Fast charging of lead/acid batteries

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Abstract

A key point in the development of storage batteries for electric vehicles (EVs) is the possibility for fast recharging. It is widely recognized that the lead/acid system represents an excellent candidate for EVs because of the low cost, durability, and expectance of improvements in the near future. The viability of the lead/acid battery for EV applications would be greatly enhanced if fast recharging could be applied to the system without shortening its life. The present paper reports the results obtained by simulating the charging behaviour with a mathematical model that is capable of predicting the behaviour of nonconventional lead/acid cells both on discharge and recharge. The effects of important parameters such as plate dimensions, acid distribution, and porosity of the active mass are taken into account. The data obtained with the simulation are compared with results got from fast-recharge testing of commercial batteries.

Introduction

The demand for electric vehicles (EVs) has grown noticeably in recent years, both because of the increased concern over environmental and energy problems and because of the achievement of significant goals in scientific and technological research. In addition, the introduction of EVs has been facilitated in some countries by the introduction of new specific laws. It is well known that EVs still suffer from two principal limitations: low autonomy and high cost. It is also widely recognized that the weak point, in spite of the significant efforts made in the last decade, is the lack of suitable batteries, that have good specific energy and power performance, long life, and low cost. It has been pointed out [1], however, that the lead/acid battery represents an excellent near-term candidate for EV applications.

A key point in the development of storage batteries for EVs is the possibility of fast recharging. The viability of the lead/acid battery for EV duties would be greatly enhanced if fast recharging could be applied to the system without shortening its life. During recharge, it is possible for valve-regulated batteries (VRBs) to experience a significant increase in the internal pressure (see Fig. 1) due to the evolution of a large amount of gas. This results in a continuous loss in battery weight and, after a certain number of cycles, the charge factor rises appreciably. This effect is shown in Fig. 2. In this case, the battery under test failed after 300 cycles (100% depth-of-discharge) because of drying out of the absorptive glass mat separator. A good recharge

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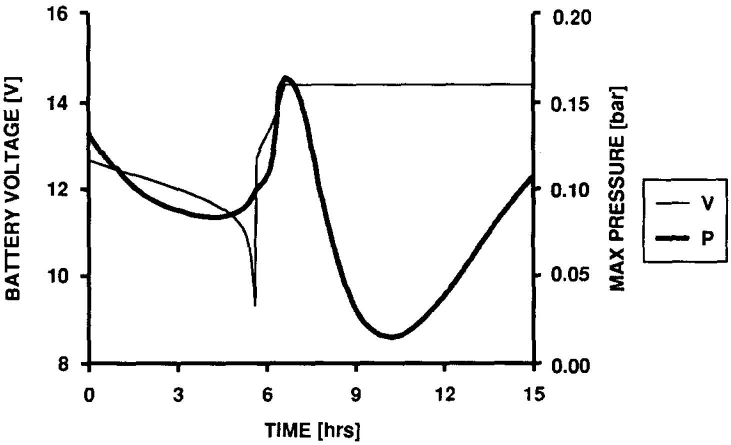

Fig. 1. Internal pressure increase during the charging process; $I_{max}=C_1$, $V_{max}=14.4$ V.

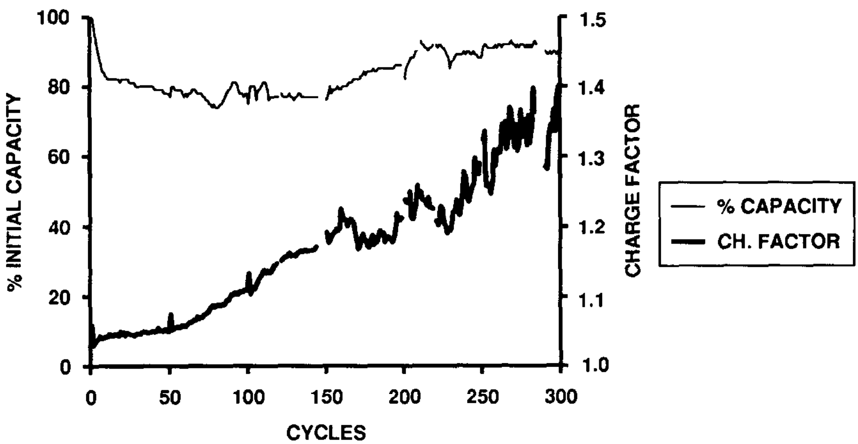

Fig. 2. Behaviour of capacity and charge factor during cycling.

system and optimization of some of the cell-design parameters can avoid or ameliorate the problem.

The use of simulation methods, in comparison with a pure experimental approach, has the advantage of reducing the time required for experiments through allowing the selection of specific tests. These tests are identified from extensive simulation trials of the effect of variations in many different parameters.

Experimental

The theoretical approach was based on a mathematical model that has been previously discussed [2]. This model has been improved in the present investigation to account for different charging modalities (step-charging) and gas reactions. For each run, simulation gives the following information: electric potentials in the solid and liquid phases; overvoltages (for charging and discharging reactions and for gas-evolution reactions); ionic and electronic current densities; faradaic efficiencies; acid concentration; porosity; degree of discharge.

In order to compare simulated and laboratory tests, a FIAMM valve-regulated stand-by battery (type MONOLITE 12SLA50) was chosen as the reference battery. The following characteristics of the reference battery were used in the calculations: capacity 660 Ah m^{-2}; acid concentration 5.26 mol l^{-1}; thickness of negative and positive plates 3 mm; thickness of separator 2 mm; porosity of separator 0.95.

Each cell in the battery was connected to a manometer in order to record continuously the internal pressure. A temperature probe was also used to monitor the internal temperature. The gas escaping from the valves was passed through a digital flowmeter.

The battery was subjected to various deep discharges (i.e., 100, 80 and 60%) and recharged at the same voltage with different current limits. Pulsed recharge was also investigated.

Results

A complete discharge at the *C*/20 rate was simulated in order to obtain the starting conditions for the charging tests. The discharge curves are reported in Fig. 3, where the initial porosity (ϵ) of the active mass has been introduced as a parameter. The possibility of changing the porosity is worth considering because it represents an area of technological improvement in the development of lead/acid batteries for EV applications.

Constant-current charging was simulated, starting from the conditions obtained in the previous discharge tests. Charging was terminated when the cell voltage reached the value of 2.4 V. Some of the simulated charging curves are reported in Fig. 4 for different porosity values.

The charge received by the cell as a function of the initial porosity of the active mass for different charging rates is given in Fig. 5. The charge has been computed up to the final voltage and takes into consideration the gassing reactions. It can be seen that, for low charging rates (*C*/10), the influence of porosity on the accepted charge is unimportant. For higher charging rates, an increase in porosity is beneficial. It should be noted, however, that the advantage of a porosity increase depends on the geometry of the battery; if the plate thickness is kept constant, increasing the

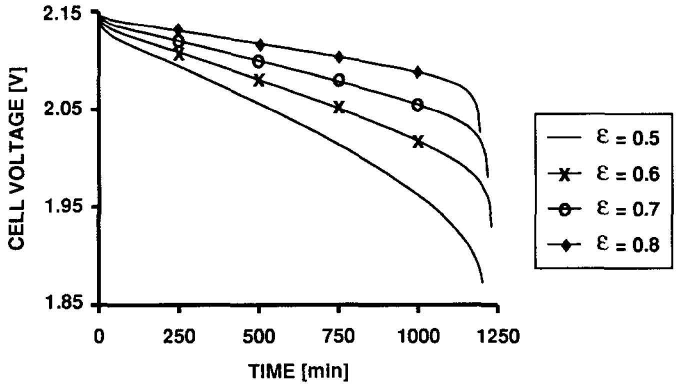

Fig. 3. Computed discharge curves (*C*/20) for different porosity values.

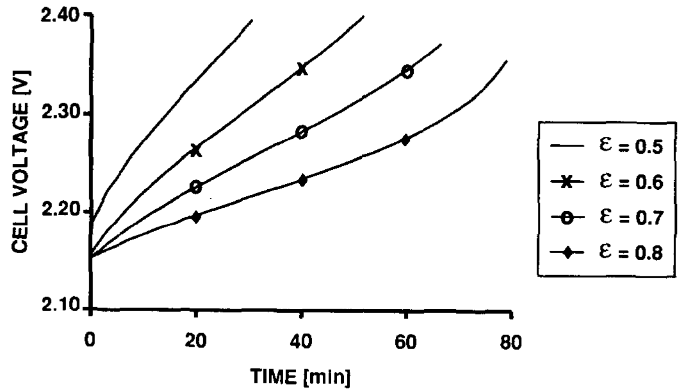

Fig. 4. Computed high-rate charging curves for different porosity values.

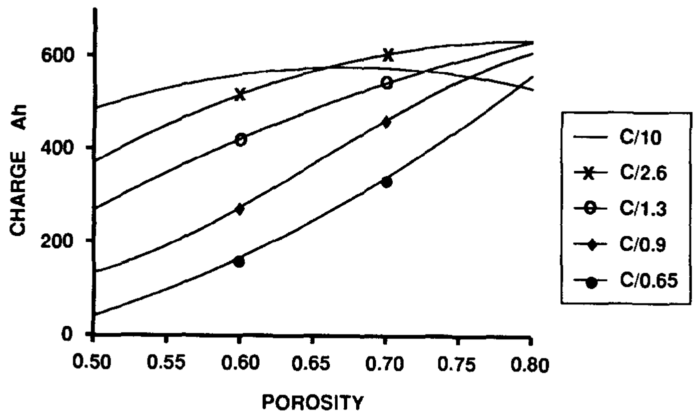

Fig. 5. Capacity of the model cell vs. active mass porosity for different charging rates.

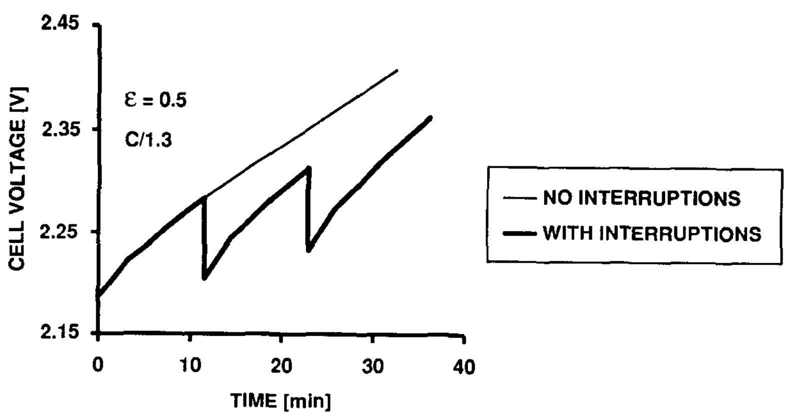

Fig. 6. Simulated charge curve with two interruptions.

porosity requires an increase in the plate surface area, in order to maintain the same total capacity of the battery. This results in a reduction of the current density referred to unit area of the plate surface.

Constant-current charging was modified by introducing a few interruptions during the procedure. This modification was introduced to reduce both the acid concentration gradients and the corresponding polarization. The results of the simulation of these interrupted tests for a porosity of 0.5 and for two charging rates is reported in Fig. 6. The cumulative results are indicated in Fig. 7.

Multistep charging at different currents has also been simulated. The results are shown in Fig. 8. Here, the curve for a test that includes a rest period at the end of each step is also given. Multistep charging was also tested on a 50-Ah, 12-V VRB with the target of a quick recharge at the highest efficiency without damage to the battery. The system was also simulated for batteries under different states-of-charge. The value of the constant current and the voltage limits for each step were chosen following an examination of the increments in internal pressure and gas evolution. The preliminary results obtained with this charging method are reported in Table 1

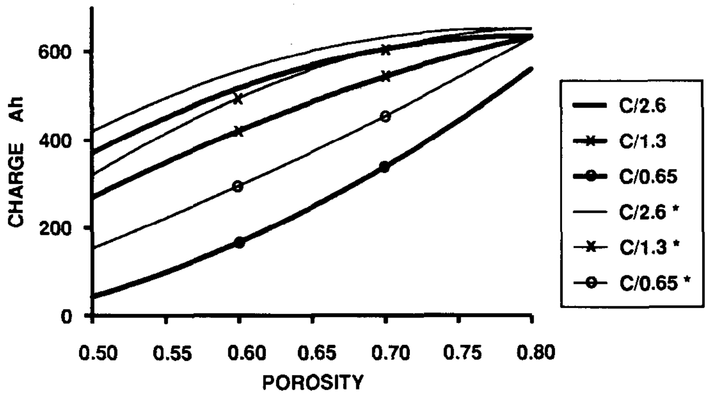

Fig. 7. Capacity of the model cell vs. active mass porosity for continuous and interrupted (*) charge.

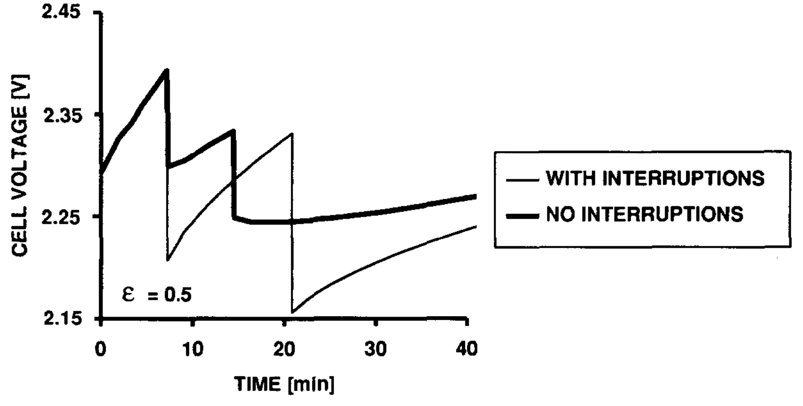

Fig. 8. Simulated multistep (800/500/250 A) charge with and without interruption at end of each step.

TABLE 1

Gas evolution under different charging conditions

Charging method	Discharge (%)	Charge current (A/Ah)	Charge to 107% (min)	Evolved gas (cm^3)
IU	100	0.8	377	2000
Pulse	100	0.9	355	500

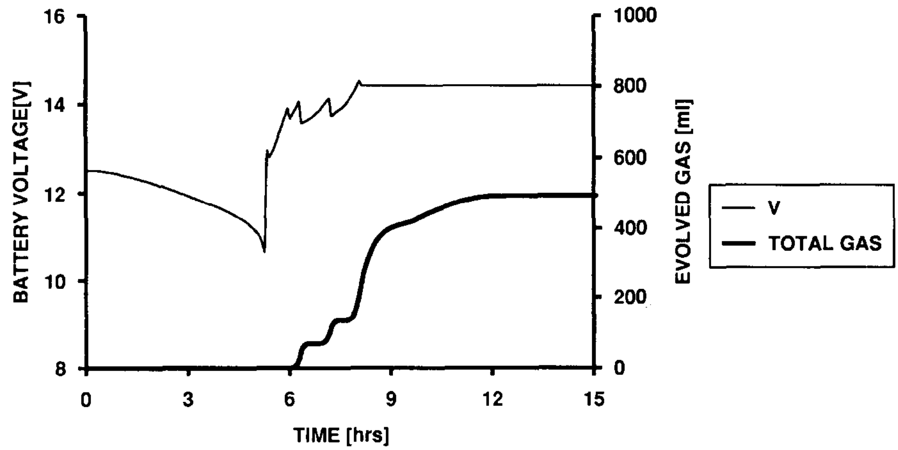

Fig. 9. Cumulative gas evolution during pulse charging.

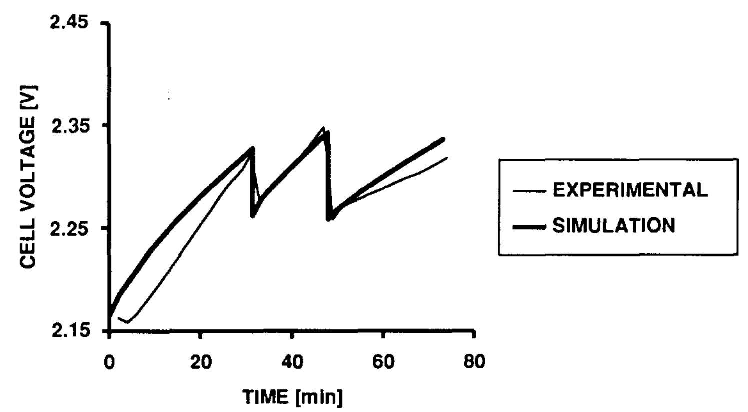

Fig. 10. Comparison of a simulated and experimental multistep charge curve for a 50-Ah cell.

and displayed in Fig. 9. The data indicate the possibility of recharging more than 50% of the capacity in the first 30 min, and 107% in less than 6 h, with very low gas emission.

The validity of the simulation method was verified by comparing the experimental data of a charge test with three current steps with that predicted by the simulated curve, Fig. 10. Very good agreement between the experimental and computed data was observed.

Conclusions

The following preliminary conclusions can be drawn from the simulated and laboratory tests reported here.

1. The mathematical model is a useful tool for investigating the charging conditions of the lead/acid battery. This is because, on the one hand, it notably shortens the time required for laboratory testing and, on the other hand, it can yield interesting information on the performance of systems that are not yet commercially available because of technological limitations.

2. Both increasing the porosity of the active mass and applying step charging have been examined as possible methods for the development of lead/acid systems with fast-charging capabilities. In particular, the increase of porosity, which according to the present technology is <0.6, can be regarded as an interesting means for obtaining charging characteristics suitable for EV applications.

References

1 J.F. Cole, *J. Power Sources, 40* (1992) 1–15.
2 M. Maja, G. Morello and P. Spinelli, *J. Power Sources, 40* (1992) 81–91.