

RESEARCH AND DEVELOPMENT OF IMPULSIVE DUCTS IN GERMANY

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RESEARCH AND DEVELOPMENT OF IMPULSIVE DUCTS IN GERMANY

INVESTIGATED AND REPORTED UPON

BY: -

A. K. Oppenheim, Ph.D., D.I.C.

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I Introduction

An impulsive duct is a power generator the principle feature of which is a pulsating gas column and intermittent combustion. It is also known as the gas column engine, intermittent duct, recoil propulsion unit, buzz bomb motor, aero- or hydro-pulse motor, etc., and its numerous applications cover a variety of patents, designs and projects referring to the jet propulsion of aircraft. The principle of these engines was developed in Germany during the war and applied to the V.1 flying bomb motor. This adaptation of the impulsive duct was designated AS 014 in Germany, or FZG 76 in Great Britain.

II Summary

German research work on impulsive ducts was confined to the following centres:-

1. Argus Aeroengines (Berlin), under Dr. Ing. G. Diedrich, and sponsored by the Luftfahrtministerium.
2. Munich - where the original inventor Ing. Paul Schmidt worked.
3. Engine Research Institute, Technical University of Stuttgart, where research work on model impulsive ducts was carried out under Professor Kamm. The firm of Alfred Kärcher (Winnenden, near Stuttgart) collaborated.
4. Schmidding Werke, Schmiedeberg, near Riesenberg, Schlesien - investigations sponsored by Schmidding. The firm of Klockner-Humboldt-Deutz A.G. collaborated.

Although by the end of the war the development of fundamental principles was well advanced (flying bomb engines were in production), it was considered that they were not completely understood. Up to that time calculations were largely empirical, and based on experimental data, so, in order to carry out a more detailed investigation, a special committee of scientists was formed. The work of this committee is described in Section VII.

III Development of the duct under the Luftfahrtministerium

Dr. Ing. G. Diedrich started his research work on impulsive ducts at Argus Aeroengines (Berlin) in Nov. 1939. He was subsequently transferred to the Luftfahrtministerium in 1943 to correlate research work carried out by other establishments.

Dr. Diedrich prepared a report (ref. 1) consisting of five parts:-

- a) Historical outline of the development.
 - b) Aero-resonator testing plants.
 - c) Constructional development of the aero-resonator.
 - d) Theory of the combustion process.
 - e) Methods of increasing the power developed.
- Parts a) and b) only have been published to date.

In a review of patents, Diedrich classifies impulsive duct designs into two groups:

- a) Non-resonators.

The inventions of Lorin (France 1908), Holzwarth (England 1908), Goddard (U.S.A. 1931), Stipa (Italy 1940), and Fairey (England 1942) are placed in this group.

- b) Aero-resonators.

The inventions of Marconnet (France 1909), Karavodine (England 1910), Zselyi (1913), Rheinst (Holland 1930) and Schmidt-Argus (Germany 1930-40) are placed in this group.

It should be noted that a non-resonator can be converted into an aero-resonator by adjusting the frequency of opening of the automatic inlet valve to correspond with the natural frequency of the duct. The design of this valve constitutes the main problem in the operation of an aero-resonator, and the best contribution to its solution was advanced by P. Schmidt, who invented the "mouth-organ" type reed valve, which was adopted by Argus and later incorporated in the V.1 motor.

Diedrich's early experiments at Argus Aeroengines were carried out on a small aero-resonator of the evaporation type, the design of which was based upon the inventions of Rheinst (Swiss Patent No. 196312 of 1930)(fig. 1). The object of these experiments was to develop an auxiliary motor for assisted take-off.

The first impulsive duct (fig. 2) was constructed in 1939. Design details are as follows:

Exhaust pipe - length 60 cms., diameter 2 cms.

Frequency of operation - 200 cycles/sec.

The duct was supplied with compressed air and petrol.

According to Diedrich it was merely a resonator-burner. The air intake was constructed in such a

way that the hydraulic resistance to inflow was much less than the resistance to outflow. The effect of self-ignition was apparent from the first tests, and, on account of the glowing exhaust pipe, it was termed "glow-pipe" or "residual-gas" ignition.

As a result of collaboration with P. Schmidt further impulsive duct developments occurred. In 1940 a non-resonator burner type (fig. 3) was constructed. In this design approximately 10% of the air was supplied by a compressor, and the remainder was induced through the spring valve by suction. Finally, in 1941, the prototype of the V.1 motor (fig. 4) was produced, which has remained comparatively unaltered since then.

Diedrich considered that a most important step in the development of the impulsive duct was the construction of the fuel mixing device. This was the result of intensive research, carried out by Diedrich, who concluded that a high velocity of air at the point of fuel injection was necessary. This produces an intimate mixing of the air with the fuel. The device finally designed by Diedrich (and adopted by Argus Aeroengines) is a suction mixing type, and consists of an atomiser placed in the throat of a venturi-shaped air passage (fig. 5).

The first trials of the Diedrich-Argus duct as a thrust generator were carried out in Feb. 1941, with the duct mounted on a car, which was driven at speeds up to 60 m.p.h. In April 1941 flight tests were made with the duct installed beneath the fuselage of a small biplane. The idea of using the duct for flying bomb propulsion was advanced in 1942, and this gave a strong incentive to the final development of the Argus duct, which was conducted in establishments such as Fiesler Zelle (construction of the V.1 plane designed by Ing. Lusser), Ascania (steering and control gear), Wankel V.W. (test of spring valves), Peenemunde (experimental runs and launching site 1944), L.F.A. Volkenrode (wind tunnel tests) and D.F.S. Ainring (test plants development).

Wind tunnel tests by Dr. Zobel at L.F.A. Volkenrode 1943, showed a rapid drop in thrust at the flight speed of 180 kms./hr., which was the proposed flight speed of the V.1 bomb. This was due to the drag, which was subsequently reduced by redesigning

the inlet nozzle, and thus decreasing the intake losses.

It was planned by the Luftfahrtministerium to set up a basic research establishment at Ainring, under the direction of Professor Georgii. The development of a correct technique for experimental testing was undertaken, and a complete test plant was built, with test benches specially designed for impulsive ducts.

At the same time, scientists throughout Germany were encouraged to conduct research work independently. Thus several reports of a theoretical nature appeared e.g. a study of the stability of the cycle by Professor Bechert and Dr. Marx of Giessen University (ref. 10).

Diedrich tried several methods for improving the thrust output and efficiency. Of these the following are of interest:-

a) Addition of nitrous oxide (G.M.1) to the combustion air as an oxygen carrier; this produces a substantial increase of thrust.

b) Special construction of spring valves ("Sickenklappe") which would improve the free passage of air and thus increase the volumetric efficiency. These were developed at Wankel V.W. by Professor Triebrigg.

c) Combination of an aero-resonator with a Lorin impulsive duct (fig. 6). An order for a prototype of this unit was placed with P. Schmidt (Munich) in 1943.

d) Construction of a duct comprising an auxiliary turbine fed with gases from the combustion chamber (fig. 7) - tested at Peenemunde in 1945.

IV Work of Paul Schmidt

Schmidt's early inventions constitute attempts to improve the performance and efficiency of aircraft propulsion plants. In 1928 he decided that the most promising objective of research in this field, would be the study of the generation of thrust from intermittent explosions of petrol-air mixtures.

By the end of 1929, he had applied for a patent for a thrust generator (fig. 8). It consisted of (i) a centrifugal blower (ii) a conical combustion chamber (iii) a diffuser and fuel jet (iv) an ignition plug

and (v) a Melot type thrust augmentor. Schmidt realised that, although theoretically such a thrust augmentor should produce approximately 50% increase of thrust, in practice little thrust augmentation was obtained because of the high mixing losses. He was convinced, however, that the acceleration of a large mass of air in the form of an air-piston, was essential in order to obtain sufficient thrust from the combustion of a comparatively small mass of fuel-air mixture.

In April 1930 he put forward the following proposals in German Patent No. 523655.

"A method for the production of driving forces on aircraft by the detonation of combustible mixtures, characterised by the fact that a quantity of air, the weight of which exceeds that of the combustible mixture by a multiple, is accelerated directly through the force of the excess pressure of the mixture exploded."

These proposals contained the first sketch of an impulsive duct. With reference to fig. 9, the working cycle may be described as follows:

Position (a) represents the combustion of a petrol-air mixture occupying a small section of the duct near the inlet valve. The excess pressure of the explosion initiates a movement of the air-piston in the direction of the open end, and, at the same time, reacts on the closed valve, producing the effective propulsive force.

Position (b) represents an intermediate position of the combustion front following the expansion of the hot gases.

Position (c) represents the instant when the pressure of the expanding gases falls below atmospheric, thus causing the valves to open and a fresh charge of air to be induced.

Position (d) represents a further time interval, when the fuel is injected into a portion of the fresh air column now filling a large part of the duct.

Position (e) represents the instant when the duct is filled with a fresh charge of fuel-air mixture in front of the column of air. At this instant ignition occurs, and the cycle recommences.

At the request of M. of S., Dr. W. Stern (Chief Scientist, V.R.I., Germany) and the present author,

Paul Schmidt has prepared a report (ref. 2) describing his work. It is divided into three parts.

I Invention, research, and conflicts.

Schmidt describes the development of his early inventions, which was stopped abruptly in 1940 by the interference of the Luftfahrtministerium. The results of his experiments on single explosions in scale model ducts containing various fuel-air mixtures, details of combustion and gas flow experiments, and bench test results from full scale impulsive ducts are worthy of note.

Schmidt admits that his basic ideas were not original, having been put forward by Karavodine in 1910, (fig. 10), but he claims to have discovered this at a later stage in his work.

He concentrated upon the development of full scale ducts. Bench test measurements of the performance of his latest duct (No. SR 500 - produced in 1940) are represented in figs. 11 and 12. They indicate a thrust of approximately 550 kgms. and a petrol consumption of 0.8 gms./sec./kgm. thrust. The duct consisted of a conical section and a straight tube. The former had a diameter of 450 mms. behind the inlet valves, and increased to 510 mms. diameter at a section approximately 500 mms. behind the inlet valves, where it was joined to the straight tube, which was approximately 2.9 mtrs. long.

In conjunction with his work on simple impulsive ducts, referred to by the inventor as "Schmidt-ducts" or "Schmidtrohr", Schmidt developed units comprising a free piston compressor, which were referred to as "Schmidt-engines" or "Schmidtmotor". Prototypes of the latter appeared before the Schmidt ducts. Research work on these units had to be abandoned in 1934, owing to the complete lack of interest shown by the Luftfahrtministerium. He resumed this work, however, at a later date, and in 1944-45 carried out bench tests on the latest version of this engine, illustrated in fig. 13.

It was designed as a high altitude propulsion unit, and was charged by a single-stage blower, driven by a gas turbine. The existing prototype is without these auxiliaries, and oscillograph pressure measurements, taken from the test bench in 1945 and illustrated in fig. 14, show that peak combustion pressures

were approximately 100 atmos.

It was Schmidt's opinion that his engine could attain high overall efficiency, and compete with existing aeroengines.

A petrol consumption of 175 grms./thrust H.P. at a sea level flight speed of 1,000 kms./hr., corresponding to an overall efficiency of approximately 20%, was claimed. This would increase with higher speeds, and the output was limited to the range 200-400 thrust H.P.

The relatively high performance of these engines was said to be due to the speed of the free piston, which was approximately five to ten times that of an orthodox aeroengine piston, and to the high combustion pressures obtained.

II Description and evaluation of details.
This part, written in 1944, presents a detailed analysis of each component of the impulsive duct, including basic theory, design methods and calculations, bench test results and performance, and suggestions for improvements. The working cycle, described in greater detail, emphasizes (fig. 15) the action of the air swing-back at the rear of the duct. Fig. 15 is self-explanatory. Horizontal broken lines denote air, vertical broken lines denote combustible mixtures, and the dotted area denotes burnt gases from the previous cycle.

Schmidt measured the velocity of the flame front, and found it to be approximately 200 mtrs./sec. in a single explosion duct. He also established that the compression waves were propagated with a mean velocity $C_m = 800$ mtrs./sec. As the observed frequency of combustion in the experimental duct of length $L = 2.43$ mtrs. was $n = 82.5$ cycles/sec., the number of waves travelling along the duct during one cycle is given by:

$$Z = \frac{C_m}{nL} = \frac{800}{82.5 \times 2.43} \approx 4$$

Calculations of pressure changes, mass flow, exhaust velocity, thrust and efficiency are based on the assumption of simple harmonic oscillations of the air particles. The mouth-organ inlet valve (fig. 16)

is designed in such a way that the natural frequency of the reeds is equal to the frequency of the working cycle of the duct.

A special fuel mixing device (fig. 17) which, as distinct from Diedrich's mixer, is a pressure type, was designed. Schmidt expected these mixers to be superior to the venturi injectors in the V.1 engine. A number of such fuel mixers (fig. 18), each approximately $\frac{3}{4}$ " diameter and placed behind the inlet valve, should reduce the fuel consumption, since their action is intermittent and automatically synchronised with the combustion cycle, whilst Diedrich's mixtures flow continuously. Moreover, by occupying a comparatively small space, they enable a duct to be designed, which is aerodynamically superior to the Argus design, which must have an enlarged combustion chamber to accommodate the venturi tubes, and create satisfactory conditions for ignition.

An example of bench test results is illustrated in Fig. 19, which shows the net thrust (gross thrust less ram drag) and specific fuel consumption of duct No. SR 100.

Schmidt used the term "specific thrust", defined as the ratio of the thrust obtained to the cross-sectional area of the duct, and determined typical values e.g. 0.27 - 0.35 kgms./sq.cm. for the Argus AS 01A, which was a large duct, (565 mms. max. diameter, 350 mms. tailpipe diameter, 340 kgms. thrust). Ducts of smaller cross-section and increased length did not yield these figures.

In considering possible improvements, Schmidt suggested that development should be directed towards obtaining higher combustion pressures and cycle frequencies. He quotes as a practical possibility, pressures of approximately 5 atmos., which he recorded during single explosion experiments. In his opinion, higher frequencies could be obtained in ducts having a small ratio of combustion chamber cross-section to tailpipe cross-section, which would also reduce drag.

III Fundamentals, computations and prospects.
A more comprehensive analysis is given in this part, which was written at a later date.

An interesting comparison of the thermodynamic efficiency of an impulsive duct with that of a Lörin athodyd, operating on the Lenoir cycle, is given in figs. 20 and 21. In fig. 20 Q' represents the heat generated by ram effects, and Q represents the heat of combustion. The advantage of the Schmidt cycle is most marked at low speeds, when the ram effect is small, but falls off rapidly with increasing flight Mach No. Thus, at zero forward speed, the efficiency of the impulsive duct is 30%, whereas that of the Lörin duct is zero, but at a Mach No. of unity the efficiency has fallen to three times that of the Lörin duct.

The assumption of constant pressure combustion in the athodyd is reasonable, but the assumption of constant volume combustion in the impulsive duct is an idealisation. Schmidt therefore introduced a combustion efficiency factor (η_g) and evaluated the overall efficiency of the duct (η) as a function of the flight speed (V) for different values of η_g and the excess air factor (k) (fig. 22).

He considered that a combustion efficiency of 60% could be achieved, and that it should be possible to obtain 80% under development. The overall efficiency would then become approximately 9-12% at a flight Mach No. of unity and an excess air factor of 3.

V Research work at Stuttgart

The experimental work was carried out by Dipl. Ing. W. Dürr and the firm of Alfred Kärcher, under the direction of Professor Kamm, who collaborated with Schmidt. The objects of the research were (i) to develop a small size heat generator with a comparatively high heat output and (ii) to carry out an investigation of scale model impulsive ducts.

The first object is especially attractive because of the high heat transfer coefficient which can be obtained in the duct, where the combustion gases are in a state of turbulence due to the pulsating flow.

Experiments were initiated on straight tubular ducts of Schmidt design (fig. 23). The first, 100 mms. diameter and 3 mtrs. long, had a heat output

of 300,000 WE/hr., which was considered too high. Accordingly efforts were made to construct smaller models (20-40 mms. diameter), but, after one year's work, they had not been successful.

It was discovered however that the tubular duct did not have to be straight; it could be twisted into any shape without affecting its action.

In the next stage of the research a small heat generator (fig. 24) was developed. It worked without a valve, on vaporised petrol supplied at a pressure of approximately 30 lb./sq.in. The fuel system consisted of a pressurised tank, similar to that used in a simple blowlamp, an evaporator with a starting burner and an injector. During the working period of the duct the fuel was vaporised by passing the supply pipe through the combustion chamber. The duct worked quite well, and the performance (fig.25) indicated a peak pressure during the combustion cycle of 0.15 atmos. The main disadvantages of this duct were the difficulties connected with the vaporisation of fuel e.g. carbon deposits on the fuel leads and choking of the injector.

These disadvantages were overcome by the development of a heater utilising liquid fuel without pre-vaporisation or pre-compression (fig. 26). The fuel was sucked into the combustion chamber by the depression developed there during the cycle. To obtain these conditions the air inlet was fitted with a non-return valve, and the combustion chamber joined to a long resonating exhaust tube. The non-return valve consisted of a circular aluminium plate approximately 3 ins. diameter, containing a number of equally spaced hemispherically seated holes approximately $\frac{1}{4}$ " diameter. Small hemispherical cups were held loosely over each hole by a circular steel gauze bolted to the plate through the centre (see fig. 27). Further details of the heaters are as follows:

Frequency - - 60-120 cycles/sec.

Tube length - 1300 mms. (fig. 29).

Peak pressures - 1.7 atmos. and -0.75 atmos. (fig. 28)

Heat output - 30,000 kgrm.cals./hr.

Finally the hot gas blower for aeroengine ground heating was developed, and manufactured by Kärcher. In

this adaptation, the heat generated by the impulsive duct is transferred to a large mass of air, which is induced across the tubing, and mixed with the exhaust, by means of a Melot type augmentor fitted to the open end of the exhaust tube. The temperature of the exhaust gases is thus reduced to approximately 120°C., with the heat output remaining at 30,000 kgrm. cal./hr.

At this stage the second object i.e. the investigation of scale model impulsive ducts had gained in importance. The V.1 flying bombs were in full production and, by model research, it was hoped to determine and improve the altitude performance.

The scale models ranged from 40 mms. to 100 mms. diameter. Three main combustion chamber shapes were investigated (fig. 31) (i) the conical-shaped 95 B, (ii) the barrel-shaped 95 A₂ and (iii) the cylindrical 95 Z model. The inlet valve was of the same type as that fitted to the hot gas blower (fig. 27). The research was carried out in the high altitude wind tunnel at the Institute*. It was established that the amount of induced air depends to a marked extent on the shape of the combustion chamber. Fig. 32 shows a comparison between 95 A₂ and 95 Z (95 B had an increased valve diameter and a larger combustion chamber and it cannot therefore be taken into account for comparison), which are exactly the same size. Type 95 Z, with a sudden change of cross-section between the combustion chamber and the exhaust pipe, shows a greater decrease in the rate of induced air flow, than in type 95 A₂.

The dependents of the temperature on the rate of air flow was represented by the following empirical equation:

$$\frac{G_1}{G_2} = \left(\frac{T_2}{T_1} \right)^{0.70}$$

* Heat Engines Laboratory of the University of Stuttgart at present attached to the Dept. of Theoretical Physics under the direction of Professor Fues. The laboratory, heavily damaged during the war, is now in charge of Dr. Paul Riekert, former assistant of Professor Kamm, who is now in the U.S.A.

The available thrust (net thrust less the aerodynamic drag) of a duct 40 mms. diameter, plotted against altitude, for a flight speed of 600 kmtrs./hr., is shown in fig. 33. The thrust law for this flight speed is given by:

$$\frac{S_H}{S_0} = \left(\frac{\gamma_H}{\gamma_0} \right)^{1.39}$$

where S = thrust

γ = air density

Suffix (h) refers to the altitude concerned

Suffix (o) refers to standard sea level conditions.

The performance investigation consisted of determining the available thrust and specific fuel consumption, for various altitudes and flight speeds. Typical results are illustrated in fig. 35. It was established that the best method of mounting a duct on a flying body was that illustrated in fig. 36, where the body forms a reservoir for the induced air, and thus reduces the drag.

Finally, very attractive and interesting experiments were carried out on the combination of a number of ducts coupled together as one unit. If correctly coupled two or three ducts worked successfully in phase i.e. the combustion in each of the ducts followed at equal time intervals. Fig. 37 represents the effect of coupling two or three ducts, and it shows that the mean change of thrust ~~is~~ obtained is much more favourable in this case, than in the case when each duct works independently.

The coupling could be affected by a cross-duct, the length of which must be adjusted so that the component ducts work successively i.e. at equal time intervals between the corresponding phases of their cycles. For example, in the case of two ducts, if the pressure in one attains its peak value, the pressure in the other should be at its lowest value. Thus if l denotes the length of the duct and x the distance of the cross-duct junction from the inlet valve, the length of the cross-duct is given by:

$$a = 2(l - x)$$

If the ducts are coupled at the inlet valve ($x = 0$)

the distance would be $a = 2l$; if they are coupled at the exhaust end ($x = l$), the corresponding distance $a = 0$. The effect of the length of the cross-duct on thrust and fuel consumption is shown in fig. 38.

The simplest way to couple three ducts is by binding together their exhaust ends. Figs. 39 - 41 represent photographs of such a unit found at Professor Kamm's Institute. Further development was stopped by the end of the war. It should be noted, however, that it was considered by the Germans to be so promising, that a design consisting of two ducts of the type used in the flying bomb (AS 014) coupled together, was under construction, and it was expected to obtain a thrust of 660 kgrms. (double that of the AS 014) at once, with possibilities of a subsequent improvement to 800 kgrms.

The end of the war also hindered investigations into the use of fuels other than petrol for impulsive ducts, commenced as the last stages of research at the Institute. Preliminary experiments carried out with heavy fuel and coal dust were, according to Dr. Riekert, quite promising, but they have not been mentioned in Dürr's paper (ref. 3). The only evidence of this work is the experimental set-up left at the Institute and represented on figs. 42 - 45, which show photographs of the set-up, details of the fuel supply, and the valveless inlet nozzle.

VI Research work by Schmidding

The Luftfahrtministerium placed an order with Messrs. Klockner-Humboldt-Deutz A.G. (KHD) for the development of an impulsive duct, the design of which was to be based upon proposals advanced by Drs. Schwürle and Elwert on behalf of Schmidding. Work was commenced by an attempt to improve the performance of a Rheinst aero-resonator (fig. 1), but, after introducing several improvements (Lederle's invention, see ref. 4 page 76) and registering patents, this research was terminated.

The main effort was then directed towards the development of a KHD Engine, or Schmidding Unit, consisting of a number of ducts working in parallel, and mechanically synchronised. This was accomplished by having several cylindrical combustion chambers placed side by

side around the circumference of a circle. The unit was fitted with a rotating inlet valve at the front, of the combustion chambers, and a similar exhaust valve at the rear. The layout resembled the Stipa invention (patent, Italy 1940). The cycle time for each duct is given by:

$$T = n \cdot dt$$

where dt = time interval between explosions in adjacent ducts.

n = no. of ducts.

The practical and theoretical investigations of the KHD Engine, were put under the charge of Dr. Richard Brandt, who described his work in three papers (refs. 5, 6 and 7) dealing mainly with theoretical aspects of jet propulsion and combustion flames in tubes, with special application to impulsive ducts.

His first paper on jet propulsion motors with continuous and intermittent combustion formed his Doctor's Thesis, and is of a general and fundamental nature characteristic to a paper of this kind. It is a purely theoretical work, in which the author presents an analysis of such problems as development of power from combustion, the energy balance, efficiency of jet propulsion units, kinetics of combustion flames, combustion flames in tubes (open and closed), ignition and combustion of fuel-air mixtures, etc.

Some of the results of his investigations are represented in fig. #6, showing the dependence between the overall efficiency of the duct (the product of internal and external efficiency) at a flight speed of 250 mtrs./sec., and the excess air ratio for the following cases:

- a) Rapid combustion.
- b) Slow combustion.
- c) Constant pressure combustion.

In the first two cases, comparison is also made between the assumption of no heat flow across the duct walls, and of heat flow across the walls $q_p = 0.2q$, where q denotes the heat of combustion.

The case of constant pressure combustion has been evaluated under the assumption of ram efficiency approximately equal to 90% and the diffuser efficiency approximately 95%.

The case of "rapid combustion" implies the development of a steady detonation wave. Brandt found that the thermodynamic efficiency of a cycle consisting of this type of combustion, an adiabatic expansion and a constant pressure exhaust is approximately 10% higher than the efficiency of a Lenoir cycle i.e. a cycle similar to the former, but with combustion at constant volume. If it is assumed that the heat of combustion $q = 650$ cal./kgm., $\gamma = 1.3$ and $R = 29.4$ kgms.*C. (conditions obtaining in practice) the efficiency becomes $\eta_{th} = 30.2\%$.

He established that, theoretically, if the combustion front velocity is not less than 100 mtrs./sec., the cycle efficiency is approximately the same as for constant volume combustion. The flame velocity attained in the V.1 flying bomb duct was approximately 70 mtrs./sec., but, according to Brandt, the improvement of this velocity up to 110-120 mtrs./sec. seemed possible.

Brandt was especially interested in combustion involving a detonation wave. He analysed the conditions leading to the development of a steady detonation wave, and described some very interesting considerations of this problem in his second paper (ref. 6).

His last paper (ref. 7), dealing with unsteady flow in pipes, has not been completed and is under preparation in Ulm, Germany.

VII Theoretical aspects.

The theory of operation of impulsive ducts attracted the attention of Germany's leading scientists, who contributed many papers pertaining to special aspects of the problem.

An early contribution was made by Professor Busemann in 1936, who presented a theory for a version of the Schmidt-engine comprising a free-piston combustion chamber. A most interesting result from this work is the evaluation of the H.P., which could be developed theoretically in a duct of this type, as a function of the ratio of flight speed to the relative velocity of the exhaust gases (assumed to have a constant value of $V_0 = 1,230$ mtrs./sec.) $\epsilon = V/V_0$, for

different values of the ratio of the mass of induced air at each cycle to the corresponding mass of the fuel mixture $\lambda = G_2/G_1$ (fig. 47). The combustion cycle was assumed to be a simple Lenoir type with efficiency $\eta_p = 28\%$. Unfortunately the usual type of impulsive duct fitted with a non-return valve was not considered by Professor Busemann since, at the time of his report, this type had not been developed.

Professor Busemann's assistant, Dr. G. Guderley, introduced a number of refinements to the theory by taking into account compressibility effects, and his analysis of the performance of the Schmidt-duct both at rest and under flight conditions appeared as an Interim Confidential Volkenrode Report (ref. 9) in 1939.

It is unfortunate that the copy of this paper supplied to the author is in parts unreadable, and no opinion can be expressed as to the value of its contents.

In 1943 a Professor K. Bechert and Dr. H. Marx produced a very laborious and lengthy report (ref. 10) on order from the Luftfahrtministerium. It dealt mainly with the stability of the combustion cycle and the ensuing problems such as fuel supply, atomisation, optimum air-fuel ratio, etc. The theory was based upon the assumption of oscillations of finite amplitude and, according to the authors, their analytical calculations were in good agreement with experimental results.

It has been realised in Germany that further development of the impulsive duct depends to a great extent on investigations of the fundamentals of unsteady flow of gases. Fundamental research was carried out at Volkenrode by Professor O. Lutz and his collaborators (ref. 11). Dr. Hummel, working under his direction, investigated the so-called "ponderomotoric" effect of an oscillating gas column in a pipe (ref. 12). This effect can be observed in an arrangement as shown in fig. 48, where, by causing pressure waves to be propagated along a pipe closed at one end, a positive thrust in the direction of the closed end is obtained. According to Professor Lutz this is due to the fact that the efflux takes the form of a turbulent jet whereas

the influx is laminar (fig. 49). This is of direct interest to the development of impulsive ducts, where, as was pointed out by Schmidt (see fig. 15) and subsequently revealed by theoretical investigations of Professor Schultz-Grunow, the action of the air induced at the back of the tube (air swing-back) is of great importance to the working cycle. It contributes to the compression of the subsequent charge and assists the ignition (fig. 52).

Professor Lutz conducted the experiments with Melot type thrust augmentors applied to unsteady jets. He concluded that the augmentation effect in this case is much greater than with steady flow, thus confirming the arguments put forward by Ing. Schmidt at the start of his work.

Professor Lutz obtained a series of photographs by use of the interferometer method, which show details of mixing of two gas streams in an augmentor applied to an unsteady jet. It appears from them that with a design giving the correct ratio of mixing gases, the induced air is accommodated between the club-shaped portions of the exhaust gases (fig. 50) and, since then no mixing occurs, the mixing losses are minimised. In fact, from measurements taken simultaneously, the thrust augmentation produced is as high as 50% of the net thrust of the unaugmented jet.

Unpublished results of experiments on nitrous oxide injection into impulsive ducts are held by Professor Lutz. The nitrous oxide (G.M.1) which is added as an oxygen carrier to the combustion air, produces a substantial improvement in the efficiency.

Important contributions to the study of theoretical gas dynamics as applied to impulsive ducts, were made by Professor Sauer (ref. 13) and Professor Schultz-Grunow (refs. 14 and 15). Their methods are based upon the Riemann theory of unsteady flow, in which the transmission of a pressure wave is used as a flow characteristic. The propagation of such a wave is represented graphically on a time-distance diagram. The most conclusive of the above reports is the last one (ref. 15) presented in 1946. As the copy available at the German Documents Unit is not very clear, it is described here in detail, presenting, at the same time, a good example of the method.

For waveform calculations the following relationship is used:

$$\Delta u = \frac{\gamma - 1}{2} \Delta a$$

where Δu = change in gas velocity

Δa = change in the local velocity of sound

γ = ratio of specific heats

The velocity of propagation of a pressure wave is given by:

$$w = \pm a + u$$

where w = velocity of propagation

a = local velocity of sound (the plus and minus signs signify the positive and negative directions along the x-axis)

u = velocity of the particles

The pressure rise during combustion was taken from experimental results and the corresponding change of state was assumed to take place adiabatically and simultaneously throughout the whole mass of the unburnt charge (hence horizontal pressure lines in fig. 51). It was further assumed that the duct was cylindrical, and that the exhaust gases had the same ratio of specific heats as the unburnt charge. These assumptions imply that the duct is originally filled with a homogeneous gas at constant pressure, which is subjected to an adiabatic change impressed on a limited region from the outside.

A graphical construction of the wave propagation was devised. This is shown in fig. 51 in the form of a time-distance diagram, in which pressure waves are represented by continuous lines and rarefaction waves by broken lines. From such diagrams, by considering sections at $x = \text{constant}$, or at $t = \text{constant}$, the time variation of the pressure (velocity, etc.) at any cross-section, or the pressure (velocity, etc.) distribution along the x-axis at any given time, can be determined. The non-dimensional parameters $\tau = a_1/l$ for time, and $\xi = x/l$ for distance were used, where

l = length of the duct

a_1 = local velocity of sound in the initial state of the air at rest.

The state of the gas within the boundaries of each zone is considered to be constant, but varies from one zone

to another, being indicated in each zone by the two non-dimensional parameters of state a/a_1 (upper figure) and u/a_1 (lower diagram).

In order to simplify the interpretation of the diagrams a sketch of the wave propagation, constructed with the help of fig. 51, is shown in fig. 52. In this diagram positive and negative pressures are indicated by plus and minus signs, whilst the arrows indicate the direction of flow. The physical interpretation of this diagram is facilitated by remembering the fact that waves of compression are reflected as waves of compression from a closed end, and as waves of rarefaction from an open end, and waves of rarefaction are reflected as waves of rarefaction from a closed end, and as waves of compression from an open end. In the latter instance an inflow of air from the surroundings takes place at the open end.

The compression waves $A'A''$, originating from combustion during the first and second working cycles, initiate an expulsion of the gas at positive pressure and sonic velocity from the end of the duct. For this reason the rarefaction waves $B'B''$ are reflected as waves of rarefaction $C'C''$ until this excess positive pressure has been reduced. The subsequent rarefaction waves $D'D''$ will be reflected as compression waves $E'E''$, producing an atmospheric state at rest. Such a state exists in all regions marked I.

The rarefaction waves $C'C''$ initiate a suction period at the duct inlet. When the first wave arrives the valves are still shut and, owing to inertia, will open gradually. The first waves are therefore reflected as waves of rarefaction $F'F''$, and the last ones as compression waves G' during the first working cycle, whilst no reflection takes place in subsequent cycles. Waves G' combine with the pressure waves A'' originating from the second ignition, thus amplifying their effect. The waves of rarefaction F' are reflected as compression waves H' from the end of the duct, and cause an inflow with maximum gas velocity $u/a_1 = 0.18$. This air finally occupies one eighth of the duct.

This phenomenon of inflow (or air swing-back) at the end of the duct, has been demonstrated experimentally by Paul Schmidt (fig. 15). It appears from subsequent considerations that it plays an important part in the

working process of the duct.

Waves H' cause an excess pressure to persist at the inlet end after completion of combustion. The time variation of pressure at the front end of the duct, deduced from the time-distance diagram, is shown in fig. 53. It compares favourably with the experimental results obtained by Paul Schmidt (fig. 54). Incidentally, the theoretical pressure change at the inlet as deduced from the time-distance diagram, explains the origin of the saddle (marked with the letter H) on the experimental curve of fig. 54. This saddle is apparently caused by waves H (fig. 52) originating from rarefaction waves F' produced by reflection of the rarefaction waves C' at the valves, which are then about to open. The saddle is therefore entirely due to the valves, and the stiffer the springs, the more nearly should the saddle approximate to a point.

Furthermore the graphical analysis of the flow phenomena in an impulsive duct shows that an essential criterion for correct functioning of the duct is the production of compression waves.

Firstly, it can be seen that ducts decreasing in diameter towards the rear end will not function well (see ref. 14). Secondly, the functioning of the duct depends on the opening ratio of the valves, i.e. on the ratio of maximum free cross-section of the valves to the duct cross-section. It can be deduced from fig. 52 that if this ratio is too large the duct will not function. This is caused by the fact that in the case of an opening ratio which is too large, the majority of waves reflected from the valves are compression waves G , and very few rarefaction waves F' are reflected. The waves H' , reflected subsequently from the open end, are thus entirely waves of rarefaction and they result in a weakening of the subsequent explosion. If, however, the opening ratio is correct, the majority of waves are rarefaction F' (fig. 52). The corresponding reflections are compression waves H' accompanied by an air swing-back, and the subsequent explosion is reinforced.

These considerations explain clearly one of the most important features of the flow in an impulsive duct, namely, the effect of valve design on the correct functioning of the duct. Expressed in simple terms, if the

opening ratio is too large the flow through the duct predominates over the oscillation process, and, in order to ensure sufficient pressure rise during combustion, a return oscillation, or air swing-back action, is necessary.

Under flight conditions an increased pressure level at the valves is obtained, the difference corresponding to the dynamic head. If the flight speed is too high this rise in pressure makes it impossible for the induced fresh charge to be at a pressure lower than the exhaust. This results in a condition similar to that arising from excessive valve-opening ratio, and the duct will fail to function for the same reason. Moreover, if the valve-opening ratio is constant, the compression shock which initiates the combustion becomes weaker as the flight speed increases.

Since automatic inlet valve opening would be impracticable, Professor Schultz-Grunow suggests the adaptation of a cap placed in front of the inlet valves (fig. 55). This cap would reduce the effect of the full dynamic pressure, normally acting directly on the valves, and would also diminish the total drag of the duct. The annular entry slot could be designed in such a way that the fresh air would remain at approximately atmospheric pressure regardless of flight speed. An alternative measure for reducing the losses caused by an incorrect valve-opening ratio, could be effected by a mechanical control of the entry cross-section leading to large valve-opening ratios over shorter periods, instead of small ratios extending over large periods. This would reduce the flow losses at entry, whilst enabling, at the same time, a late and very sudden opening of the valve. A late opening would cause very powerful rarefaction waves F' , since the first rarefaction waves C' would now meet a closed valve. A sudden opening would produce compression waves G' , and both effects would increase the subsequent explosion and the thrust.

Although the application of the method of characteristics, as presented in the above considerations, explains clearly the qualitative details of the gas flow, its use for design or even for a comparison of the performance of various ducts is limited, since it cannot be applied to the detailed analysis of combustion proper. At the outset the flame front

travel has to be assumed, as was done by Professor Schultz-Grunow and Professor Sauer who based their calculations on Schmidt's experimental data.

It is interesting to note that in Germany no research work has been carried out on specific combustion problems which would lead to the calculation of the flame front travel in the duct. Such work would bridge the gap left between the theories of Professor Busemann, Professor Bechert and Schmidt, based on the assumption of sinusoidal oscillations, and the detailed analysis of the propagation of pressure waves as presented by Professor Schultz-Grunow and Professor Sauer.

REFERENCES.

<u>No.</u>	<u>Author.</u>	<u>Title.</u>
/DOCS/2445/ 1/1	Diedrich G.	The Aero-resonator Power Plant of the V.I. Flying Bomb. Volkenrode Report in five parts (Parts I and II only completed in 1946).
/DOCS/2445/ /2	Schmidt P.	Schmidt-duct. Invention, Development and Research. Monograph submitted by the Author, Munich, 1947
/DOCS/2445/ /3	Durr W.	Model Research on Intermittent Ducts. Report on research work carried out at Institute fur Kraftfahrtwesen, Technische Hochschule, Stuttgart, 1946.
/DOCS/2445/ /4	Schmidding	Documents Nos. PG/11504-PG/11544, NID/24/100/45.
/DOCS/2445/ /5	Brandt R.	Jet Propulsion with Intermittent Combustion. Report on research work carried out at Schmidding Werke and Klockner-Humboldt-Deutz A.G., Ulm, 1946.
/DOCS/2445/ /6	Brandt R.	Detonative Combustion in Pipes. Schmidding Werke Report, Schmeideberg, 1945.
/DOCS/2445/ /7	Brandt R.	Unsteady Flow Process in a pipe. Report under preparation at Ulm.
/DOCS/2445/ /8	Busemann A.	Report on Paul Schmidt Impulsive Duct. Volkenrode Report No. F.B. 530, 1936.
/DOCS/2445/ /9	Guderley G.	Intermittent Jet Propulsion with Compressible Charge. Volkenrode Report No. M67139g. Kdos. Braunschweig, 1939.
/DOCS/2445/ /10	Bechert K. and Marx H.	A note on the Theoretical Description of the Process in Schmidt-duct. Report of the Institute Theoretical Physics, Giessen University, No. G. 20/43g. Kdos. Giessen, 1943.
/DOCS/2445/ /11	Hummel E.	Experiments to increase the Performance and Reliability of the V.I. Impulsive Duct. R. & T. 665.

REFERENCES.

<u>Ref. No.</u>	<u>Author.</u>	<u>Title.</u>
BIOS/DOCS/2445/ 28571/1	Diedrich G.	The Aero-resonator Power Plant of the V.I. Flying Bomb. Volkenrode Report in five parts (Parts I and II only completed in 1946).
BIOS/DOCS/2445/ 2857/2	Schmidt P.	Schmidt-duct. Invention, Development and Research. Monograph submitted by the Author. Munich, 1947
BIOS/DOCS/2445/ 2857/3	Durr W.	Model Research on Intermittent Ducts. Report on research work carried out at Institut für Kraftfahrtwesen, Technische Hochschule, Stuttgart, 1946.
BIOS/DOCS/2445/ 2857/4	Schmidding	Documents Nos. PG/11504-PG/11544, NID/24/100
BIOS/DOCS/2445/ 2857/5	Brandt R.	Jet Propulsion with Intermittent Combustion. Report on research work carried out at Schmidt Werke and Klockner-Humboldt-Deutz A.G., Ulm,
BIOS/DOCS/2445/ 2857/6	Brandt R.	Detonative Combustion in Pipes. Schmidding Werke Report, Schmeideberg, 1945.
BIOS/DOCS/2445/ 2857/7	Brandt R.	Unsteady Flow Process in a pipe. Report on preparation at Ulm.
BIOS/DOCS/2445/ 2857/8	Busemann A.	Report on Paul Schmidt Impulsive Duct. Volkenrode Report No. F.B. 530, 1936.
BIOS/DOCS/2445/ 2857/9	Guderley G.	Intermittent Jet Propulsion with Compressible Charge. Volkenrode Report No. M67139g. Kdo Braunschweig, 1939.
BIOS/DOCS/2445/ 2857/10	Bechert K. and Marx H.	A note on the Theoretical Description of the Process in Schmidt-duct. Report of the Institute Theoretical Physics, Giessen University, No. G. 20/43g. Kdos. Giessen, 1945.
BIOS/DOCS/2445/ 2857/11	Hummel E.	Experiments to increase the Performance and Reliability of the V.I. Impulsive Duct. R. & T. 665.

Ref. No.

BIOS/DOCS/2445/ 2857/12	Hummel E.	Investigation of the Ponderomotoric Effect of of Oscillating Air Columns. R. & T. 662.
BIOS/DOCS/2445/ 2857/13	Sauer R.	The Theory of Impulsive Ducts, Parts 1 and 2. Volkenrode Report No. F.B. 1864 of 1943.
BIOS/DOCS/2445/ 2857/14	Schultz- Grunow F.	Gasdynamic Investigation of Impulsive Ducts Part 1 and 2. Volkenrode Report No. F.B. 201
BIOS/DOCS/2445/ 2857/15	Schultz- Grunow F.	Flow Phenomena in an Impulsive Duct. Interim Volkenrode Report 1946.

All documents may be inspected at the Board of Trade, Technical
Information and Document Unit, German Division, 38/46, Cadogan Square,
London, S.W.1.

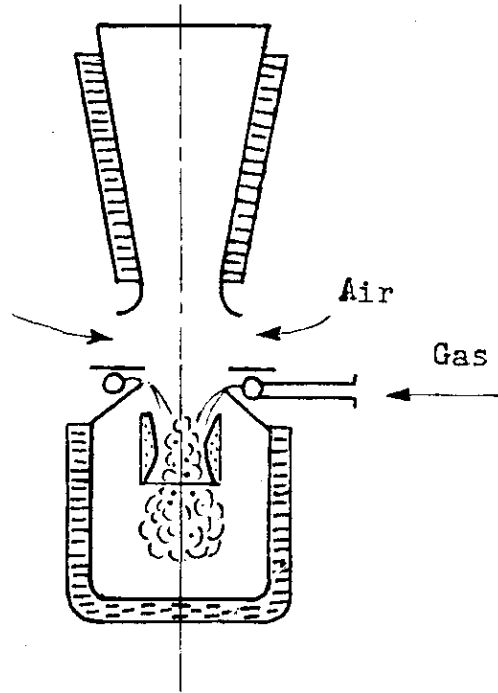


Fig.1. Rheinst evaporation aero-resonator (1930).

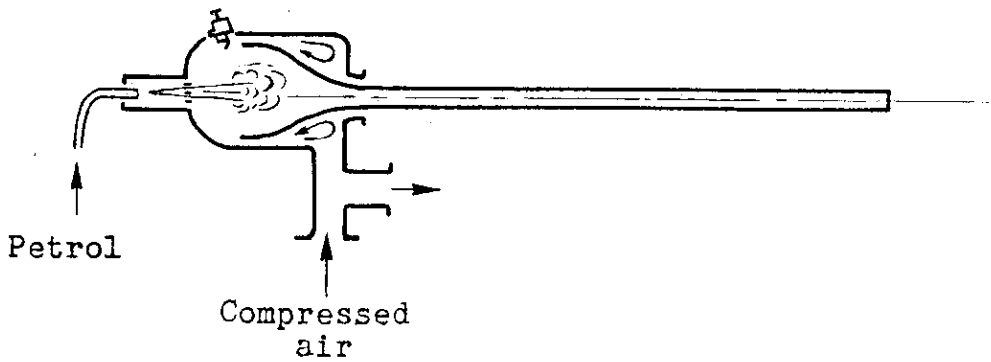


Fig.2. Diedrich/Argus resonator burner (1939)

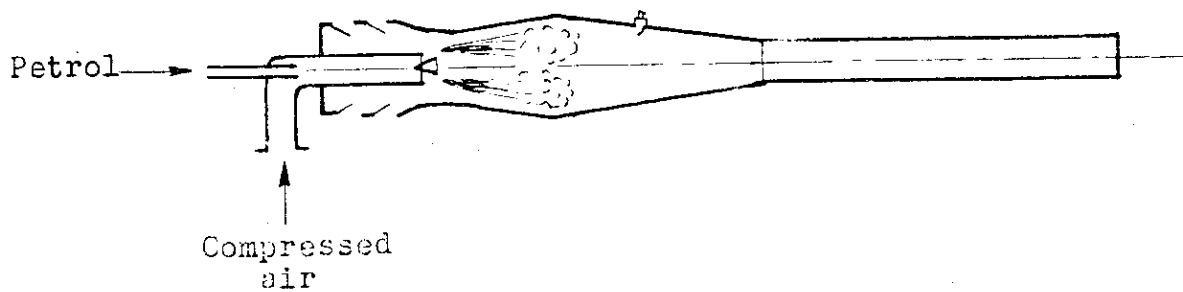


Fig.3. Argus non-resonator burner (1940).

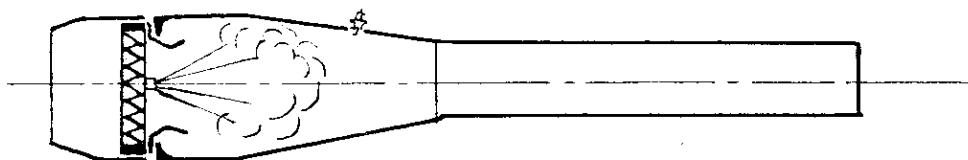


Fig.4. Argus aero-resonator (1940).

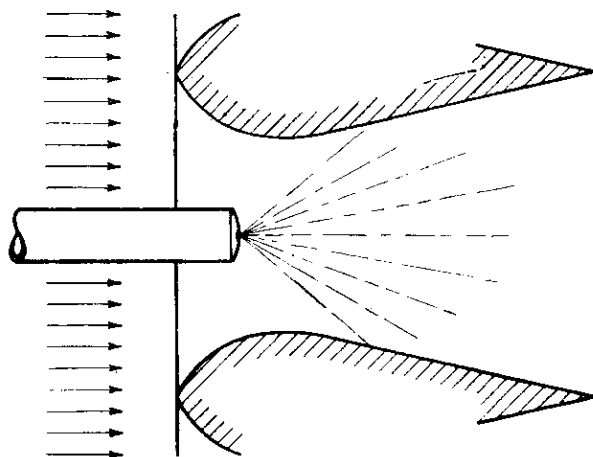


Fig.5. Diedrich suction fuel mixing device.

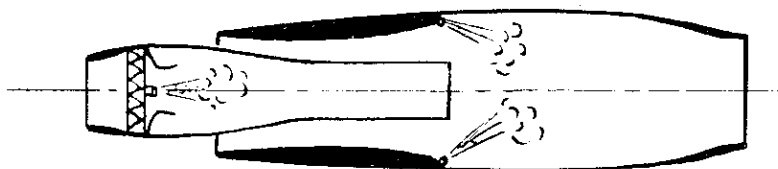


Fig.6. Diedrich aero-resonator combined with the Lorin propulsive duct(1943).

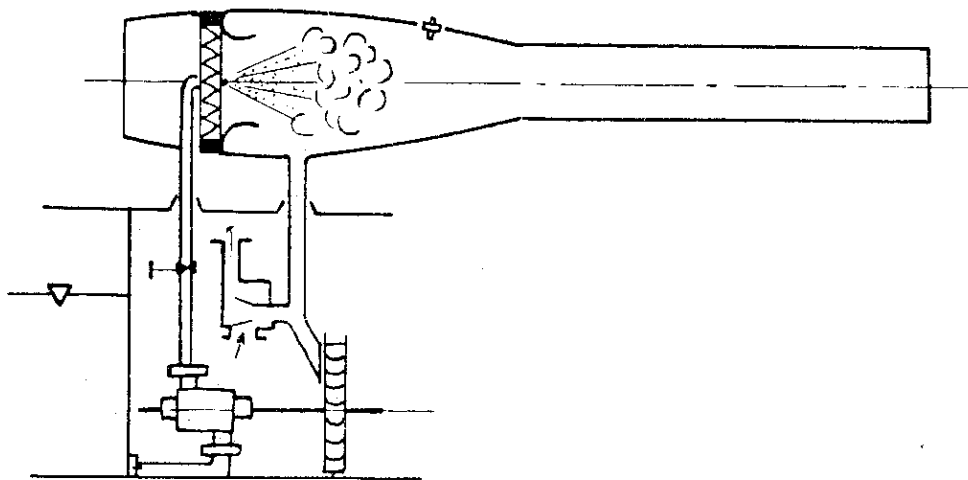


Fig.7. Diedrich aero-resonator with an auxiliary turbine (1944/45).

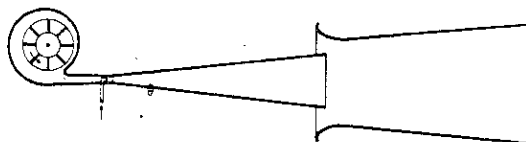


Fig.8. Schmidt patent of 1929.

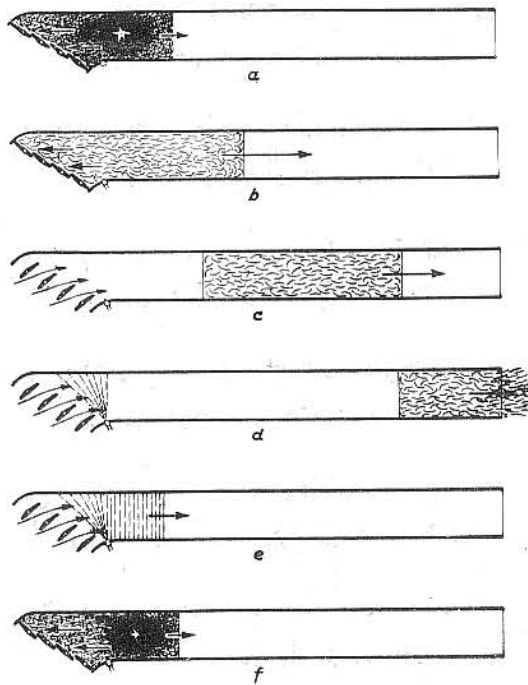


Fig.9. Schmidt patent of 1930.
(German Patent Nr.523655)

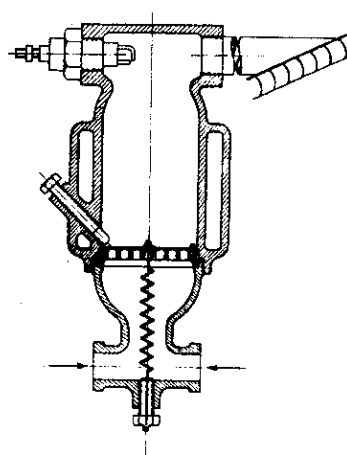


Fig.10. Karavodine combustion chamber (1910).

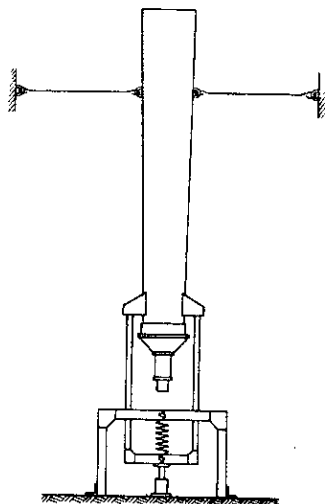


Fig.11. SR500 on the test bench (Schmidt).

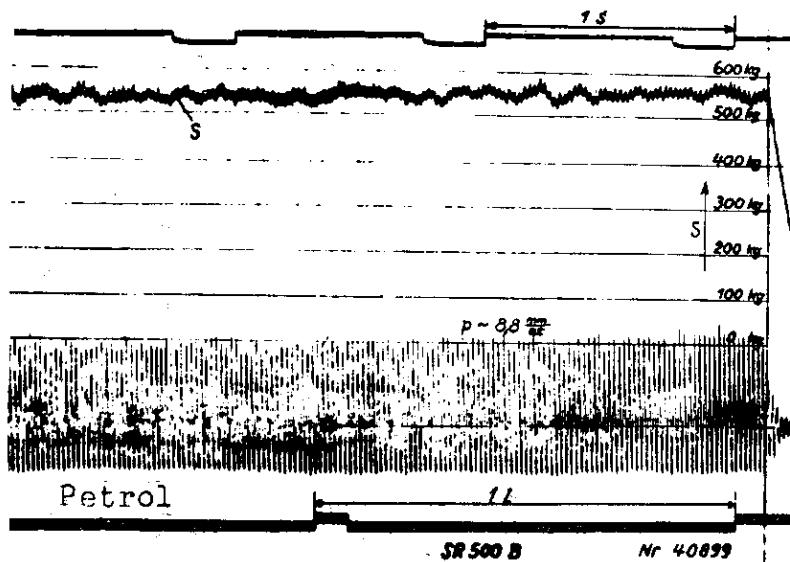


Fig.12. Results of test bench measurements of SR500 (Schmidt).

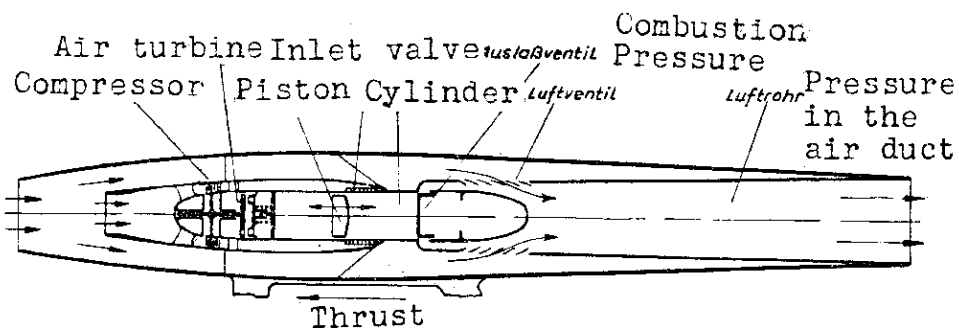


Fig.13. Schmidt engine

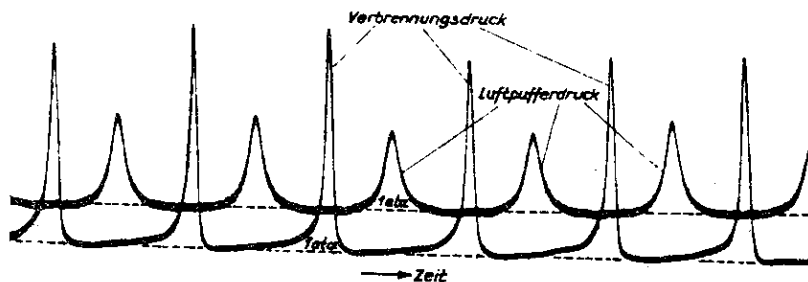


Fig.14. Pressure changes in the combustion chamber and in the air duct of Schmidt engine (Schmidt).

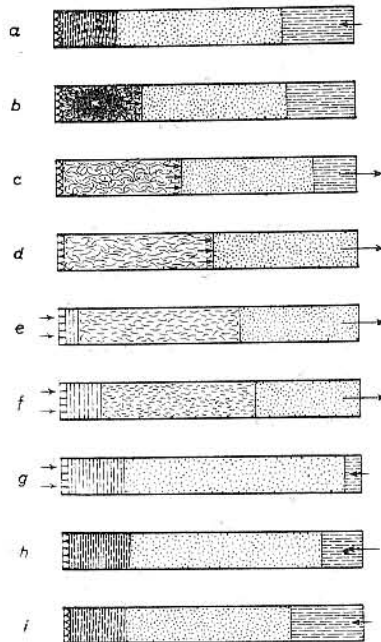


Fig.15. Working cycle of impulsive duct
(Schmidt 1944).



Fig.16. Schmidt mouth-organ inlet valve
(exploded view).

Intermittent jets
of fuel mixture

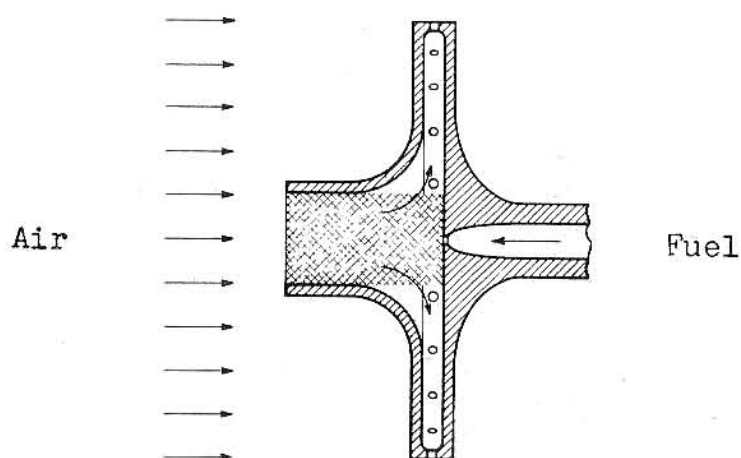


Fig.17. Schmidt fuel mixer.

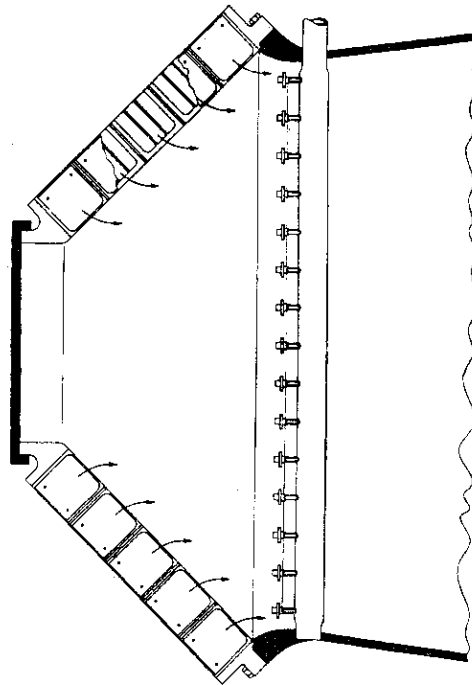


Fig.18. Intake of SR500 showing inlet valves and fuel mixers (Schmidt).

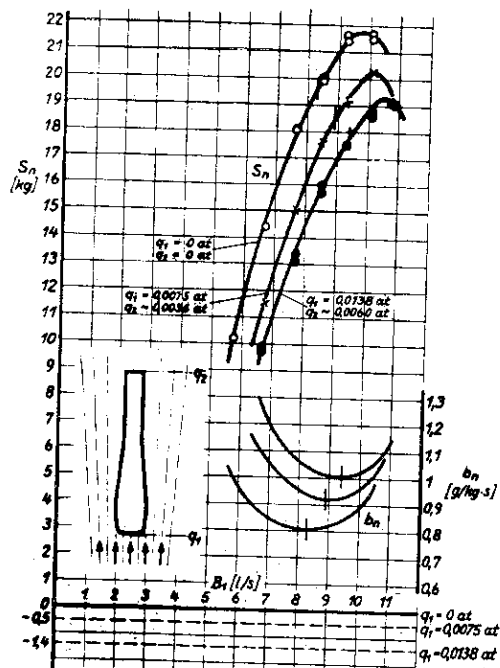


Fig.19. Test bench results of SR100 (Schmidt).

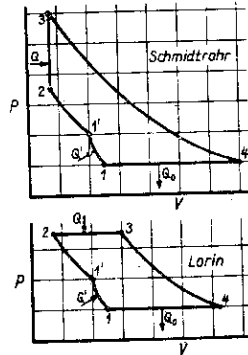


Fig.20. Theoretical cycles of impulsive and propulsive ducts (Schmidt).

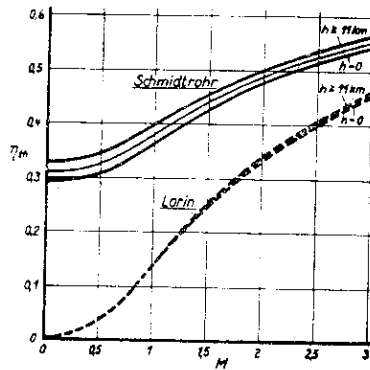


Fig.21. Comparison of thermal efficiencies of impulsive and propulsive duct (Schmidt).

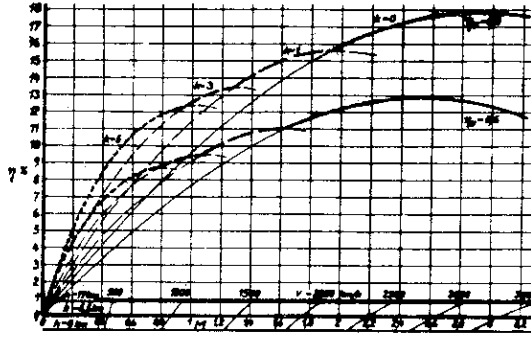


Fig.22. Theoretical overall efficiency of impulsive duct as a function of flight velocity (V or M), air excess ratio (k), and combustion efficiency (η_g) (Schmidt)

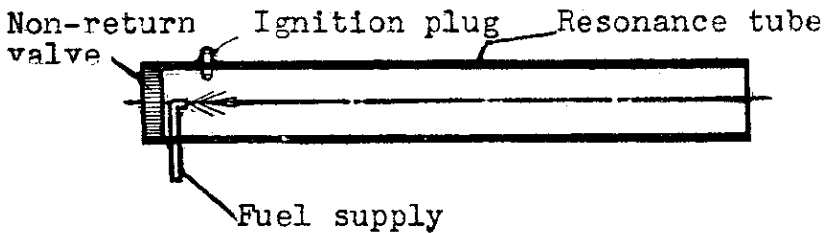


Fig.23. Simple impulsive duct (Durr).

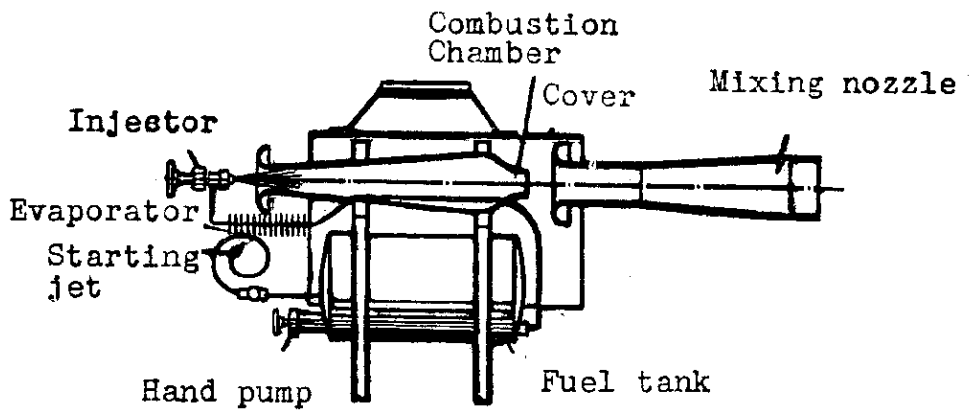


Fig.24. Small heat generator (Durr).

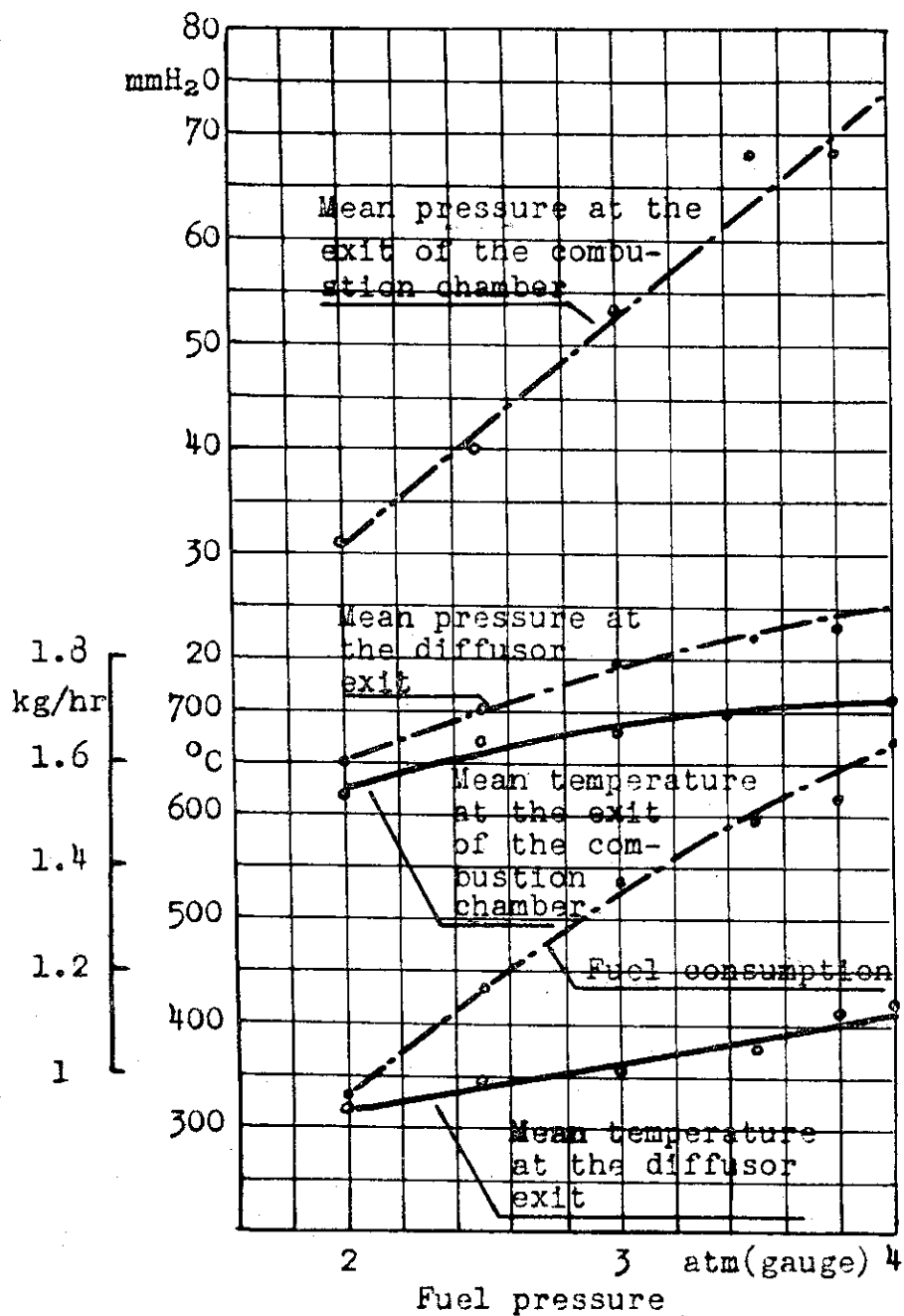


Fig.25. Experimental results of small heat generator.(Durr).

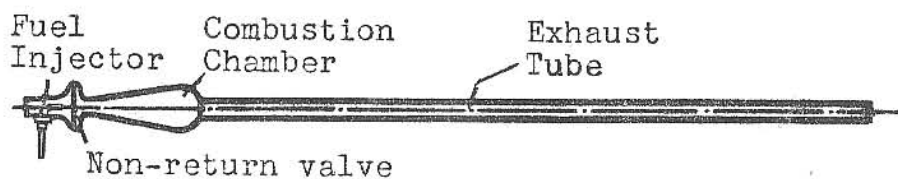


Fig.26. Lay-out of the hot-gas blower (Durr).

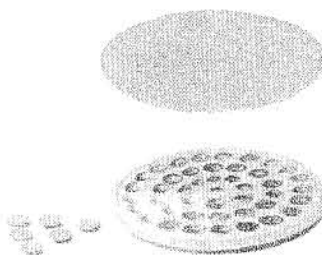


Fig.27. Automatic inlet valve of the hot-gas blower.

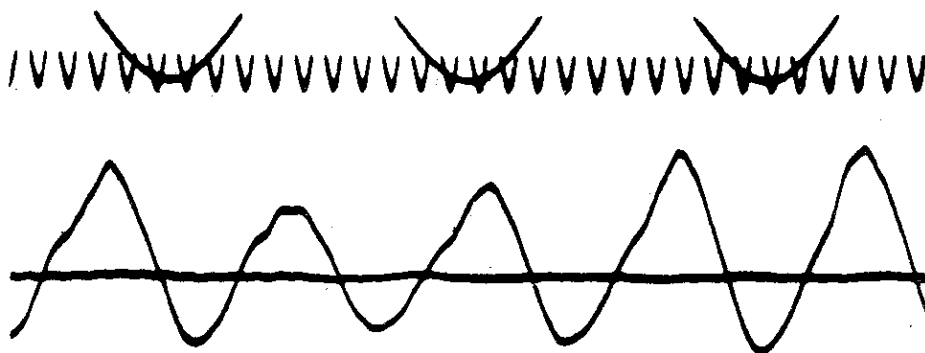


Fig.28. Pressure change in the combustion chamber of a hot-gas blower with the resonance tube 1300 mm long (Durr).

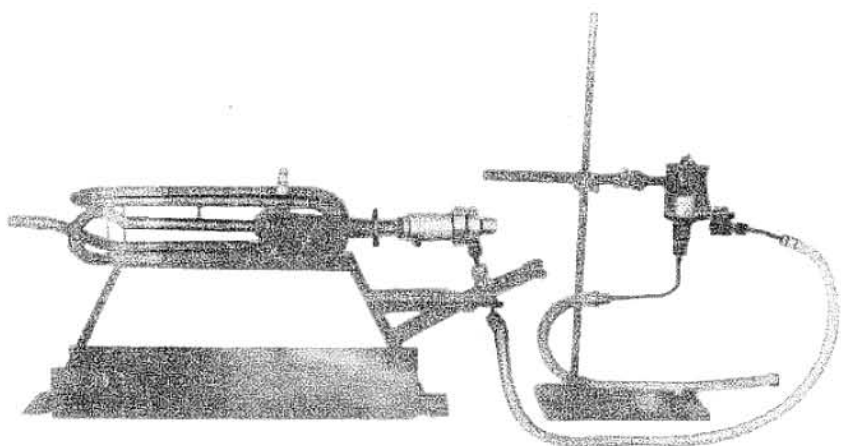


Fig.29. Resonance tube of a hot-gas blower.
13mm inside diameter. (Durr).

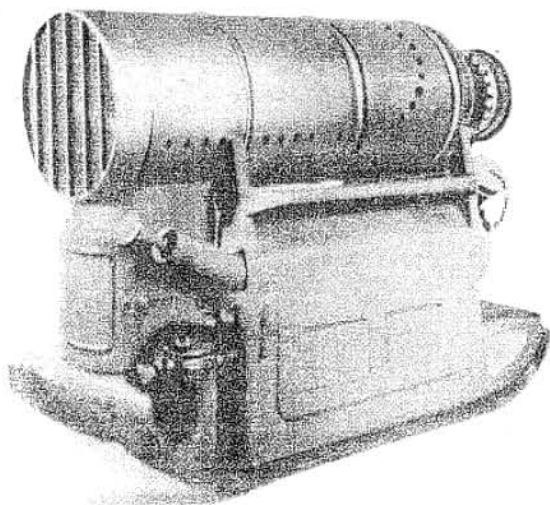


Fig.30 Hot-gas blower manufactured by Kärcher.
Heat output: 30000 kcal/hr.

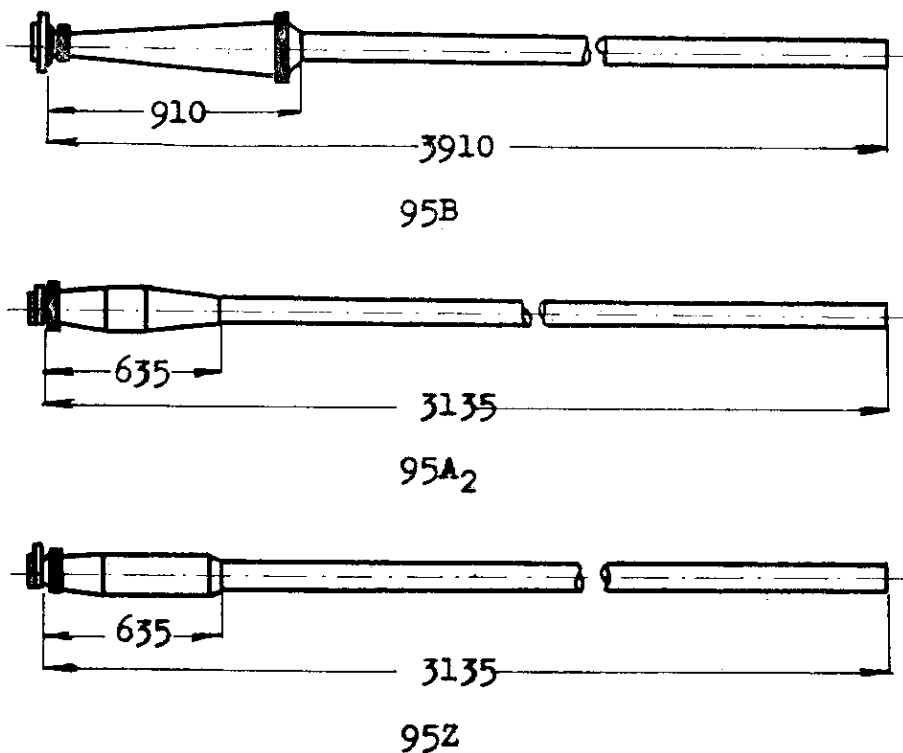


Fig.31. Three main types of model ducts investigated at Prof.Kamm Institute.(Dürr)

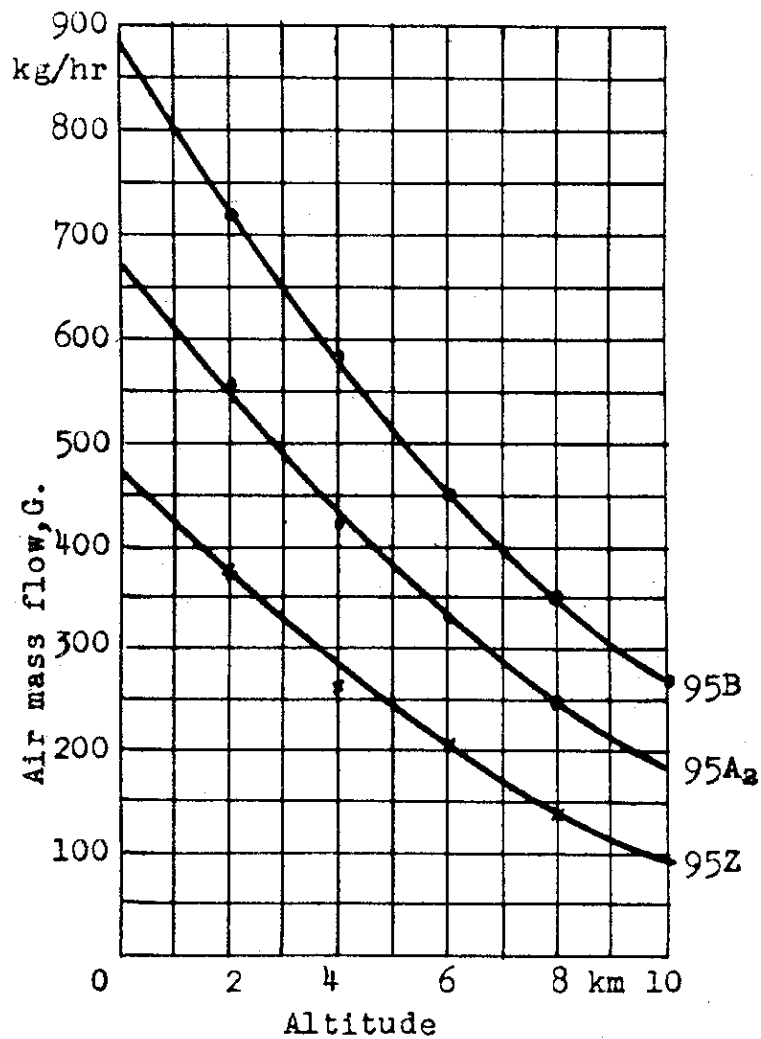


Fig.32. Air mass flow through three model ducts at ram pressure of 600mm water.(Durr).

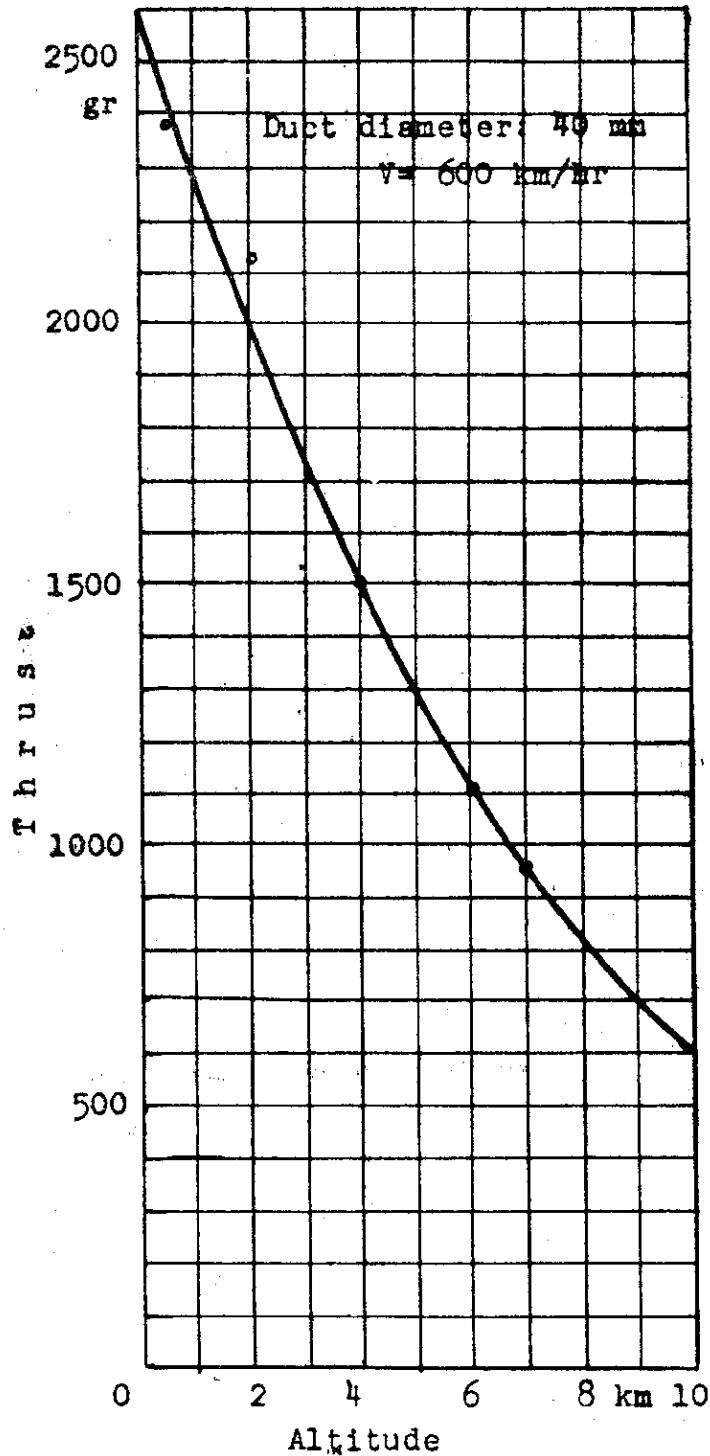


Fig.33. Decrease of thrust with altitude
(Durr)

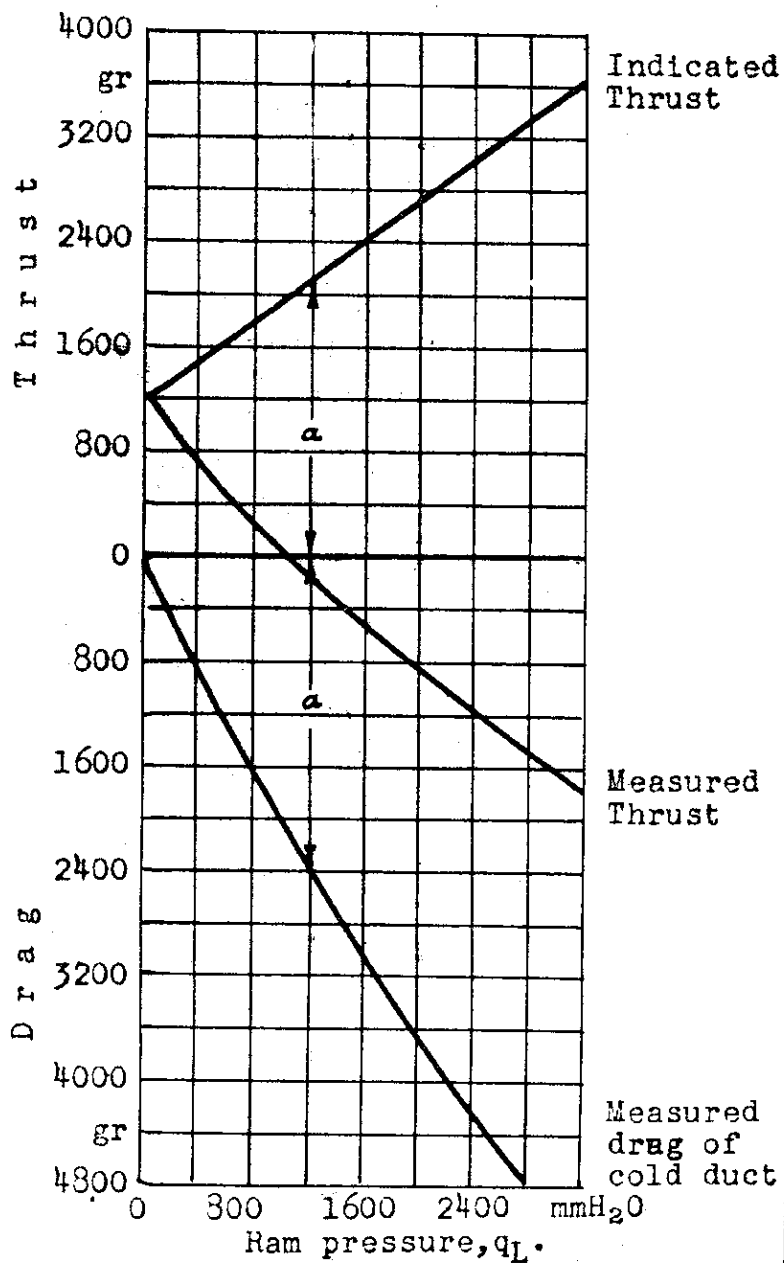


Fig. 34. Evaluation of indicated thrust. (Durr)

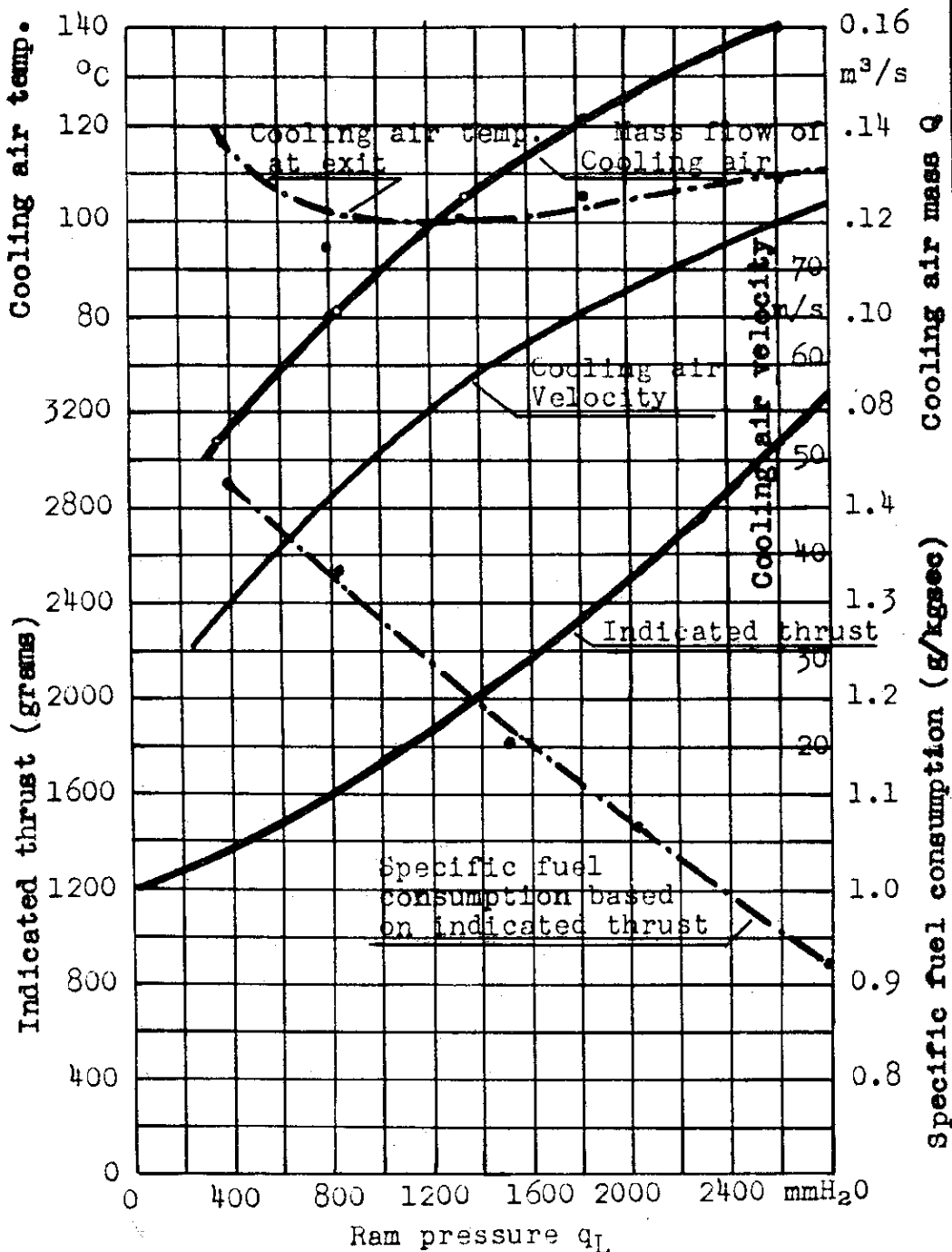
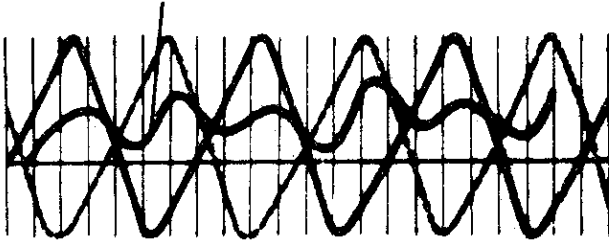


Fig.35. Test bench results of a model duct.
(40mm diameter)



Fig.36. Best method of mounting the impulsive duct on a flying body.(Durr).

Mean thrust



Mean thrust

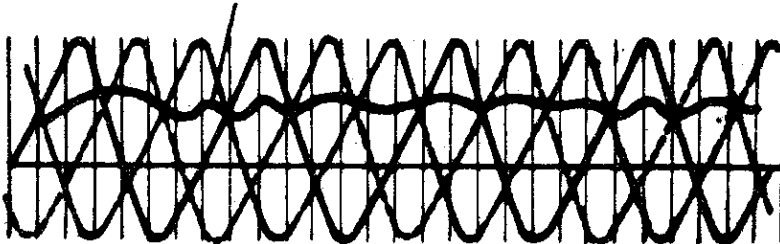


Fig. 37. Theoretical change of thrust of two(upper graph) and three(lower graph) impulsive ducts coupled together.(Durr).

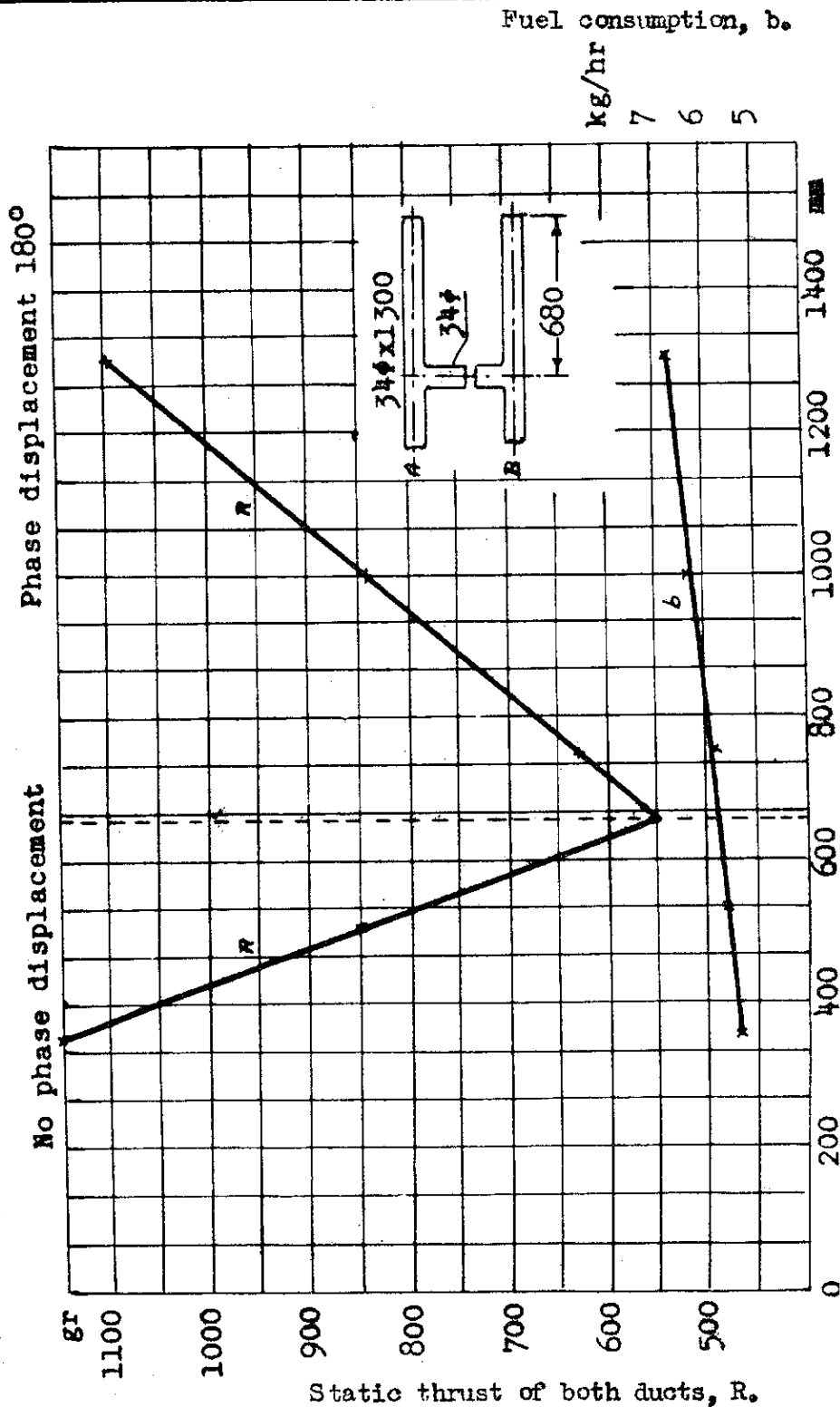
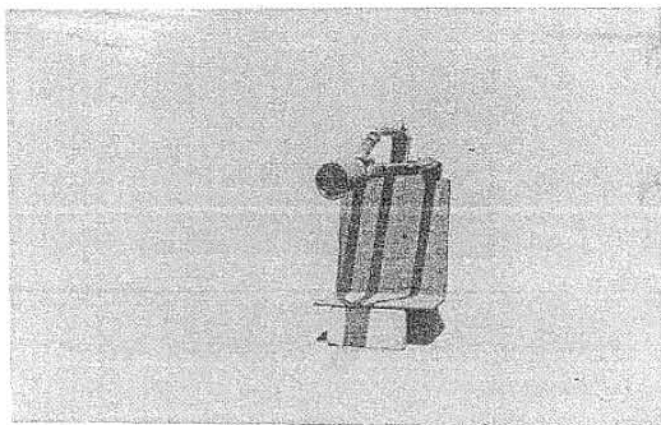
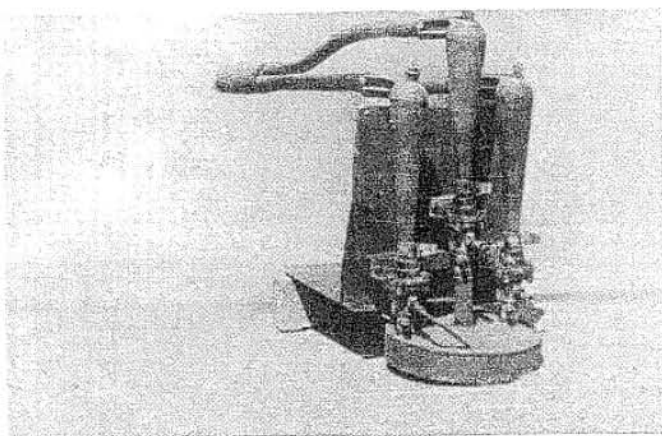
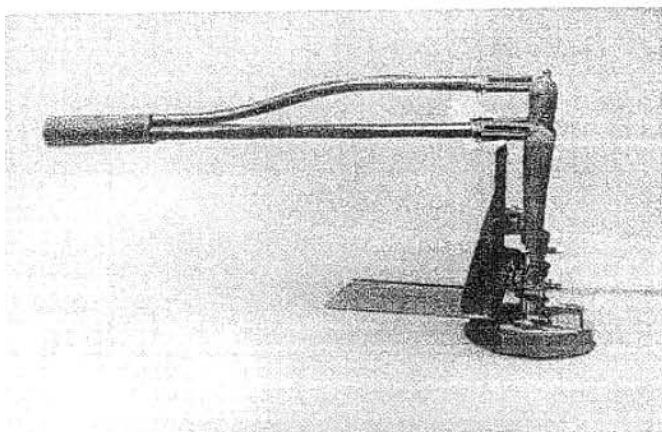
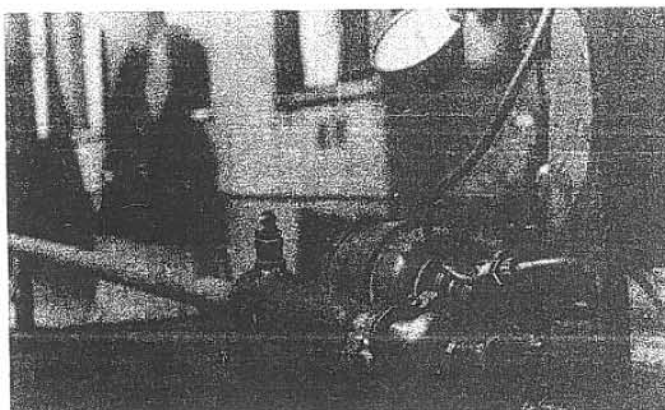
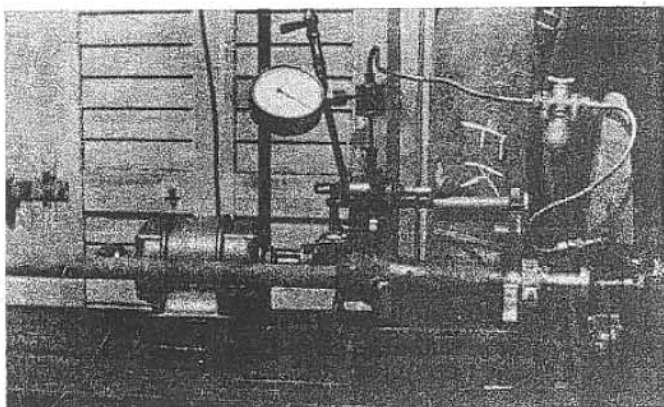
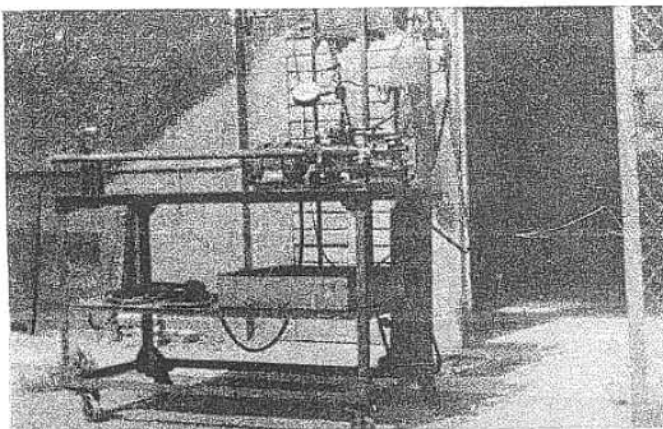


Fig. 38. The dependence of thrust and fuel consumption on the length of the cross-duct. (Durr).



Figs.39-41. Three-duct unit at Prof.Kamm Institute.



Figs.42-44. Experimental set-up at Prof.Kamm Institute.
-53-

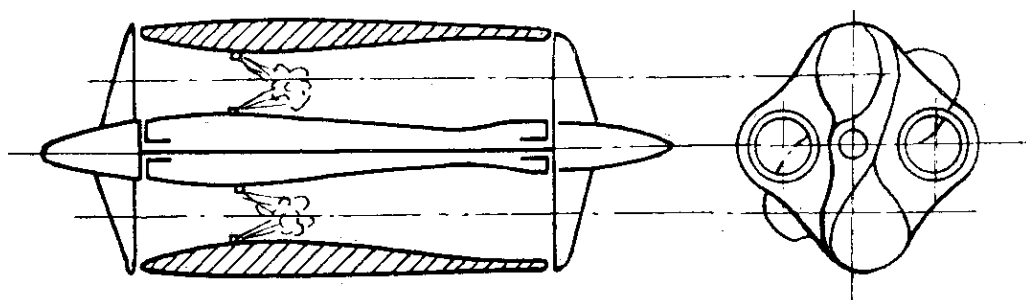


Fig.45. Stipa patent (Italy,1940).

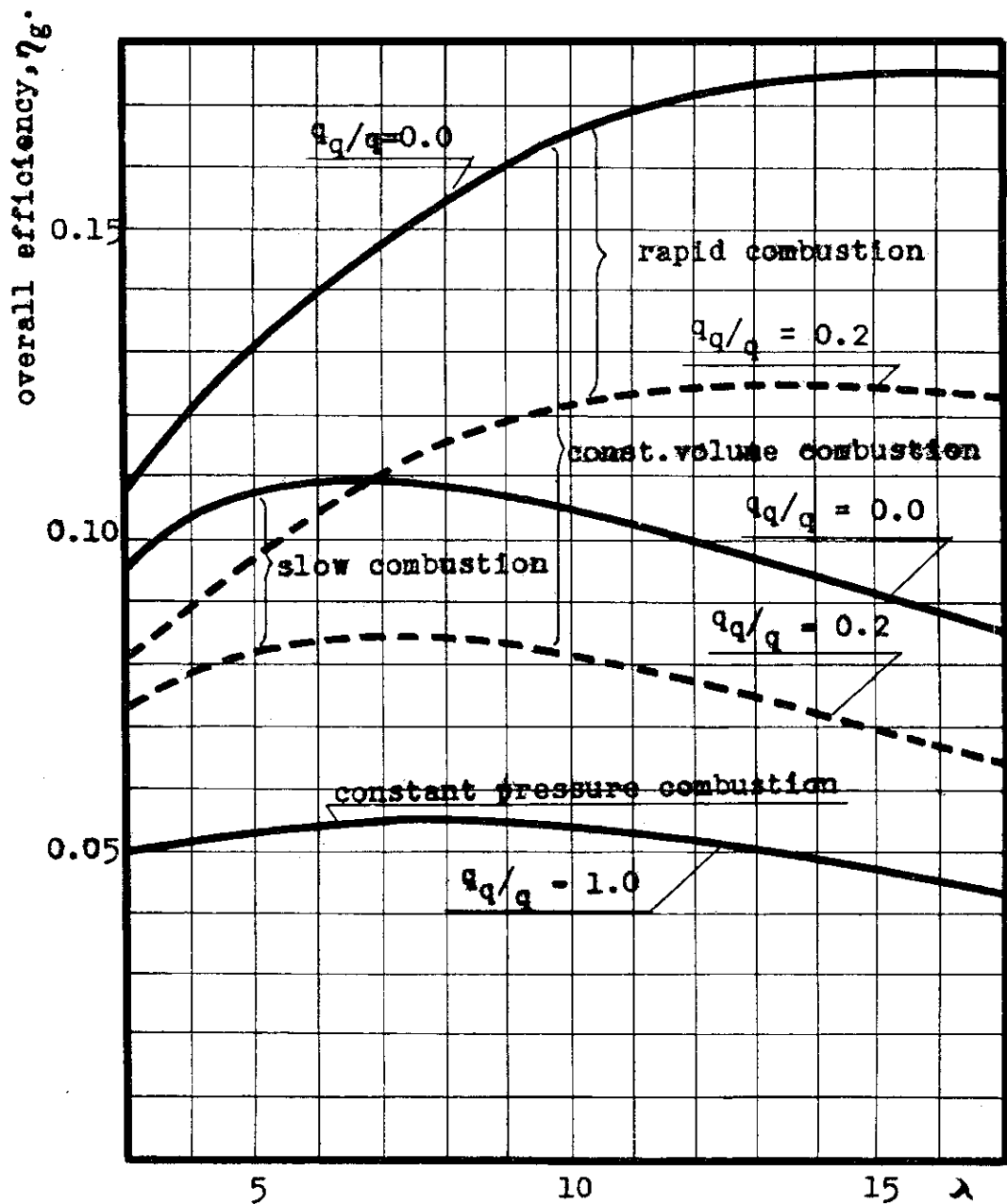


Fig-46. Overall efficiency, η_g , of a duct as a function of air-excess ratio, λ , evaluated for the following three cases:

1. constant pressure combustion
 2. slow constant volume combustion
 3. rapid constant volume combustion
- Assumed flight velocity $V = 250$ m/sec. (Brandt).

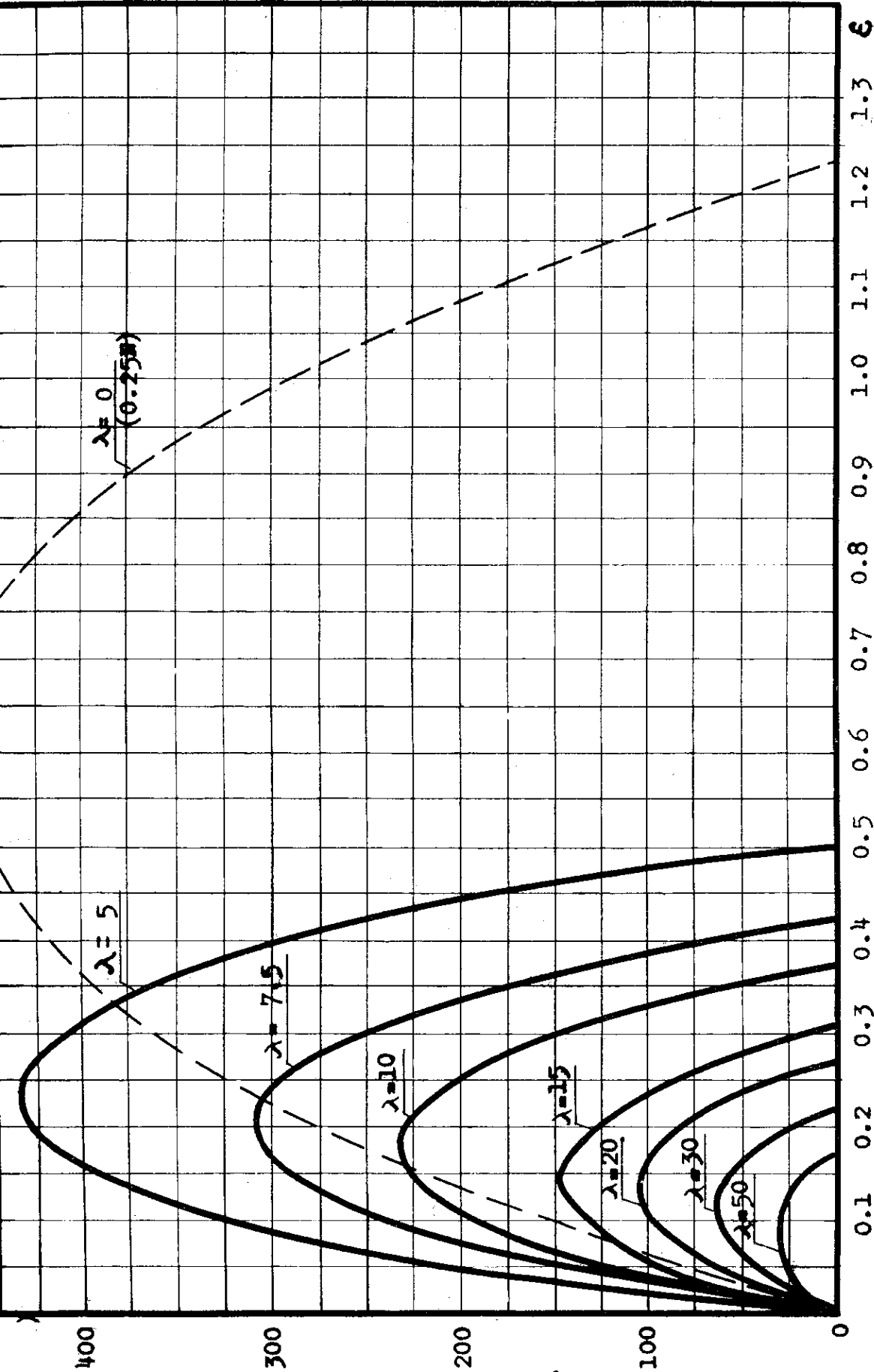


Fig. 47. Horse power developed in Schmidt engine as a function of the ratio of flight velocity to the relative velocity of exhaust gases, $\epsilon = V/V_0$, for different values of the ratio of induced air to the fuel mixture, λ . (Busemann).

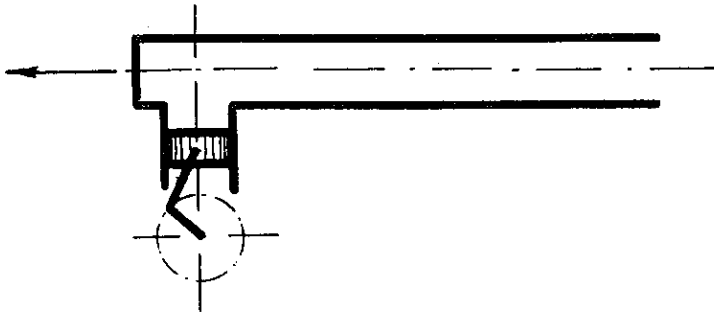


Fig. 48. Dr. Hummel experimental arrangement for the study of the "ponderometric" effect of oscillating gas columns.

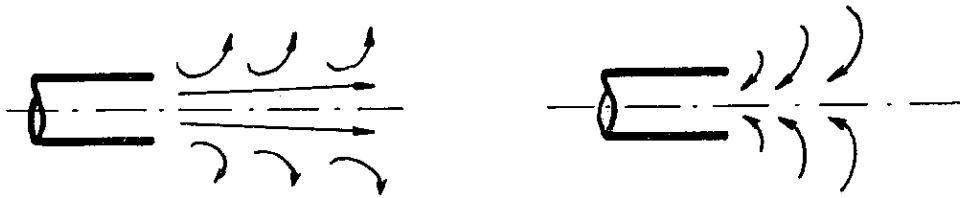


Fig. 49. The process of efflux and influx of the oscillating gas column in an open pipe. (Lutz)

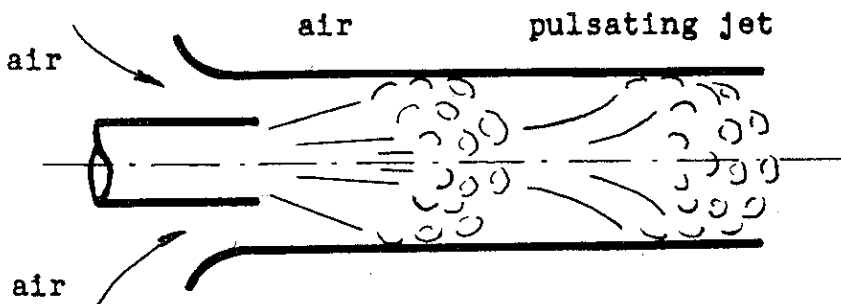
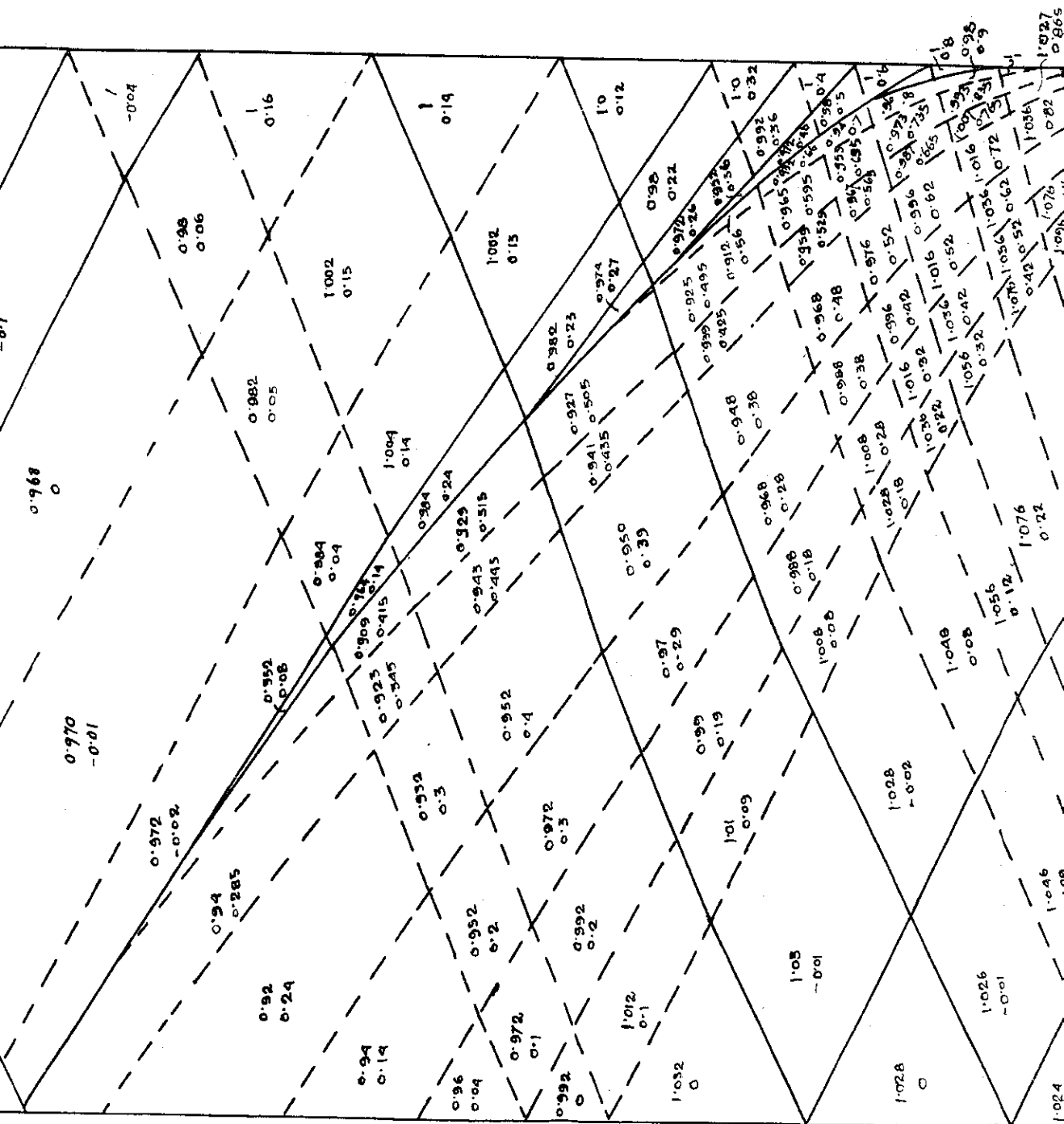
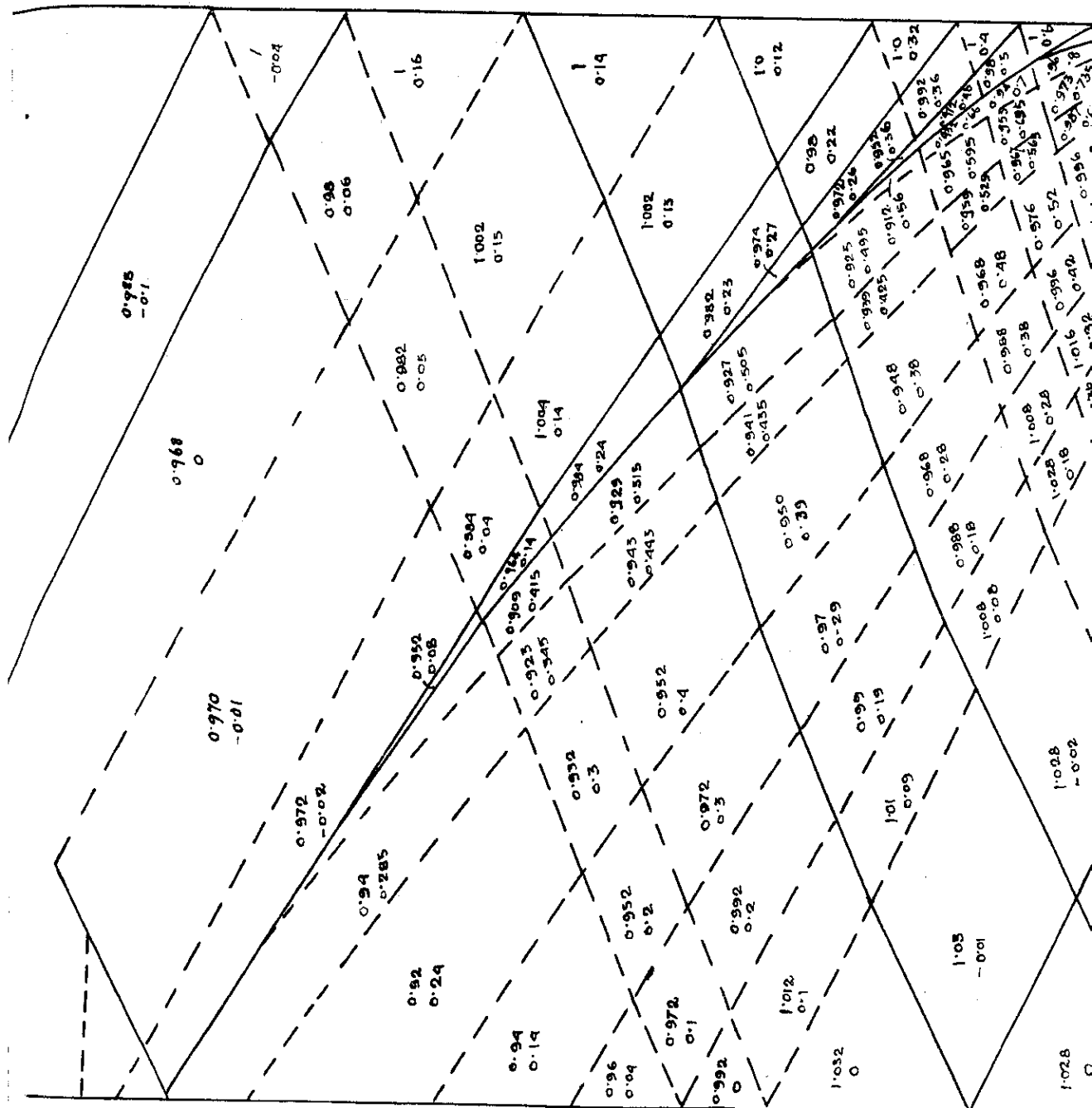
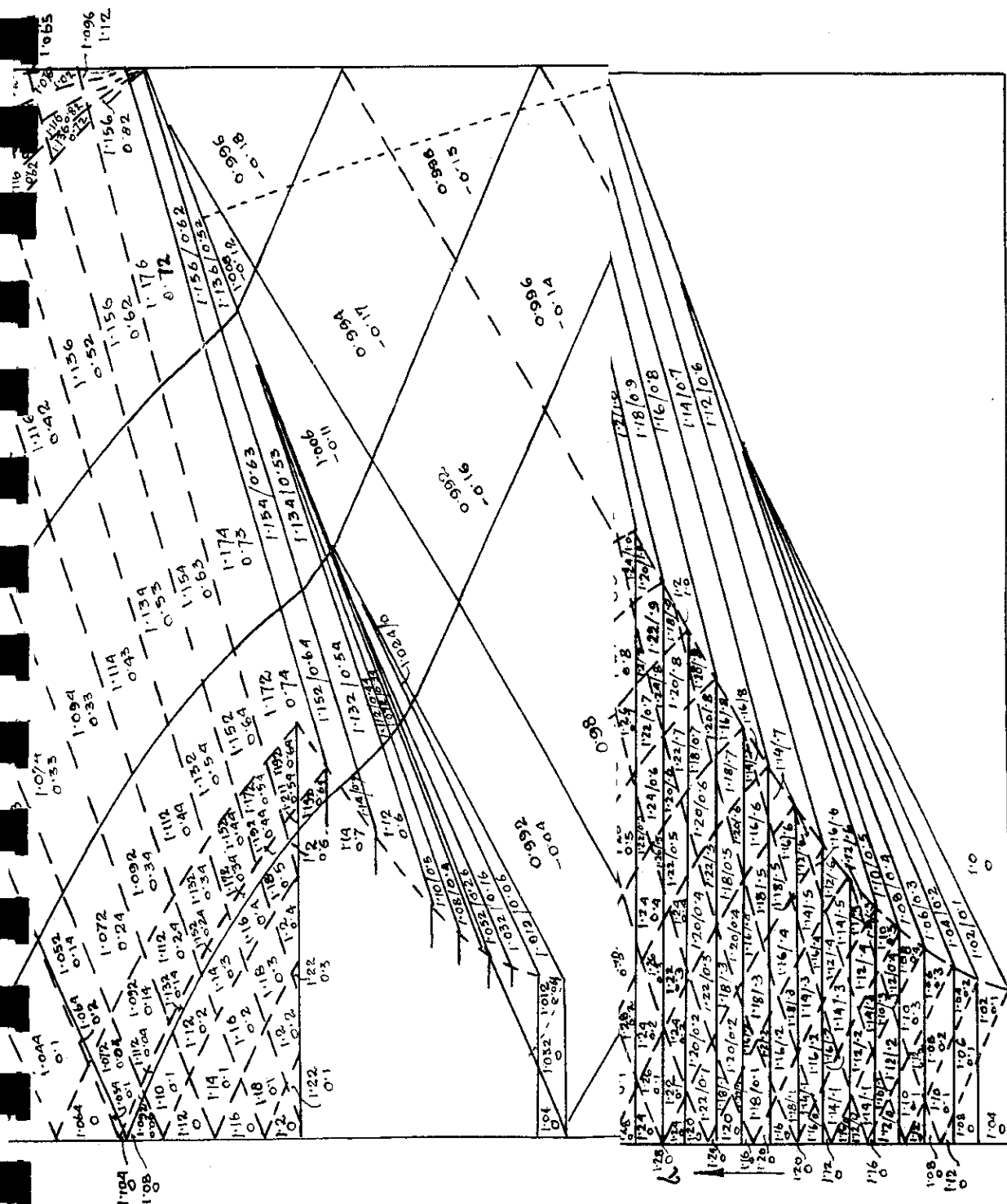


Fig. 50. Thrust augmentation of a pulsating jet. (Lutz).







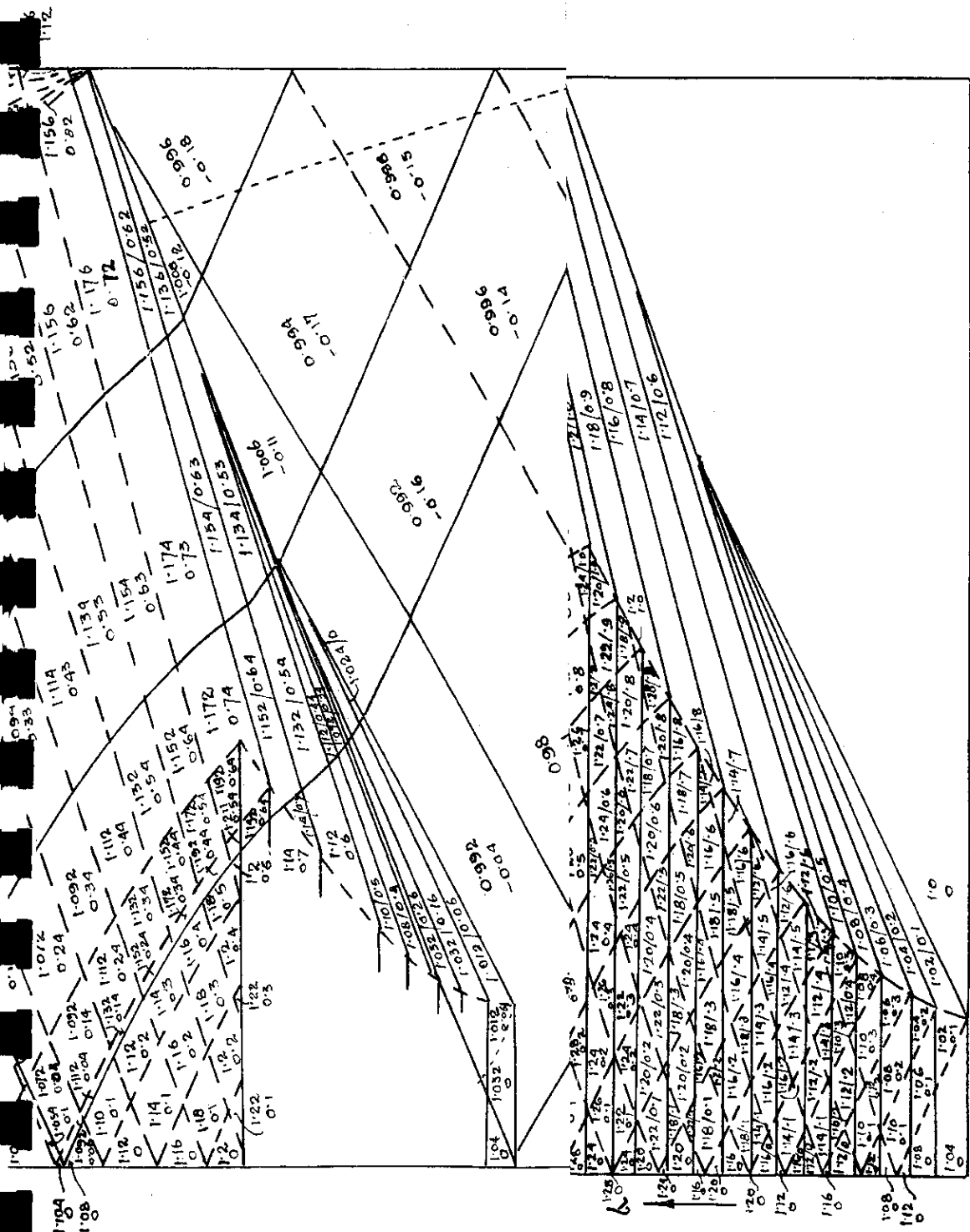
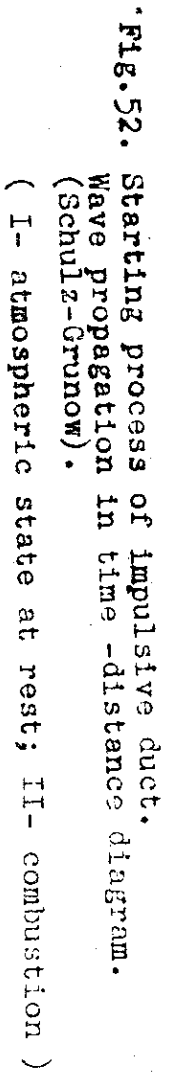


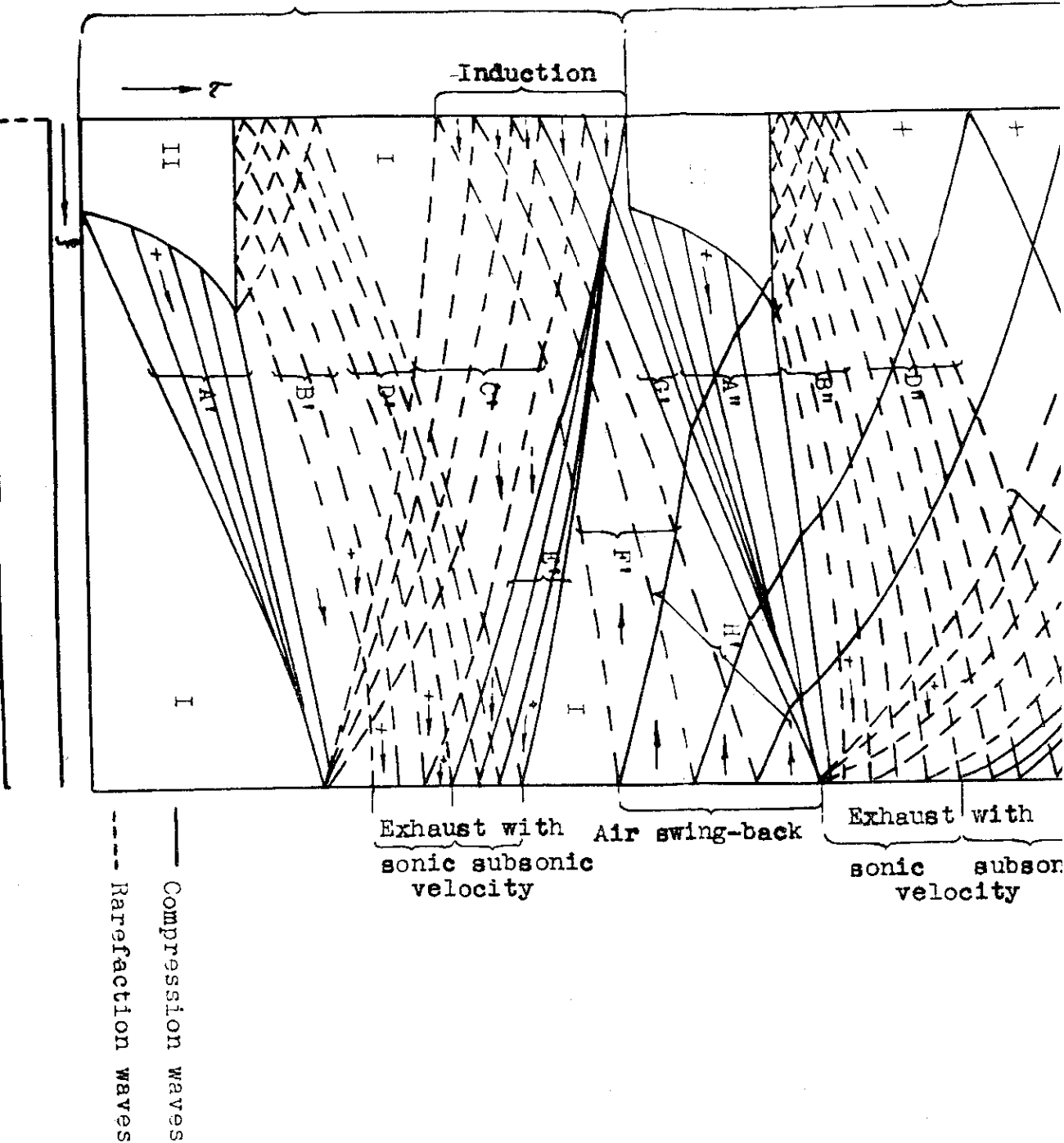
Fig.51. Construction of wave propagation in the duct. (Schulz-Grunow).

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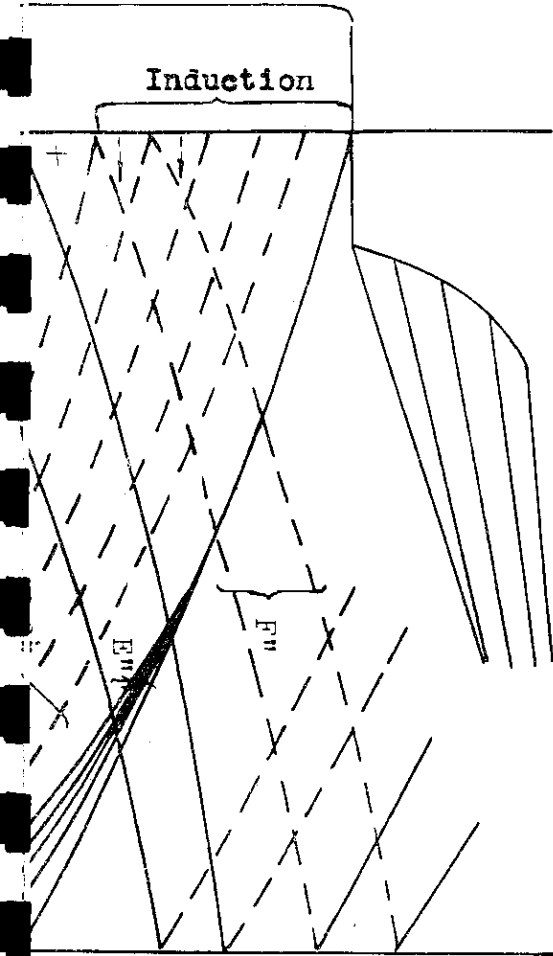
First working cycle

Second working cy



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Induction



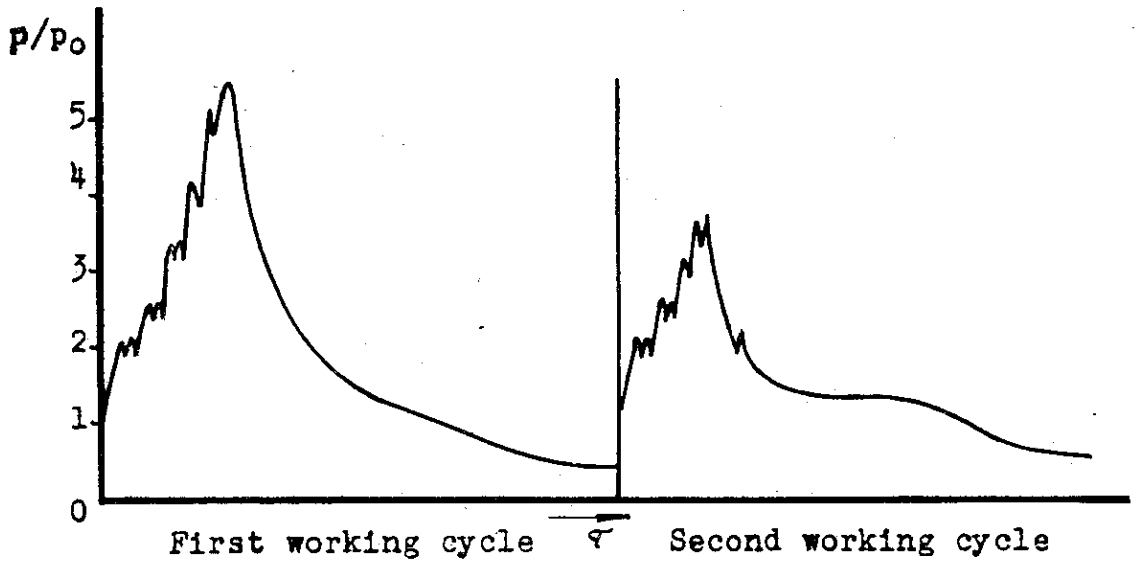


Fig. 53. Theoretical pressure variation at the front end of the duct (Schulz-Grunow)

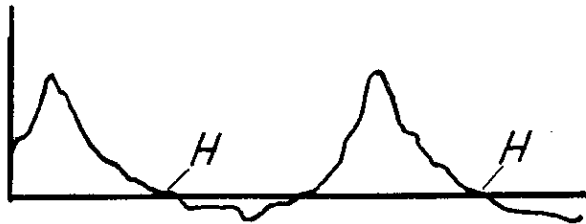


Fig. 54. Indicated pressure at the front end. Experimental diagram of P. Schmidt. (Schulz-Grunow)

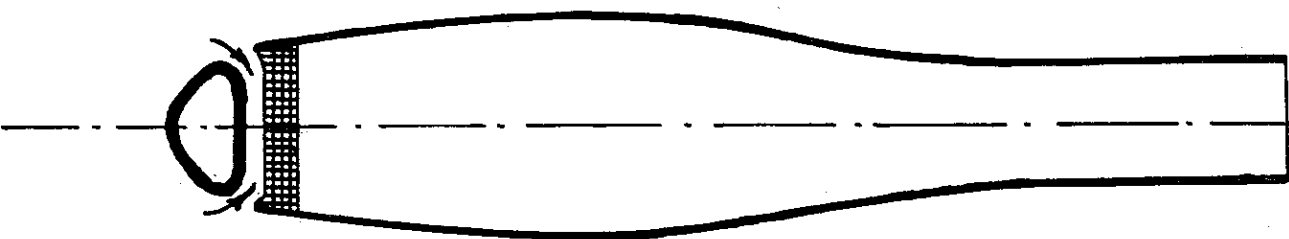


Fig.55. Impulsive duct with nose-cap for reducing the effects of dynamic pressure at valves.
(Schulz-Grunow)