While water management is crucial throughout the entire cell, the current research intends to examine the two-phase exiting flow of air and water vapor occurring in the gas diffusion layers. In addition, a possible non-wetting scenario has also been investigated. To further the understanding of hydrogen fuel cells, a wind channel was constructed with a variable fan speed and channel height. This apparatus allowed experimenters to observe the two-phase flow of air and water vapor that occurs in the gas diffusion layers of the fuel cells. Experiments were conducted to aid in the correlation of the resulting air speed due to the influence of channel height and fan speed. Because of the difficulty in experimentally finding the air velocity, a correlation between the channel height, fan velocity, and air speed was needed. By using analysis of variance, residuals, and regression an equation for predicting the air velocity was found with a 95% confidence interval. The data were found to be normally distributed with the exception of one outlier. The accuracy of the model increased when both the channel height and fan speed were used as regressor variables.

Introduction

The first working fuel cell was developed in 1839 and the 1960's fuel cells aided in the Apollo missions. With the advances made in electrochemical processes, a broad range of applications is expected in the future. As a potential candidate for an environmentally benign and an efficient electric power generation technology, proton exchange membrane (PEM) fuel cells are now attracting enormous interest for various applications such as low-emission vehicles, distributed home power generators, and power sources for small portable electronic products [1, 2, 3]. Recent studies indicate that water management is crucial for efficient operation of PEM fuel cells [4, 5]. The water content of the polymer electrolyte must be sufficient to provide good ionic conductivity, but too much water can flood the pores of the catalyst and gas-diffusion layers.

In the process of producing electricity by means of PEM fuel cells, hydrogen fuel passes through an anode catalyst layer where the hydrogen gas separates into protons and electrons. The protons pass through the PEM while the electrons pass through an external circuit producing electricity. On the other side of the PEM at the cathode catalyst layer, electrons and protons combine to form water as a by product. At both the anode catalyst layer and the cathode catalyst layer, a gas diffusion layer serves to evenly distribute the gases to optimize the fuel cell performance [6, 7].

Under certain operating conditions, water may condense into a liquid while still inside these channels resulting in a two-phase exiting flow involving the growth and migration of water droplets. Excessive growth of water droplets can lead to a “pinch-off” phenomenon in which the liquid coalesces across the channel completely blocking the flow. Pinch-off of a single channel has been known to lead to a cascading effect blocking several channels and thus inhibiting the fuel cell process and ultimately the power production of the fuel cell [4, 5]. The pinch-off phenomenon ends with the collapse of a narrow gas passage inside these small channels. This narrow passage has the potential to cause a non-coalescence or non-wetting scenario which is the focus of this paper. To investigate the possible role of non-wetting, a small scale “wind channel” was constructed. A quasi two-dimensional droplet was situated inside the wind channel and the influence of airflow, and channel height were investigated with the intention of creating and sustaining a non-wetting scenario. Statistical analyses were carried out to determine the relationship between air velocity and both channel height and fan speed.

Measurement and Data Analysis

Measurement of air velocity, channel height, and droplet volume must be recorded in order to investigate the influence of airflow and channel height to create and sustain a non-wetting condition. Channel height and droplet volume are recorded through the use of a z-positioning plate and syringe pump with relative ease. The air velocity is controlled by a computer fan which is operated by a DC power supply and is dependent on both fan speed and channel height. The current procedure of recording the air velocity is through a flow visualization technique which involves recording the distance that a particle travels in a specified time. Data collected from the experiment is presented in Table 1. For each trial run, the experiment was conducted three times and the average airspeed was recorded in the table. Table 2 presents the raw data for the experiments and was used for the Analysis of Variance – ANOVA [8] and Tukey’s test [9].

The objective of this project is to perform the following statistical analysis on the data points and determine the validity of the results: Analysis of Variance [8], Tukey’s Test [9], Analysis of Residuals [10], and Multiple Regression Model [11, 12]. The Two-Factor Analysis of Variance performed on the data allows testing the hypothesis that there is no significant effect for each of the factors, fan speed and channel height, and the interaction between them. The test procedure is shown in Table 3. The decision to reject or accept that there is not a significant effect is determined by the F-test: The null hypothesis, H_0 will be rejected if the equation (1) is true.

$$F_0 > F_{\alpha,a-1,N-a} \tag{1}$$

The second statistical analysis performed on the data was Tukey’s Test, which is a test based on the studentized range distribution. This test was performed to make a comparison of all possible pairs of means. The null hypothesis is H_0: $\mu_i = \mu_j$ for all $i \neq j$. The studentized range distribution is given in equation (2).

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$$q = \frac{\bar{y}_{\max} - \bar{y}_{\min}}{\sqrt{MS_E / n}} \tag{2}$$

Table 1: Airspeed data collected from experiments

Fan Speed (V)	Channel Height (mm)	Airspeed (cm/s)
12	2	8.50
11	2	6.00
10	2	3.83
9	2	3.00
8	2	2.83
12	3	48.44
11	3	27.68
10	3	26.00
9	3	18.75
8	3	15.63
12	4	103.80
11	4	86.50
10	4	69.20
9	4	62.50
8	4	40.00
12	5	256.62
11	5	126.87
10	5	110.000
9	5	95.000
8	5	82.500

Table 2: Distance (cm) data from flow visualization technique.

	Channel Height (mm)			
Fan Speed (V)	**2**	**3**	**4**	**5**
12	0.3, 0.25, 0.3	0.3, 0.3, 0.25	0.6, 0.6, 0.6	0.85, 0.95, 0.85
11	0.3, 0.3, 0.3	0.15, 0.15, 0.15	0.5, 0.5, 0.5	0.7, 0.75, 0.75
10	0.35, 0.4, 0.4	0.25, 0.25, 0.25	0.4, 0.4, 0.4	0.75, 0.75, 0.7
9	0.25, 0.35, 0.3	0.3, 0.3, 0.3	0.5, 0.5, 0.5	0.65, 0.6, 0.65
8	0.3, 0.3, 0.25	0.25, 0.25, 0.25	0.4, 0.4, 0.4	0.55, 0.55, 0.55

Table 3: Analysis of Variance table for the two-way-classification fixed-effect model

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0
A treatments	SS_A	$a-1$	$MS_A = \frac{SS_A}{a-1}$	$\frac{MS_A}{MS_E}$
B treatments	SS_B	$b-1$	$MS_B = \frac{SS_B}{b-1}$	$\frac{MS_B}{MS_E}$
Interaction	SS_{AB}	$(a-1)(b-1)$	$MS_{AB} = \frac{SS_{AB}}{(a-1)(b-1)}$	$\frac{MS_{AB}}{MS_E}$
Error	SS_E	$ab(n-1)$	$MS_E = \frac{SS_E}{ab(n-1)}$	
Total	SS_T	$abn-1$		

The largest sample mean is represented by $\bar{y}_{\max}$ and the smallest sample mean is represented by $\bar{y}_{\min}$. Two means are considered significantly different if equation (3) is true.

$$\left|\bar{y}_i - \bar{y}_j\right| > T_\alpha \tag{3}$$

where:

$$t_\alpha = q_\alpha(v_1, v_2)\sqrt{\frac{MS_E}{b}} \tag{4}$$

The third statistical analysis performed was an analysis of the residuals. This analysis was performed in order to check model validity. The residuals were calculated using:

$$e_{ij} = y_{ij} - \hat{y}_{ij} \tag{5}$$

ANOVA assumes that the observations are normally distributed and independent and this can be checked by plotting corresponding residual graphs. The normally distributed assumption is checked by plotting the residuals on a normal probability paper. For the assumption of equal variance at each factor level, the residuals are plotted against the factor level.

The fourth and final analysis performed on the data was to construct a multiple regression model. This was performed in order to gain a better understanding of the relationship between airspeed and both channel height and fan voltage. The data were fitted to a linear model:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon \tag{6}$$

where, y represents the air speed, x_1 represents the channel height, and x_2 represents the fan voltage. The regression coefficients are found using the matrix format:

$$\begin{bmatrix} n & \sum_{i=1}^{n} x_{i1} & \sum_{i=1}^{n} x_{i2} & \cdots & \sum_{i=1}^{n} x_{ik} \\ \sum_{i=1}^{n} x_{i1} & \sum_{i=1}^{n} x_{i1}^2 & \sum_{i=1}^{n} x_{i1}x_{i2} & \cdots & \sum_{i=1}^{n} x_{i1}x_{ik} \\ \vdots & \vdots & \vdots & & \vdots \\ \sum_{i=1}^{n} x_{ik} & \sum_{i=1}^{n} x_{ik}x_{i1} & \sum_{i=1}^{n} x_{ik}x_{i2} & \cdots & \sum_{i=1}^{n} x_{ik}^2 \end{bmatrix} \begin{bmatrix} \hat{\beta}_0 \\ \hat{\beta}_1 \\ \vdots \\ \hat{\beta}_k \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} y_i \\ \sum_{i=1}^{n} x_{i1}y_i \\ \vdots \\ \sum_{i=1}^{n} x_{ik}y_i \end{bmatrix}$$

It is often necessary to construct confidence interval estimates for the regression coefficients. These confidence intervals are found using:

$$\hat{\beta}_j - t_{\alpha/2,n-p}\sqrt{\hat{\sigma}^2 C_{jj}} \le \hat{\beta} \le \hat{\beta}_j + t_{\alpha/2,n-p}\sqrt{\hat{\sigma}^2 C_{jj}} \tag{7}$$

The significance of regression can also be tested. This determines whether there is a linear relationship between the dependent variable, y and the independent variables x_1, and x_2. The appropriate hypotheses are:

$$H_o : \beta_1 = \beta_2 = 0 \qquad (8)$$
$$H_1 : \beta_j \neq 0 \quad \textit{for at least one } j$$

Rejection of H_o implies that at least one of the independent variables contributes significantly to the model. The model adequacy is checked using the coefficient of multiple determination. The coefficient of multiple determination R^2 is defined as,

$$R^2 = \frac{SS_R}{S_{yy}} \qquad (9)$$

R^2 is a measure of the amount of reduction in the variability of y obtained by using the regressor variables. In a simple linear regression case, the value must be $0 \leq R^2 \leq 1$. A larger value of R^2 usually implies a better regression model. However, by adding a variable to the model, the R^2 value always increases and does not necessarily imply a good regression model.

Results and Discussion

Results from this analysis are presented in Table 4 in the form of an ANOVA table. From the table, it can be seen that the main effects of fan speed and channel height affect the air velocity. Also, since 29.8628>2, there is an indication of interaction between these two factors. It can also be concluded that there is at least one mean that is different. The Tukey's test can be used to find which means are different.

Table 4: ANOVA: two-way classification fixed effect model

SV	SS	df	MS	F	F_0
Fan Speed	0.124417	4	0.031104	53.3516	2.61
Column Height	1.90379	3	0.634597	1088.5	2.84
Interaction	0.208918	12	0.01741	29.8628	2
Error	0.023335	40	0.000583		
Total	2.26046	59			

Since it was determined that interaction was significant, comparisons between the means of one factor may be obscured by the AB interaction. In this case, Tukey's test is applied with one factor set at a particular level. The results from Tukey's test are displayed in Tables 5 and 6. The values were tested for a significance level of α=0.05. The highlighted values in the tables indicate the only comparisons with no significance in the difference in means. The residuals for the data were plotted normally and for each factor to check the validity of the model. The normal probability plot of the residuals is graphed in Figure 1. This plot has a point on the tail that does not fall exactly along a straight line passing through the center of the plot. This could indicate that either there is a potential problem with the normality assumption or that that point is an outlier. Figures 2 and 3 plot the residuals versus the channel height and fan speed respectively. There is some indication that the channel height of 5mm and the fan speed of 12V results in

Table 5: Tukey's test for fan speed at fixed channel height values

Fan Speed Tα=0.011814				
	Height=2mm	**Height=3mm**	**Height=4mm**	**Height=5mm**
$\lvert y_1 - y_2 \rvert$ =	0.02	0.12	0.1	0.682
$\lvert y_1 - y_3 \rvert$ =	0.1	0.02	0.2	0.685
$\lvert y_1 - y_4 \rvert$ =	0.02	0.02	0.1	0.585
$\lvert y_1 - y_5 \rvert$ =	0	0.02	0.2	0.502
$\lvert y_2 - y_3 \rvert$ =	0.08	0.03	0.1	0.003
$\lvert y_2 - y_4 \rvert$ =	0	0.1	0	0.097
$\lvert y_2 - y_5 \rvert$ =	0.02	0.14	0.1	0.18
$\lvert y_3 - y_4 \rvert$ =	0.08	0.09	0.1	0.1
$\lvert y_3 - y_5 \rvert$ =	0.1	0.01	0	0.183
$\lvert y_4 - y_5 \rvert$ =	0.02	0.05	0.1	0.083

Table 6: Tukey's Test for Channel Height at Fixed Fan Speeds

Channel Height Tα=0.010723					
	Speed=12V	**Speed=11V**	**Speed=10V**	**Speed=9V**	**Speed=8V**
$\lvert y_1 - y_2 \rvert$ =	0	0.14	0.12	0	0.03
$\lvert y_1 - y_3 \rvert$ =	0.32	0.2	0.02	0.2	0.12
$\lvert y_1 - y_4 \rvert$ =	1.2	0.43	0.353	0.333	0.27
$\lvert y_2 - y_3 \rvert$ =	0.32	0.34	0.14	0.2	0.15
$\lvert y_2 - y_4 \rvert$ =	1.2	0.57	0.473	0.333	0.3
$\lvert y_3 - y_4 \rvert$=	0.88	0.23	0.333	0.133	0.15

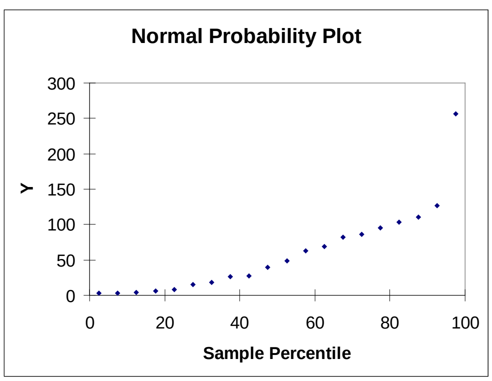

Figure 1: Normal probability plot

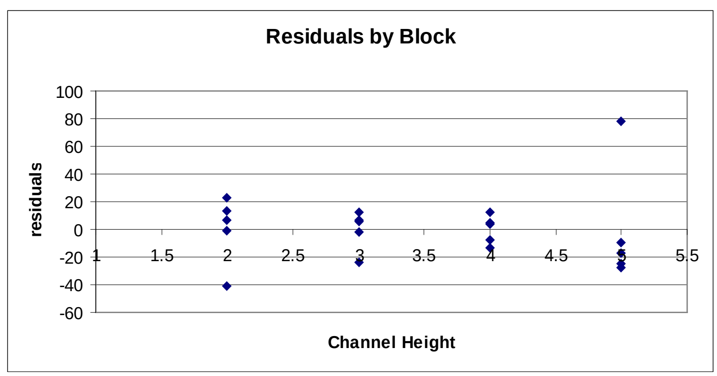

Figure 2: Residuals versus channel height

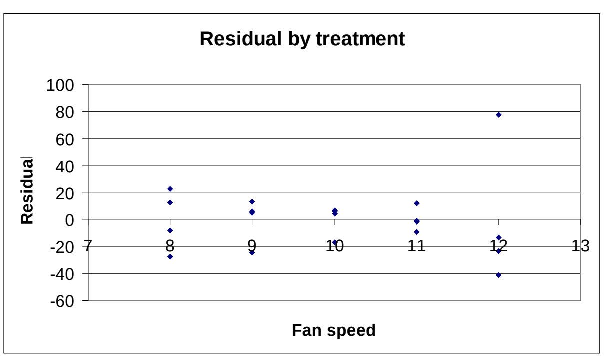

Figure 3: Residuals versus fan speed

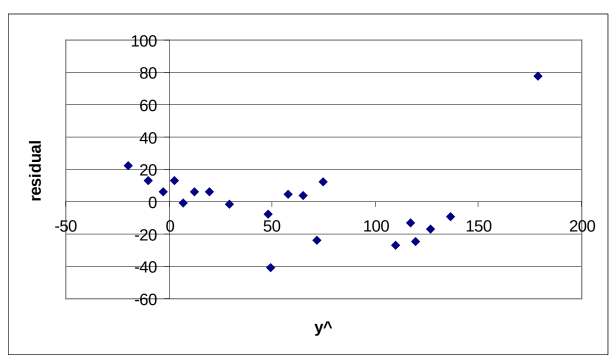

Figure 4: Residuals versus fitted values

slightly lower variability than the other variables. The graph of residuals versus fitted values is shown in Figure 4. This graph also suggests that there may be an outlier in the data. Besides that the data seems balanced and therefore the linear assumption holds true. With the use of excel, the fitted regression model was found to be:

$$y = -247.08 + 15.5148x_1 + 43.3191x_2$$

A 95% confidence interval was also fitted to the model for each of the regressor coefficients. The upper and lower values for these intervals are presented in Table 8.

Table 8: Confidence interval for regressor coefficients

Variable	Upper 95%	Lower 95%
β_0	-356.98	-137.18
β_1	5.55	25.48
β_2	30.71	55.93

The analysis of variance for significance of regression is presented in Table 9.

Table 9: ANOVA for significance of regression

SV	df	SS	MS	F_o	$F_{0.05,2,17}$
Regression	2	56542.01	28271.01	31.68	3.59
Residual	17	15172.95	892.53		
Total	19	71714.97			

Since $F_o > F_{0.05,2,17}$, the air velocity is related to fan speed, channel height, or both. This does not necessarily imply that the relationship found is an appropriate one for predicting the air velocity as a function of the channel height and fan speed. Further tests of model adequacy are required.

The coefficient of multiple determination was found to be $R^2=0.788$. This means that 78.8% of the variability in air velocity is explained when the two regressor variables, channel height and fan speed are used. A model relating air velocity to fan speed only was developed. The R^2 value for this model was 0.134. Therefore, adding the variable channel height, to the model has increased R^2 from 0.134 to 0.788.

Conclusions

A wind channel was constructed with a variable fan speed and channel height. This apparatus was used to observe the two-phase flow of air and water vapor that occurs in the gas diffusion layers of the fuel cells. Experiments were conducted and the data collected were analyzed to find the influence of channel height and fan speed on air velocity. Because of the difficulty in experimentally finding the air velocity, a correlation between the channel height, fan velocity, and air speed was needed. Using analysis of variance, residuals, and multiple regression an equation for predicting the air velocity was found with a 95% confidence interval. The data were found to be normally distributed with the exception of one outlier. The accuracy of the model increased when both the channel height and fan speed were used as regressor variables.

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