Studies in Electrostatics

Part 6: The Leyden jar and Other Capacitors

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Discovery

The identity of the discoverer of an effective capacitor has long been contested[1,2]. It now appears that, chronologically, this honour belongs to Ewald von Kleist, the Dean of Kammin Cathedral in Pomerania. He was intrigued by the brush discharge visible in a dark room around the prime conductor of an electrostatic generator, and sought to 'catch' it upon a nail protruding from a glass jar containing a little water. By 1745 he had learnt how to accumulate sufficient charge for him to walk about with the glow from the point of the nail acting as a portable lamp. The benevolent cleric must also have investigated other properties of his phial, for he later wrote to colleagues that the shock ('schlacht'- blow) from improved versions could 'knock a child of eight or nine right off its feet'! Kleist's correspondents were at first unable to repeat his demonstrations because they (and probably Kleist himself) did not initially appreciate the importance of the hand holding and surrounding the jar as an outer, earthed, electrode.

Meanwhile, in the Netherlands, several amateurs were interested in electrical phenomena. One of them was the lawyer Andreas Cunaeus, and hearing about the success of the German Bose in obtaining sparks from water, in 1746 attempted to emulate him with a wire from a frictional machine dipping into water in a flask held in his hand. These conditions were the same as Kleist's, so it was inevitable that in due course he too would receive a strong shock. He reported the matter to Van Musschenbroeck, an experienced natural scientist who taught mathematics and philosophy at Leyden[3] and operated a well-equipped laboratory where he repeated the experiment. The shock he received was so severe that he told Réaumur that he 'thought he was done for'. Musschenbroeck's reports electrified Europe: every philosopher wanted to investigate the 'terrible jar', although generally recognizing that it was better to witness its effect on someone else! [4] Thus the gallant Professor Winkler reported that his wife was unable to walk for the rest of the day when he had used her to short-circuit a charged jar. The deceptively simple apparatus was soon identified with Leyden–although Musschenbroeck himself never claimed to have invented it.

Improvements

Splashes or vapour from contained water could easily degrade the insulating properties of the glass in the original pattern of Leyden jar, so it was soon replaced by lead or tin foil to form an internal conductive coating. An outer layer of metal foil also proved beneficial, especially when it was realized that good earthing of the outside was essential. [5] Comparison with Franklin's flat pane capacitors led to recognition of the action of the glass jar as a dielectric separating conductive inner and outer electrodes, and indicated the improved performance to be gained from specially-blown thin glass vessels coated inside and out with a maximum area of foil. This was limited in practice by the eventual tendency for a highly charged jar to discharge over its neck. This point of weakness could be reduced by covering only the base and lower 2/3 of the walls, and closing the neck with a mahogany stopper pierced by a metal rod connected to the interior foil by a hanging chain. A metal ball at the apex reduced losses by brush discharge. Lacquering of exposed glass with shellac reduced the tendency of soda glass to form a hygroscopic film, and kept the interior sealed and dry (Fig. 1). Several jars might be connected together as 'batteries': series or parallel arrangements were possible (see formulae in Part 4). These would have been superior to the 'gallon size' Leyden jars that have sometimes been described.

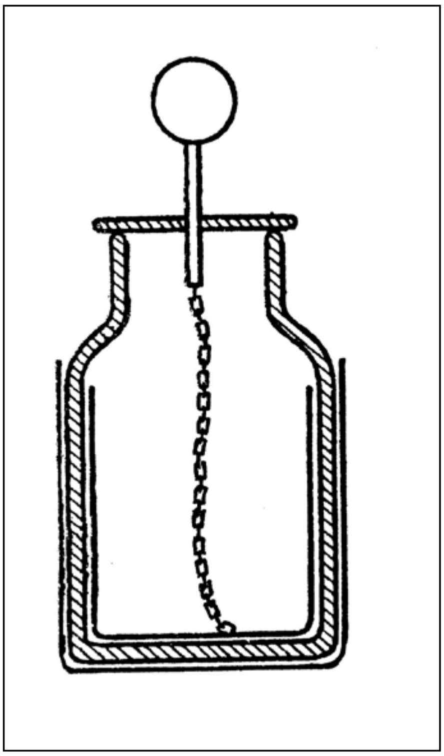

Fig. 1 *Construction of the traditional Leyden jar.*

Fig. 2 *Modern reconstruction of a Leyden jar.*

Experimental Assessment

A soda glass food jar, 21.5 cm high by 8.5 cm outside diameter with 2 mm walls, had a maximum capacity of 1.1 litres. This is comparable with many historical Leyden jars. It was lined to a depth of 14 cm with aluminium kitchen foil, on both inside and outside surfaces. (White glue proved easier to use than the historical shellac in alcohol.) The total area of foil was 860 cm^2, and it enclosed a volume of 0.7 litres. The original screw cap was pierced with a central 25 mm hole, into which was inserted a rubber stopper bearing a vertical metal rod. The latter was tipped with a 20 mm bronze ball (these are commercial items) and a springy wire soldered to the lower end to contact the internal foil electrode. The rubber stopper and the glass above the foils separated one from the other, so careful cleaning and lacquering was important to ensure good insulation. The apparatus is shown in Fig. 2.

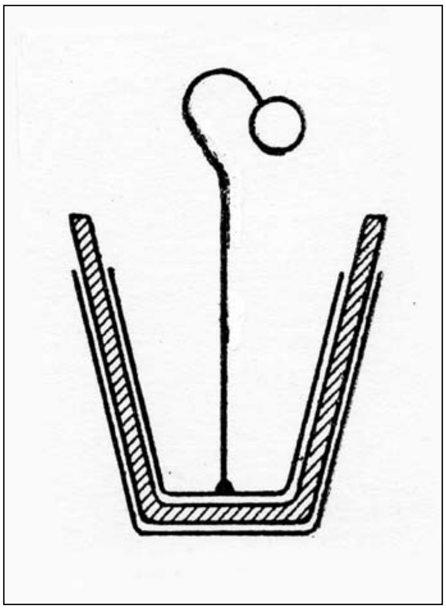

Fig. 3 *Franklin's 'dissectible' Leyden jar.*

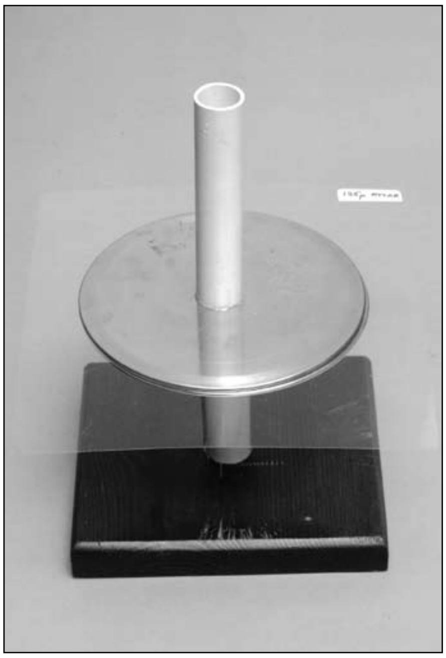

Fig. 4 *Parallel plate capacitor.*

The calculated capacitance of the jar when treated as two concentric cylinders (Part 4, equation 3) was 1.2 nF. Its measured value (Wayne Kerr component meter) was 1.3 nF, the extra amount being attributed to the foil-covered base where the glass was of indeterminate thickness. It has been seen above (Part 4) that even quite large 'prime conductors' had capacitances of no more than 20-30 pF., so a single Leyden jar represented an increase in capacitance of some 50x. At a fixed charging potential this would result in considerably more intense sparks and shocks containing 50x the energy.

The Dissectible Leyden Jar

Franklin[6] sought to find the seat of the energy in a charged Leyden jar by making the conical form diagrammed in Fig. 3. It could be charged with an electrophorus or an electrostatic machine in the usual way with the outer electrode earthed, or a suitable machine could produce opposite charges on the inside and outside of an isolated jar. First the inner electrode, and then the glass vessel, were lifted out with insulated tongs and placed separately on an insulating sheet. Both metal parts could then (he claimed) be shown with an electroscope to be uncharged, and might be touched together or handled with impunity. However, much to the surprise of the spectators, when the jar was re-assembled a spark would jump across when a shorting device was applied between the outer coating and the knob of the jar. Franklin drew the reasonable conclusion that the energy of the charged jar resided in the glass, putting it in a state of strain analogous to the mechanical energy stored in a compressed spring.

Textbook writers generalized Franklin's experiment by saying that the energy of a charged capacitor resides in its dielectric, and the 'dissectible jar' became a classic demonstration.[7] Strictly though, this is *not* what Franklin showed (his work was limited to *glass* dielectric) and invites the question of where the energy is stored in an air-spaced capacitor! The awkward matter was simply omitted from many 19th century texts, and the question shelved.

It was resurrected by Addenbrooke[8] in 1922, who thought of trying the experiment using an open conical vessel cast from paraffin wax to replace the glass. He found that the separated metal coatings then carried strong and equal charges of opposite sign - as might have been intuitively expected. Discharging them, followed by re-assembly around the wax dielectric, gave a jar with virtually no charge. Addenbrooke went on to show that if the glass vessel of the standard assembly was thoroughly dried by baking, and then used in a glove box containing anhydrous calcium chloride, it behaved exactly like the paraffin wax version.

The reason is that (soda) glass is a treacherous insulator. Under ordinary conditions it slowly reacts with atmospheric moisture to form a surface film of sufficient conductivity for small sparks and brush discharges to leap to it from the metal electrodes as the three components are successively separated. The transferred charge then spreads over the semi-conducive layer. The situation is reminiscent of the electrophorus, where the diminishing capacitance consequent upon dismantling causes the potential of the cover plate to be magnified as the components are parted. It will also be observed that, as separation occurs, much of the apparatus forms a 'Faraday cup' helping to guide and confine the discharge.

Strangely, Addenbrooke's paper did not become generally known, and Gross[9] appears unaware of it in his 1944 examination of the dissectible condenser. Fortunately, Zeleny[10] located the work, and carried out further experiments confirming Addenbrooke's views. In particular, he employed much higher potentials (up to 9500 V as against 600 V) and found that disruptive and brush discharges occurring in the air gap between coatings and glass dielectric were then readily visible in the dark. At these potentials (not very high in electrostatic practice) Zeleny found that not only was charge transfer facilitated, but so too was loss from the dismantled jar. Consequently the potential shown by the re-assembled apparatus was never as great as its original value.

Modern views associate most of the energy of a charged capacitor with the field generated by charges on the plates, with polarization of the dielectric possibly making a small contribution.

Parallel Plate Capacitors

The fact that any shape or size of vessel could be used to construct a Leyden jar suggested to many early electricians on both sides of the Atlantic[2] that its function was not to act as a 'bottle' to contain the 'electric fluid', but simply to separate and insulate two conductive electrodes. Experimental investigation of the influence of area and thickness was made easier by using plane sheets of glass: square panes were employed by Benjamin Franklin, and this type of construction became identified with him. Faraday investigated insulators such as wax, shellac and mica, compared them with air and glass, and showed that their dielectric properties were not identical with their insulating powers (see Part 4). The advent of plastics made a much wider selection of materials available for the construction of capacitors. Vast numbers are now mass-produced for the electronics industry, for which purpose a sandwich or coating of metal foil within a flexible dielectric film is commonly rolled to reduce its size while doubling its capacitance.

Experimental Investigation

In order to obtain a better quantitative idea of the value to be associated with early plane capacitors, two 15 cm diameter aluminium discs mounted on PVC handles (as used for the electrophori in Part 5) were arranged as shown in Fig. 4. 23 cm squares of various sheet-form dielectrics were placed between them, being kept in place by gravity. The resulting capacitances were measured with a Wayne Kerr bridge, being too large for the 'charge sharing' method of Part 2 to be applied. Results are listed below:

Dielectric	**Thickness** (mm)	**Capacitance** pF
Polystyrene	1.75	224
Soda glass	2.0	413
Mylar	0.125	886
Polythene	0.04	1258(1.3 nF)
Mylar	0.07	1370(1.4 nF)
Polythene	0.02	1733(1.7 nF)

Not only do the plastics have a higher dielectric constant than air, but they also prevent the electrical breakdown that would otherwise occur in such narrow gaps between electrodes at high potential differences.

As the capacitance of the isolated upper plate is only 5 pF, it will be seen that a very large increase is brought about by opposing it with a second plate separated by a thin dielectric. A charge applied to the glass-separated assembly leaked away much faster than with the plastics, although coating it with shellac varnish helped.

Notes and References

1. W.D. Hackmann, *Electricity from Glass: The History of the Frictional Electrical Machine 1600-1850* (Sijthoff & Noordhof 'Science in History 4', 1978).

2. J.L. Heilbron, *Electricity in the 17th and 18th centuries : A Study of Early Modern Physics* (University of California Press, 1979), Ch.13.

3. At the time, the usual spelling for this Dutch town employed 'y' rather than 'i'

4. Front cover of *Bulletin of the Scientific Instrument Society* for March 2005, No. 84.

5. W.D. Hackmann, 'Leyden Jar' in R.Bud and D.J Warner, eds., *Instruments of Science* (Science Museum, 1998).

6. I.B. Cohen, *Benjamin Franklin's Experiments* (Harvard University Press, 1941).

7. R.M. Sutton, *Demonstration Experiments in Physics* (McGraw-Hill, 1938), p. 275.

8. G.L. Addenbrooke, 'A Study of Franklin's Experiment on the Leyden jar with Movable Coatings', *Philosophical Magazine* **43** (1922), pp. 489-493.

9. B. Gross, 'On the Experiment of the Dissectible Condenser', *American Journal of Physics*, **12** (1944), pp. 324-329.

10. J. Zeleny, 'Observations and Experiments on Condensers with Removable Coats', *American Journal of Physics*, **12** (1944), pp. 329-339.

Last Part (No. 7): Sparks and Shocks

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