AIP | Journal of Applied Physics

Resistance as Dissipation into Many Reactive Circuits: Landau Damping and Nyquist's Noise Theorem

O. Buneman

Citation: J. Appl. Phys. **32**, 1783 (1961); doi: 10.1063/1.1728437
View online: http://dx.doi.org/10.1063/1.1728437
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v32/i9
Published by the American Institute of Physics.

Letters to the Editor

Resistance as Dissipation into Many Reactive Circuits: Landau Damping and Nyquist's Noise Theorem

O. BUNEMAN
Stanford Electronics Laboratories, Stanford, California*
(Received March 2, 1961)

NONRADIATIVE dissipation, such as friction and ohmic resistance, is not a loss of energy but its dispersal into a large number of degrees of freedom. Irreversibility is the improbability of reconcentration of energy into its initial ordered form.

One would therefore expect a network of very many undamped resonating circuits to exhibit resistive properties in its transient response. Indeed, it should be possible to simulate resistances by such purely reactive elements, in close analogy with the physical process of ohmic heating, i.e., conversion of electrical energy into molecular and lattice vibrations. (In a closed, nonradiating system these are undamped.)

Let

$$Y=\sum_{\nu}\frac{1}{2jL_{\nu}(\omega-\Omega_{\nu})}$$

be the admittance of a network with resonance frequencies Ω_{ν} and associated inductances L_{ν}. Let the frequencies Ω_{ν} be ordered in ascending magnitude. Both Ω_{ν} and $-\Omega_{\nu}$ should occur in the summation, with the same inductance.

If there are many terms and the values L_{ν} are related to Ω_{ν} in a nonerratic fashion, a convenient method of evaluating the sum is to consider small ranges $d\Omega$ of the resonant frequencies, to define the amount of inverse inductance L^{-1} in such a range as $Bd\Omega$ and to convert[1] the sum into an integral:

$$Y=\frac{1}{2}\int_{-\infty}^{+\infty}\frac{Bd\Omega}{j(\omega-\Omega)}=\frac{1}{2}\int_{-\infty}^{+\infty}\frac{Bd\Omega}{s-j\Omega}.$$

We are concerned with a problem of transience; hence, the introduction of the "s" used in Laplace transform theory, in place of $j\omega$.

In general, B depends on Ω. The case of constant B leads to divergence of the integral but this simple and interesting case can be approximated arbitrarily closely, without loss of convergence, by taking

$$B=B_0/(1+\Omega^2/\Omega_0^2)$$

with sufficiently large Ω_0. The integration is effected by completing the path around a large semicircle in the upper half-plane and contracting around the only pole at $\Omega=+j\Omega_0$. The pole at $\Omega=-js$ is in the lower half-plane, by the rules of Laplace transform theory ($\mathrm{Re}\,s>0$).

The result,

$$Y=\pi B_0/[2(1+s/\Omega_0)],$$

shows that the effective impedance of our network consists of a resistance $2/\pi B_0$ and an inductance $2/\pi B_0\Omega_0$. The latter vanishes in the limit $\Omega_0\rightarrow\infty$. The simulation of resistance by reactive elements is thus established. The conductance with $\Omega_0\neq\infty$ is $\frac{1}{2}\pi B/(1+\omega^2/\Omega_0^2)=\frac{1}{2}\pi B(\omega)$, and this formula for the conductance is obtained also with more general forms of $B(\Omega)$ than that assumed here.

Our picture of dissipation assists the understanding of Landau[2] damping of disturbances with wave number k in a collision-free plasma. The electron streams passing through the plasma with their continuously distributed velocities v provide a continuous range of resonance frequencies $\Omega=kv$.

Moreover, Nyquist's[3] noise theorem is readily obtained from this resonant-circuit model of resistance. If the network is shorted at the port of measurement after having been in thermal contact with the surroundings, each circuit will be left oscillating with energy

$$\tfrac{1}{2}L_{\nu}|I_{\nu}|^2+\tfrac{1}{2}C_{\nu}|V_{\nu}|^2=L_{\nu}|I_{\nu}|^2=C_{\nu}|V_{\nu}|^2=KT,$$

from which we deduce

$$|I|^2=KT/L_{\nu}=KTBd\Omega=2KTGd\Omega/\pi,$$

where G is the "conductance" identified above. This is Nyquist's formula.

* The work reported here was supported by the Air Force.
[1] The spacing $\delta\Omega$ in any actual discrete frequency spectrum sets a limit to the validity of this conversion, consequently, our deductions are restricted to time intervals less than about $1/\delta\Omega$.
[2] L. Landau, J. Phys. (U.S.S.R.) 10, 25 (1946).
[3] H. Nyquist, Phys. Rev. 32, 110 (1928).

Thermionic Emission of UC-Nb*

R. H. ABRAMS, JR., AND F. E. JAMERSON
General Motors Research Laboratories, Warren, Michigan
(Received March 29, 1961)

RECENT experiments on thermionic conversion of heat to electricity utilizing reactor heat sources[1] have stimulated interest in uranium-bearing cathodes.[2,3] The thermionic constants and spectral emissivity have been measured on a uranium carbide-niobium disk, UC (80 volume %)-Nb (20 volume %), of 2.34 cm in diameter and 0.51 cm in thickness.

The sample was prepared[4] by green pressing a powder mix containing 80 volume % UC of 6 w/o carbon and 20 volume % Nb into a 2.54-cm disk. The green press was then loaded into a carbon-coated niobium container and was pressure bonded for 3 hr at 1700°K under a helium gas pressure of 680 atm. After pressure bonding, the niobium cladding was machined. The UC-Nb was metallographically polished, examined, and vacuum heated to 1970°K without evidence of melting. The sample was then repolished, and vacuum heated to 1970°K.

Spectral emissivity was found by comparing optical pyrometer readings of the surface and a hohlraum, assuming the surface and the interior of the disk to be at the same temperature. The emissivity at 0.65 μ varies from 0.7 at 1100°K to 0.6 at 1700°K.

For the emission experiment, the UC-Nb served as an electron bombarded cathode of a plane parallel diode in a vacuum of $\sim10^{-5}$ mm Hg. To minimize anode heating, voltage was swept rapidly by hand. Data were recorded with an oscillograph over the temperature range 1380° to 1960°K for electric field strengths up to 23 000 v/cm. Corrected current densities of 6×10^{-4} to 1.4 amp/cm² were obtained. Schottky temperatures were lower than the observed temperatures (pyrometer readings corrected for emissivity) indicated field-strength limitations. Values of saturated current were obtained by passing a line with an observed-temperature slope through the highest data points. This is deemed reasonable since Schottky temperatures agree with

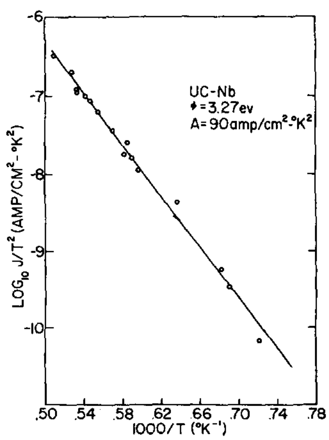

FIG. 1. Richardson plot for UC-Nb obtained from corrected Schottky curves.

observed temperatures at considerably higher fields for uranium carbide.[3] This analysis yields saturated current values that may be conservative. The resulting Richardson plot of Fig. 1 was analyzed by a method of least squares to obtain the Richardson constants $\phi=3.27$ ev, and $A=90$ amp/cm^2 °K^2. Expressed in terms of a temperature dependent work function,

$$\phi(T)=3.27+2.5\times10^{-5}T \text{ ev.}$$

The contributions of R. F. Hill, C. B. Leffert, W. J. Le Gray, and R. Silver to this experiment are gratefully acknowledged. The continued support of Dr. D. H. Loughridge and Dr. L. R. Hafstad of this work is greatly appreciated.

* This work is supported in part by the Office of Naval Research.
[1] G. Grover, Nucleonics 17, 54 (1959); F. E. Jamerson, IRE Natl. Conv. Record 8, 66 (1960).
[2] R. W. Pidd, G. M. Grover, D. J. Roehling, E. W. Salmi, J. D. Farr, N. H. Kinkorian, and W. G. Witteman, J. Appl. Phys. 30, 1575 (1959).
[3] G. A. Hass and J. T. Jensen, Jr., J. Appl. Phys. 31, 1231 (1960).
[4] Fabricated by Battelle Memorial Institute.

Forces in Dielectric Fluids*

James D. Horgan and David L. Edwards
Department of Electrical Engineering, Marquette University, Milwaukee, Wisconsin
(Received April 17, 1961)

THE purpose of this letter is to point out that certain electrihydrodynamic phenomena observed in dielectric liquids are most likely due to the ionization of the fluid, rather than to the polarization of the dielectric as previously supposed. Consider the arrangement shown in Fig. 1. The ring is of copper, with 2.54 cm i.d. and 0.635 cm axial length. The shield is brass foil, 12.7 cm in diameter and 15.24 cm in length. The fluid is a commercial transformer insulating oil. A similar arrangement, without the shield and disk was described by Pohl.[1]

When the shield and disk are removed and 9000–14 000 v dc applied to the electrodes, fluid is pumped vertically upwards as a fountain originating at the point of the needle. Because very similar results are obtained with the needle at either polarity it may seem that the principal action is due to the dielectrophoretic process described by Pohl, i.e., due to the forces experienced by molecular dipoles in a nonuniform field. The direction of such forces is not directly dependent on the direction of the field. If the principal effect was due to ionization produced by contamination, cosmic rays, and terrestrial radioactivity as suggested by Pierce[2] then, since ions of one sign would be dominant, the effect of changing polarity should be quite noticeable. Ionization can also be caused by a corona discharge at the needle point as stated by Stuetzer.[3] In such phenomena, the polarity of the charged particles in the body of the fluid is the same as that of the needle, and very similar results should be observed with the needle at either polarity.

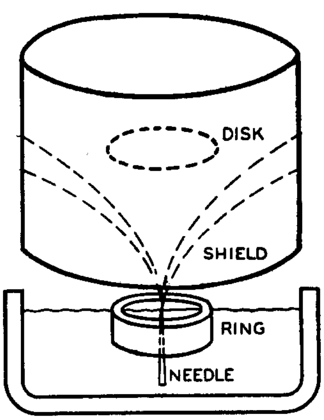

FIG. 1. Schematic of ring, needle, shield, and disk.

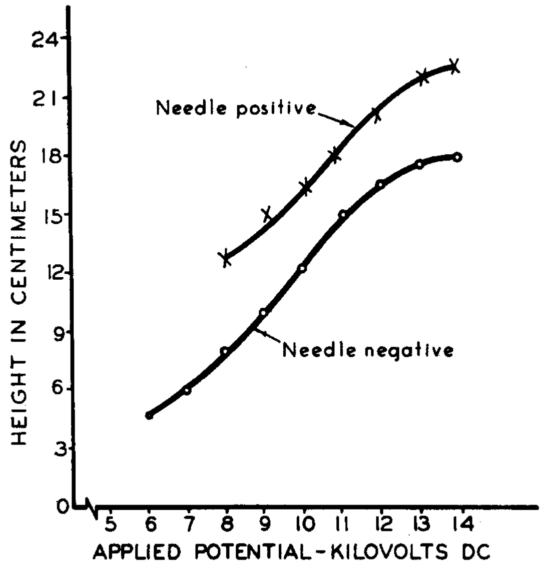

FIG. 2. Fountain height vs applied voltage.

To demonstrate that this is indeed a phenomenon dependent on the presence of charged particles rather than the dielectrophoresis process, the shield shown in Fig. 1 was added to the basic configuration. If the dielectrophoresis process is dominant, then changes in the potential and polarity of the shield should have little effect on the height of the fountain observed, since this is dependent primarily on the electric field intensity at the needle. In fact, however, reversal of the polarity of the shield potential relative to the needle potential results in very marked effects on the fountain height.

With ring and shield grounded and the needle positive, relatively large fountains are generated as shown in Fig. 2. Similarly, with ring and shield positive and the needle grounded, large fountain effects are observed. However, if the shield and needle are positive and the ring grounded, a relatively small (1–2 cm) fountain effect was observed for voltages in the range 8000–14 000 v. Similar small effects were observed with shield and needle grounded and ring positive. Such observations indicate that ions of the same polarity as the needle are dominant in the fluid, are therefore repelled from the needle and attracted to or repelled from the shield, depending on the polarity of the latter. To further demonstrate this, a conducting disk was lowered into the field region, as indicated in Fig. 1. When the disk is at the same potential as the ring, the fountain height can be increased 5–8 cm. When the disk is at the same potential as the needle, the fountain height is decreased, and can in fact be reduced to zero by properly lowering the disk.

* This work was supported by the National Science Foundation.
[1] H. A. Pohl, J. Appl. Phys. 29, 1182 (1958).
[2] E. T. Pierce, J. Appl. Phys. 30, 445 (1959).
[3] O. M. Stuetzer, J. Appl. Phys. 30, 984 (1959).

Formation of Liquid Jets in Nonuniform Electric Fields

Herbert A. Pohl
Plastics Laboratory, Princeton University, Princeton, New Jersey
(Received May 8, 1961)

THE present note by Horgan and Edwards demonstrates that the energy required for sustaining pumping action on liquids in nonuniform electric fields is supplied by current flow, and therefore involves electrophoresis.

This same conclusion is reached by thermodynamic arguments, for dielectrophoretic motion, which arises in a sense by