Designing a lead-acid battery involves determining the required battery capacity based on power and the discharge rate (C-rate). This homework outlines the steps needed to design a lead-acid battery for a given power requirement and C-rate.

1 Required Capacity (Ah)

The required capacity is calculated using the power demand, operating voltage, and C-rate.

$$I = \frac{P}{V}$$

Where:

- P = Power Requirement (W)
- V= Operating Voltage (V)

The required battery capacity is:

$$\text{Capacity(Ah)} = \frac{\text{I}}{\text{C}-\text{rate}}$$

2 Battery Sizing

To size the battery, the energy capacity and the number of cells are calculated.

Energy Capacity:

$$\text{Energy(Wh)} = \text{Power(W)} \times \text{Time(h)}$$

Number of cells in a lead-acid battery:

$$\text{Number of cells} = \frac{\text{Total Voltage (V)}}{\text{2Vper cell}}$$

For a 12V battery, 6 cells are required.

3 Battery Chemistry and Configuration

Lead-acid batteries come in various types such as flooded, AGM, and gel. The choice depends on the application and maintenance requirements.

4 Discharge Characteristics

The capacity of lead-acid batteries is subject to Peukert's law, which states:

$$\text{Effective Capacity} = \text{Rated Capacity} \times \left(\frac{1}{\text{C}}\right)^{\text{n}}$$

Where n is the Peukert exponent, typically between 1.1 and 1.3 for lead-acid batteries.

5 Thermal Management

Thermal management is important as lead-acid batteries are sensitive to temperature variations. Charging and Maintenance Charging protocols need to be carefully managed to avoid overcharging. Flooded batteries require maintenance, while AGM and gel batteries are maintenance-free.

6 Determine Plate Dimensions

The effective area of a plate in a lead-acid battery refers to the surface area actively participating in electrochemical reactions. The following steps is to calculate the effective area of a battery plate. The first step is to calculate the area of a single plate based on its width (W) and height (H).

$$A_{\text{single}} = W \times H$$

If the plate has two active sides:

$$A_{\text{plate}} = 2 \times A_{\text{single}} = 2 \times W \times H$$

Consider the Number of Plates

If the battery has n_p positive plates, the total surface area is:

$$A_{\text{total}} = n_p \times A_{\text{plate}}$$

Surface Utilization Factor

The surface utilization factor η, typically between 0.8 and 0.9, accounts for the actual surface area available for reactions. The effective area is:

$$A_{\text{effective}} = \eta \times A_{\text{total}}$$

Example Calculation

Given:

- Plate width $W = 0.15\,\text{m}$
- Plate height $H = 0.2\,\text{m}$
- Number of positive plates $n_p = 20$
- Surface utilization factor $\eta = 0.85$

Step 1: Calculate the area of a single plate:

$$A_{\text{single}} = 0.15\,\text{m} \times 0.2\,\text{m} = 0.03\,\text{m}^2$$

$$A_{\text{plate}} = 2 \times 0.03 = 0.06\,\text{m}^2$$

Step 2: Calculate the total area for 20 positive plates:

$$A_{\text{total}} = 20 \times 0.06\,\text{m}^2 = 1.2\,\text{m}^2$$

Step 3: Calculate the effective area:

$$A_{\text{effective}} = 0.85 \times 1.2 = 1.02\,\text{m}^2$$

7 Calculation of Weight of a LAB

To calculate the weight of a lead-acid battery, including the weights of active materials such as lead dioxide, sponge lead, sulfuric acid, and the battery casing.

Step 1: Determine Battery Capacity (Ah)

The battery's capacity is denoted as C_{battery} Ah. The total weight of the battery is proportional to its capacity.

Step 2: Estimate the Active Material Weights

The weights of the active materials, which primarily determine the battery weight, are calculated as follows:

Lead Dioxide (PbO_2) Weight

The weight of lead dioxide per ampere-hour is approximately 0.037 kg/Ah:

$$W_{\text{PbO2}} = 0.037 \times C_{\text{battery}}$$

Sponge Lead (Pb) Weight

The weight of sponge lead per ampere-hour is approximately 0.036 kg/Ah:

$$W_{\text{Pb}} = 0.036 \times C_{\text{battery}}$$

Sulfuric Acid (H_2SO_4) Weight

The weight of sulfuric acid per ampere-hour is approximately 0.024 kg/Ah:

$$W_{\text{H2SO4}} = 0.024 \times C_{\text{battery}}$$

Step 3: Include the Weight of Casing and Other Components

The battery casing and other components typically contribute around 10-15% of the total battery weight. Let $p_{\text{components}}$ be the percentage for casing and additional components.

$$W_{\text{components}} = p_{\text{components}} \times (W_{\text{PbO2}} + W_{\text{Pb}} + W_{\text{H2SO4}})$$

Step 4: Calculate Total Battery Weight

The total weight of the battery is the sum of the active material weights and the casing weight:

$$W_{\text{battery}} = W_{\text{PbO2}} + W_{\text{Pb}} + W_{\text{H2SO4}} + W_{\text{components}}$$

Example Calculation

Given:

- Battery Capacity: $C_{\text{battery}} = 100\,\text{Ah}$
- Component weight percentage: $p_{\text{components}} = 0.1$ (10%)

Step 1: Calculate the weights of the active materials:

$$\begin{aligned} W_{\text{PbO2}} &= 0.037 \times 100 = 3.7\,\text{kg} \\ W_{\text{Pb}} &= 0.036 \times 100 = 3.6\,\text{kg} \\ W_{\text{H2SO4}} &= 0.024 \times 100 = 2.4\,\text{kg} \end{aligned}$$

Step 2: Calculate the weight of the components:

$$W_{\text{components}} = 0.1 \times (3.7 + 3.6 + 2.4) = 0.97\,\text{kg}$$

Step 3: Calculate the total battery weight:

$$W_{\text{battery}} = 3.7 + 3.6 + 2.4 + 0.97 = 10.67\,\text{kg}$$

8 Required Sulfuric Acid

The steps to calculate the required amount of sulfuric acid for a lead-acid battery are as follows. The amount depends on the battery's capacity, the total volume of electrolyte, and the concentration of sulfuric acid.

Step 1: Determine Battery Capacity (Ah)

The first step is to determine the battery capacity in ampere-hours (C_{battery}).

Step 2: Estimate Total Volume of Electrolyte

The volume of electrolyte needed is approximately 0.06 to 0.08 liters per ampere-hour of battery capacity. The total volume of electrolyte can be estimated as:

$$V_{\text{electrolyte}} = C_{\text{battery}} \times \text{volume per Ah}$$

For example, if the battery has a capacity of 100 Ah and 0.07 liters per Ah is assumed:

$$V_{\text{electrolyte}} = 100 \times 0.07 = 7\,\text{liters}$$

Step 3: Determine Concentration of Sulfuric Acid

Lead-acid batteries typically use a sulfuric acid solution at a concentration of 30-40% by weight. For this example, assume a 35% concentration.

Step 4: Calculate the Amount of Sulfuric Acid

The amount of sulfuric acid in the electrolyte is given by:

$$W_{\text{H2SO4}} = V_{\text{electrolyte}} \times \rho_{\text{electrolyte}} \times \%\text{H2SO4}$$

Where:

- $V_{\text{electrolyte}}$ is the total volume of electrolyte (liters),
- $\rho_{\text{electrolyte}}$ is the density of the electrolyte (around 1.25 kg/L),
- %H2SO4 is the concentration of sulfuric acid by weight.

For a 100 Ah battery with 7 liters of electrolyte and 35% sulfuric acid:

$$W_{\text{H2SO4}} = 7 \times 1.25 \times 0.35 = 3.06\,\text{kg}$$

Step 5: Convert to Volume (Optional)

If needed, the mass of sulfuric acid can be converted to volume using the density of pure sulfuric acid (approximately 1.84 kg/L):

$$V_{\text{H2SO4}} = \frac{W_{\text{H2SO4}}}{\rho_{\text{H2SO4}}}$$

For the above example:

$$V_{\text{H2SO4}} = \frac{3.06}{1.84} = 1.66\,\text{liters}$$

Example Summary

For a 100 Ah battery:

- Electrolyte required: 7 liters
- Sulfuric acid mass: 3.06 kg
- Sulfuric acid volume: 1.66 liters

9 The size of Electrodes

The size of the electrodes (positive and negative plates) in a lead-acid battery is crucial to determining its capacity, performance, and lifespan. The following outlines the key factors for determining electrode size, including current density, battery capacity, and plate thickness.

Current Density

Current density refers to the amount of current per unit area of the electrode, typically measured in amperes per square centimeter (A/cm^2).

$$A = \frac{I}{J}$$

Where:

- A is the electrode surface area (in cm^2),
- I is the current (in A),
- J is the current density (in A/cm^2).

For example, for a 100 A discharge current and a current density of 0.05 A/cm^2:

$$A = \frac{100}{0.05} = 2000\,\text{cm}^2$$

Battery Capacity

The battery capacity can be approximated by:

$$C = A \times d \times \text{UtilizationFactor}$$

Where:

- C is the battery capacity (Ah),
- A is the electrode surface area (cm^2),
- d is the thickness of the active material,
- Utilization Factor is typically 30-50%.

Plate Thickness

Typical plate thicknesses vary depending on the application:

- Automotive batteries: 1 to 2 mm,
- Deep-cycle batteries: 2 to 4 mm.

Electrode Dimensions

Electrode sizes vary based on application:

- Automotive batteries: 10 cm by 15 cm to 20 cm by 30 cm,
- Deep-cycle batteries: 15 cm by 20 cm to 25 cm by 40 cm.

The number of plates is often increased to achieve the required capacity.

Example Calculation

For a 100 Ah battery with a 100 A discharge current and current density of 0.05 A/cm²:

$$A = \frac{100}{0.05} = 2000\,\text{cm}^2,$$
$$\text{Number of plates} = \frac{2000}{300} = 6.67 \approx 7\,\text{plates}.$$

Summary of Electrode Sizes

Application	Current Density (A/cm²)	Plate Thickness (mm)	Surface Area (cm²)	Plate Spacing (mm)
Automotive Batteries	0.05 - 0.1	1 - 2	150 - 600	1 - 2
Deep-Cycle Batteries	0.02 - 0.05	2 - 4	300 - 1000	1 - 3
VRLA Batteries	0.02 - 0.05	1 - 3	200 - 600	0.5 - 2

10 External Dimensions

The external dimensions of a lead-acid battery are determined by several factors, including battery capacity, type (flooded, AGM, or gel), and internal design considerations such as the number of plates, plate size, and electrolyte type. The following outlines the factors that influence the external dimensions and provides typical sizes based on the application.

Battery Capacity and Plate Size

Battery capacity determines the number and size of plates, which directly influences the overall size of the battery.

Automotive Batteries (12V, 50-100Ah):

- Typical Dimensions: 175 mm × 175 mm × 190 mm to 300 mm × 175 mm × 220 mm.

Deep-Cycle Batteries (12V, 100-200Ah):

- Typical Dimensions: 250 mm × 180 mm × 250 mm to 400 mm × 180 mm × 300 mm.

VRLA/AGM/Gel Batteries (12V, 50-200Ah):

- Typical Dimensions: 150 mm × 100 mm × 200 mm to 400 mm × 200 mm × 300 mm.

2. Voltage and Number of Cells

Each lead-acid battery cell provides a nominal voltage of 2V. For a 12V battery, 6 cells are required, and the external dimensions must accommodate the size of each cell.

3. Electrolyte Type

The type of electrolyte affects the size:

- Flooded batteries require extra space for electrolyte reservoirs and water maintenance.
- AGM and gel batteries are more compact due to the absence of space for liquid movement.

4. Internal Spacing

Internal spacing between plates, separators, and electrolyte volume also affects the external size.

- Typical plate spacing: 1 to 3 mm for flooded batteries, 0.5 to 2 mm for VRLA batteries.

5. Battery Case

The external case adds thickness for insulation, mechanical protection, and space for terminals.

- Typical case thickness: 3 to 5 mm.

6. Standardized Battery Sizes

Common standardized sizes for lead-acid batteries (BCI group sizes):

- **Group 24**: 260 mm × 173 mm × 225 mm,
- **Group 27**: 306 mm × 173 mm × 225 mm,
- **Group 31**: 330 mm × 173 mm × 240 mm.

7. Example Calculation for a Custom Battery

For a 12V, 100Ah battery:

- Assume 15 cm × 20 cm plates, with 2 mm plate thickness and 1 mm spacing.
- Final dimensions: 300 mm × 200 mm × 250 mm.

Summary of Typical External Dimensions

Battery Type	Capacity (Ah)	Dimensions (L × W × H)
Automotive (12V)	50-100	175-300 mm × 175 mm × 190-220 mm
Deep-Cycle (12V)	100-200	250-400 mm × 180 mm × 250-300 mm
VRLA/AGM (12V)	50-200	150-400 mm × 100-200 mm × 200-300 mm

11 Grid Shape

The grid shape in a lead-acid battery significantly impacts performance, durability, and efficiency. The grid supports the active material and helps collect and distribute electrical current. This document outlines different grid shapes and their suitability for various battery applications.

1. Grid Structure and Shape

Rectangular Grid Pattern

A rectangular grid pattern is one of the most common designs, where bars intersect perpendicularly to form rectangular or square cells.

Pros:

- Uniform current distribution across the active material.
- Simple manufacturing process, providing good mechanical strength.

Cons:

- Higher corrosion rates near intersections due to localized current concentration.

Best Use: Automotive starter batteries, general-purpose flooded batteries.

Radial or Fan-Shaped Grid Pattern

In radial grids, the lines are arranged like spokes radiating from the center. This design improves current distribution.

Pros:

- Enhanced current distribution, reducing internal resistance.
- Reduces corrosion near the busbar.

Cons:

- More complex manufacturing process.

Best Use: Deep-cycle and high-performance batteries.

Hexagonal Grid Pattern

Hexagonal grids feature a honeycomb structure, offering strong mechanical properties.

Pros:

- Good balance of mechanical strength and current distribution.
- Reduces mechanical stress and corrosion.
- Better utilization of active material.

Cons:

- Slightly more complex and costly to manufacture.

Best Use: High-performance automotive batteries, AGM and VRLA batteries.

2. Bar Thickness and Shape

The cross-sectional shape of the bars influences performance. Common bar shapes include:

- **Rectangular bars**: Common and easy to manufacture, but may not provide the best current distribution.
- **Trapezoidal bars**: Wider base, tapering toward the top, improving contact with active material and enhancing current distribution.
- **Circular bars**: Provide uniform current distribution but are less mechanically robust.

3. Grid Size (Mesh Density)

The density of the grid affects mechanical strength and active material contact.

Coarse Mesh:

- Greater mechanical strength, suited for high-vibration environments.
- Reduced contact area with active material, lowering capacity.

Fine Mesh:

- Increases contact area, improving battery capacity.
- More prone to corrosion due to thinner bars and higher current densities.

4. Busbar Design

The busbar collects the current from the grid and transfers it to the terminals. A well-designed busbar minimizes the distance between the center of the plate and terminals to reduce resistance.

5. Recommended Grid Shape Based on Application

Application	Recommended Grid Shape	Notes
Automotive Starter Batteries	Rectangular or Radial	Simple design, good balance of strength and current distribution.
Deep-Cycle Batteries	Radial or Hexagonal	Better current distribution for deep-cycle performance.
High-Performance VRLA Batteries	Hexagonal or Radial with Trapezoidal Bars	Reduces resistance, maximizing active material utilization.
Industrial/Heavy-Duty Batteries	Rectangular with Coarse Mesh	Strong and durable for harsh environments.
High-Vibration Environments	Rectangular with Thicker Bars	Provides better mechanical support for active material.

- **Rectangular grids** are versatile and widely used in automotive and general-purpose batteries.
- **Radial grids** enhance current distribution and are suited for high-performance and deep-cycle applications.
- **Hexagonal grids** provide a balance of strength and current distribution, ideal for high-performance VRLA batteries.

Bar thickness, mesh density, and busbar design should also be considered for optimizing performance and longevity.