

Fluid Flow Aspects of Water Electrolyzers

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In considering possible processes for producing fuels as alternatives to fossil fuels, the Water Electrolysis Process is a feasible one. For example, the Water Electrolysis Process is being considered on a large scale in connection with Industrial Complexes which can desalt water, produce power and other products such as hydrogen, oxygen, ammonia, ammonia nitrate, and nitric acid (1). The energy source could be a large nuclear reactor coupled to a large electrolyzer system.

Water electrolysis is a process in which hydrogen and oxygen gases are produced from water by the application of electric energy. Perhaps the simplest method for controlling the production of these gases is to use an electrolyzer consisting of a number of electrolysis cells, using a liquid water solution as electrolyte, and connecting them hydraulically in parallel. Electrically the cells may be connected either in series or parallel.

Each cell is made up of a cathode (on which hydrogen is produced), an anode (on which oxygen is produced), and the electrolyte which flows through the cell. The anode and cathode are separated by a membrane which may be porous to liquid electrolyte but not to the gases being generated, so that the gases will not mix. A cross section of such a cell is shown in Fig. 1.

To develop a modern electrolyzer technology will require much more basic engineering information concerning two-phase flow, electrolytes, electrodes, and control than is available at present. The purpose of this paper is to present an analytical basis developed by the authors for investigating the two-phase flow occurring in an electrolysis cell along with a review of related experimental data.

The electrolysis process is complicated because of the simultaneous occurrence of coupled, non-linear, transport of mass, momentum, energy, and charge in the presence of electrochemical reactions in the electrolyte and on the electrodes. The precise definition of these processes is virtually impossible and in this paper one dimensional (or hydraulic) equations will be used to define the flow in an electrolysis cell configuration such as is shown in Fig. 1.

Tobias (2) seems to have been the first to contribute significant work on this problem. He assumed, however, that there was no membrane in the cell; that the inlet velocity was zero; and that the gas velocity was independent of void fraction. Funk and Thorpe (3) presented a more general analysis of the void fraction and current density distributions in an electrolysis cell subject only to the assumption that the gases are incompressible. Then later, Thorpe and Funk (4) presented a theoretical and experimental investigation of the pressure drop occurring in an electrolysis cell. There are also several papers on Electrochemical Machining (5,6) in which an allied problem is discussed.

TRANSPORT EQUATIONS

The equations to be derived will be based on the assumption that the flows can be considered as one-dimensional, two-phase, flows. There will be, then, only one independent space variable s .

The electrolyte flow is from the bottom toward the top in a cell of width H and length L . The cell consists of two parallel channels separated by a membrane. Flow in the hydrogen side consists of a two-phase mixture of hydrogen gas and electrolyte in a thin rectangular channel (H by y_2) formed between the membrane and the cathode. Flow in the oxygen side is similar in a channel (H by y_1). The membrane is assumed to be porous to OH^- ions and possibly to liquid electrolyte. Subscript 1 denotes the flow properties on the oxygen side while subscript 2 denotes similar properties on the hydrogen side. Various species within a channel are identified by the subscripts g for gas, v for mixture of gas and vapor, f for liquid electrolyte, and h for the hydroxyl ion. Since only an alkaline electrolyte is considered, the hydrogen ion is neglected.

The transverse current density (current flux) i in the cell is a function of position s . If the cell is vertical the coordinate s is identical with vertical coordinate z . The current flux i generates hydrogen gas on the cathode at the local mass flux rate m_{g2} . Water may evaporate into the hydrogen gas bubbles so that instead of a dry gas, a mixture of water vapor and hydrogen gas will flow upward with average velocity V_{v2} in some equivalent area proportional to the dimension y_{v2} . The gas bubbles, or voids, are contained within an electrolyte layer near the cathode surface which is called the hydrogen bubble layer of thickness δ_2 .

The liquid electrolyte flow on the hydrogen side occurs with average velocity V_{f2} in an equivalent area proportional to y_{f2} where

$$y_2 = y_{v2} + y_{f2} \quad [1]$$

A similar flow configuration exists on the oxygen side where oxygen gas is liberated on the anode at mass flux rate m_{g1} . Then

$$y_1 = y_{v1} + y_{f1} \quad [2]$$

A hydroxyl ion flux occurs through the membrane which has the net effect of transporting H_2O from the cathode side to the anode side of the cell. In addition to the ion flux, the membrane may be porous to liquid electrolyte. These fluxes through the membrane are denoted by m_h , m_f .

The definitions and derivations which follow will apply to either hydrogen or oxygen sides of the cell so that, in the interest of simplifying the notation, the numerical subscript will be omitted.

The vapor quality X , consisting of the mixture of gas and water vapor, is defined by the equations

$$X = \frac{W_v}{W} ; (1-X) = \frac{W_f}{W} \quad [3]$$

where

$$W_v = \rho_v A_v V_v \quad [4]$$

$$W_f = \rho_f A_f V_f \quad [5]$$

$$W = W_v + W_f \quad [6]$$

and ρ_f = liquid density, ρ_v = vapor density, $A_f = Hy_f$ is the area occupied by liquid, $A_v = Hy_v$ is the area occupied by vapor, V_f = average liquid velocity, V_v = average vapor velocity.

The vapor volume fraction α , sometimes called the void fraction, and the liquid holdup $(1-\alpha)$ are defined by

$$\alpha = \frac{A_v}{A} ; (1-\alpha) = \frac{A_f}{A}, \quad [7]$$

where

$$A = A_v + A_f = Hy. \quad [8]$$

If equations [3] to [7] are combined, the following important equation is obtained

$$\frac{1-\alpha}{\alpha} = \sigma \left(\frac{1-X}{X} \right) \left(\frac{\rho_v}{\rho_f} \right), \quad [9]$$

where σ is the slip ratio (also called the phase velocity ratio) defined by

$$\sigma = \frac{V_v}{V_f}. \quad [10]$$

In general the slip ratio depends on pressure p , void fraction α , mass flow rate W , channel area A , density ratio ρ_v/ρ_f and channel orientation.

Most of the engineering quantities of interest in an electrolysis cell, such as electrolyte ohmic resistance or pressure drop, are functions of the void fraction α ; the void fraction, in turn, depends on the slip ratio σ which in general is unknown. There are several models which express the void fraction, slip ratio relationship. The simplest model is the homogeneous model in which σ is assumed unity.

Continuity Equations (Mass Transport)

At some position s along the electrolysis cell shown in Fig. 1, consider an elemental control volume for the gas phase. Gas is considered to be generated at the interface between liquid electrolyte and gas phases. This gas enters the gas phase control volume and is represented as a source of strength m_g . The quantity m_g is a transverse flux having units of $\text{gm cm}^{-1} \text{sec}^{-1}$.

The law of conservation of mass as applied to the gas phase control volume is

$$\frac{d W_g}{ds} = m_g, \quad [11]$$

where W_g is the mass flow rate of gas in the channel.

In a similar way, the continuity equation for the liquid electrolyte phase is derived as

$$\frac{d W_f}{ds} = -m_g + (\pm)m_h + (\pm)m_f, \quad [12]$$

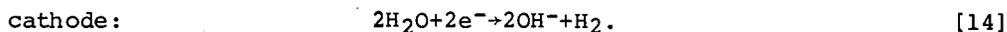
where the mass flux rate m_g is given by

$$m_g = \lambda_g i, \quad \lambda_g = \frac{N_g}{\epsilon_g}. \quad [13]$$

The atomic weight of the gas is N_g while its valence upon electrolytic decomposition is e_g . The proportionality constant λ_g is the electrochemical equivalent.

The mass flux m_f is non-zero only if the membrane is porous to liquid electrolyte; if the membrane does have this property, then both the magnitude and sign of the term m_f depend on the pressure distributions along the two sides of the membrane.

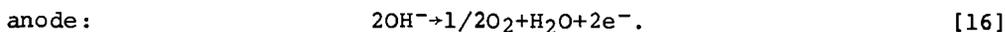
The hydroxyl ion flux m_h can be related to the flux m_g from the equation of the electrochemical reaction occurring in the channel. On the cathode side, for example, the equation is



For every gram of hydrogen generated on the cathode side, there are 17 g of hydroxyl ions passing through the membrane; this ion flow is provided by the liquid electrolyte phase. Thus on the cathode side, the minus (-) sign is selected for m_h and

$$\text{cathode:} \quad m_h = -17m_g. \quad [15]$$

On the anode side, the electrochemical reaction is



Thus for every gram of oxygen generated, there are 2.125 g of hydroxyl ions flowing through the membrane into the oxygen channel. In this instance, the plus (+) sign is selected for m_h and

$$\text{anode:} \quad m_h = 2.125m_g. \quad [17]$$

The foregoing development has not considered the mass transport due to water evaporation into the hydrogen or oxygen bubbles. However, it can readily be shown that if the gases are assumed to be saturated with water vapor, the mass fraction of the hydrogen or oxygen gas in the vapor mixture is

$$f_g = \frac{1}{1 + \frac{M_w}{M_g} \left(\frac{P_w}{P_t - P_w} \right)}, \quad [18]$$

where P_w is the water vapor pressure and P_t is the total bubble pressure; M_w , M_g are molecular weights of water and gas respectively.

Rewriting equations [11], [12] to account for water vapor transfer, along with definitions made previously, the continuity equations become

$$\frac{d}{ds} w_v = \left[1 + \frac{M_w}{M_g} \left(\frac{P_w}{P_t - P_w} \right) \right] \lambda_g i, \quad [19]$$

$$\frac{d}{ds} w_f = \left[(\gamma - 1) - \frac{M_w}{M_g} \left(\frac{P_w}{P_t - P_w} \right) \right] \lambda_g i + (\pm) m_f, \quad [20]$$

where

$$\begin{aligned} \lambda_g &= 0.228 \times 10^{-7}; \gamma = -17 \text{ (cathode side)}, \\ \lambda_g &= 1.824 \times 10^{-7}; \gamma = 2.125 \text{ (anode side)}. \end{aligned} \quad [21]$$

Energy Equation(Energy Transport)

The energy transport of the gas phase will be neglected due to the low thermal conductivity and heat capacity of the gas compared to that of the electrolyte. Then only the liquid phase needs to be considered.

In applying the first law of Thermodynamics as it applies to a representative control volume, it will be assumed that the transport of kinetic and gravitational specific energies are negligible compared to the specific thermal energies. Also, the energy transport due to liquid conversion to vapor is neglected. Then, an energy balance gives

$$w_f \frac{dh_f}{ds} = H(q'' + iE), \quad [22]$$

where h_f is the electrolyte enthalpy, q'' is the heat flux transferred to or from the electrolyte, and E is the ohmic voltage drop across the electrolyte. Note that

$$h_f = CT_f ; q'' = h(T_s - T_f), \quad [23]$$

where T_f is electrolyte temperature, T_s is electrode surface temperature, h is the heat transfer coefficient, and C is specific heat.

Equations of Motion(Momentum Transport)

In making the momentum balance, both vapor and liquid phases are included at the same time. Then upon applying the momentum theorem to a representative control volume, it can be shown that

$$w_f \frac{dv_f}{ds} + w_v \frac{dv_v}{ds} = -A \frac{dp}{ds} - 2H\tau - \rho_m \frac{dz}{ds}, \quad [24]$$

where τ is the average shear stress, ρ_m is the density of the two phase mixture, and p is the static pressure. In deriving this equation, the momentum transfer due to liquid conversion to vapor has been neglected.

Electrical Relations(Charge Transport)

Consistent with the one dimensional transport equations of continuity, energy, and momentum is a one dimensional transport equation of charge within the electrode gap. However, such an equation will involve ion mobilities, electrochemical reactions, and other complicated processes which will not be presented here. Instead, the electrical phenomena will be represented by a simple form of Ohm's law.

Let the sum of the electrode polarization and decomposition potentials be denoted by ΔE while the applied voltage is E_a . Then the voltage E available for overcoming ohmic resistance of the two-phase electrolyte is given by

$$E = E_a - \Delta E, \quad [25]$$

and

$$E = iR_C, \quad [26]$$

where R_C is the ohmic resistance of the cell. This resistance consists of a membrane resistance R_m in series with resistances R_1, R_2 of the

electrolyte-bubble mixtures in the oxygen and hydrogen channels of the cell. That is

$$R_C = R_1 + R_m + R_2. \quad [27]$$

The resistances R_1 , R_2 are functions of the properties of pure liquid electrolyte, the void fraction α , and the temperature T_f .

The cross section of the channel occupied by vapor at position s is proportional to Y_g . This void is distributed within some bubble layer of thickness δ . The void fraction α' based on bubble layer thickness (that is, the void fraction within the bubble layer) is defined by

$$\alpha' = \frac{Y_g}{\delta}. \quad [28]$$

The resistance within the bubble layer is some function of α' rather than α .

The total transverse resistance, per unit cross sectional area perpendicular to y is

$$R = r_{tp}\delta + r_f(y - \delta), \quad [29]$$

where r_{tp} is the two-phase resistivity in the bubble layer and r_f is the liquid electrolyte resistivity. The quantity r_f is, in general, temperature dependent, say

$$\frac{1}{r_f} = \frac{1}{r_0} [1 + \beta(T_f - T_0)], \quad [30]$$

where β represents a temperature coefficient and subscript 0 denotes conditions at the cell entrance.

The two-phase resistivity, in the bubble layer, is a function of α' assumed to be of the form

$$r_{tp} = r_f f(\alpha'). \quad [31]$$

The function f is determined from some void fraction-resistivity model which assumes a homogeneous distribution of bubbles within an electrolyte matrix. A generalization of such heterogeneous condition mechanisms is

$$f(\alpha') = (1 - \alpha')^{-n}. \quad [32]$$

Tobias (2) proposed that $n = 1.5$ while Thorpe and Zerkle (5) found that $n = 2$ gave better results in the allied problem of electrochemical machining.

It can be noted that

$$\alpha' = \frac{Y_g}{\delta} \alpha, \quad [33]$$

so that equation [29] can be written as

$$R = r_f [(y - \delta) + \delta f(\frac{Y_g}{\delta} \alpha)]. \quad [34]$$

The electrode polarization over voltages are generally assumed to obey Tafel equations of the form

$$\Delta E_p = a + b \ln i, \quad [35]$$

where a , b are constants depending on electrode material, electrolyte, temperature, and pressure. Denoting the decomposition potential by ΔE_d , then

$$\Delta E = \Delta E_{p1} + \Delta E_{p2} + \Delta E_d. \quad [36]$$

Equations [25], [26], [27], [34], [35], [36] can be combined to give an implicit relation between the applied voltage E_a , current density i , vapor void fractions α_1, α_2 , bubble layers δ_1, δ_2 , and temperatures T_1, T_2 . That is

$$i = i(E_a, i, \alpha_1, \alpha_2, \delta_1, \delta_2, T_1, T_2). \quad [37]$$

As a first approximation, the quantity E could be regarded as known independent of i which greatly simplifies the problem.

Recapitulation

The equations above represent a one-dimensional approximation of the processes occurring within the electrolysis cell. As they stand, they involve more unknowns than there are equations so that additional relations are required. Additional equations will be the equations of state of oxygen and hydrogen gases, empirical relations for the shear stresses, and either empirical or theoretical expressions for the slip ratios. Furthermore, these equations are strongly coupled together through pressure and temperature. Although this is a complicated system of non-linear, coupled, differential equations the programming of them for computer solution is not an insurmountable task.

ANALYTICAL STUDIES

It is surprisingly simple to obtain algebraic equations for the vapor quality X and void fraction α in terms of the slip ratio σ and integrals of the current density i . This is done by integrating equations [19], [20] from the inlet ($s = 0$) to some point s in the cell and substituting into equations [3], [6] to obtain

$$X = \frac{\left[1 + \frac{M_w}{M_g} \left(\frac{p_w}{p_t - p_w}\right)\right] \lambda_g H_f^s \int_0^s i ds}{W_f(0) + \gamma \lambda_g H_f^s \int_0^s i ds}. \quad [38]$$

Substitution of equation [38] into [9] then gives the void fraction α as a function of slip ratio σ , the vapor density ρ_v , and integral of the current density i .

In carrying out parametric studies of the current density distributions in electrolysis cells, Funk and Thorpe (3) used the resulting equation [9], as described above, along with the following further assumptions:

- (1) Both gas and liquid flows are assumed incompressible and isothermal. This permits a great analytical simplification in that it decouples the continuity and resistivity equations from the momentum and energy equations.
- (2) The bubble layers are assumed to extend completely across the

channels. This assumption seems to be justified from visual observations which show the bubble layer to fill the channel except in a short entrance region.

- (3) The membrane is assumed to be permeable only to the hydroxyl flux and not to liquid electrolyte.
- (4) Water vapor in the gas is assumed negligible.

With these assumptions, the system of equations reduces to a set in which there are only three more unknowns than equations; these unknowns are the applied voltage E_a and the slip ratios σ_1, σ_2 . If E_a, σ_1, σ_2 are regarded as parameters then the system can be solved simultaneously for the void fraction α and current density i . Since integration of the equations brings the cell inlet velocity into the problem as a boundary condition, it is also a parameter.

The electrical requirement is expressed by combining equations [25], [26], [27], [34], [35], [36] to obtain

$$E_a - [(a_1 + a_2) + (b_1 + b_2) \ln i + \Delta E_d] = i \{ R_m + r_f [y_1 f(\alpha_1) + y_2 f(\alpha_2)] \}. \quad [39]$$

Equation [39] along with the two equations [9] for the void fractions α_1, α_2 are a set of three equations in three unknowns α_1, α_2, i and four parameters $E_a, \sigma_1, \sigma_2, V_0$. These equations were programmed for numerical solution and solved for a specific cell geometry as defined in reference (3). By examining the resulting current density distributions it was concluded that:

- (1) The effect of slip ratio is pronounced particularly at the higher cell voltages.
- (2) The effect of cell inlet velocity is very important and particularly so at the higher cell voltages.
- (3) The void fraction distributions will be practically identical in the two sides of the cell if the hydrogen side cross section is twice that of the oxygen side and both are subject to the same inlet velocity.

These results are not entirely unexpected based on an intuitive understanding of what is occurring in the electrolysis cell. They did, however, point out the importance of making experimental studies to determine what the actual slip ratios will be in a real electrolysis cell.

Before describing these experiments, it is appropriate to mention some of the analytical results obtained by Thorpe and Zerkle (5,6) for electrochemical machining. There are two major conclusions which may be pertinent to electrolyzer design:

- (1) If the current density distribution is assumed to be constant along the cell as a first approximation, it is possible to integrate both the continuity and energy equations to obtain a remarkably simple set of algebraic equations. This makes possible the idea of fitting theoretical curves to experimental data in order to determine the heterogeneous conduction exponent n in a very simple and convenient manner.
- (2) Under certain conditions (say, of high electrolyzer output) it is possible to experience a choking phenomenon similar to that which is well known in the field of compressible flow. This is due to the presence of gas in the electrolyzer and this effect should be considered in the design of electrolyzers.

For further information, references (5,6) should be studied.

EXPERIMENTAL STUDIES

Several experimental investigations of void fraction and pressure drop occurring in water electrolysis cells have been conducted at the University of Kentucky. Instead of discussing the experimental apparatus and procedures in detail, only a summary will be presented here. References (3, 4, 7) can be consulted for detailed information.

The experimental apparatus consisted basically of a flow loop, positive displacement pump, a current source, instrumentation, and a gamma ray attenuation system for measuring void fractions. The electrolyte used was one normal KOH while the electrodes were stainless steel. The test section was made from plexiglas and stainless steel with oxygen side cross section 1" by 0.18" and hydrogen side cross section 1" by 0.18". This test section was 36" in length preceded by an entrance length of 21". The membrane consisted of a polystyrene coated nylon cloth sandwiched between two slotted plexiglas holders.

Studies of the flow pattern indicated that a bubble boundary layer existed at the test section inlet but that after a short distance (6"-8") downstream, bubbles occupied the complete cross sections dispersed as small spherical bubbles in essentially a froth flow. The flow velocities were of order of magnitude 0.5 ft sec^{-1} and the current density was of order of magnitude 250 amp ft^{-2} . This resulted in oxygen bubbles having an average diameter of about 4.5×10^{-3} inches and hydrogen bubbles having an average diameter of 3.5×10^{-3} inches. For such small bubbles, the assumption that the gas is saturated with water vapor is justified and this was assumed in calculating the vapor densities.

The slip ratio was determined in the following way. First, the void fraction was determined experimentally using a 20 mc Cesium-137 gamma source, a scintillation probe as detector, collimator, and associated electronic equipment as discussed in reference (8). Next, the vapor quality X was determined by measuring the current density distribution i , the inlet flow rate $W_f(0)$, and substituting into equation [38].

With α and X known, the only remaining unknown in equation [9] is the slip ratio σ . If the ratio $(1-\alpha)/\alpha$ is plotted against the ratio $\rho_v(1-X)/\rho_f X$, the slope of a line through the data is the slip ratio σ . Such plots indicated that the slip ratio is essentially unity.

Another way of plotting the data is to plot the void fraction α against the vapor volumetric flow fraction ϕ defined by

$$\phi = \frac{1}{1 + \left(\frac{1-X}{X}\right) \left(\frac{\rho_v}{\rho_f}\right)} \quad [40]$$

The data is plotted in this manner in Fig. 2. Also plotted in Fig. 2 are the homogeneous model ($\sigma = 1$) and Bankoff's model (9) which gives essentially the same results as those of Martinelli and Nelson (10). The figure indicates that the slip ratio is close to unity for both oxygen and hydrogen sides of the electrolysis cell. It should be remembered, though, that this conclusion is drawn for a single cell geometry and rather low throughput conditions.

The determination of the slip ratio is prerequisite to a determination of pressure drop correlations because the pressure drop

depends on the void fraction. In other words, the conclusion that the slip ratio is unity permits the pressure drop equations to be written in terms of the vapor quality X through equation [9] which, in turn, depends only on the (measured) current density distribution i and (measured) inlet flow rate $W_f(o)$.

Data reduction was carried out by evaluating the acceleration and elevation pressure drop components of equation [24] and subtracting them from the (measured) total pressure drop. In this way the frictional pressure drop component is isolated. The actual data reduction was programmed for digital computation and involved a determination of the void fraction α at the same time.

Each test run involved a determination of both the single phase pressure drop in the absence of electrolysis (which is entirely frictional) and the two phase pressure drop with electrolysis occurring. In this way, it is possible to compute a frictional pressure drop multiplier Ψ defined by

$$\Psi = \frac{(\Delta p)_{tpf}}{(\Delta p)_{spf}} \quad [41]$$

Attempts were made to correlate Ψ against several parameters including the void fraction α . These attempts led to the formulation of a variable Ω defined by

$$\Omega = \alpha \left(\frac{\lambda g i}{\rho_v V_o} \right) \left(\frac{\rho_v}{\rho_f} \right)^{1/3} \quad [42]$$

The factor $\lambda g i$ which has units and dimensions of a mass velocity is a measure of the lateral vapor mass flux away from the wall. Superficially, this factor can be viewed as an increased roughness of the electrode surface. When it is divided by the gas density ρ_v , a superficial transverse velocity is obtained. The ratio of this transverse velocity to the axial velocity at inlet V_o is a dimensionless similarity variable and a measure of dissipation in the flow. Attempts to correlate Ψ in terms of this ratio and also in terms of void fraction α indicate that Ψ should be correlated in terms of the product of the two. However, two distinct correlations were obtained in this way for the oxygen and hydrogen sides.

It was found that the two correlations for oxygen and hydrogen could be brought together by introducing the density ratio $(\rho_v/\rho_f)^{1/3}$. Thus the correlation parameter Ω was synthesized and the frictional pressure drop multiplier Ψ was correlated for both oxygen and hydrogen as shown in Fig. 3. Except for points near $\Psi = 1$ where the experimental errors can be rather large, this correlation is accurate to within ± 20 per cent.

SUMMARY

In this paper, a summary of some of the fluid flow aspects of water electrolyzers has been presented along with research which has been already published in the literature. Admittedly, the approach has been restricted to a single type of electrolyzer and to data applying only to a very restricted range of geometries and flow variables. This should, however, provide a convenient basis or point of departure for future work in the event water electrolysis becomes an important mechanism for producing fuel.

Much work remains to be done in order to advance the state of electrolyzer technology. For example, further studies should be conducted over a wider range of ambient operating pressures, tempera-

tures, flows, and current densities. Also, complete system studies should be conducted which include the problems of optimization and control.

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NOMENCLATURE (Consistent Units)

a, b,	constants in the equation describing polarization over voltage (Eq. [35])
A	channel flow area
C	specific heat of the electrolyte
E_a	voltage applied to the cell
E	voltage drop in the two phase electrolyte
ΔE_d	water decomposition potential
ΔE_p	electrode polarization overvoltage
ΔE	sum of ΔE_d and ΔE_p
H	channel width
i	current density
L	electrolyzer cell length
m	local mass flux
M	molecular weight
N	atomic weight
p	pressure
r_f	liquid electrolyte resistivity
r_{tp}	resistivity of the two-phase bubble layer
R	total cell transverse resistance
R_c	ohmic resistance of the cell
R_m	membrane resistance
T	temperature
V	fluid velocity
w	mass flow rate
x	gas quality or gas mass fraction
y	channel thickness
z	vertical coordinate

Greek Letters

α	void fraction based on channel thickness
α'	void fraction based on bubble layer thickness
β	temperature coefficient
γ	defined by equation [21]
δ	bubble layer thickness
ϵ_g	valence upon electrolytic decomposition
λ_g	constant defined by equation [13]
ρ	density
σ	slip ratio or phase velocity ratio
τ	wall shear stress
Φ	gas volume flow fraction
Ψ	two-phase flow frictional multiplier
Ω	correlation parameter

Subscripts

o	channel inlet conditions
l	anode side
2	cathode side
g	gas
f	liquid
h	hydroxyl ion
v	vapor

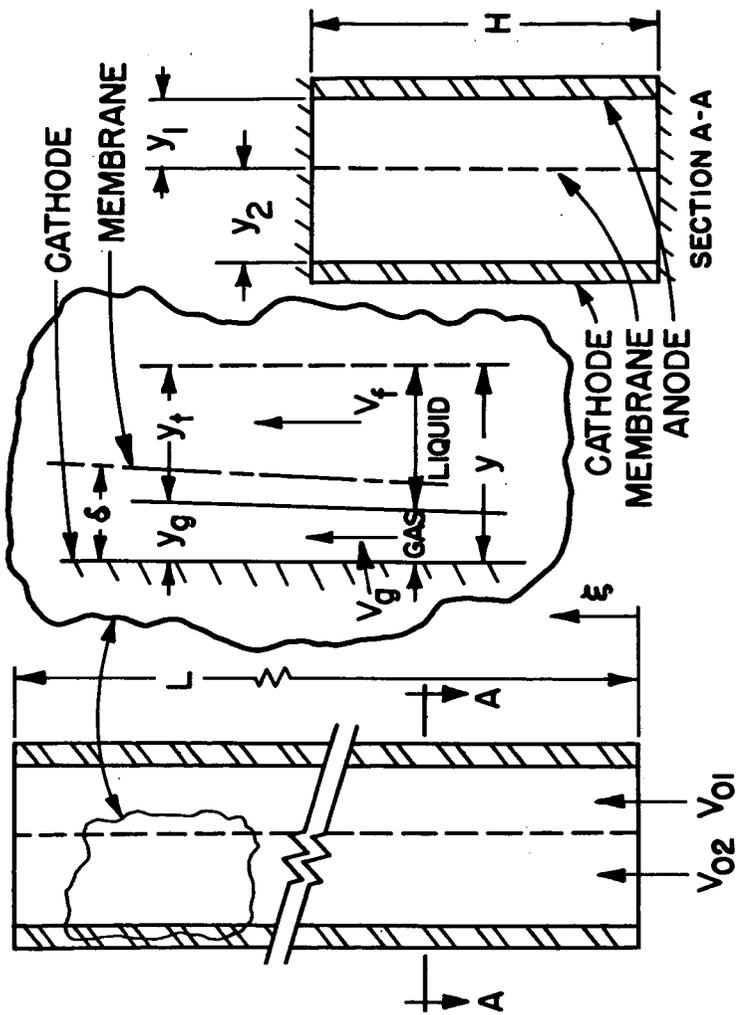


Figure 1. Electrolysis Cell Nomenclature

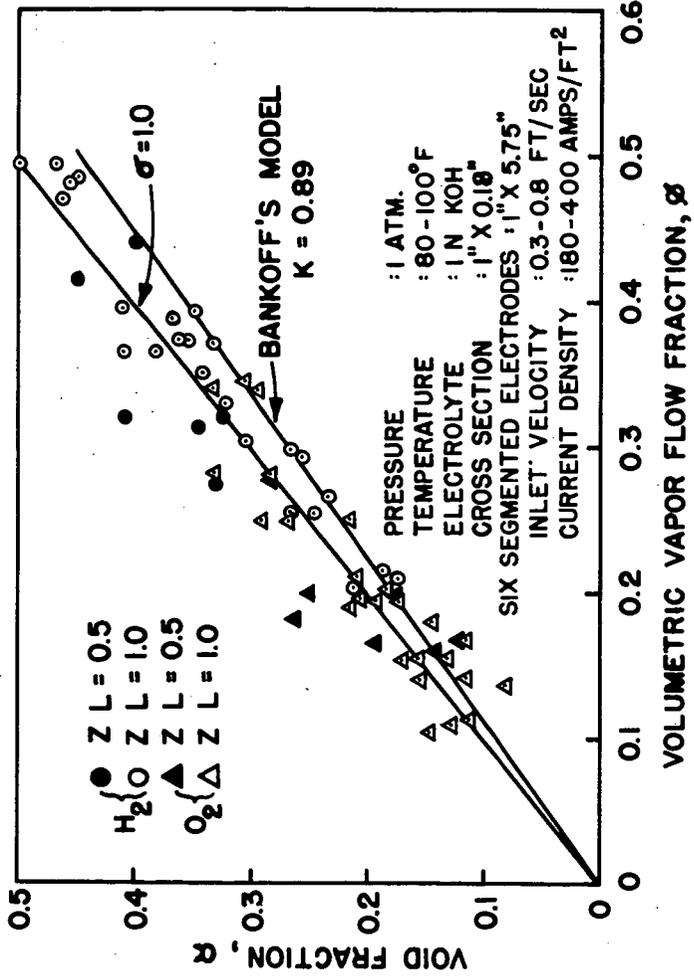


Figure 2. Void Fraction Versus Volumetric Flow Fraction

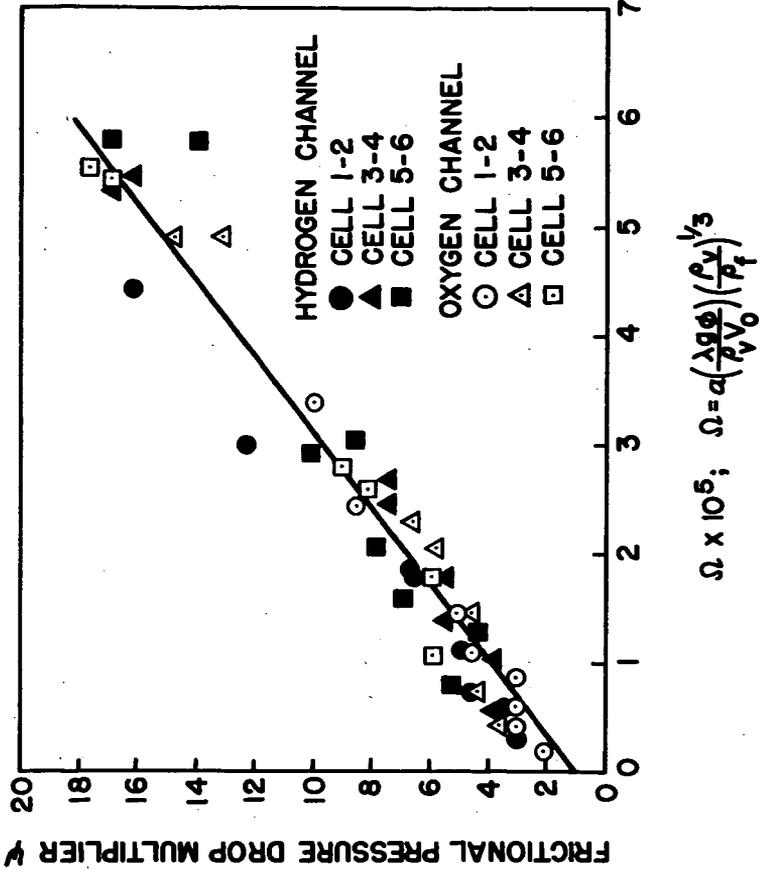


Figure 3. Correlation of Frictional Pressure Drop Multiplier