DEVELOPMENT OF A COMPRESSION APPARATUS AND STUDIES ON HEAT TRANSFER AND COMBUSTION OF RAPIDLY COMPRESSED AND OSCILLATING GASES

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PART II*

8. CALCULATIONS OF MOTION OF PISTON AND THE RESULTING GAS PRESSURE

Since compression apparatus have been adopted recently to an increasing extent for investigations into knocking combustion, self-ignition, ignition delay, etc., it was thought advisable to investigate the motion of the piston in greater detail and to see whether means could be established to calculate and predict during design, the behaviour of the piston, and thus the main characteristics of the apparatus.

8.1 *Pre-suppositions of mathematical treatment*

Due to the high piston velocity, the flow of the gas is governed by the laws of gas dynamics at high velocities and as the flow pattern is three-dimensional and affected by throttling, vorticity and turbulence, calculations are difficult. The state of the gas at any point of the piston stroke influences the piston velocity so that if the state of the gas remains unaccounted, the piston velocity can be calculated only approximately.

The simplified scheme of the apparatus is shown in Fig. 44, and the essential neglections are indicated which have been introduced. The throttling effect in

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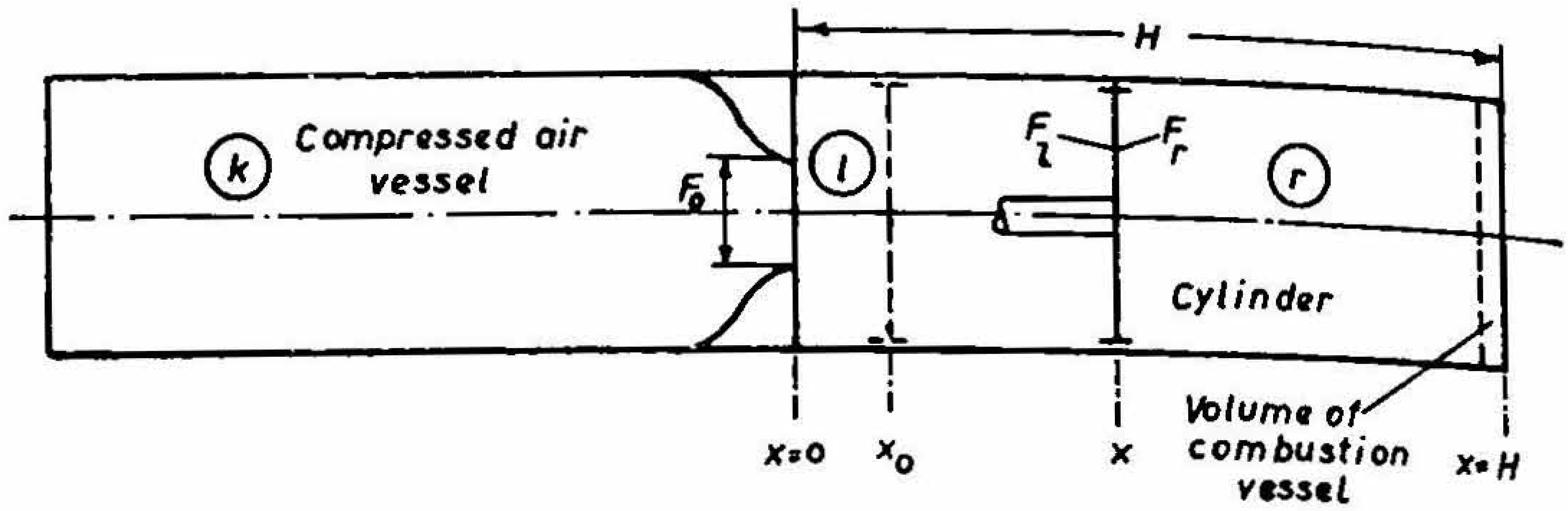

FIG. 44. Simplified scheme of compression apparatus for theoretical considerations.

the passage through the bomb valve and the adjacent portions of the apparatus have been neglected entirely and it is assumed that the change of the state of the gas in the space to the left hand side of the piston, denoted by the index (l) is adiabatic with the exponent for air equal to 1·4. At the right hand side of the piston, denoted by index r, a polytropic exponent of 1·3 is assumed as an additional variation, besides assuming 1·4. The calculation was carried out for an initial pressure in the compressed air vessel of 9 atmospheres (index k, with affix o).

8.2 *Statement of Calculation*

The following connotations have been introduced besides those already mentioned:

C (m./sec.)	..	Piston velocity
F_l (m.^{2})	..	Area of piston facing the space left to the piston
F_r (m.^{2})	..	Area of piston facing the space right to the piston
G (kg.)	..	Weight of gas
H (m.)	..	Total length of cylinder
M (kg. sec.^{2}/m.)	..	Mass of moving parts
p (kg./cm.^{2})	..	Pressure
P_R (kg.)	..	Frictional Force
u, U (kcal./kg., kcal.)		Internal energy of the gas
v (m.^{3}/kg.)	..	Specific volume of the gas
X (m.)	..	Co-ordinate of length
X_0 (m.)	..	Initial position of the pistons at the time $t = 0$.

For the piston, the equation of motion is

$$M \frac{dc}{dt} = M \frac{d^2X}{dt^2} = p_l F_l - p_r F_r - P_R + (F_r - F_l)\, p_{10} \tag{16}$$

The last term on the right hand side makes allowance for the free end of the piston rod which is subjected to the pressure outside which is equal to p_{10}. The change of state in the space at the right hand side of the piston, follows the relation

$$p_r v_r^k = p_{r0} \cdot v_{r0}^k \text{ with } v_r = \frac{F_r (H - X)}{G_r}, \; p_r = \frac{(H - X_0)^\kappa}{(H - X)} \cdot p_{r0}. \qquad (17)$$

Inside the vessel for compressed air,

$$p_k \cdot V_k^k = p_{k0} V_{k0}^k, \text{ where } V_k = G_k \cdot v_k = G_{k0} \cdot v_{k0}. \qquad (18)$$

The energy available inside the space K is given by

$$U_k = G_k \cdot u_k \qquad (19)$$

and the change, with time during the compression stroke is given by

$$\frac{dU_k}{dt} = d \frac{(G_k u_k)}{dt}. \qquad (20)$$

The condition for constant energy in the space (l) then reads

$$\frac{dU_k}{dt} + \frac{dU_l}{dt} + A \, p_l F_l \frac{dX}{dt} = 0, \qquad (21)$$

where additionally

$$G_k + G_l = G_{k0} + G_{l0}. \qquad (22)$$

The flow from the compressed air vessel into the space (l) is given by

$$\frac{dG_l}{dt} = F_0 \psi \sqrt{2g \frac{p_k}{v_k}}, \qquad (23)$$

if it is assumed that the gas enters through a convergent nozzle with the smallest cross-sectional area F_0, from the air vessel into the space (l). The choice of F_0 has to take into account the constriction in the throat and the friction. ψ is a function of the pressure ratio in both space and is discussed for instance by E. Schmidt.[28]

With the abbreviation $\phi = (G_k/G_{k0})^k$ after some calculations and introduction of frequently used thermo-dynamic equations the following system of the equations is found

$$\frac{p_l}{p_k} = \frac{k-1}{A} \frac{U_l}{F_l . X . p_{k0}} \cdot \frac{1}{\phi}; \; \phi = \left(\frac{G_k}{G_{k0}}\right)^k \qquad (24\,a)$$

$$\frac{d\phi}{dt} = -\frac{k}{G_{k0}} \cdot F_0 \sqrt{2g \frac{p_{k0}}{v_{k0}}} . \psi . \phi^{\frac{3k-1}{2k}} \qquad (24\,b)$$

$$dX = c . dt \qquad (24\,c)$$

$$\frac{dU_l}{dt} = - U_{l0}\frac{d\phi}{dt} - (k-1)\frac{U_l}{X}\cdot\frac{dX}{dt} \tag{24 d}$$

$$\frac{dc}{dt} = \left[\frac{(k-1).U_l}{A\cdot X} - F_r . p_{r0}\left(\frac{L-X_0}{L-X}\right)^n - P_R + (F_r - F_l)\, p_{l0}\right]\frac{1}{M} \tag{24 e}$$

$$p_r = p_{r0}\left(\frac{L-X_0}{L-X}\right)^n \tag{24 f}$$

8.3 *Calculation and discussion of Results*

The solution is found by applying a step by step method with linear interpolation in tables; the step Δt has to be sufficiently small. For the initial stages of the compression Δt was chosen to be $2\cdot 10^{-4}$ seconds. The result with this value Δt was checked by an increment of half this value which did not give any deviations.

At time $t = 0$, the state is given by the limiting conditions

$$\phi = 1;\; U_l = U_{l0},\, x = x_0,\, c = 0.$$

From equation (16) follows p_l/p_k and from this value ψ and with equation (17), the value $d\phi/dt$ can be found as indicating the decrease of the weight of gas in the compressed air vessel during time dt so that the new value of ϕ for the next step is $\phi + d\phi$. The change in the position of the piston follows from equation (18) to be $c.dt$. The change of internal energy U_l during dt is given with the help of equation (21) and from equation (23) finally follows the change of velocity dc so that the piston velocity for the next step is now $c + dc$. With the last mentioned relation, the pressure in the space (r) can be found for which process the exponent may be polytropic, *i.e.*, n, or adiabatic, *i.e.*, k. Due to the frictional force acting on the piston, the starting process must be calculated with $c = 0$ until a resulting piston force has been developed which equalises the frictional force, P_R, assumed to be constant.

The results of the rather lengthy calculations—dotted lines—are shown in Figs. 45 and 46 which for the sake of comparison contain also results of tests—full line. Fig. 45 shows the piston velocity and the ratio of the stroke at a given time to the maximum stroke of the piston.

The calculation shows a slower increase in the speed of the piston near its starting point. This may probably be caused by some dynamic effect of the gas which may additionally accelerate the piston probably due to the dynamic impact of the air jet impinging on the piston. The friction of the piston may also be lowered considerably as soon as the piston starts moving. The lower velocity peak of the piston as found in tests as compared to the calculation may be caused by the inertia of the gas which results in the fact that the rate of flow issued by the compressed vessel is less than it should be according to the pressure ratio, at later stages of the compression stroke.

For the same reason the distance covered by the piston differs in theory and reality. Towards the end of the motion of the piston the ratio s/s_{max} exceeds unity which is due to the fact that in the calculation, the effect of braking the piston was not taken into account. Fig. 46 shows the change of pressure with time for the gas spaces in front of, and behind, the piston according to measurements and according to the calculations. Due to the higher piston velocity found in the

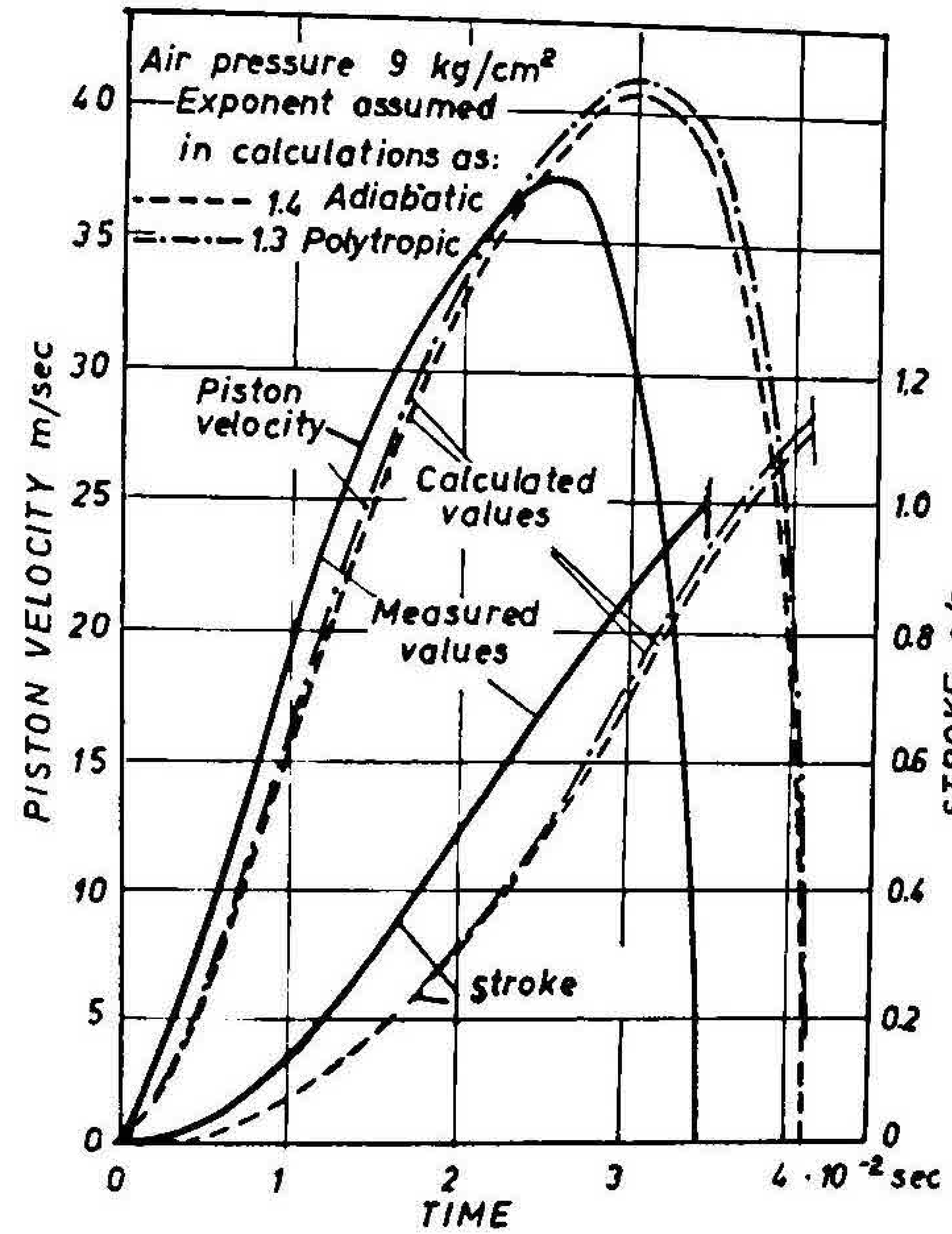

FIG. 45. Comparison of velocity and stroke of piston calculated and according to measurements for air pressure of 9 kg./cm.

experiment, the pressures will be higher in front of the piston and lower behind the piston, if these results are compared with the calculation. The effect as revealed in the diagrams of the introduction of two different exponents for compression is reasonable; the pressure calculated, assuming an adiabatic change of state is higher than the pressure resulting from a polytropic change of state.

Finally it can be stated that the calculation which rests on a stationary interpretation of the change of state renders fairly good results with a reasonable expenditure of calculating effort if compared to the procedure in reality. It is thus possible to anticipate by calculation the effects of dimensional changes during the design state.

For still higher piston velocities the inertia of the gas has to be taken into account.

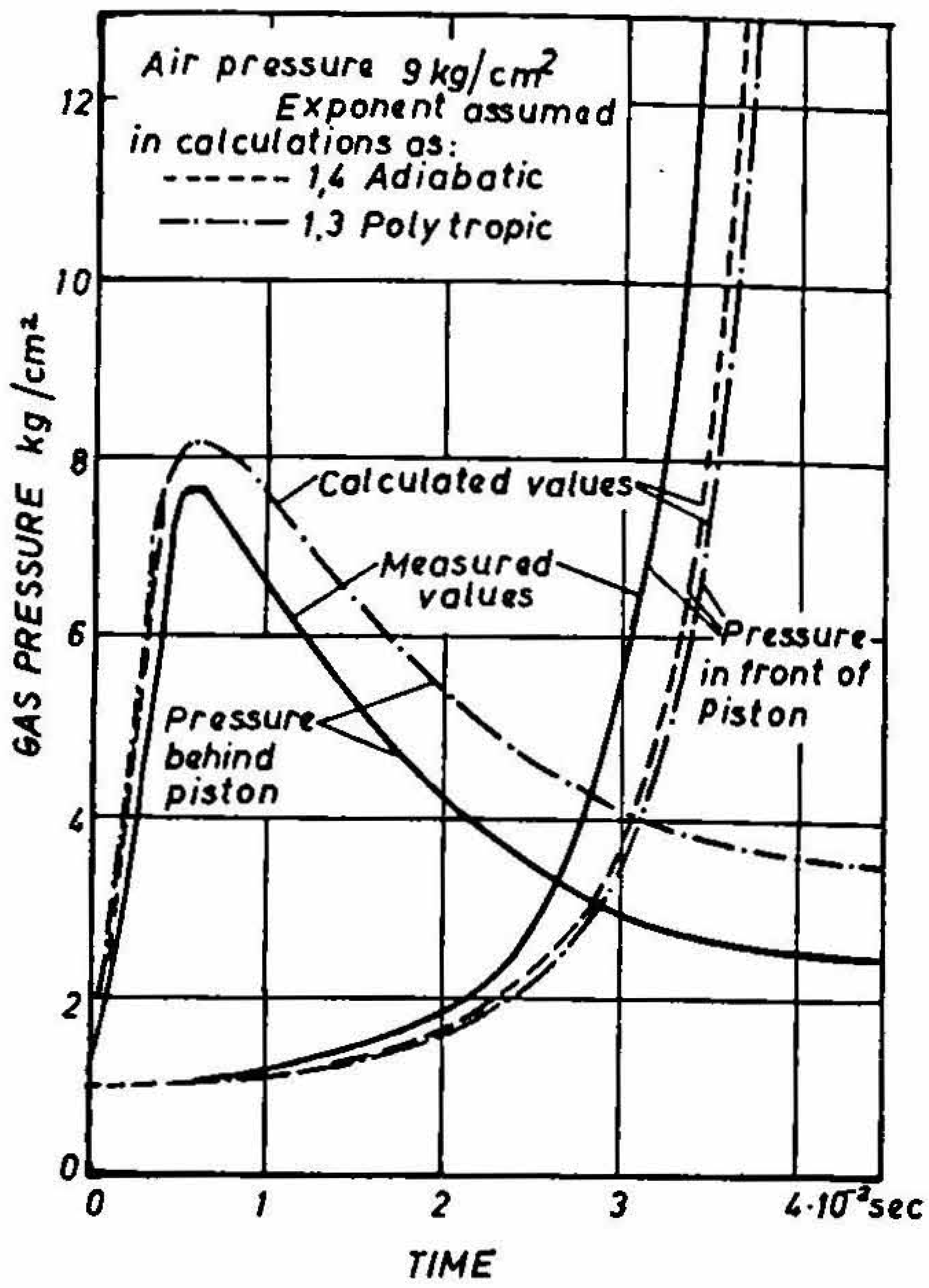

FIG. 46. Comparison of pressures in front of and behind the main piston calculated and according to measurement for air pressure of 9 kg./cm.[2]

9. EXPERIMENTS ON COMBUSTION OF OSCILLATING GASES

The velocity with which a flame propagates in a combustible gas mixture in opposition to the direction of the gas flow, depends on pressure, temperature, time of induction and the composition of the gas mixture, these factors influencing the chemical processes during the combustion. This velocity is found also in the Bunsen burner and is generally designated as normal propagation velocity. This velocity, however, is influenced by flow conditions which results in an increase of the flame velocity with respect to the unburnt matter, and represents the velocity of propagation of a flame in the axis of a combustion vessel relative to the unburnt matter supposed to be at rest. This condition can be represented by ignition at the open end of an otherwise closed vessel, for instance a long pipe. If the unburnt matter has a velocity of its own, the apparent flame velocity will be the result of superimposing the flame velocity as occurring in the gas at rest, with the velocity of the gas. The magnitude of the apparent flame velocity, however, depends furthermore on physical effects in the gas flow, *e.g.*, its vorticity, if considerable secondary movements occur in the gas flow, and its turbulence, in which case small secondary movements are encountered. Thus the apparent flame velocity will depend on the velocity of the gas in a complex manner. The expansion of th unburnt matter, furthermore, can result in an additional motion by displacing the unburnt gas, and with it the flame front. Natural convective gas motions also play a part in finally shaping the flame front, and so do, of course, external influences such as irregularities in the wall of the combustion vessel, separation of the gas flow from the wall, etc.

The influence of turbulence on the velocity of flame propagation plays an important role in motoric combustion. It is not clear whether the velocities of flames observed in internal combustion engines, which are of the order of 10 to 50 m/sec. result from the motion of vortices of burning gas or whether the "smaller grained" turbulence alone is able to raise the flame velocity to 10 till 100 times the value of the normal flame velocity.

Connected with this question is the problem of an increase of the flame velocity by oscillations which are imposed on the burning gas mixture. Nielsen[29] found by experiment that under certain conditions the combustion process initiates oscillations of the gases and subsequently the flame velocity is increased. In order to study the influence of the oscillation of the gas the oscillations were damped by coating the combustion vessel with glass wool, which resulted in a decrease of the flame velocity. From these findings, which, however, may also have been caused by the heat absorption or other effects of the greatly extended surface of the glass wool, the author derives that the oscillations are responsible for the increase of the flame velocity in the gas, possibly due to the increase in the degree of turbulence. Experiments on the excitation of oscillations in a gas space by combustion have also been undertaken by Köchling.[30]

Experiments regarding the interdependence between turbulence and flame velocity were undertaken by Damköhler[31] for propane-oxygen mixtures. The degree of turbulence in this case was given by the Reynold's number for the gas in the tube which on its open end, carried the flame (see also Ref. No. 32). This definition of the degree of turbulence which is derived from the picture of a stationary flow of a gas through a duct of given dimensions cannot be transferred easily to the non-stationary state which is encountered say in internal combustion engines. No general flow of the gas can be defined here, since only selected spaces of the gas of limited extension may take part in possibly independent motions. If the dimensions of these partial volumes are considerable, *e.g.*, if they form vortex systems created by rhythmic separations from wall members they may have superimposed turbulent mixing motions, or these may exist alone. It is thus impossible to transfer the normally accepted definition of the degree of turbulence by quoting the Reynold's number, to conditions encountered here, except if confined to a very small element of space in the gas. In the case of oscillations in a gas space in the form of longitudinal waves, the degree of turbulence of the gas will be changing with the place of such an element considered, and with time, and the motion of the unburnt gas will be additionally of influence.

Stationary burning flames in gases where subjected to sound radiation by Hahnemann and Ehret.[33] The impact of sound waves resulted in a small increase of the normal flame velocity.

Since investigations of combustion in turbulent gases have not yet shown flame velocities of the order found in internal combustion engines, it was considered essential to investigate the combustion under conditions prevailing in the combustion space after the compression stroke. The circumstances of combustion in the compression apparatus are similar to those encountered in an internal combustion engine cylinder in as much as the mixture is compressed before ignition; values of pressure and temperature can be arranged to be similar or equal to those in an engine cylinder. The combustible charge in the engine does not seem to oscillate with noticeable pressure amplitudes, and for the sake of maintaining the same conditions in the compression apparatus the oscillations should be avoided, which could easily be done by limiting the velocity of the piston.

The following effects, however, may be borne in mind. In the cylinder of an internal combustion engine due to the inertia of the gas at accelerating and decelarating the piston, pressure differences are set up in the charge between the gas layers immediately adjacent to the piston and adjacent to the cylinder top. The order of magnitude can be estimated in accordance with a calculation by Pfriem[22] and can amount up to 1·4% of the external pressure. This pressure difference will be equalised by oscillations in the first instance along the axis of the cylinder which together with their reflections on the walls may influence the flame velocity considerably, though they may not be noticeable in normal pressure diagrams.

The motion of a gas enclosed in a vessel and initiated by the combustion of the gas, has been outlined by Damköhler[34] and experiments have been undertaken by Steinicke[19] for propane air-mixtures in long combustion vessels. Steinicke used for his experiments the same combustion vessel as has been used for the work referred to here and a comparison of his results can already give some indication regarding the influence of gas oscillations on the apparent flame velocity.

This comparison, however, would contain some uncertainty since the states of the gas mixture before ignition differ and since the combined influence of pressure and temperature on the flame velocity is difficult to judge and has not yet been very correctly established.[19]

The effect of oscillations, on the flame velocity, therefore, has been established by comparison of the velocity of the flame measured in the oscillating gas space with the flame velocity in the space when the oscillations are damped, with the help of the damping tube described above—see Figs. 33 and 34. Thus an influence of the difference of the state of the gas has been eliminated completely if only it can be assumed that the effect of periodically changing the state of the gas say pressure and temperature, *i.e.*, during the oscillations is equal to the effect of the average value of the state if maintained nearly stationary.

The experiments thus intended to find out the influence of oscillations of large pressure amplitudes in a gas on the apparent flame velocity. It was not possible to cover the field entirely especially in its theoretical aspects since a much larger material would have to be provided, especially for establishing a quantitative correlation between the degree of turbulence in the closed gas space and the flame velocity.

9.1. *Lay-out of experiments*

The hitherto undertaken tests dealing with the dynamics of the apparatus are made with air and for the combustion experiments special equipment for the supply of a correct gas mixture had to be prepared. Mixtures of propane and air are used, and in the first instance a stœchiometric mixture $\lambda = 1$, and a mixture with 20% excess air, *i.e.*, $\lambda = 1 \cdot 2$ have been investigated. Immediately after the compression stroke the mixture was ignited and the combustion has been photographed on a rotating film. A general scheme of the apparatus is given in Fig. 47.

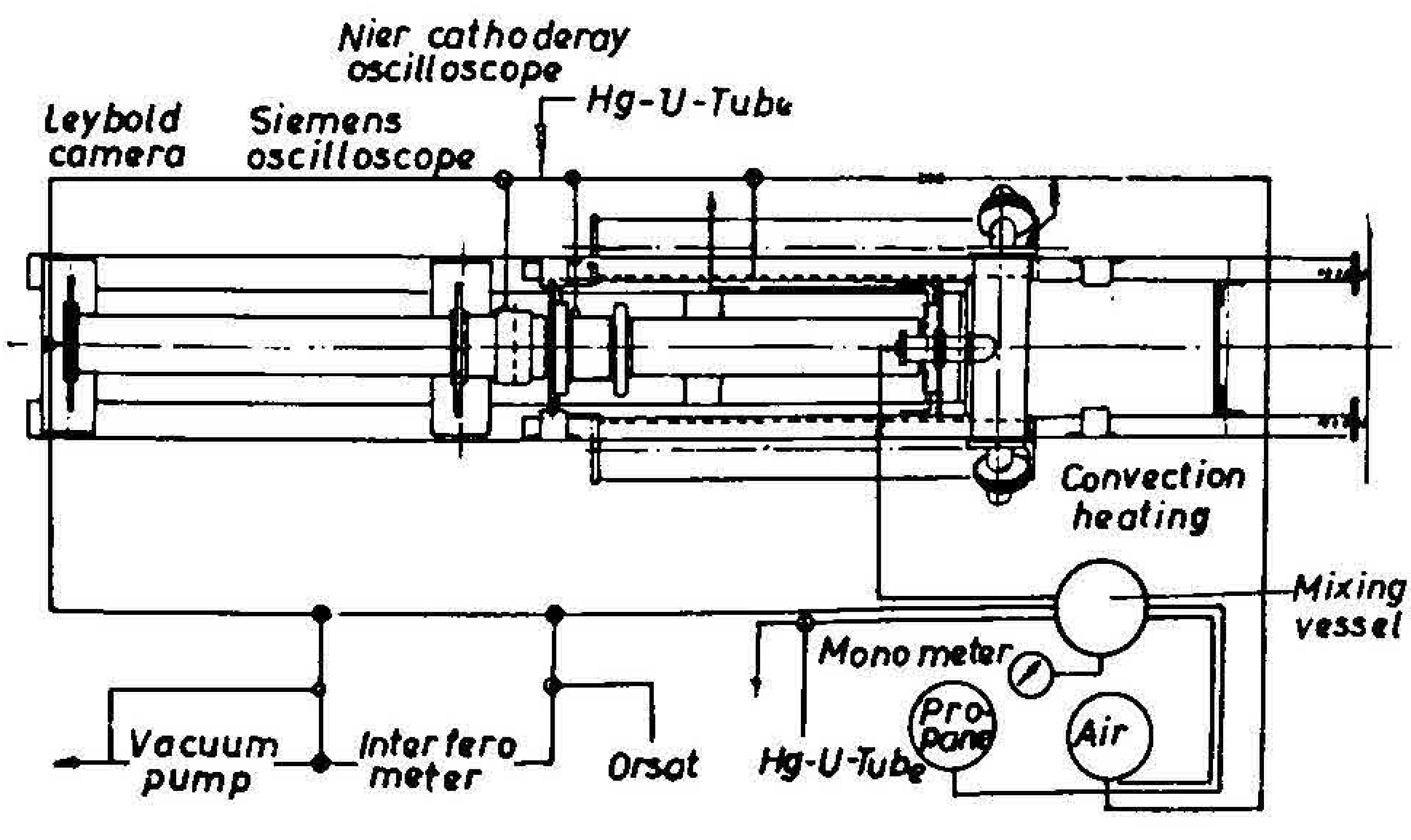

FIG. 47. Pipe circuit of compression apparatus.

9.11. *Preparation of combustible gas mixture*

The components of the mixture are led separately into the mixing vessel, which has been evacuated first. Propane is admitted until the partial pressure of the required mixture strength is reached. Air is added afterwards up to the required total pressure of the mixture. The propane partial pressure is measured with a mercury U-gauge and the total pressure by a precision manometer. Since the mixture may not be quite homogeneous immediately after it has been prepared the vessel is heated on one side for 12 hours so that the natural convective flow equalised the mixture.

For the test itself the compression apparatus is prepared for accepting he gas mixture, in the following way. The piston is in the low:r dead centre and the valves which lat:r on separate the combustion space from the cylinder are open.

The total volume in front of the piston which will later on be occupied by the combustible mixture, and also the space between the main valve and the piston are now evacuated, the pressure during this operation being indicated on a special mercury U-gauge. As soon as this pressure reaches its minimum value combustible gas is admitted from the mixing vessel and occupies the space in front of the piston with the inclusion of the combustion space. The gas pressure is raised until it exceeds slightly the atmospheric pressure and can be read at the U-gauge attached to the apparatus. At this stage the space between the piston and main valve is connected with the outer atmosphere. The cumbustible gas mixture is now made to flow through the apparatus, since at that stage the gas mixture may still be contaminated with air which had remained in the apparatus. Through a throttling nozzle at the end of the combustion space the gas leaves the apparatus and the pressure of the mixture in the apparatus is maintained above that of the atmosphere by further supply from the mixing vessel. At all times a small positive pressure difference exists between the combustible mixture and the outer air thus preventing any air from entering the apparatus. The gas leaving the apparatus thus will, with gradually increasing exactness, represent the correct mixture, as is present in the mixing vessel. In order to be sure that at that time the composition of the gas is not any more affected by traces of air, the gas is directed through an interferometer. As soon as the instrument ceases to show any changes in the composition of the gas mixture it can be assumed that the composition of the gas in the compression apparatus is the desired one.

As has already been mentioned the required mixture strength is regulated by changing the partial pressure of propane. Since propane is admitted to the mixing vessel at rather low pressure, deviations from the ideal gas law need not be expected. The accuracy, however, up to which the total pressure can be regulated could be doubted since the precision manometer may give rise to some errors. In order to be sure, every one complete charge of the mixing vessel which was sufficient for five different tests, was analysed chemically, and was found to coincide with what the partial pressure method indicated.

Whilst the combustible mixture is continuously passing through the space in front of the main piston the container for the compressed air is pressurized. This pressure is read on a precision manometer for air. Possible and unavoidable small leakages of the main valve cannot influence the composition of the combustible mixture now since leaking air enters the space behind the piston and escapes from there into the free atmosphere, and cannot influence the composition of the combustible mixture, since its pressure is slightly higher than the atmosphere as already mentioned. The connection from the space behind the piston to the free atmosphere is closed only immediately before the experiment starts.

After closing all connections towards the atmosphere and towards the mercury gauge the combustible gas mixture by operating the main valve, is rapidly compressed and ignited. For the ignition and for the timing with respect to the stroke of the piston or the operation of the bomb valves special arrangements are necessary.

9.12. *Electrical circuit and ignition of compressed gas mixture*

The electrical circuit of the apparatus is shown in Fig. 48. For the ignition an ignition coil and a contact breaker is adopted and furthermore a main switch which allows to switch off the ignition circuit if so desired. A normal sparking plug with 14 mm. thread (M. 14 × 1·25) is used.

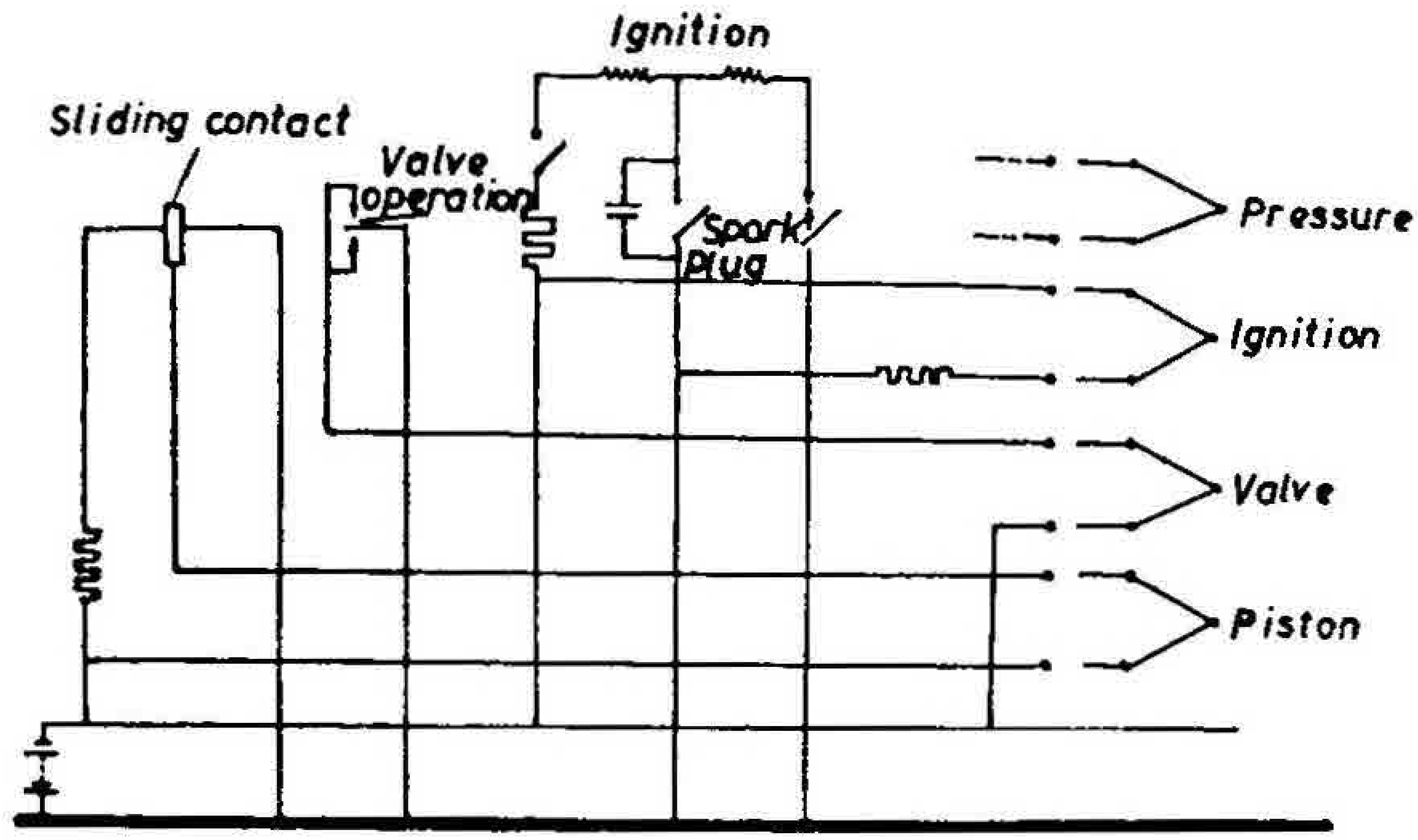

FIG. 48. Electrical circuit for compression apparatus.

Special attention is paid to timing the ignition. The spark can be allowed only after the valves of the combustion vessel have been closed as otherwise the flame would also ignite the mixture retained in the cylinder. After closing the bomb valves the gas experiences a rapid decrease of temperature—see Fig. 37, so that the spark must operate near the moment where the valves close so that ignition occurs at the undisturbed temperature level induced by compression. It is also desirable to vary the time for ignition slightly, with respect to the operation of the valves.

These requirements are met by an arrangement shown in Fig. 49. The upper horizontal part of the frame which operates the bomb valve as already explained carries a member extending beyond its pivot. If the frame is moved which allows the valves to close, this member after a certain amount of turning opens the ignition circuit and thus acts as contact breaker in the primary circuit of ignition. In this moment ignition occurs. Since the position of the contact breaker can be adjusted with respect to the frame, the angle covered by the frame and thus the time expanded between the closing of the bomb valve and the ignition can be varied. If by some fault the bomb valves are not operating properly, no ignition will occur.

9.13 *Recording of process of combustion*

After ignition has taken place the flame proceeds essentially along the axis of the comb ustion vessel. The propagation of the flame in a darkened room can be photographed in its own light on a rotating film. The axis of the film drum is parallel to the longitudinal axis of the combustion vessel so that the film moves at right angle to the direction of the propagating flame—see Fig. 50. The aperture of the camera will remain open during combustion. In known manner the flame

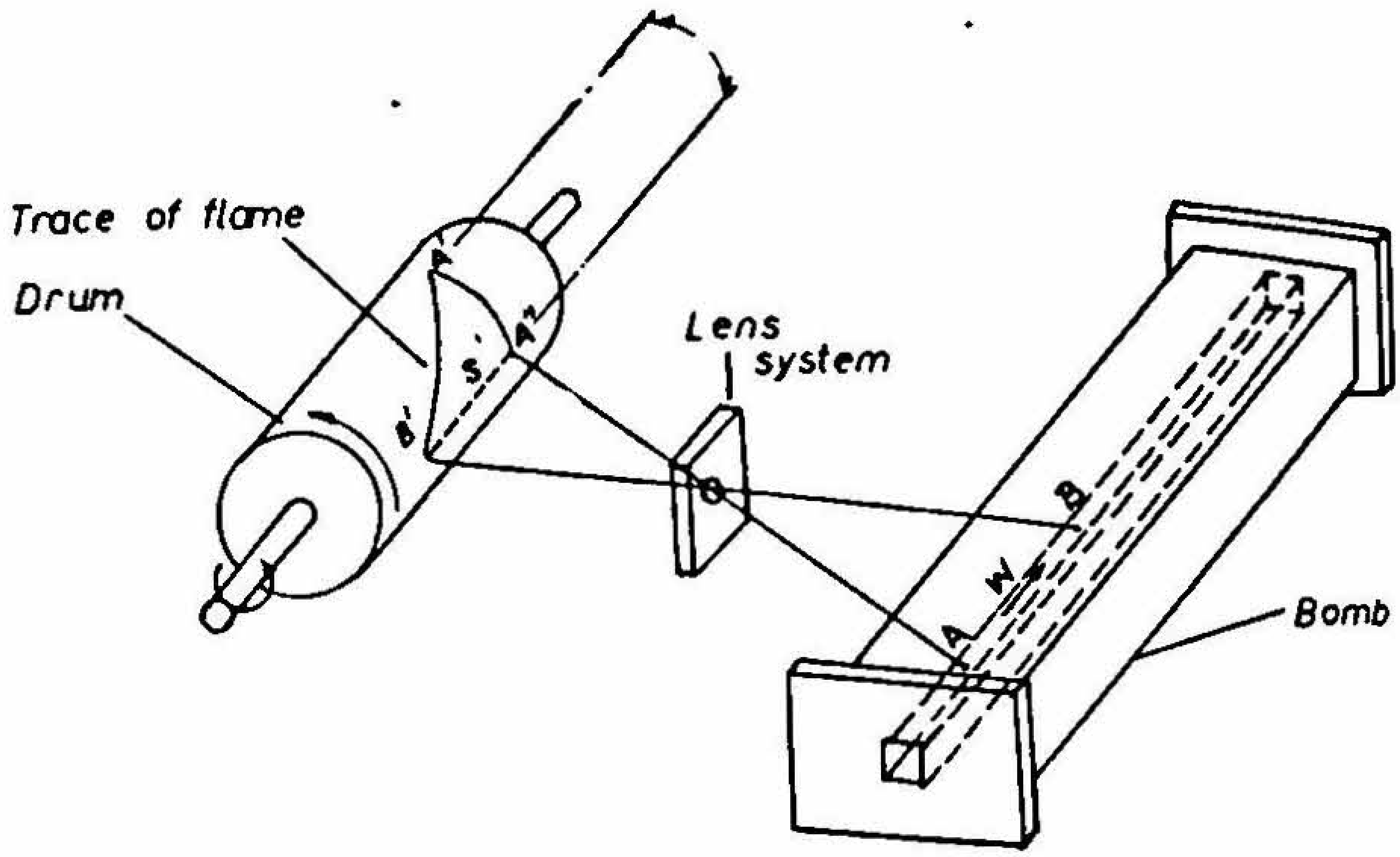

FIG. 50. Scheme of evaluation of flame velocity

velocity W can be found from the inclination α of the trace of the flame on the film with respect to the direction of motion of the film, if the film velocity z is known. The camera used was a Leybold camera with mirror deflection, and at a later date a photographic recording device was applied as is normally used to photograph oscillograms of cathode ray oscillographs, equipped with stroboscopic indication of the speed of the drum. The film used had a sensitivity of 23/10 deg. Din and was 8 cm. broad.

9.2. *Test results and consequences*

The results of the experiments are shown first with the help of some typical flame photographs.

In Fig. 51 the trace is shown of a flame in a combustible gas mixture, strength $\lambda = 1 \cdot 16$, with an initial pressure of one atmosphere. The gas is not compressed. At the initial stages of the trace oscillations of the flames are noticeable which have been explained by Steinicke[19] as a consequence of periodic separations of eddies from the wall. In the second window, *i.e.*, between the first and the second horizontal interruption of the flame trace, a backward directed motion of the burnt matter can be seen. Combustion occurs even behind the flame front. The flame, in its later stages, burns undisturbed and with constant velocity.

In Fig. 52 the combustion has been photographed of the same gas mixture after previous compression with an initial air pressure of 5 atmospheres, *i.e.*, a gas pressure at the end of compression of roughly $2 \cdot 5$ atmospheres. The return motion of the burnt matter behind the main flame front can be seen very distinctly. The trace of some separate and slower burning gas particles can be distinguished clearly and it seems they move backwards at a rate dependent on their distance at right angles to the wall. Starting from 52 on the scale of the ordinate, the trace of a flame from a combustion at normal pressure and without pre-compression can be seen. Since the photograph is very weak, due to the small amount of light emitted by the combustion this trace is marked by several white dots. From the difference of the inclination of these traces the difference in flame velocity can clearly be noticed.

In Fig. 53, two combustions have been photographed of gas mixtures with equal mixture strength $\lambda = 1$. It can be seen that the results are equal and thus are reproducible; the air pressure was 5 atmospheres.

The difference in flame velocity for different pressures of the compressed air is shown in Fig. 54 for mixture strength of $\lambda = 1$. The trace near to the origin of the co-ordinate system is related to a pressure of the compressed air of 7 atmospheres, and the second trace to a pressure of 5 atmospheres, which corresponds to a pressure in the gas after compression of 12 and 8 atmospheres respectively. With the pressure of the compressed air, the pressure and the temperature of the gases is increased and also the frequency and amplitude of the pressure oscillations. If it is assumed that the influence of the higher pressure would be eliminated by the influence of the higher temperature a direct correlation would result of the flame velocity with the characteristic values of gas oscillations. In the last stage of combustion, oscillations of high frequency can be noticed at already diminished flame velocity and these oscillations are found mainly during the combustion of highly pre-compressed mixtures. Steinicke made the same observations during combustion of gases under elevated initial pressure in the same combustion vessel, but these oscillations occurred there only in mixtures with basically high flame velocity. Fig. 55 shows the last phase of the combustion of a mixture with $\lambda = 1{\cdot}2$. As was the case in Fig. 54, high frequency oscillations occur after the flame front has passed the third window so that it may be assumed that a small discontinuity in the wall at the juncture between the metal and the glass window may have initiated the oscillation which subsides as the flame progresses further.

Ultimately in Figs. 56 and 57 the influence of the damping of the oscillations and the influences of the pressure of the compressed air on the apparent flame velocity shall be shown. In Fig. 56, the pressure of the compressed air is kept constant and the velocity of the flame along the combustion vessel has been drawn for a mixture strength of $\lambda = 1$ characterised by the full line, and for $\lambda = 1{\cdot}2$ characterised by the dotted line. The flame velocity in the undamped gas space is indicated by a thick line and the flame velocity in the damped gas space is indicated by thin lines. The damping effects mostly the initial stages of the combustion causing the oscillations to subside quickly so that in total the degree of turbulence becomes smaller.

As a whole damping has a marked effect, and this indicates clearly, that oscillations effect the flame velocity.

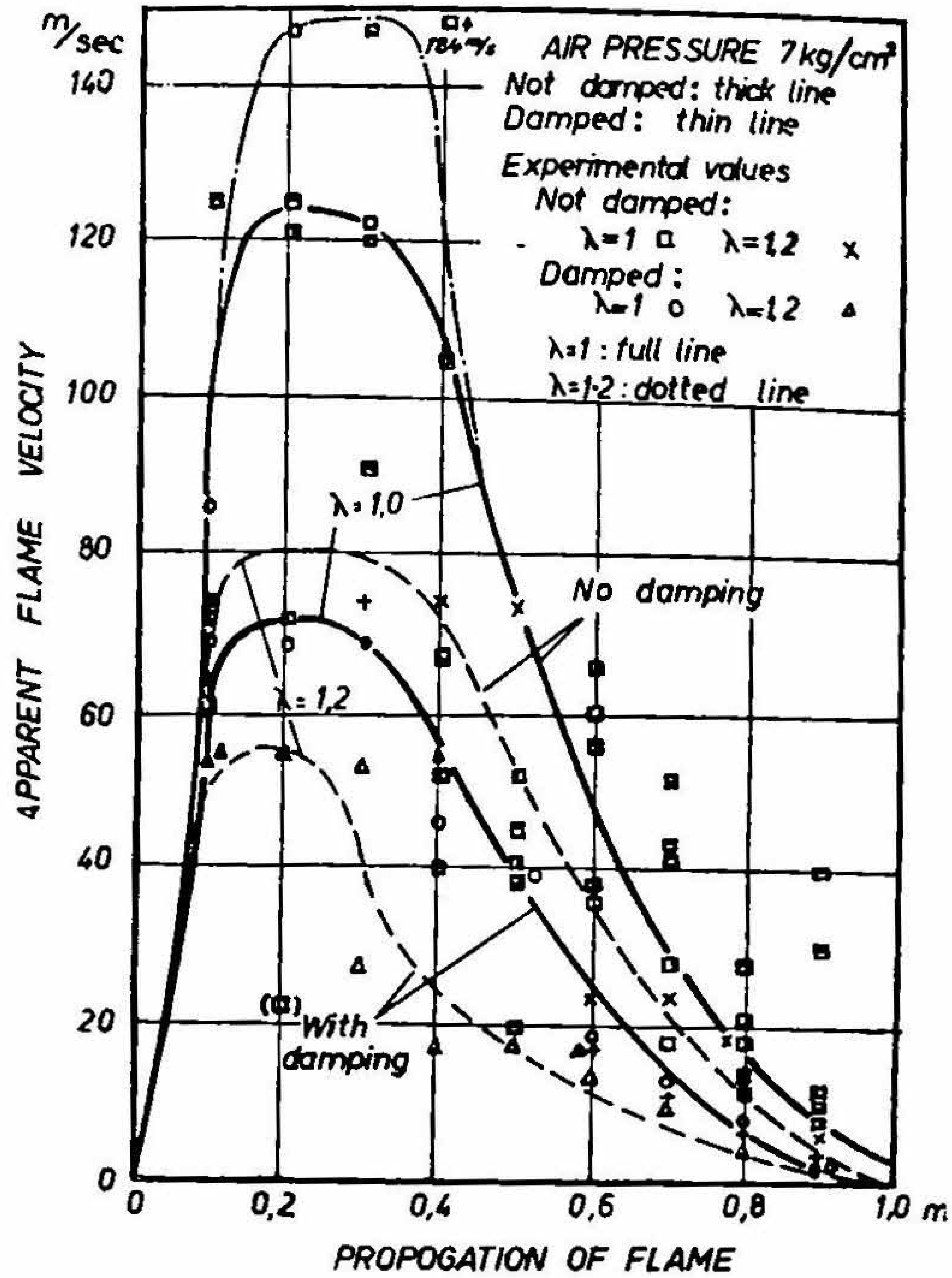

Fig. 56. Flame velocity in oscillating precompressed propane-air-mixture. $\lambda = 1$, $\lambda = 1 \cdot 2$, Air pressure = 7 kg./cm.² for damped and undamped oscillations. Gas pressure at beginning of combustion about 12kg./cm.²

In one exceptional case, as is indicated in the Fig. 56 as a chained line a flame velocity of 150 m./sec. was measured and one instance occurred where the flame velocity was as high as 180 m./sec.

In Fig. 57, the flame velocity is drawn for a combustible mixture of mixing strength $\lambda = 1 \cdot 2$, for an air pressure of 7 atmospheres,—full line—and for 5 atmospheres—dotted line. The thin lines indicate again the experiments undertaken with the damping tube attached to the combustion vessel and the thick line indicates those tests without damping the gas oscillations.

From the experiments it can be concluded that for the gas mixtures of strength $\lambda = 1$ and $\lambda = 1 \cdot 2$, the flame velocity increases with the intensity of the oscillation of the gas. The increase of the flame velocity is the consequence of the additional motion of the gas due to the longitudinal oscillation and thus is apparently caused by the turbulence accompanying this motion.

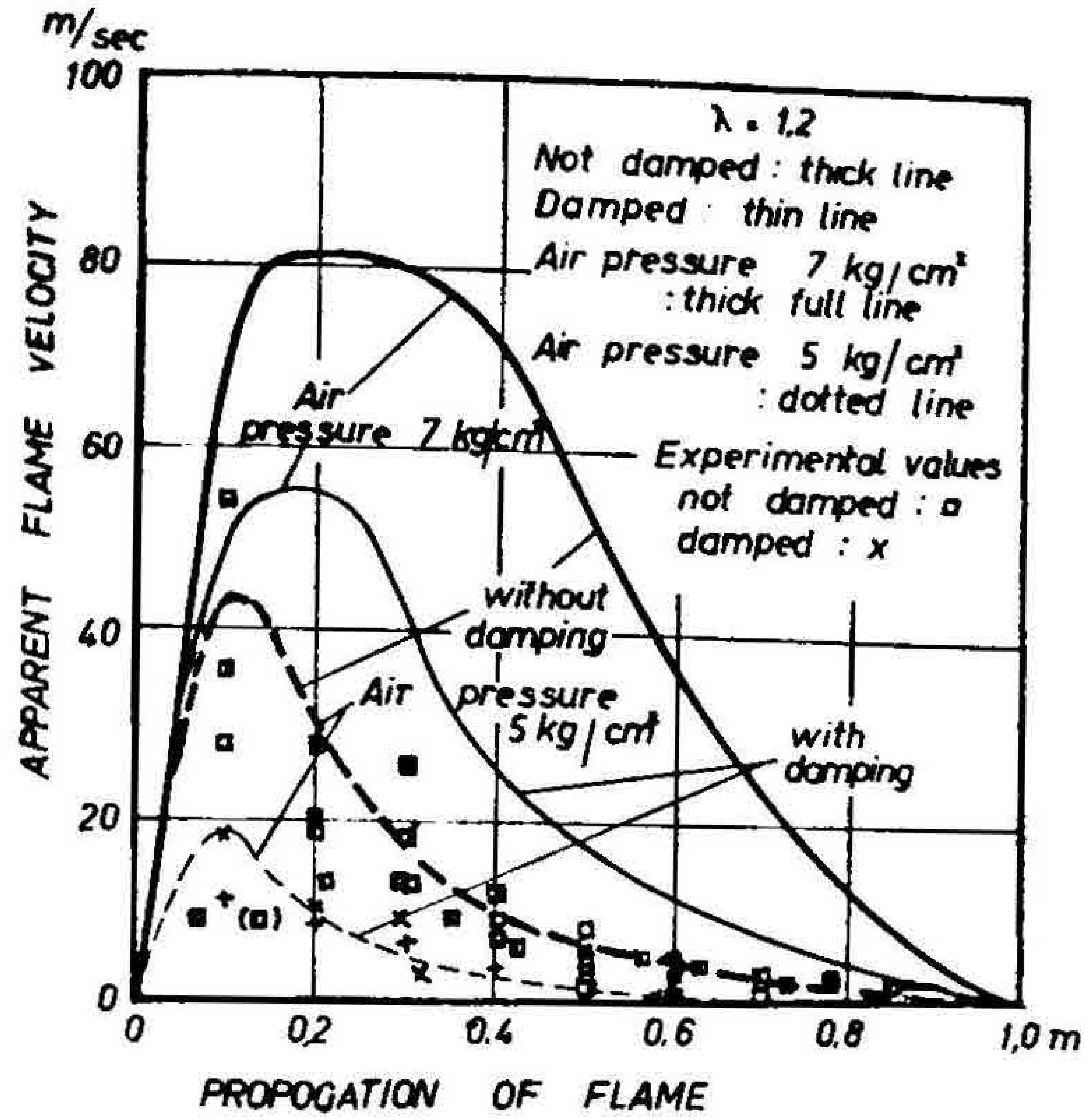

FIG. 57. Flame velocity in an oscillating precompressed propane-air-mixture. $\lambda = 1 \cdot 2$ compressed with air pressure of 5 and 7 kg./cm. for damped and undamped oscillaions, gas pressures at beginning of combustion about 8 and 12 kg./cm.[2] respectively.

The flame velocities are of the order of those met in Internal Combustion Engines and are higher by a factor of about 10 than values found by Damköhler and Steinike.

10. CONCLUSIONS

The compression apparatus has been used within the scope of this report mainly to show the increase of heat transfer and flame velocity in oscillating gases. Thus the application of the compression apparatus is different from experiments which have been conducted with similar techniques, and which aimed mainly at investigating the kinetics of reactions of combustion processes.

The reason for this limitation is the following:

The insight into the peculiarities of the apparatus make it appear doubtful whether the method of adiabatic compression renders dependable results with reasonable expenditure. The high velocity of the piston results in the creation of pressure waves which are reflected on the walls, and the increased heat transfer from the gas to the wall, result in a peculiar distribution of temperature and pressure in the combustion space and additionally, in a sudden drop of the temperature of the gas after compression so that the kinetics of reactions are severely affected. Thus the ignition delay can be affected from zero till a 100%,[30] if compared with ideal adiabatic compression, and the velocity of reaction can be doubled by an increase in temperature of only 10 to 20 degrees. The uncertainty outlined is increased if influences are taken into account of turbulence, convection, superposition of pressure waves, heat transfer effects, and radiation. Under these circumstances, a generalisation of results found in compression apparatus must be met with some care, and an alternative method would doubtless be of considerable help.

The aim to compress adiabatically a gas mixture and also to ignite a gas mixture by compression alone can probably be reached by a slight modification of an auxiliary component part of the apparatus described in this report, *i.e.*, the pneumatic operation of a valve in the first version of the apparatus. In principle, a small pressure vessel was rapidly opened and a very steep increase in pressure in the duct down-stream was noticed—see Fig. 27.

If the outlet pipe for the compressed gas is a straight tube and filled with the reacting gas and if the vessel containing the compressed gas is made sufficiently long so that no pressure waves are reflected at the far end until after a considerable time has elapsed, the rapid opening of the vessel would cause a shock wave to pass the gas mixture in the tube. The gas mixture would experience a rapid increase in pressure and temperature which may even lead to self ignition. The change of state involved would be carried out with such rapidity that heat transfer considerations could be neglected entirely.

The examination of the process necessitates a Schlieren apparatus or a cathode ray oscillograph. The arrangement proposed here has the advantage of introducing a definite change of state which depends solely on the pressure ratio adopted. It does not depend on the velocity of a piston and the velocity distribution, nor on heat transfer conditions and influences from pressure waves and their turbulence. The creation of a shock wave in the proposed way with the help of the influx of a gas leads to a definite shock front which would not be disturbed by reflected pressure waves which would be the case if shock waves are produced say by detonation of small explosive charges.

11. Synopsis and Acknowledgement

In the present report, details of the design and development of an apparatus is given which subjects gases especially combustible mixtures to a single and rapid compression, with a maximum piston stroke of roughly one meter, the time of compression being 0·03 till 0·05 seconds. The highest piston velocity exceeds 50 m./sec. for pressures of the compressed air driving the piston, of 15 atmospheres.

The kinematics of such apparatus are theoretically derived and compared with the actual data.

The combustion vessel is a bomb of one meter length and a cross-section of 24 times 24 mm., and equipped with 8 windows, four on each side. A valve operated in correlation to the position of the main piston prevents any changes in volume after the compression of the gas. The average pressure in the compressed

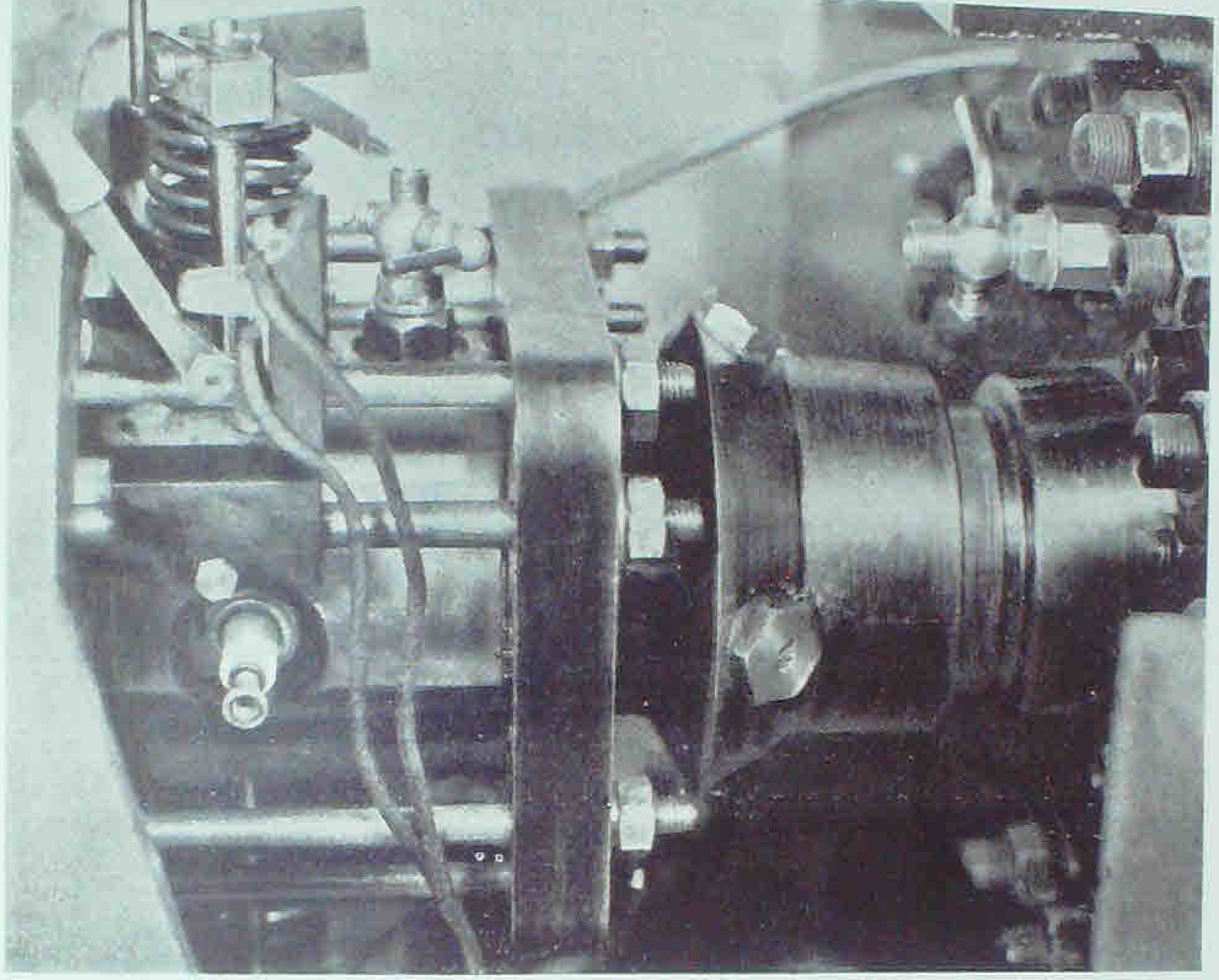

FIG. 49. Photograph of contact breaker for ignition.

FIG. 51. Combustion of a propane-air-mixture at initial pressure at 1 atm. $\lambda = 1 \cdot 2$.

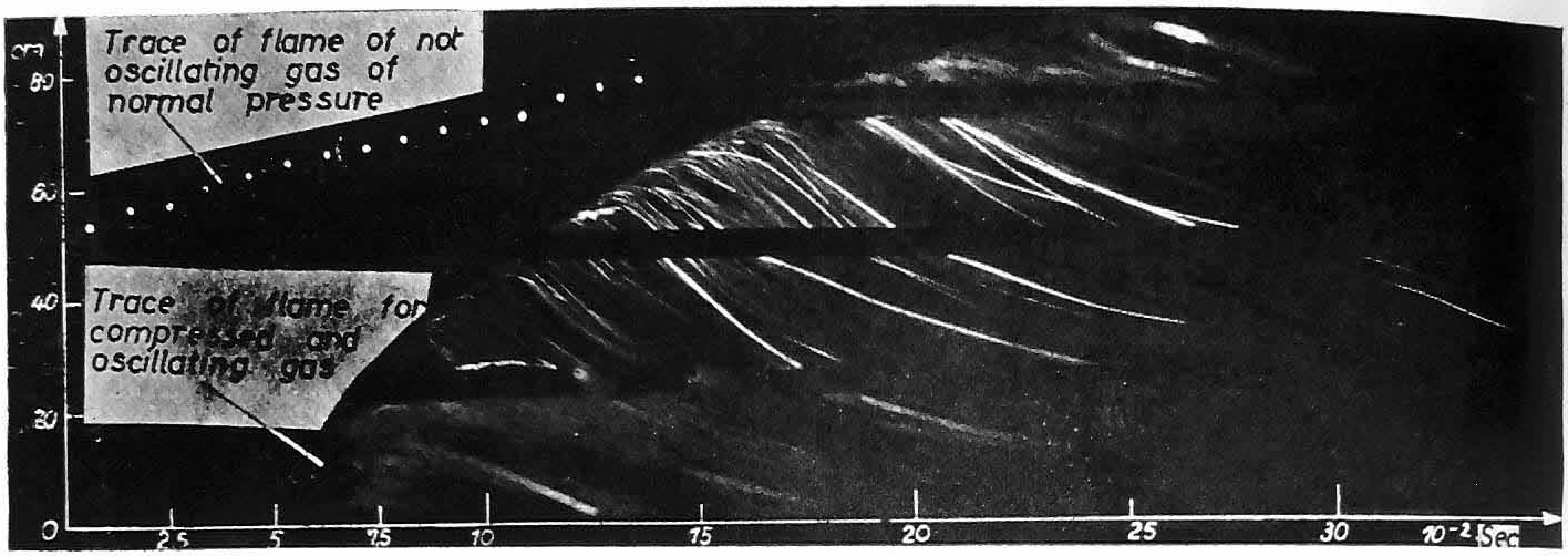

FIG. 52. Combustion of a precompressed propane-air-mixture $\lambda = 1 \cdot 2$ (air pressure 5 ata) in comparison with the combustion of a mixture $\lambda = 1 \cdot 2$ of atmospheric pressure.

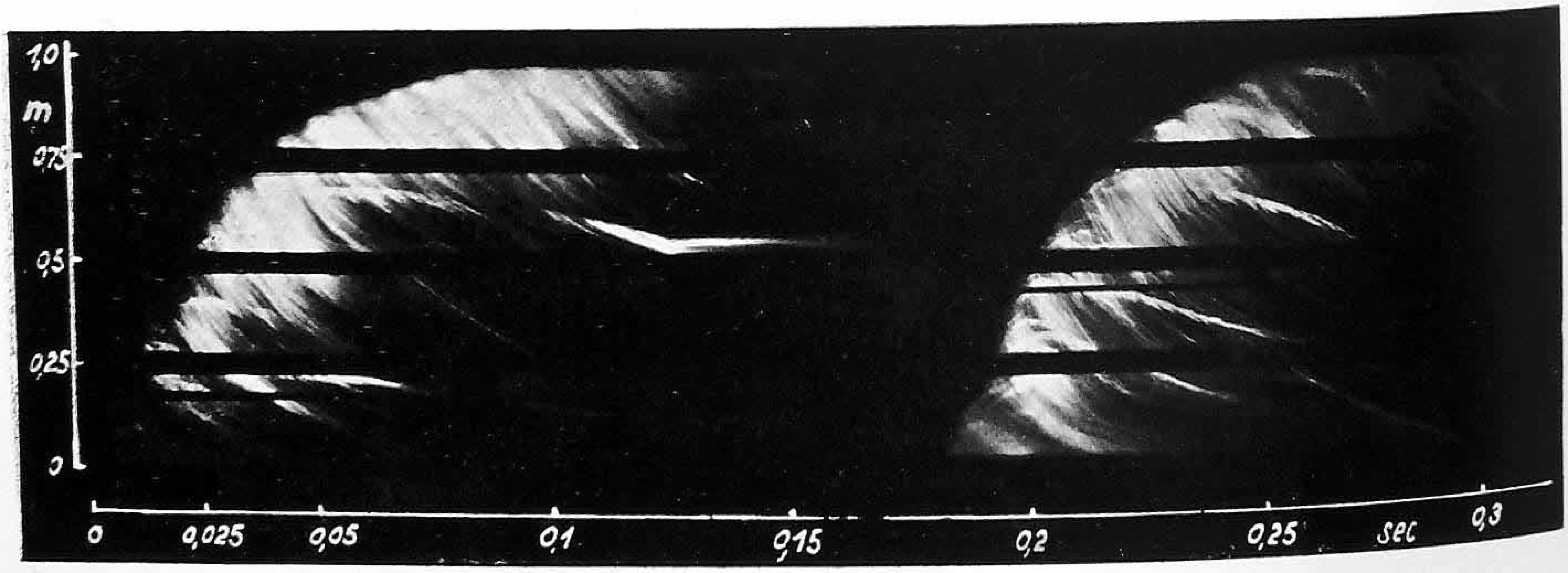

FIG. 53. Combustion of precompressed oscillating propane-air-mixtures $\lambda = 1$ (air pressure 5 ata).

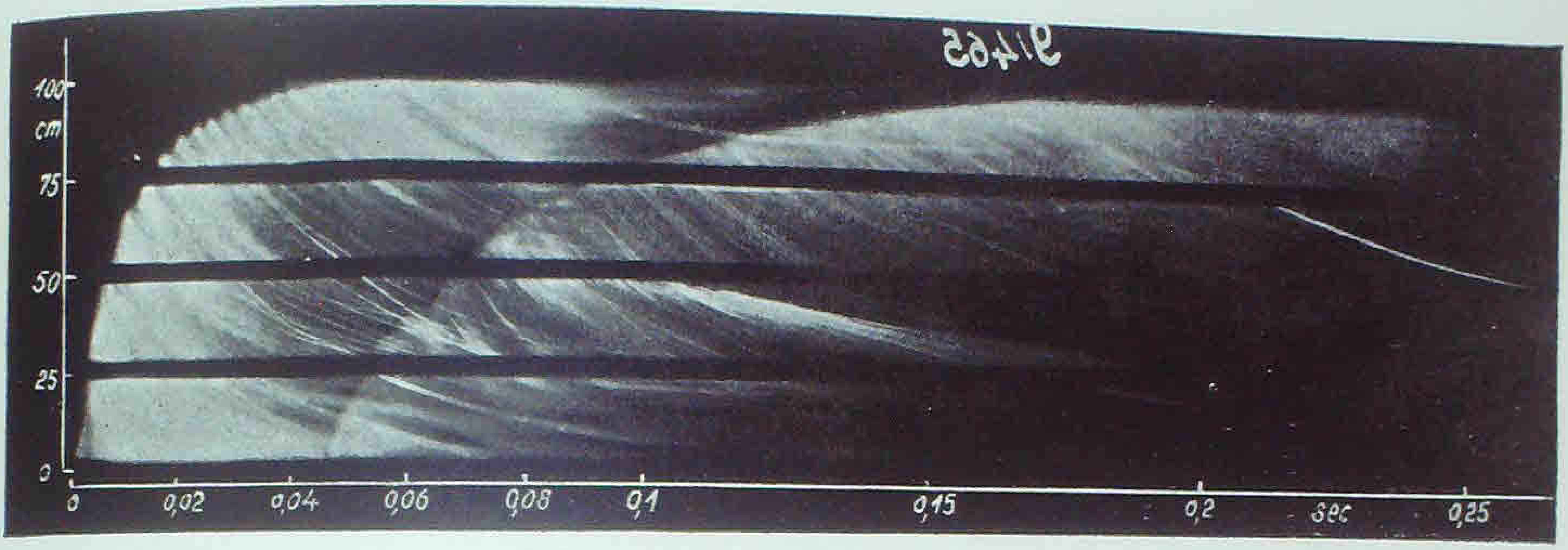

FIG. 54. Combustion of precompressed oscillating propane-air-mixtures $\lambda = 1$
(Air pressure, first trace: 7 ata second trace: 5 ata)

FIG. 55. End phase of combustion of a precompressed and oscillating procane-air-mixtures
$\lambda = 1 \cdot 2$ (air pressure 7 ata)

gas in the combustion vessel can reach 30 atmospheres, Fig. 36, and the temperature is more than 600 deg. K—Fig. 37.

The compressed gas in the combustion vessel oscillates with frequencies of 140 till 200/sec. The change of pressure with time in the combustion vessel is measured and from the frequency of pressure fluctuations, the change of temperature with time in the compressed gas is derived. Thus it is possible to find the order of the heat transfer coefficient of oscillating gases, and the inter-dependence of the heat transfer coefficient at any moment from the pressure amplitudes and also the frequency of the oscillation—Figs. 42 and 43. Increases of the heat transfer coefficient in oscillating air by a factor of 20 to 30 as compared to that for air at rest are experienced.

For the investigation of flame velocities in oscillating gases propane-air-mixtures of stœchiometric mixture strength and excess air of 20% are rapidly compressed and ignited. The apparent flame velocity depends largely on the pressure amplitudes and the frequency of the oscillation, Fig. 57, and is increased considerably if compared to combustion of the gas at rest. This is proved by damping the oscillations of the gas, Fig. 56. The magnitude of the flame velocities-experienced is in the order of 80 to 120 m./sec., and this coincides with flame velocities found in internal combustion engines.

On evaluating results of compression apparatus with respect to kinetics of reactions taking place, the experiments reveal that the increase of heat transfer has to be taken into account which influences the temperature in the compressed gas and thus the induction period. Besides this, the instationary distribution of pressure in the combustion space, can cause local differences in the state of the gas, varying with time, and may be responsible for ignition and for the particular magnitude of flame propagation.

A method for the investigation of kinetics of reactions avoiding the disturbing effects mentioned is proposed which essentially provides for the compression of the gas with the help of a shock wave.

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