

The Contact Surface in an Electromagnetic Shock Tube

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An investigation of the luminosity structure, electron density, temperature, and arrival time of electrode material in the shock heated region of the plasma produced in a T-tube has disclosed that for the conditions studied the luminosity from this region originates primarily from gases that have passed through the contact surface. A plausible explanation for this mixing of discharge gases with shock heated gas is discussed. The proposed inertial instability of the contact front is an alternative explanation rather than radiation absorption in the gas ahead of the luminous plasma for the high values of temperature and anomalous values of electron density that have been measured in electromagnetic shock tubes by numerous workers.

For high MACH numbers and an initial pressure of the order of 1 mm Hg CLOUPEAU¹ has shown that most of the luminosity in an electromagnetic H-shaped shock tube originates from the plasma produced by the driving current and not from gases that are shock heated. This conclusion is in agreement with the work of JEANMAIRE, KLINGENBERG and REICHENBACH² and of BARNARD and CORMACK³. CHANG⁴ has shown that the distance required for dissociative equilibrium to be reached is long, typically 0.4 to 4 cm for a M25 shock passing into un-preexcited hydrogen at an initial pressure of 0.2 mm Hg. McLEAN, FANEUFF, KOLB and GRIEM⁵ have explained their much shorter observed times to reach equilibrium as being due to the absorption of radiation in the gas in front of the shock. BREDERLOW⁶ has determined the position of the contact front and has observed luminosity emanating from the shock-heated region in hydrogen in a T-tube. The object of the present work is to extend BREDERLOW's investigations by making a spectroscopic study of the plasma produced under transition conditions when the gas in the shock heated region is becoming luminous. Spectroscopic methods described by GRIEM⁷ and the method of determination of the source of the plasma, based on the arrival time of certain impuri-

ties (NAGAKAWA and EARNSHAW⁸), are used. The effect of the heavy particles introduced by the driving discharge (CORMACK⁹) on the motion of the contact front is considered. The results are suggestive of an alternative mechanism to that proposed by McLEAN, FANEUFF, KOLB and GRIEM⁵ that would explain the short time to reach equilibrium and the high value of temperature and anomalous values of electron density that have been measured by numerous workers using electromagnetic shock tubes. The mechanism that is proposed is in agreement with the work of CLOUPEAU¹.

Apparatus

The T-type shock tube used had an internal diameter of 30 mm and contained 6 cm long electrodes of the same design as those used by BREDERLOW⁶. The $V \times B$ electrodes and wire net used by BREDERLOW⁶ were omitted. A 7.8 μ F capacitor was used as a current source and a 8 mm diameter 19 cm long carbon rod of d. c. resistance 130 milliohms was mounted as near as possible to the rear of the electrodes to serve as a back-strap and as a damping resistance. The current waveform observed with a ROGOWSKI coil encircling one arm of the T-tube was nearly critically damped and had only one overshoot. Current observations¹⁰ were made at shock tube pressures of 0.1, 0.25, 2.5 and 9.8 mm Hg

¹ M. CLOUPEAU, *Phys. Fluids* **6**, 679 [1963].

² P. JEANMAIRE, H. KLINGENBERG, and H. REICHENBACH, *Z. Naturforschg.* **18 a**, 318 [1963].

³ A. J. BARNARD and G. D. CORMACK, *Proc. 6th Int. Conf. on Ionization Phenomena in Gases*, Paris 1963, to be published.

⁴ C. T. CHANG, *Proc. 6th Int. Conf. on Ionization Phenomena in Gases*, Paris 1963, to be published.

⁵ E. A. McLEAN, C. E. FANEUFF, A. C. KOLB, and H. GRIEM, *Phys. Fluids* **3**, 843 [1960].

G. BREDERLOW, *Z. Naturforschg.* **18 a**, 868 [1963].

⁷ H. GRIEM, *Proc. 5th Int. Conf. on Ionization Phenomena in Gases*, Munich 1961; North-Holland Publishing Company, Amsterdam 1962, p. 1857.

⁸ Y. NAGAKAWA and K. EARNSHAW, *Proc. 6th Int. Conf. on Ionization Phenomena in Gases*, Paris 1963, to be published.

⁹ G. D. CORMACK, *Canad. J. Phys.* **41**, 1591 [1963].

¹⁰ These observations and other more complete details about the work described here are presented in a report to be published by the Institut für Plasmaphysik, Garching bei München.



of Hydrogen and capacitor voltages of 7, 10 and 14 kV. The maximum value of the current increased slightly when the initial pressure in the shock tube was increased. The ratio of the amplitude of the second current pulse to the first was 1/5 and the duration of the first current pulse was 3.9 to 4.15 μsec , the higher value being observed for low initial pressures and low capacitor voltages. The position of a small abrupt increase in the magnitude of dI/dt was observed at times of from 0.36 to 2.6 μsec after the current had started to flow. The lower value was observed when the pressure in the shock tube was 0.1 mm Hg and the capacitor voltage 14 kV and the higher value at a pressure of 9.8 mm Hg and a capacitor voltage of 7 kV. From the observed dependency of this time on the initial pressure in the shock tube and on the capacitor voltage, it could be concluded that this discontinuity in dI/dt was probably caused by the stopping of the axial motion of the current path between the electrodes. Such a conclusion is supported from simple acceleration theory by both the sign and the magnitude of the observed increase in dI/dt . Theory predicts that

$$\Delta(dI/dt) \approx -L_1 I \Delta(dx/dt) / (L_0 + L_1 x)$$

where $\Delta(dI/dt)$ is the increase in dI/dt at the time $t = \tau$ that is caused by a sudden decrease in the current sheet velocity of an amount $\Delta(dx/dt)$. L_1 is the inductance per unit length of the driver. L_0 is the time-independent inductance of the driving circuit and x is the distance that the current sheet has travelled down the tube at time $t = \tau$. This equation is valid only for a brief time after $t = \tau$. From the known circuit parameters and the values observed for t , the distance that the driving current moved down the tube could be calculated from simple acceleration theory [CORMACK⁹, equation (5)] to be always of the order of magnitude of the electrode length. This value is in agreement with the work of MUNTENBRUCH¹¹. He determined with magnetic probes that the driving arc does not go down a T-tube a distance past the electrodes of greater than about one tube diameter. It was concluded from the current measurements that the driving discharge did not travel down the tube to the location where spectroscopic observations were made, which was at $x = 24$ cm from the center of the arms of the T-tube. At a pressure of 2.5 mm Hg and a capacitor voltage of 10 kV, the plasma arrived at $x = 24$ cm 8.6 μsec after the current started to flow. When the capacitor was discharged from 13 kV the plasma took 6.8 μsec to travel to the observation point. Thus all spectroscopic measurements were made at a time when major magnetohydrodynamic effects due to the driving current were small. It is of further interest to note that the preceding measurements show that the ρ_1/ρ_0 data of BREDELOW⁶ should be multiplied by a factor of about 0.6. The corrected ρ_1/ρ_0 curves are then in close accord with snowplough theory, for a shock moving into gas that is not pre-excited.

A Steinheil $f/10$ three-glass-prism spectroscope equipped with either a mounting for photographic plate or a four-photomultiplier adaptor was used for the spectroscopic measurements. A limited amount of information on the spatial distribution of the plasma luminosity transverse to the axis of the tube could be obtained because two photomultipliers received radiation from a region 2 mm high and a fraction of a mm wide and the other two photomultipliers from a region of the same size but displaced by 3 mm in a direction transverse to the axis of the tube. Similarly each line in the time-integrated spectra recorded on photographic plates was due to the radiation coming from a region in the plasma 5 mm high with a blank region in the middle of height 1 mm. The blank region was caused by an aperture inserted at the entrance slit of the spectroscope. The spectral resolution of the spectroscope with the photomultiplier adaptor attached was sufficient to resolve lines at 4300 Å separated by 0.35 Å when the entrance and exit slits were 20 μ wide.

The same image convertor camera and rotating mirror camera as used by BREDELOW⁶ were employed for determining the velocity and the luminosity structure of the plasma.

Spectroscopic Measurements

With hydrogen in the shock tube at an initial pressure of 2.5 mm Hg and 10 kV on the capacitor, the velocity of the luminosity front at $x = 24$ cm was 1.5 cm/ μsec . Reflected shock observations with the image convertor camera and the rotating mirror camera used as a smear camera showed that there was no luminous incident shock in front of the main luminosity. A non-luminous shock-heated region having an axial dimension of less than about 5 mm could however have been present. The accuracy of measurement, about 1 mm, was insufficient to resolve whether or not the incident luminous front reached the reflector plate. At no time was the luminosity immediately in front of the reflector plate observed to be reproducible. A spectroscopic investigation of the plasma within 1 mm of the reflector plate was not attempted both because of the severe spatial requirement and the observed irreproducibility. BREDELOW⁶ has investigated the properties of the plasma produced under similar conditions. For example, in his Fig. 2, picture II, the velocity of the first luminosity front is 1.67 cm/ μsec and the initial pressure 2.5 mm Hg. For these conditions he detected a contact front moving with a velocity of 1.41 cm/ μsec at a distance behind the first luminosity front of about 8.6 mm. It is of interest to determine the state of the plasma both in front

¹¹ H. BRINKSCHULTE and H. MUNTENBRUCH, *Physikal. Verhandl.* **13**, 197 [1962].

of and behind this contact front. Thus electron density n_e measurements were made by observing the half-width of the emitted H_β line, temperature T measurements were made by the method described by GRIEM⁷ — by observing the ratio of total H_β intensity to the intensity of the underlying 100 Å wide continuum, and the arrival time of the Cr I 4254.35 Å line was measured. The first two measurements provided information on the state of the luminous plasma and the last the source of the plasma. The source could be pre-excited gas in front of the shock (McLEAN, FANEUFF, KOLB and GRIEM⁵) or gases from the driving discharge (CLOUPEAU¹).

Time integrated spectra of the radiation from the plasma revealed lines of H_β , H_γ and H_δ . When the amount of exposure was increased by using the most sensitive available spectroscopic plates and 200 firings of the shock tube for each exposure, then H_ϵ and the resonance lines of Cr I, Fe I, Si II and Ca II became just detectable. The metallic lines originated from material coming from the stainless steel electrodes and from two set-screws that joined these electrodes to the conductors in the arms of the T-tube.

At a luminosity front velocity of 1.5 cm/ μ sec the amplitudes of the photomultiplier signals often differed by as much as a factor of two for different firings of the shock tube. Shot-to-shot irreproducibility also affected the shape of the signals. The shape of the signal observed with a photomultiplier viewing a narrow region in the center of the H_β line was identical to that of the signal from a photomultiplier viewing the center of the H_γ line for the same shot when both photomultipliers received light from the same region of plasma. The shape of two such signals often differed considerably when the photomultipliers viewed regions of plasma separated 3 mm in a radial direction. Thus *the plasma being studied was markedly inhomogeneous*. Therefore the method of measuring spectroscopic quantities was modified to reduce errors caused by this inhomogeneity and the shot-to-shot irreproducibility. For example, all subsequent measurements were made with two photomultipliers that viewed the same region of plasma. Also all measurements were normalized to a simultaneously recorded standard signal. For example, a point on the H_β profile was obtained by simultaneously recording the oscillograms of the signals from two photomultipliers, one viewing the middle of H_γ and the other the radiation

in a narrow wavelength interval at the desired wavelength in H_β . The second signal was corrected to a small extent for photomultiplier spectral sensitivity from the manufacturer's data, for spectroscope dispersion and for the underlying continuum signal. This corrected signal within H_β was proportional to the intensity of the radiation in the wavelength interval defined by the slit widths. The continuum signal was measured by recording the signal from a photomultiplier that viewed a 10 Å interval centered on 5134 Å. The continuum signal at the desired wavelength within the H_β profile was determined by extrapolating the signal measured at 5134 Å using the theoretical continuum intensity vs. wavelength relation and appropriate corrections for slit widths, photomultiplier spectral sensitivity and spectroscope dispersion. These corrections were made in this manner since no absolute calibration of the optical system was made. The corrected H_β signal was then divided by the simultaneously observed H_γ signal and the resulting values at times of 0.2, 0.5, 1.0, 1.5, 2.0, 3.0 and 4.0 μ sec after the arrival of the luminosity plotted as points of H_β profiles. Errors due to shot to-shot irreproducibility were further reduced by recording and analyzing sufficient data to give about 35 points on each line profile. The size of the entrance slit and exit slits of the spectroscope were small enough to introduce negligible instrument broadening of the H_β line. $n_e(t)$ was then determined from each line profile from curves given by Kitayeva and Sobolev¹². The $n_e(t)$ results for a luminosity front velocity of 1.5 cm/ μ sec are presented in Fig. 1. The slight discontinuity between 0.5 and 1.0 μ sec behind the luminosity front is at the position where BREDELOW⁶ has observed a contact front. The theoretical value for n_e at equilibrium behind a shock having a front velocity of 1.5 cm/ μ sec and moving into unexcited hydrogen at 300 °K and 2.5 mm Hg pressure is less than $10^{13}/\text{cm}^3$. Thus the observed value for n_e , $\sim 10^{16}/\text{cm}^3$, is considerably higher than that directly due to shock heating.

The temperature measurements were made by first integrating each observed H_β line profile to obtain the total line intensity then dividing by the extrapolated value of the continuum signal noted above. The observed ratios of line intensity to 100 Å continuum intensity and the observed values of $n_e(t)$

¹² V. F. KITAYEVA and N. N. SOBOLEV, Proc. 5th Int. Conf. on Ionization Phenomena in Gases, Munich 1961; North-Holland Publishing Company, Amsterdam 1962, p. 1897.

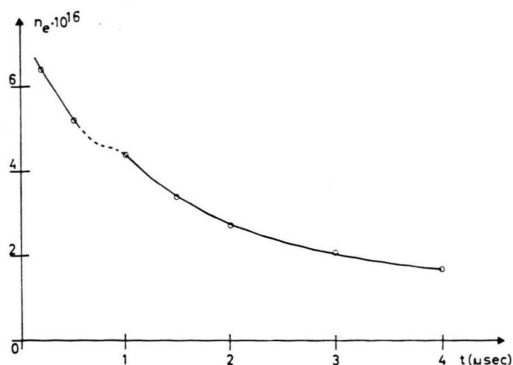


Fig. 1. Electron density throughout luminous plasma. The velocity of the luminous front at the observation location, $x=24$ cm, was 1.5 cm/ μ sec. $t=0$ defines the arrival of the first luminosity at $x=24$ cm.

were then compared with curves given by GRIEM⁷ for intensity ratio as a function of T and n_e . The result $T(t)$, temperature as a function of time after the arrival of the luminosity front, is presented in Fig. 2. Again a discontinuity is evident at $0.5 < t < 1.0$ μ sec. The temperature is lower in front of this discontinuity than immediately behind it. The temperatures shown in Fig. 2 could be too high because radiation from weak Fe I lines in the 10 Å wavelength interval centered about 5134 Å has been neglected. However these lines were never observed even on the spectral plates exposed to the light from 200 firings of the shock tube. The observed temperatures are in approximate agreement with the results of RAMSDEN and McLEAN¹³. They measured a temperature of 1.8 eV for a M20 shock passing into

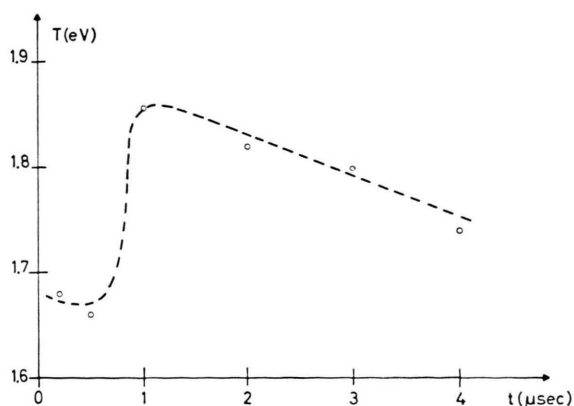


Fig. 2. Temperature throughout luminous plasma. Experimental conditions were the same as for Fig. 1.

¹³ S. A. RAMSDEN and E. A. McLEAN, *Nature, Lond.* **194**, 761 [1962].

hydrogen initially at 0.5 mm Hg pressure. For a 1.5 cm/ μ sec shock moving into hydrogen at 300° K and a pressure of 2.5 mm Hg the temperature predicted from shock theory is 0.35 eV. Thus the measured temperature throughout the luminous plasma is higher than that predicted by the theory for a shock moving into unexcited, un-preheated gas. It must be stressed that not too much emphasis should be placed on the accuracy of the measured values of temperature, primarily because thermal equilibrium has been assumed to exist.

The arrival time of the chromium line radiation was observed with the two photomultipliers that

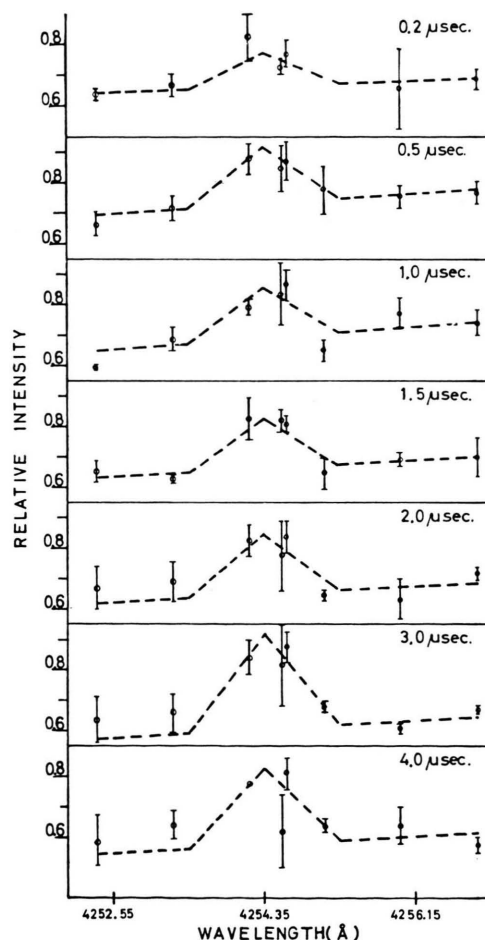


Fig. 3. Detection of Cr I 4254.35 Å. Slit widths were of such a size that the luminosity width in these graphs should ideally be 1.8 Å wide and of the triangular shape shown. Experimental conditions were as in Fig. 1. The ordinate of each graph is the ratio of the signal observed near 4254.35 Å to a normalizing signal at 4426.6 Å. Each point is the mean value of up to 8 observations and each error bracket denotes the standard error of the mean.

received light from the same region of plasma. All spectroscopy slits were opened to $100\ \mu$ to provide maximum sensitivity to line rather than continuum radiation. One exit slit was centered on $4426.6\ \text{\AA}$ to provide a normalizing signal and the other was scanned from shot-to-shot in small wavelength intervals about $4254.35\ \text{\AA}$. The observed signal on or near $4254.35\ \text{\AA}$ was divided by the normalizing signal to reduce the effects of the shot-to-shot irreproducibility, then plotted as a function of wavelength and time. The graphs shown in Fig. 3 show that there is chromium throughout the luminous plasma. The luminous plasma thus is not solely shock heated gas but is also gas that has been accelerated by the driving discharge.

Chromium arrival time measurements were repeated at a capacitor voltage of 12 kV and a resulting shock velocity at $x = 24\ \text{cm}$ of $2.0\ \text{cm}/\mu\text{sec}$. This velocity is the same as that studied by BREDERLOW⁶, for example in his Fig. 2, picture III. The arrival time results were identical to those at the lower velocity. The luminous plasma thus still contained gas that originated from the driving discharge. The capacitor voltage was then increased to 13 kV giving a shock velocity of $2.5\ \text{cm}/\mu\text{sec}$ at $x = 24\ \text{cm}$. Small signal amplitude and shot-to-shot irreproducibility obscured any positive evidence that chromium was again throughout the plasma. Arrival time measurements made with the lines Ca II $3933.67\ \text{\AA}$ and Si II $4128.11\ \text{\AA}$ also gave indefinite results. The maximum value of $n_e(t)$ determined from the half-width of the H_β line was $1.2 \times 10^{17}/\text{cm}^3$ whereas the value predicted by shock theory is of the order of $10^{13}/\text{cm}^3$. Again the observed value of n_e was higher than that predicted for a shock moving into unexcited, un-preheated gas.

Luminosity Structure

Typical image convertor camera pictures of the plasma produced at various luminosity front velocities are given in Fig. 4*. Each velocity given is that of the first detectable luminous region at $x = 24\ \text{cm}$. Although different firings of the shock tube resulted in somewhat different luminosity structures for the same discharge conditions, the following properties are considered to be representative for each particular velocity. As noted by BREDERLOW⁶ the luminous

plasma at the lower velocities does not contact the walls. For $v < 2\ \text{cm}/\mu\text{sec}$ the luminosity front has the same slope as observed by both LIEBING¹⁴ and BARNARD and CORMACK³ in quite different geometries of electromagnetic shock tubes. In all of the pictures regions of luminosity can be seen moving ahead of and faster than the region of major luminosity. In particular, it follows from the observed luminosity structures and the chromium arrival time measurements that $n_e(t)$ and $T(t)$ in Fig. 1 and 2 for $0 < t < 1\ \mu\text{sec}$ are values for plasma that has passed through the contact front. For example, in the lower picture of the luminosity that is shown for $v = 1.5\ \text{cm}/\mu\text{sec}$ a non-homogenous, non-plane, faintly luminous region can be seen preceding the main luminosity. This faint luminosity does not have the characteristics that are normally attributed to heating by a plane shock: homogeneity and either a plane and well-defined or plane and diffuse front. *Thus this luminosity does not come from shock heated gas.* It is also of interest to note that this faint region is not detectable later when the plasma has moved further down the tube, for example in the middle and upper pictures at this velocity. This previously luminous gas must be present in the non-luminous shock-heated region and must affect the properties of the gas in this region. Because only luminous plasmas have been studied in the present work this additional heating mechanism of non-luminous shock-heated gases has not been investigated further. For $v > 2\ \text{cm}/\mu\text{sec}$ the luminous front becomes sloped in a direction opposite to that observed for $v < 2\ \text{cm}/\mu\text{sec}$ and is now tending to become well-defined. However the slope of this front increases as the plasma moves down the tube. Thus there is still some mechanism present that is preventing the usual stabilizing characteristic of a shock from being operative. The dependancy of the angle of the front on the capacitor voltage could be due to the motion of a region of heavy particles inside the plasma. The driving current sputters off material from the anode of the driver and any glass subjected to electron bombardment, for example that near the tip of the anode. The heavy ions are then accelerated both down the tube and in a transverse direction. The amount of transverse motion that occurs increases with increasing capacitor voltage. Thus at $x = 24\ \text{cm}$ and at low voltages the region of sputtered material

* Fig. 4 on p. 938 a.

¹⁴ L. LIEBING, Phys. Fluids **6**, 1035 (1) [1963].

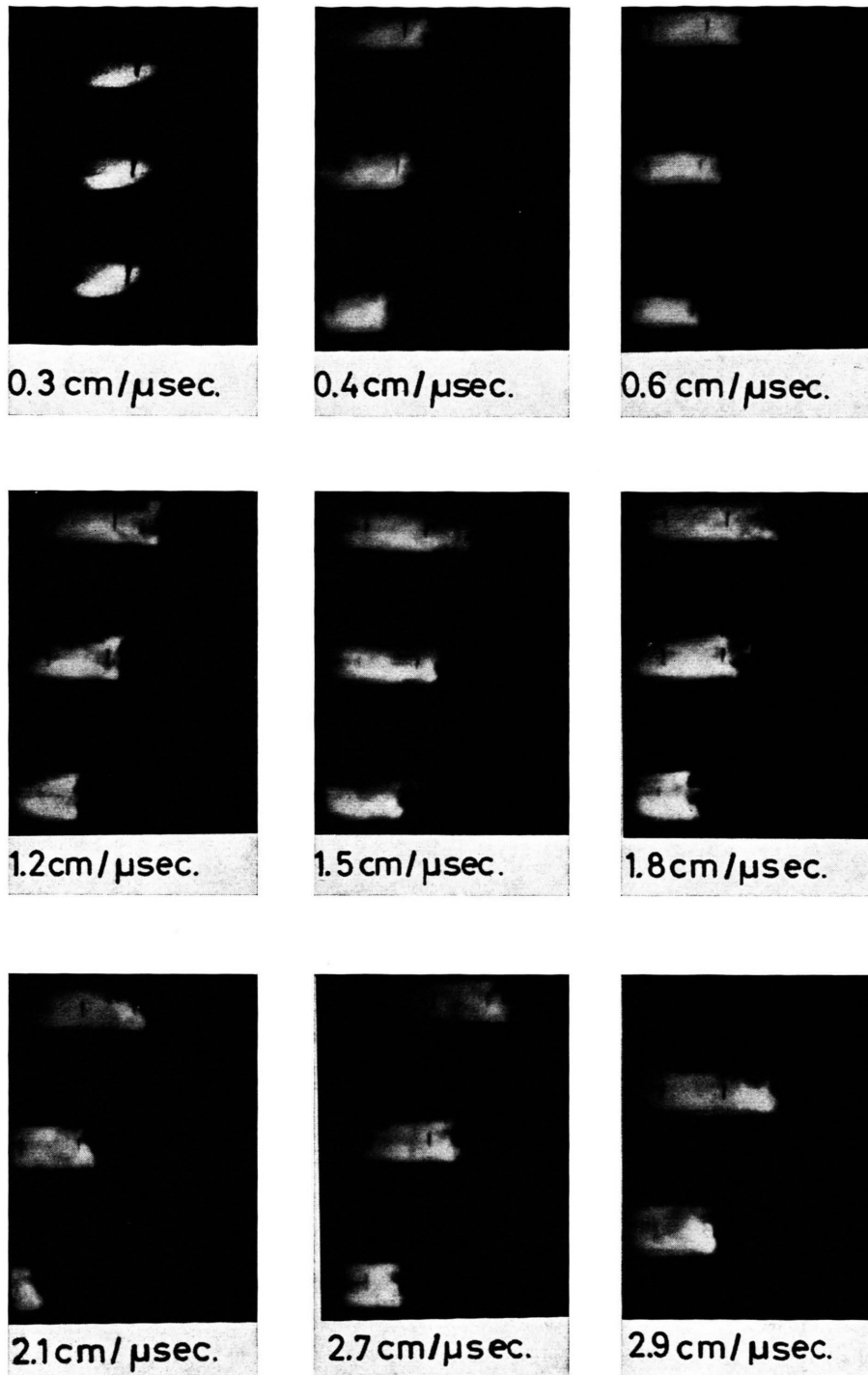


Fig. 4. Luminosity structure of plasma. Fiducial marks are at $x=19, 22$ and 25 cm. Luminosity front velocities at $x=24$ cm are given. Each set of two or three pictures is of the same plasma and the delay time between each picture is $1.2 \mu\text{sec}$. The initial pressure in the shock tube was 2.5 mm Hg and

different velocities were obtained by varying the capacitor charging voltage. The left side of each picture is cut off by a diaphragm and the different vertical spacings between pictures does not affect the magnification.

could still be at the top of the tube whereas at higher voltages the region could have been accelerated sufficiently in the transverse direction to be at the bottom of the tube. This explanation for the change in angle is only a proposed explanation. Although the front is non-reproducible and non-plane when $v > 2$ cm/ μ sec, no regions of plasma were observed to be ejected through the front at these high velocities. Also at these high velocities the plasma was more homogeneous.

Reflected shock pictures revealed a zone of non-luminous shock heated gas in front of the luminous plasma when $v < 1.5$ cm/ μ sec. The accuracy of observation, about 1 mm, was insufficient to resolve whether or not a zone existed at higher velocities. Plots of either arrival time or velocity as a function of capacitor voltage could be asymptotically approximated by two straight lines that intersected at a velocity of about 1.5 cm/ μ sec. It is concluded that below this velocity a non-luminous shock preceded the luminous plasma and that for velocities greater than approximately this value the luminosity front coincided with the shock front.

Discussion

The presence of the discharge gases in the region of shock heated gas shows that the enthalpy, pressure and density in the luminous region of the shock heated gas cannot be predicted by the simple RANKINE-HUGONOT relations. Rather if one insists on using these relations one must take into account for example the increase in the enthalpy in this region that comes from the energy flow across the contact front. This energy is transferred by radiation, thermal conduction, and mass transfer. The present observations have shown that the flow of high temperature gases through the contact front and their resultant mixing with the shock heated gas is a major contribution to this energy flow. The RANKINE-HUGONOT equations could be modified, most simply but not adequately, by introducing one term in the energy equation. This term would be an enthalpy term that would take into account the energy that is transported into the shock heated region by the discharge gases that pass through the contact surface. Such a term would be mathematically equivalent to the radiative energy transfer term that has been proposed by McLEAN, FANEUFF, KOLB and GRIEM⁵ to explain their high temperature and low electron density observations.

Mechanisms such as proposed by CLOUPEAU¹ will contribute to the spreading out of the contact front. In the present experiments an inertial instability of the contact front can explain the presence of the ionized heavy atoms in the shock heated gas and the observed structures of the luminosity. The passing of regions of plasma through the contact front could be due to not only a non-homogeneous mass density distribution behind the front but also by the motion of regions possessing a higher-than-average momentum. The latter mechanism would account, for example, for the shape of the luminosity front shortly after a second region of plasma accelerated by the second half-cycle of current has overtaken the luminosity front produced by the first half-cycle of current. A typical smear picture showing this phenomenon is given by CLOUPEAU¹ in his Fig. 4. It is believed that this phenomenon is not responsible for the shape of the luminosity front in the present experiments. For example, in the smear pictures given by BREDERLOW⁶ in his Fig. 2, II and III, a second faint region of luminosity can be seen about 5 μ sec behind the primary front.

This second region is accelerated by the second half-cycle of current, however to a velocity that is insufficient for the overtaking of the primary front. When the plasma behind the contact front has a non-homogeneous mass density distribution, the motion of each small region of non-homogeneity is deceleration dependant. The deceleration of the plasma in an electromagnetic shock tube is usually of the order of 10^{11} cm/sec². The deceleration is in such a direction as to favor RAYLEIGH-TAYLOR or other inertial instabilities that would develop on the surface of the contact front when the mass density of the gases behind the front exceeds that of those before the front. The marked lack of inhomogeneity behind the contact front for $0.6 < v < 2$ cm/ μ sec favors the passage of regions of plasma through the front rather than the more-ordered RAYLEIGH-TAYLOR instability. Such motion of regions has been recorded in numerous photographs in the present work. The lack of homogeneity and the persistence of the internal structure of the luminosity indicates that mixing through diffusion and turbulence are of minor importance in comparison to mixing that is due to the motion of inhomogeneous regions. The increase in homogeneity observed when $v > 2$ cm/ μ sec and the smoothing out of the shape of the luminosity front could be explained by enhanced diffusion at the

higher temperature and the probable joining together of the shock front with the luminosity front (see also CHANG¹⁵). The persistence of the structure of the luminosity is still evident at these higher velocities. For example, the slope of the front increases as the plasma moves down the tube. This tendency of the front to become less plane as the plasma moves down the tube has also been noted by McLEAN, FANEUFF, KOLB and GRIEM⁵. The present work indicates that the region immediately behind the luminosity front is partially composed of gases accelerated by the driving discharge. The actual shape of the front would be determined by a balance between the stabilizing effect of the shock (FREEMAN¹⁶) and the unstabilizing effect of inertial instabilities. One further noteworthy characteristic introduced by the deceleration of the shock front in an electromagnetic shock tube is the introduction of a deceleration-dependency of the density on the distance from the front. This deceleration-dependency is expressed accurately by blast-wave theory. The magnitude of the inertial effects acting on regions near the contact surface can be estimated by comparing the scale heights (OPIK¹⁷) of hydrogen and chromium. For example, the scale height for 5,000 °K hydrogen atoms subjected to a deceleration of 10^{11} cm/sec² is 3.2 cm and for gaseous chromium 0.1 cm. The difference in these scale heights indicates that there can be a mass filtering action at the contact front. Heavy particles and/or regions of higher than average value of local mass density can move through the contact front. Since the deceleration of the plasma invariably increases when the velocity of the plasma is increased or when the initial gas pressure is decreased, it follows that the mass filtering action would be more pronounced under conditions of high velocity and low density, the regime of operation that has been of most interest to users of electromagnetic shock tubes.

The instability mechanism that has been proposed could have a wide range of applicability. For example, there have appeared numerous papers dealing with electromagnetically-driven shock waves in which irreproducibility is a common characteristic. Irreproducibility favors the inertial instability explanation for the inapplicability of the simple RANKINE-HUGONOT relations rather than the radiative energy transfer mechanism proposed by McLEAN, FANEUFF, KOLB and GRIEM⁵.

It has been established for the conditions studied that the region immediately ahead of the contact front is inhomogeneous and contains high temperature, high electron density gas that originates from behind the contact front. It cannot be concluded that this mixing process occurs under all conditions in electromagnetic shock tubes. For low velocities and high initial pressures JEANMAIRE, KLINGENBERG and REICHENBACH² have shown that a shock front can exist in a T-tube. The presently proposed instability mechanism could however account for the failure of numerous workers to obtain impurity-free, homogeneous plasmas formed behind plane shock fronts under conditions of low initial pressure and high velocity in electromagnetic shock tubes.

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¹⁵ C. T. CHANG, *Phys. Fluids* **4**, 1085 [1961].

¹⁶ N. C. FREEMAN, *Proc. Roy. Soc., Lond. A* **228**, 341 [1955].

¹⁷ E. J. OPIK, *Physics of Meteor Flight in the Atmosphere*, Interscience Publishers Ltd., London 1958, p. 8.