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Influence of grid design on current distribution over the electrode surface in a lead-acid cell

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Abstract

The current distribution over the plate surface in lead-acid cells was determined by means of a newly proposed method based on electrical measurements on a model. The method, which is much simpler than mathematical analysis of model systems, can be used to find the optimum grid design. Six illustrative examples and mathematical formulae for two special cases are presented. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Grid design; Electrode surface; Lead-acid

1. Introduction

It has long been known that the properties of lead accumulators are adversely affected by non-uniform current distribution over the plate surface. This is to a considerable extent influenced by the design of lead grids, but their optimization has been based usually on experience. The current distribution over the plate surface is generally, owing to ohmic losses, the more non-uniform the higher is the discharge rate and the larger are the plates. A mathematical theory of this phenomenon, which impairs the utilization of the active material, was presented by several authors [1]. In batteries for high-rate discharge, it is desirable to minimize their inner resistance. This can mainly be done by minimizing the plate resistance, hence, by optimizing the grid design. Therefore, a mathematical method based on a grid model was proposed by Tiedemann et al. [2] and further developed by Sunu and Burrows [3,4] to describe the behaviour of real plate electrodes in batteries. The whole procedure is, however, very complicated, and so we attempted to propose a much simpler method based on electrical measurements.

2. Principle of the method

A single cell of a lead-acid battery was modelled by an electrical equivalent circuit consisting of a pair of commercial lead grids of dimensions 14.4×11.2 cm^2, 7.7 cm apart. These were provided with tabs and mutually interconnected by a system of parallel, thin resistance wires, 7.7 cm in length, representing the sum of ohmic resistances of electrolyte and active mass and of polarization resistances. The grids were mounted on a support from two organic glass plates, as can be seen from the photograph (Fig. 1). Nine wires were welded to each of the 21 horizontal ribs at points lying in the middle between two neighbouring vertical ribs, giving together 189 measuring points per grid. The grids were loaded with a DC current of 2 A causing a measurable ohmic voltage drop on the wires of a resistance of 0.338 Ω each. From this and the measured voltage drop values, the resulting current distribution over the whole grid area was found for various configurations of the current leads. The model can be considered to represent the current distribution in a real cell if the electrode polarization is a linear function of the current density, i.e., if the polarization resistance is constant. This is plausible at a low depth and rate of discharge (since otherwise the active surface area of the electrodes

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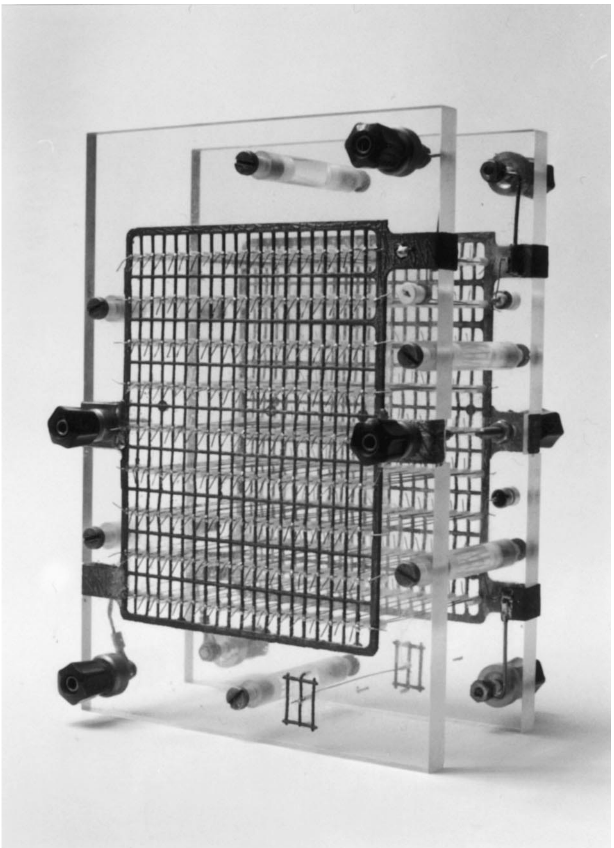


Fig. 1. View of the measuring system mounted on an organic glass support. The system permits measurements at different tab positions. The single wire at the bottom was used for measurement of its resistance.

would decrease considerably leading to an increase of the polarization resistance). The idea of a linear polarization curve has been used not only in approximate models of battery discharge [5,6] but also in the advanced theory [4] with satisfactory results.

3. Results of measurements

The results are summarized in Fig. 2. Each scheme corresponds to two overlapping grids. The location of tabs (for current leads) is also shown. Curves of equal current values were plotted directly in the scheme of the grids. Triangles indicate sites with the maximum and minimum current values. Labels indicate local current values in milliamperes. Schemes **A** and **B** correspond to the case where the two tabs overlap. Scheme **C** shows the results for the usual arrangement with tabs located at the opposite corners at the top of both grids. The same arrangement but with inclined ribs distributed somewhat radially is shown in Scheme **D**. A less usual arrangement of the tabs is shown in Schemes **E** and **F**, where the tabs are located at the top of one grid and at the bottom of the other grid.

An overview of all the variants studied is presented in the form of a table in Fig. 3. The worst arrangement turned out to be that with tabs at the overlapping corners of the two grids (cf. **A**), with maximum and minimum currents 2.28 and 0.69 mA, giving a measure of non-uniformity $2.28/0.69 = 3.30$, and that (cf. **B**) where the corresponding values are 2.21 mA, 0.72 mA, and 3.07. These arrangements are characterized by the lowest degree of symmetry and hence, by the most non-uniform current distribution. It can be seen that when the tabs are placed close to each other, the degree of non-uniformity is highest. This is because the regions of higher ohmic potential drop (IR) values in the solid phase come close to each other.

When, on the other hand, the regions of higher IR values on one plate are situated against those of lower IR values on the other plate (cf. **E**, **F**), the degree of non-uniformity is much lower. Thus, a favourable arrangement of the tabs corresponds to the Scheme **F**, where the maximum and minimum currents are 1.54 and 0.89 mA, and the degree of non-uniformity is as low as 1.73.

The favourable effect of the radial ribs which minimize the IR values in the solid phase (variant **D**) is obvious by comparing with variant **C**, corresponding to the ‘‘classical’’ grid with orthogonal ribs, the tab configuration being the same. In variant **C**, the maximum and the minimum currents are 1.72 and 0.69 mA and the measure of non-uniformity is 2.49, whereas in the variant **D** the corresponding values are 1.57 mA, 0.84 mA, and 1.87, evidence for improved properties of this grid design. This is obviously because the density of the ribs is highest at the tab, thus decreasing the ohmic voltage drop in the grid region where the electronic current (flowing in the grid) is most intense.

Our results refer to grids without the active material. As follows from the earlier theoretical and experimental results [3,7], the influence of the positive active material on the grid conductivity is negligible, however, the negative active material (in the charged state) contributes appreciably to the grid conductivity. This effect could be taken into account by using dry-charged negative plates instead of the unpasted grids. Thus, the degree of non-uniformity would be somewhat decreased. Accordingly, if a better grid design with a lower degree of non-uniformity is found by our method using unpasted grids, it will perform still somewhat better in the pasted state. However, since the method is comparative in nature, the results of optimization would remain valid regardless of whether the grids were pasted before the measurements or not.

Appendix A

It may be of interest to introduce some more general theoretical results. First, let us consider the case **B** (with

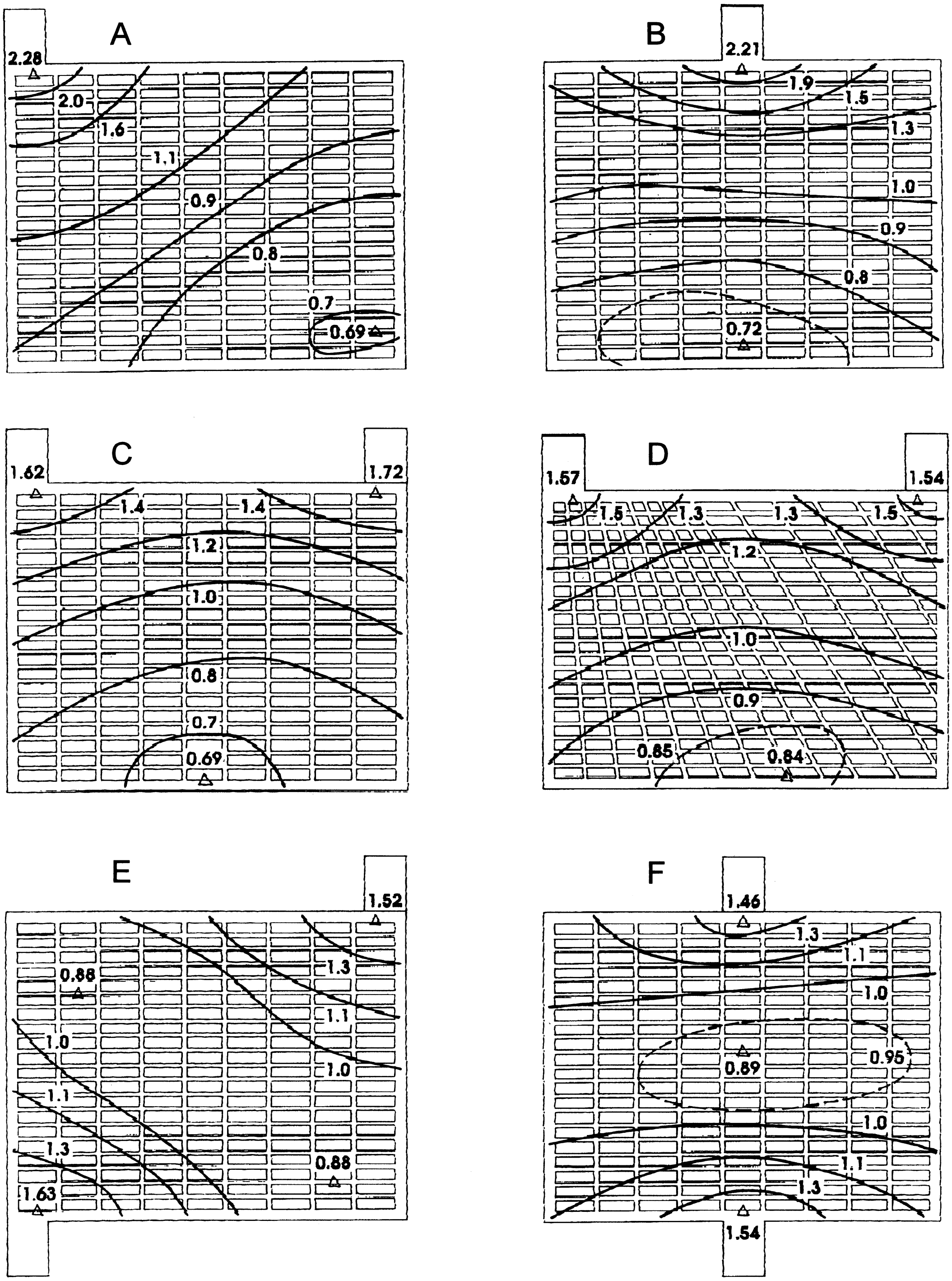


Fig. 2. Current distribution over the grid area for the six variants, **A**–**F**, differing by the position of tabs and by the arrangement of ribs.

tabs at the top), and assume that the width of the electrodes, w, is much smaller than their height (length), L. Further, we denote y as the perpendicular coordinate (with origin at the top of the electrodes), I_T the current flowing through the tabs, and $j(y)$ the local current density perpendicular to the plate surface at a point y. We assume SI units. The current distribution over the plate surface along the y coordinate can approximately be calculated by the method of current lines as in the case of plate electrolysers [8] with the following result (cf. Ref. [1]):

$$j(y) = (I_T\sqrt{\kappa}/2w)\cosh[(L-y)\sqrt{\kappa}]/(\sinh(L\sqrt{\kappa}) \quad (1)$$

where

$$\kappa = (\rho_+/d_+ + \rho_-/d_-)/(R_{p_+} + R_{p_-} + d_e\,\rho_e) \quad (2)$$

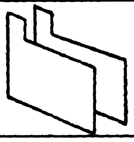
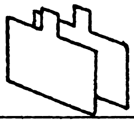
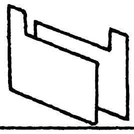
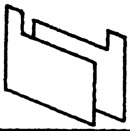
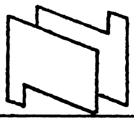
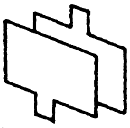
	I_{max}	I_{min}	$\frac{I_{max}}{I_{min}}$
 A	2.28	0.69	3.304
 B	2.21	0.72	3.069
 C	1.72	0.69	2.493
 D	1.57	0.84	1.869
 E	1.63	0.88	1.852
 F	1.54	0.89	1.730

Fig. 3. Overview of the results for the six variants. The degree of non-uniformity is defined as the ratio of the maximum to the minimum current, I_{max}/I_{min}, flowing between the grids.

where ρ_+ and ρ_- denote effective resistivities of positive and negative plates, d_+ and d_- their half-thicknesses, R_{p+} and R_{p-} their polarization resistances, d_e thickness of the electrolyte layer between them, and ρ_e resistivity of the electrolyte layer (eventually including separator). The polarization of the cell is equal to the difference between the equilibrium voltage, U_r, and the voltage under load, U:

$$U_r - U = (R_{p_+} + R_{p_-} + d_e\,\rho_e)(I_T\sqrt{\kappa}/2w)\coth(L\sqrt{\kappa}) \quad (3)$$

Case **F** (with negative tab at the top and the positive at the bottom) is more complicated; the corresponding formulae were found, under the same assumptions, as follows:

$$j(y) = (I_T\sqrt{\kappa}/2w)\big[\alpha\cosh[(L-y)\sqrt{\kappa}] + (1-\alpha)\cosh(y\sqrt{\kappa})\big]/\sinh(L\sqrt{\kappa}) \quad (4)$$

where

$$\alpha = (\rho_-/d_-)/(\rho_+/d_+ + \rho_-/d_-) \quad (5)$$

and the cell polarization is now given in the form:

$$U_r - U = (R_{p_+} + R_{p_-} + d_e\,\rho_e)(I_T\sqrt{\kappa}/2w)\,\Theta(\alpha, L\sqrt{\kappa}) \quad (6)$$

where we have introduced the auxiliary function

$$\Theta(\alpha, L\sqrt{\kappa}) = (2\alpha^2 - 2\alpha + 1)\coth(L\sqrt{\kappa}) + \alpha(1-\alpha) \times L\sqrt{\kappa} + 2\alpha(1-\alpha)/\sinh(L\sqrt{\kappa}) \quad (7)$$

By comparing the two cases, it can first be seen that the current distribution is substantially different: from Eq. (1) it follows that the local current density, $j(y)$, decreases from a maximum at $y = 0$ (from the tab position) to a minimum at $y = L$ (at the bottom), whereas Eq. (4) predicts the occurrence of a minimum somewhere between $y = 0$ and $y = L$; if the effective resistivities of the two electrodes are equal, then $\alpha = 0.5$ and the minimum is at $y = L/2$, exactly in the middle of the electrode. Typically, the value of α is somewhat lower than 0.5, since the effective resistivity of the *pasted* negative plate is lower than that of the positive (i.e., $\rho_- < \rho_+$) and their thicknesses are roughly the same. With decreasing value of α, the position of the minimum shifts upwards (to the top of the electrodes).

The cell polarization is directly proportional to the total current, I_T, since we assume constant polarization resistances of both electrodes. If $L\sqrt{\varkappa} \ll 1$, the function $\Theta(\alpha, L\sqrt{\kappa})$ becomes very close to cot $h(L\sqrt{\kappa})$, hence, the formula (6) gives practically the same results as Eq. (3). This case is typical since usually $L \ll 1$ m and the effective resistivities of the electrodes are much smaller than the polarization resistances, hence, $\kappa \ll 1\ \mathrm{m}^{-2}$.

The distribution of local current densities depends, in both cases under discussion, on the parameter $L\sqrt{\kappa}$. The value of the function $\cosh(L\sqrt{\kappa})$ can be taken as a measure of non-uniformity of the current distribution. With decreasing $L\sqrt{\kappa}$, this function approaches unity and the current distribution, as defined by Eq. (1) or Eq. (4), becomes more uniform.

A.1. Conclusions

The proposed method, based on electrical measurements, enables optimization of lead grids for lead-acid cells to be performed sufficiently reliably and more easily than with engineering methods based on mathematical analysis of model cells.

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