

Investigations on the Fluid Dynamics Of Spark Discharges¹

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Acoustical effects have been immemorially associated with spark discharges in thunder and lightning. Scientifically, however, the earliest association was probably that of Toepler, who used (1850) the light of spark discharges to make visible the accompanying air-pressure waves.

The investigation of spark discharges has been intensively carried on, yielding information in breakdown of the gas, and on the nature of the emitted radiation, temperatures and ion concentrations in the discharge, and the changes which occur in these quantities in time. If the breakdown of the dielectric be the phase of the discharge to which the term "spark" is restricted, then it is reasonable to say that a rather complete understanding of the spark is available. On the other hand, if the entire discharge is included in the term, much remains obscure. It is sometimes stated that the discharge after the disruption of the dielectric is simply to be regarded as an arc at high current. Our investigations have led us to the conclusion that this description is wrong when applied to the open spark; that the entire discharge has a unique character, and that a complete understanding of it cannot be achieved until the fluid flow processes present in the discharge have been considered.

In 1944, Rayleigh made the observation that the luminosity of an electrodeless discharge overflowed into side avenues out of the exciting field, and persisted as it flowed for times up to 10^{-5} second. Zanstra suggested that recombination of outflowing ions produced in the discharge could account for the long duration of the supposed afterglow, but Lee showed that the luminosity in the Rayleigh experiment was ejected in bursts, or fronts, whose space distribution could only be explained by assuming a continuing excitation of the gas during the expansion. An extensive investigation of the phenomenon was then undertaken with the support of the United States Office of Naval Research. It was found that the expansion of the excited gas during and after the discharge of electrical energy into the gas is in general completely analogous to the expansion of any compressed fluid upon the abrupt release of pressure.

Such an expansion comprises three main processes. First, a moving interface exists between the flowing gas originally external to the discharge, and the as yet undisturbed stationary gas also originally external to the discharge. This interface is known as a "shock wave" and moves with a speed many fold greater than the speed of sound in the stationary gas, and roughly 30% greater than the speed of the flowing gas behind the interface. Stationary gas molecules pile up as the interface moves, and the concomitant compression and entropy increase which occur across the interface raise the temperature by a large factor. The compression, when great enough, is accompanied by the production of a luminosity whose exact mechanics is not understood.

The second process is a moving interface between the flowing gas originally internal to the discharge and the flowing gas originally external to it. This interface is known as a "contact surface", and moves with the flow velocity of the gases, which is the same on either side of the interface. Pressure is also constant across this interface.

The expanding gas originally internal to the discharge can be looked upon as a gaseous piston which drives the external gas ahead of it. The contact interface is the head of this piston. When viscous heat transfer

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effects are negligible, the speed of flow of the gas will be constant all the way from the shock interface, past the contact interface and up to the foot of the third process, the *rarefaction* wave. This region is spoken of as a plateau.

The rarefaction wave is the region of pressure transition between the flowing gas originally interior to the discharge, and the as yet undisturbed, stationary gas originally internal to the discharge.

The rarefaction undergoes a complex motion. The velocity of the foot of the rarefaction is composed of a velocity equal to that which sound would have in the expanded, flowing, internal gas (directed inwardly, or away from the flow direction) combined vectorially with the outwardly directed flow velocity of the expanding internal gas. The motion of the head of the rarefaction wave is a motion at sound speed in the unexpanded, undisturbed internal gas, directed away from the flow direction. At intermediate points the wave moves with an appropriate combination of the local sound velocity and flow velocity.

The simplest equations governing the expansion are those for an ideal gas having a temperature-independent specific heat at constant volume. While it is not to be expected that highly ionized gases will behave wholly as ideal gases, comparisons have been made between experiment and ideal gas theory to test the fluid dynamic theory of the discharge to a first approximation. If U is the speed of the shock interface, u is the speed of the gaseous piston, and c_0 is the speed of sound in the undisturbed gas outside the discharge, then

$$\mu u / (\mu - 1) = U c_0^2 / U.$$

The constant μ is a function of the specific heats. i. e.

$$\mu = (C_p + C_v) / (C_p - C_v);$$

absence of dissociative processes at the shock is assumed in these expressions.*

To carry ideal gas theory across the shock interface is fairly reasonable, since the maximum dissociation to be expected is not very large. To continue on and apply it across the interface between the internal and external gases is extremely doubtful, because of the high temperatures and extreme dissociation present in the internal gas. Nevertheless such calculations are interesting for the numbers they yield. Thus the following formula for initial temperature (T_2) of the spark discharge can be derived.

$$T_2 / T_0 = 2.78 U^2 / C_0^2 = 1.85 U^2 / C_0^2 + \sqrt{U^2 / C_0^2} + \dots$$

for a monatomic gas. For ratios of U/C_0 of 10, which are commonly observed, T_2 would have been 12,000° K on ideal gas theory.

The expansion mechanism just described applies to the situation in which there are no chemical reactions at the shock front. If reactions are possible, the wave front may become a detonation or deflagration wave.

* These equations follow by elementary manipulation from three conditions which the gas must fulfill across the shock interface.

- | | |
|--|---|
| (1) Conservation of mass
per unit area in | $(U - \mu) \rho_1 = U \rho_0$ |
| (2) Conservation of momentum | $p_1 + (U - \mu)^2 \rho_1 = p_0 + U^2 \rho_0$ |
| (3) Conservation of energy | $(p_1 + p_0) (\tau_0 - \tau_1) / 2 = e_1 - e_0$ |

In addition to the quantities defined above, p is pressure, τ is specific volume, e is specific energy, while the subscript 0 refers to the gas at rest and 1 refers to the moving gas.

EXPERIMENTAL RESULTS

Turning to the experimental studies of the spark discharge at low pressure which are interpretable on the fluid theories just discussed, the bulk of measurements has been made using a very simple arrangement. A capacitor of 5 to 15 microfarads is charged to a potential of 1000 to 10,000 volts and discharged via a switch through a gas at 1/10 to 100 mm Hg pressure. The gas is usually confined in a cylindrical tube, and heavy nickel electrodes are introduced in the tube at strategic locations. One tube design which we have greatly favored is an imitation of the so called "shock tube", used in aerodynamic studies. It is shown in figure 1.

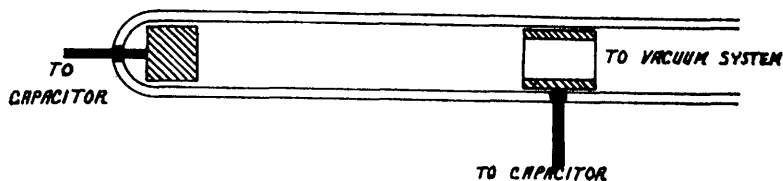


Figure 1.

A sequence of the theoretical events which were described previously as expected in such a shock tube is shown in figure 2.

Several experiments were performed to establish the fluid flow explanation of the luminous expansion effects. The luminous expansion itself was observed by the same rotating mirror technique which Rayleigh applied to it. Velocities of advance of luminosity could be established with fair precision ($\sim 10\%$). Lack of precision was caused by structure of the front, which we became partially able to understand and either eliminate or recognize and select against. Nevertheless there remained a small speed variation with time which made it impossible to assign a single constant speed to the flow, as ideally required.

Identification of the luminous expansion front with one of the critical processes of fluid flow was the first major problem. Two experiments showed that there is actual gas motion accompanying the luminosity. In the first, a 1000 A° thick diaphragm of cellulose nitrate was placed across the tube at the hollow electrode, and a different internal and external gas employed at the same time. Invariably the spectrum of the internal gas could be detected at all points in the expansion chamber. In a second experiment a magnetic field was placed at right angles to the gas velocity and a pair of probes set at right angles to both of these. Potentials at the probes were measured oscillographically, and calculation yielded ion velocities in substantial agreement with the speed of advance of the more commonly observed luminous fronts. Since this measurement also indicated gas motion outward from the discharge chamber, a contact surface must have existed in the flow. Therefore, because the usual luminous front had this same flow speed, we identified this usual form of luminous front as a contact surface.

The next problem was to detect the shock front which should be traveling in advance of any contact surface. The first evidence for the existence of this shock front came from reflection studies of the expansion. If the expansion chamber be terminated by an obstruction the flowing gas must come progressively to rest after the shock wave reaches the obstruction. This interfacial process of bringing the flowing gas to rest recedes along the expansion chamber counter to the direction of gas flow, and is itself a shock wave, which is termed a "reflected" shock. It moves first through the external gas, and then collides with the internal gas at the contact

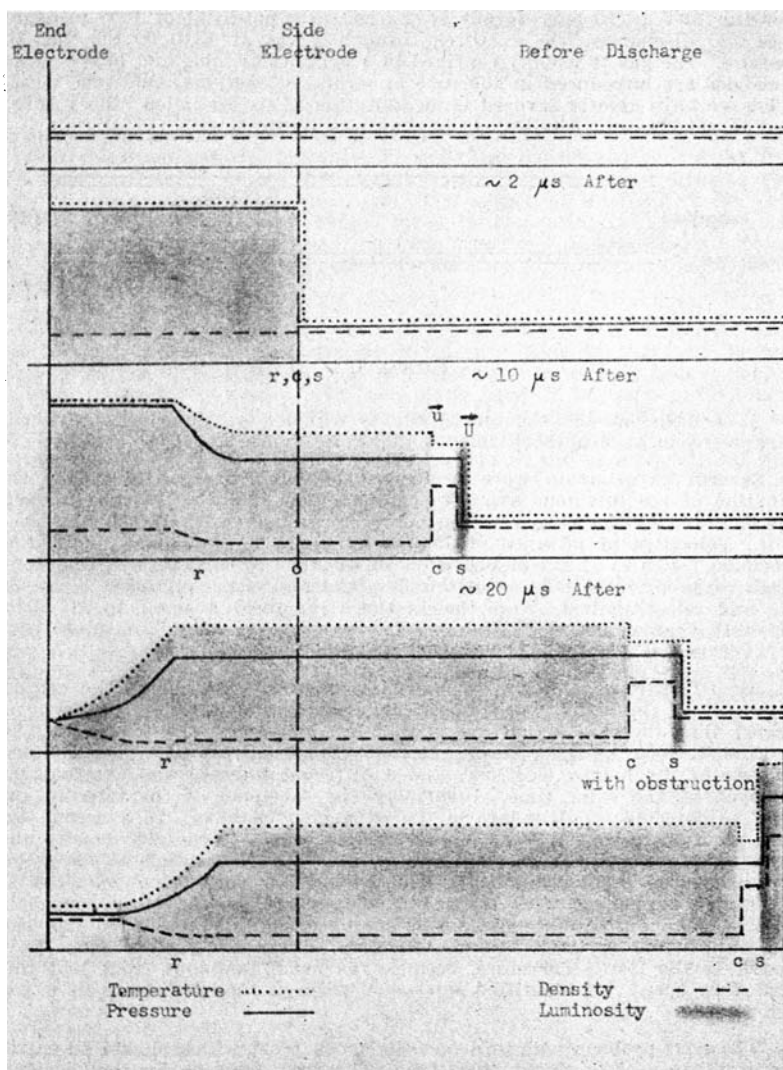


Figure 2

surface where an "interaction" and "refraction" of the shock occurs. In early mirror records of the expansion into an obstructed chamber, these interactions could be clearly seen at some distance away from the obstruction, implying the existence of the reflected shock and consequently of the primary shock also. Later, examination of a large variety of mirror records of obstructed expansion showed that as initial gas density was decreased, the structure of the record underwent a striking change. First, as the density was decreased, the reflected shock revealed itself by becoming luminous. Then at still lower densities, the primary shock also became luminous so that the leading edge of the luminous expansion at sufficiently low densities is a shock and not a contact surface. Finally, at extremely low densities (the exact range depends upon the nature of the gas), the contact surface became indistinguishable, and the entire luminosity was radiated from the shock front. It is nearly always possible to discriminate between the shock and contact surfaces by determining whether they reflect before or upon reaching an obstruction.

The most interesting conclusion at this point is that the original Rayleigh phenomenon, owing to the pressure range in which it was observed, is a self-luminous shock front propagating into the external gas.

Experimental detection of the accompanying rarefaction wave was afforded by the transition in flow velocity across the wave. At the head of the wave the gas is unexpanded and the flow velocity is zero. At the foot of the wave the flow velocity equals the velocity of the gaseous piston or contact surface. Thus as the rarefaction wave moves into the undisturbed gas the particles are accelerated continuously from zero velocity up to the velocity of the contact surface. Using the rotating mirror technique, localized inhomogeneities in the discharge chamber luminosity were observed to undergo such accelerations. The acceleration process moved away from the contact surface while the particles were accelerated toward it; thus showing the presence of a rarefaction wave.

Having detected and identified the critical interfaces in the flow, we next proposed to make a quantitative study of the degree to which the flow equations are fulfilled to confirm the identification positively. To detect the shock fronts even when they are non-luminous, a magnetic pickup was employed. With this pickup time of flight curves for the shock could be plotted for comparison with mirror records of the motion of the luminous contact surface. Over the measured range, the speed of the shock was in general much more constant than the speed of the contact surface. Since the theory discussed above ignores accelerations, calculation was made of the speed u^* of an idealized contact surface to match the constant speed shock, and this was compared with the actual decelerating contact speeds. It was found that the value u^* always agreed with that of the actual contact at some point along its course. During the early stages of expansion the actual contact advanced $\sim 10\%$ faster than predicted, while during the later stages it was often $\sim 10\%$ slower than predicted. Explanations of this behavior are easy to devise, in terms of dissociation, preheating, etc. The foregoing quantitative studies were conducted in helium, neon, argon, and xenon.

The fluid dynamic character of the expansion of the luminosity in the Rayleigh phenomenon, as opposed to such processes as excitation by jets of electrons, diffusive recombination, or migration of resonance radiation, can now be regarded as established.

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