DESIGN OPTIMIZATION OF TALL TUBULAR LEAD/ACID CELLS BASED ON AN ANALYSIS OF THE REACTION DISTRIBUTION

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Summary

In order to estimate the discharge performance of tall lead/acid cells (with tubular positives), changes in current and potential distributions with discharge progress were calculated with a computer on the basis of plate resistance and the current–potential–time relationship between small facing parts of positive and negative plates. The taller the cell, the larger the voltage drop along the plates. Thus, the discharge time became shorter despite a large amount of available active mass remaining in the bottom part of the plates.

Various current-collector designs were evaluated, *e.g.*, one with varying resistance at each height; a side conductor placed along the plates and connected to them at the top, centre and bottom, etc. Results revealed an optimum collector design with which the maximum discharge capacity could be obtained. Furthermore, it was shown that the side conductor markedly improved the discharge performance because the active mass near the connecting parts was appreciably used.

Introduction

Lead/acid battery grids have been designed with computers to improve voltage characteristics. For example, Tiedemann *et al.* [1] demonstrated that computer analysis was useful to solve the potential distribution over the grids. Current and potential distributions at the initial stage of discharge have also been analysed with a computer according to a three-dimensional electric circuit model including polarization and electrolyte resistance between the plates [2]. However, as the discharge voltage of the lead/acid cell gradually falls with time because of the depletion of the active materials, voltage change with discharge time should also be analysed in order to evaluate cell performance.

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In this study, the discharge curves of tall lead/acid cells that are effective in improving the power and energy density per unit floor space have been analysed with a computer. In particular, the influence of current-collector design on cell performance has been examined.

Experimental

Model of discharge process

If the effect of the plate height only is considered, the change in the current distribution with discharge time of a lead/acid cell can be represented by the schema shown in Fig. 1. Here, the magnitudes of current and resistance are shown by the arrow thickness and sawtooth pitch, respectively. Before the discharge, when the cell is fully charged the electrolyte concentration is uniform. Under these conditions, the characteristics of the electric circuit elements between the plates are also uniform throughout the entire cell. When current flows into and out of the top of this electric circuit, the current flowing between the positive and negative plates decreases down the system because of the increasing voltage drop caused by the plate resistance (Fig. 1(a)). As the discharge proceeds, the upper part of the plate is more deeply discharged and increases in both the electrolyte resistance and the polarization will occur due to depletion of the active materials. At this stage, the current distribution is almost uniform throughout the cell (Fig. 1(b)). Finally, the upper part reaches a completely discharged state (Fig. 1(c)).

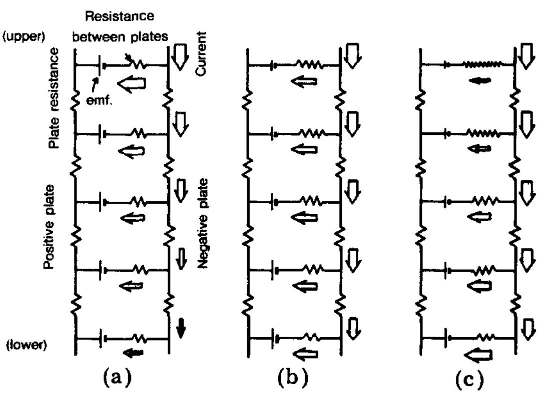

Fig. 1. Schema of changes in the current distribution in the plates during discharge of a lead/acid cell: (a) onset of discharge; (b) discharge in progress, (c) end of discharge.

Change in electric characteristics

In order to determine the change in the electric characteristics between plates of no resistance during discharge, a small tubular-type lead/acid cell with 10 cm high plates and current inlets or outlets at both top and bottom was discharged at various current densities in different concentrations of sulphuric acid.

The discharge voltage E (V) of the small cell can be represented as a function of current density i (A cm^{-2}) and a dimensionless discharge depth Q as follows:

$$E = \text{e.m.f.} - F - GQ - (H + IQ)i - J\exp(KQ) \quad (1)$$

where e.m.f. is the electromotive force and F to K are constants. The relation between the discharge capacity C (A h cm^{-2}) and the current density can be expressed by Peukert's equation:

$$C = ai^b \quad (2)$$

where a and b are constants.

The results given in Fig. 2 show that these equations satisfactorily represent the discharge curves of a small cell. In addition, the changes in the discharge curves with electrolyte concentration can be expressed by these equations, provided the above constants are rewritten as first-order concentration functions.

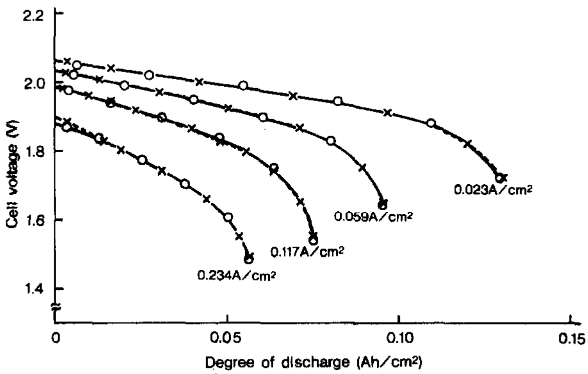

Fig. 2. Comparison between calculated (—x—) and measured (—o—) discharge of a small lead/acid test cell; 1.28 S.G. H_2SO_4.

Computer calculation

Changes in the current, voltage drop and discharge depth in the electric circuit of Fig. 1 were calculated with a computer using data for the plate resistance and the change in the electric characteristic between the plates at various points. The procedure adopted was as follows:

(i) calculation of the current distribution just after onset of discharge;

(ii) calculation of the amount discharged at each part of the plate after a short period;

(iii) calculation of the new electric characteristics between the plates based on an increase in the depth of discharge;

(iv) calculation of the new current distribution with the change in the electric characteristics;

(v) repetition of (ii) - (iv).

Results and discussion

Discharge behaviour of tall lead/acid cells

Figure 3 shows the discharge curves of a tall lead/acid cell with tubular positive plates of height 80 cm, width 30 cm, and thickness 0.8 cm. The broken curves show computer calculated results and the full curves represent the experimentally determined discharge curves. It can be seen that there is good agreement between the calculated and measured curves over a wide range of current density, *viz.*, from 0.110 A cm^{-2} (0.5 h rate) to 0.013 A cm^{-2} (10 h rate).

Figure 4 shows the calculated discharge behaviour (*i.e.*, changes in current density, degree of discharge and voltage drop over the plates) at an

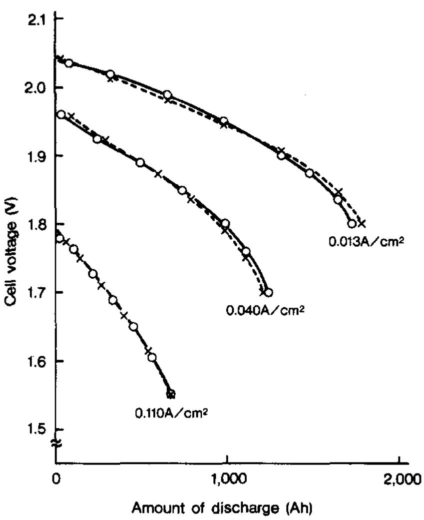

Fig. 3. Comparison between calculated (—x—) and measured (—o—) discharge characteristics of a tall lead/acid cell; 1.28 S.G. H_2SO_4.

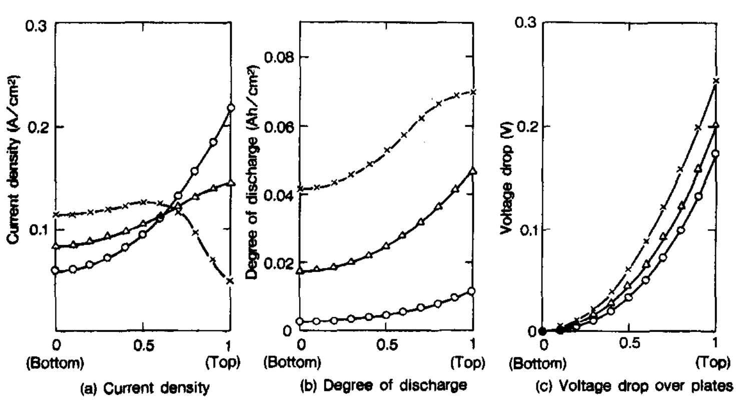

Fig. 4. Discharge behaviour of a tall lead/acid cell; average current density 0.11 A cm^{-2}; 1.28 S.G. H_2SO_4. Discharge: o, 10%; △, 50%; x, 100%.

average current density of 0.110 A cm^{-2}. The results of Figs. 4(a) and (b) demonstrate that the discharge reaction mainly takes place in the top part of the plates during the initial stage of discharge, becomes more uniform as discharge proceeds, and finally occurs between the centre and the bottom part because the top reaches a fully discharged state. Furthermore, available active material remains in the bottom part of the plates even at the end of discharge. As shown in Fig. 4(c), the voltage drop over the plates gradually increases with the change in current distribution.

The effect of plate height on the discharge curves is shown in Fig. 5, where all the plates have the same resistance per unit height and are discharged at the same current density. It can be seen that the initial discharge voltage is lowered by 270 mV and the discharge time by 73% when 160 cm high plates are used in place of 40 cm high plates. Changes in current distribution over plates of various heights are presented in Fig. 6. Corresponding distributions of the degree of discharge and the voltage drop for the same plates at the end of discharge are given in Fig. 7. The ratio of the current density at the top to the bottom of 160 cm plates is about forty at the initial stage (Fig. 6). The degree of discharge of 160 cm plates is reduced to only 60% of that of 40 cm plates even at the top because of the higher current density (Fig. 7). Plates of 40 cm height can be utilized uniformly, but as the height is increased the voltage drop becomes larger. Thus, the cell reaches the end voltage before the reaction takes place in the bottom part.

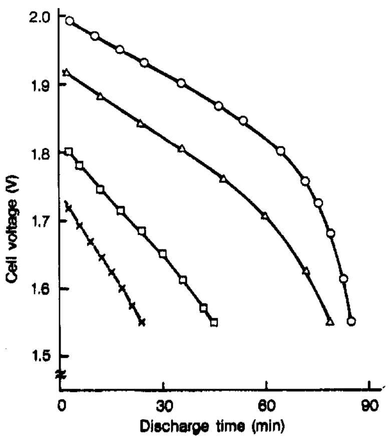

Fig. 5. Relationship between lead/acid discharge characteristics and plate height. Average current density 0.069 A cm^{-2}; 1.30 S.G. H_2SO_4. Plate height: ○, 40 cm; △, 80 cm; □, 130 cm; ×, 160 cm.

Design optimization of tall lead/acid cells

Since, as mentioned above, plate resistance plays an important role in the performance of tall lead/acid cells, we have examined the influence of the resistance design of the current collector on cell discharge curves. In

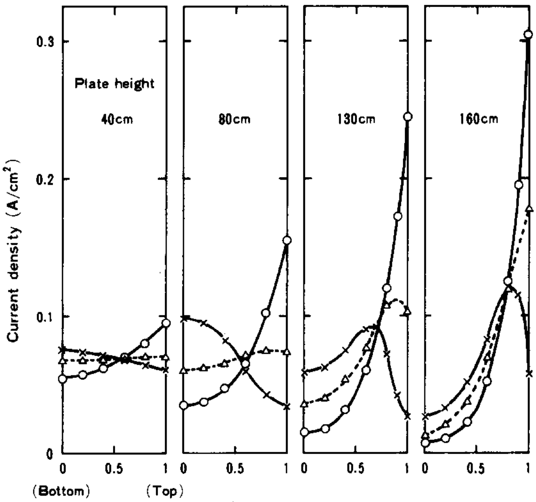

Fig. 6. Changes in current distribution over lead/acid plates of various heights. Average current density 0.069 A cm^{-2}; 1.30 S.G. H_2SO_4; ○, onset of discharge; △, 50% discharge; ×, 100% discharge.

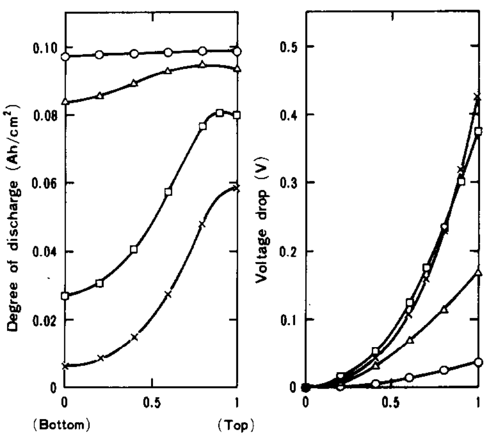

Fig. 7. Effect of lead/acid plate height on the distribution of the degree-of-discharge and voltage drop at the end of discharge. Average current density 0.069 A cm^{-2}; 1.30 S.G. H_2SO_4. Plate height: ○, 40 cm; △, 80 cm; □, 130 cm; ×, 160 cm.

this study, a cell with 0.9 cm thick tubular positive plates was analysed with a computer.

Figure 8 shows the effect of current-collector resistance on both the cell discharge curves and the degree of discharge of the plates. The data show that as the relative resistance of the current collector is reduced from 1 to 0.25, the discharge time increases by a factor of two. This is mainly because the bottom part of the plate can be utilized. The current-collector weight is more than 20% of the total cell weight, and if the former is increased fourfold, then the cell weight is increased by over 60%. Therefore,

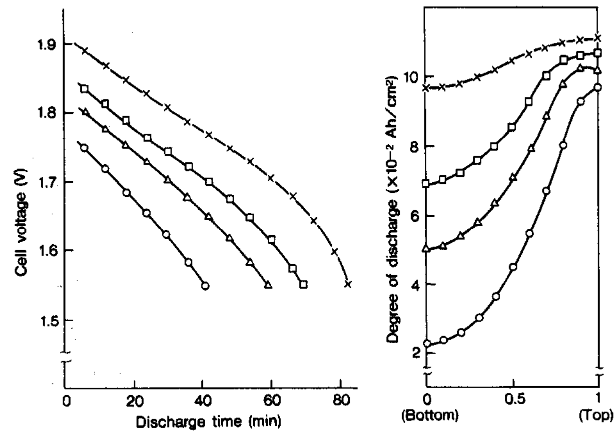

Fig. 8. Effect of collector resistance on lead/acid discharge curves and degree of discharge at the end of discharge. Average current density 0.076 A cm^{-2}; plate height 120 cm; positive tube diameter 0.9 cm; 1.28 S.G. H_2SO_4. Relative collector resistance: ○, 1.0; △, 0.67; □, 0.5; ×, 0.25.

an alternative method should be considered to accomplish high performance tall lead/acid cells.

The effect of the resistance design of the current collector on the discharge curves and the degree of discharge is shown in Fig. 9: the circles are for a collector of uniform resistance; the triangles are for a collector that has decreasing resistance toward the top in three steps; and the squares correspond to a tapered collector of continuously decreasing resistance toward the top. Although the latter two collectors improve the discharge performance, they exert little beneficial effect on the utilization of active

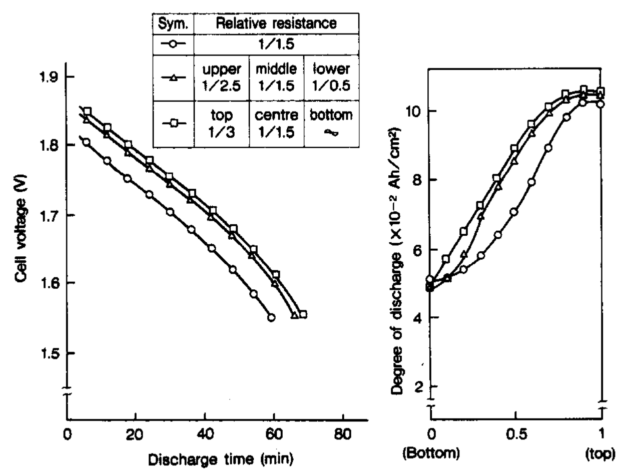

Fig. 9. Effect of collector shape on the lead/acid discharge curves and the degree of discharge at the end of discharge. Average current density 0.076 A cm^{-2}; plate height 120 cm; positive tube diameter 0.9 cm; 1.28 S.G. H_2SO_4. Collector shape: ○, uniform resistance; △, varying resistance in three steps; □, continuously varying resistance.

material near the bottom of the plate. Thus, these collectors have no significant effect on the discharge performance. Table 1 shows the relationship between the resistance design of the current collector and the discharge time, based on three-step variation of collector resistance from top to bottom and on the same total collector weight. There exists an optimum resistance ratio to achieve the maximum discharge time. Figure 10 shows the relationship between total weight of the current collector and the discharge time. Curve c corresponds to the optimum resistance design in a three-step variation that was evident in the data of Table 1. Curve b corresponds to the optimum design for continuously varying resistance determined in the same way. Although these optimum designs improve the discharge performance, their effect was below that expected. On the other hand, copper has a conductivity about twenty times greater than that of lead alloys, and if this metal can be used as a collector, the cell discharge performance will be markedly improved, as shown by curve d in Fig. 10.

TABLE 1

Relationship between collector shape and discharge time for cells with the same total collector weight
Plate height, 120 cm; positive tube diameter, 0.9 cm; H_2SO_4 of specific gravity 1.28

Relative resistance			Discharge time (% of that with no plate resistance)	
Upper	Middle	Lower	0.076 A/cm^2 discharge	0.026 A/cm^2 discharge
1/1.5	1/1.5	1/1.5	67.5	89.7
1/2	1/1.5	1	74.0	91.5
1/2.25	1/1.5	1/0.75	75.5	92.1
1/2.5	1/1.5	1/0.5	74.9	91.2

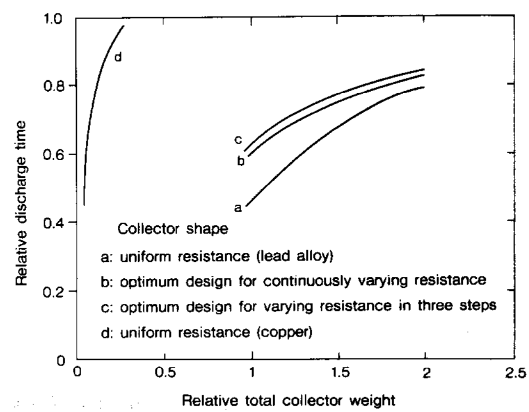

Fig. 10. Relationship between total collector weight and discharge time of the lead/acid cell. Average current density 0.076 A cm^{-2}; plate height 120 cm; positive tube diameter 0.9 cm; 1.28 S.G. H_2SO_4. Collector material: curves a - c, lead alloy; curve d, copper.

Figure 11 shows a computer-based calculation of the effect of a side conductor on cell discharge performance. In these cells, the side conductors have the same value, or half the value, of the plate resistance per unit height and are placed along the plates and connected to them at the top, centre and bottom. The data show that the side conductor has a prominent effect on improving the discharge performance. This is because the active materials near the connecting parts become appreciably used.

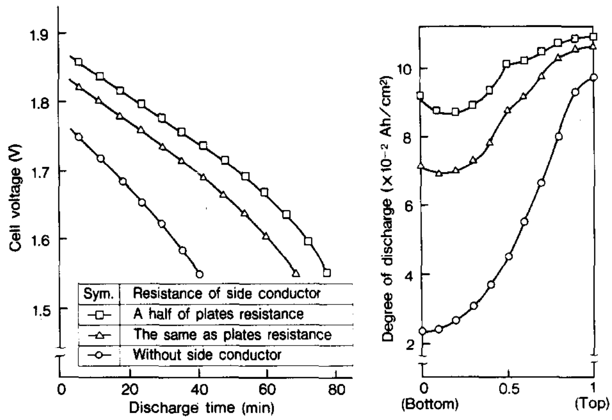

Fig. 11. Effect of a side conductor on the lead/acid discharge curves and the degree of discharge at the end of discharge. The side conductor is connected to the plate at the top, centre and bottom. Average current density 0.076 A cm^{-2}; plate height 120 cm; positive tube diameter 0.9 cm; 1.28 S.G. H_2SO_4.

Conclusions

For tubular positive-plate cells, calculated discharge curves (based on the analysis of changes in potential, current and discharge depth with progress in discharge) agree well with measured discharge curves. Computer analysis of plate parameters is considered to be an effective method for improving the discharge performance of tall tubular lead/acid cells.

References

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