DEVELOPMENT OF A COMPRESSION APPARATU AND STUDIES ON HEAT TRANSFER AND COMBUSTION OF RAPIDLY COMPRESSED AND OSCILLATING GASES[†]

By H. A. Havemann[*]

CONTENTS

P

Summary .. ..

Part I

1. Introduction—
   1.1 The method of adiabatic compression 60
   1.2 Review of previous work and literature 61
   1.3 Requirements for the new apparatus 63
2. Development of the New Compression Apparatus 65
   2.1 Layout of the first version 65
   2.11 General set-up of the first version 65
   2.12 Closing the combustion vessel 68
   2.2 The Layout of the second version 72
   2.21 General set-up 72
   2.22 Closing the combustion vessel 72
3. Measuring Devices of the Compression Apparatus 75
   3.1 Motion of piston 75
   3.2 Motion of valves 75
   3.3 Pressure measurements 75
4. Experimental Results and Evaluations 76
   4.1 Motion of piston 76
   4.2 Motion of valve 77
   4.3 Variations of pressure 79
   4.4 Variations of temperatures 87
5. Heat Transfer for Oscillating Gases 88
   5.1 Basic considerations 88
   5.2 Comparison of rejected heat quantities 90
   5.3 Heat transfer coefficient 94
6. List of References 98
7. List of Symbols 101

[†] The investigation was commenced at the Institute for Aero engine technics at the Techni- cal University at Brunswick, and was completed at the Research Establishment for Aero- nautics at Brunswick, Völkenrode, West-Germany. It forms the basis for further work on the rate of combustion as also the rate of heat transfer of oscillating gases undertaken in the Department of Internal Combustion Engineering at the Indian Institute of Science.

[*] Department of Internal Combustion Engineering, Indian Institute of Science, Bangalore- India.

PART II*

8. CALCULATIONS OF MOTION OF PISTON AND THE RESULTING GAS PRESSURE
  8.1 Pre-suppositions of mathematical treatment
  8.2 Statement of calculation
  8.3 Calculation and discussion of results
9. EXPERIMENTS ON COMBUSTION OF OSCILLATING GASES
  9.1 Lay-out of experiments
  9.11 Preparation of combustible gas mixture
  9.12 Electrical circuit and ignition of compressed gas mixture
  9.13 Recording of process of combustion
  9.2 Test results and consequences
10. CONCLUSIONS
11. SYNOPSIS AND ACKNOWLEDGEMENT

---

* Part II will appear in Vol. 37, No. 2, April issue, 1955.

SUMMARY

After a review dealing with the experimental apparatus so far developed for investigating self-ignition and knocking properties of explosive gas mixtures by adiabatic compression, the development of a new compression apparatus is described. The dynamics of the apparatus, possibilities for their calculation and the state of the compressed medium are studied, and it is shown that in this type of apparatus the gas after compression is oscillating with considerable pressure amplitudes. The heat transfer and the flame velocity of the oscillating gas is examined experimentally and is found to be increased considerably if compared to a gas at rest. The flame propagation in rapidly compressed and spark ignited propane air mixtures in a closed vessel is photographically recorded, and the results for oscillating and non-oscillating gases are compared.

The findings of the investigation with the new compression apparatus are that in oscillating gases the transfer of heat to the walls of the container is greatly intensified, and furthermore, that the flame velocity is considerably increased.

The report is subdivided into two parts, the first outlining the development of the compression apparatus and the studies of heat transfer in oscillating gases as also the references. The second part comprises the study of combustion of oscillating gases after rapid compression as also the experimental set-up, and conclusions.

PART I

1. INTRODUCTION

1.1 *The method of adiabatic compression*

Amongst the different possibilities of experimentally investigating the self-ignition properties of gas mixtures,*[1] the method of adiabatic compression by means of a rapidly moving piston offers special advantages. It allows the wall of the reaction vessel being maintained at approximately the initial low temperature. In this way, influences from the wall on the reactions taking place in the combustion vessel are avoided. A further advantage of the method of adiabatic compression is given by the fact that the rate of temperature increase is the same for different points in the gas mixtures. Both advantages cannot be gained if the combustible mixture would be heated by raising the temperature of the walls of the vessel.

Applying the method of adiabatic compression, however, heat is transferred to the wall from layers of the hot gas which are situated close to a cool wall, and through the influence of turbulence in the gas during the process of compression also those layers may be affected and contribute to the heat transfer which are situated at a greater distance from the wall. A convective heat flow due to the causes indicated will normally not have enough time to develop if the compression is carried out sufficiently quickly. In the case of a very rapidly moving piston, however, a pressure gradient may be set up in the direction of the motion of the piston which will create a non-uniform temperature distribution in addition to that caused by influences of cold walls and the resulting convective motion of the gas.

Results which have been found by applying the method of adiabatic compression thus become dependent on the geometry of the walls and the piston velocity and/or the time of compression. In order to diminish the losses due to dissipation of heat, short periods for the compression should be preferred and in this way influences from pre-reactions which take place during compression may also be decreased. It is, however, unavoidable that these reactions will start before the highest compression temperature is actually obtained.[2] These conditions make it difficult to indicate the actual temperature in the gas after compression and this compression end temperature is even more difficult to measure due to the fact that the time of compression is very short, *i.e.*, $2\text{–}3 \cdot 10^{-2}$ seconds.

A theoretical treatment faces also considerable difficulties. The change of state of the gas mixture, especially in the case of combustible fuel-vapour air mixtures, does not obey the ideal gas law and deviates due to the effects of the atomic number, the inter-dependence of specific heats with temperature and pressure and due to the presence of traces of oil or water vapour, so that a statement for a polytropic change of state is not very helpful.[18] As will be shown later, the difficulties are increased due to the fact that in front of the piston in the moment of reversing its direction of motion considerable differences of pressure are set up and also differences of temperature within the gas space. The pressure differences may cause oscillations of the gas with considerable pressure amplitudes, which subside only slowly, and the resulting high pressure and temperature peaks may initiate locally self-ignition in the gas mixtures for which the average state of the gas cannot be made responsible.

In spite of the uncertainties in defining the final temperature in the gas mixture, the method of rapid compression which has been suggested first by Nernst and which has been taken up by different research workers with different experimental set-ups, has attained considerable importance more recently, especially in connection with investigations on the kinematics of reactions of knocking combustion. Attention is centred on the possibilities to influence knocking combustion by additives and on studying the general influences of the state of the compressed gas on the ignition delay.

1.2 *Review of previous work and literature*

For the investigation of combustion and also for studying the self-ignition properties, the mixture has to be brought in as short a time as possible to the elevated pressure and to the elevated temperature. In the case of compression with the help of a piston the velocity of the piston should attain its maximum value towards the end of the compression stroke so that the state of high pressure and high temperature has a small effect inasmuch as pre-reactions are concerned. The main difficulty from a design point of view is thus due to the fact that the piston should come to a standstill at a particular point of its stroke, and near the end of its stroke and should be arrested there without the pressure increase of the subsequent combustion imposing any motion on the piston. Only in this case the combustion would take place at constant volume.

The different apparatus for rapid compression approach these problems in different ways; Falk[3] accelerated the pistion by a free falling weight and the piston was stopped by the explosion of the mixture itself and thus was accelerated backwards. The innermost position of the piston was recorded by a ring on the piston rod and from this the gas temperature was derived. A similar design was applied by Cassel[4] together with Dixon,[5] who pointed out the consequences of the piston being able to move freely: the compression stroke continues during the period of induction and thus it is difficult to arrive theoretically at the ignition temperature. Cassel[4] also underlined the possibility of pressure waves as a consequence of the rapid piston motion. Dixon and co-workers[6] used a pendulum for accelerating the piston. Provision was made to limit the stroke of the piston but it could not be arrested at any particular position.

A different solution of the problem was tried by Tizard and Pye[7–9] by using an arrangement designed by Ricardo. The piston stroke was 203 mm. and the bore 114 mm., the time of compression was 0·08 seconds. For a closer study, reference may be made to the literature indicated. The distribution of the velocity of the piston along its stroke seems not to be very favourable.

Another apparatus was designed by Dûchêne[10, 11] and his predecessors[12]—which also adopted a pendulum for accelerating the piston. This apparatus was used to study the effects of anti-detonative agents. The piston had a conical nose which fitted closely into a bore and thus to some extent the piston was arrested at the point of maximum stroke.

Rastetter and vonWeber[13] used an apparatus with pendulum driven piston to compare the combustion in their apparatus with that taking place in an internal combustion engine. The same investigations were carried out by Broersma[14] with the help of the apparatus designed by Dûchêne which in the meantime was redesigned to use compressed air for moving the piston. Very thorough investigations have been carried out by Jost and his co-workers[15, 16] and he also made use of a free falling weight to accelerate the piston. Whilst the average piston velocity in the apparatus of Dûchêne and Pye was only 3 metres per second, the piston velocity in this case went up to 10 metres per second. Pressure waves may not have influenced the results of the tests since the piston velocity appears to be too small. Jost further introduced a design for arresting the piston at its lowest point, and thus realised combustion taking place at constant volume. Heavy vibrations affected the pressure indicator in the combustion space and it appeared uncertain whether the design really resulted in the combustion occurring exactly at constant volume. A step further was made by F.A.F. Schmidt and co-workers.[17] Schmidt used compressed air with a maximum pressure of 40 atmospheres which accelerated the piston up to a velocity of 50 metres per second. The piston was blocked at maximum stroke by metal blades which were deflected, and the return motion of the piston was thus prevented by partly the deformation of these blades, and partly by cones which by the action of compressed air grasped the piston rod and thus prevented it from being pushed back by the combustion pressure. These investigators studied also the influence of the piston velocity: on the ignition delay and also the correlation between the geometry of the apparatus and the resulting effects on heat transfer conditions.

The technique adopted in the earlier work acquires some importance in the light of the intention to develop the compression apparatus to a laboratory instrument for defining the knock rating of fuels. For this reason the dynamics of the new design have been investigated carefully. A first step in this direction has been undertaken recently by C. F. Taylor and C. S. Taylor.[18] They developed a compression apparatus with which the auto-ignition characteristics of several fuels under various conditions of mixture strength, compression ratio and temperature were investigated as also the behaviour of knock inhibitors, such as tetraethyl lead, and knock inducers, such as ethyl nitrite. The comparison of detonating tendencies must include the consideration of length of the delay period and an evaluation of the rate of pressure rise during auto-ignition.

1.3 *Requirements for the new apparatus*

The new apparatus followed a slightly different set-up as compared with the older designs as outlined above. The combustion of the compressed mixture was intended to take place in a long vessel which was provided with windows, and which had been designed by Steinicke.[19] The investigations were thought to give an indication of the flame velocities of pre-compressed combustible mixtures and it was expected on the start of the investigation that oscillations of the gas may be of some influence on the flame velocity. In order to disclose the effects ~~of pressure~~ waves initiated by the motion of the piston a Schlieren apparatus was planned to be installed at a later date and photographic records were intended to be made during the combustion process. The present report, however, is limited inasmuch as photographic records of the combustion have been obtained only by using the light emitted by the flame traversing the pre-compressed mixture when ignited from a sparking plug under non-detonative conditions.

The design of the apparatus emphasises specially that the gas mixture after attaining the final compression pressure, is not allowed to expand in any measure. This has been accomplished by a method which deviates from all methods applied so far: The combustion vessel has been detached from the cylinder in which the piston moves and both spaces can be separated with the help of a valve. This valve in the moment of maximum stroke of the piston, will be closed with the help of special means either pneumatic or mechanical, and thus a constant volume is ensured during the combustion irrespective of the further movement of, and the possibility to arrest, the piston. The combustion space must be insulated carefully against vibrations set up mainly by decelerating the piston, since only a shock insulated combustion space would allow correct photographic recording and exact

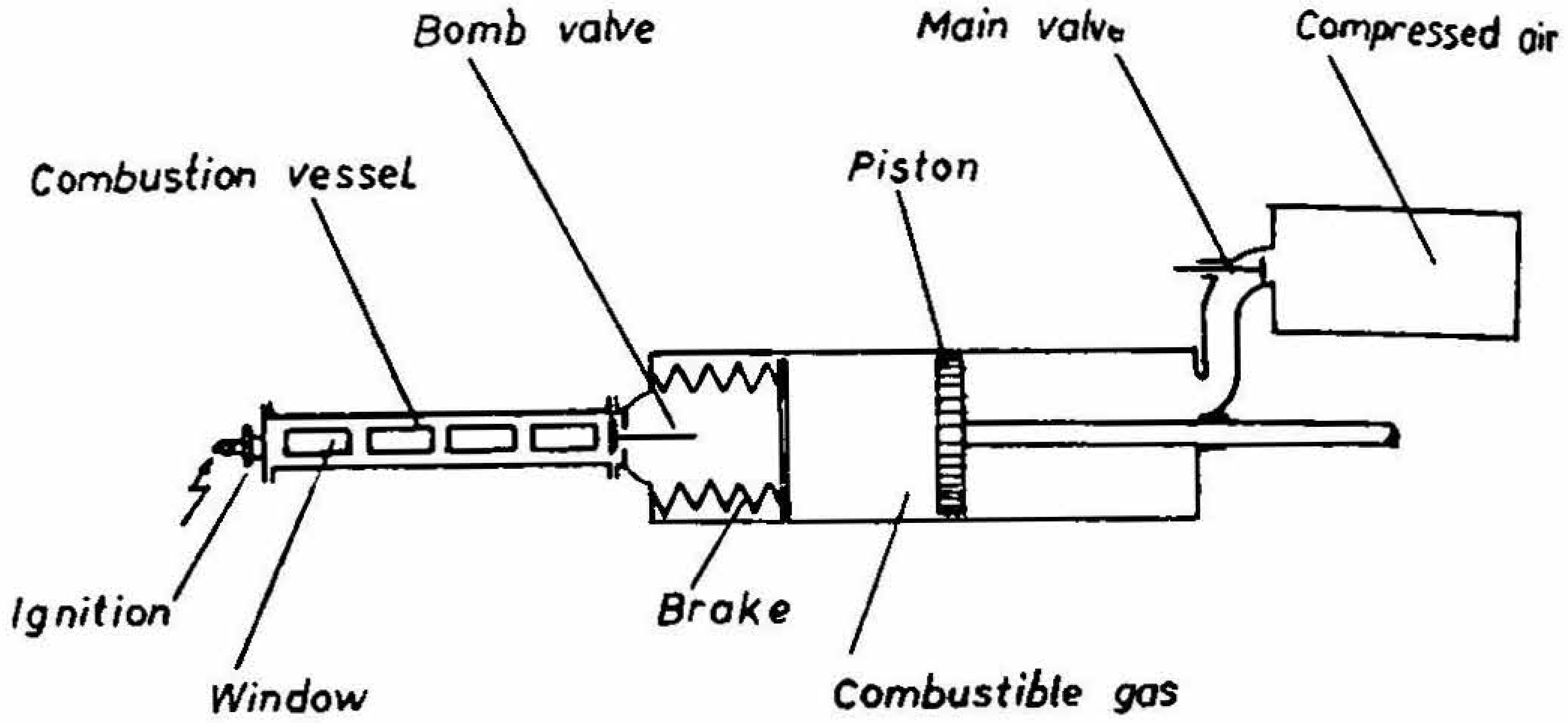

FIG. 1 (*a*).

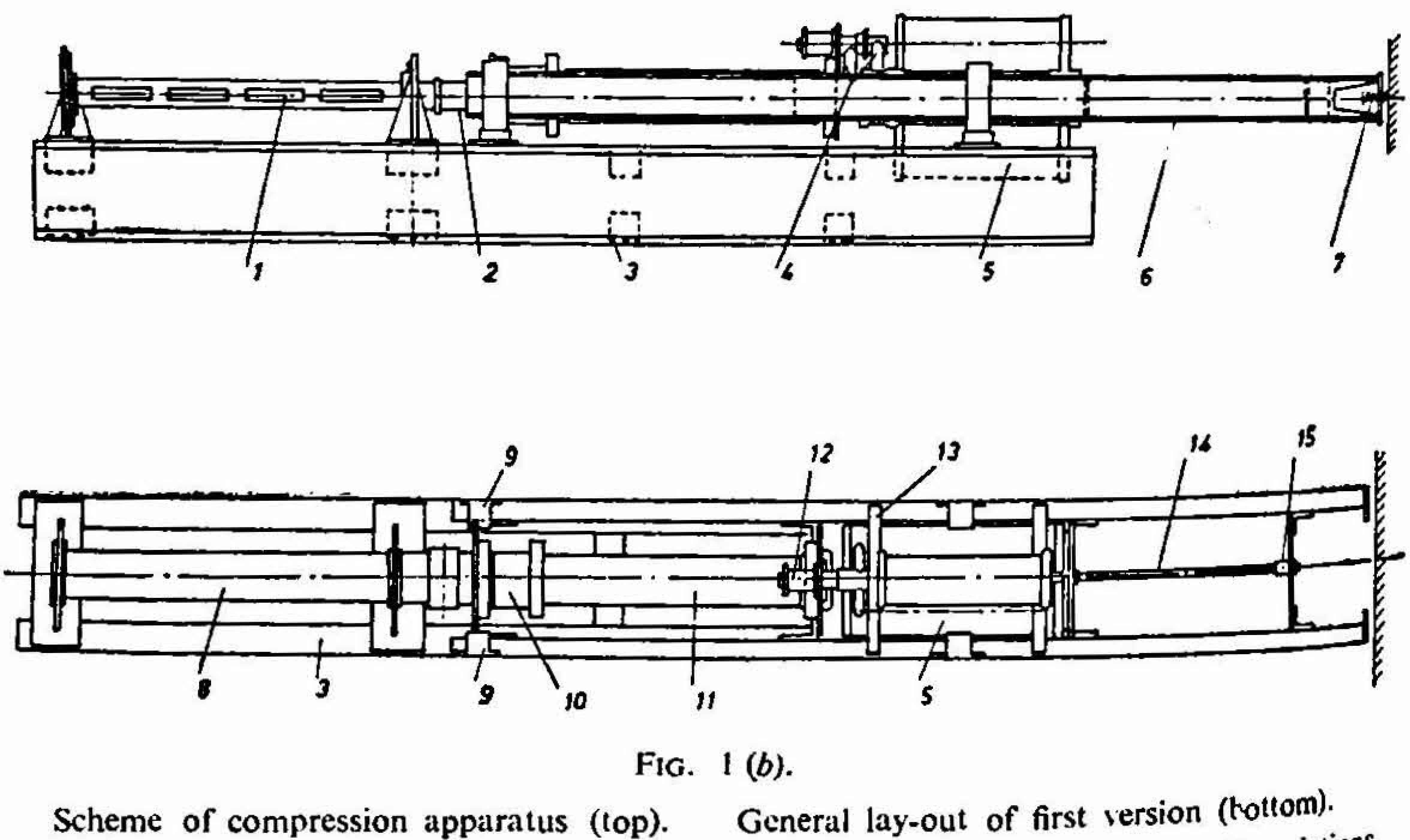

FIG. 1 (*b*).

Scheme of compression apparatus (top). General lay-out of first version (bottom).

1. Window of combustion vessel. 2. Housing for bomb valve. 3. Foundations. 4. Compressed air pipes. 5. Compressed air containers. 6. Frame. 7. Springs for frame movements. 8. Combustion vessel. 9. Bearings for lengthwise movements of frame. 10. Air cushion to decelerate main piston. 11. Cylinder for main piston. 12. Device for rapid release of compressed air. 13. Support for compressed air vessels. 14. Piston rod. 15. Bearing for piston rod.

measurements of pressures. Another requirement was that no traces of oil used for lubricating the piston and the cylinder should alter the composition of the compressed charge.

2. DEVELOPMENT OF THE NEW COMPRESSION APPARATUS

The aim of the development was an apparatus which fulfils the requirements listed above and which will be described with the help of the schematic sketch in Fig. 1 above.

On the right-hand side, a vessel containing compressed air is shown which is closed by a valve. After opening this valve the compressed air enters through the pipe indicated by the cylinder in which the main piston is located. By the expansion of the compressed air entering the cylinder the piston is accelerated very rapidly especially since its initial position is at the utmost right-hand side of the cylinder. On moving forward the piston transfers the combustible gas through an open valve into the combustion vessel. On approaching the upper dead centre of the piston the velocity of the piston will gradually be diminished and ultimately the piston is brought to rest with the help of a special arrangement say of springs which absorb the energy from the moving piston. At the same time the valve which terminates the combustion vessel will be closed by a specially controlled either pneumatic or mechanical, action. Inside the bomb the combustible mixture is now in a state of elevated temperature and elevated pressure. The charge can be ignited by a sparking plug which is indicated in the sketch on the left-hand side. The proceedings of the combustion can be observed from outside through the windows of the vessel. There are four windows on each side of the bomb and thus it is possible that the flame front can be photographed without appreciable interruptions on a film which moves at right angles to the axis of the combustion vessel.

The development towards the final state of the apparatus proceeded in two steps, incorporating two different methods which will be explained now.

2.1 *Lay-out of the first version*

The first version of the compression apparatus is defined by the adoption of a pneumatic action to move the valve which closes the combustion vessel. Before describing the details of this arrangement, the underlying principle may be described.

2.11 *General set-up of the first version*

The dimensions of the compression apparatus were defined by the necessity to obtain at least a compression ratio of about 10 to 1 when using the combustion vessel with the eight windows as compression volume. The maximum piston stroke thus is roughly 1050 mm. and the piston diameter is 160 mm. It may be mentioned that according to considerations given above the heat dissipated from the compression cylinder depends also on the piston diameter. For diameters exceeding 120 mm. the decrease of losses of heat with increasing piston diameter, becomes negligible. The theoretical treatment of allied questions has been undertaken by Pfriem.[20]

In Fig. 1 the general set-up of the compression apparatus is shown. The combustion vessel has been mounted on very heavy profiles of 320 mm. height so as to ensure stability and absence of vibrations. The bomb as a whole can be deflected around the longitudinal axis to facilitate photographic recording. The cylinder in which the piston travels when agitated by the compressed air, forms a design unit together with the compressed air vessels and the arrangement for decelerating the main piston. This group is held together with the help of two profiles of 140 mm. height and is allowed to move with respect to the combustion vessel by provision of roller bearings which are designed in such a way that the whole group can be moved axially. The unit is connected through strong springs with a big mass which has no connection with the combustion vessel. Thus the combustion vessel is totally insulated against any push or pull resulting from the acceleration and deceleration of the piston.

The pipe connecting the cylinder with the compressed air vessel contains the valve for suddenly opening this vessel and thus for starting the piston motion. This valve will be denoted further as the main valve.

Main valve.—This valve has been designed very carefully. Since the combustible mixture is adjacent immediately to the front of the piston also before the compression stroke, it is necessary that the compressed air is allowed to act on the back of the piston only during the compression stroke. Otherwise small leakages of compressed air would change the composition of the combustible mixture, which is not very likely to happen if the time is very short during which the pressure difference between the driving air and the combustible mixture acts on the piston. On the other hand t was necessary for accelerating the piston sufficiently rapidly that the opening of the valve be accomplished as rapidly as possible and with the least amount of throttling of the compressed air.

The working of the main valve is shown schematically in Fig. 2. The vessel for the compressed air is disconnected by a simple valve, from the pipe lines which lead into the cylinder and behind the main piston. The pressure necessary to assure the tightening of the valve is transmitted to the valve from a screw with the help of two steel rods. The faces of the rods are rounded with the exception of the middle portion on their faces where a small plane section has been created. Thus, if the two rods are exactly in line, they can transmit an axial and very large force, but a small force acting at right angles to their axis can cause them easily to deviate from their original direction. To facilitate this, a short stem is applied at the point where the two rods are in contact with each other, and rests on both rods thus situated at right angles to their axis. This stem can be moved with the help of a lever. If the lever and thus the stem is moved downwards, the two rods after a very small deflection from their position according to the plane part of their surfaces, will attain an unstable position and will under the action of the

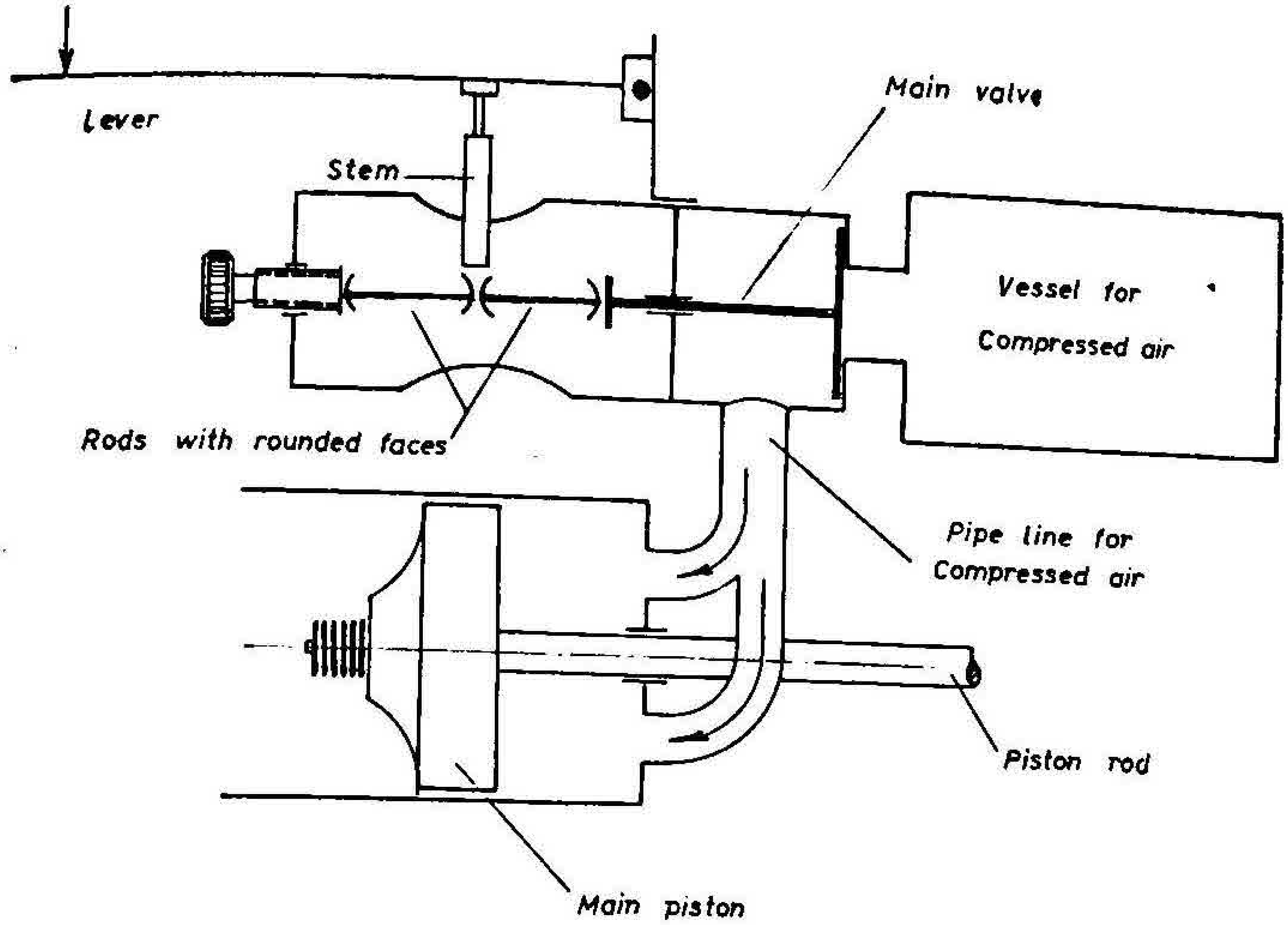

FIG. 2. Starting the main piston.

force exerted by the valve, give way further and thus allow the valve to open the passage for the compressed air. In this way the total unrestricted cross-sectional area of the passage will be opened in a very short time. The valve, moreover, has been designed in such a way that in the moment where air is allowed to actually flow, the valve itself has already attained a certain velocity, and thus the time where the passage is restricted by the moving valve itself is still further reduced. The space which encloses the two rods has to be secured thoroughly by a strong metal cover since the kinematic energy of the freed rods is very considerable.

Main piston.—The main piston is manufactured from light alloy and attention has been given to keep the weight very low. The piston has four piston rings. The cylinder walls have been honed. Glycole has been used as a lubricant but lubrication is restricted to the very least amount. If during the compression stroke air should pass on to and contaminate the layers immediately adjacent to the piston the combustion in the combustion vessel will not be affected since those layers will not participate in combustion since they remain in the space between the valve situated at the entrance of the combustion space and the piston. For the same reason traces of the lubricant will not be able to enter the combustion space.

At the rear side of the piston a piston rod is arranged which penetrates the lid of the cylinder through sealing packings. On its front the piston has several layers of disc springs of different thickness so that a progressively increasing force will be exerted on the piston before its reverse motion starts. With the help of these springs, the piston makes contact with the brake piston after having finished its free compression stroke.

Brake piston.—Its design and its mode of operation can be derived from Fig. 3. The brake piston transmits the energy of the main piston to a cushion of air which if compressed, exerts initially a small but later on a progressively harder braking resistance. The air cushion will attain a higher pressure than will be experienced in the compression vessel since its volume is reduced at a higher rate. Thus the brake piston will easily oscillate and these oscillations can be damped by arranging suitable nozzles in the wall of the air cushion. The combustible mixture flows through the hollow shaft of the brake piston and through a short intermediate pipe which is arranged to allow for an axial motion of the cylinder with respect to the combustion vessel. The combustible mixture thus enters the space which contains the valve which serves to disconnect the combustion space from the cylinder.

2.12 *Closing the combustion vessel*

The difficulties arising from the desire to arrest the main piston at the point of maximum stroke and to use the piston itself to seal the combustion space have been mentioned already. Moreover a piston which is equipped with piston rings is not very suitable for tightly sealing a space of higher pressure for a longer duration. Thus in the present design the combustion vessel is closed with the help of a special valve which will further on be denoted as bomb valve and which, in the first version of the apparatus has been operated pneumatically by compressed air.

Design of the bomb valve.—The stem of the valve which is shown in Fig. 4 is hollow and thus allows the combustible mixture to pass through it. The diameter of the stem is only slightly smaller than the diameter of the valve seat. The mixture enters through four openings in the wall of the stem and through the stem itself into the combustion space. These openings are situated very close to the valve seat and the transition space between valve seat and the combustion space proper is shaped so as to impose the smallest possible resistance by specially shaping the wall of that space and the hood of the valve. This space forms at the same time the transition from the circular cross-section of the shaft of the brake piston and of the stem of the valve, to the rectangular cross-section of the combustion space. On the opposite end of the stem the valve carries a small piston equipped with two piston rings which forms a small circular space and which creates a small space disconnected from the combustion space.

Operation of the bomb valve.—The underlying idea is that the valve is operated by compressed air when entering the small circular space behind the piston attached to the stem of the valve so that the valve is moved in opposition to the direction of the flow of the combustible mixture, until the valve closes and thus disconnects the combustion space from the cylinder, making it impossible that any further exchange of gas occurs between the combustion space and the main cylinder. It is necessary that the compressed air is admitted into the said small space very rapidly and in relation to the position of the main piston. The pressure of combustion would increase the pressure acting on the valve, as soon as the valve is closed and the charge is ignited.

The simplest possibility to operate the valve would be to use the compressed air which is contained in the air cushion behind the brake piston and which is transmitted from the cushion to the circular space by means of a pipe connection which is indicated as a dotted double line in Fig. 6. It is, however, necessary to arrange an additional non-return valve in the said connection so as to prevent the compressed air which has entered the circular space, from expanding backwards due to a subsequent increase in the volume of the air cushion as a consequence of oscillations of the brake piston. Tests with this arrangement indicated, however, that the return valve operates not sufficiently quickly—*see* Fig. 26.

The arrangement described for operating the bomb valve pneumatically from the brake air cushion had therefore to be replaced by a system which is shown schematically in Fig. 5. It is essentially the same system which has been adopted

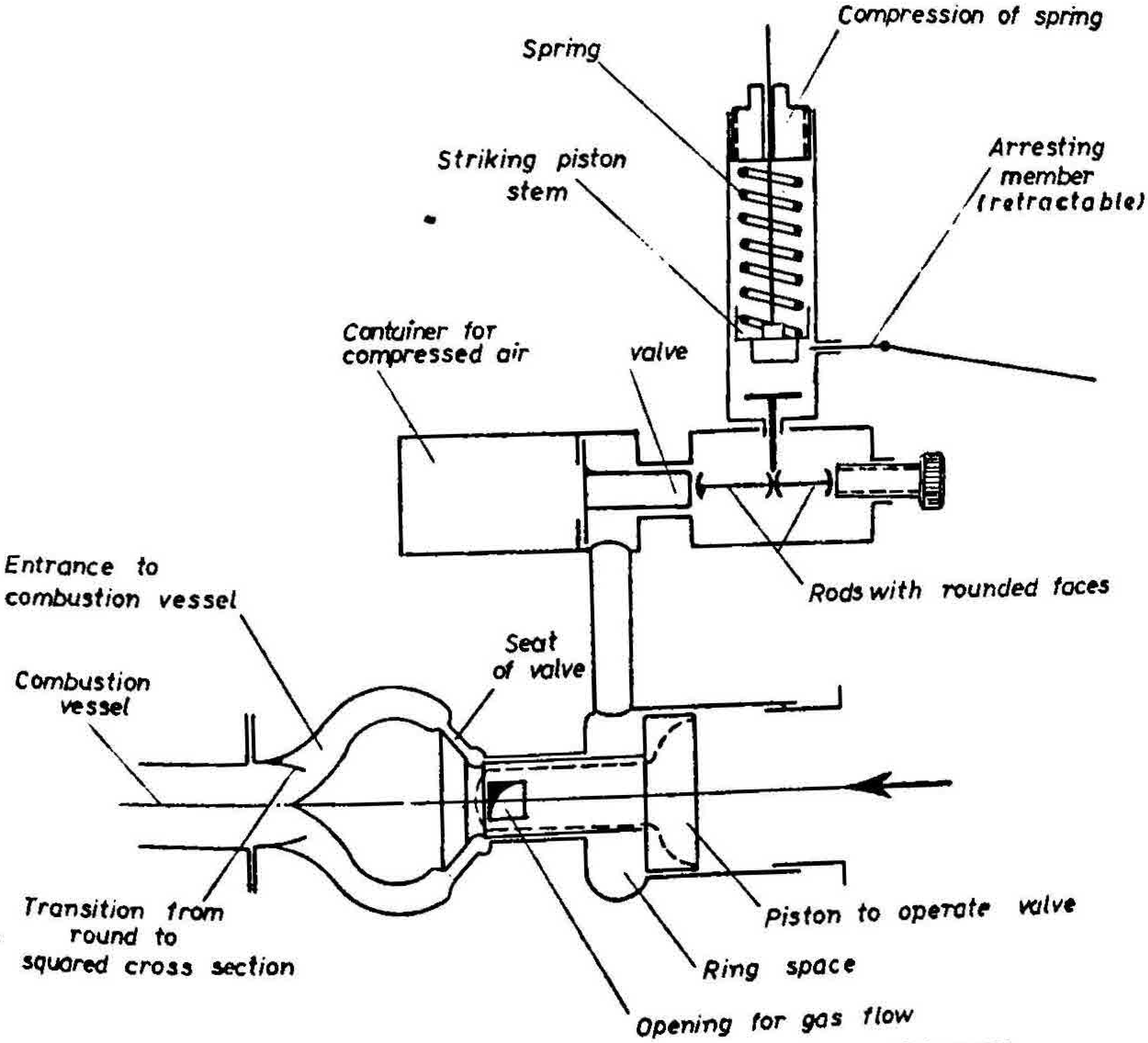

FIG. 5. Operation of bomb valve by compressed air from special source.

to driving the main piston by having compressed air rushing into the space behind the said piston, and which is now applied to move the bomb valve. The compressed air meant to close the bomb valve is stored in a small vessel which is sealed by an axially movable valve forced on to its seat with the help of a screw and two rods with curved faces.

As was the case when operating the main valve these rods are made to deviate out of the straight direction by a short stem. This stem which in the case of the main piston was operated by hand is operated here automatically and in relation to the main piston as can be seen from Fig. 5. The head of the stem is situated inside and at the bottom of a short cylinder which contains another piston loaded by a spring. This piston is held in its position above and at some distance from the head of the stem, and made to withstand the downward directed forces of the spring by a cylindrical member which protrudes into the cylinder supporting the spring loaded piston and thus prevents the piston from moving downwards and coming in contact with the head of the stem. If the cylindrical member, however, is retracted the piston is freed and moves downwards under the action of the expanding spring, and will hit the head of the stem. The stem in turn will make the two rods to deviate from their position so that the valve sealing the compressed air is allowed to move so that the compressed air can enter the circular space behind the valve piston and close the bomb valve.

This procedure can be timed in accordance with the motion of the main piston. The retreating motion of the member supporting the spring loaded piston is started at the given moment with the help of a lever mounted in such a way that it can be operated from the main piston rod with the help of a connection between this lever and the said member. According to the position of the lever with respect to the piston rod and thus the main piston itself, the correlation is given between the position of the main piston and the time for closing the bomb valve. No serious reaction will be exerted on the main piston since the effort to retreat and move the cylindrical member can be diminished by shaping the tip of the arresting member more or less conically. The co-operation and correlation of the individual parts of the apparatus are shown in Fig. 6.

The test procedure will thus be the following:—

First the main piston is started by opening the main valve and thus by allowing the compressed air to enter the space behind the main piston. The combustible mixture in front of the main piston is compressed as the main piston proceeds, and passes through the hollow shaft of the brake piston and the bomb valve into the combustion vessel. Shortly before the main piston has obtained its maximum stroke, its velocity will be reduced by its contact with the brake piston. At the same time, through the action of the lever and the connection from the lever to the arresting member from a cam on the piston rod, the bomb valve is pneumatically operated by the mechanism described above and thus the bomb valve disconnects the combustion space from the cylinder and prevents the combustible mixture

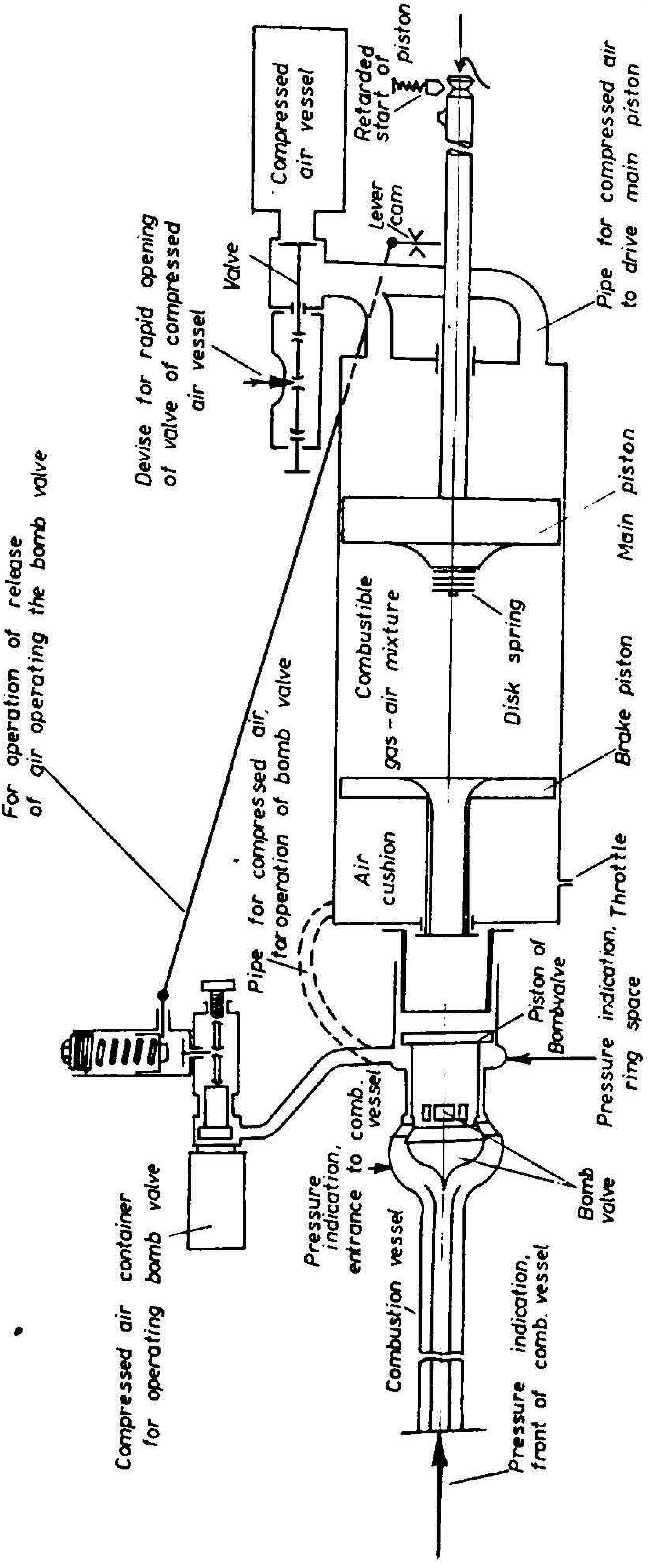

FIG. 6. Scheme of compression apparatus, first version.

there from being influenced by whatever may happen in the cylinder and in the cushion space.

Delay in starting the main piston.—If the main piston is situated not at the utmost end of the cylinder, that means if a smaller compression ratio is required the rate of pressure increase behind the main piston will be smaller since the compressed air has to fill up a comparatively larger volume behind the piston. The smaller the compression ratio, the smaller would be the rate of build-up of pressure behind the piston. The main piston, however, commences its movements at very small pressure differences. It was found that less than 20 mm. Hg are sufficient to cause it to move. The consequences would be that for small compression ratios only a comparatively small amount of compressed air will be able to enter the space behind the piston before its start and the resulting piston velocity would be diminished.

This disadvantage was eliminated by an arrangement which worked as follows:—

The main piston is retained at its initial position chosen according to the compression ratio desired, by a force of pre-determined magnitude, and consequently the piston will not be allowed to move until the force exerted on it by the compressed air supersedes the outer forces applied for its retention. Practically, two clamps fitted at the front with rollers were embracing the piston rod from above and below with the help of adjustable springs acting on a conical collar on the main piston rod. According to the pressure exerted by these springs on the clamps the exact force, *i.e.*, the air pressure to overcome the retaining action of the clamps could be varied. This design is shown schematically also in Fig. 6.

2.2 *The lay-out of the second version*

2.21 *General set-up*

The first version was not quite satisfying with respect to the following points:

The piston velocity was considered to be too low and the volume for the compressed air for driving the main piston was subsequently increased to about 60 litres. The cross-sectional area of the duct between the compressed air storage tank and the cylinder was increased.

The arrangement for braking the main piston has the disadvantage that the compression ratio is correlated to the position of the brake piston and thus becomes rather uncontrollable. In the second version, the brake piston was replaced by a packet or six spiralic springs so that the compression ratio became dependent only of the position of the main piston and can now be derived from a record of the movement of the main piston. The general lay-out of the second version is shown in Fig. 7.

2.22 *Closing the combustion vessel*

Though the pneumatic governing of the bomb valve worked to satisfaction the time for the motion of the valve measured to be $3–4 \times 10^{-3}$ sec. was considered

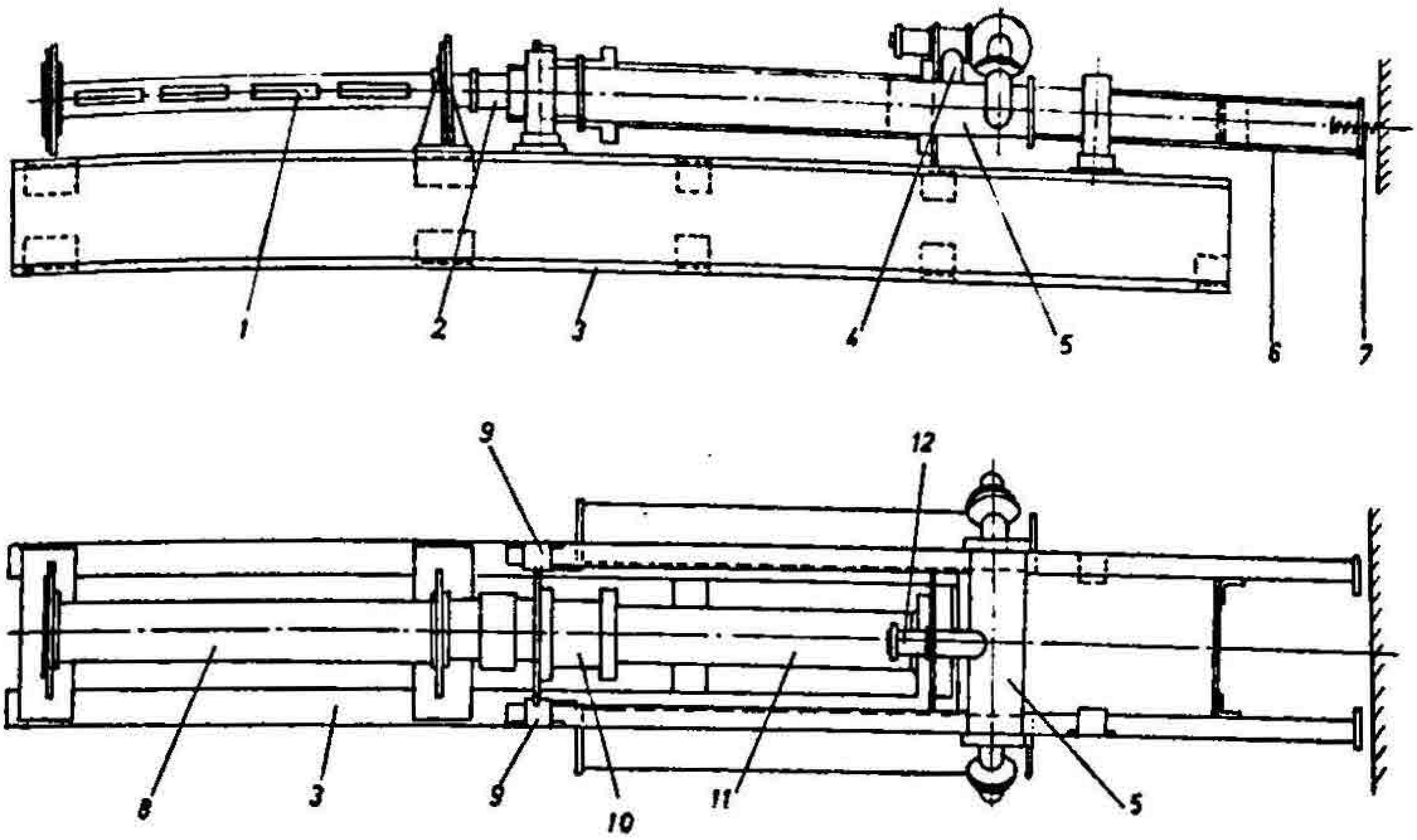

FIG. 7. Scheme of lay-out of compression apparatus, second version.

1. Window of combustion vessel. 2. Housing for bomb valve. 3. Support for combustion vessel. 4. Pipe for compressed air. 5. Compressed air vessel. 6. Frame. 7. Spring for frame. 8. Combustion vessel. 9. Bearing for lengthwise movement of frame. 10. Brake cylinder for main piston with air cushion. 11. Cylinder for main piston. 12. Device for rapid release of compressed air.

to be too long. Another disadvantage was the fact that the geometric shape of the interior of the combustion vessel was irregular mainly due to the shape of the transition portion between the bomb valve seat and the combustion space proper. This may have affected the rate of combustion and the propagation of the flame in an uncontrollable manner.

In the second version, two bomb valves are provided and are operated mechanically, *see* Fig. 8. Both valves are situated in opposition to each other and they are of quite conventional design. Their seat is submerged into the wall of the combustion vessel so that, if both valves are closed, the cross-section of the combustion space and its surface is not affected in any way. For the period of flow of the combustible mixture into the combustion space, both valves are open and are maintained so against the action of two valve springs by allowing their stems to rest against two levers which are interlinked by a member connecting the end of both levers, thus forming a rectangular frame. In the upper half of Fig. 8, this position is given. Both levers are allowed to turn around a line which is parallel to the axis of the two valves. Thus, if the frame constituted by the two levers and the connecting member, is turned about its axis by a certain angle, the stem of the two valves became free and the valves will close simultaneously according to the effect of the two respective springs. This position has been shown in the lower part of Fig. 8. The dislocation of the frame can be correlated to and operated

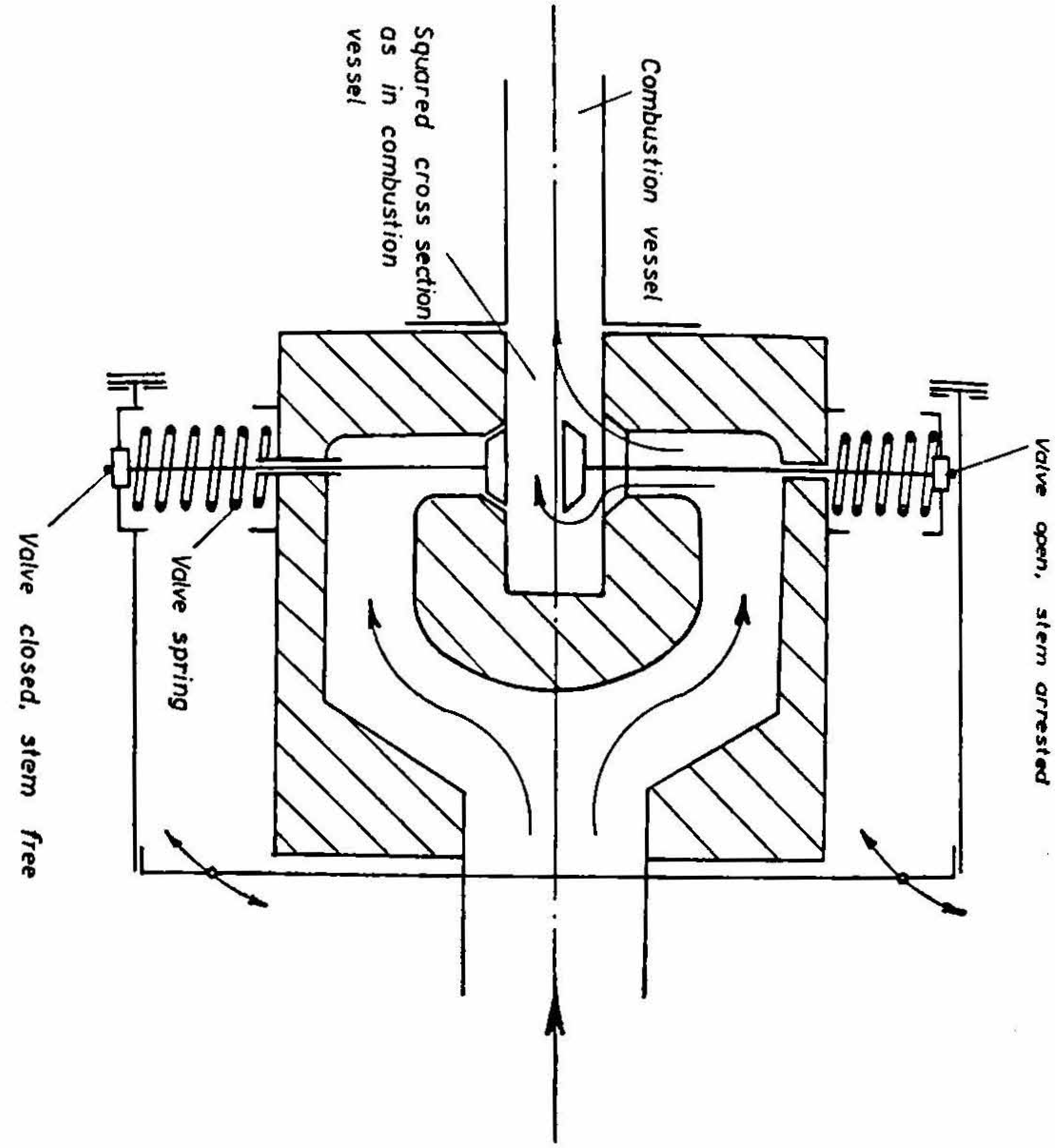

FIG. 8. Scheme of machanical operation of bomb valves.

from, the main piston rod through a cam and lever in a similar way as was applied for operating the valves in the first version.

Figure 9 shows a sectional drawing of the medium part of the second version. It shows the springs for the deceleration of the main piston and the passages for the gas between the cylinder and the combustion vessel proper. The flow of the mixture shortly before entering the combustion space proper is divided into two branches with one valve operating in each branch. A pressure pick-up point is provided at right angles to the axis of the valves and so is a sparking plug for igniting the charge in the combustion vessel. Figure 10 shows a photograph of the valve mechanism as described. The spring operating the upper valve can be seen and the upper part of the frame for the operation of the valves. In order to diminish the friction between the stem of each valve and the frame when the latter is moved a small sphere has been incorporated into the uppermost part of the valve stem. A small contact can be seen in the photograph above the valve. It is used as an electrical contact for measuring the duration of the motion of the bomb valve and its relation to the position of the piston. The vertical connecting member completing the frame is manufactured from tubular material in order to minimise inertia forces. It can be seen in Fig. 11. The operation of the frame can also be seen in Fig. 11 as far as the frame is concerned, and in Fig. 12, the lever can be seen which is operated by the cam on the piston rod. In Fig. 11, the conical bearing can be seen which allows for an axial motion of the frame carrying the cylinder with the piston and the compressed air vessel.

Figs. 11 to 14 give furher views on the apparatus.

3. MEASURING DEVICES OF THE COMPRESSION APPARATUS

The devices for recording the dynamics of and the changes of state during the compression stroke are equal for both apparatus; *see* also Fig. 48.

3.1 *Motion of piston*

It has already been mentioned that the piston velocity and its distribution along the piston stroke influences the rate of reactions. For this reason, measurements have been carried out to show the correlation between the pressure in the compressed air vessel and the velocity of the piston. For the first version of the apparatus, the stroke of the piston was varied, but for the second version, the piston in the moment of starting its motion was always adjacent to the back of the cylinder.

The following arrangement has been made for recording the motion of the piston. To the end of the piston rod an electric contact spring is attached which during the motion of the piston is led along a wire expanded parallel to the piston rod, thus constituting a sliding contact. The wire is part of an electrical circuit and thus the difference in potential is recorded with the help of an oscillograph (Siemens). This oscillograph thus shows the motion of the piston on the recording paper of the rotating film drum constituting a time-stroke-diagram of the motion. On the recording paper, time intervals of (2×10^{-3}) seconds are indicated.

This arrangement has also been used to indicate the exact moment when the piston starts its motion. The contact spring brakes a contact which short-cuts the wire up to this position. Thus on the diagram the beginning of the motion of the piston is indicated by a steep decrease of voltage and subsequently the piston motion diagram is written (*see* Fig. 15).

3.2 *Motion of valves*

For the different valves, the time of motion and the beginning of the motion is required. At the beginning and at the end of the motion electrical contacts are made and both electrical impulses are transmitted to the oscillograph.

3.3 *Pressure measurements*

At different positions of the apparatus the pressure is measured with the help of piezo-electrical pressure elements of specially high natural frequency which have been designed by Gohlke.[21] The position of the pressure measurements are denoted in Fig. 6. The galvanometer suspension wires of the oscillograph have a frequency of 5000 per second; the amplifier used was also designed by Gohlke. Experiments for a first orientation were carried out with a cathode-ray oscillograph built by Nier.

On using the galvanometer type oscillograph, one difficulty was encountered inasmuch as the starting of the recording should be timed such that one complete rotation of the recording drum should record all measured quantities. This was accomplished by having an electrical contact attached to the lever operating the main valve which allows the compressed air to enter the cylinder. Thus the shutter of the oscillograph was opened exactly at the beginning of the test and the shutter is closed automatically after one complete rotation of the recording drum. By slightly adjusting the electrical contact a correct co-ordination between the shutter of the oscillograph and the commencement of the motion of the piston could be obtained. The arrangement as described can be seen in Figs. 12 and 13.

4. EXPERIMENTAL RESULTS AND EVALUATIONS

4.1 *Motion of piston*

Figure 15 shows a piston motion diagram and the pressure diagram for the first version of the apparatus with the pressure being recorded at the front of the combustion vessel. The bomb valve is not agitated in this case. The distance of the time marks is $2 \cdot 10^{-3}$ seconds. It can be seen that the piston oscillates and that points of inversions of motion are correlated to pressure peaks. The second increase of the pressure after the first pressure peak is due to the motion of the brake piston. This part of the pressure diagram cannot be used and thus has to be eliminated by the action of the bomb valve.

From the slope of the time-stroke curve of the motion of the piston the velocity of the piston can be defined. Figures 16 till 19 show the evaluation with respect to the piston velocity along the piston stroke for different pressures of compressed air, for the first version. Figure 20 gives the scatter of the values evaluated from a greater number of tests. For the second version, the velocity distribution of the piston along its stroke is shown in Fig. 21. The stroke of the piston depends on the arrangement made for decelerating the piston and the correlation between piston stroke, and compression ratio depending on the pressure of the compressed air is shown in Fig. 22. The curve shown for the compression ratio is related only to the second version of the apparatus but it must be stressed that the values indicated can be increased considerably by only slightly changing the dimensions of the combustion vessel so that investigations into compression-ignition could be carried out easily.

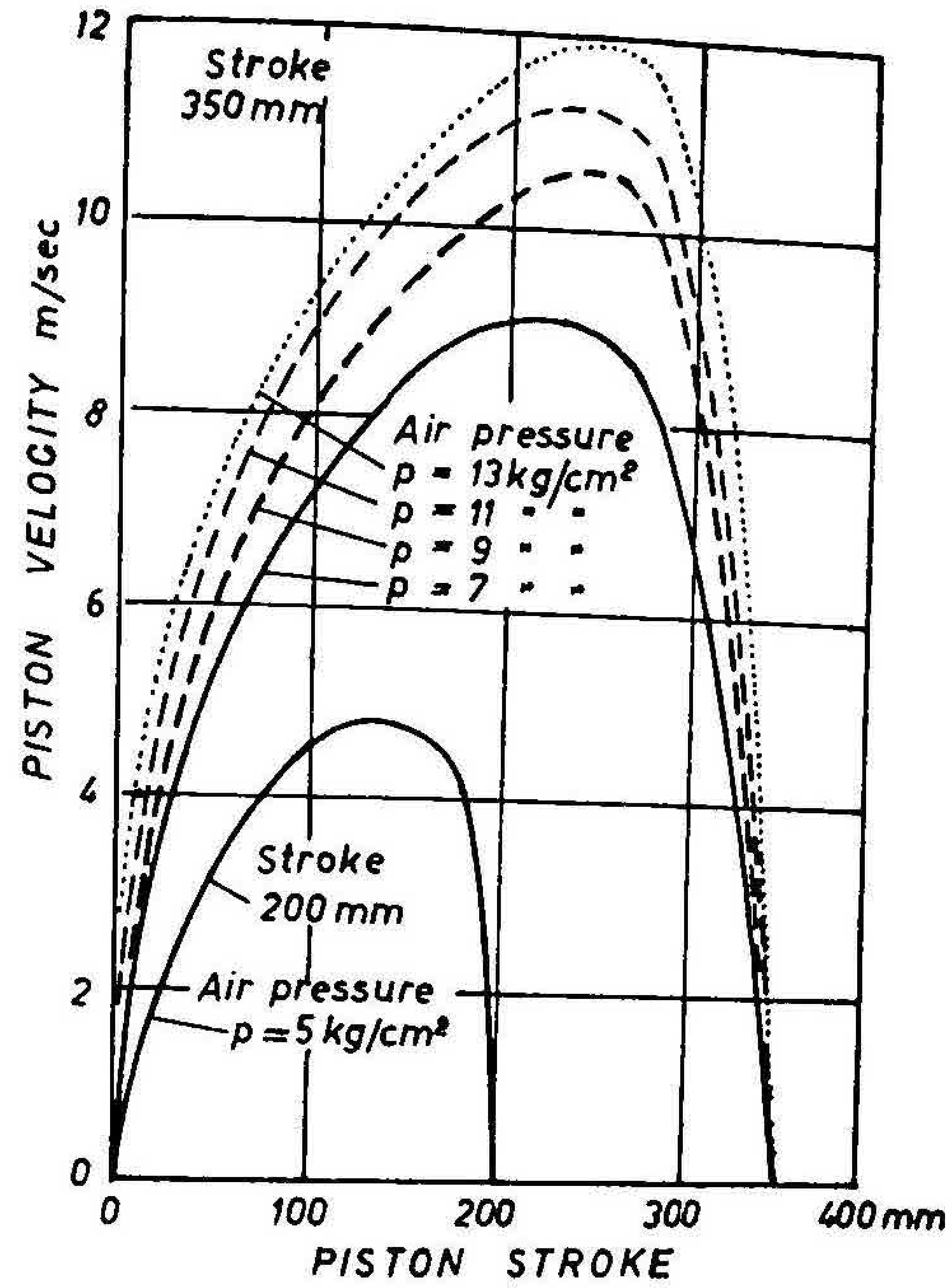

FIG. 16. Interdependence of piston velocity and motion of piston for a stroke of 200 mm. and 350 mm. for air pressure of 13, 11, 9 and 7 kg./cm.²

As a comparison of the two versions of the compression apparatus, the Figs. 23 till 25 show the time for compression and the average and the maximum velocity of the piston depending on the compressed air pressure. The effects of the changes in the design made are clearly to be seen.

4.2 *Motion of valve*

The co-ordination between the motion of the valve and the motion of the piston and thus also the pressure obtained, can be clearly seen from the diagram of the oscillograph.

The diagram shown in Fig. 26 has been drawn with the cathode-ray oscillograph and was obtained from the first version of the apparatus with the simple connection from the compressed air cushion behind the brake piston to the ring space of the bomb valve. It shows the pressure in the ring space of the bomb valve and the pressure indicated at the face of the combustion vessel. It can be seen from a comparison of the related pressures that the valve closes too late. The second compression stroke of the piston which is indicated by the renewed ncrease of pressure in the ring space opens the valve and increases the pressure

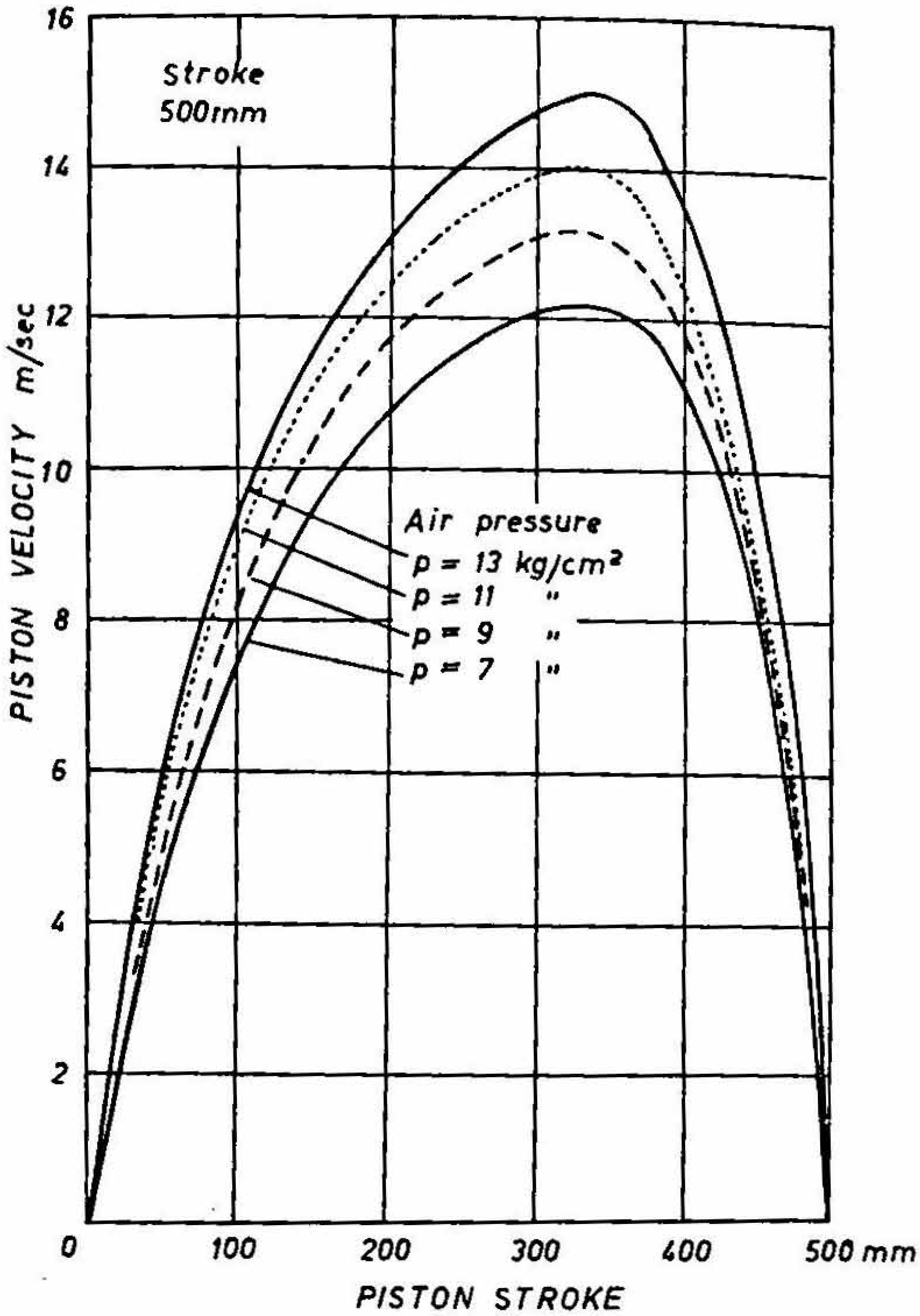

FIG. 17. Interdependence of piston velocity and motion of piston for a stroke of 500 mm. for air pressures of 13, 11, 9 and 7 kg./cm.²

in the combustion vessel. Due to the inertia of the gas, the second pressure peak in the ring space is higher than the first peak. As a consequence of the difficulties indicated the inherently simple arrangement had to be discarded and all attempts made to introduce reliably working return valves could not bring this arrangement to the necessary perfection. Since the cathode-ray oscillograph used here is not applicable to recording more electrical impulses, only the galvanometer type oscillograph was used later on.

A diagram taken with the galvanometer type oscillograph is shown in Fig. 27. Pressures in the ring space and at the front of the combustion vessel have been recorded simultaneously. As compared to the design underlying Fig. 26, the bomb valve in this case is operated by a small separately operated compressed air vessel as shown in Fig. 6. The very rapid increase of pressure in the ring space of the valve is remarkable, and thus a very highly accelerated motion of the valve has been accomplished. The duration of the motion of the valve is indicated by

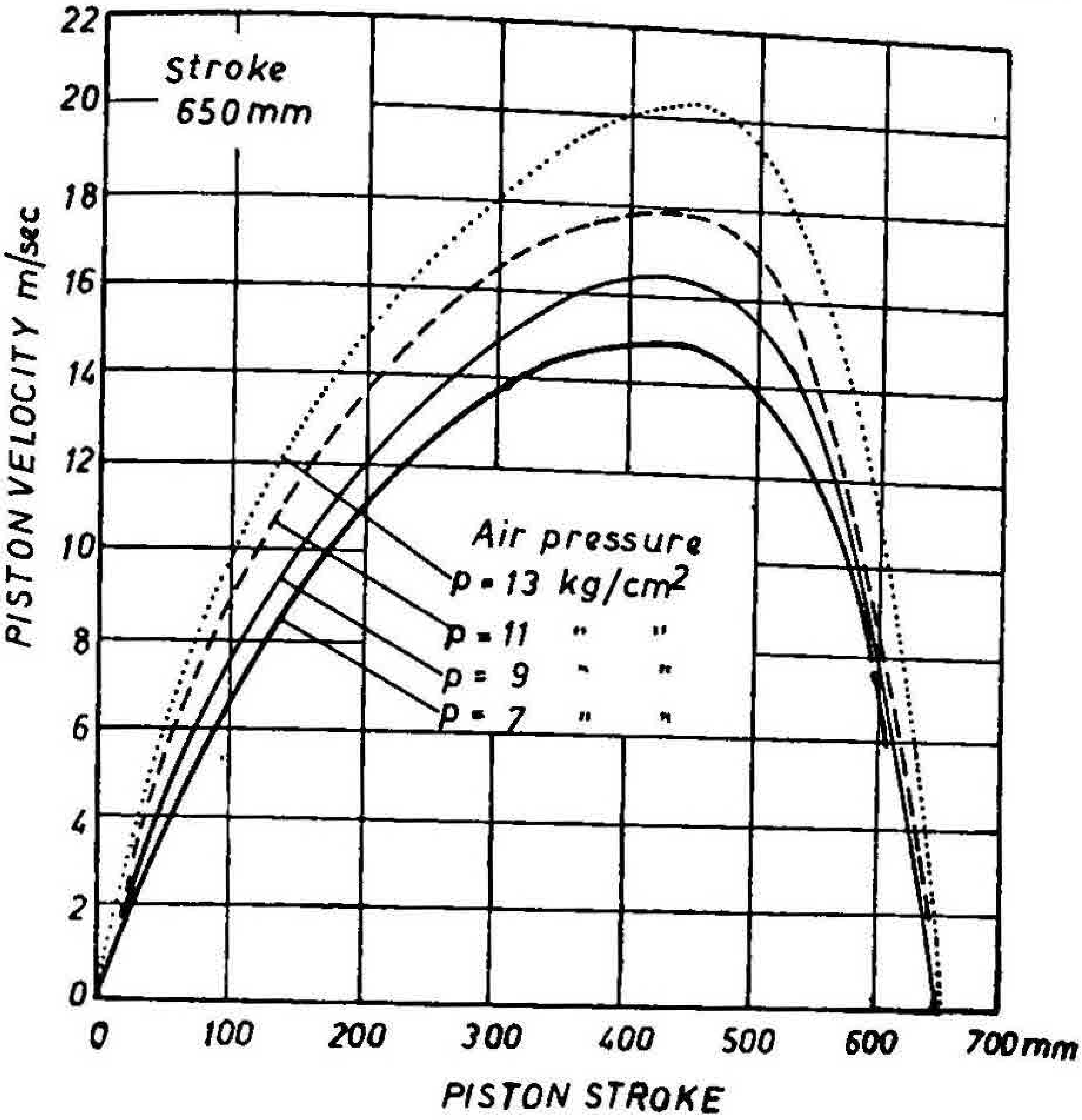

FIG. 18. Interdependence of piston velocity and motion of piston for a stroke of 600 mm. for air pressures of 13, 11, 9 and 7 kg./cm.²

two electrical contacts at the beginning and at the end of the motion. In Fig. 28, an additional contact has been introduced for the main valve so as to show the duration of its motion and this has been indicated in the diagram. This diagram has been taken from the second version of the apparatus and thus the bomb valve is operated mechanically as explained in Fig. 8.

From a greater number of tests, Figs. 29 and 30 have been derived. They show the time of motion of the compressed air operated bomb valve of the first version depending on the difference between the pressure in the combustion vessel and the pressure of the compressed air operating the valve. Figure 30 shows for the second version the time for the motion of the main valve and of the bomb valves depending on the pressure of the compressed air.

4.3 *Variations of pressure*

The change of state experienced by the gas in the space in front of the piston is irreversible since pressure differences are also imposed on the gas as a consequence of its inertia and due to the acceleration of the piston, and since the change of state is connected with throttling and heat transfer under considerable temperature differences. The magnitude of the pressure difference between layers of gas adjacent to the surface of the piston and if remaining essentially at rest can be calculated

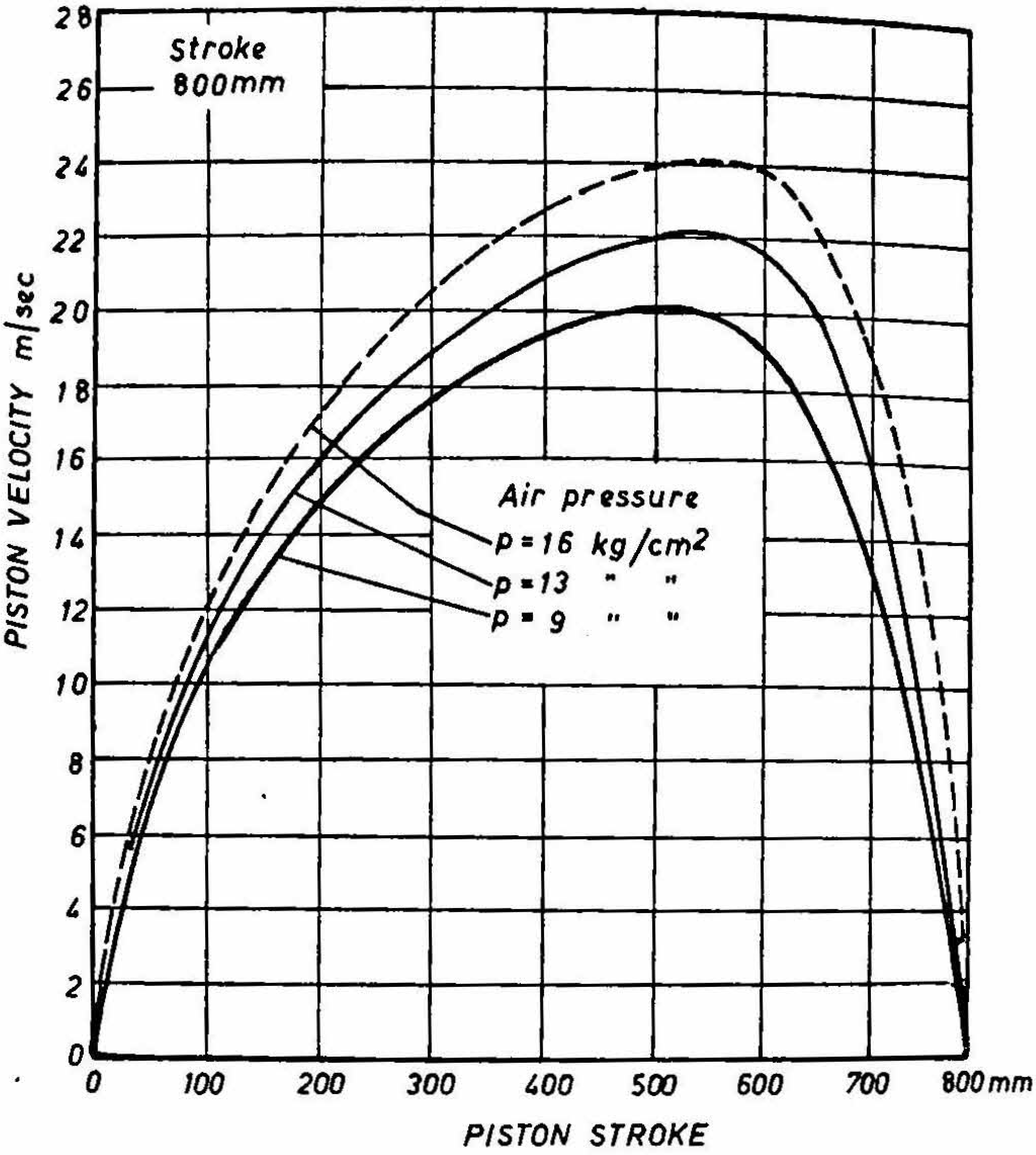

FIG. 19. Interdependence of piston velocity and motion of piston for a stroke of 800 mm. for air pressures of 16, 13 and 9 kg./cm.^{2}

according to Pfriem[22] by assuming plane fields of states without vorticity and disappearing heat exchange to the wall. These conditions, however, are not fulfilled here and especially the heat transfer inside the combustion vessel to the cool walls is considerable, especially since the ratio of surface to volume of the gas space is large and the walls have a high thermal capacity.

In order to gain some indication regarding the change of state of the gas in the space in front of the piston a number of measurements have been undertaken which are concerned mainly with the change of the state of the gas there after the closure of the combustion vessel. The state, or the sequence of thermodynamic states experienced by the mixture there are responsible mainly for the reactions in the gas. In order to eliminate the chemical influences, the measurements have been done in the first instance with air only.

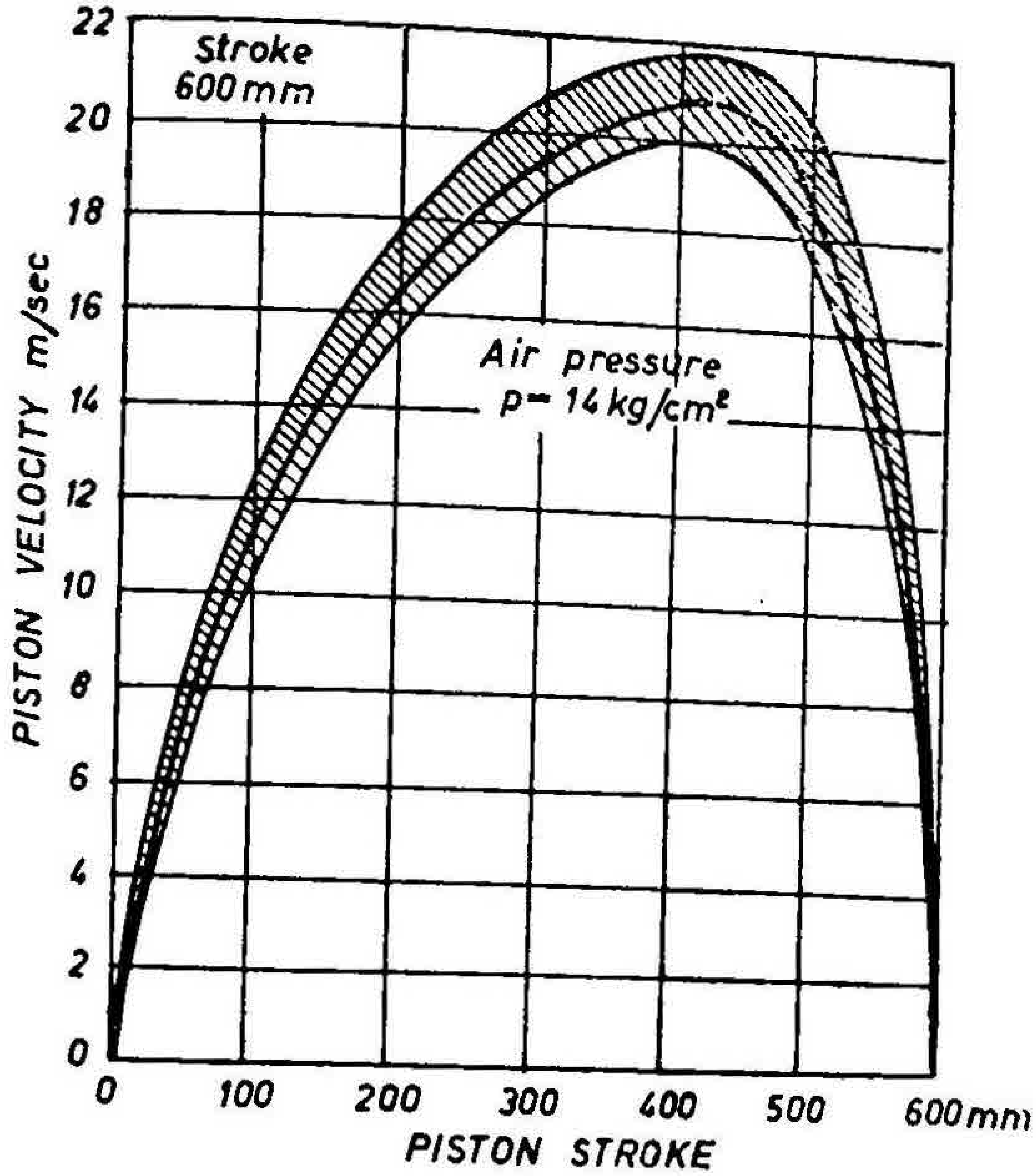

FIG. 20. Scattering of values of piston velocity for a stroke of 600 mm. and air pressures of 14 kg./cm.²

As can be seen from the pressure diagram—*see* Fig. 28 or 31, that the gas in the combustion space is subjected to rapid oscillations. Figures 31 and 32 give an indication of their nature. Figure 31 gives the pressure variations as measured on the front of the combustion vessel for the second version of the apparatus with mechanical operation of the bomb valves, and Fig. 32 shows the pressure at the entrances to the bomb and at the front of the bomb, Fig. 32 (*a*) showing the relations of pressure immediately at the end phase of the compression and the commencement of the oscillations. Figure 32 (*b*) shows the relative order of the oscillations some time after the bomb valve has been closed. By thermal damping and by friction the gas oscillations are subsiding gradually. It may be mentioned that for these recordings two separate amplifiers were necessary.

In order to find out the effect of these oscillations, *e.g.*, on the velocity of flame propagation it would be desirable to damp the oscillations. It would thus easily be possible to show experimentally the influence of oscillations under conditions of pressure and temperature which, in the average, are the same and thus can be compared under the exclusion of other disturbing factors.

The length of the combustion vessel constitutes half the wave-length of the oscillation. Thus it must be possible to damp efficiently the oscillations by

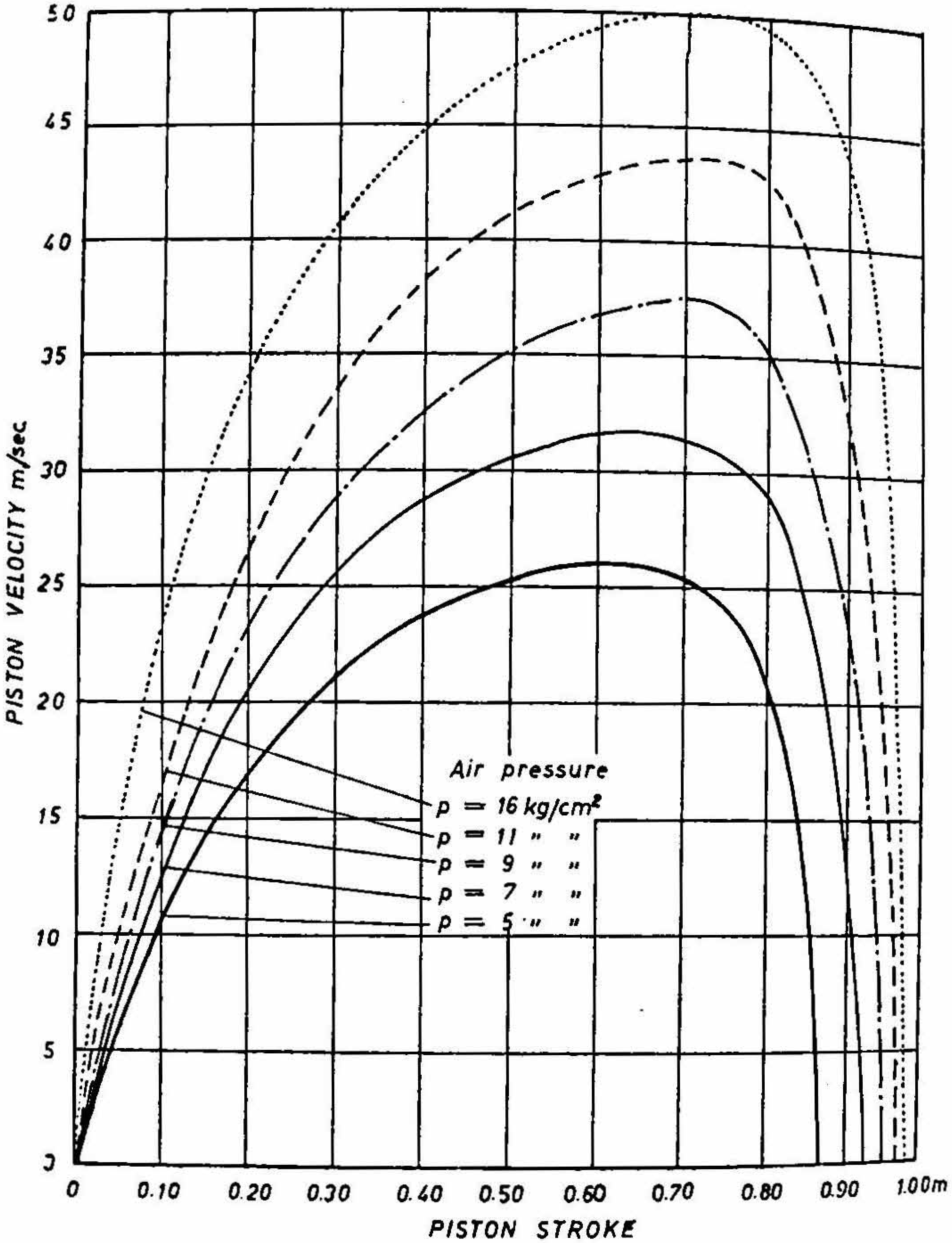

FIG. 21. Piston velocity *versus* piston stroke for different air pressures, second version.

providing a pipe at right angles to the axis of the vessel with a length equal to a quarter of the wave-length which creates interference, and damping. At the end of this damping pipe, the pressure wave entering this pipe is reflected so that the phase difference of the oscillation at the open end of the pipe amounts to half the wave-length of the fundamental oscillation. Thus the oscillations in the bomb should be suppressed or at least the standing wave will be damped energetically. Figures 33 and 34 if compared show the effect of the damping pipe: the oscillations shown

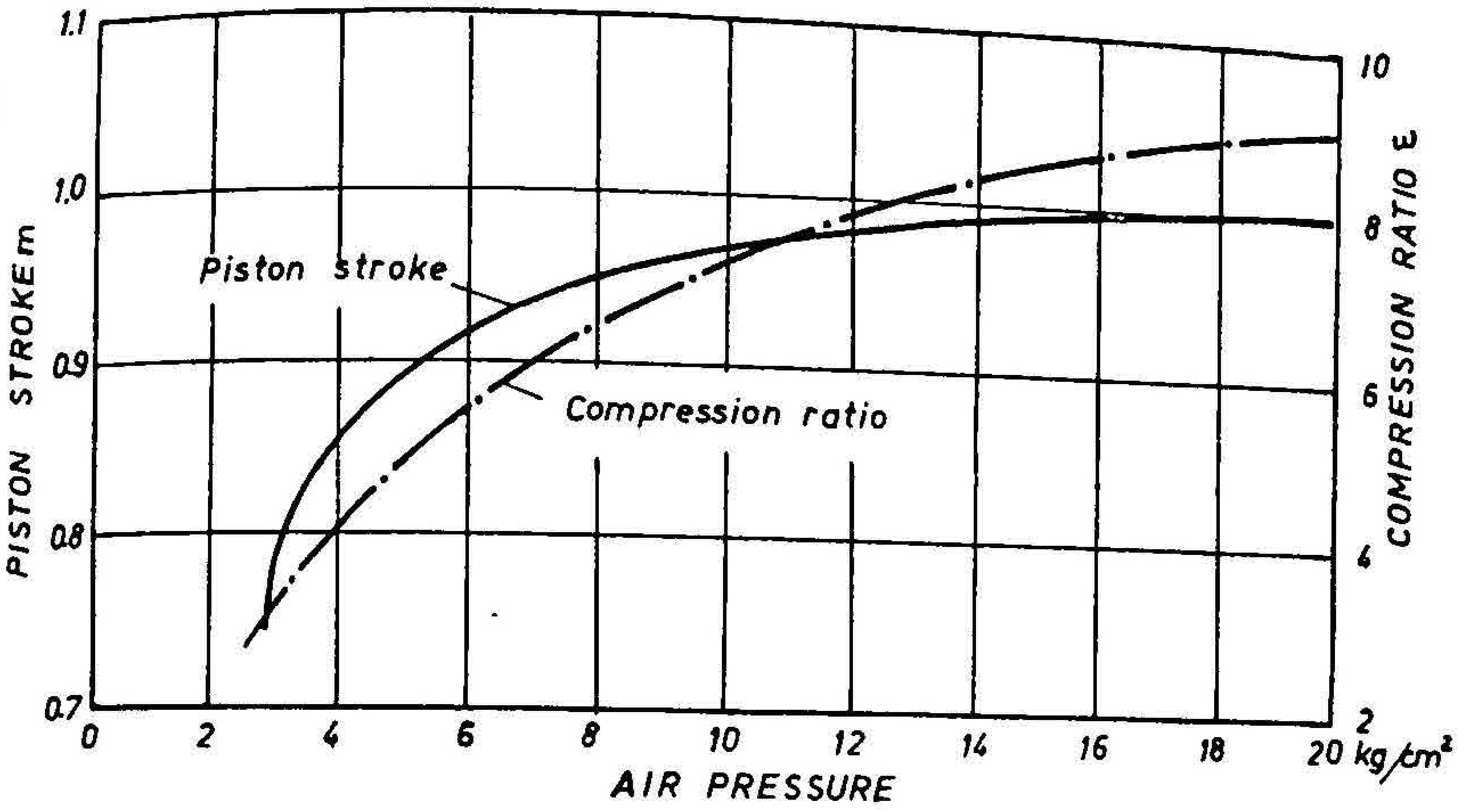

FIG. 22. Piston stroke and compression ratio *versus* air pressure, second version.

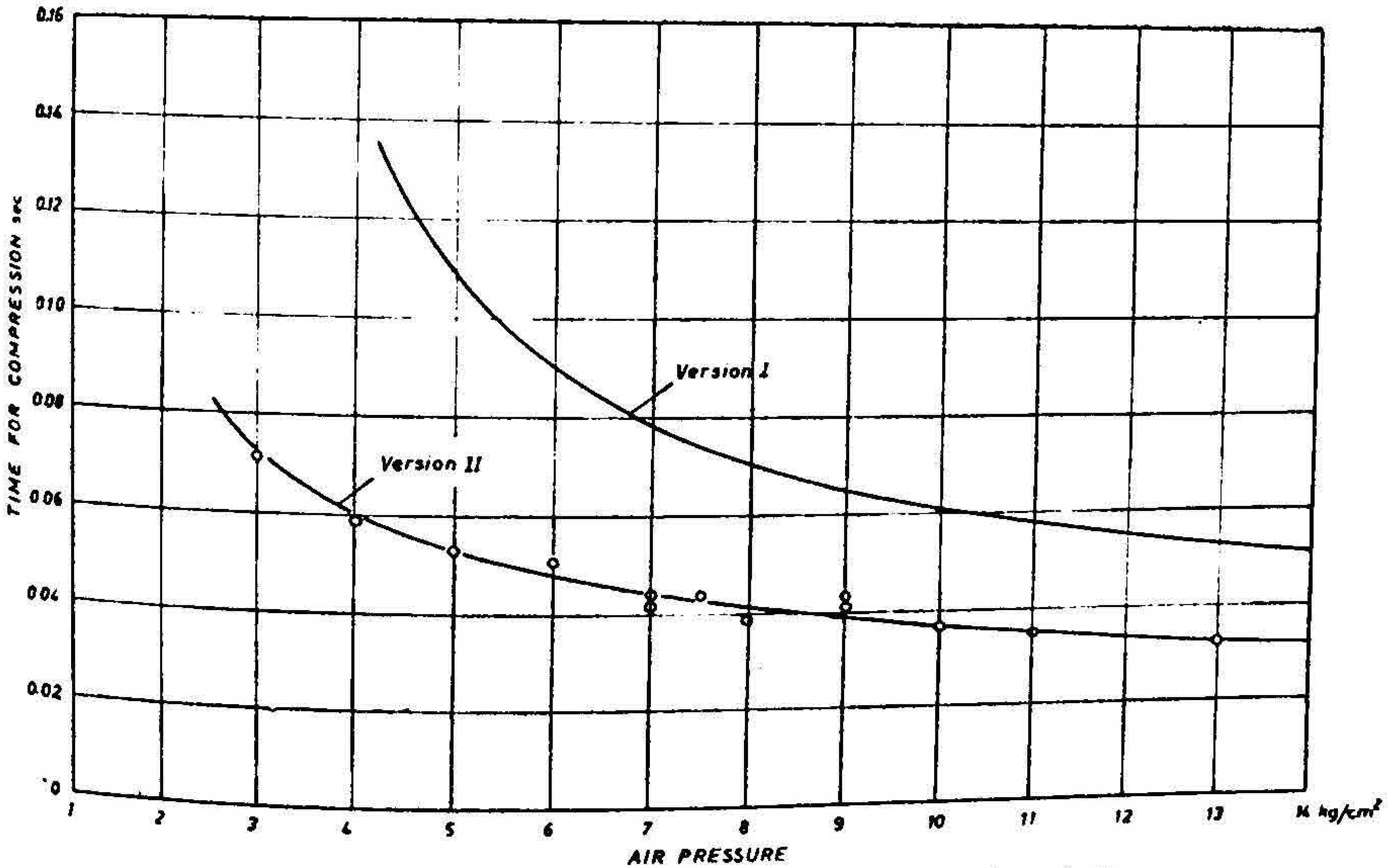

FIG. 23. Time of compression *versus* air pressure for both versions.

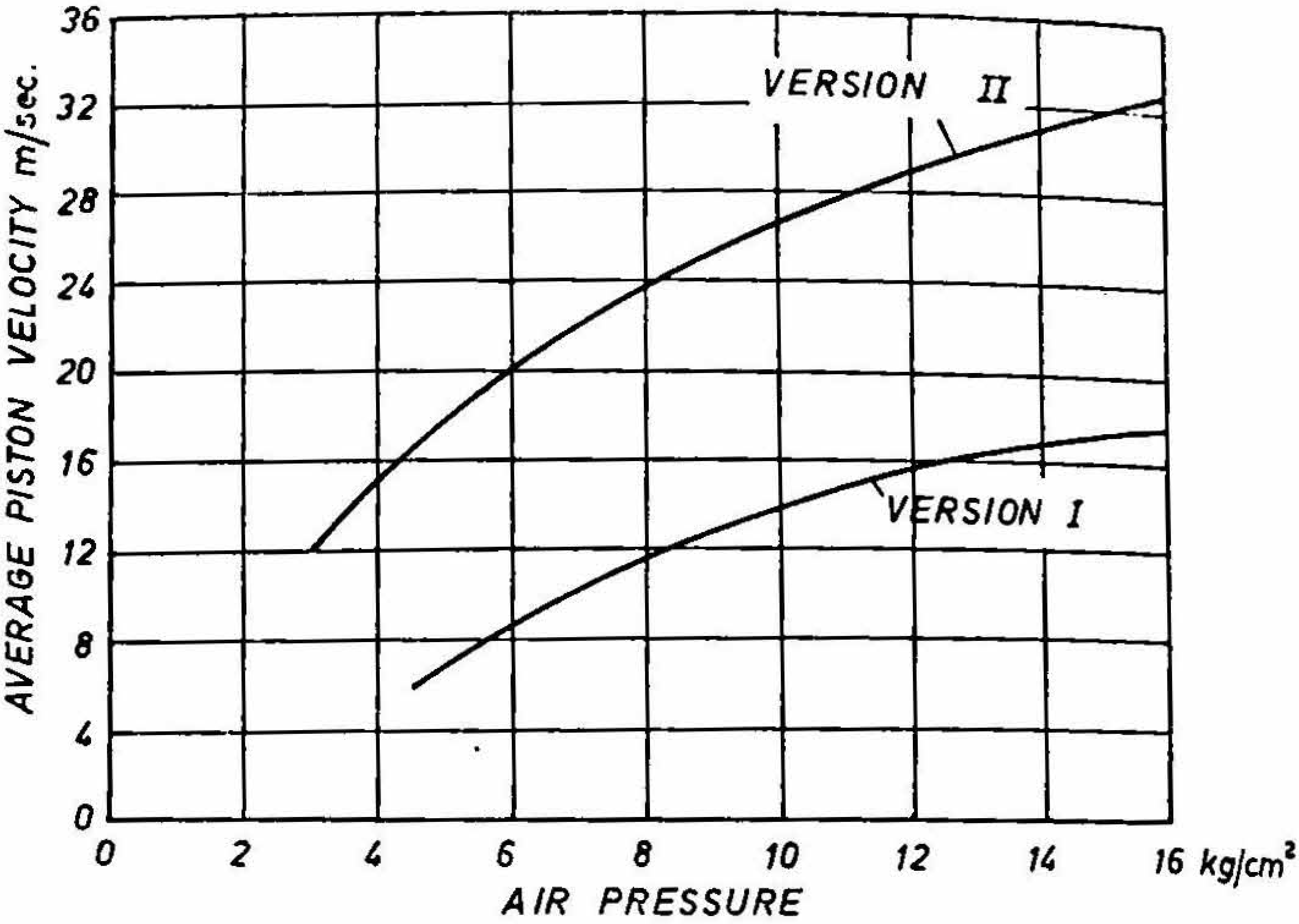

FIG. 24. Average piston velocity *versus* air pressure for both versions.

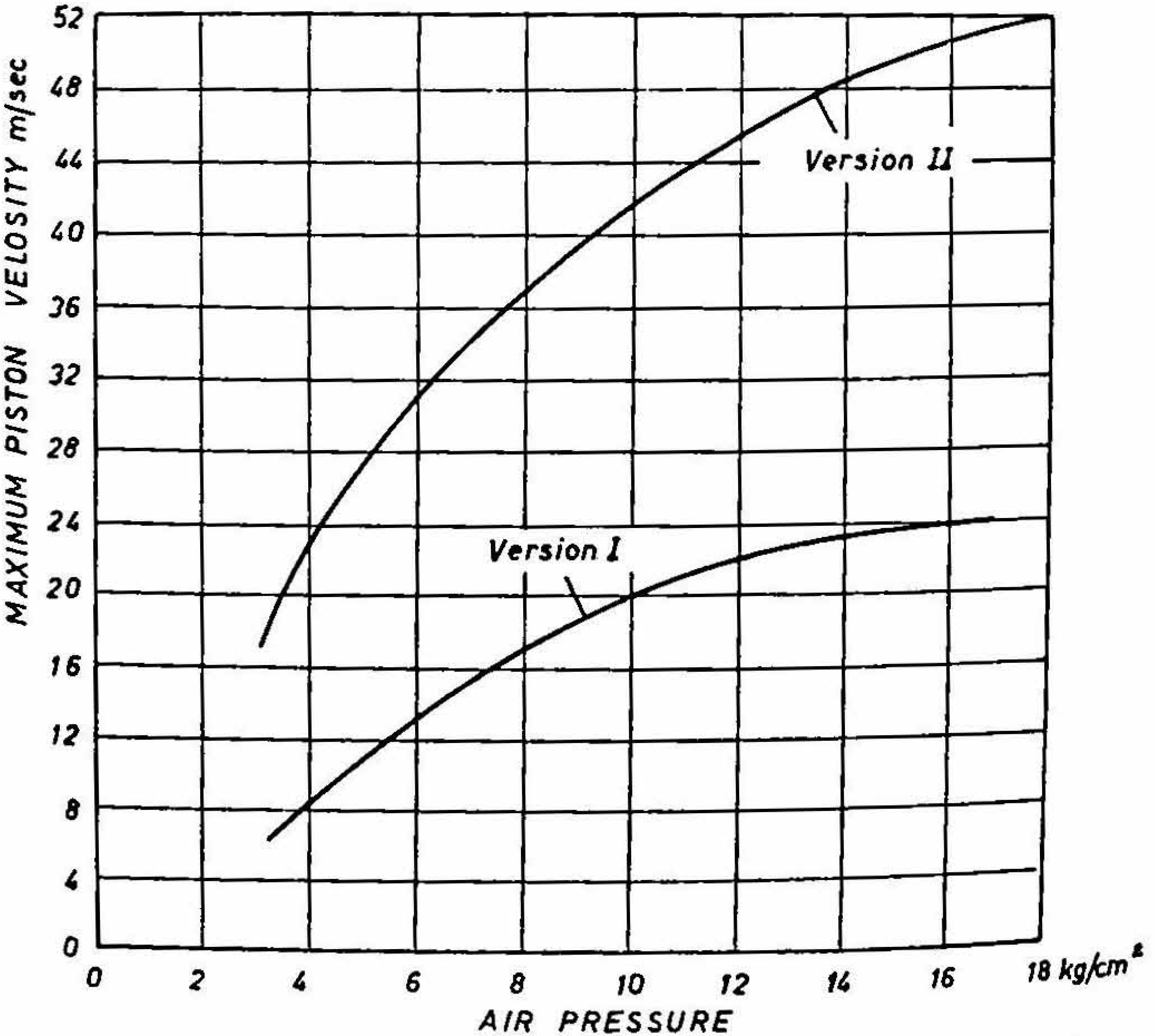

FIG. 25. Maximum piston velocity *versus* air pressure for both versions.

in Fig. 33 are damped as shown in Fig. 34. These pressure recordings have been made on the first version of the apparatus.

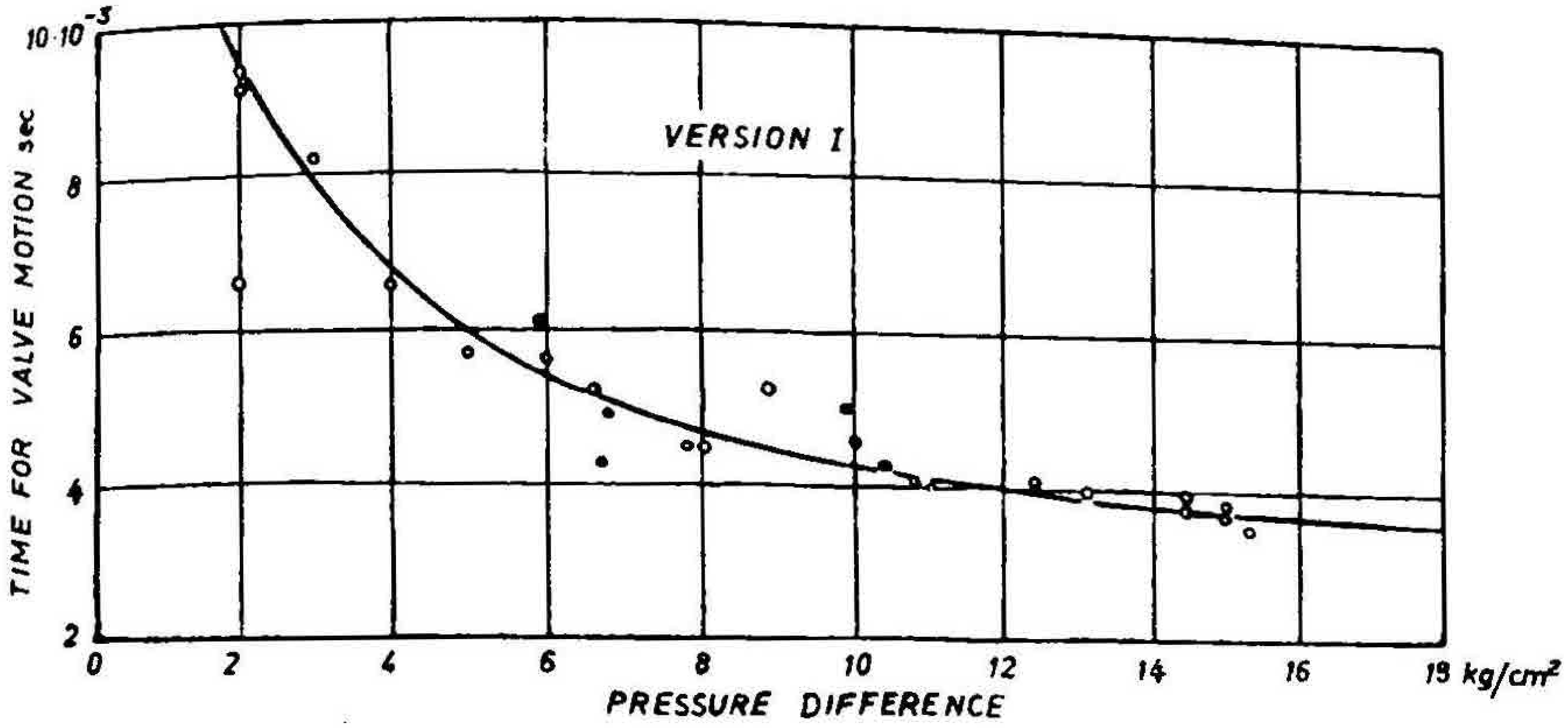

FIG. 29. Duration of motion of bomb valve in relation to pressure difference between combustion vessel and operation air, first version.

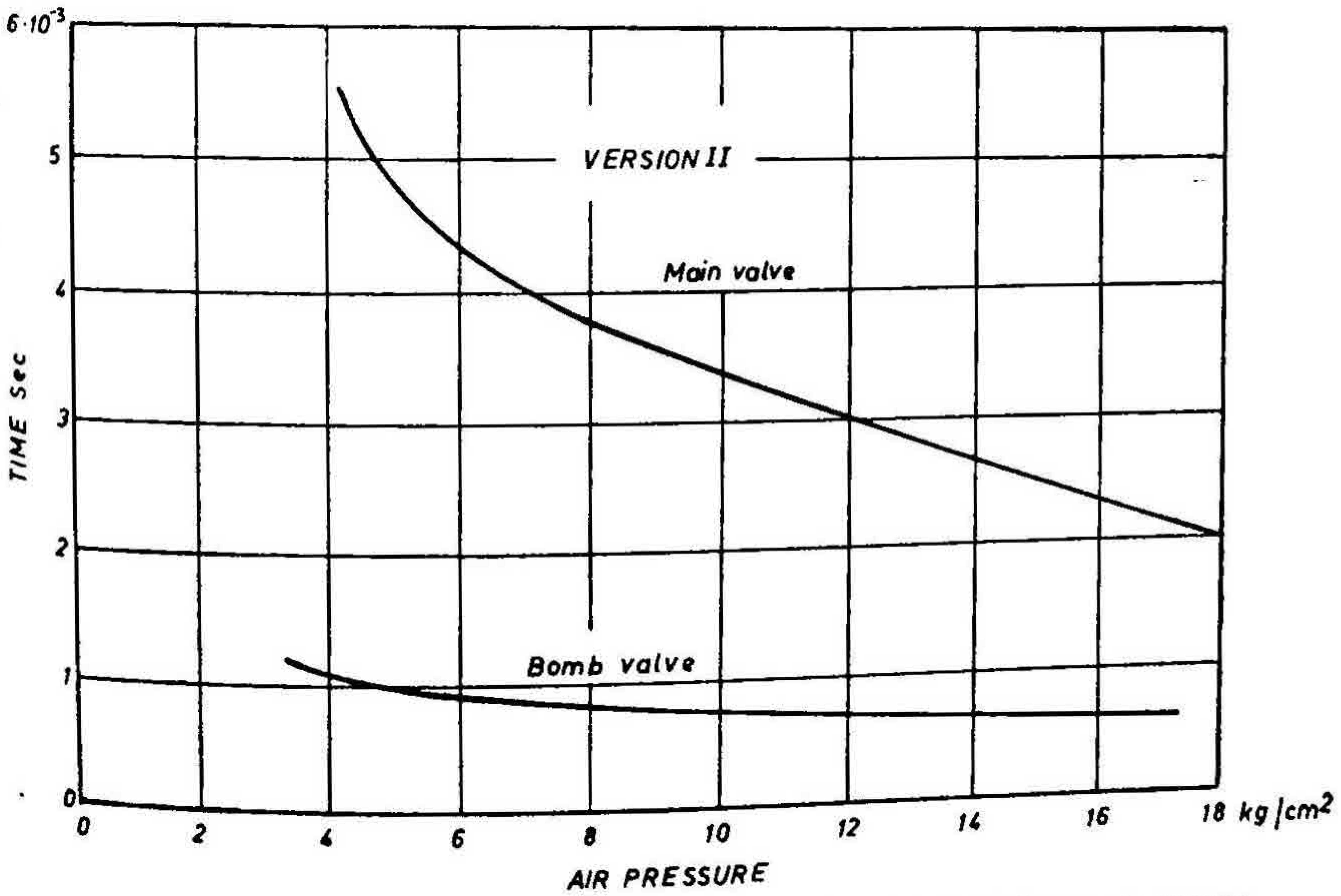

FIG. 30. Duration of motion of bomb valve and of main valve in relation to air pressure.

The creation of the oscillations can be explained as a consequence of the fact that when the bomb valves at the entrance to the combustion vessel are about to close, a strong and essentially axially directed gas flow passes through the entrance to the bomb whilst the gas near to the front of the bomb is essentially at rest. Due to the inertia of the gas, the gas near the entrance and its surroundings inside the bomb retains its motion even after the valves have been closed and thus a space of smaller pressure than the average is created at this end of the bomb if compared to the pressure that exists on the opposite end. The equalisation of this pressure difference causes the oscillations as seen in the diagrams indicated. Similar conditions will be created as soon as the piston is rapidly arrested, as is the case in the other compression apparatus, so that results obtained there will be influenced by gas oscillations.

A more exact study of the conditions under which oscillations are created can be undertaken theoretically by applying methods of gas dynamics. For the present case, however, the throttling effect at the entrance to the bomb and the pressure distribution with time in front of the entrance to the bomb had to be taken into account. Certain work in this direction has been done by F. Schultz-Grunow.[23]

Figure 35 gives the pressure distribution depending on time as obtained from several test runs, for pressures in the compressed air vessel of 9, 7 and 5 atmospheres and the highest and the lowest values of pressure amplitudes have been

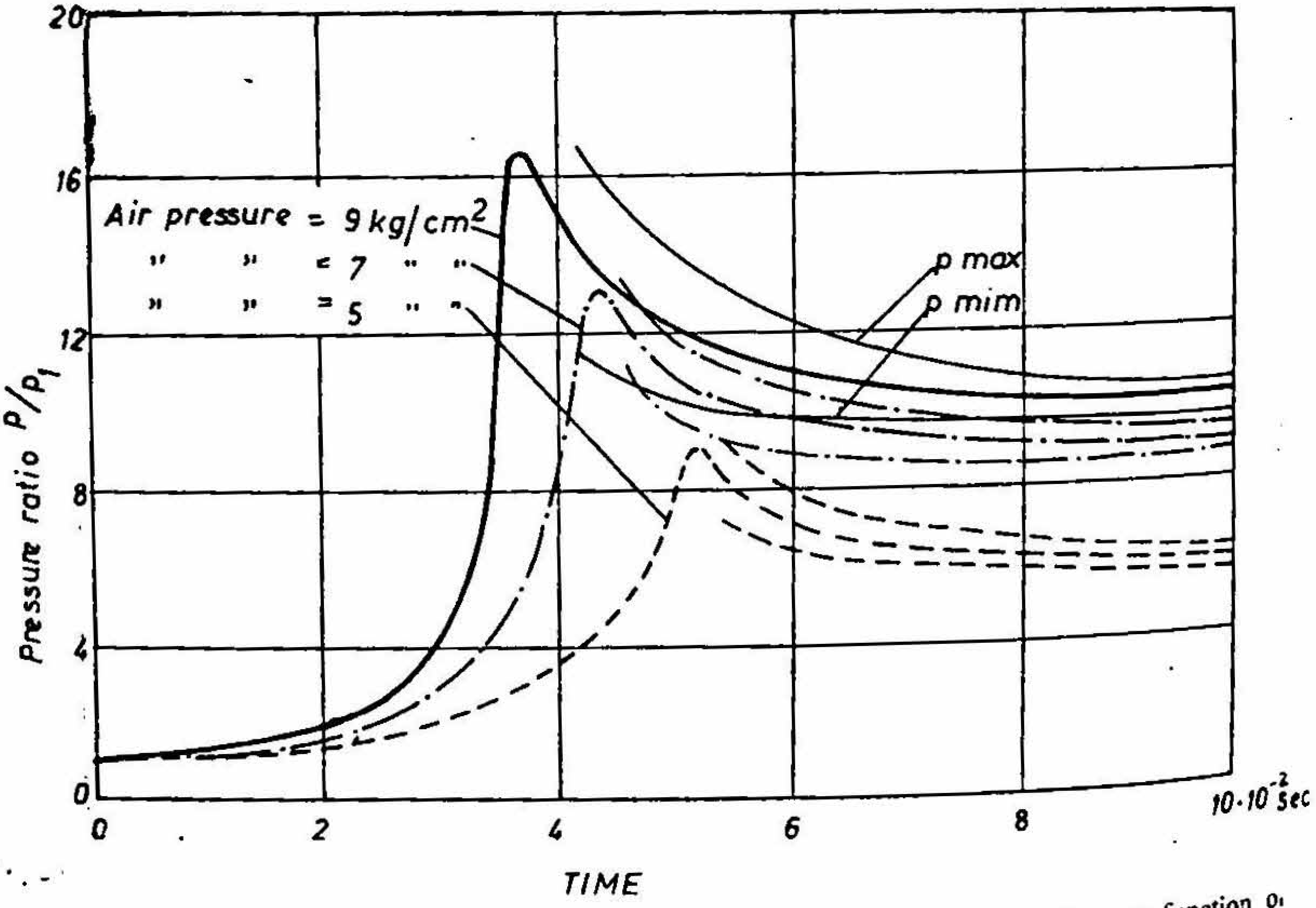

FIG. 35. Ratio of pressure in combustion vessel to initial pressure there as function of time for different air pressures, with indication of pressure amplitudes of oscillations.

indicated by thin lines. Figure 36 shows the highest pressure peaks obtained for both versions of the apparatus as a function of the pressure of the compressed air.

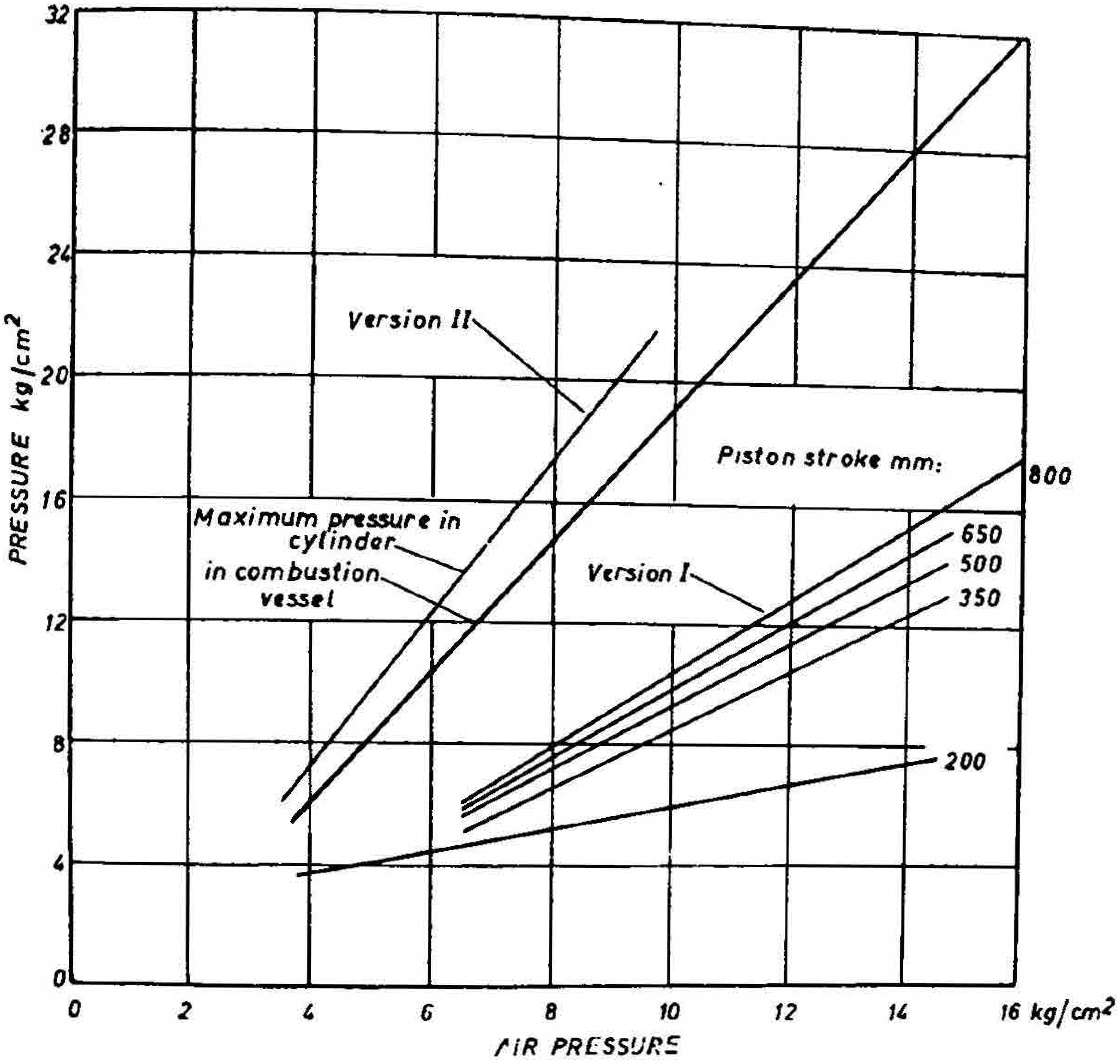

FIG. 36. Highest pressures for both versions depending on air pressure.

These data as shown can be applied also and very nearly for the compression of combustible gas air mixtures.

4.4 *Variations of temperatures*

It is required to measure the temperature of the gas in the combustion space after compression and separation of this space from the cylinder. Since the time of compression is of the order of 0·03 to 0·04 seconds the recordings of thermocouples would be inaccurate due to their inertia. Therefore the oscillations themselves have been used as indication of the average temperature in the gas space.

It has been shown that after closing the bomb valve the gas oscillates with amplitudes which are slowly subsiding. If the bomb contains an ideal gas, and air can be regarded as ideal gas within the limits of pressures encountered, the average temperature of the gas can be derived from a comparison of the frequency of the oscillation at elevated temperature with the frequency of the oscillation in the gas space at normal temperature. Since an ideal gas is presupposed the velocity of propagation depends on the temperature alone and is independent of pressure.

If a (m./sec.) denotes the velocity of sound, l (m.) the wave-length and f (l./sec.) the frequency then

$$a = l.f \tag{1}$$

Furthermore, the velocity of sound, *i.e.*, the velocity of propagation of a pressure wave in a gas follows the relation

$$a = \sqrt{gk\mathrm{RT}} \tag{2}$$

where

g denotes the acceleration due to gravity (m./sec.^{2}),

k the ratio of the specific heats at constant pressure C_p and constant volume C_v (—);

R the Gas constant (mkg./kg. deg.);

T the absolute temperature (deg. K.)

From both equations follows that

$$\frac{T_2}{T_1} = \left(\frac{f_2}{f_1}\right)^2 \cdot \frac{k_1}{k_2} \cdot \frac{R_1}{R_2} \tag{3 a}$$

or roughly

$$\frac{T_2}{T_1} \approx \left(\frac{f_2}{f_1}\right)^2 \tag{3 b}$$

within a region where the specific heats are constant and where the gas can be considered as ideal. At normal temperature T_1 the frequency of the gas space f_1 can be defined theoretically and thus the possibility is given to evaluate the pressure diagrams with respect to the change of temperature with time after the compression stroke has been completed, by measuring the time between two subsequent pressure peaks (*see* also Fig. 28).

The change of average temperature with time after the closure of the combustion vessel is shown in Fig. 37. The time has been taken from the moment the bomb valves are closed. For this point no indication can be given with regard to the average temperature on the ground of considerations outlined above but it is possible to draw some conclusions by adopting the first theorem of thermodynamics.

5. HEAT TRANSFER FOR OSCILLATING GASES

5.1 *Basic considerations*

The heat transfer of oscillating gases does not seem to have been considered yet with exception of a report by Sinn.[24] The importance of the question,

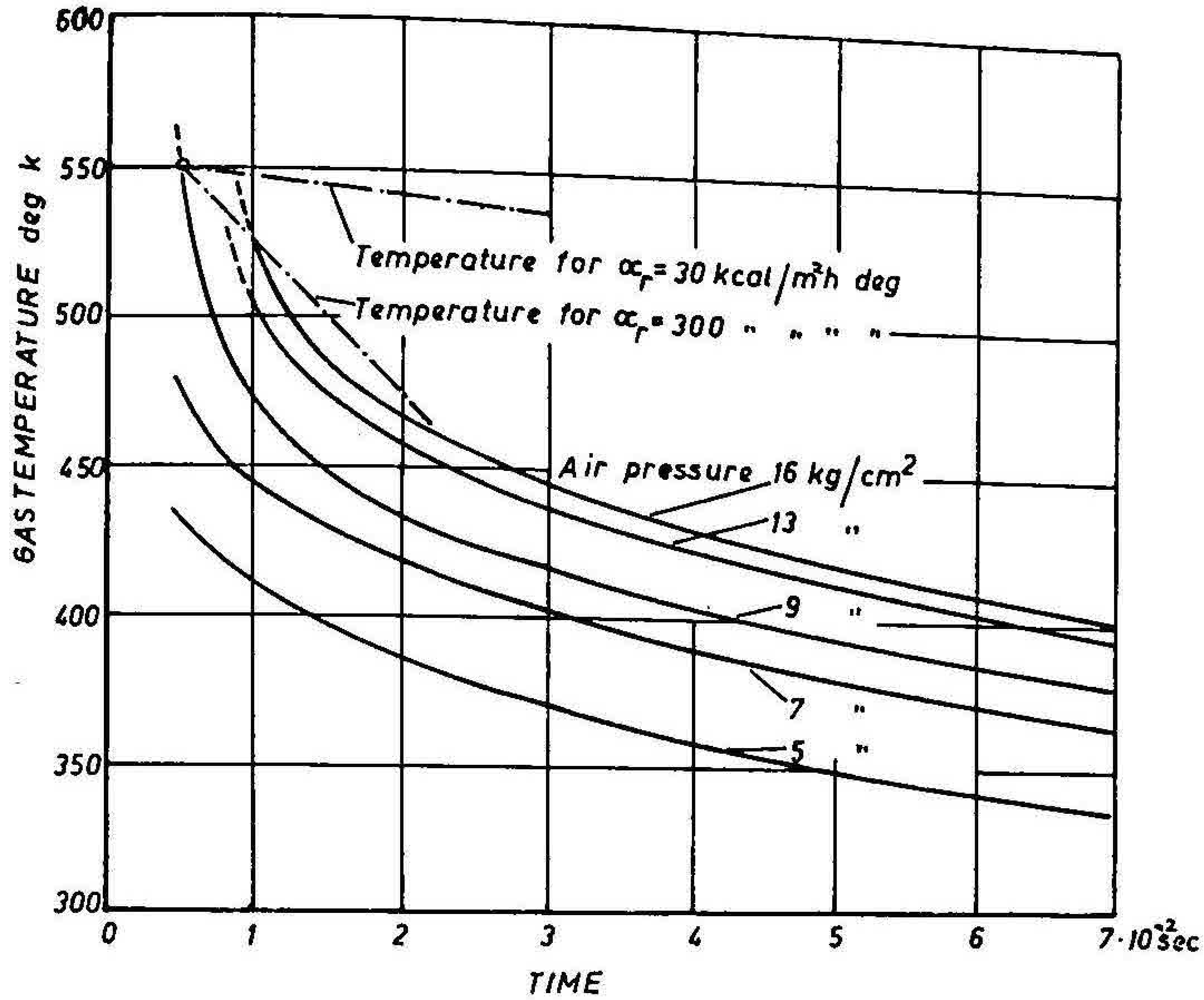

FIG. 37. Interdependence between average gas temperature in the combustion vessel and time expanded from its closure.

however, has been underlined by E. Schmidt,[25] in connection with considerations regarding the knocking Combustion in Otto-engines. It must be expected that steep pressure waves of the gas caused by the sudden combustion of part of the charge increase the rate of heat transmitted to a wall due to the fact that the gas immediately adjacent to the wall is rapidly compressed and thus is heated with an increase in the rate of heat transfer resulting. This may be interpreted as a change in the conception of the boundary layer which instead of exerting a certain insulating effect under normal conditions assists in the transfer of heat when subjected to the impact and reflection of a pressure wave or a shock wave. A further effect may be that a consequence of turbulent mixing hot gas particles may be brought near to or precipitated into contact with, the wall surface. Thus the gradient of the temperature distribution is increased and results in an increase of heat transfer.

Since the gas in the combustion vessel of the compression apparatus oscillates, as the diagrams have shown, it can be expected that due to the reasons given above the heat transfer to the wall is increased also in this case. A comparison with the heat transfer for the gas being at rest should result in some findings regarding the increase of the rate of heat transferred due to oscillations.

5.2 *Comparison of rejected heat quantities*

From the experiments and evaluations as mentioned above the change of temperature with time after the closing of the bomb is known, (*see* Fig. 37). For a comparison the figure contains the temperature change with time for a gas at rest with two different heat transfer coefficients α as it results theoretically when assuming a constant wall temperature and constant specific heat of the gas, and if heat transfer by convection and radiation is neglected.

During a time increment dt (hour/L.) a gas of temperature T_G (deg. K.) dissipates to a wall held at the constant temperature T_W a quantity of heat dQ (kcal.) according to the relation

$$dQ = \alpha_r \cdot F \cdot (T_G - T_W) \cdot dt \tag{4}$$

where α_r (kcal./m^{2}h deg.) denotes the heat transfer coefficient α for the gas at rest and F (m.^{2}) is the surface taking part in heat transfer. At the same time the change of the internal energy of the gas is equal to the amount of heat dissipated

$$dQ = G_B \cdot c_r \cdot dt_G \tag{5}$$

where G_B is the weight of gas contained in the combustion vessel. Thus the change of gas temperature with time is given by

$$T_{G_0} = T_G \cdot e\left(- \frac{\alpha \cdot F}{G_B \, c_r} \cdot t \right) \tag{6}$$

where T_{G_0} is the temperature of the gas at time $t = 0$ which is Fig. 37 was chosen to be 550° K. The heat transfer coefficient α_r for the gas at rest under the conditions given, is roughly 30 (kcal./m^{2}h deg.) and thus the gas temperature would change along the line indicated and as can be seen depends only to a very small degree on time, as far as considered here. If α_r is assumed to be 300 (kcal./m^{2}h deg.) it can be seen from the figure that even this assumption of the heat transfer coefficient α does not represent the rate of heat transfer actually encountered in the bomb, *i.e.*, if the gas is oscillating. The actual heat transfer coefficient α thus must be, at least in the first stages, much higher than even the assumed value of 300 kcal/m^{2}h deg.

The comparison of the amount of heat which is transmitted to the wall from a gas assumed to be at rest and from an oscillating gas, is carried out in the following way:—

For the compression stroke until the closure of the combustion vessel the variation of temperature can be found by applying repeatedly the characteristic equation of an ideal gas.

$$P \cdot V = G \cdot R \cdot T_G \tag{7}$$

by measuring simultaneously the pressure P (kg./m.^{2}) and the volume V (m.^{3}) of the gas quantity G (kg.) taking part. This implies that there is an equal distribution of pressure in the gas space. The evaluation, however, showed that from a piston speed of about 35 m./sec. onwards, which corresponds to a pressure in the compressed air container of 9 atmospheres, the actual temperature was found to be distinctly different from that calculated in this way. Thus the method outlined is limited to a lower piston velocity and consequently to a lower pressure of the compressed air, *i.e.*, to 5 and 7 atmospheres respectively. The temperatures thus defined are understood always to be average values in the gas space.

The temperature thus calculated has been plotted in Figs. 38 and 39 for the indicated compressed air pressures. For the sake of a comparison the temperature calculated with the assumption of adiabatic compression for adiabatic walls has been plotted in the same figures.

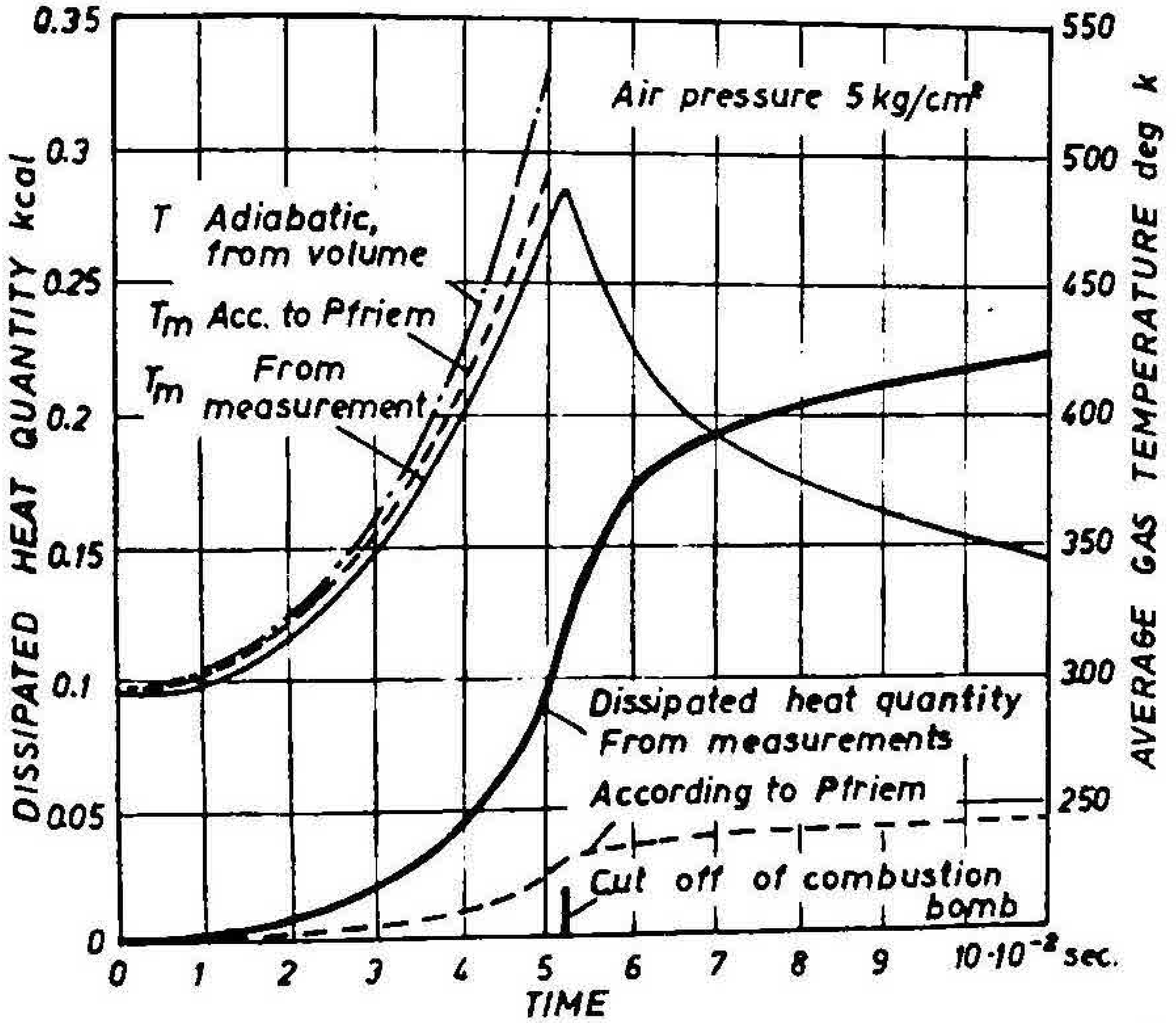

FIG. 38. Dissipated heat quantities and temperature in combustion vessel *versus* time for air pressure of 5 kg./cm.^{2}

The amount of heat which is transferred to the walls from the gas is given by

$$dQ = c_v dT - APdV \tag{8}$$

where $c_v dT$ is the change of internal energy (kcal.) of the gas due to a change in temperature and $APdV$ is the amount of energy (kcal.) transferred on to the gas from the piston. Thus from the variation of temperature the amount of heat could be derived which has been dissipated from the gas upto any moment of the compression stroke.

After the end of the compression stroke, *i.e.*, after the combustion vessel has been closed the quantity of heat dissipated can be found from the temperature curve (*see* Fig. 37) by again applying the equation (8) with $dV = 0$ with the assumption of a constant wall temperature and constant specific heats of the gas.

In Figs. 38 and 39 the heat quantities dissipated have been plotted together with the temperature depending on the time expended from the beginning of the compression stroke (full line).

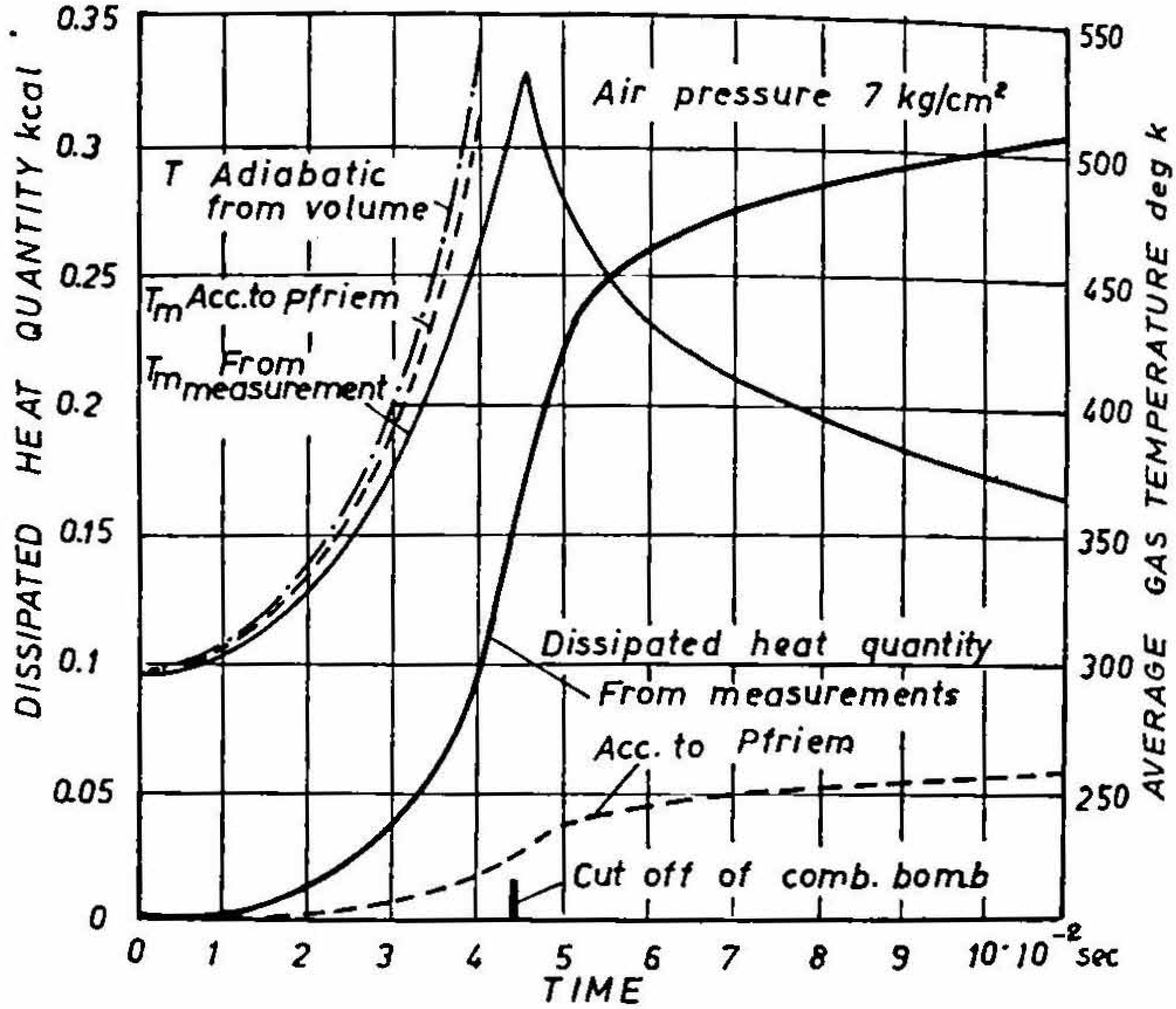

FIG. 39. Dissipated heat quantities and temperature in combustion vessel *versus* time for air pressure of 7 kg./cm.²

Pfriem[20] has given a method to define the amount of heat dissipated from a gas to a wall at any moment during a sudden change of state, if the change of pressure with time is given. If the gas undergoes sudden changes of pressure due to a rapid compression the influence of the motion of gas particles on being compressed has to be taken into account. The heat created during compression can also affect considerably the heat transfer to the walls. This method thus has been used to compare the results gained from the compression apparatus with the theoretical results to be expected on the ground of Pfriem's report.

The essential presuppositions of this method are freedom from convectional heat transfer and freedom from turbulence in the gas space, with the walls of the gas space remaining at constant temperature. Since the last condition mentioned—constant wall temperature—holds certainly for the compression apparatus due to the shortness of the procedure, the deviations between results derived from the measurements on the apparatus and the results of the theorem according to Pfriem must be essentially due to the turbulence and the oscillations of the gas. A convectional flow of the gas is also not likely to be set up during the compression due to the shortness of the time available.

The result of applying the method of Pfriem has been included in Figs. 38 and 39. For details of the calculations reference 20, may be consulted which also contains some examples of applications of the method.

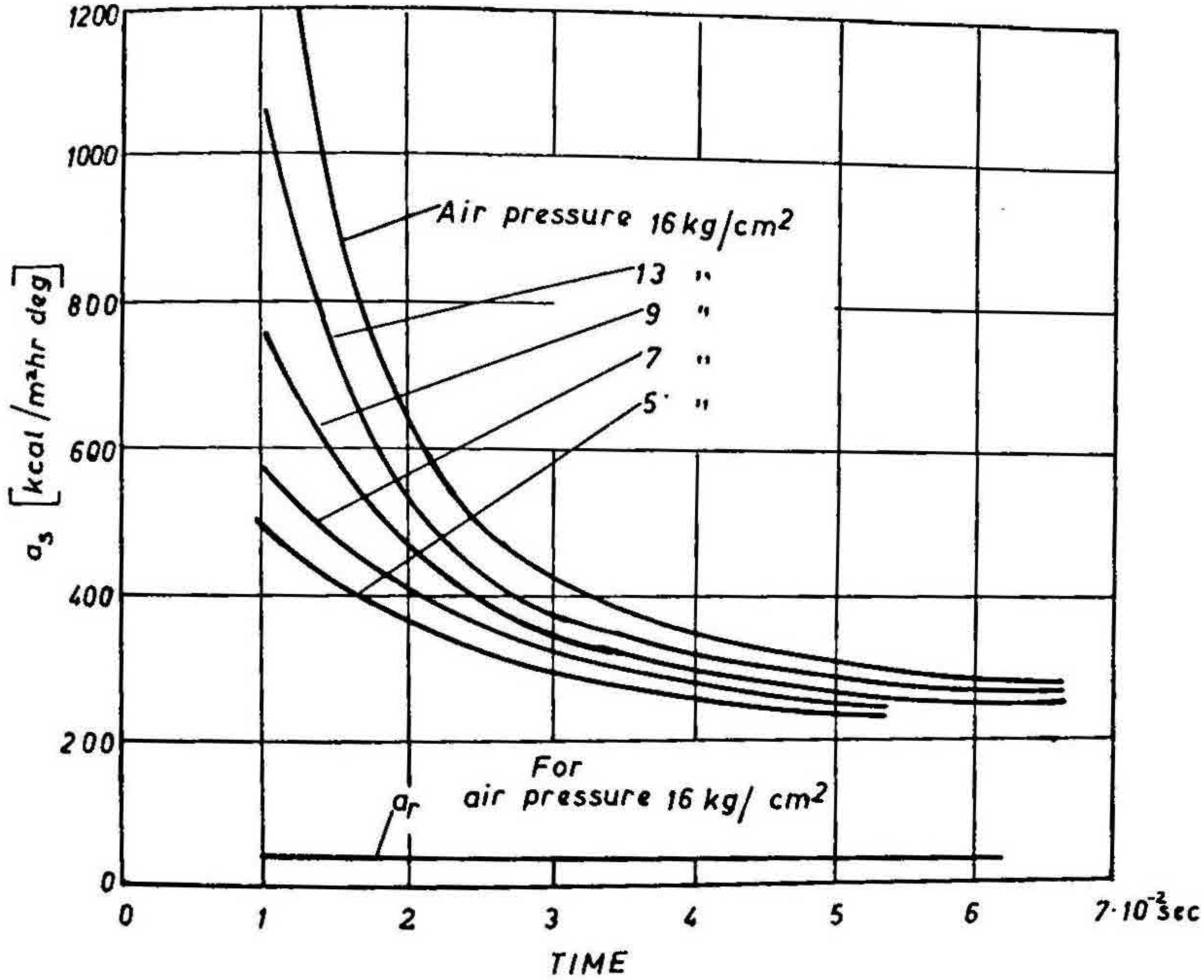

FIG. 40. Interdependence of heat transfer coefficient a_s for oscillating air after cut-off of the combustion vessel; a_r = coefficient for non-oscillating gas.

The temperature distribution resulting from the application of Pfriem's method to the compression stroke is indicated as dotted line which lies between the temperature found from evaluating measurements as indicated and found when assuming an adiabatic change of state. The line denoting the calculated dissipated quantity of heat, indicated by a dotted line, shows even here differences if compared with the rate of heat losses derived from the evaluation of measurements (full line). The turbulent state of the gas during compression may be esponsible for this and this effect may be increased by pressure differences set up when the compression stroke starts.

After closing the combustion vessel the difference between the heat quantities dissipated from the oscillating gas and from a gas at rest can be very clearly seen from a comparison of both figures. Thus a considerable increase in the rate of heat transfer from oscillating gases as compared to a gas at rest can be assumed.

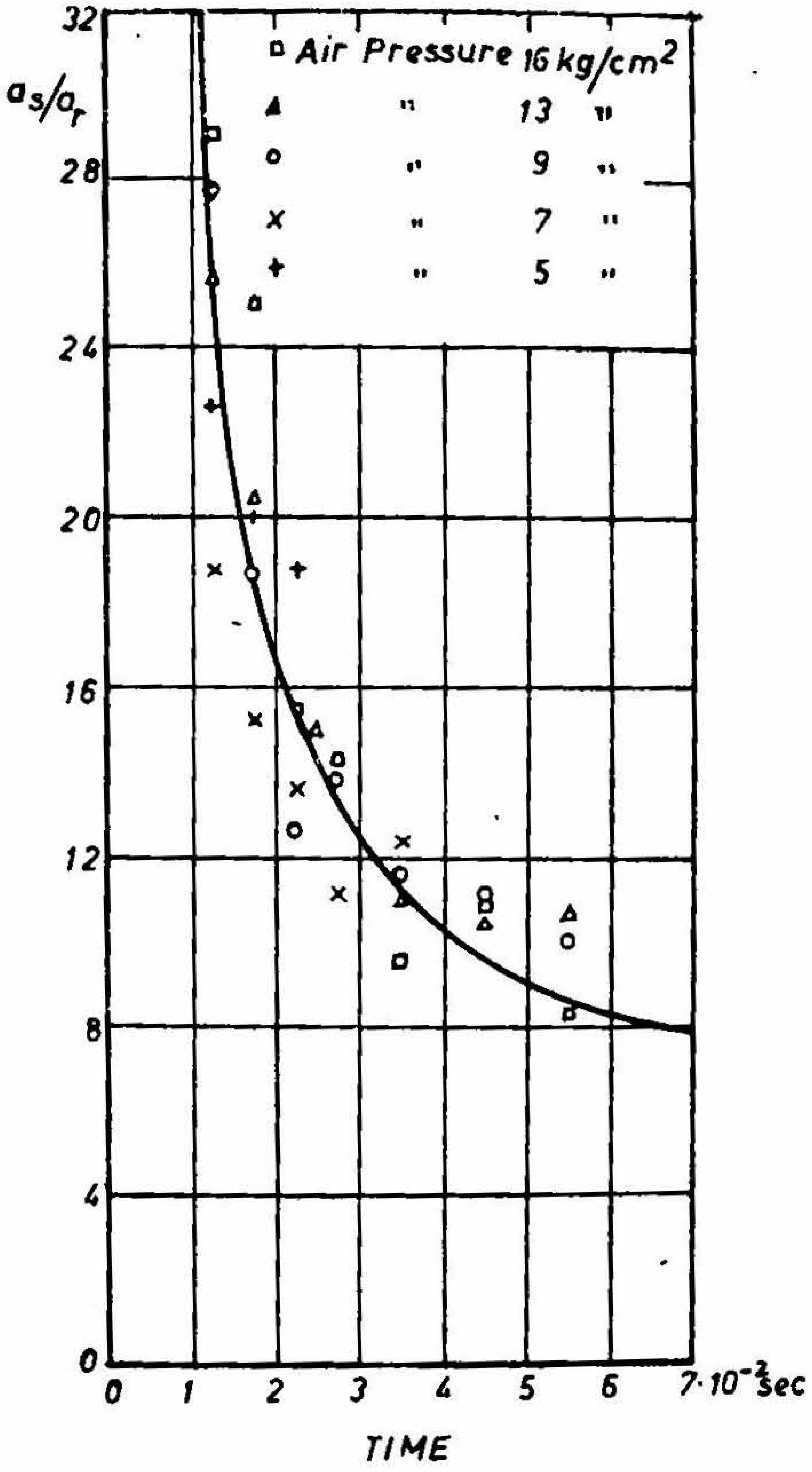

FIG. 41. Interdependence of ratio of heat transfer coefficients for oscillating and non-oscillating gas with time expanded after cut-off of combustion vessel.

5.3 *Heat transfer coefficient*

Beyond the qualitative considerations made so far the measurements carried out allow an evaluation with regard to the heat transfer coefficient α for gases.

The oscillations shortly after the closure of the bomb valves seem not to be established clearly but have superimposed and are disturbed possibly by turbulent mixing and by oscillations of higher frequency. These disturbances, however, are damped rapidly so that after some time from the point of the separation of the combustion space from the cylinder the fundamental oscillations of the gas can be regarded as to be solely responsible for the increase of heat transfer.

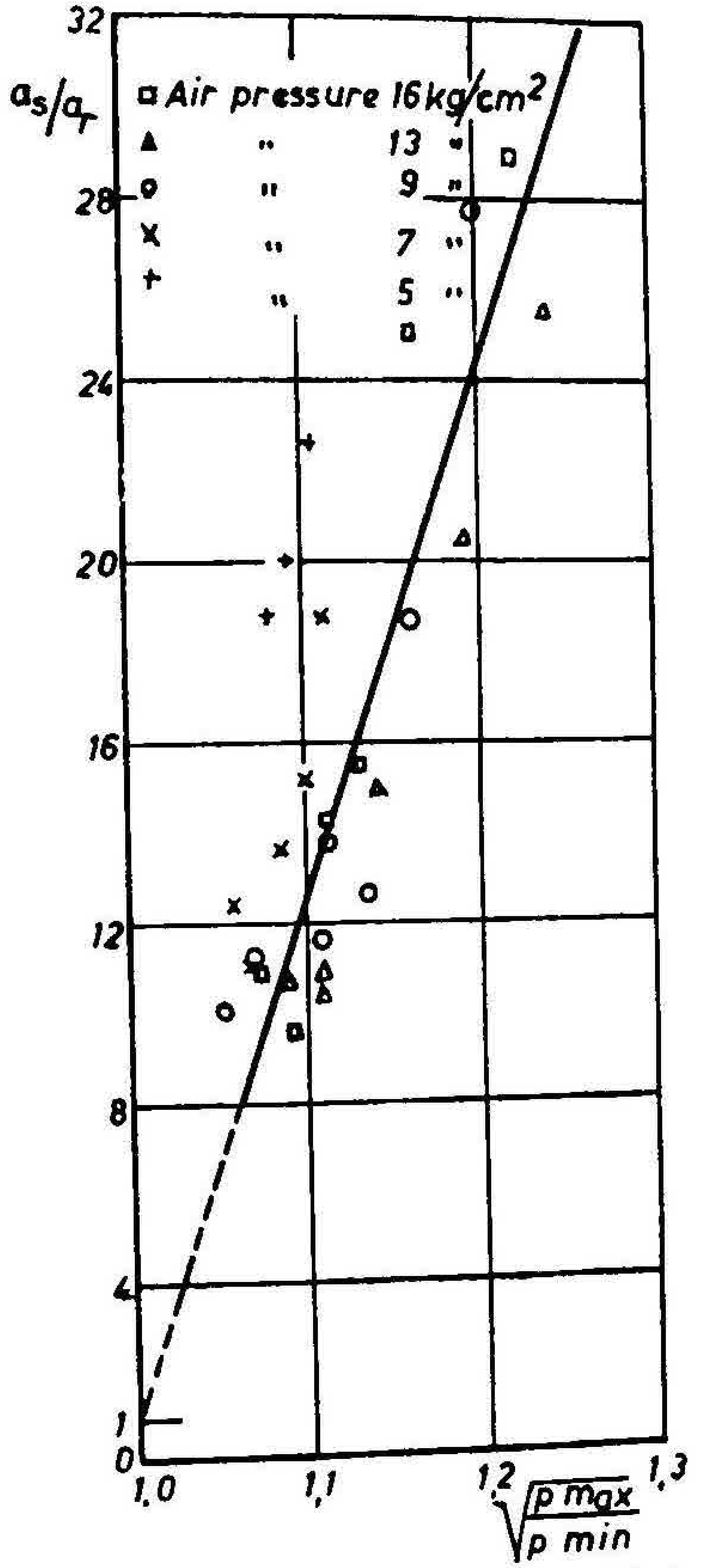

FIG. 42. Interdependence of ratio of heat transfer coefficients with pressure limits of the oscillations.

The heat transfer coefficient a_s between two moments 1 and 2 is found from the relation

$$a_s = \frac{Q_{12}}{F\,(T_{G12} - T_w)\,\Delta t} = \frac{G_B \cdot C_v \cdot (T_{G1} - T_{G2})}{F\,(T_{G12} - T_w) \cdot \Delta t}, \qquad (9)$$

where Q_{12} is the amount of the heat (kcal.) dissipated during the time increment Δt (h) and T_{G12} is the average temperature considered during Δt, and taken from temperatures T_{G1} and T_{G2} at the beginning and the end of Δt. In Fig. 40 the heat transfer coefficient thus resulting has been plotted for the condition of oscillating gases, depending on time, for different initial pressures of the compressed air supply. The region immediately adjacent to the closure of the bomb valves has been neglected.

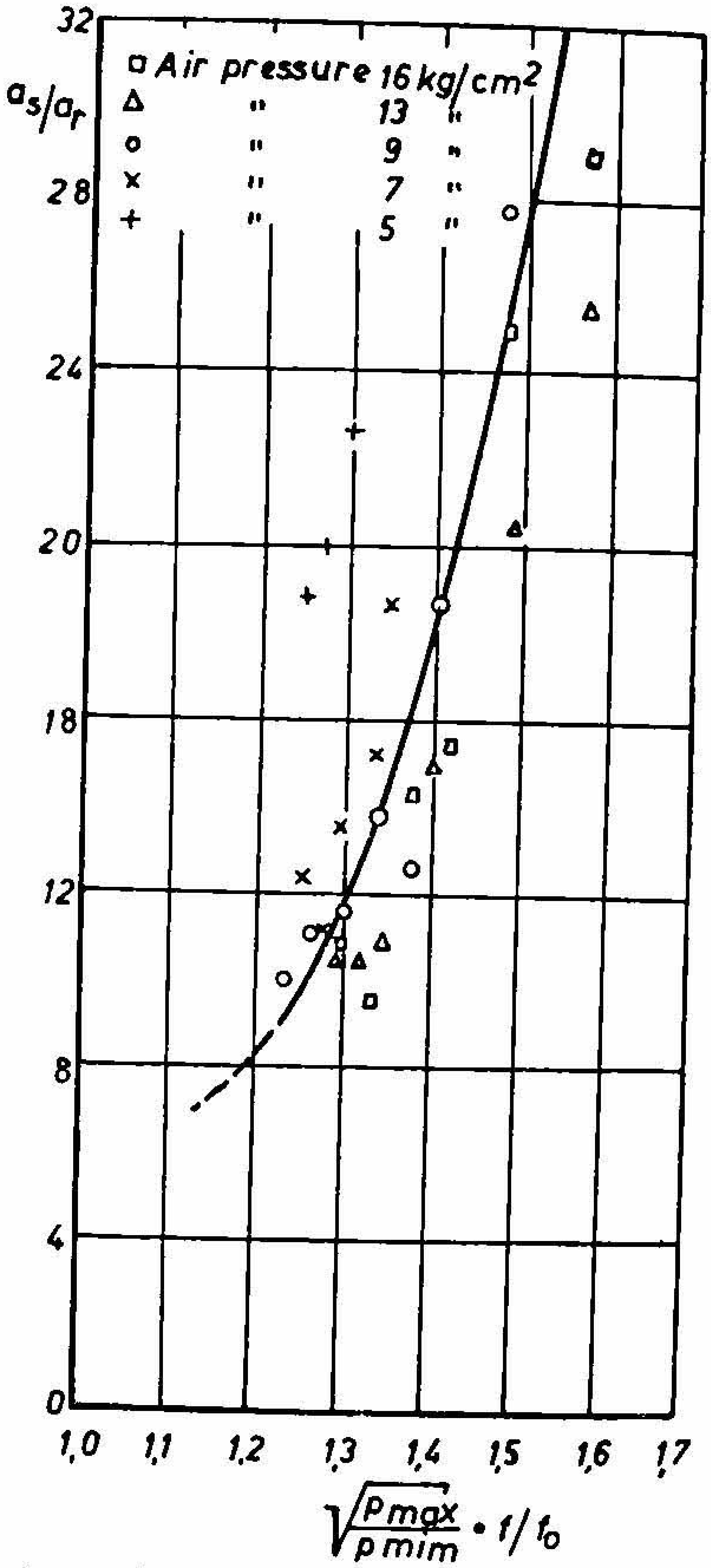

FIG. 43. Interdependence of ratio of heat transfer coefficients for oscillating and non-oscillating gas with pressure limits and frequency of the oscillations.

Characteristic for the increase of the heat transfer coefficient is a magnitude which could be expressed as the ratio of the heat transfer coefficient of the oscillating gas to that of a gas at rest.

If considered more closely the heat transfer between a wall and a gas really kept at rest, is possible only if the gas of higher temperature is situated on the top of the cooler wall. Only in this case—or in the opposite case, that a warm wall is situated on the top of a cool gas—the gas is at rest if foreign forces are absent, and purely conductive heat transfer is realised. In other cases a convective flow of the gas and the heat is set up and this may also happen inside the combustion space. The flow patterns thus established in the neighbourhood of the walls will, however, influence each other and as a whole a natural convectional flow will be established, superimposed on the generally axial flow, due to the longitudinal oscillation. For the comparison a value α_r was used which characterises the heat lost by a vertical wall to air[27] assuming that the inversion of the direction of the flow of heat is of negligible influence only.

In the lower part of Fig. 40 the value α_r thus derived has been plotted for a state of the gas resulting from a pressure in the compressed air supply of 16 atmospheres. This value thus was derived from average values of pressure and temperature in the gas space if compressed as indicated, according to the relation[27]

$$\alpha_r = 0,64 \cdot c_L \sqrt[4]{p^2 (T_{G_{12}} - T_w)} \tag{10}$$

c_L is a magnitude depending on the mean temperature derived from the gas temperature $T_{G_{12}}$ and T_w of the wall; p (kg./cm.^{2}) denotes the average pressure in the gas space. In the evaluation the value of the constant has been increased to 0·72, to make allowance for the somewhat greater influence of the horizontal walls of the combustion vessel on the rate of heat transfer.

For other values of the compressed air pressure smaller value of α_r are found.

The interdependence of the ratio α_s to α_r at first for air as gas is given in Fig. 41. The indicated experimental results show that the correlation can be represented fairly well by one curve, and seems to be rather independent from the individual test, and thus from the pressure of the compressed gas in the bomb.

The ratio α_s/α_r will be dependent on the gas pressure only to a small extent and mainly on the limiting values of the pressure fluctuations, but possibly also on the frequency of the oscillations.

More detailed investigations showed that the interdependence with the pressure amplitudes can be expressed as a function of the ratio of the highest and the smallest pressures experienced in the oscillation of the gas in the form

$$\frac{\alpha_s}{\alpha_r} = f\left(\sqrt{\frac{p_{max.}}{p_{min.}}}\right) \tag{11}$$

which can be written as

$$\frac{\alpha_s}{\alpha_r} = \sqrt{\frac{p_{max.}}{p_{min.}}} + 116 \cdot 5 \left(\sqrt{\frac{p_{max.}}{p_{min.}}} - 1\right) \tag{12}$$

where the ratio $p_{max.}/p_{min.}$ can be replaced by a term containing the pressure amplitude Δp and the average mean pressure p_m according to the relation

$$\frac{p_{max.}}{p_{min.}} = \frac{\Delta p}{p_m - \frac{\Delta p}{2}} + 1 \tag{13}$$

The function is plotted, together with test results, in Fig. 42.

It can, furthermore be expected that an interdependence exists between the ratio of the heat transfer coefficients and the frequency of the oscillation which may be expressed as the ratio of the actual frequency, say at elevated temperature f (l/sec.) to the fundamental frequency of the gas space at normal temperature f_0 so that the correlation has the form

$$\frac{\alpha_r}{\alpha_t} = f\left(\sqrt{\frac{p_{max.}}{p_{min.}}}\ \frac{f}{f_0}\right) \tag{14}$$

The scatter of test results does not allow a more detailed evaluation but a relation was tried following the form

$$\frac{\alpha_r}{\alpha_t} = f\left(\sqrt{\frac{p_{max.}}{p_{min.}}} \cdot \frac{f}{f_0}\right) \tag{15}$$

This function is shown in Fig. 43. The lower and dotted part of the curve is uncertain. For a gas at rest, $f_0 = 0$, the ratio of the heat transfer coefficient becomes unity and thus for a gas space at normal temperature oscillating with disappearing pressure amplitude a value between 5 and 7 for the ratio of the heat transfer coefficient could be anticipated.

In reality, the ratio of heat transfer coefficients will actually depend on material constants too, probably for instance, on the ratio of specific heats and also magnitudes characterising the oscillating progress of the gas in detail. It would be necessary to study further, the degree of turbulence as existing in an oscillating gas due to the longitudinal motion of the molecules; any experiments will have to avoid damping of those oscillations, as far as possible, so that stationary conditions are ensured.

(*To be continued*)

6. LIST OF REFERENCES

1. Jost, W. .. *Explosions-und Verbrennungsvorgänge in Gason*, 32, Berlin, Springer, 1939 also (35).

2. Schmidt, E. and u. E. Mühlner .. "Vorreaktionen im Ottomotor," *Forschg. Ing. Wes.*, 1942. 13 (5), 186–97.

3. Falk, G. .. "Die Entzündungstemperaturen von Gasgemischer," *Ann. Phys.*, 1907, 24 (4), 450.

——— .. "The ignition temperatures of gaseous mixtures," *J. Amer. Chem. Soc.*, 1907, 29 (11), 1536.

4. Cassel, H. .. "Uber die Entflammung und Verbrennung von Sauerstoff-Wasserstoffgemischen," *Ann. Phys.*, 1916, **51** (4), 23.

5. Dixon, H. B. .. "The ignition and propagation of explosions," *J. Chem. Soc.*, 1911, **99** (1), 588.

6. Dixon, Bradshaw and Campbell "The firing of gases by adiabatic compression, Part I," *Ibid.*, 1914, **105** (2), Part II, **190**, 2027 and 2036.

7. Tizard, T. T. .. "The causes of detonation in internal combustion engines," *Proc. North-East-Coast-Inst. Engrs.*, 1920-21, **37**, 381.

8. Tizard and Pye, D. R. .. "Experiments on the ignition of gases by sudden compression," *Phill. Mag.*, 1922, **49** (6), Ser. Juli–Dez.

9. dgl .. "Ignition of gases by sudden compression," *Ibid.*, 1926, 7, Ser. 1, 1094.

10. Dûchêne .. "Etudes de la combustion des melanges gazeus," *Publ. sci. techn. Ministere de l'Air*, Paris, 1932, No. 11.

11. dgl .. *Bulletin Technique*, No. 54, 1928. Service technique de L' Aeronautique.

12. Aubert, Dumanois and Pignot "Sur l'effet des antidetonants," *C.R. Acad. Sci.*, Paris, T. 186, 1928, 1298.

Pignot .. "Sur l'inflammation adiabatique," *Ibid.*, T. 182, 1926, 376.

Aubert u. and Dûchêne .. "Sur la propagation de la combustion," *Ibid.*, T. 189, 1930, 123.

13. v. Weber and u. Rastetter "Die Selbstzündung von Kohlenwasser-stoffen bei der adiabatischen Kompression," *Nature-wise*, 1939, **27**, 164; *see also* Jost, Teichmann and Rögener, ref. No. 15, 318.

14. Brœrsma, G. .. "Measurements on detonation in Dûchêne apparatus," *J. Aeron. Sci.*, 1940, **8** (2), 62

15. Jost, Teichmann and u. Rögener "Reaktionskinetische Untersuchungen zum Klopfvorgang. I, II, III, *Z. Elektro-chem.*, 1947, **47**, 262, 297 and 307.

16. Jost, W. .. "Die physikalisch-chemischen Grundlagen der Verbrennung in Motor," *Schriften D.dtsch. Akad. d. Luftfahrtforschg.* No. 9. München und Berlin, Oldenbourg, 1939, 133.

17. Schmidt, F. A. F. .. "Motorische und physikalische Untersuchungen über das Wesen des Klopfvorganges," *MTZ.*, 1943, **5** (2). 41–6.

Scheuermeyer-Steigerwald "Die Messung des Zündverzugs verdichteter Kraftstoff-Luftgemische zur Untersuchung der Klopfneigung," *Ibid.*, 1943, **5** (8/9), 229–35.

18. Taylor, C. F., Taylor, E. S., Livengood, J. C., Russell, W. A. and Leary, W. A. "Ignition of Fuels by Rapid Compression," *Soc. Automotive Engrs. Trans.* April 1950, **4** (2), 232–70. Discussion 271–4. *See also* Eng. Index, 1950, 99.

19. Steinicke, H. .. "Gasbewegung und Turbulenz bei Explosionen in einer langgestreckten Bombe," *Jahrbuch* 1943, *der deutschen Luftfahrtforschung*, II, A 010.

Schmidt, E. Steinicke, H. and Neubert, U. "Aufnahmen der Verbrennung von Gasgemischen in Rohren mit dem Eigenlicht der Flamme und bei Schlierenbeleuchtung VDI," *Forschungsheft*, 431, Düsseldorf, 1951.

20. Pfriem .. "Der Wärmeübergang bei schnellen Druckänderungen in Gases," *Forschg. Ing. Wes.* **13** (4), 150–64.

21. Gohlke, W. .. "Quarzdruckmessgeräte hoher Eigenfrequenz," *VDI-Forschungsheft*, 1941, **407**.

22. Pfriem .. "Zur Frage des Gasdruckes auf bewegte Wände," *Forschg. Ing. Wes.*, 1942, **13** (2), 76–81.

——— .. "Der Einfluss der Kolbenbeschleunigung auf die Verdichtung von Gasen," *Ibid.*, 1942, **13** (3), 112–24. *See also* reference in *Z.VDI.*, 1943, **87** (21/22).

23. Schultz-Grunow, F. .. "Nichtstationäre eindimensionale Grsbewegung," *Ibid.*, 1942, **13** (3), 125–34.

24. Sinn, R. .. "Wärmeübergang bei schwingenden Gasen," *Z.VDI.*, 1939, **83**, 1197.

25. Schmidt, E. .. "Über das Klopfen und die damit verbundens Verminderung des Wirkungsgrades von Otto-Motoren," *Schriften d.dtsch. Akad. d. Luft-fahrt-forschg.*, No. 9, 215-30.

26. v.Eberan, R. and v. Binark, H. "Wärmeübergang beim Klopfen im Ottomotor," *Z.VDI.*, 1944, **88** (1/2), 24.

27. Merkel, F. .. *Die Grundlagen der Wärmeübertragung*, Stein-Kopff, 1927, 127*f*, also Hütte, 27th edn.

28. Schmidt, E. .. "Einführung in die Technische Thermodynamik," *2. Aufl.*, Berlin, Springer 1944, 239. *Thermodynamics, Principles and Application to Engineering*, 1949, translation from the third German edition, by T. Kestin, Oxford, Clavendon Press.

29. Nielsen, H. .. "Einfluss der Eigenschwingung brennender Gasgemische auf die Brenngeschwindigkeit," *Forschg. Ing. West.*, 1933, 4 (6), 300.

30. Köchling, A. .. "Dynamische Vorgänge bei klopfender Verbrennung, Deutsche Kraftfahrtforschg," No. 75, *VDI-Verlag*, 1943.

31. Damköhler, G. .. "Einfluss der Turbulenz auf die Flammenge-schwindigkeit in Gasgemischen," *Jahrbuch* 1939, *der deutschen Luftfahrtforschung*, Triebwerk II 3/21.

32. Mache, H. .. "Der Ubergang zwischen laminarer und lurbulenter Strömung von Gasen in einem kreiszylindrischen glatten Rohr," *Forschg. Ing. Wes.*, 1943, **14**, 77–81.

33. Hahnemann-Ehret .. "Uber den Einfluss starker Schallwellen auf eine stationar brennende Gasflamme," *Zeitschr. f. techn. Physik.*, 1943, **24** (10/12), 228–41.

34. Damköhler, G. .. "Gasbewegung in einem geschlessenen Verbrennungsraum bei einseitiger Züngung," *Jahrbuch* 1938, *der deutschen Luftfahrtforschung*, Ausg. Triebwerk, II, 62–75.

35. Jost, W. .. *Explosion and combustion proceses in gases*, English translation of the German edition by Huber O. Croft, McGraw-Hill publications in Aeronautical Sciences, 1946.

7. LIST OF SYMBOLS

A	(kcal./mkg.)	Mechanical equivalent of heat
a	(m./sec.)	Sound velocity
a, a_r	(kcal./m^{2}h deg.)	Heat transfer coefficient, for gas at rest
a_k	(kcal./m^{2}h deg.)	Heat transfer coefficient for oscillating gas
c	(m./sec.)	Piston velocity
c_1	(–)	Coefficient for defining a_r
c_p	(kcal./kg. deg.)	Specific heat at constant pressure
c_r	(kcal./kg. deg.)	Specific heat at constant volume
Δt	(sec., h.)	Increment of time
ϵ	(–)	Compression ratio
F	(m.^{2})	Surface area, frontal area
f	(l./sec.)	Frequency of oscillation of the gas in closed combustion vessel
ϕ	(–)	Ratio of quantities of air
g	(m./sec.^{2})	Acceleration due to gravity
G	(kg.)	Quantity of gas (weight)
H	(m.)	Length of cylinder
k	(–)	Ratio of specific heats = c_p/c_r
l	(m.)	Wave-length of gas oscillation
L	(m.^{3}/m.^{3})	Volume of air available for combustion of unit volume of combustible gas
$L_{min.}$	(m.^{3}/m.^{3})	Volume of air necessary for stoichiometric combustion of unit volume of combustible gas
λ	(–)	Air-ratio $L/L_{min.}$
M	(kg. sec.^{2}m.$^{-1}$)	Mass of moving parts
n	(–)	Exponent of polytropic compression
P	(kg./m.^{2})	Pressure
P_r	(kg.)	Frictional force
p	(kg./cm.^{2} atmospheres)	Pressure
$p_{max.}$	(kg./cm.^{2} atmosphere)	Limiting value of pressure amplitudes, maximum pressure
$p_{min.}$	(kg./cm.^{2} atmosphere)	Limiting value of pressure amplitudes, minimum pressure

Ψ	(–)	Function of pressure ratio
Q	(kcal.)	Heat quantity
Q_{12}	(kcal.)	Heat quantity transmitted during time interval 1 to 2
R	(mkg./kg. deg.)	Gas constant
s	(m.)	Piston stroke at time t
$s_{max.}$	(m.)	Total piston stroke
T	(deg. K.)	Absolute temperature, degree Kelvin
T_G	(deg. K.)	Gas temperature, degree Kelvin
T_W	(deg. K.)	Wall temperature, degree Kelvin
t	(sec. h.)	Time
u, U	(kcal./kg, kcal.)	Internal energy of gas
v, V	(m.^{3}/kg. m.^{3})	Volume of gas
w	(m./sec.)	Apparent flame velocity
x	(m.)	Distance, co-ordinate
z	(m./sec.)	Film velocity.

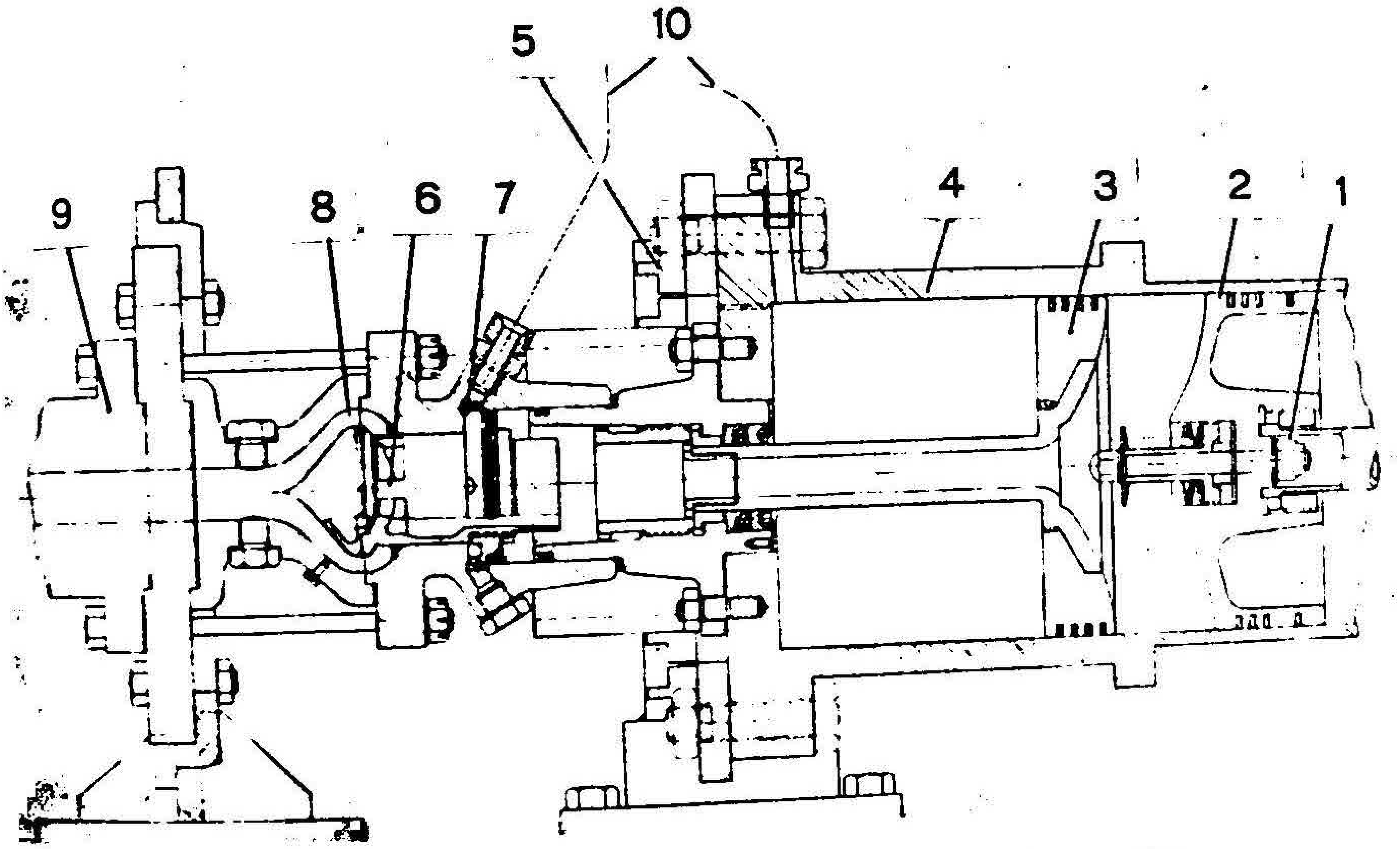

FIG. 3. Sectionalised view of the medium part of the compression apparatus.

1. Piston Rod. 2. Main piston. 3. Brake piston. 4. Cylinder. 5. Bearing for axial motion of cylinder assembly. 6. Pneumatically operated valve. 7. Ring space at valve. 8. Entrance to combustion vessel. 9. Combustion vessel. 10. Duct for pneumatically operating the bomb valve to the right; direct connection from airsuction to the left: duct for compressed air supply.

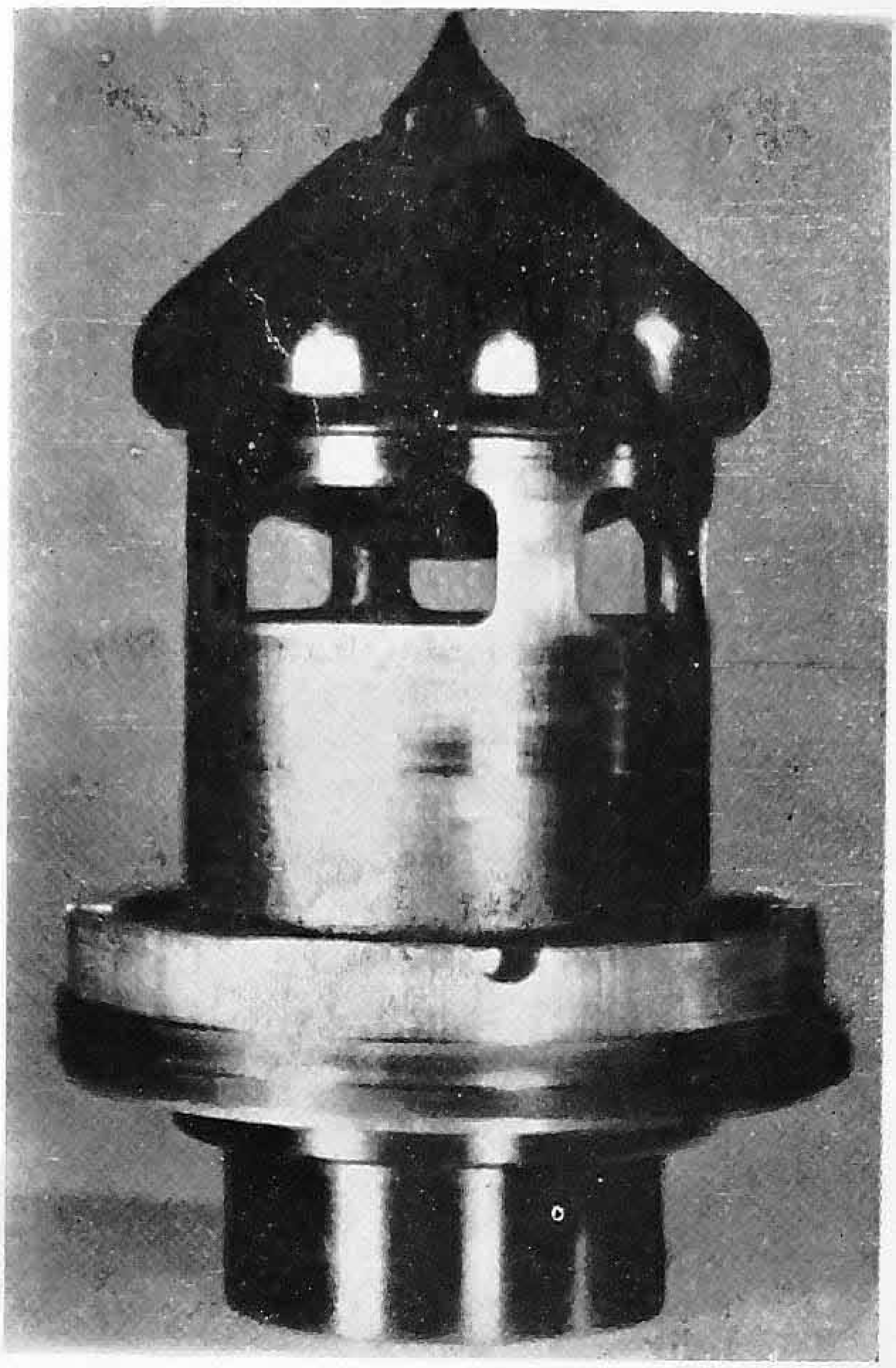

FIG. 4. Compressed air operated valve.

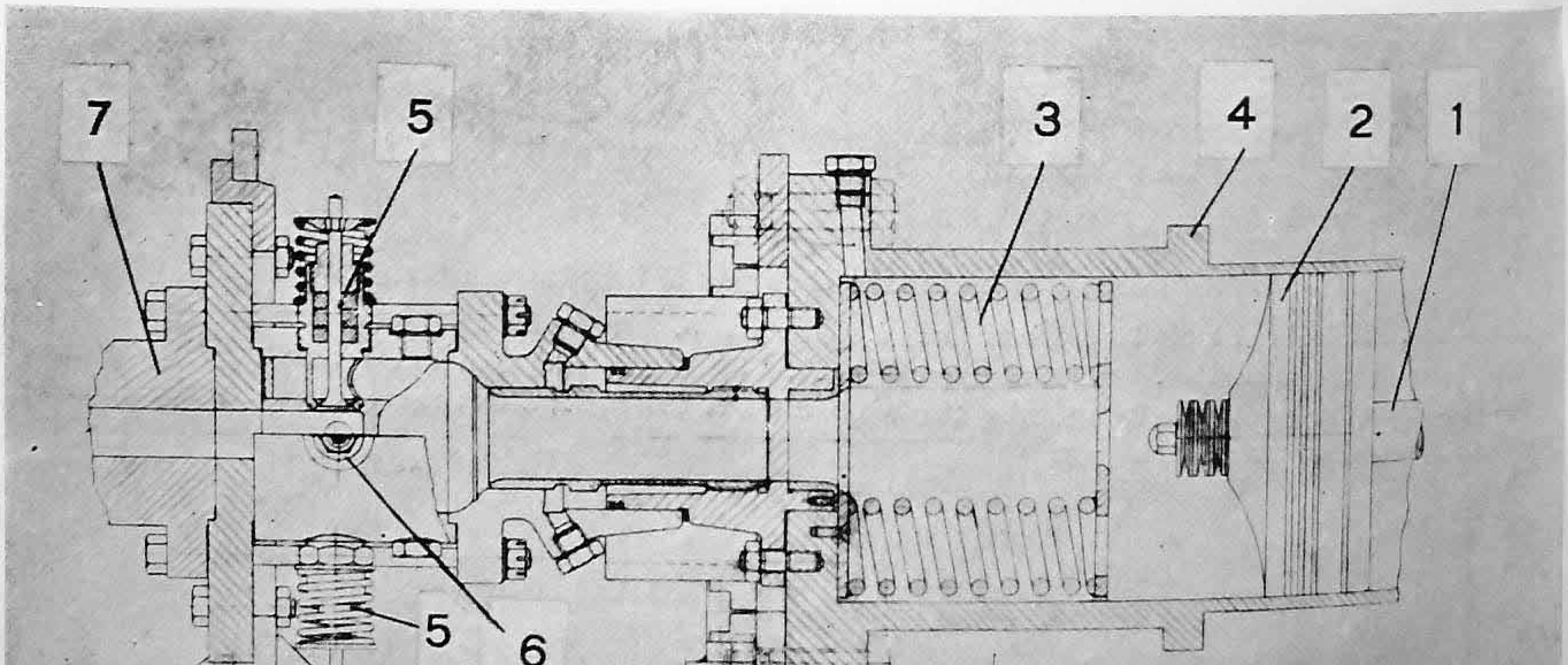

FIG. 9. Sectionalised view of medium part of compression apparatus, second version.

1. Piston rod. 2. Main piston. 3. Springs. 4. Cylinder. 5. Bomb valves. 6. Pressure pick-up point and entrance to combustion vessel. 7. Combustion vessel.

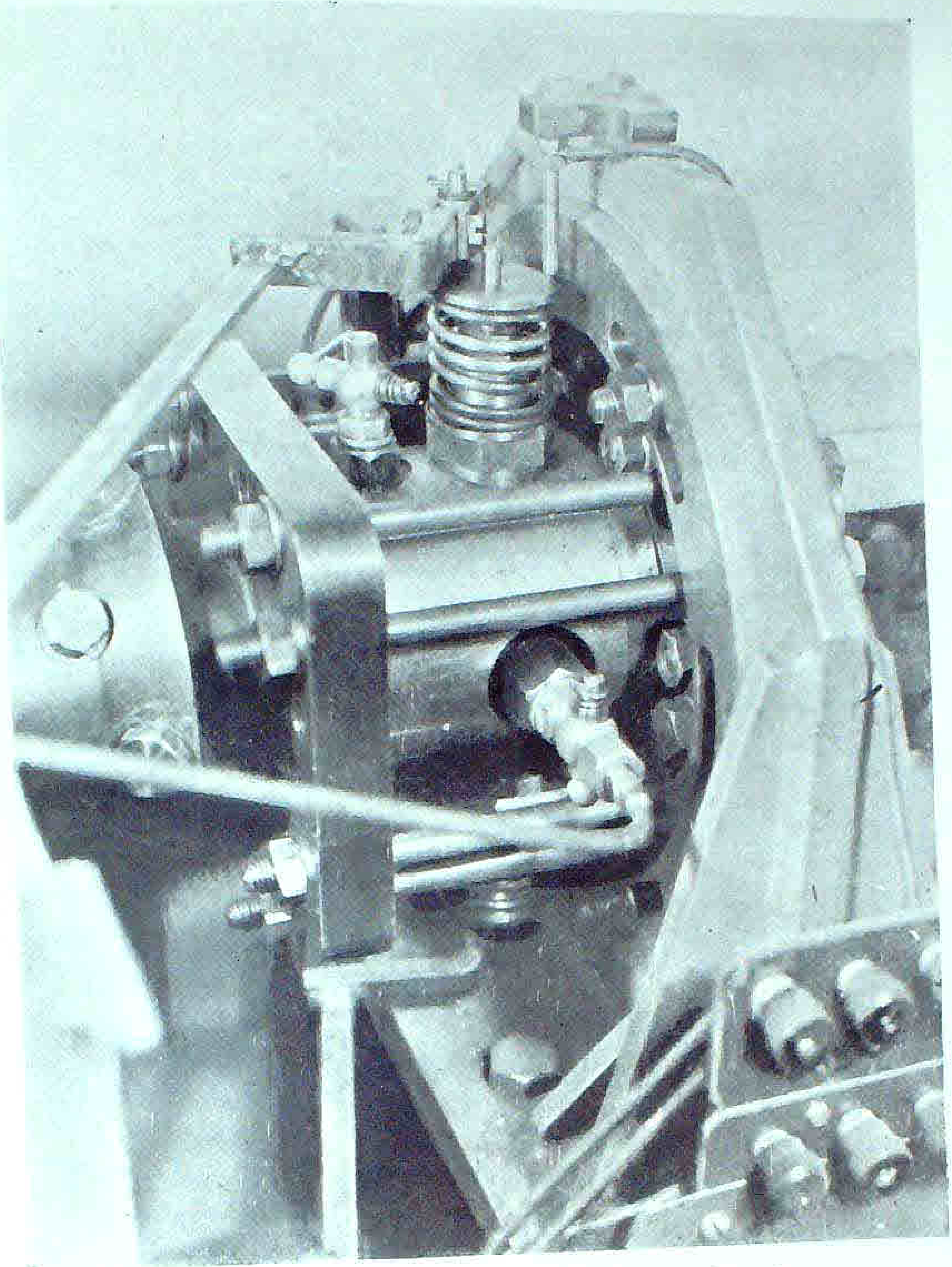

FIG. 10. Mechanical operation of bomb valve.

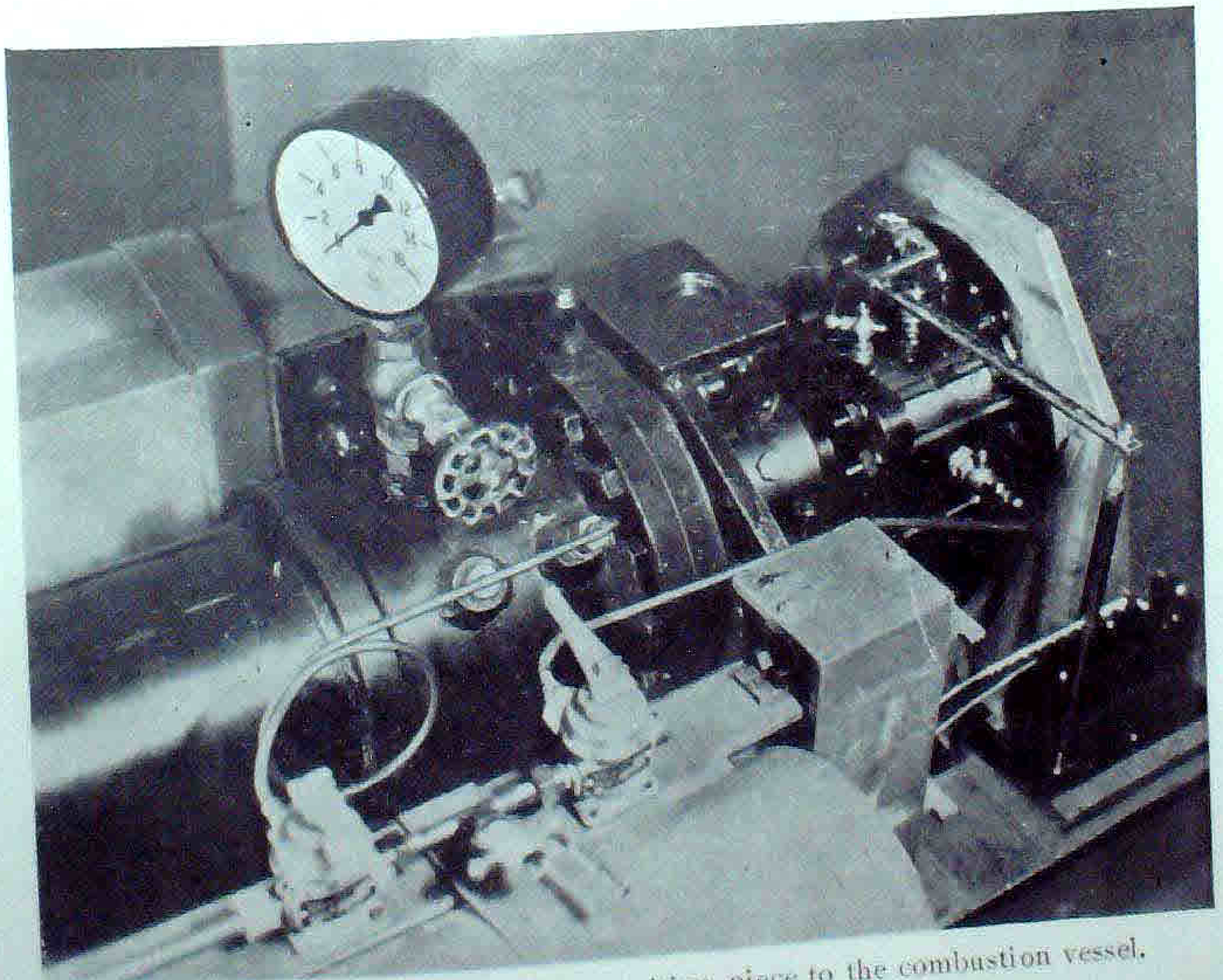

FIG. 11. End of cylinder, and transition piece to the combustion vessel.

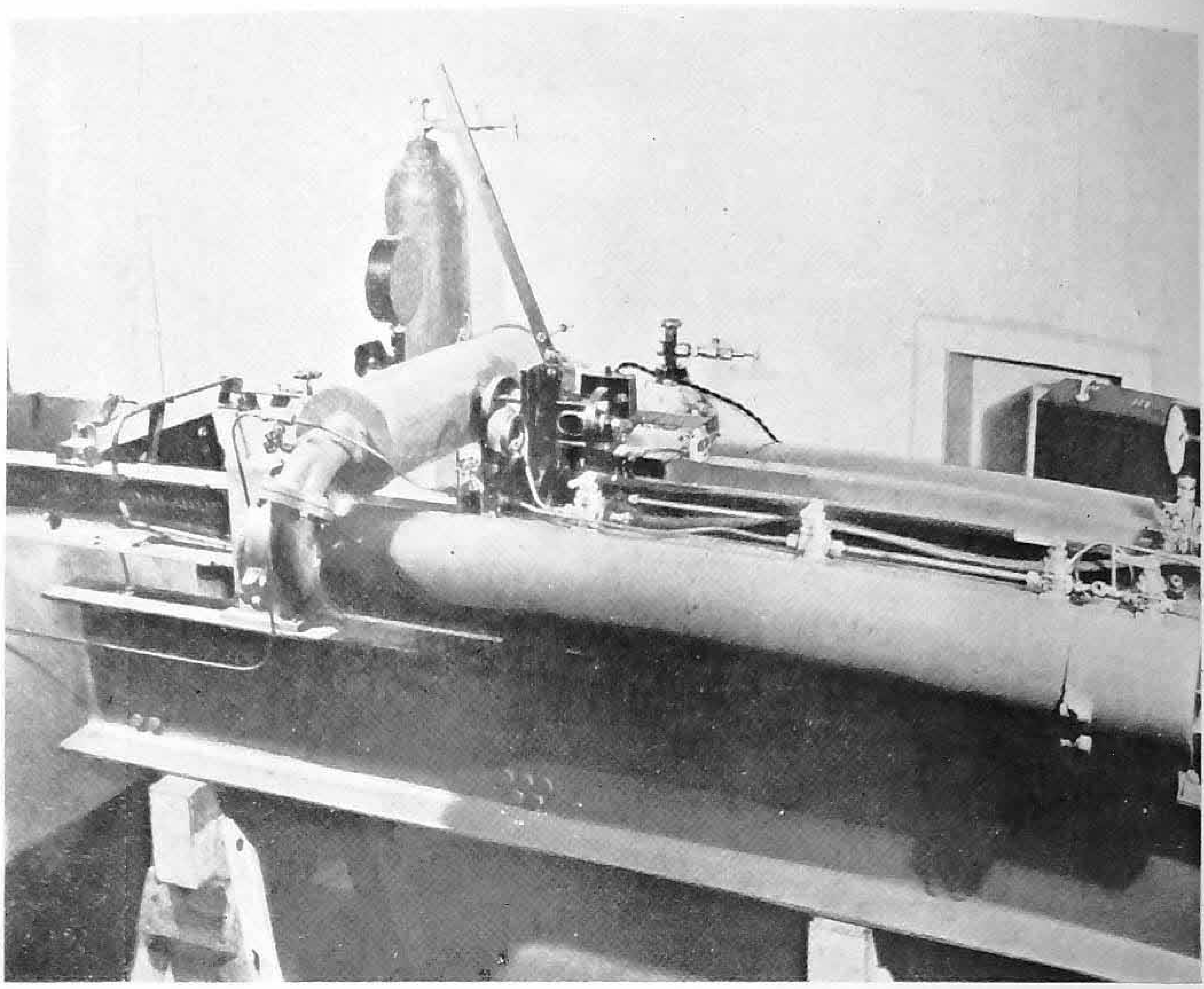

FIG. 12. Compressed air container, and gear for main valve operation.

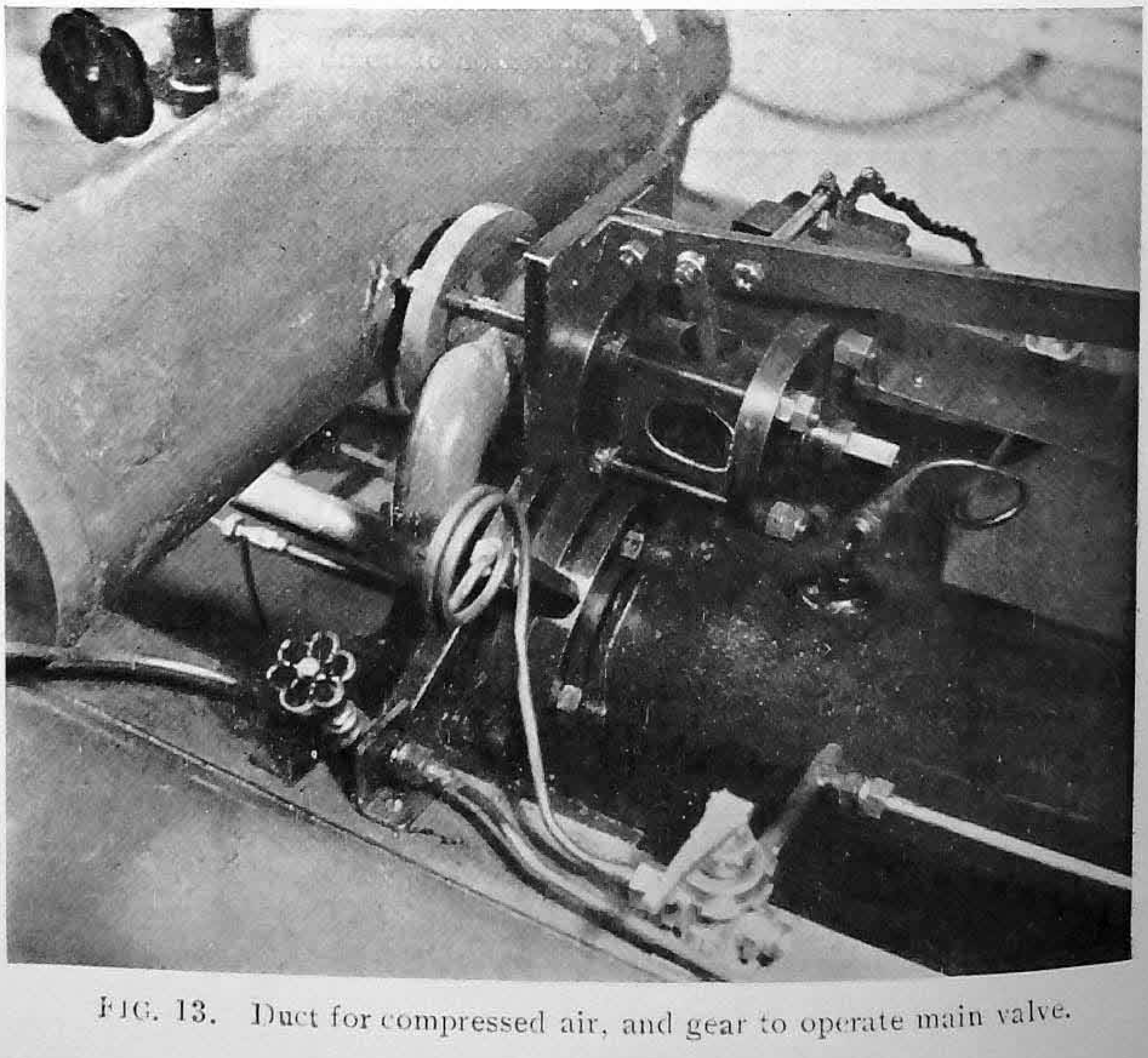

FIG. 13. Duct for compressed air, and gear to operate main valve.

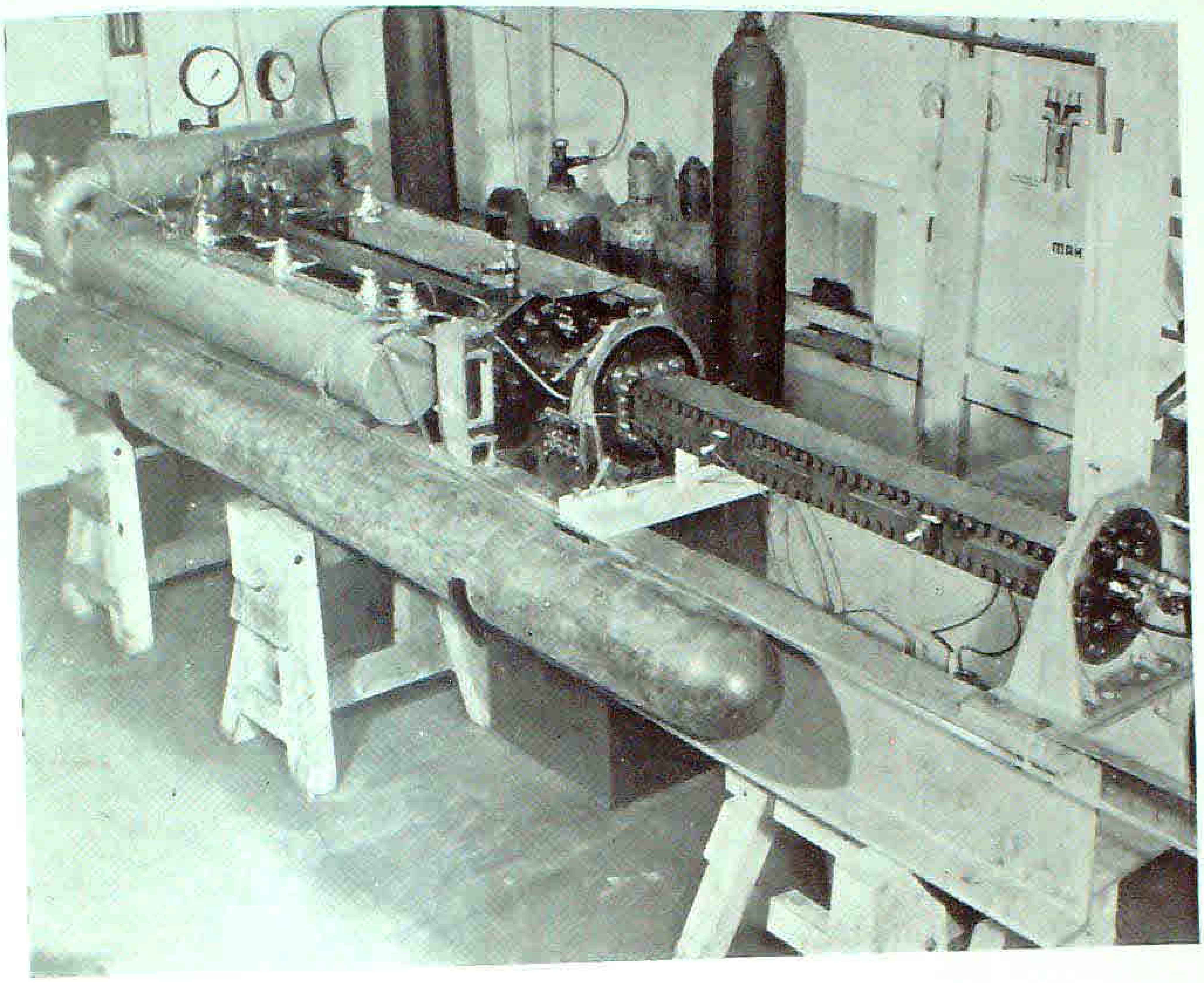

FIG. 14. General view of compression apparatus, final version.

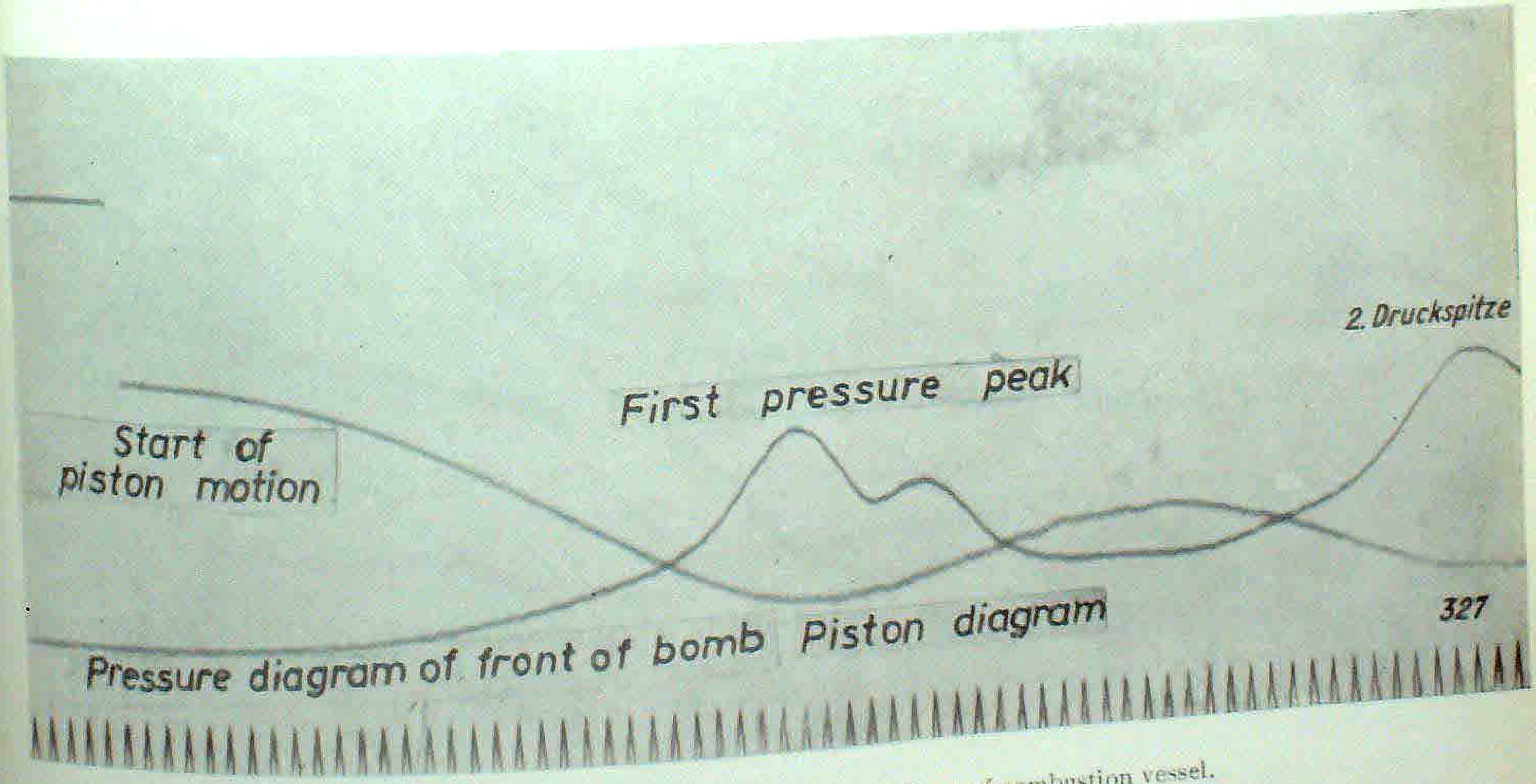

FIG. 15. Pressure and motion diagram at front of combustion vessel.

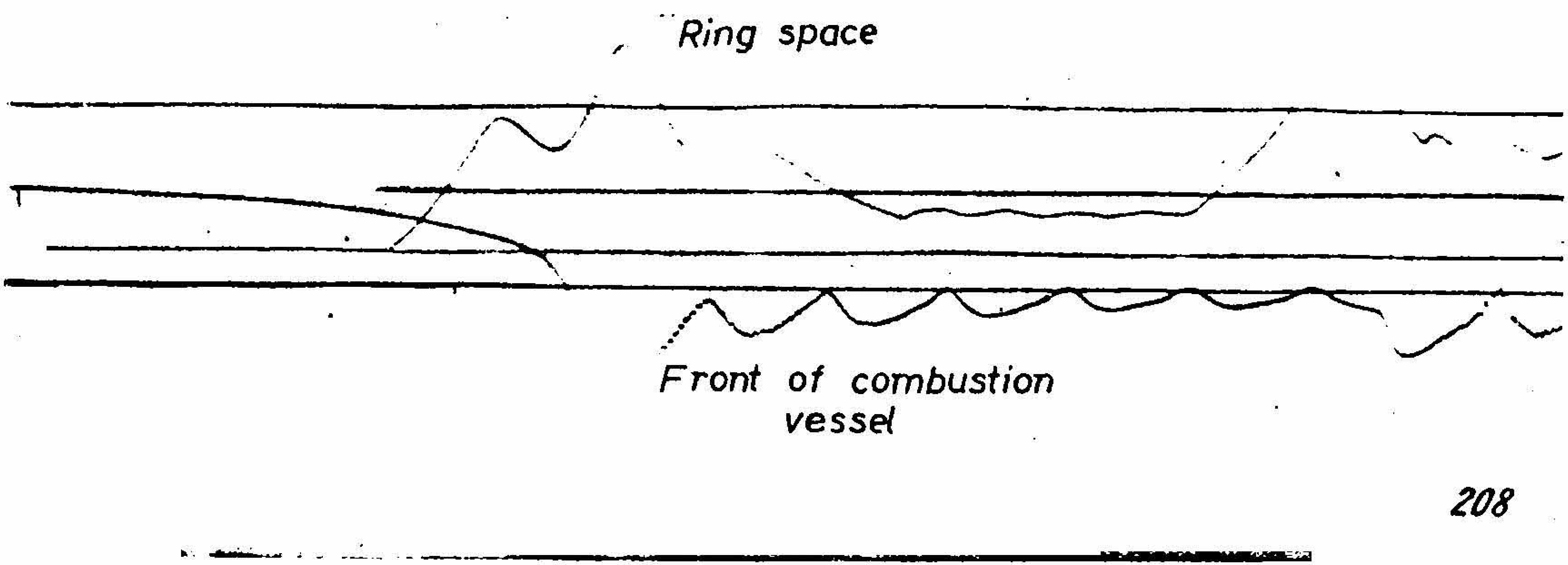

FIG. 26. Pressure in ring space of bomb valve and at the front of combustion vessel, first version

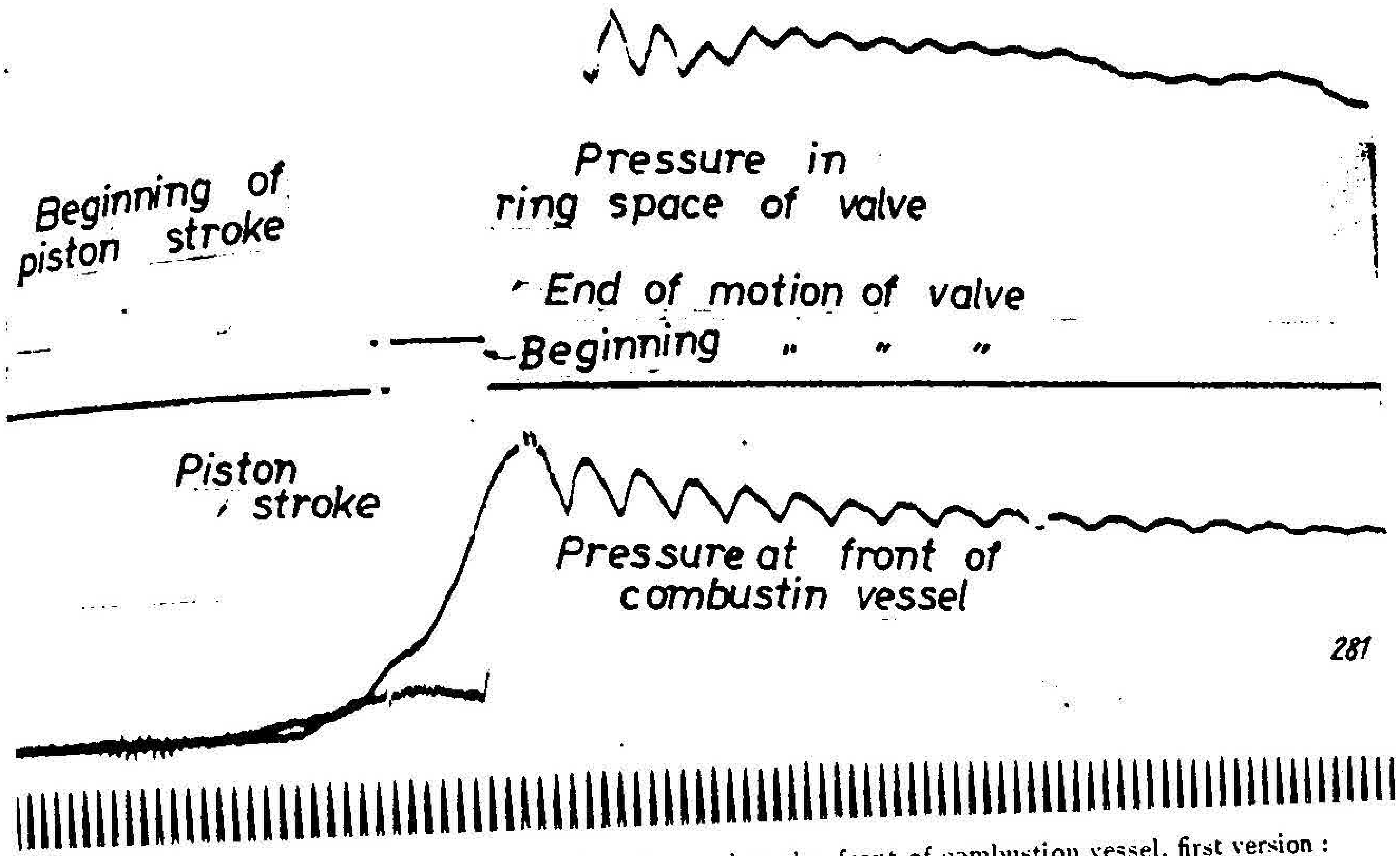

FIG. 27. Pressure in ring space of bomb valve and at the front of combustion vessel, first version: the valve operated from separated compressed air supply

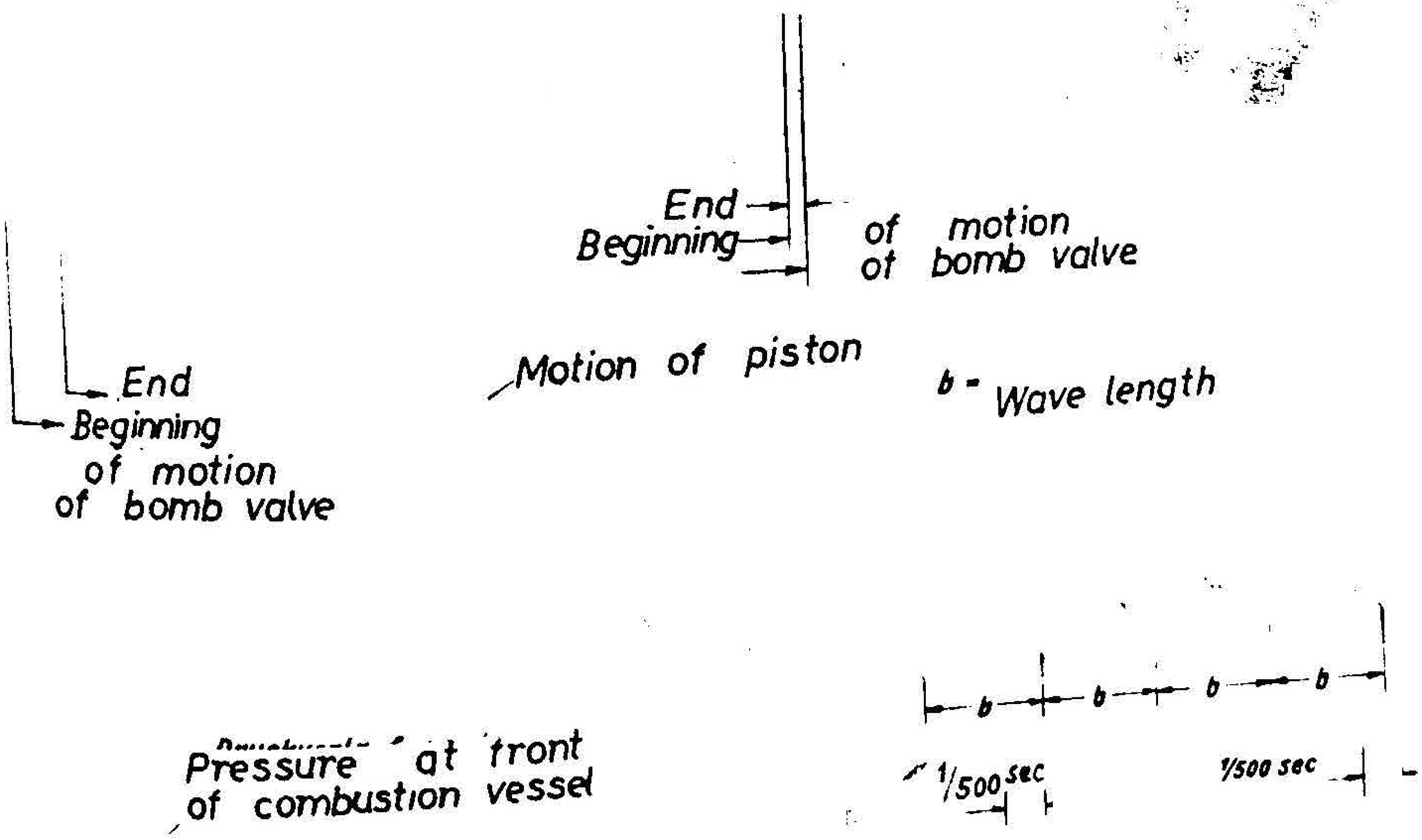

FIG. 28. Motion of valve and pressure at front of combustion vessel, second version.

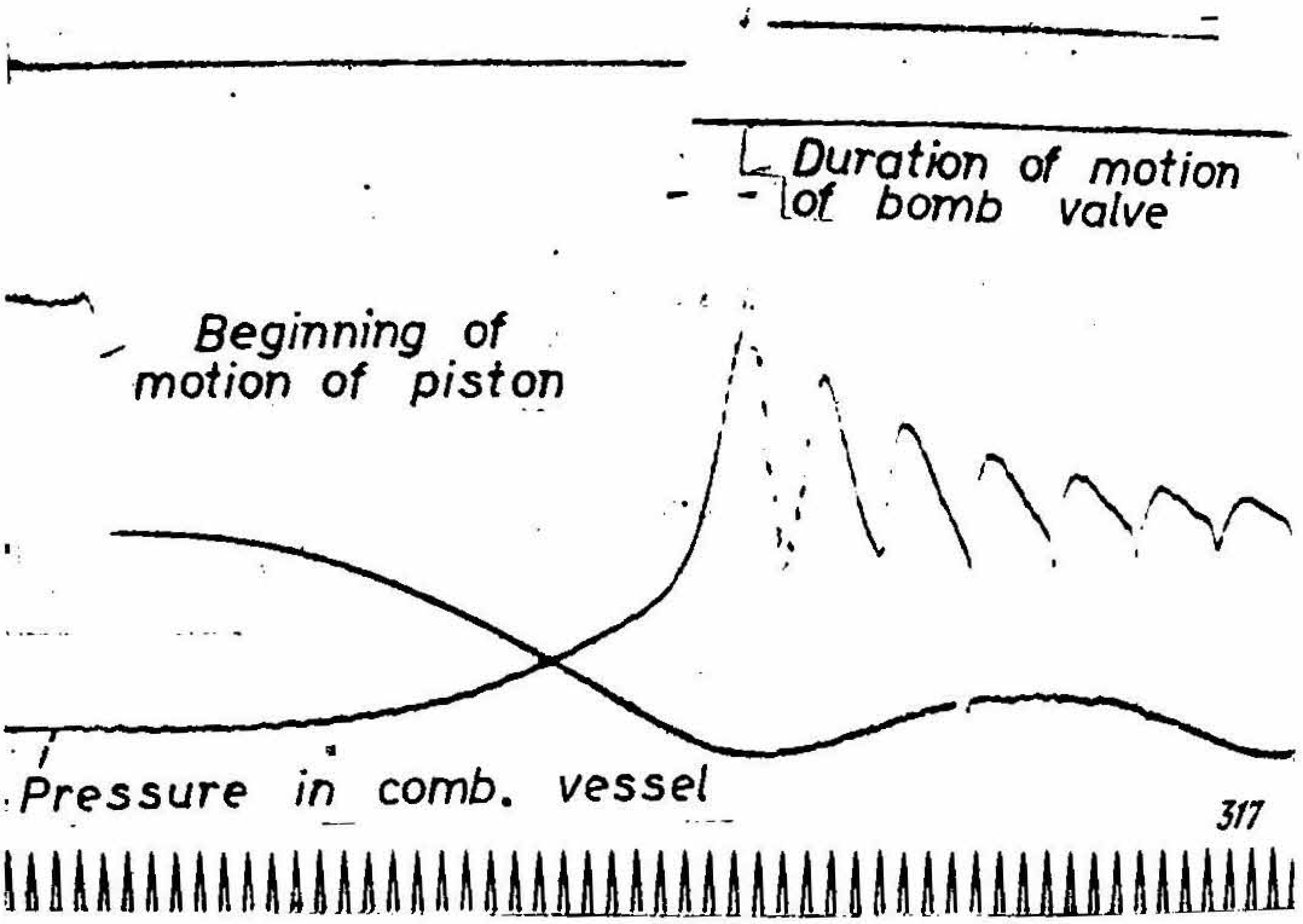

FIG. 31. Pressure at front of combustion vessel, second version.

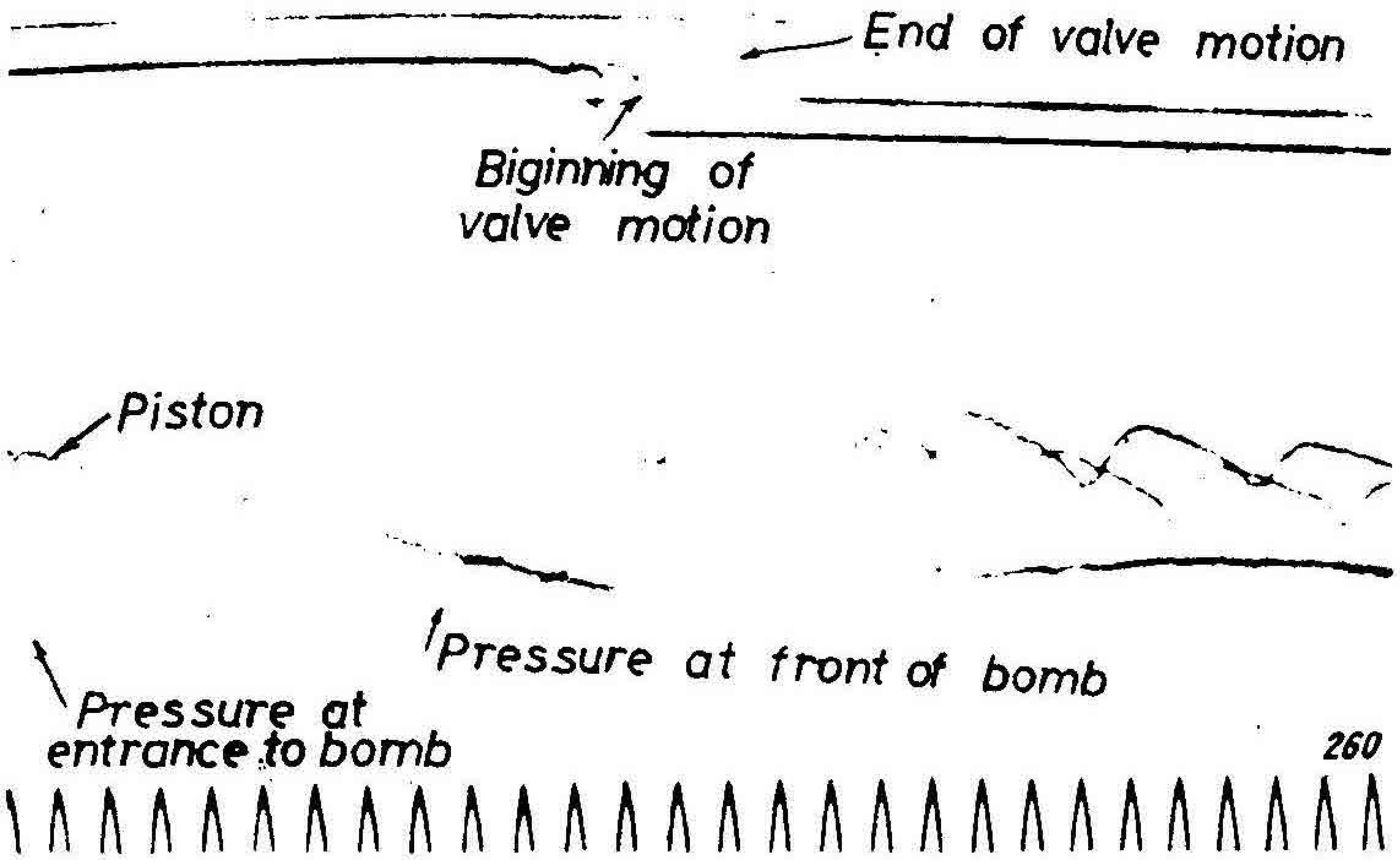

FIG. 32 (a). Pressure diagram at entrance and at front of combustion vessel, first version.

FIG. 32 (b). Pressure diagram at entrance and at front of combustion vessel, first version.

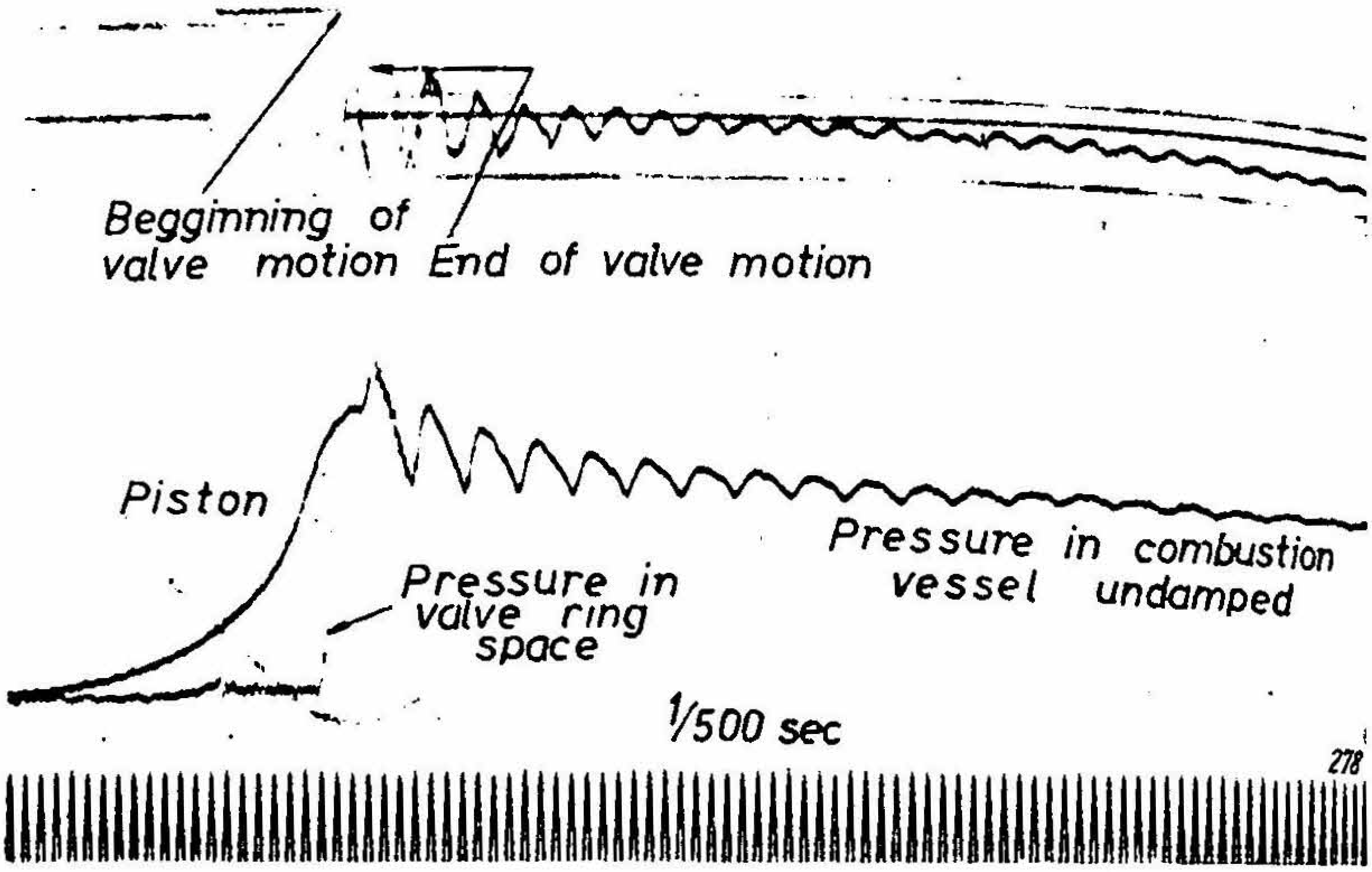

FIG. 33. Pressure in valve ring space and at entrance to combustion vessel, oscillations not damped.

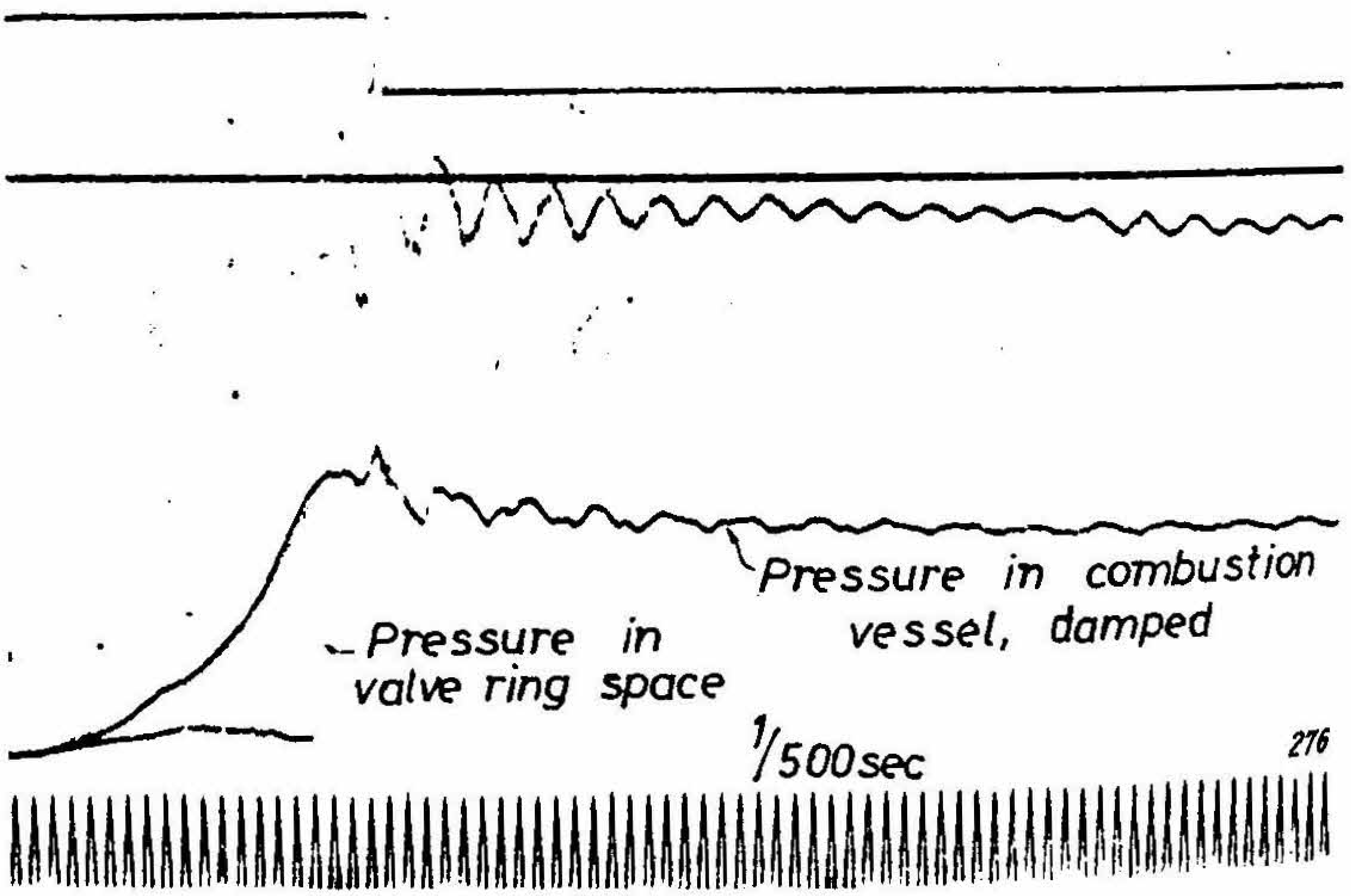

FIG. 34. Pressure in valve ring space and at entrance to combustion vessel, oscillations damped.