CURRENT DISTRIBUTION OVER THE ELECTRODE SURFACE IN A CYLINDRICAL TYPE VRLA CELL DURING DISCHARGE

P. Křivák, P. Bača, P. Bocek

Faculty of Electrical Engineering and Communication Technologies, Brno Technical University

Abstract

The current distribution on the surface of lead-acid accumulator electrodes during discharge was determined mathematically for a cylindrical type cell for hybrid electric vehicles by using an equivalent electrical circuit. The dependence of the internal resistance on the current and on the charge passed was determined by measurements on an experimental cell. The results are presented in the form of 3-D diagrams for different states of discharge.

Results and discussion

As a continuation of our past research work on the modelling of current distribution on the surface of standard lead-acid battery plate electrodes in the course of discharge for various configurations of the current tabs [1], we used a similar model also for a cylindrical type VRLA cell designed for hybrid electric vehicles. The unrolled cell electrodes are shown in Fig. 3. The equivalent electrical circuit corresponding to an elementary cell is shown in Fig. 1. We have shown that our method can successfully be applied [1] even to the case where the constant discharge current causes changes in the internal cell resistance.

The internal resistances, Rv_k, between the cell elements depend on the discharge current, I, and on the charge passed, Q. The course of this functional dependence was determined on a laboratory cell for various discharge currents. The values of Rv_k involving the electrolyte resistance, contact resistance between the lead grid and the active mass, the active mass resistance, and the polarization resistance were fitted by the following exponential function by using the least squares method:

$$Rv_k = 3.18 + 23000 \times QI + 1.5\times10^{-11} \exp(4565Q + 2556I - 28) \qquad (1)$$

The elementary resistances of the positive and negative grids were determined as follows:

$$R_x^+ = 4.33 \times 10^{-3}\ \Omega \qquad R_y^+ = 1.732 \times 10^{-3}\ \Omega$$
$$R_x^- = 3.215 \times 10^{-3}\ \Omega \qquad R_y^- = 9.285 \times 10^{-4}\ \Omega \qquad R_{xo} = 4.48 \times 10^{-4}\ \Omega \qquad (2)$$

where R_x denotes the resistance of a horizontal rib section of 4 mm in length, R_y the resistance of a vertical rib section, 10 mm in length, and R_{xo} resistance of a frame section of 4 mm in length.
With the positive electrode, the contribution of the active mass to the conductivity of the grid is only slight. However, with the negative electrode, the contribution of the active mass

to the grid conductivity is considerable and therefore it must be taken into account in the calculations.
It has been found that the conductivity of the negative active mass decreases during the discharge approximately in a linear fashion. Thus, the dependence of the elementary resistances of the negative electrode on the charge passed may approximately be expressed as

$$R_x^- = 1/(310 - 4570Q), \qquad R_y^- = 1/(1077 - 28547Q) \qquad (3)$$

After application of the first and second Kirchhoff laws to nodes and loops of the whole equivalent circuit, we obtain a system of linear equations whose solution gives the sought distribution of local potentials and currents. Since the resistances are time-dependent, the calculations were performed in the following steps:

Step 1: $i = 1$, $t_1 = 1$ s, $\Delta t_1 = 1$ s. The initial value of $R_1 = 3.18\ \Omega$ is the same for all elements of the internal resistance Rv_k and the distribution of the potentials in the nodes of the equivalent circuit is calculated. The node potentials of the k-th element, V_k^1 and W_k^1, are used to calculate the corresponding voltage and current:

$$U_k^1 = V_k^1 - W_k^1, \qquad I_k^1 = U_k^1/R_k^1 \qquad (4)$$

The charge passed through the k-th element is calculated from the current as

$$Q_k^1 = I_k^1 \times \Delta t_1 \qquad (5)$$

Step 2: $i = 2$, $t_2 = 160$ s, $\Delta t_2 = t_2 - t_1$. The internal resistance corresponding to the k-th element is calculated from eq. (1). Afterwards the node potentials are calculated and from these the corresponding values of voltage and currents are determined as in step 1. The charge passed through the k-th element is then calculated as

$$Q_k^2 = Q_k^1 + I_k^2 \times \Delta t_2 \qquad (6)$$

The calculations are continued according to step 2 up to the value of $t_n = 15900$ s (100% state of discharge).

The time step of $\Delta t = 159$ s is suitable since the errors due to linearization are negligible. Higher values of the time step cause higher linearization errors, and lower values lead to a sensible increase of the calculation time.
The results of the calculation of the current distribution over the electrode surface are shown in the form of 3-D diagrams in Figs. 4 – 8 for values of Q corresponding to 0, 60, 85, 95, and 100% of discharge. The current values plotted correspond to an electrode element (*cf.* eq. (4)). The total current was $I = 4$ A and the discharge capacity $C = 17.66$ Ah.
It is apparent from Figs. 4 – 8 that, at the beginning of discharge, the regions close to the current tabs are most appreciably loaded with the current, especially in the central region of the cylindrical cell where the tabs are closer to one another. (Note that the tabs of the positive grid are shifted against those of the negative.) Therefore, these regions are discharged first and due to this fact their internal resistance attains its highest value. Since the discharge current is kept constant, the decreasing current density in the regions of increasing internal resistance leads to a current density increase in the other regions, especially in the last stage of discharge. This behaviour leads to gradual exploitation of all regions of the electrodes, as the discharge continues. Nonuniformity of the current distribution in the cylindrical cell increases considerably close to the end of discharge.
For comparison, analogous calculations were performed for the case where extended current tabs are located at opposite ends of the electrodes (see Fig. 9). In this case the current distribution during discharge is uniform over the whole electrode area.

Conclusions

At present, our work continues to evaluate the computational data characterizing the distribution of the resistance, and charge for the unrolled model of the studied cylindrical cell during discharge. In addition, model of the cell with extended current tabs located at opposite ends of the electrodes gives a more uniform current distribution over the electrode area.

Acknowledgement

This work was supported by the Advanced Lead-Acid Battery Consortium (Project No. N4.2), a program of the International Lead Zinc Research Organisation and the Grant Agency of the Czech Republic (Grant. No. 102/02/0794).

References

1. P. Král, P. Křivák, P. Bača, M. Calábek, K. Micka: *J. Power Sources* **105** (2002) 35 - 44.

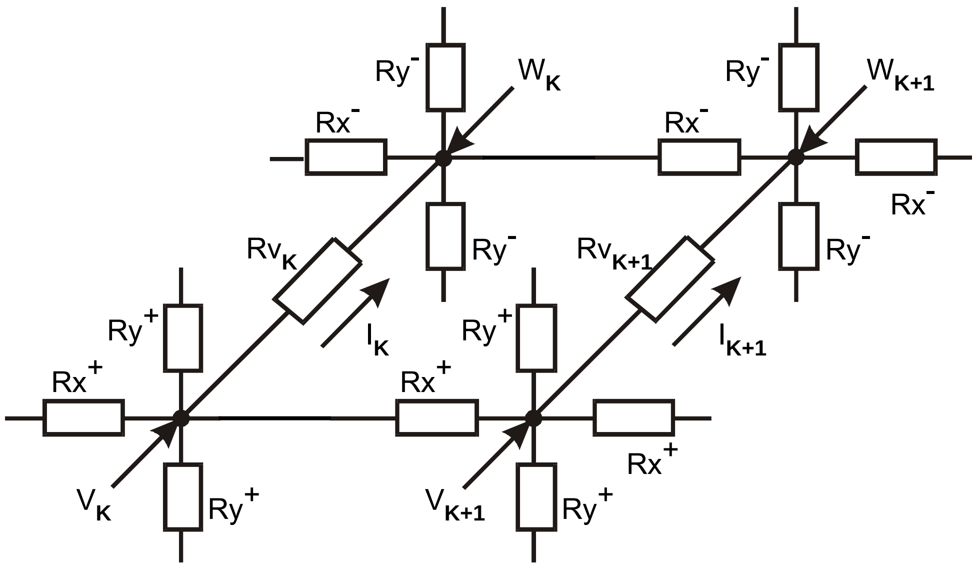


Fig. 1. *Part of electrical equivalent circuit used to calculate the current distribution over the electrode surface.*

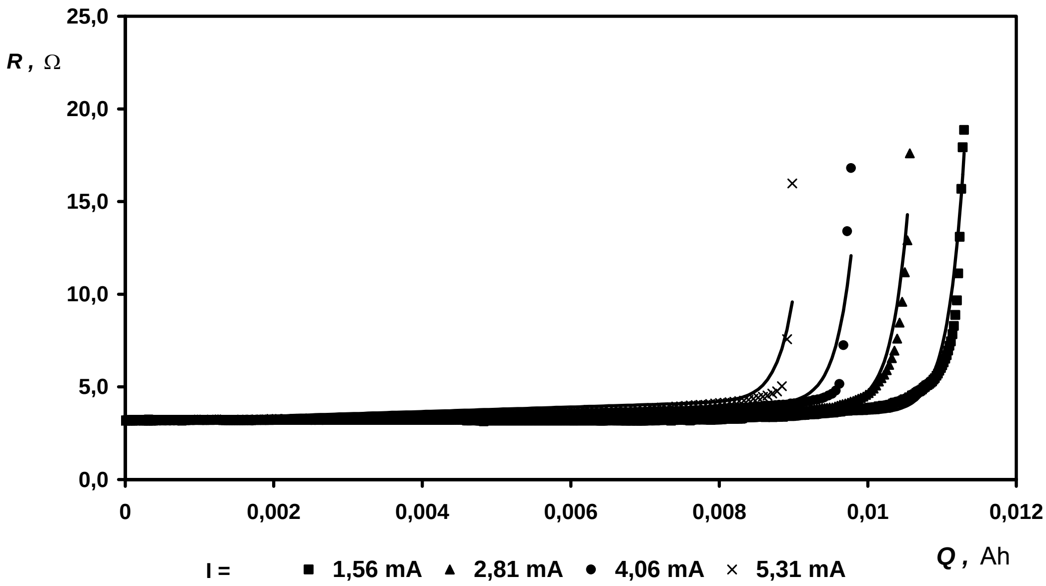


Fig. 2. *Dependence of internal resistance of an electrode element (a grid window) on the charge passed at discharge currents varying from 1.56 to 5.31 mA. The experimental points were fitted by the regression function (1).*

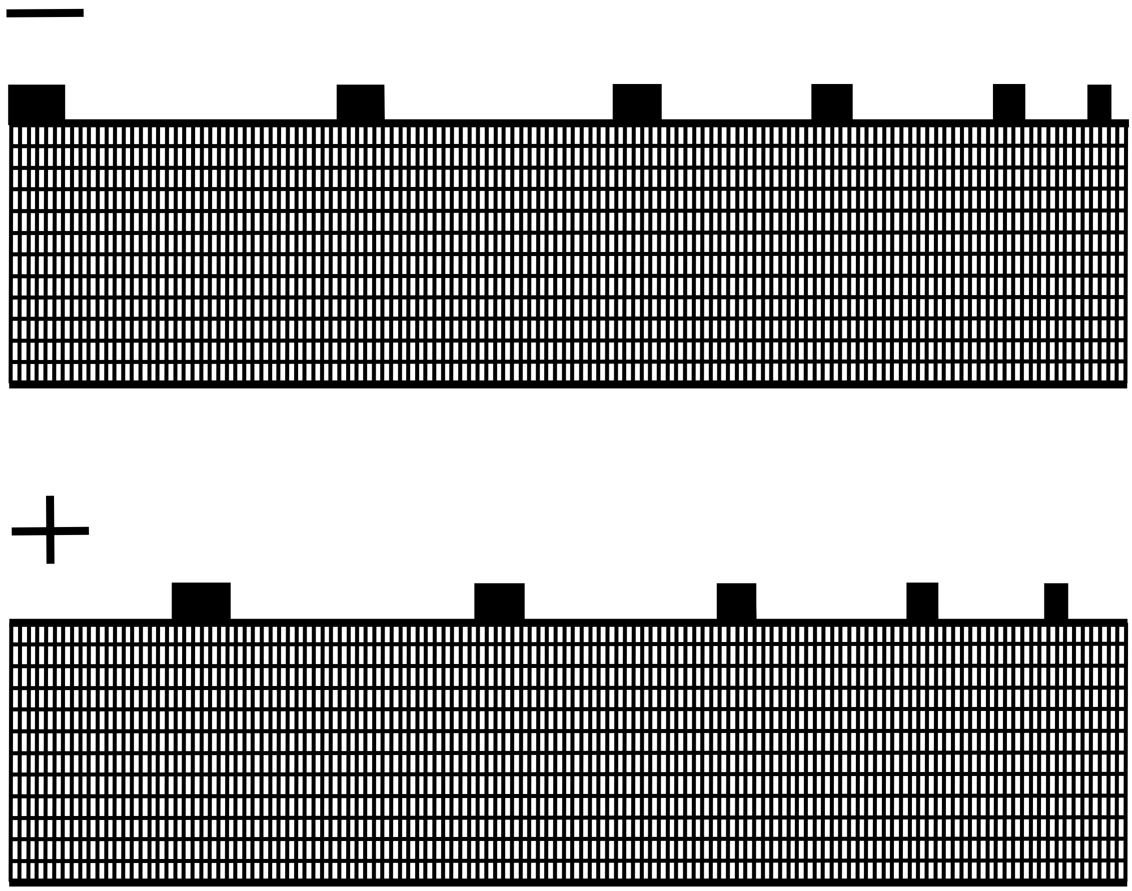
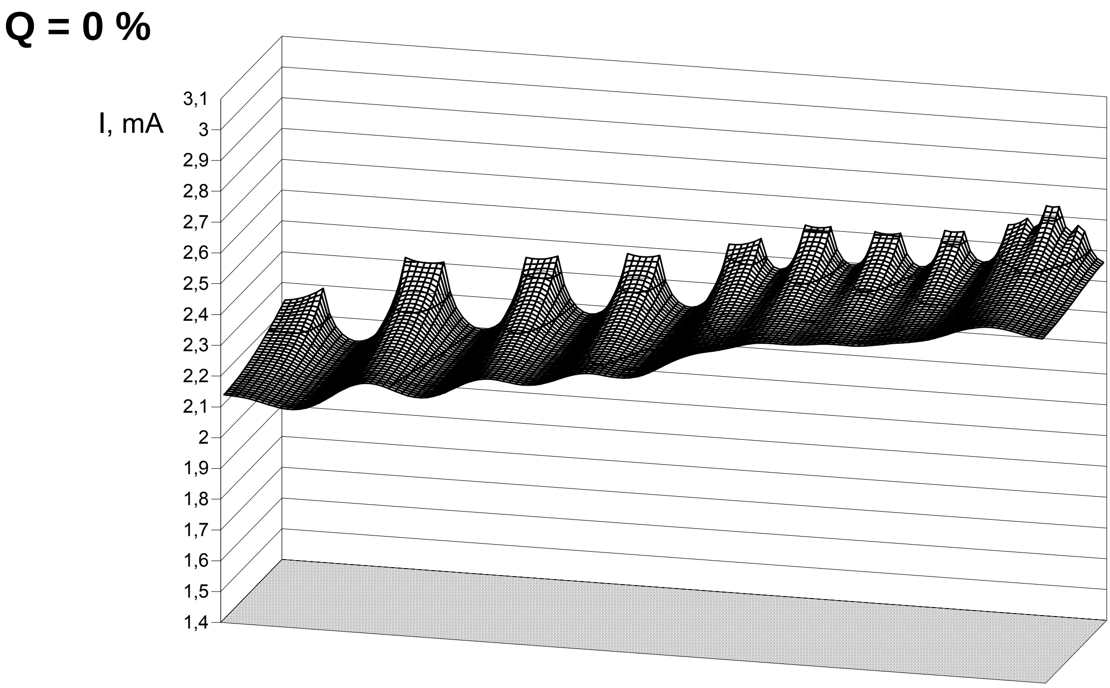


Fig. 3. *Unrolled model of cylindrical cell. Top: negative electrode, bottom: positive electrode.*



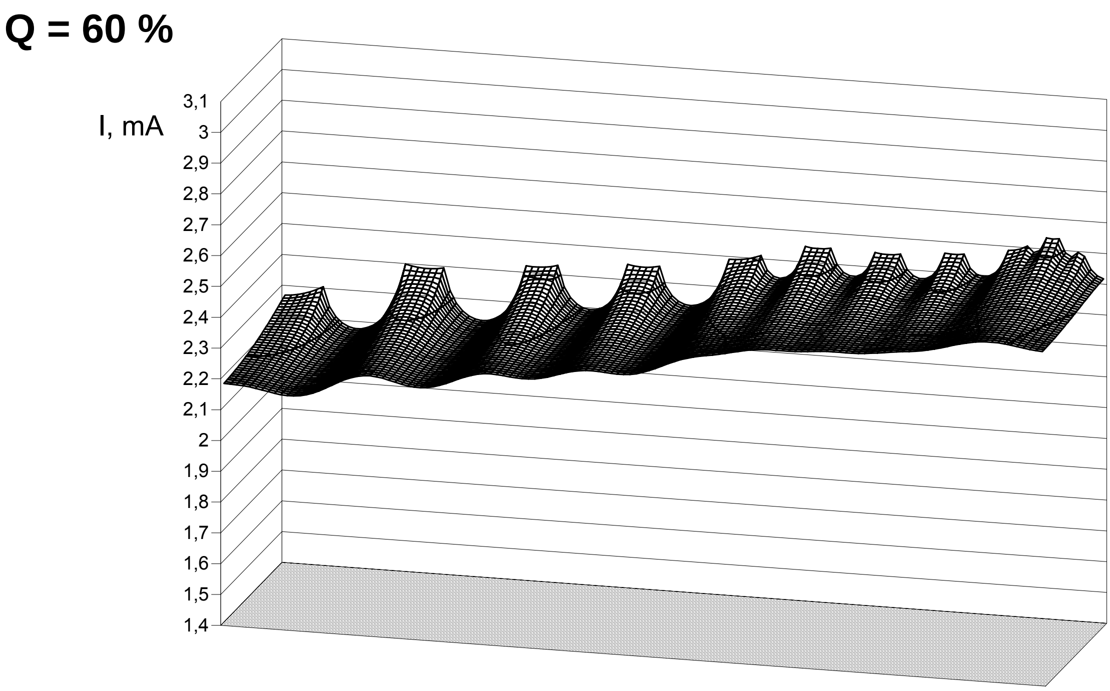
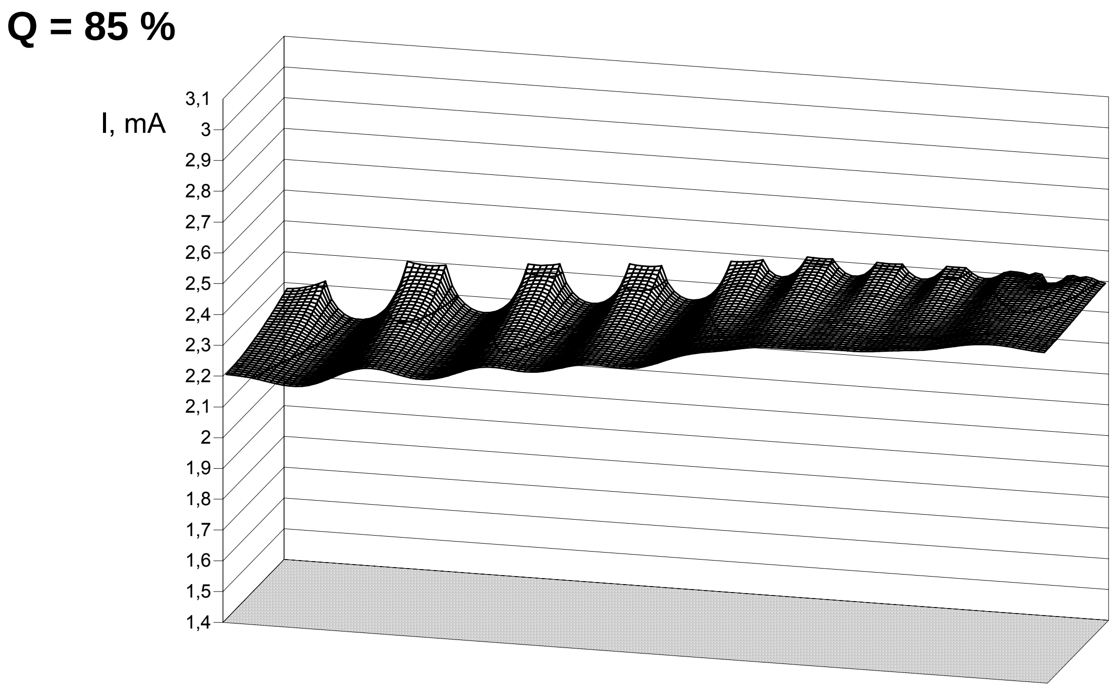


Fig. 4-5. *Current distribution for an unrolled cylindrical type cell. Discharge state Q = 0% and 60%.*



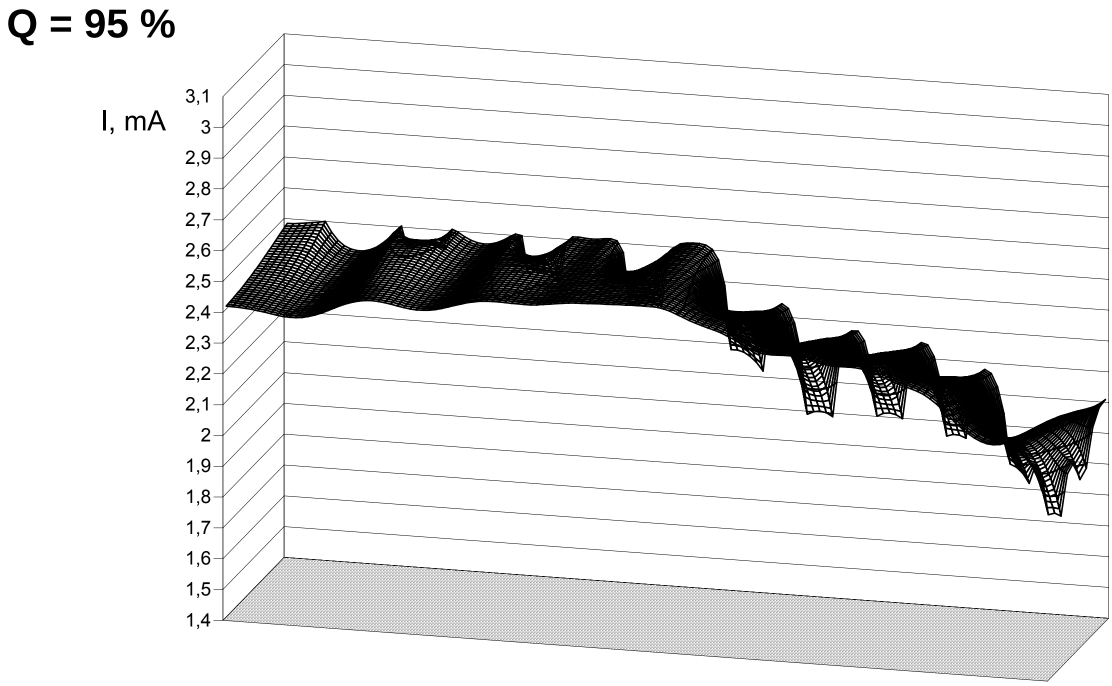


Fig. 6-7. *Current distribution for an unrolled cylindrical type cell. Discharge state Q = 85% and 95%.*

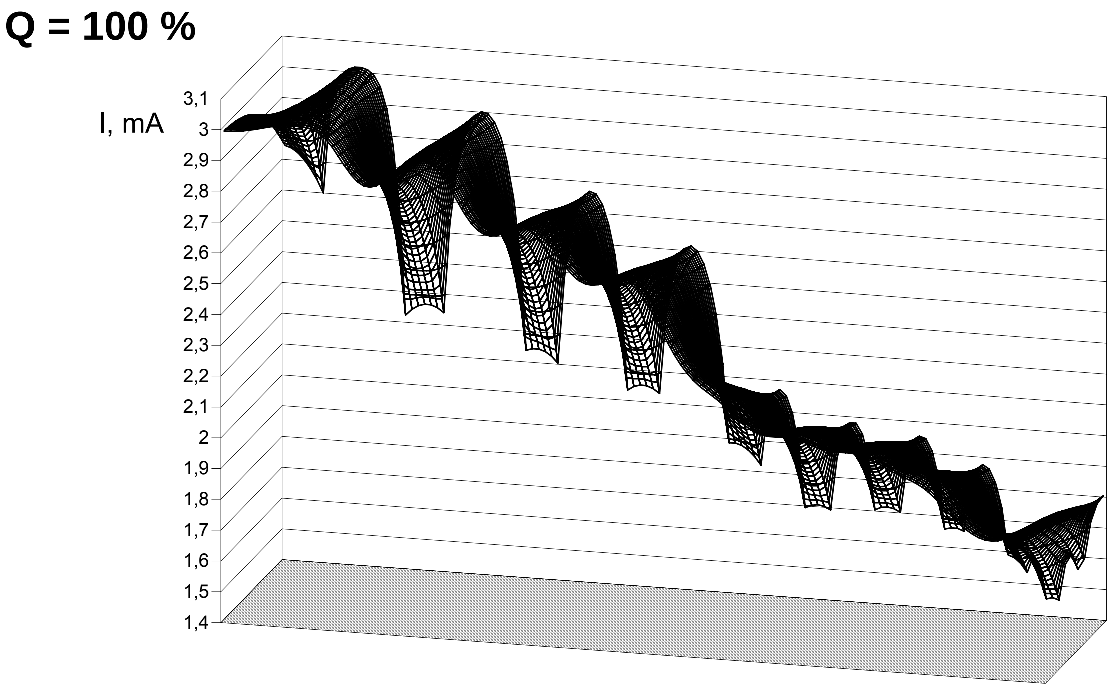


Fig. 8. *Current distribution for an unrolled cylindrical type cell. Discharge state Q = 100%.*

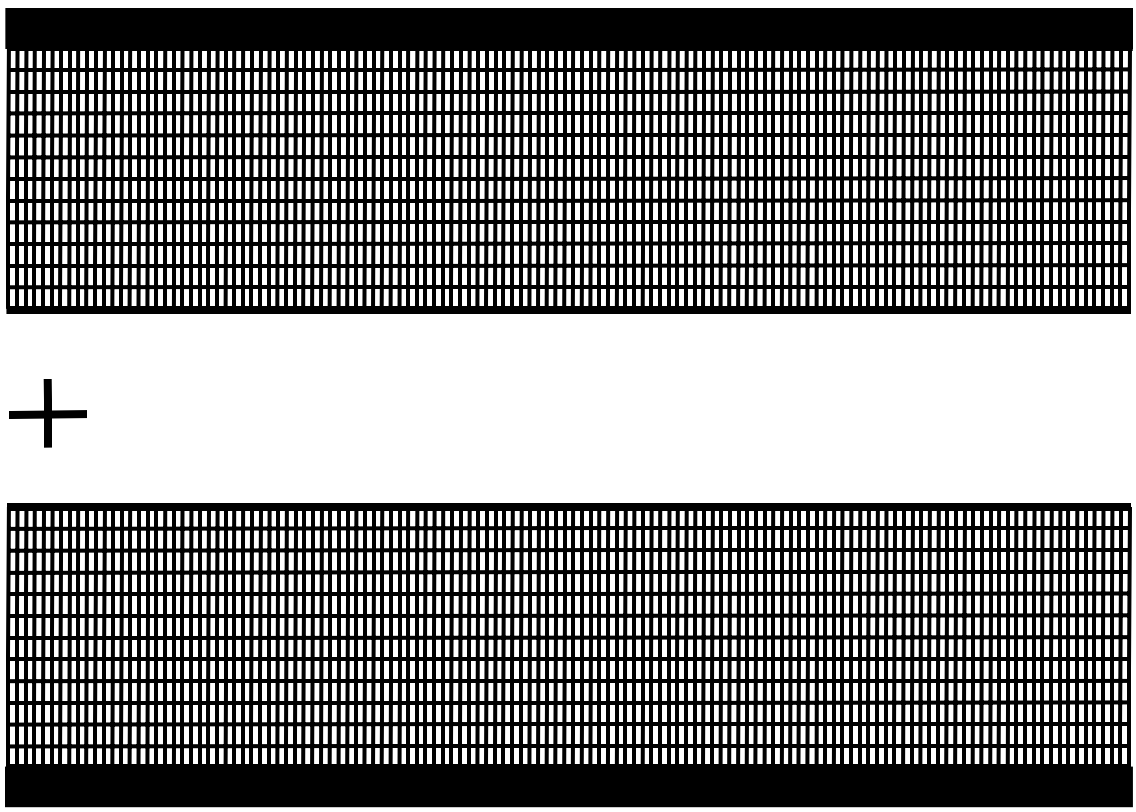
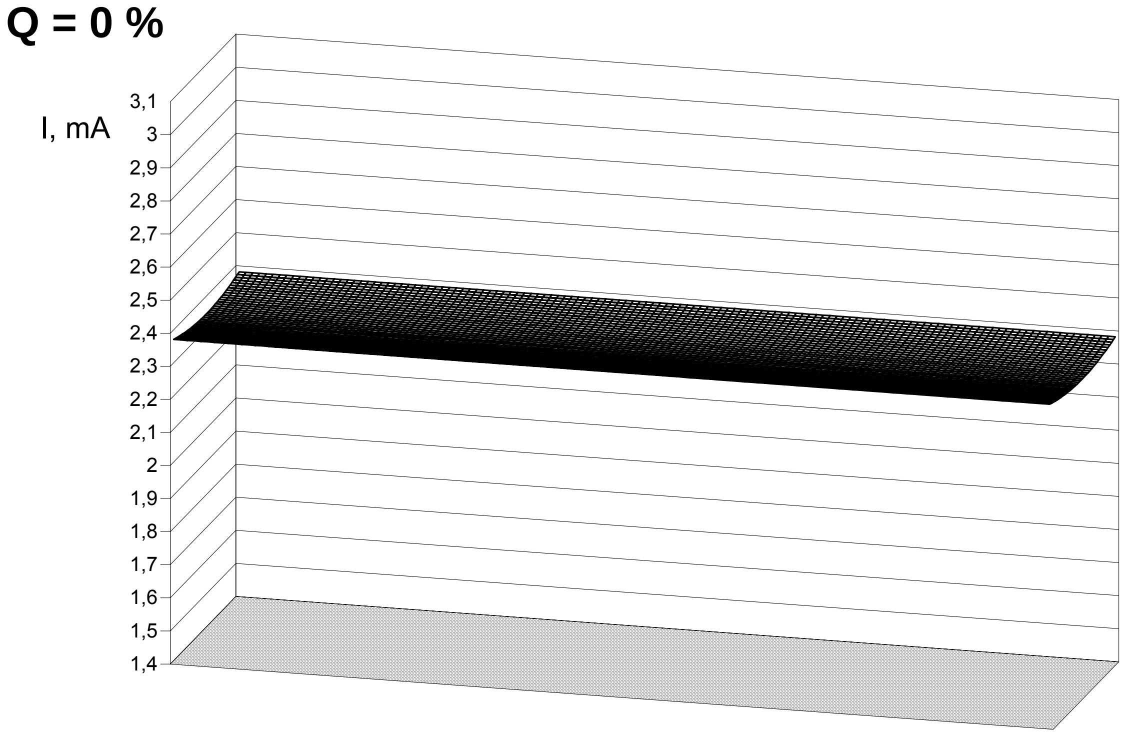


Fig. 9. *Unrolled model of cylindrical cell with extended tabs located at opposite ends of the plate electrodes. Top: negative electrode, bottom: positive electrode.*



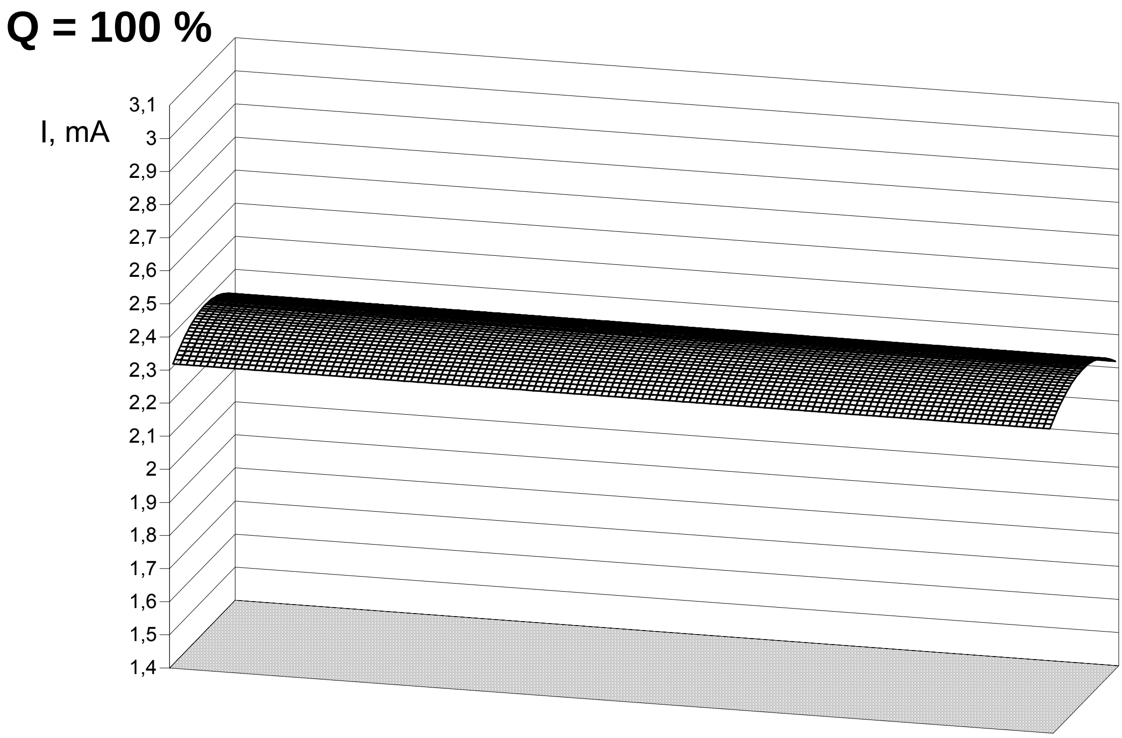


Fig. 10-11. *Current distribution for an unrolled cylindrical type cell with extended tabs located at opposite ends of the plate electrodes.*
Discharge state Q = 0% and 100%.