5.8. EXPERIMENTAL CONFIRMATION OF A MATHEMATICAL MODEL FOR THE DESIGN OF CATHODIC PROTECTION SYSTEMS

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ABSTRACT

This work deals with the experimental confirmation of a boundary element model developed for the calculation of current and potential distribution in sacrificial anode or impressed current cathodic protection systems. Tests have been carried out with an ad- hoc built cell, in 3.5% NaCl solution and under variable hydrodynamic conditions. The cathode was made of a carbon steel sheet divided into small elements on which current and potential have been measured. The data obtained from computer run are in agreement with experimental results.

INTRODUCTION

The achievement of adequate current and potential distributions represents a paramount goal in the design of cathodic protection systems for offshore structures. Infact, poor design methods leading to underprotection can result in expensive retrofittings, while conservative design methods leading to overprotection, besides causing waste of money, can result in damages for some materials (e.g. embrittlement of high strength steels). An efficient and reliable design method is therefore believed to represent a valuable investment for companies involved in the design and operation of offshore platforms.

Traditional design methods, based on the designer's experience and the use of average values for current densities, disregard the problem of calculating the current and potential distribution; for this reason they cannot assure the required reliability, especially in case of complex structures or whenever there is a lack of experienced data (e.g. new sites of installation). On the contrary the adoption of computer modelling techniques, allowing the direct calculation of the current and potential distribution, can represent, if properly supported by a sound background of data, a major improvement towards the optimiza-

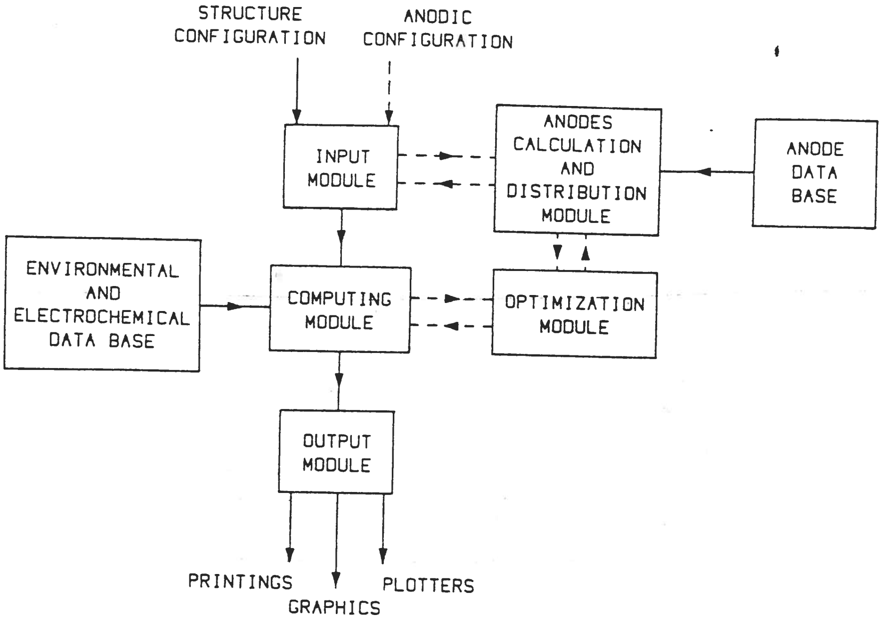

Fig. 1 - Structure of the program.

tion of cathodic protection systems.

These considerations led three Italian companies, Agip, Snamprogetti and Tecnomare, to carry out a joint research project aimed at developing a computer program for the optimum design of cathodic protection systems for offshore steel structures. The project, with IMI (Istituto Mobiliare Italiano) financial support, started in 1984 and ended in 1986.

DESCRIPTION OF THE COMPUTER PROGRAM

The program, whose structure is shown in Fig. 1, is constituted of 5 main modules and 2 data bases. Each of the modules represents one or more subprograms, that are briefly described in the following.

The input module performs the tasks of reading the structural data from the same files used for the structural analysis programs and preparing the input for the computing module.

The anodes calculation and distribution module allows the automatic calculation of number, type and distribution of sacrificial anodes on a steel jacket; this feature is useful in case of design of cathodic protection systems for new platforms.

The computing module computes the potential and the current density on the structure, solving the Laplace equation by means of the Boundary Element Method.

The optimization module allows the optimization of the number and distribution of anodes along the structure.

The output module presents the results of the calculation in form of printings, plotters or graphics.

The anode data base contains all the information relevant to commercial anodes, in order to allow the selection of the best anode for each specific application.

The environmental and electrochemical data base contains the polarization curves (describing the relationship between potential and current density on the steel surface) and the environmental data (water resistivity, etc.) relevant to the geographical site considered.

The main capabilities of the program include:
- bidimensional analysis
- tridimensional global analysis of complex tubular structures (e.g. steel jackets)
- tridimensional detailed analysis of selected parts (typically structural nodes)
- analysis of sacrificial anodes or impressed current systems
- possibility of solving cases of primary, secondary or tertiary distribution.

EXPERIMENTAL CONFIRMATION

Purpose of this experimental confirmation was not just to assess the computing module ability to solve the problem of current and potential distribution, since such capability had already been proved |1-3|. What was really pointed out was the efficiency of the whole model in dealing with the calculation of current and potential distribution on a cathodically protected structure; the characteristics of the various phases composing the model have been deeply examined alongwith related problems, either mathematical, as in the structure representation, or merely electrochemical, as in the definition of boundary conditions.

For simplicity's sake, the environmental conditions adopted involved boundary conditions not evolving in time, contrary to what happens in marine environment due to the formation of a calcareous deposit on the protected structure. The experimental conditions adopted can however represent, to a certain extent, the actual condition of a bare and not precorroded (either sandblasted or pickled) steel structure during the initial cathodic polarization in sea water.

Under the test conditions selected, the environment velocity plays a very important role because it directly affects the limiting current density for oxygen reduction. Therefore, when defining boundary conditions, a convective mass transport problem arose, which was only partly solved based on correlations reported in literature | 4-8 |, in spite of the relative simplification of the cell used.

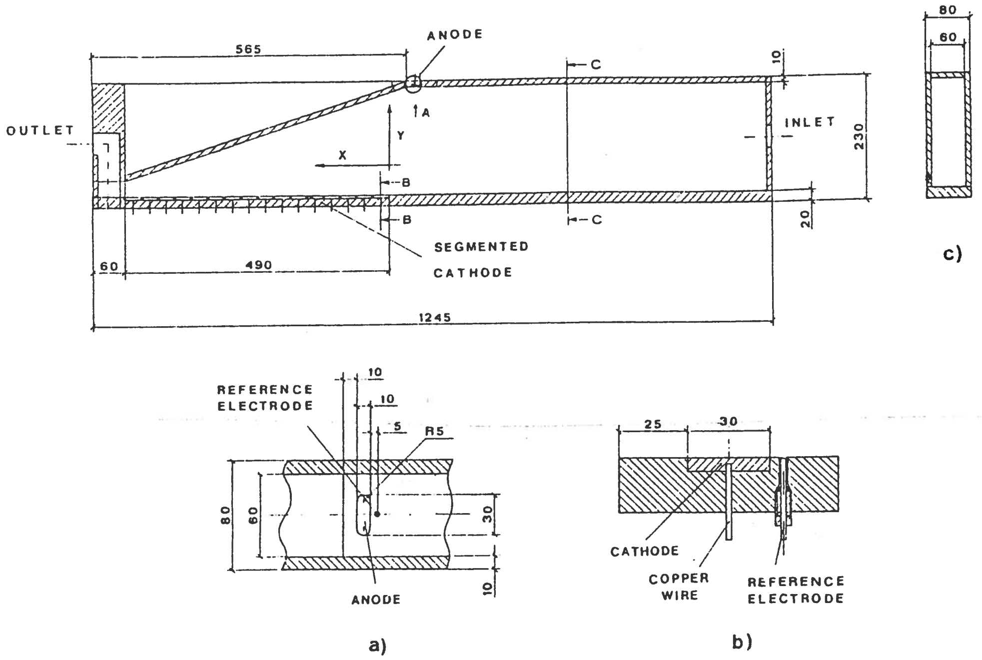

Fig. 2- Geometrical characteristics of the cell (sizes in mm). Horizontal section and other views: a) Detail A, view in direction of arrow, b) B-B sectional view, c) C-C sectional view.

Tests have been performed in 35 g/l NaCl solution, as for polarization measurements |9 |. The geometrical characteristics of the cell used are shown in Fig. 2.

The cell is made of perspex, the anode is made of a commercial zinc alloy and the segmented cathode is made of API 5L grade X65 steel already used for polarization tests |9 |. (Before tests, both the anode and the cathode were smoothed with emery paper up to 1000 mesh, rinsed with distilled water and degreased with ethyl alcohol). The anode surface is about 2.8 cm^2. The segmented cathode consists of 16 separate square elements (3x3 cm), placed in the variable width part of the cell, so that hydrodynamic conditions are different for each element. (Elements are numbered so that cathode no. 1 is the closest to the anode and cathode no. 16 is the farthest). The overall length of the segmented cathode is 49 cm, the useful length of which is only 48 cm. The cell is about 125 cm long in order to make the flow homogeneous near the cathode and to reduce turbulence. Inlet and outlet ports are aligned so as to allow cell assembling in a loop test section. Ag/AgCl reference electrodes are plugged in through holes placed near the anode and near each cathode (distance about 0.5 cm). The current of each cathode is measured as potential drop over a variable resistor, adjusted at 0.5 Ω before test. Measurements have been made using a 60-channel data logger. The

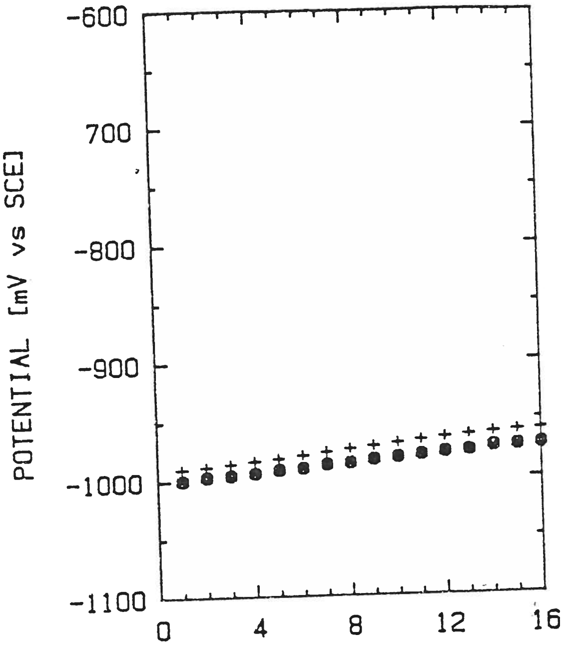

Fig. 3 - Potential distribution on the segmented cathode of the cell shown in Fig. 2. Segments are numbered so that cathode no. 1 is the closest to the anode and cathode no. 16 is the farthest. API 5L grade X65 steel cathode, 35 g/l NaCl solution, 20.5°C, pH 7.2, dissolved O_2 7.2 ppm, flow rate 110 l/h, sacrificial anode cathodic protection system.
(o) Experimental
(*) Calculated, boundary conditions at the cathode according to Eqs.(1) and (2)
(+) Calculated, boundary conditions at the cathode according to Eqs. (1) and (3)

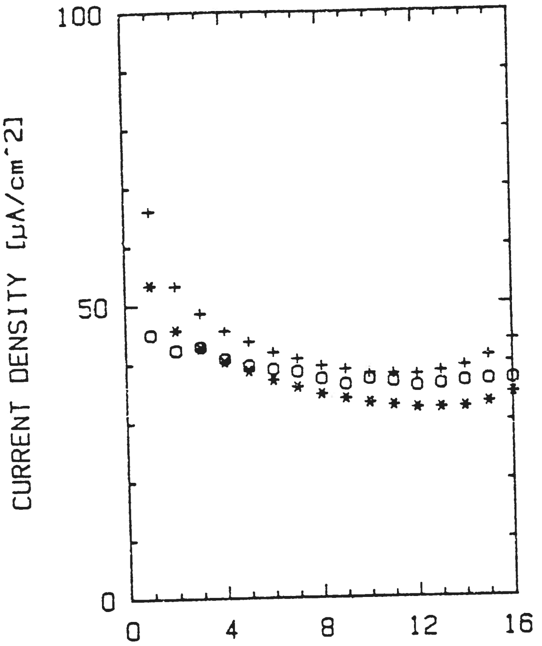

Fig. 4 - Current density distribution on the segmented cathode of the cell shown in Fig. 2. Experimental conditions as in Fig. 3.

solution circulating system provided the control of flow rate and temperature, alongwith the monitoring of pH and dissolved oxygen (under air saturation conditions).

Two series of tests have been performed. The first series of tests refers to a sacrificial anode cathodic protection system and has been carried out at 19÷21°C with different flow rates (ranging between 100 an 2000 l/h). The second series of tests refers to an impressed current cathodic protection system, obtained connecting a galvanostat between the anode and the segmented cathode. In this case, measurements have been made at 20°C and at a flow rate set at 500 l/h with different currents emitted by the anode (between 5.2 and 8 mA).

RESULTS AND DISCUSSICN

Some distribution curves measured on the segmented cathode of the cell shown in Fig. 2 are reported in Figs. 3, 5, 7 and 4,6,8, respectively regarding poten-

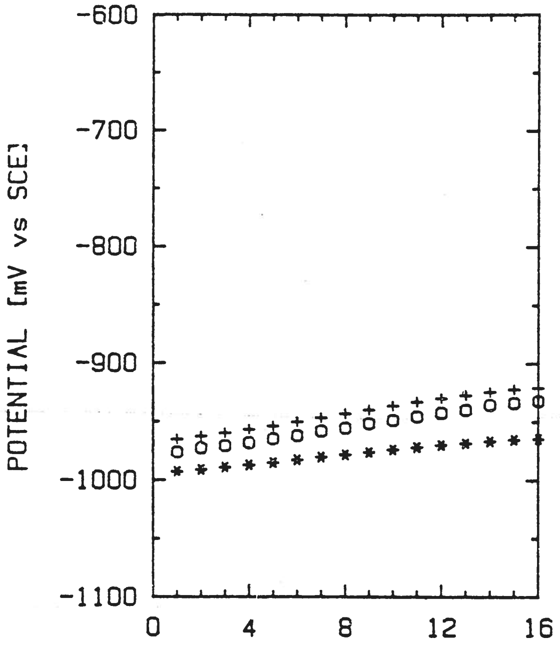

Fig. 5 - Potential distribution on the segmented cathode of the cell shown in Fig. 2. Flow rate 1000 l/h, other experimental conditions as in Fig. 3.

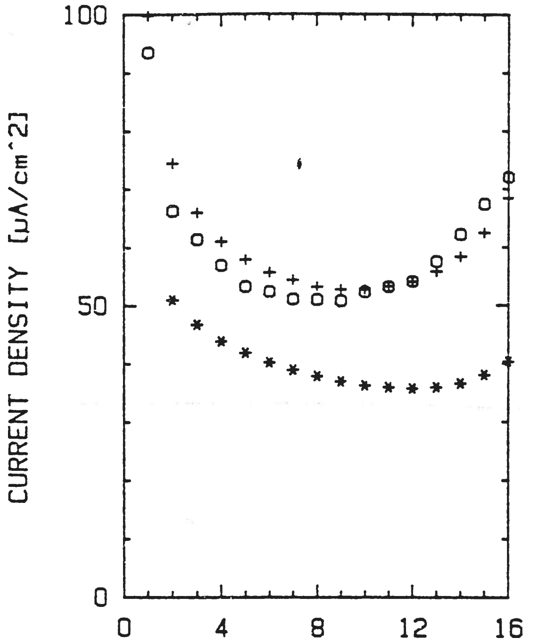

Fig. 6 - Current density distribution on the segmented cathode of the cell shown in Fig. 2. Flow rate 1000 l/h, other experimental conditions as in Fig. 3.

tial and current density.

As to the comparison with the results of the calculation procedure, it has to be pointed out that non-linear boundary conditions with regard to cathode are considered. (As far as the anode is concerned, boundary conditions are constant potential type or constant current density type, respectively for tests with sacrificial anode or with impressed current). The following expression has been adopted for the cathodic polarization curve |9|:

$$i = I_{Fe} \exp(E/B_{Fe}) - i_L - I_H \exp(-E/B_H) \quad (1)$$

$I_{Fe}=1.5\mathrm{x}10^{7} A/cm^2$, $I_H=8\mathrm{x}10^{-14} A/cm^2$

$B_{Fe}=RT/F=25.3$ mV, $B_H=2RT/F=50.6$ mV

(i is in A/cm^2 and E in mV vs SCE).

The parameter i_L (limiting current density for oxygen reduction) is determined both by hydrodynamic and environmental conditions; therefore, its value depends on the flow rate and on the position of the cathode in the cell too, besides that on the dissolved oxygen concentration and temperature. Initially i_L has been estimated by means of the following theoretical correlation valid for laminar flow between parallel plate electrodes | 8 |:

$$Sh = 1.2325 \left(Re\ Sc\ \frac{d}{x}\right)^{1/3}$$

in terms of the dimensionless Sherwood, Reynolds and Schmidt numbers, or:

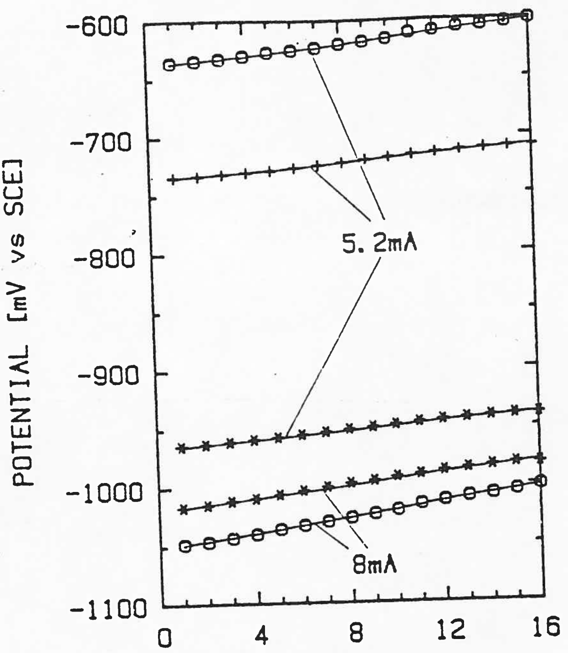

Fig. 7 - Potential distribution on the segmented cathode of the cell shown in Fig. 2. API 5L grade X65 cathode, 35 g/l NaCl solution, 20°C, pH 7.2, dissolved O_2 7.4 ppm, flow rate 500 l/h, impressed current cathodic protection system, current as indicated.

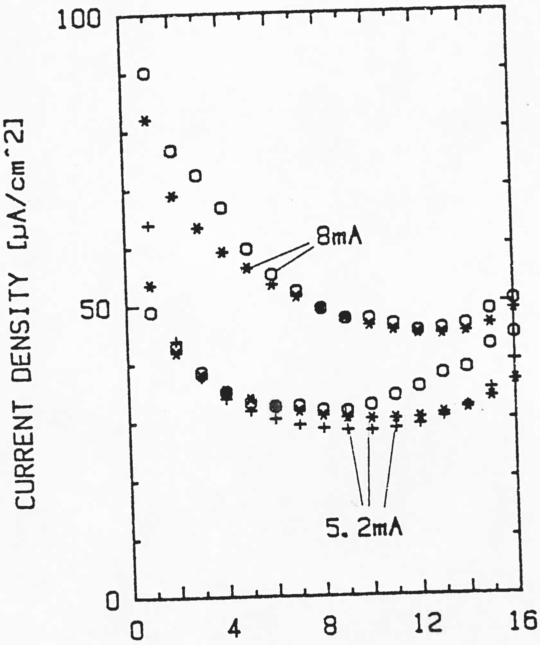

Fig. 8 - Current density distribution on the segmented cathode of the cell shown in Fig. 2. Experimental conditions as in Fig. 7.

$$i_L=1.2325\ nFCD^{2/3}\ \Phi^{1/3}\left(\frac{h+y}{2h^2y^2x}\right)^{1/3} \quad (2)$$

where x is the distance in cm along the segmented cathode starting from the edge of cathode no. 1, y is the variable width of the cell given by:

$$y(cm) = 19.5-0.337x,$$

h is the cell height equal to 6 cm. (See also list of symbols at the end of the paper).

The above-said correlation (2) doesn't seem to be able to predict with enough accuracy the limiting current density for the cell used; in fact, comparing the calculated and the experimental results of some tests, where the current density exchanged on the cathode is almost equal to the limiting current density (tests performed with impressed current of 6 and 5.2 mA and tests with sacrificial anode at a flow rate of 1000 and 2000 l/h), a considerable discrepancy is observed (see e.g. Figs. 6 and 7, respectively regarding current density and potential distribution).

The limiting current density for the cell considered can be obtained with better accuracy following this semiempirical correlation:

$$i_L=2.3\ nFCD^{2/3}\left(\frac{\Phi}{x}\right)^{1/3}\left(\frac{1}{hy}\right)^{1/2} \quad (3)$$

that is expressed in dimensionless numbers as follows:

$$Sh=2.3(Re\ Sc)^{1/3}\left(\frac{h}{x}\right)^{1/3}\left(\frac{h}{y}\right)^{1/6}\left(\frac{L}{h}\right)^{2/3}\left(\frac{yo}{y}\right)^{1/3}$$

where y_o and L are respectively the cell width in correspondence of x=0 (y_o=19.5 cm) and the cathode overall length (L is also the length referred to in the Reynolds and Sherwood numbers, instead of the hydraulic diameter d).

The correlation (3) has been obtained from the results of tests performed with a flow rate equal or lower than 1000 l/h, that is under laminar flow hydrodynamic conditions. Such conditions have been proved by introducing a colored liquid in some points of the cell. This technique also revealed the presence of turbulence in correspondence of the cell cathode at flow rate values equal to 2000 l/h. Under such conditions the correlation (3) is unable to make a correct estimate of the limiting current density.

As to the discrepancy of about 100 mV which persists in the potential distribution reported in Fig. 7 for the test performed with impressed current of 5.2 mA, it must be remembered that at potentials more positive than -700 mV vs SCE in the experimental polarization curves for API 5L grade X65 steel rotating disk electrode in aerated 35 g/l NaCl a shift by 80 mV in the anodic direction occurs as compared with the analytical expression(1) probably due to film formation on the steel |9|.

CONCLUSIONS

Both bibliographic and experimental data gave a positive confirmation of the boundary element model adopted for the calculation of current and potential distribution in a cathodic protection system in absence of calcareous deposits. Moreover, these data completed and underlined the validity of non-linear boundary conditions proposed for the steel structure, being representative of the situation undergone by a bare and not precorroded structure in the initial phase of cathodic protection.

In absence of calcareous deposits, for the boundary conditions definition it is necessary to solve a problem of oxygen convective transport to the surface. This can be achieved for relatively simple geometries based on semiempirical correlations reported in literature. For more complex geometries the hydrodynamic equations can be solved by using numerical methods.

The results obtained in this research are meant to be a preliminary step in the distribution calculation in marine environment. Additional studies are required to solve some aspects of boundary conditions definition, and namely it is necessary:

i) to study the effect of the calcareous deposit on the polarization curve. To this purpose, a model developed by us proved to be applicable and gave acceptable results during computer simulation tests on experimental data reported in literature. This part of the study will be dealt with in detail in a separate paper.

ii) to investigate the effect of hydrodynamic conditions on limiting currents using numerical methods for structures of geometrical characteristics closer to reality.

iii) to design such systems that, once placed in the location where the offshore structure has to be built, will be able to record useful data for the distribution calculation and for actual boundary conditions definition (values and variations in time of the limiting current, parameters of calcareous deposit growth, temperature, flow conditions, etc.).

iv) to acquire additional data from structures in operation.

As far as this latter aspect is concerned, the application of mathematical models for distribution calculations on existing polarized structures is very useful both because this allows a more simplified and economical monitoring of the structures themselves |10|, and because data of extreme importance can be collected.

LIST OF SYMBOLS

B_{Fe} = RT/F (V)
B_H = 2RT/F (V)
C = concentration of dissolved O_2 (mol/cm^3)
d = hydraulic diameter = 4 x area/perimeter = 2 yh/(y+h) (cm)
D = diffusion coefficient of dissolved O_2 (cm^2/s)
E = electrode potential (V vs SCE)
F = Faraday's constant (As/equiv.)
h = cell height (cm)
i = current density (A/cm^2)
i_L = limiting current density for O_2 reduction (A/cm^2)
I_{Fe}, I_H = constants (A/cm^2)
L = cathode overall length (cm)
n = equivalent per mole (equiv/mol)
R = ideal gas constant (J/mol°K)
Re = Reynolds number = vd/ν, or v_oL/ν (dimensionless)
Sc = Schmidt number = ν/D (dimensionless)
Sh = Sherwood number = $i_Ld/nFDC$, or $i_LL/nFDC$ (dimensionless)
T = temperature (°K)
v = flow velocity = Φ/yh (cm/s)
v_o = flow velocity in correspondence of $y = y_o$ (cm/s)
x = distance along cathode (cm)
y = cell width (cm)
y_o = cell width in correspondence of x=0 (cm)
Φ = volumetric flow rate (cm^3/s)
ν = kinematic viscosity (cm^2/s)

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