19th Asian Battery Conference& Exhibition

Optimization of grid configuration by investigating its effect on positive plate of lead acid batteries via numerical modelling

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New applications of Lead Acid Battery (EFB)

Higher discharge rates during their lifetime

Ohmic voltage losses become more important in current collecting system

It is known that Plate grid play the main role for passing the current through the plate so the grid plate design optimization is the most important item to decrease Ohmic voltage losses in current collecting system.

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Each grid of SLI (starting, lighting, and ignition) battery is usually made of two sections

1-Rectangular frame surrounded a network of wires

2-Lug on top of the frame basically used for carrying the current in or out of the plate

During the discharge or charge process, electric current generated or applied,moves through both lug and grid wires in opposite directions and ohmic voltage losses in current collecting system become more important.

The configuration of grid wires and location of lug play an important role in minimizing the ohmic drop that will provide:

Uniform current distribution

More reaction sites on the electrode

Numerical methods have been employed to investigate the effect of 4 different parameters on the performance of positive electrode of lead-acid batteries via modeling the current and potential distribution through gird wires, active material and adjacent electrolyte to the surface of each grid as below:

- A. Grid configuration
- B. Lug position
- C. Diagonal wire angles
- D. Tapering wires towards the plate's lug

Theory

The molar flux of a charged species (j) in an electrolyte arises from three transport mechanisms:

1. i.e. migration
2. i.e. diffusion
3. i.e. convection

$$N_j = -z_j \mu_j F C_j \nabla \Phi - D_j \nabla C_j + C_j v$$

The total ionic current density (i) is given by assigning the charge to flux of each species and summing over all species

$$i = F \sum_j z_j N_j$$

$$i = -F^2 \nabla \Phi \sum_j z_j^2 \mu_j C_j - F \sum_j z_j D_j \nabla C_j + F v \sum_j z_j C_j$$

Parameter	Definition
N_j	Ionic flux
z_j	Charge
μ_j	Ionic electrochemical mobility
F	Faraday's constant
C_j	Concentration
∇	Differential operator
Φ	Electrostatic potential outside the electric double layer
D_j	Diffusion coefficient
v	Bulk average fluid velocity

The following electrochemical reaction takes place at the positive electrode during charge and discharge

$$PbSO_4 + 2H_2O \leftrightarrows PbO_2 + SO_4^{2-} + 4H^+ + 2e-$$

The equilibrium potential of the half-cell can be calculated regarding to below equation:

$$E_{PbO_2/PbSO_4} = 1.683 - 0.118\,pH - 0.059 \log a_{H_2O} + 0.029 \log a_{SO_4^{2-}}$$

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We considered some other key parameter in designing battery plates

1-The (α) ratio between the grid weight (Wgrid) and the active mass weight (W_{PAM}).

$$\alpha = W_{grid}/(W_{PAM} + W_{grid})$$

The value of α varies between 0.35 and 0.60, with a tendency to reduce this value as much as possible, as the plate capacity depends on the amount of active mass contained.

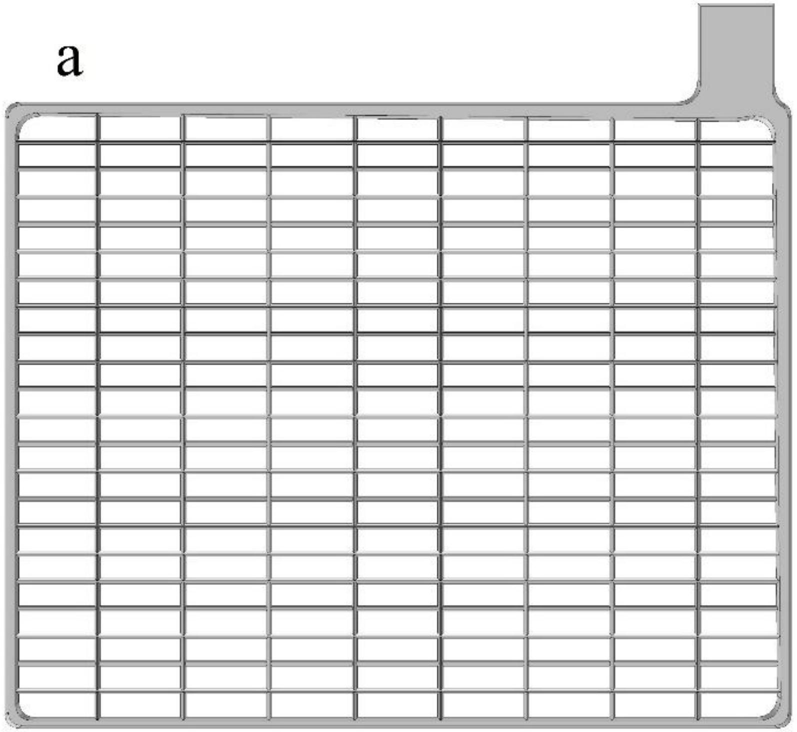
2-The (γ) ratio which accounts for the critical role of the grid-PAM interface under deep-cycling duty. The γ coefficient reflects the amount of active mass per square centimeter of grid surface (Sgrid) (g of PAM per cm2 of grid collector surface).

$$\gamma = W_{PAM}/S_{griD}$$

It is worth mentioning that the lower γ value causes the more grid surface and therefore the lower current density in high rate discharge.

A-Grids configuration : 6 different grid design were considered as below

a



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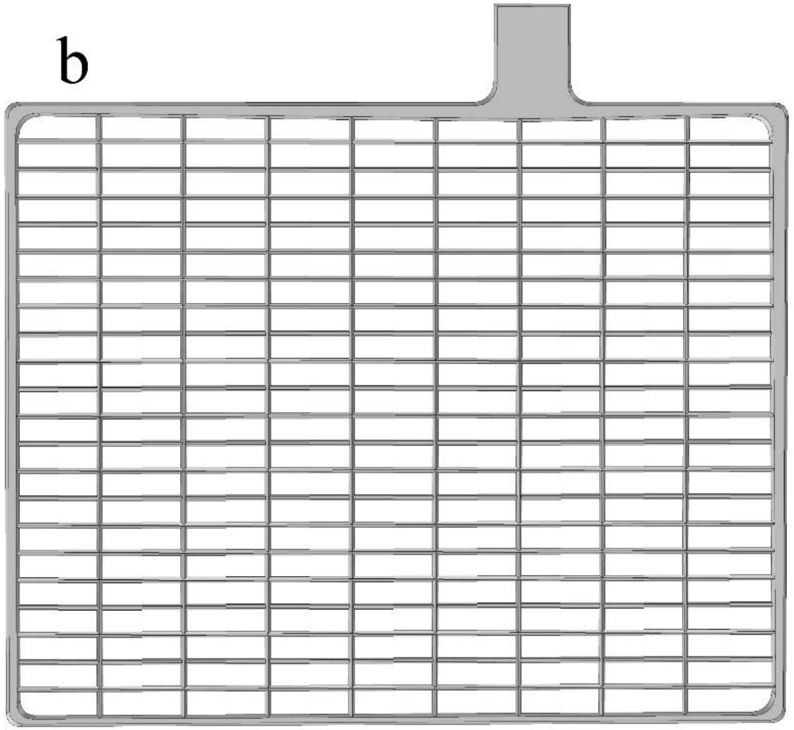


A: Conventional Side-lug grid:

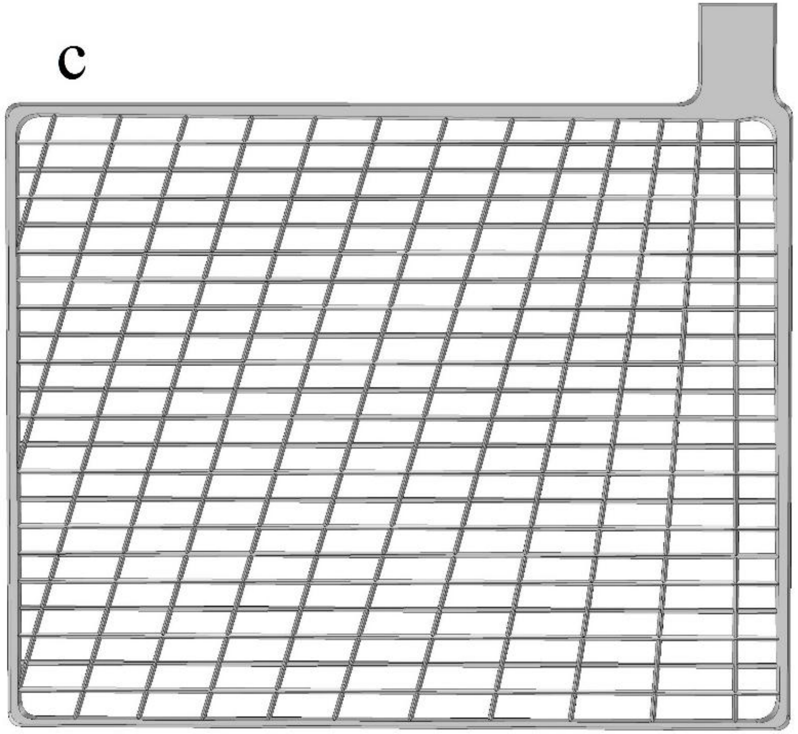
Consisting of interconnected vertical and horizontal wires encompassed by a rectangular frame with a lug located nearly on the top right corner of the frame.

B: conventional middle lug grid:

Has the same design as the previous one except that the lug is closer to the midpoint of the frame which results in shortening the electric current path from the most part of the plate to the plate lug and is expected to reduce the voltage drop.

A-Grids configuration : 6 different grid design were considered as below

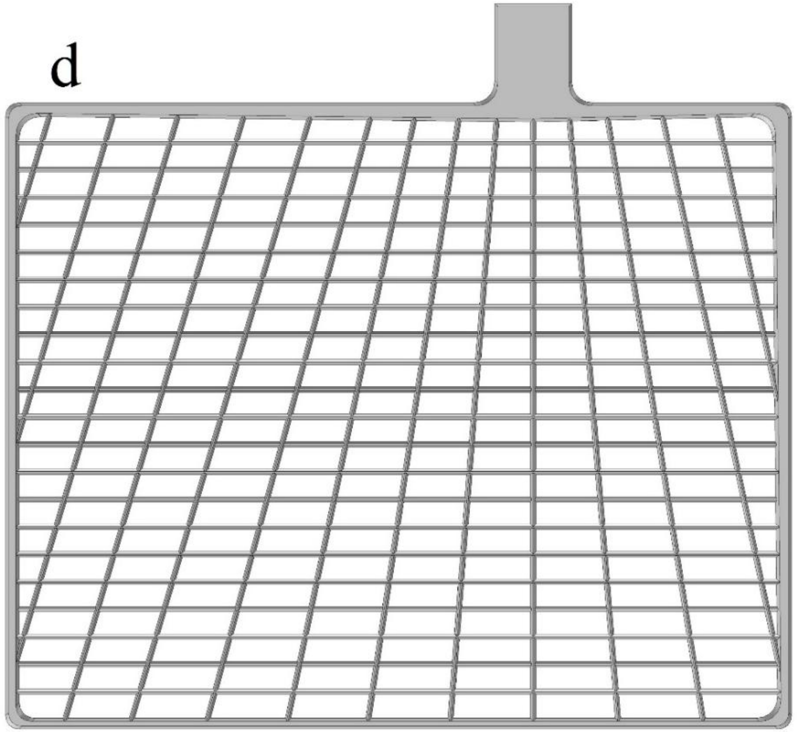
c



C: **Diagonal Side-lug grid:**

Consists of parallel horizontal wires which are crossed by a series of skewed wires headed toward the lug and to improve the current collecting ability.

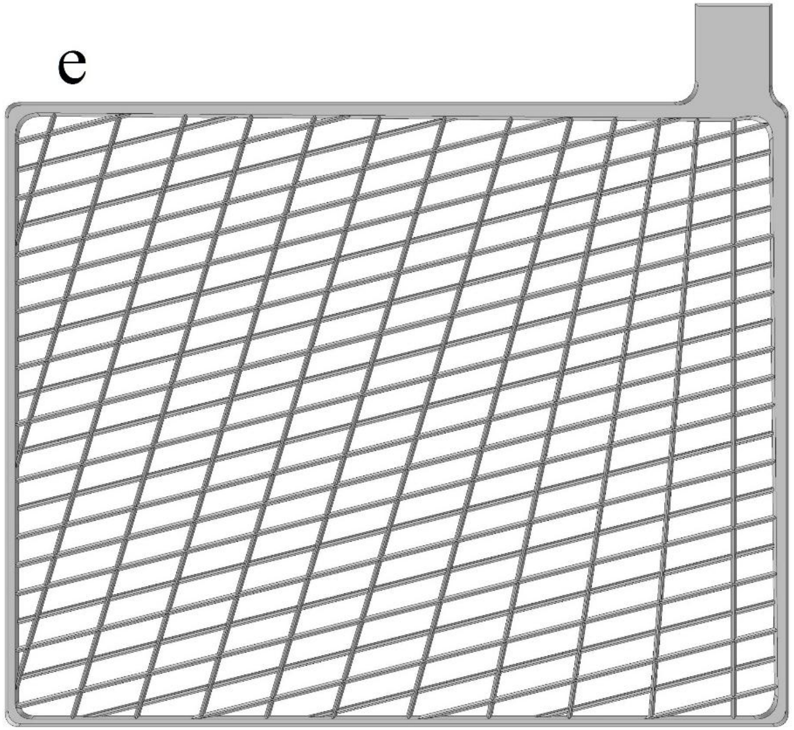
d



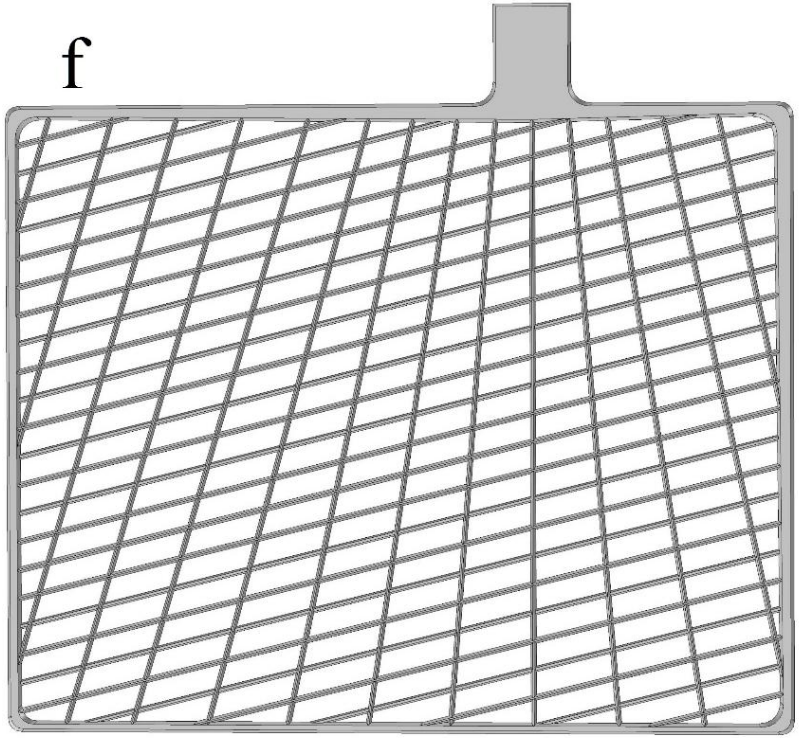
D: **Diagonal Middle-lug grid:**

Designed with same horizontal and diagonal vertical wires except that they headed toward the middle-positioned lug.

A-Grids configuration : 6 different grid design were considered as below



E: Double-diagonal Side-lug grid :
Consisting of skewed wires but horizontal wires transformed to parallel diagonal wires which is expected to reduce ohmic drop; this design is called double-diagonal side-lug grid.



F: Double-diagonal Middle-lug grid:
Presents doubled-diagonal middle lug design.

The dimensions of the frame and lug as well as thickness of the lug are similar in all cases for eliminating any possibilities for unfair comparison between models.

The conductivity and density of lead and lead dioxide are allocated to grid and active material are similar for all modles.

The models are designed in a way that mass of each grid as well as α parameter are practically equal for all grid configurations.

All models have same PAM weight 97.5g and same α value of 0.361

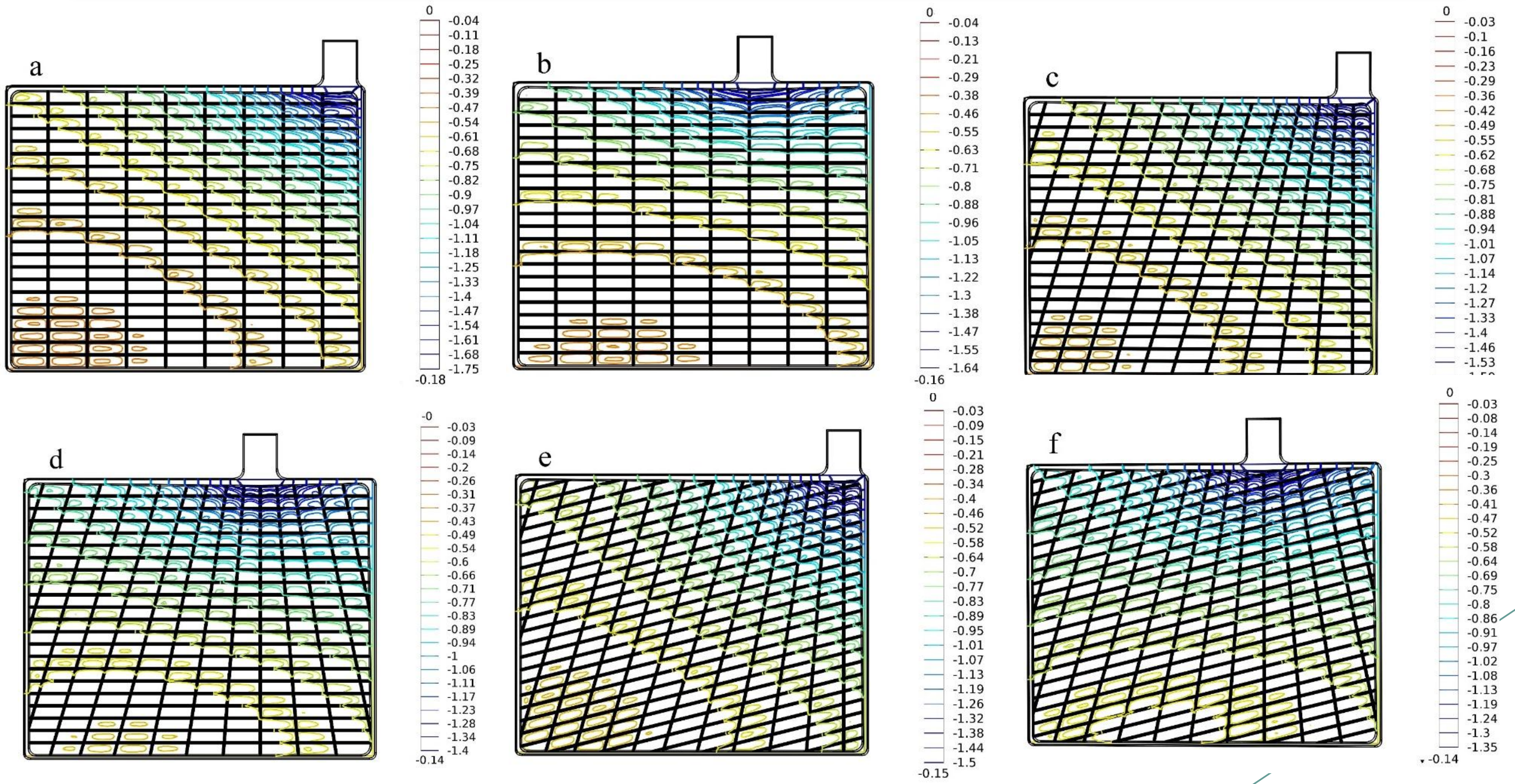
The specifications of six described models are as below Table.

Design Code	Models*	Grid Weight (g)	γ $\gamma = W_{PAM}/S_{grid}$
A	Conventional Side-lug	54.77	0.77
B	Conventional Middle-lug	54.79	0.77
C	Diagonal Side-lug	54.38	0.71
D	Diagonal Middle-lug	54.6	0.70
E	Double-diagonal Side-lug	55.01	0.69
F	Double-diagonal Middle-lug	55.23	0.69

Regarding to same PAM weight for all designs ,The lower γ value means the more grid surface and therefore the lower current density in high rate discharge.

A-2-1-Effect of grid configuration on Electrodes Potential distribution

With employing Comsol software, a 3D numerical model has been developed to investigate the potential distribution in the six different grid configurations and the results are as below :



A-2-1-Effect of grid configuration on Electrodes Potential distribution

Design Code	Models	E_{min} (V)	E_{max} (V)	ΔE (V)
A	Conventional Side-Lug	-0.19	-0.04	0.15
B	Conventional Middle-Lug	-0.18	-0.04	0.14
C	Diagonal Side-Lug	-0.18	-0.05	0.13
D	Diagonal Middle-Lug	-0.14	-0.05	0.09
E	Double-diagonal Side-Lug	-0.17	-0.05	0.12
F	Double-diagonal Middle-Lug	-0.14	-0.05	0.09

Maximum and minimum potential values for different configurations

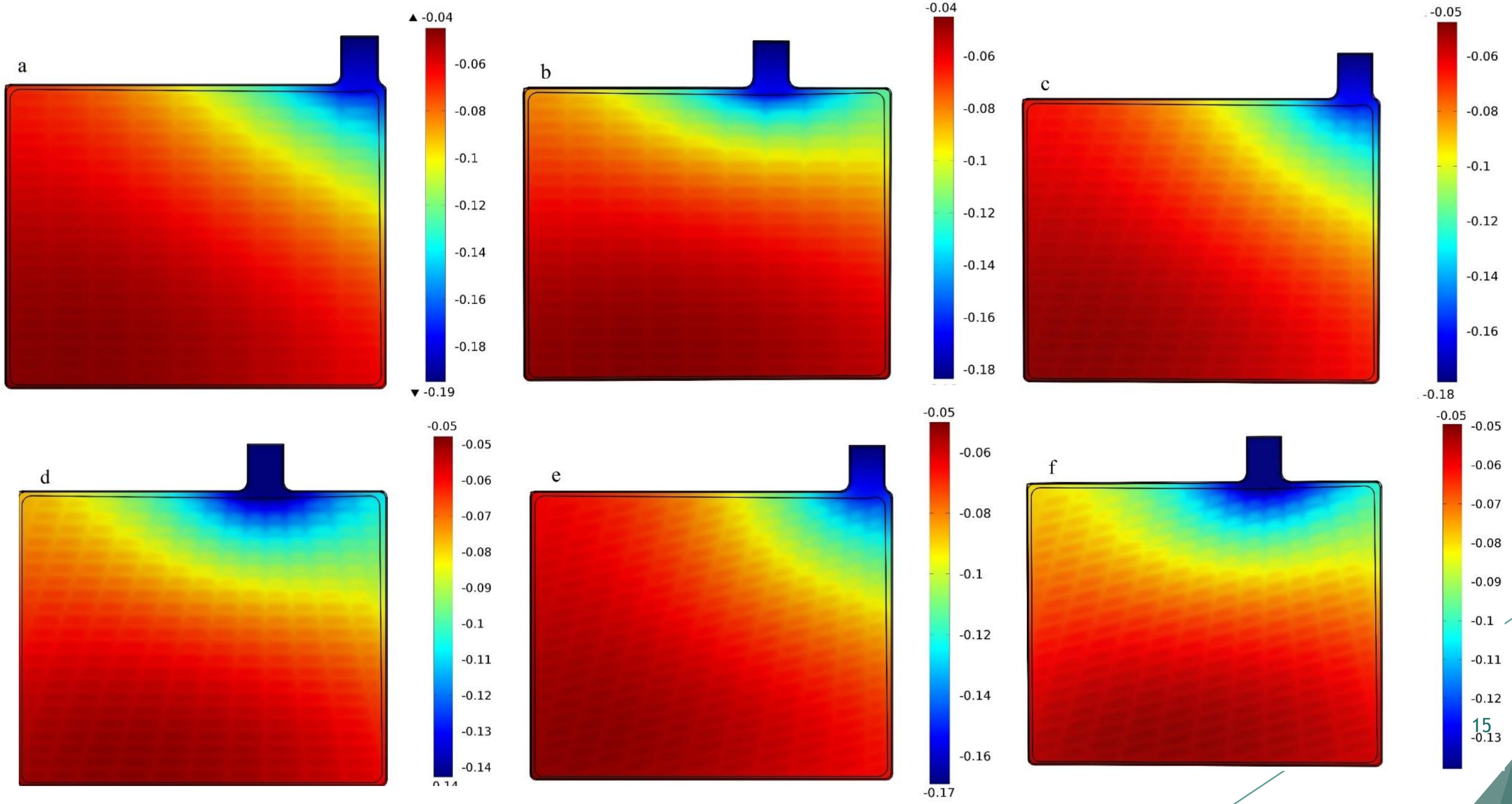
It is evident that in models which lug is nearer to the midpoint of the frame, minimum values are higher.

Also it could be gathered from the statistics in above table that the maximum potential values in diagonal and double-diagonal configurations are not as low as conventional design near the lug, regardless to its lug position.

Differences in maximum and minimum potential values in each and every model indicate that model F and D has the most uniform potential distribution through the whole grid with just 90 mV difference between the highest and the lowest potential value.

A-2-2- Effect of grid configuration on Potential distribution through the active material and adjacent electrolyte to the plate

With employing Comsol software, a 3D numerical model has been developed to investigate the potential distributions through the active material and adjacent electrolyte to the plate in the six different grid configurations and the results are as below :



A-2-2- Effect of grid configuration on Potential distribution through the active material and adjacent electrolyte to the plate

Design Code	Grid name	E_{min} (V)	E_{max} (V)	ΔE (mV)
1.a	Conventional Side-Lug	-0.177	-0.046	$\boxed{0.131}$
1.b	Conventional Middle-Lug	-0.166	-0.047	0.119
1.c	Diagonal Side-Lug	-0.161	-0.049	0.112
1.d	Diagonal Middle-Lug	-0.142	-0.051	0.091
1.e	double-diagonal Side-Lug	-0.152	-0.052	0.1
1.f	double-diagonal Middle-Lug	-0.137	-0.054	$\boxed{0.083}$

Maximum and minimum potential values of active material and adjacent electrolyte to the plate for different configurations.

The lowest and highest potentials and therefore the most non-uniform potential distribution belong to conventional side-lug configuration .

In the other side stands the double-diagonal middle-lug configuration with the minimum gap between its maximum and minimum potential values that is 37 percent lower than of the former one.

Furthermore to investigate the effect of lug position on this parameter a comparison has been made which suggests that when lug is positioned nearer to center of the frame the potential distribution is more uniform and the difference value is reduced by 9, 19 and 17 percent for conventional, diagonal and double-diagonal respectively.

A-2-2- Effect of grid configuration on Potential distribution through the active material and adjacent electrolyte to the plate

Design Code	Grid name	E_{min} (V)	E_{max} (V)	ΔE (mV)
1.a	Conventional Side-Lug	-0.177	-0.046	0.131
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1.d	Diagonal Middle-Lug	-0.142	-0.051	0.091
1.e	double-diagonal Side-Lug	-0.152	-0.052	0.1
1.f	double-diagonal Middle-Lug	-0.137	-0.054	0.083

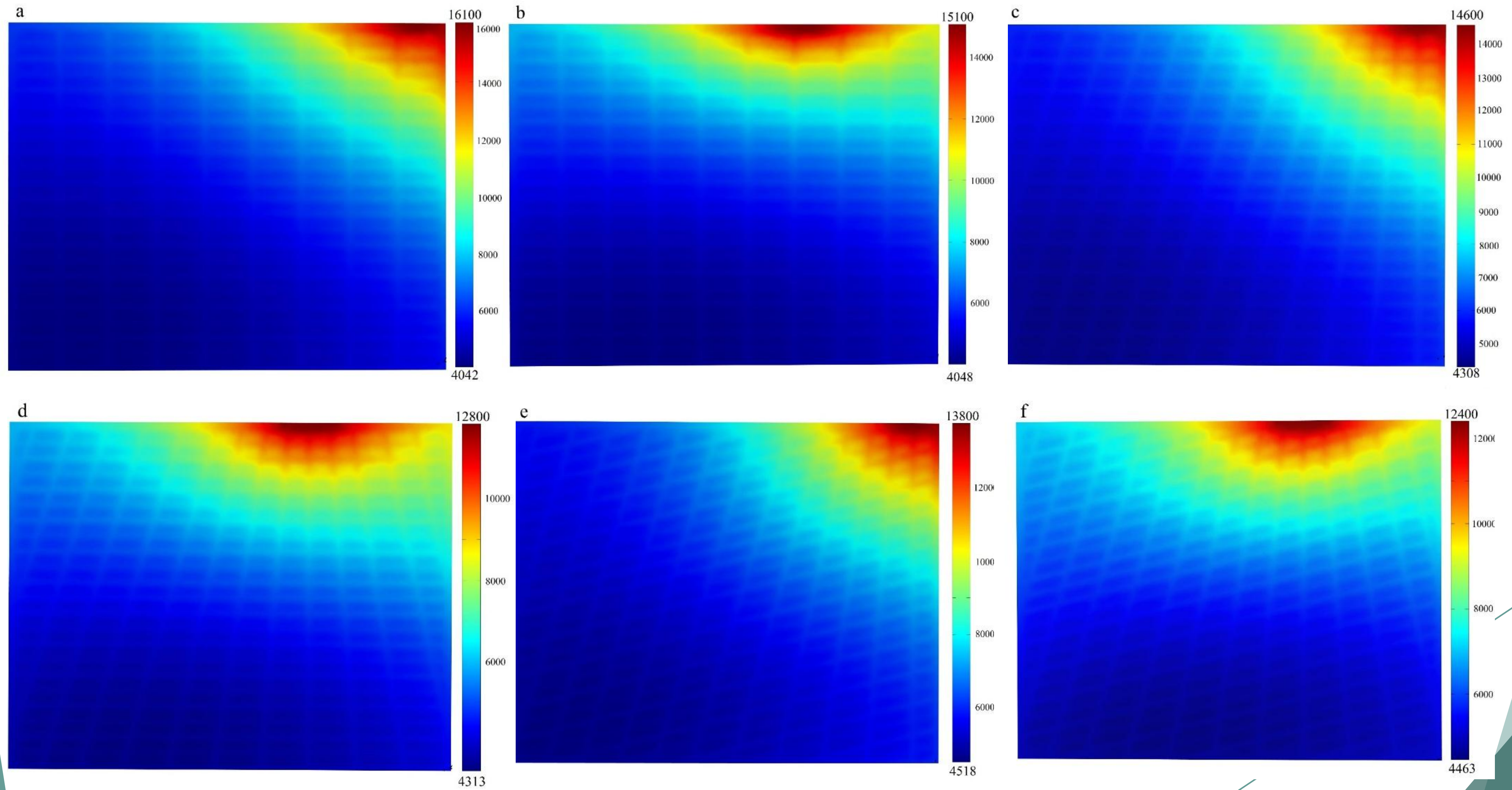
The effect of grid configuration also could be shown with comparing the differences between maximum and minimum for each model which shows 23 and 30 percent reduction for diagonal and double-diagonal middle-lug designs respectively comparing to conventional one.

More wire density in the upper right corner of the frame is the reason for more uniform potential distribution through the grid as well as active material and adjacent electrolyte to the grid.

Another talking point is that positioning the lug nearer the midpoint of the frame shortens the electric current path from each part of the plate to the plate lug and hence reduces the voltage drop and increases current collecting ability.

A-3- Effect of grid configuration on Current density distribution

With employing Comsol software, a 3D numerical model has been developed to investigate the effect of grid configuration on current density distribution in the electrolyte adjacent to surface of each plate and the results are as below :



Distributions of current density (A/m^2) in the electrolyte adjacent to surface of each grid with different configurations

A-3- Effect of grid configuration on Current density distribution

Design Code	Grid name	i_{min} (A/m²)	i_{max} (A/m²)	Δi (A/m²)
A	Conventional Side-Lug	4042	16100	12058
B	Conventional Middle-Lug	4048	15100	11052
C	Diagonal Side-Lug	4308	14600	10292
D	Diagonal Middle-Lug	4313	12800	8487
E	double-diagonal Side-Lug	4518	13800	9282
F	double-diagonal Middle-Lug	4463	12400	7937

Maximum and minimum current density values in the electrolyte adjacent to surface for different configurations.

Since the whole current produced in a battery plate passes through the lug, this section carries highest current density value. It is crystal-clear that the more wire density near the lug in diagonal and double-diagonal resulted in lower current density, 9 and 14 percent respectively comparing to conventional one.

In the other hand, middle-lug configuration causes 8, 17 and 15 percent increases in current density distribution for conventional, diagonal and double-diagonal designs respectively.

It should be stated that ohmic resistance in the electrolyte plays a role in current density distribution, indeed models with more available surface shows more uniform current density distribution.

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B-Lug position

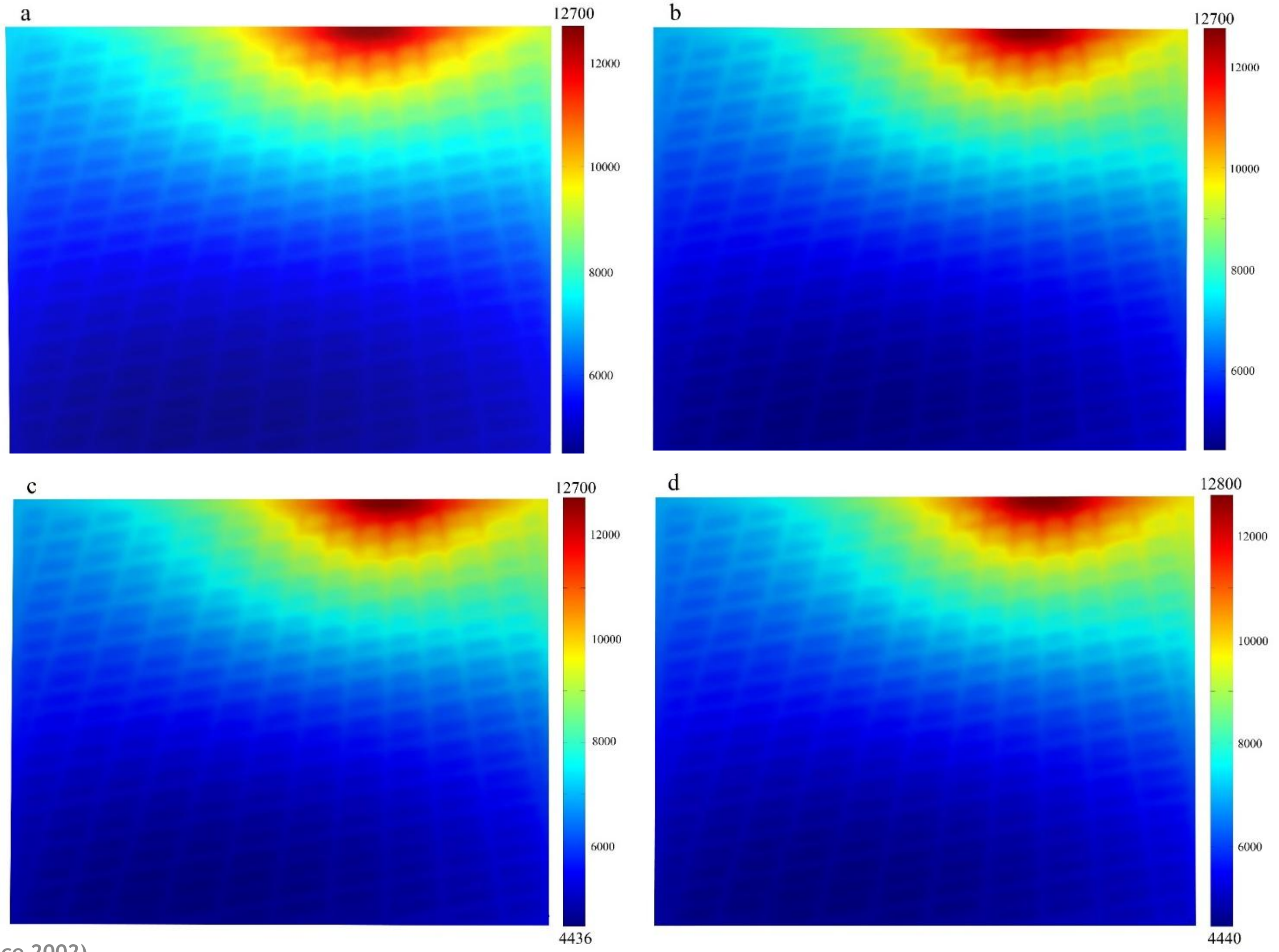
Design Code*	Distance to grid midpoint (mm)	Distance between positive and negative lugs (mm)
A	22.5	45
B	25	50
C	27.5	55
D	30	60

As it was shown in the previous section, grids with their lugs in the middle show the best performance, so for finding an optimal and practical position for the lug, a grid with four different lug positions was designed.

The lugs positions is listed in above Table and Double-diagonal design is used in all grids and all other parameters are the same between these four designs.

B-1-The effect of lug position on Current density distribution

3D numerical model has been developed With employing Comsol software to investigate the Distributions of current density (A/m^2) in the electrolyte adjacent to surface of each plate with different lug positions for 4 different lug position and the results are as below :



B-1-The effect of lug position on Current density distribution

Design Code*	Distance to grid midpoint (mm)	Distance between positive and negative lugs (mm)	i_{min} (A/m²)	i_{max} (A/m²)	Δi (A/m²)
A	22.5	45	4435	12700	8265
B	25	50	4436	12700	8264
C	27.5	55	4436	12700	8264
D	30	60	4440	12800	8360

Maximum and minimum current density values in the electrolyte adjacent to surface for different lug positions.

As the result shows, there is not a considerable difference between first three designs in current density distribution .

The results shows that with increasing the distance between lugs more than a certain level, the performance will drop rapidly.

This result is consistent with what is really happening in battery industry, as most manufacturers use either second or third design.

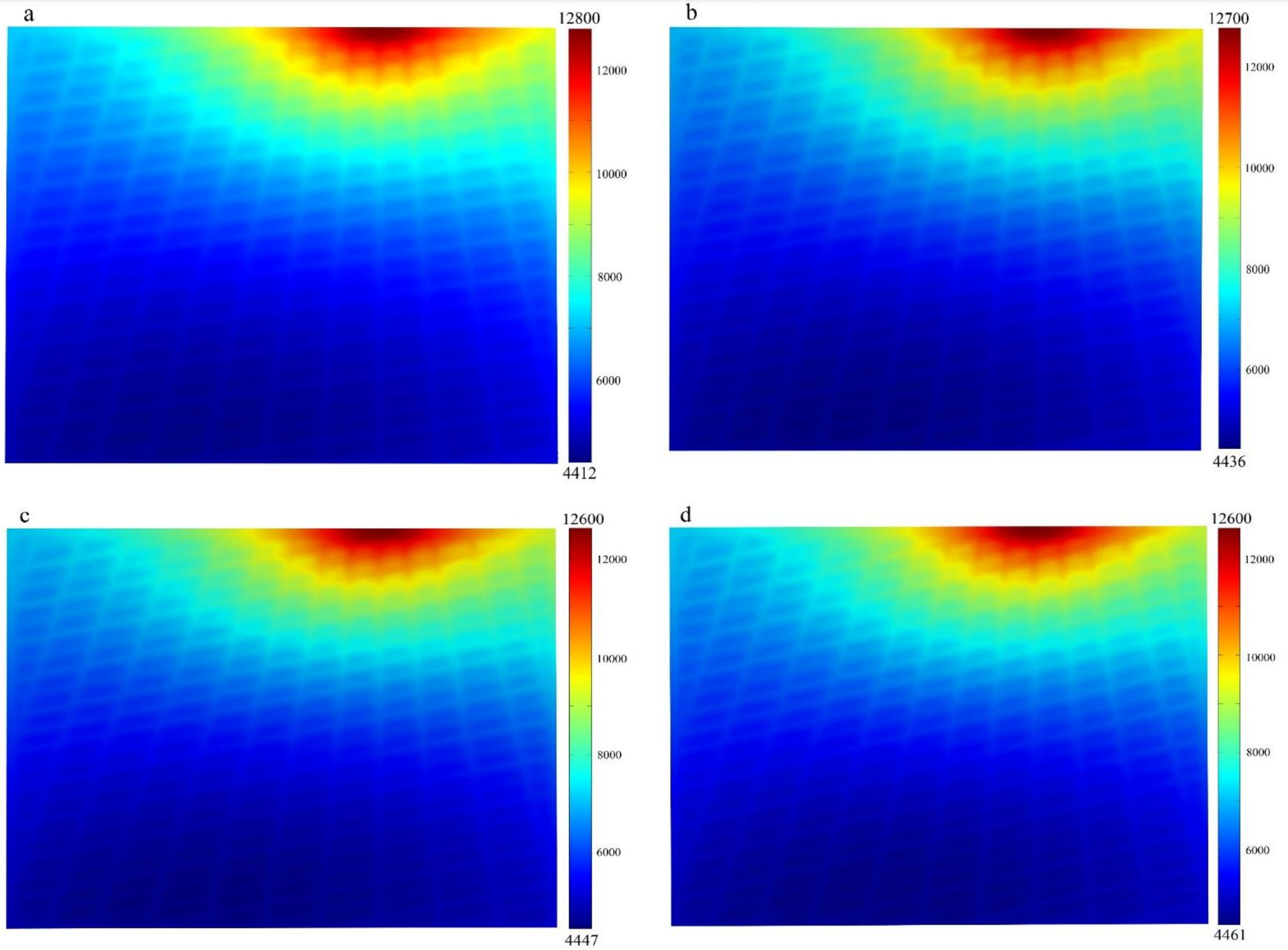
C- Wire angles

To investigate the effect of parallel diagonal wires on the electrochemical performance of positive grid, the best design (F) was employed as the base design and the wire angles changed from 8 to 14 degree. The design characteristics are illustrated in below table.

Design Code*	Wires angle
A	8
B	10
C	12
D	14

C-1-The effect of Wire angles on Current density distribution

With employing Comsol software, a 3D numerical model has been developed to investigate the distributions of current density (A/m^2) in the electrolyte adjacent to surface of each plate with four different wire angles and the results are as below :



C-1-The effect of Wire angles on Current density distribution

Design Code*	Wires angle	i_{min} (A/m²)	i_{max} (A/m²)	Δi (A/m²)
A	8	4412	12800	8388
B	10	4436	12700	8265
C	12	4447	12600	8153
D	14	4461	12600	8139

Maximum and minimum current density values in the electrolyte adjacent to surface for different wire angles.

As it is highlighted in above table with increasing the wire angles the maximum current density decreases and in the same time current density distribution becomes more uniform, decreasing from 8388 A/m² to 8139 A/m² as wires angle increase from 8 to 14 degree, however with increasing the angle of wires, gravity grid casting becomes more difficult.

D- Tapering wires towards the lug

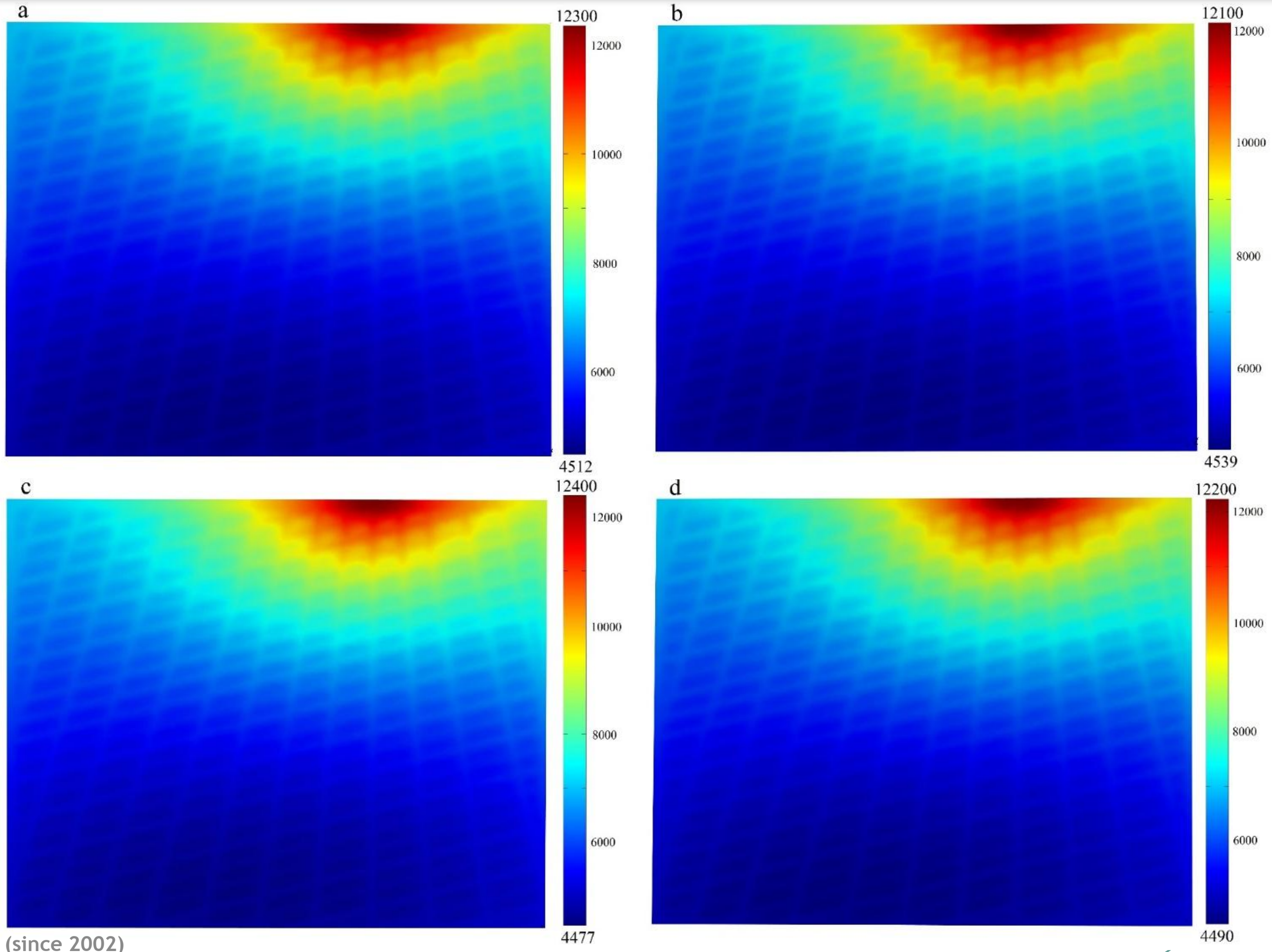
Design Code	Tapering Degree	Tapering Point
A	1.2	Bottom
B	1.4	Bottom
C	1.2	Midpoint
D	1.4	Midpoint
Base	…	…

Since all currents which produced by the positive plate should pass through the lug, with moving from the bottom of the grid towards its lug, current and therefore current density increases significantly. Hence, with increasing the wire width from the bottom to the top, which provides more surface, very high current density near the lug could be prevented and more uniform current distribution would be achievable.

In this step, double-diagonal grid with wire angle of 14 degree and with 22.5 mm distance from the midpoint used as a base design. Tapering degree, which means the ratio between the widths of wires in the top to their width in the bottom, were chosen as 1.2 and 1.4. Furthermore in other two designs wires were tapered from the midpoint of the grid to the top with the same degree as the first two designs. Design characteristics of these designs are available in above Table.

D-1-The effect of Tapering wires towards the lug on Current density distribution

With employing Comsol software, a 3D numerical model has been developed to investigate the distributions of current density (A/m^2) in the electrolyte adjacent to surface of each grid with different tapering currents degrees that are shown as below :



D-1-The effect of Tapering wires towards the lug Current density distribution

Design Code	Tapering Degree	Tapering Point	i_{min} (A/m²)	i_{max} (A/m²)	Δi (A/m²)
A	1.2	Bottom	4512	12300	7788
B	1.4	Bottom	4539	12100	7561
C	1.2	Midpoint	4477	12400	7923
D	1.4	Midpoint	4490	12200	7710
Base	…	…	4461	12600	8139

Maximum and minimum current density values in the electrolyte adjacent to surface for grids with different tapering currents degrees

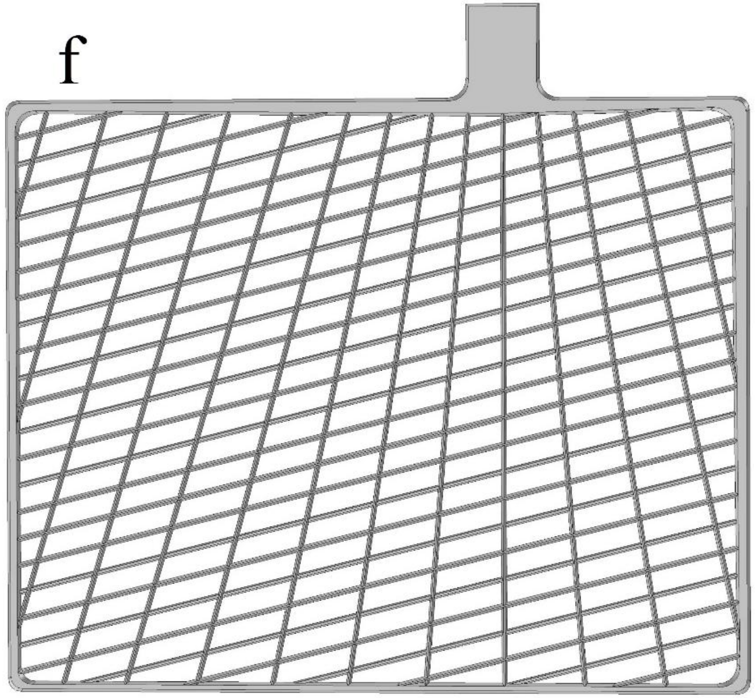
All designs show a much lower maximum current density and more uniform current distribution through the grid, so with tapering wires towards the lug an improvement in the performance of the plate could be seen clearly.

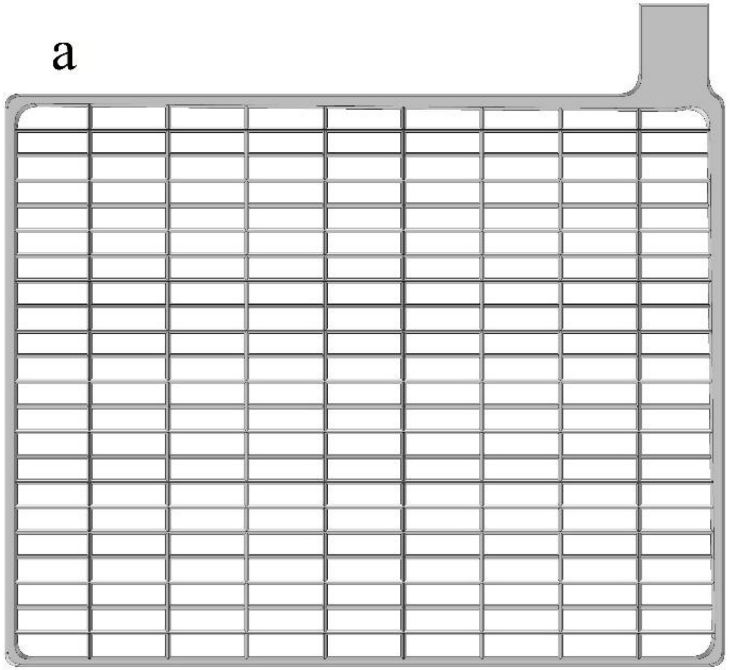
With increasing the tapering degree the difference between minimum and maximum current density decreases and also the maximum current density itself, however it should be noticed that too high tapering degrees may cause very thin wires in the bottom and therefore shedding of active material, which is one the most common reasons for lead acid battery failures.

With comparison between A and C and also B and D designs, it could be concluded that tapering the wires from the bottom of the grid causes much better results than tapering them from the midpoint, regardless to their tapering degree.

Conclusion

With comparison between all designed models with almost the same weight, it becomes evident that the best design is Middle-Lug double-diagonal design with the closest lug to the midpoint, which tapered from the bottom of the grid with ratio of 1.4 and the worst one is conventional Side-Lug.





Conclusion

The achievement of optimization for different design parameters was 37 percent improvement in current density distribution and also 33 and 40 percent improvement in potential distribution through the active material and adjacent electrolyte and electrode respectively between the best and worst designs.

In brief it could be concluded that with providing more surface near the lug, very high current densities could be prevented and also with directing horizontal and vertical wires towards the lug, current collecting ability improves substantially.

Positioning the lug closer to the midpoint of the grid causes shortening the current pass for most part of the grid and therefore reduces ohmic drop and gives more uniform potential and current distribution through the whole grid.

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