Dialysis

Objective

The objective of this experiment is to measure the overall mass transfer coefficient for a hollow fiber membrane dialyzer and determine the individual contributions of the lumen, membrane, and shell mass transfer resistances.

Introduction

Dialysis is the transfer of solute molecules across a membrane by diffusion from a concentrated solution to a dilute solution. This phenomenon is used to remove solutes from liquid mixtures in the biomedical, biotechnology, and chemical industries. The largest commercial market is for *hemodialysis* membranes. These membranes are used to manufacture artificial kidneys that can replace the function of human kidneys. The current market for *hemodialyzers* is approximately one billion dollars per year.

Hemodialyzers consist of a *bundle* of 10,000 – 15,000 hollow fiber membranes; see Figure 1. The ends of the bundle are encased in *tubesheets* and the tubesheets seal to an external plastic housing that encloses the fiber bundle. The case possesses two external ports on either end of the fiber bundle and two ports along the periphery of the case. This design allows introduction of a fluid stream through one of the end ports into the fiber lumens (i.e., interior) and withdrawal from the opposing end. Similarly, one may introduce a fluid stream into the shell (i.e., space external to the fibers) through a peripheral port and withdraw it from the other. Such hollow fiber modules are the mass transfer equivalent of a shell and tube heat exchanger – two fluid streams flow through the hollow fiber or tube bundle, without direct mixing, while mass or heat transfer occurs across the fiber or tube wall. The blood and dialysate flow counter-currently to each other as in heat exchangers.

In operation, *blood* flows through the fiber lumens while *dialysate* flows through the shell. The wastes produced by cell metabolism diffuse from the blood to the diaysate, due to a concentration difference, which ‘cleans’ the blood. The fiber wall is porous with pores large enough to permit passage of low molecular wastes but small enough to prevent loss of proteins, blood cells, and other large plasma components. The dialysate serves as a reservoir into which the wastes accumulate and are removed ultimately.

Additionally, water flows across the fiber wall due to a small pressure difference between the blood and dialysate. This *ultrafitration* is necessary to remove excess water from blood plasma and maintain a proper water balance. However, we will not explore its effect on mass transfer in the experiments performed here.

A healthy kidney removes blood wastes and excess water. It also performs other functions such as maintenance of acid-base balance and hormone production. If kidney failure occurs, a person must seek replacement therapy within a week. While hemodialysis only partially replaces kidney function, patients can survive for extended periods. Long-term survival is dependent on obtaining a kidney transplant.

Analogous to heat transfer, Equation (1) gives the moles of solute that pass across the membrane during dialysis,

$$J = k_o A\left(\Delta C_{lm}\right) \tag{1}$$

where the notation is defined in Table 1.

Table 1. Nomenclature

Symbol	*Definition*
A	External membrane area: the area based on the fiber outer diameter (m^2)
C	Solute concentration ($mole/m^3$)
ΔC_{lm}	Logarithmic mean concentration difference ($mole/m^3$)
D	Diffusivity (m^2/s)
ID	Fiber inner diameter (m)
J	Moles transferred across the membrane (mole/s)
k	Mass transfer coefficient (m/s)
k_o	Overall mass transfer coefficient (m/s)
L	Fiber length (m)
N	Number of fibers
OD	Fiber outer diameter (m)
Q	Flow rate (m^3/s)
R	Mass transfer resistance (s/m)
R_o	Overall mass transfer resistance (s/m)
α	Coefficient in Equations (6) and (7)
ϕ	Fiber packing fraction (total fiber cross-sectional area/case area)
Subscripts	*Definition*
1	Value per fiber
i	Inlet value
l	Value for lumen fluid (feed or blood)
m	Value for membrane
o	Outlet value
s	Value for shell fluid (dialysate)

The logarithmic mean concentration difference across the membrane between the inlet and outlet is defined as,

$$\Delta C_{lm} = \frac{\left(C_{l,i} - C_{s,o}\right) - \left(C_{l,o} - C_{s,i}\right)}{\ln\left[\left(C_{l,i} - C_{s,o}\right)/\left(C_{l,o} - C_{s,i}\right)\right]} \tag{2}$$

For given inlet concentrations, flow rates and a desired solute removal rate, the required membrane area is dictated by Equation (1). As the overall mass transfer coefficient increases the area decreases. Consequently, the value of k_o is used as a characteristic measure of module performance. One desires large values of k_o to minimize membrane cost, reduce the required dialysate flow rate, and reduce the volume of feed contained in the module. Feed volume is particularly important in hemodialysis since the removal of too much blood at the initiation of dialysis can be life threatening.

Three mass transfer resistances contribute to the overall mass transfer coefficient, k_o, as illustrated in Figure 2. These are: (1) the lumen side or feed resistance, R_l, (2) the membrane resistance, R_m, and (3) the shell side or dialysate resistance, R_s. The overall resistance, R_o, is the sum of the three individual resistances and is related to k_o through Equation (3),

$$\frac{1}{k_o} = R_o = R_l + R_m + R_s \tag{3}$$

Likewise, the lumen and shell resistances are related to the lumen and shell mass transfer coefficients through Equations (4) and (5),

$$R_l = (OD/ID)(1/k_l) \tag{4}$$
$$R_s = 1/k_s \tag{5}$$

Furthermore, the literature (Elmore and Lipscomb, 1995; Bao et al., 1999) suggests that the mass transfer coefficients are related to flow rate by,

$$Sh_l = \frac{k_l ID}{D} = 1.76\left(\frac{Q_{l,1}}{DL}\right)^{1/3} = \alpha_l\left(\frac{Q_{l,1}}{DL}\right)^{1/3} \tag{6}$$
$$Sh_s = \frac{k_s OD}{D} = (3.45\phi + 0.092)\left(\frac{Q_{s,1}}{DL}\right)^{1/3} = \alpha_s\left(\frac{Q_{s,1}}{DL}\right)^{1/3} \tag{7}$$

where the subscript 1 indicates the flow rate per fiber and ϕ is the fiber packing fraction defined as the ratio of the cross-sectional occupied by the fibers (lumen area plus area occupied by fiber wall) to the cross-sectional area of the case that encloses the fiber bundle. Note that these correlations assume all fibers are identical, the fluids possess a constant Newtonian viscosity, and solute diffusion in the fluid is Fickian.

The membrane resistance, R_m, is dependent on the material and process used to manufacture the fibers and cannot be estimated a priori – one must determine its value experimentally. R_m is not sensitive to either feed or dialysate flow rate and is equal to the inverse of the membrane mass transfer coefficient, k_m.

To evaluate module performance *a priori* (i.e., calculate k_o without performing a dialysis experiment) one must specify the feed and dialysate flow rates (the operating conditions) and the following module design variables: k_m, ID, OD, N, L, and ϕ. Alternatively one can measure performance experimentally and calculate k_o.

Equipment

The experimental equipment consists of a Fresenius F80A hemodialyzer, four digital paddle wheel flowmeters, four conductivity meters, three peristaltic pumps and two tanks. Figure 3 illustrates the apparatus while Table 2 provides known module design details for this unit.

Because of cost and safety concerns, we will use a sodium chloride solution as the feed and tap water as the dialysate to evaluate module performance. Pump 1 controls the feed flow rate. Pump 2 in combination with Pump 1 determines the ultrafiltration rate – the ultrafiltration rate is equal to the difference between the flow rates of Pump 1 and Pump 2. For this laboratory, you will set the ultrafiltration rate to zero. Pump 3 controls the dialysate flow rate. The conductivity meters provide a measurement of solution conductivity at the inlet and outlet for both the feed and dialysate. A correlation of conductivity with salt concentration is provided in the Appendix. The Appendix also contains calibration curves for the flow and conductivity meters.

Table 2. Dialysis Module Specifications

	Fresenius F80A
Number of fibers	12,288
Overall module length (cm)	29.3
Active fiber length (cm)	22.6
Fiber OD (μm)	285
Fiber ID (μm)	205
Case inner diameter (cm)	5.17

Experimental Procedure

This experiment is controlled using National Instruments LabVIEW software. If the control program is not running, contact the laboratory instructor. The user controls the three peristaltic pumps from a graphical interface. Pressing the up/down arrows adjusts the pump setting. Alternatively, one can enter a number from the keyboard. Note that you must press the *Enter* key after entering a number for the change to occur.

You are to design a set of experiments to evaluate k_o as a function of feed and dialysate flow rate. Both flow rates cannot exceed 800 ml/min due to flow meter limitations. Additionally, flow rates below 100 ml/min are not recommended because module performance is poor and long run times are required to reach steady state. The design should also allow you to calculate experimental values for α_l, α_s, and k_m.

Data can be recorded manually in a laboratory notebook, or electronically using the *Save Data to File* feature of the control program. This feature does not record the entire session. However, each time that the switch is "flipped" to yes 25 data points are saved to the file C:\\Internet Lab\Raw Data\Dialysis Lab. The first time that data is saved, the *Add Data to End of File* switch must be set to *No*. This will create a new file. When saving subsequent data sets, set the *Add Data to End of File* to *Yes* to append data to the file without losing the previously recorded data. Note that if the *Add Data to End of File* switch is left in the *No* position, a new file will be created and previously recorded data will be lost.

When data acquisition is complete, shut the pumps off by setting pump set points to zero (0). After the pumps have stopped press the *Exit* button. This starts an automatic system flushing cycle that will last ~20 seconds. At the conclusion of the flushing cycle the program will end.

Data Analysis

Your data analysis should include calculation of the following quantities:

1. Surface area of the membrane module.
2. Experimental values of the overall mass transfer coefficient as a function of feed and dialysate flow rate.
3. Predicted values of the overall mass transfer coefficient, obtained using Equations (1)-(7), for each experimental run.
4. Experimental values of α_l, α_s, and k_m.

Please provide the units for each result and use the appropriate number of significant figures.

Laboratory Report

Your laboratory report should be prepared using the guidelines provided by the instructor. Additionally, the following questions should be addressed in your discussion of the results:

1. How does k_o depend on feed flow rate? On dialysate flow rate? Is the dependence on flow rate *qualitatively* consistent with the predictions of Equations (1)-(7)? Are the experimental and theoretical values in good *quantitative* agreement?
2. How do the experimental values of α_l and α_s compare with the literature values in Equations (6) and (7), respectively? Can you explain any differences?
3. Virtually all dialysis processes operate with counter-current flow of the feed and dialysate. Why is co-current or cross-flow operation not used?
4. How would you change the design of the F80A module to improve performance (i.e., increase k_o)?
5. Do you believe the value of k_m determined using salt water will be the same as the value observed during actual hemodialysis? Why or why not?
6. Which side (tube or shell) is mass-transfer-rate controlling? How would you enhance the mass transfer rate?
7. What health and safety concerns exist during hemodialysis? How would you address these?

Literature Cited

R.H. Perry and D. Green, Eds., *Chemical Engineers' Handbook*, 6th Ed., McGraw-Hill, New York (1984).

S. Elmore and G.G. Lipscomb, "Analytical Approximations of the Effect of a Fiber Size Distribution on the Performance of Hollow Fiber Membrane Devices," Journal of Membrane Science 98 (1995) 49-56.

L. Bao, B. Liu, and G.G. Lipscomb, "Entry Mass Transfer in Axial Flows Through Randomly Packed Fiber Bundles," AIChE Journal 45 (1999) 2346-2356.

Figures

Figure 1. Schematic of a typical hollow fiber membrane module and the case that holds it.

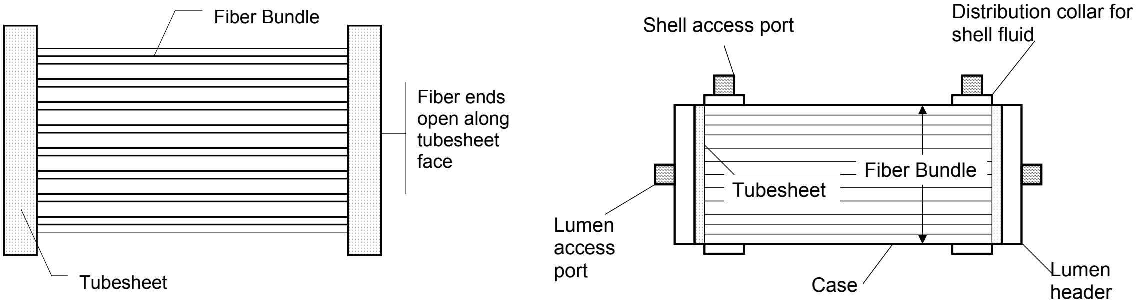


Figure 2. The variation in solute concentration that exists from the interior (lumen) to the exterior (shell) of a hollow fiber dialysis membrane. The concentration gradients in the lumen fluid, membrane wall, and shell fluid give rise to the mass transfer resistances.

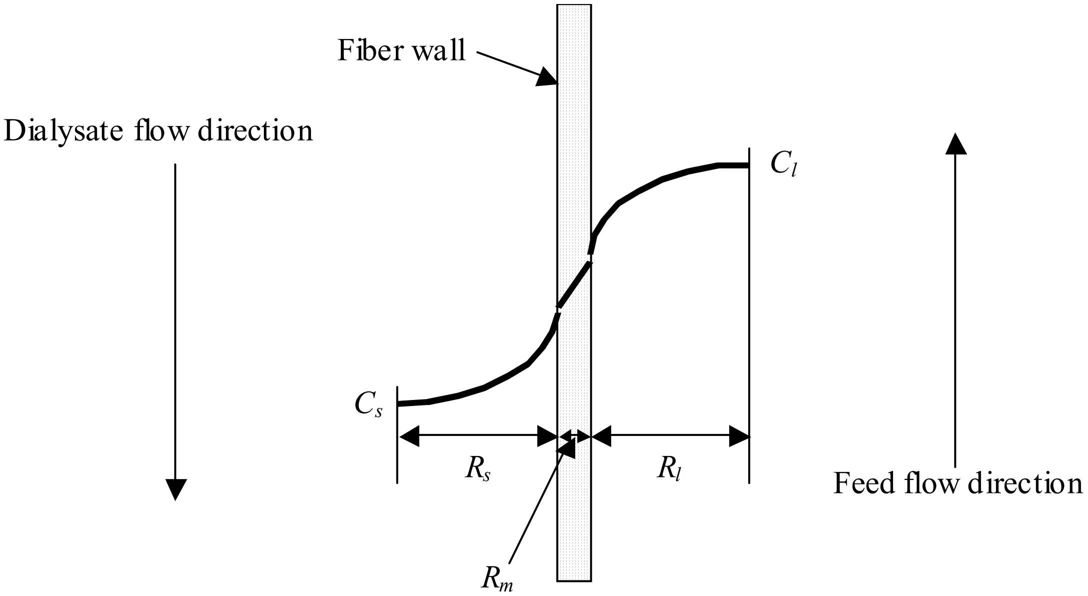
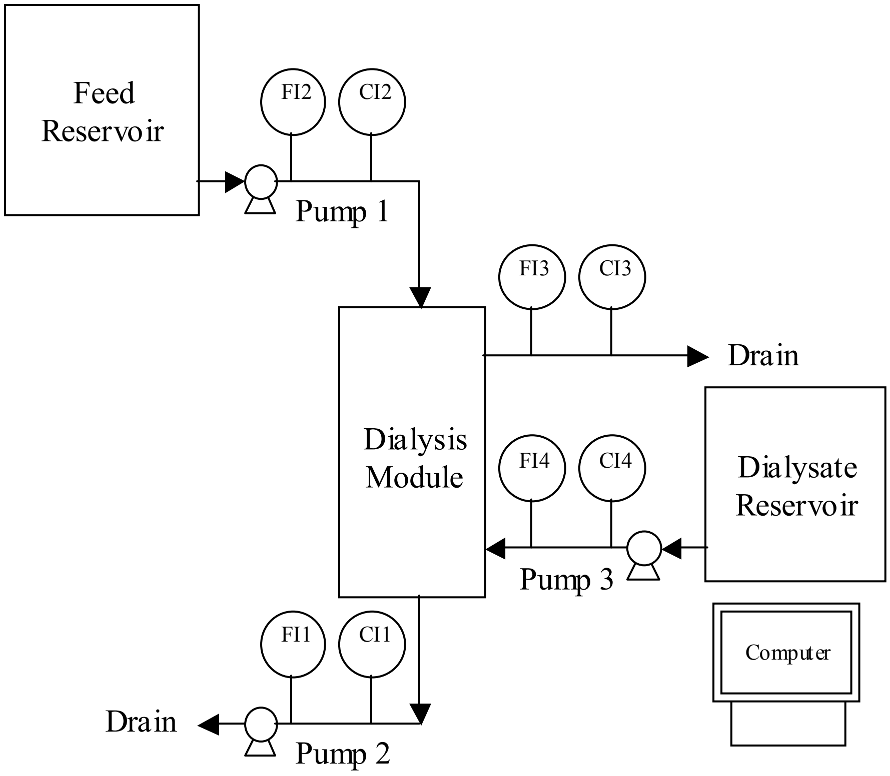


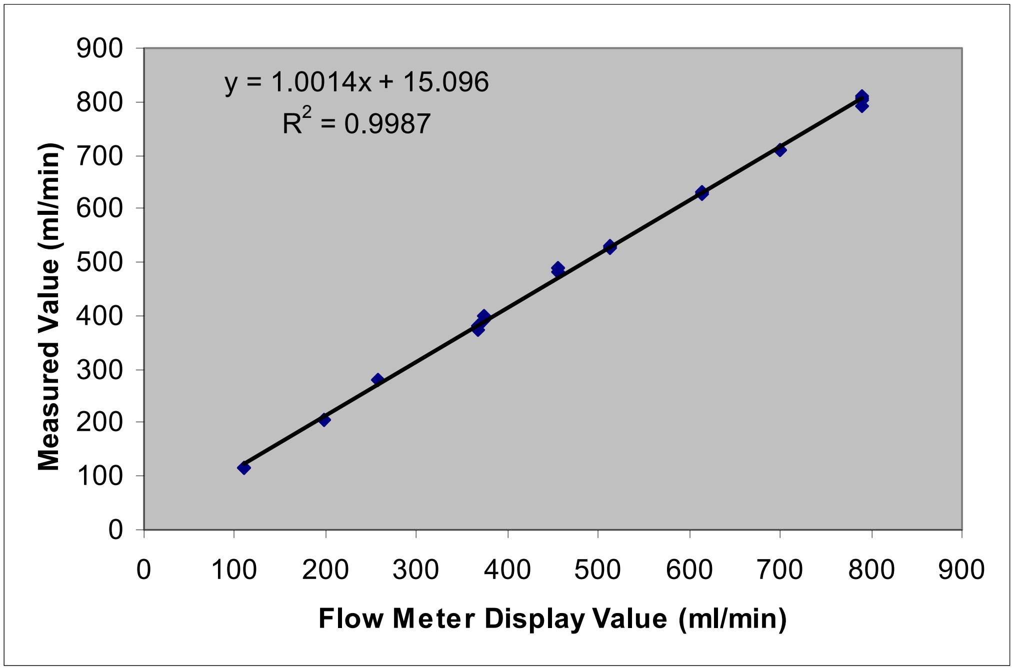
Figure 3. The experimental apparatus. Note that FI*i* indicates flow meter *i* while CI*j* indicates conductivity meter *j*.



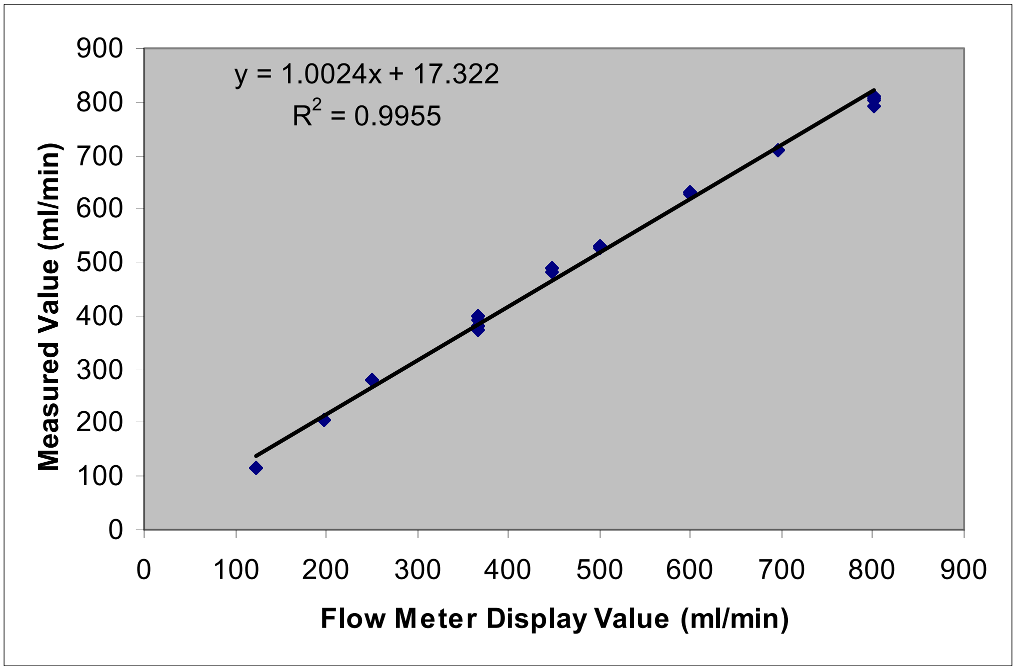
Appendix

Calibration and correlation curves for flow and conductivity meters.

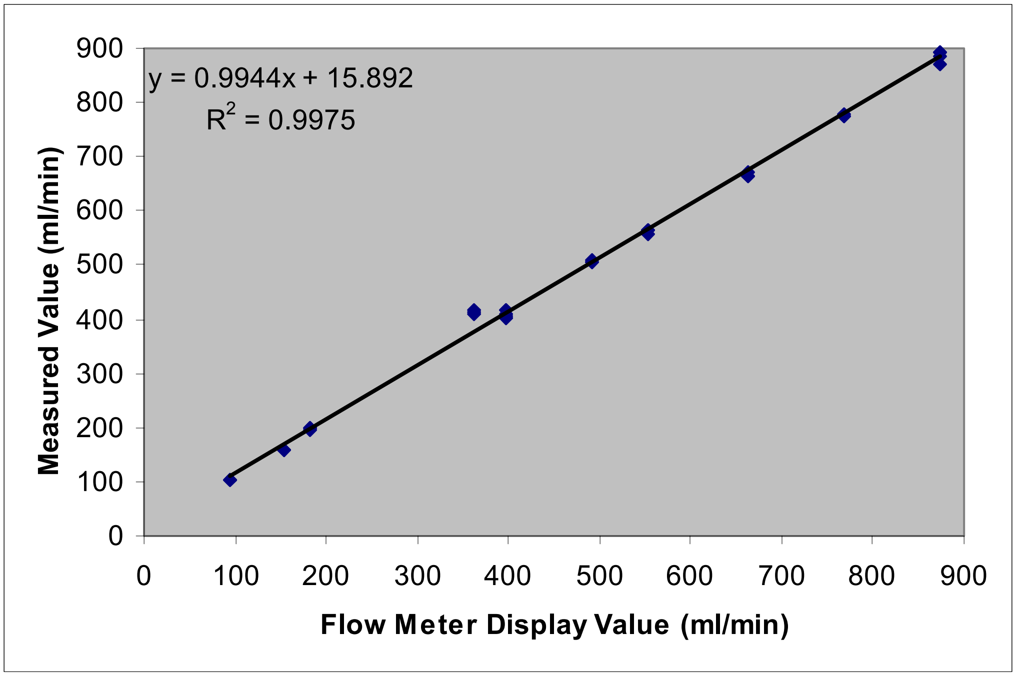
Calibration curve for flow meter 1.



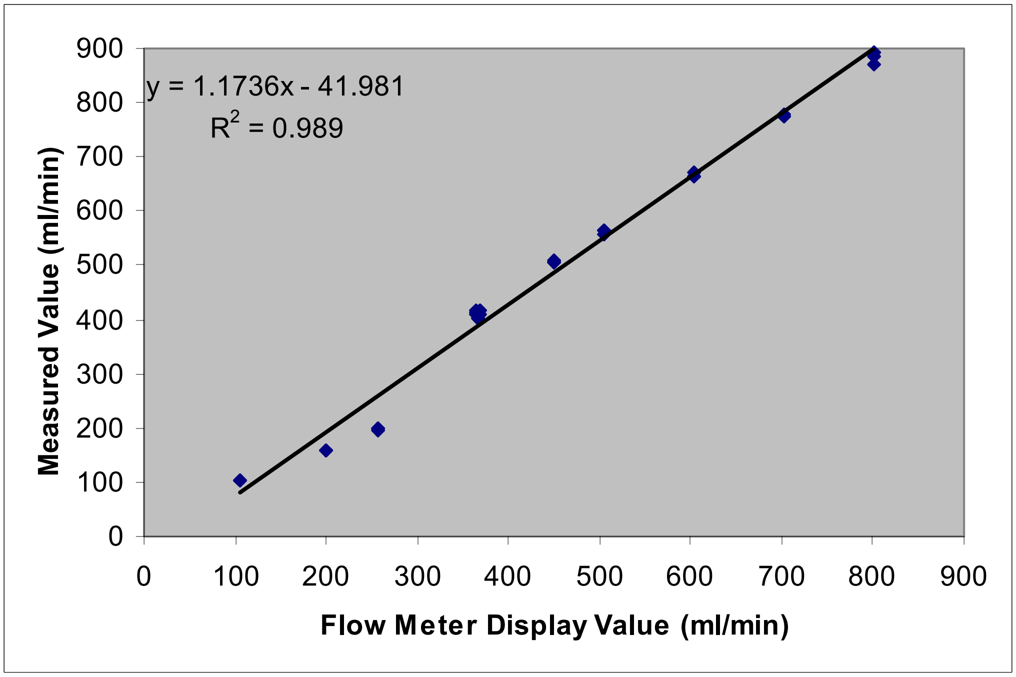
Calibration curve for flow meter 2.



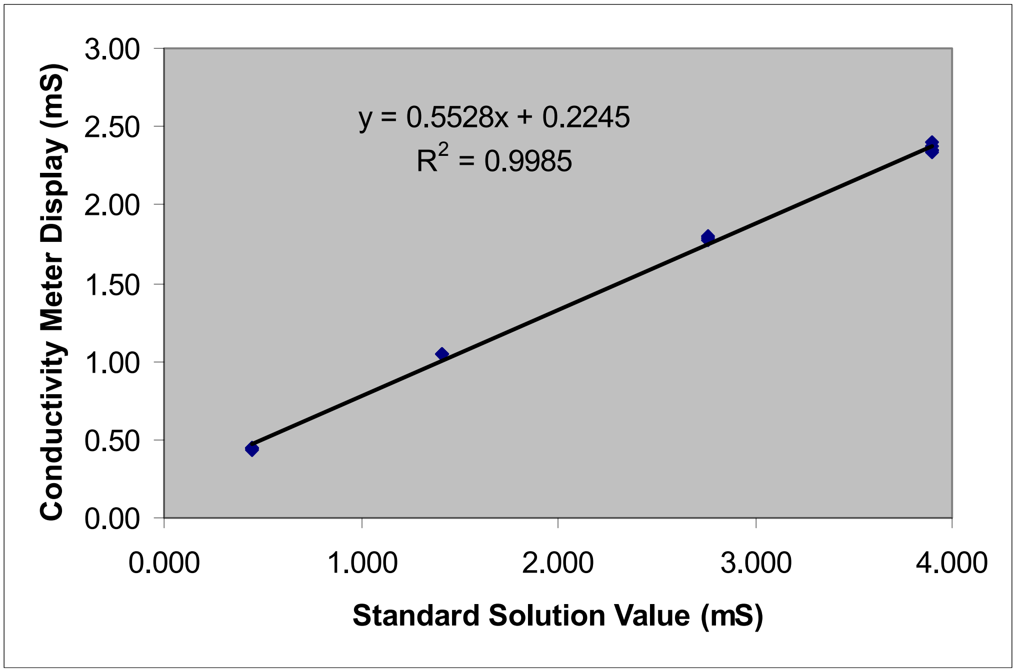
Calibration curve for flow meter 3.



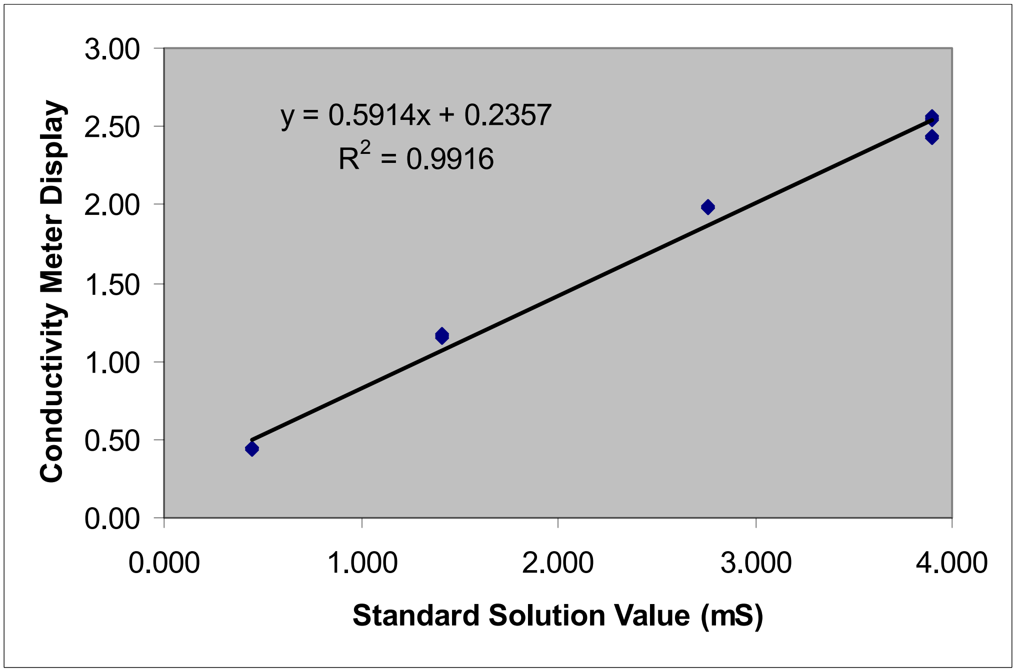
Calibration curve for flow meter 4.



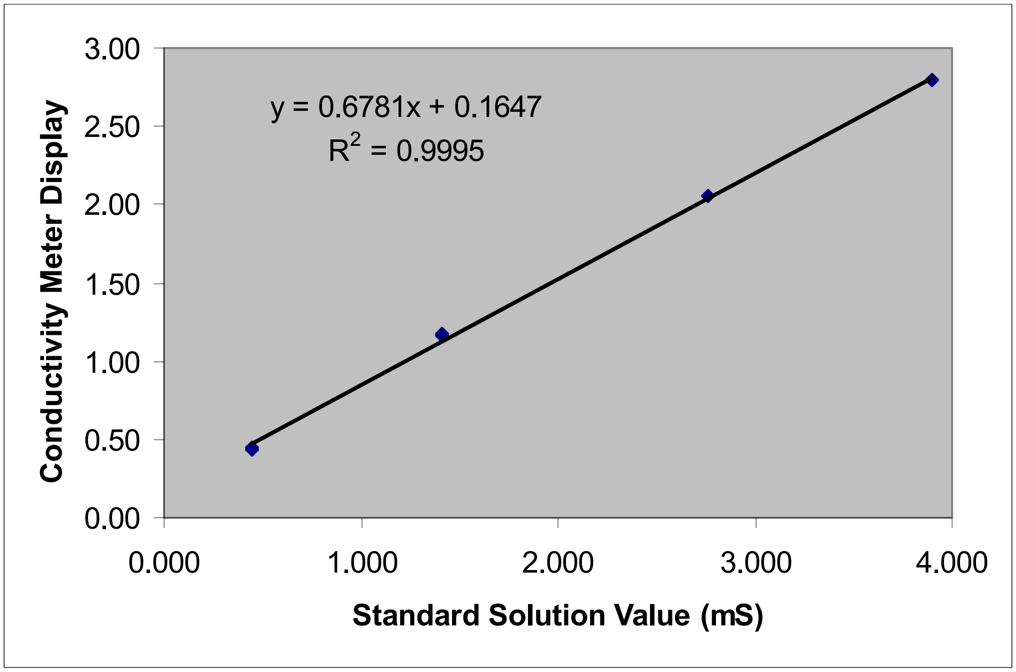
Calibration curve for conductivity meter 1.



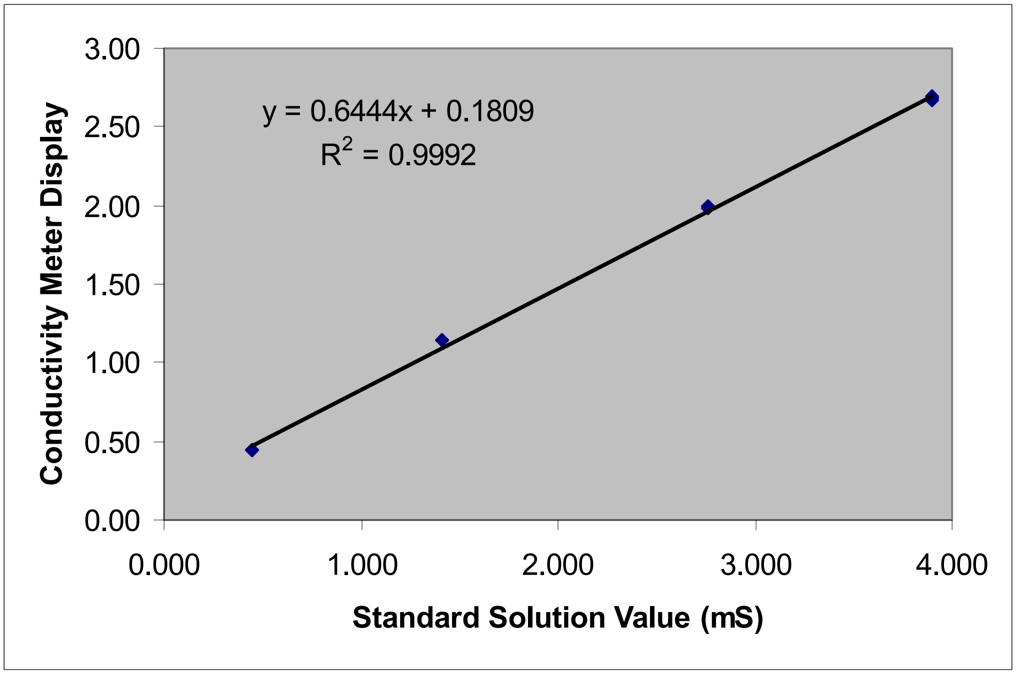
Calibration curve for conductivity meter 2.



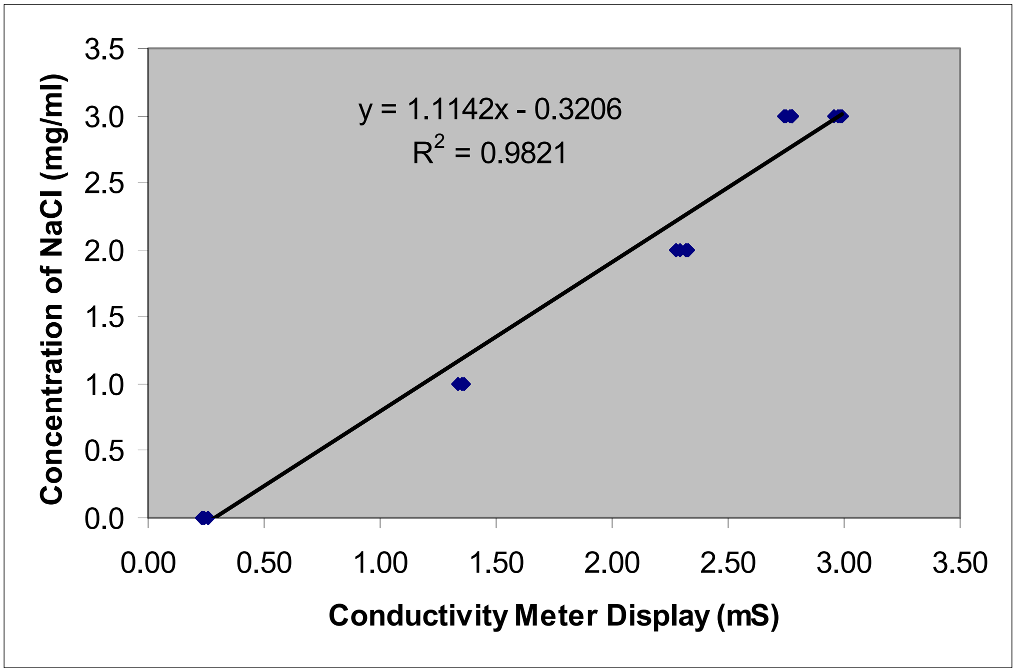
Calibration curve for conductivity meter 3.



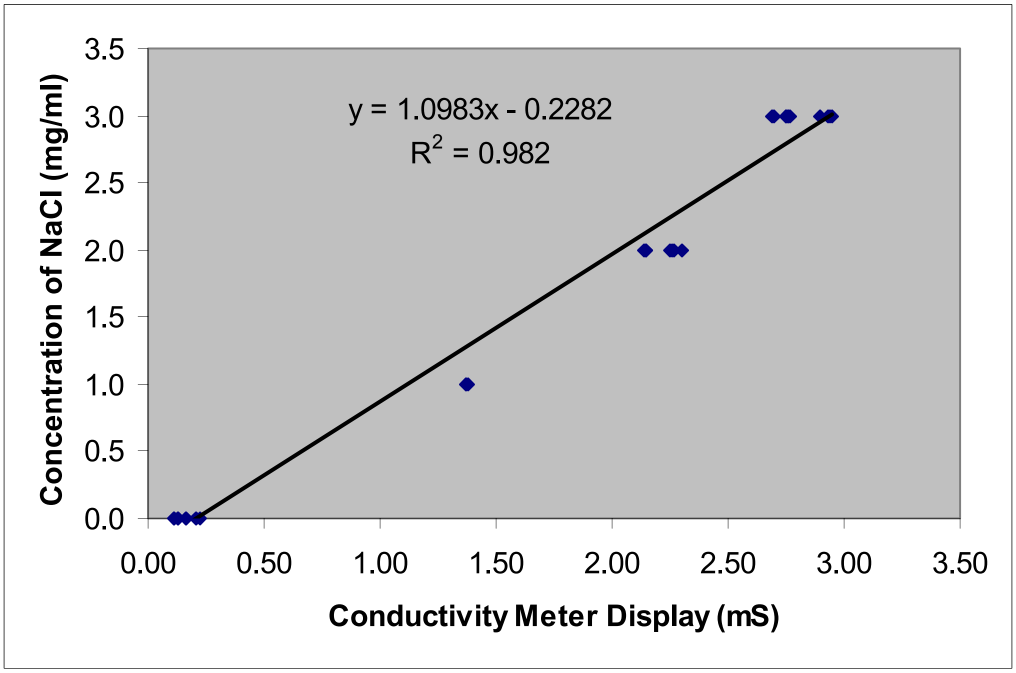
Calibration curve for conductivity meter 4.



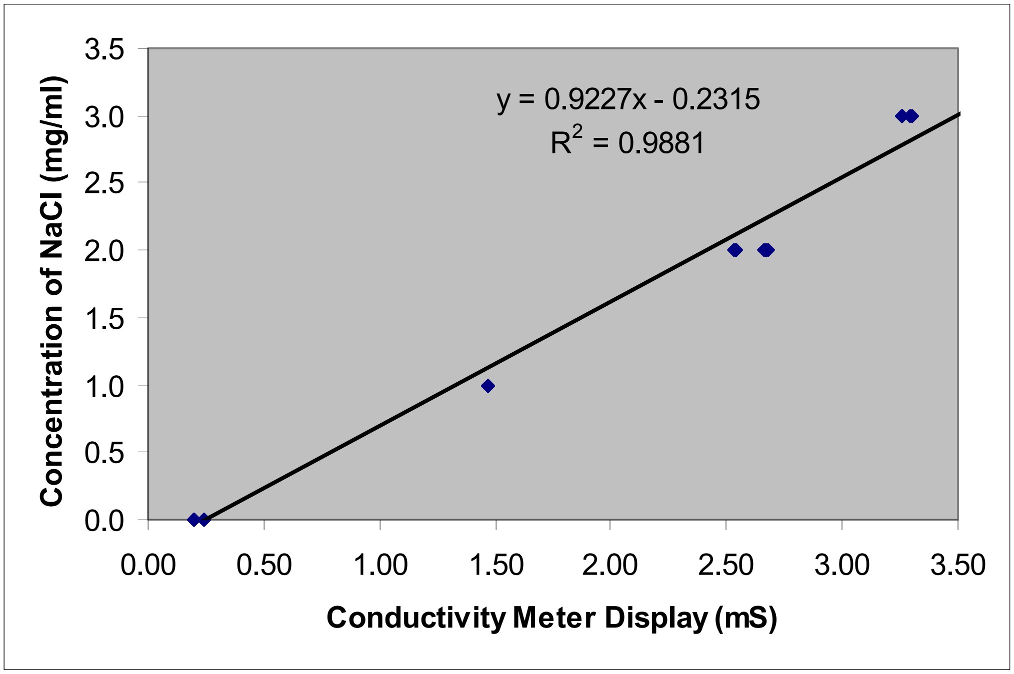
Conductivity-concentration correlation for conductivity meter 1.



Conductivity-concentration correlation for conductivity meter 2.



Conductivity-concentration correlation for conductivity meter 3.



Conductivity-concentration correlation for conductivity meter 4.