Dec. 4, 1934.

H. HOLZWARTH

1,982,665

EXPLOSION TURBINE

Filed April 19, 1929

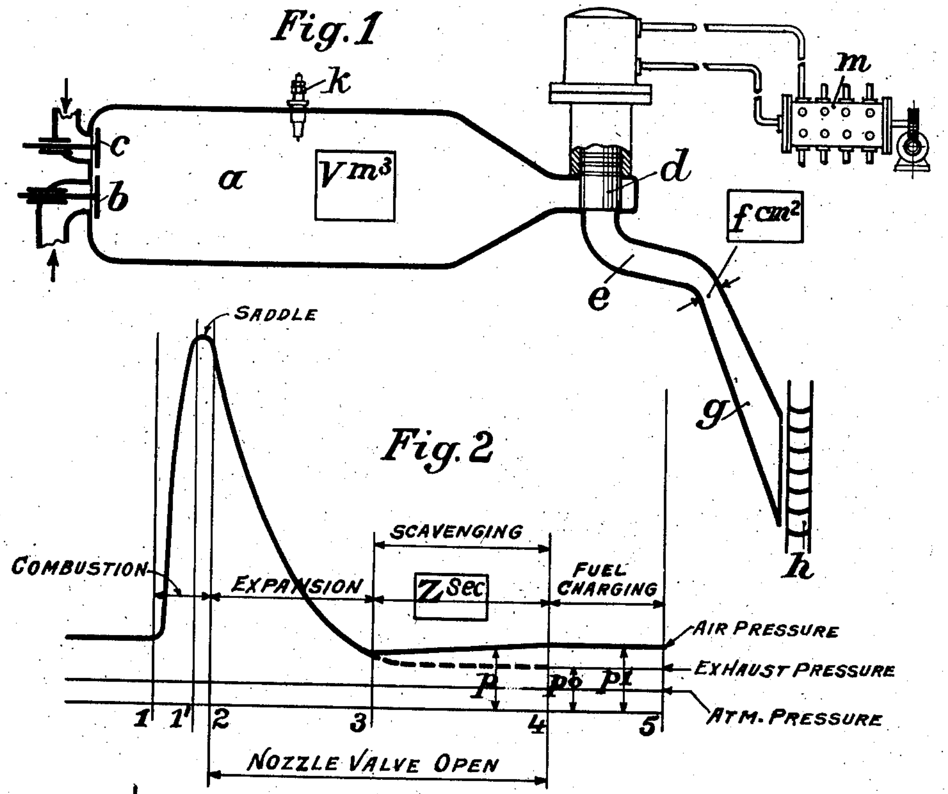
Fig. 1

Fig. 2

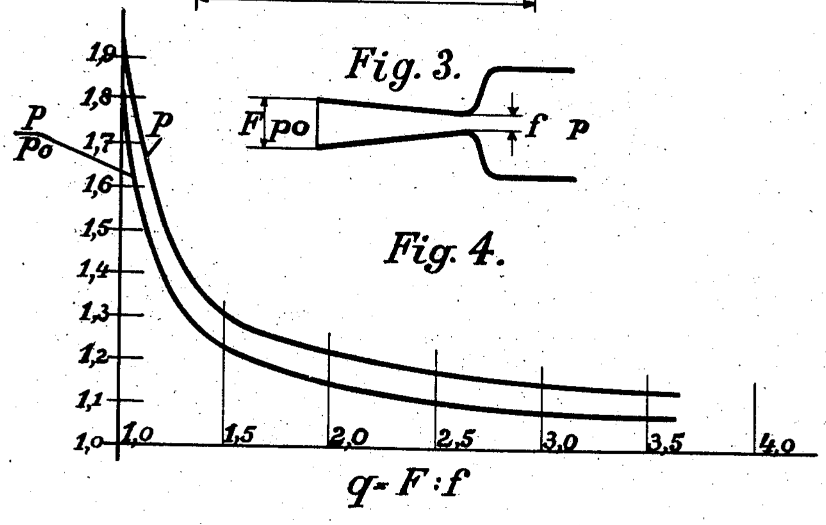
Fig. 3.

Fig. 4.

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Patented Dec. 4, 1934 **1,982,665**

UNITED STATES PATENT OFFICE

1,982,665

EXPLOSION TURBINE

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Application April 19, 1929, Serial No. 356,446
In Germany April 30, 1928

4 Claims. (Cl. 60—41)

My invention relates to explosion turbines of the Holzwarth type wherein charges of fuel and air are periodically fed to one or more explosion chambers associated with the rotor of the turbine to be exploded in such chambers under constant volume and then discharged at predetermined instants into an expansion nozzle which directs the combustion gases against the blades of the rotor, each explosion and expansion being followed by a scavenging period during which the residual explosion gases are driven out of the explosion chamber through the same expansion nozzle; and more particularly to the constructional relationship of certain parts of such turbine whereby a stable and efficient operation of a plant of this type for indefinite periods is obtained.

My present invention has for its primary object the construction of an explosion turbine, of the type referred to, which will be stable in operation, that is, will operate for an indefinite time without difficulty or stoppage from premature ignition. It has for its secondary object the construction of such a turbine which will be not only stable but as efficient as otherwise possible. It is obvious that, whatever may be the degree of efficiency of such an engine, any substantial lack of stability will be fatal to its operation as a whole, and that therefore its construction must be designed first for stability and only secondarily for an efficiency as high as possible under the circumstances. While, therefore, in carrying out my invention, other things being equal, considerations of stability must dominate any relevant constructional detail of the engine, even at the cost of maximum possible efficiency, it is in some cases possible that such a maximum efficiency may nevertheless be obtained. I have found that the relative size of the smallest cross-section of the nozzle through which the residual gases escape as they are expelled from the combustion chamber is an important element of such an engine and largely determines its stability of operation, and as I have already pointed out heretofore in my pending application Serial No. 186,094, the relative size of the smallest cross-section of the nozzle through which the gases expand is an important element in operating such an engine efficiently. As my invention relates to an engine in which both the expanding gases and the scavenged gases escape through the same nozzle, it is obvious that there is a close inter-relation between the factors governing stability and the factors governing efficiency, and that for the proper designing of a commercial engine of this type both sets of factors must be taken into consideration. As already stated, however, the factors making for stable operation must in any event be controlling and the factors making for highest possible efficiency can be permitted to prevail only in so far as they do not interfere with the former set of factors.

As it is usually the primary endeavor of the mechanical engineer so to design an engine as to obtain the highest possible efficiency I will first give a brief description of the features which should be given consideration when designing an engine of this type from the standpoint of highest efficiency, that is, other things being equal, from the standpoint of the avoidance as far as possible of heat losses during the expansion of the gases. It is believed also that in this way the problem which remained even after I had discovered the principles of construction for obtaining highest efficiency will be better understood; it is the primary object of my invention to solve this problem.

In my copending application Serial No. 186,094 filed April 23, 1927, I have disclosed that an extraordinarily large amount of heat, up to 40% and even more of the heat energy of the gases, is lost by the expanding gases in their passage from the explosion chamber to the nozzle, a loss whose magnitude had never before even been suspected, and that such loss, which is due primarily to the whirling of the gases in the nozzle chamber connecting the outlet end of the explosion chamber with the nozzle, can be very greatly reduced by observing the following constructional formula

$$\frac{f}{V}=40 \text{ to } 100$$

where f = the smallest nozzle cross-section measured in square centimeters and V=the volume of the combustion chamber measured in cubic meters, it being assumed that the nozzle valve is as large as practicable and is opened as quickly as possible.

As explained in the above cited application, a nozzle dimensioned in accordance with this formula has a minimum cross-section which is considerably below that recommended by the prior art, and in fact such constructional relationship is quite contrary to the teaching of the prior art which called for a nozzle opening as large as practicable to permit rapid discharge of the gases.

The above constructional relationship is the result of my discovery that it is more important to prevent whirling in the nozzle channel than to discharge the gases in a minimum of time if excessive heat losses in such channel are to be avoided;

and that the prevention of such whirling is effected by reducing the minimum nozzle cross-section to such an extent that upon opening of the nozzle valve (which, as is known, should be opened as quickly as possible), pressure is rapidly built up in the channel as the gases discharge thereinto until it is equal to the pressure prevailing in the combustion chamber thus serving to prevent to a large extent the whirling of the gases, such equality being attained at the cost of only a comparatively small drop in the pressure of the gases from the maximum explosion pressure. In order to advance the instant at which this equality is maintained, I make the nozzle channel leading to the nozzle as small as possible, and in a further development of the idea, I have departed from the teaching of the explosion turbine art and also from the steam turbine art by employing, for each combustion chamber, a single discharge nozzle having a single unobstructed outlet, as disclosed in my copending application Serial No. 186,095, filed April 23, 1927. In this way, for a given total effective area of nozzle outlet, I obtain a nozzle having a much smaller circumferential length than, for instance, a nozzle whose outlet is divided into a number of passageways by vanes or blades but has the same given total effective area. I am thus enabled to construct the nozzle channel between the nozzle valve and the point of minimum cross-section of the nozzle as small as possible, so that the advantages in heat economy obtained by constructing the turbine in accordance with the formula

$$\frac{f}{V}=40 \text{ to } 100$$

may be more completely realized, as with a smaller nozzle channel the pressure is more rapidly built up therein and made equal to that prevailing in the explosion chamber upon opening of the nozzle valve.

I have observed in the operation of a number of explosion turbines built by me in accordance with the rules and formulas available in this art, even those built in accordance with the formula hereinabove explained, that after the turbine has been running for a short time, pre-ignition sets in, whereupon the operation of the turbine becomes unstable and finally ceases. This condition pointed to the fact that a very high temperature, sufficient to ignite an incoming charge, had been reached in the explosion chamber. Both practice and theory have demonstrated that this rise in temperature cannot ordinarily be prevented by pumping more or cooler cooling medium through the cooling jackets with which the explosion chambers are usually provided.

The present invention aims to prevent such pre-ignition and to provide an explosion turbine which is stable in operation and at the same time suffers a minimum of heat losses, so that the efficiency thereof is maintained at a high level.

I have determined that this pre-ignition is due to incomplete scavenging of the combustion chamber of the residual combustion gases, such residual gases progressively raising the explosion temperature until they are sufficiently hot to ignite the incoming charge even though admixed with a large proportion of scavenging air. That the presence of comparatively small amounts of residual gases in each successive fuel and air charge in the explosion chamber could so detrimentally affect the operation of the turbine was hardly to be expected, as explosion engines in general are known to operate satisfactorily with no or only partial scavenging. This undesirable condition can be prevented in accordance with my invention by observing a certain minimum relationship discovered by me, and capable of being expressed mathematically, between certain elements of the explosion turbine and the time allotted to the scavenging portion of the explosion cycle of the combustion chambers. I have found that the duration of the scavenging period is of the highest importance and that the same is organically linked up with the dimensions of certain elements of the explosion turbine, and that this minimum relationship must be adhered to before a turbine stable in operation can be constructed. That this relationship existed was never before known, nor can the mathematical expression thereof be deduced from the hitherto known relationships between the parts of an explosion turbine. This new relationship discovered by me must moreover be observed before advantage can be taken of the optimum relationship

$$\frac{f}{V}=40 \text{ to } 100$$

referred to above.

To aid in a better understanding of my invention, reference is had to the accompanying drawing, in which Fig. 1 is a diagrammatic view of an explosion turbine of the Holzwarth type; Fig. 2 is a diagram of a typical explosion cycle of such turbine; Fig. 3 shows diagrammatically a view of the expansion nozzle, and Fig. 4 is a graph illustrating certain relationships between the air and exhaust pressures and the dimensions of the nozzle.

Fig. 1 shows an explosion chamber *a* of substantially cylindrical form which is periodically charged with a mixture of air and fuel through the valves *b* and *c*, the mixture being exploded therein at predetermined instants by means of a spark plug or other ignition element *k*. After the explosion a nozzle valve *d* is opened and the combustion gases are permitted to escape into the nozzle channel *e* which directs them into an expansion nozzle *g* and they are then discharged against the blades *h* of the turbine rotor. It will be understood that the valves *c*, *b*, and *d* are timed and controlled in any suitable manner, as for instance by a controlling mechanism in the form of a pressure oil distributor *m* shown more in detail in my Patent No. 877,194.

After the explosion and discharge of the gases from the combustion chamber *a*, the latter is scavenged of the residual combustion gases. This scavenging may be effected by means of a stream of scavenging air charged by a separate scavenging valve (not shown), but I prefer to effect such scavenging by means of the air designed to support the combustion of the fuel. To this end, the combustion chamber *a* is made of elongated form, as illustrated, and the nozzle valve *d* kept open during the initial charging period for the combustion air. Due to the elongated form of the chamber this combustion air pushes the residual combustion gases before it in the manner of a piston. The nozzle valve is so timed that it is closed at the moment that the advance portion of such air reaches the outlet end of the combustion chamber. The piston effect may be increased by making the inlet end of the explosion chamber conical as shown in my copending application Ser. No. 376,135, filed July 5, 1929 and in my United States Letters Patent No. 1,810,768. By so employing the charging air to effect scavenging of the chamber, I reduce the time for a complete explosion cycle by the time required to charge a separate stream of scavenging air.

In the design of an explosion turbine which is to have a given capacity it is necessary first to determine the number of explosion cycles that are to take place in each combustion chamber per minute. It is, of course, generally desirable to have as many explosions per minute as possible in order to increase the capacity of the machine and thus increase the power output per ton of weight.

In addition to the number of cycles to be employed per minute, it is necessary to determine also the size of the combustion chamber, the size of the nozzle valve, the minimum cross-sectional area of the nozzle, and the various pressure relations to be employed. The considerations involved in the dimensioning of these several elements are not simple and are not of a purely mathematical nature. These considerations include the following:

1. The pressure at the outlet end of the nozzle.
2. The pressure of the scavenging air.
3. The expansion ratio of the nozzle (a De Laval nozzle is employed).
4. The minimum cross-sectional area of the nozzle.
5. The form or shape of the combustion chamber, its ratio of length to diameter, and the appendages upon its inlet and outlet ends.
6. The degree of whirling of the residual combustion gases with the incoming charge of scavenging air.
7. The extent of heat exchange between the combustion gases and the walls of the combustion chamber, the nozzle channel and the nozzle.
8. The temperature of the combustion gases.
9. The permissible amount of residual combustion gases in the new explosive charge.

Of the above, only the factors 1, 2 and 3 can in general be determined mathematically from known data. With respect to the factor 5, certain rules of construction for explosion chambers may be applied upon which factors 6 and 7 are in part dependent. The number, size and form of the combustion chamber will in part depend upon the capacity of the turbine, which in a measure controls also the temperature of the combustion gases indicated under 8, and will depend in part also on the nature of the fuel employed, which in turn bears a relation also to the permissible amount of residual combustion gases referred to under 9.

My researches have indicated that the size of the minimum cross-section of the nozzle, listed under 4, is of very great importance. As above indicated, by reducing this minimum nozzle cross-section below the size heretofore employed in this art, I reduce the amount of heat lost in the nozzle channel due to whirling, and though I increase the loss dependent on the time factor, yet the resultant is an enormous increase in heat economy. On the other hand I have found that pre-ignition is caused by the presence of residual combustion gases in the new charges fed to the explosion chambers, and that it is necessary to insure as complete scavenging as possible. The completeness of the scavenging will depend, at least in part, upon the time allowed for the same and upon the size of the minimum cross-section of the nozzle.

As previously mentioned, it is generally desirable to have as many explosion cycles per minute as possible. One way in which this has been attained has been by reducing the scavenging period by making the minimum nozzle cross-section relatively large to permit discharge of the residual gases within a minimum of time. This reduction in scavenging time and increase in nozzle cross-section I have found to have more or less critical limits from the standpoint both of stable operation and of efficiency, first because of my discovery that it is incomplete scavenging that is responsible for the gradual building up of the temperature within the combustion chamber which ultimately causes pre-ignition, and that therefore sufficient time must be allowed to permit substantially all of the residual combustion gases to escape from the combustion chamber; and secondly, because as the minimum nozzle cross-section is increased, the volume of the nozzle channel is likewise increased so that, as explained above in connection with my copending application Serial No. 186,094, the heat losses due to whirling in such channel are enormously increased. Different considerations thus require different sizes of minimum nozzle cross-section and different scavenging periods. I have determined, as indicated below, that a definite relation exists between the scavenging period, the size of the explosion chamber, and the minimum nozzle cross-section, which relation defines the conditions for both stable and efficient explosion turbine operation.

In the calculation of the time allotted to each of the steps comprising the explosion cycle, which may be based on the diagram shown in Fig. 2 of the drawing, each cycle is divided into the following time divisions: first, the explosion, which in the drawing is indicated as taking place at the point 1 and consumes the time 1—1′; secondly, the so-called "saddle" from the instant 1′ to the instant 2, during which the nozzle valve is kept closed to insure complete combustion of the exploded charge, the valve being quickly opened when the instant 2 is reached; thirdly, the expansion during the interval 2—3 against the exhaust pressure p_0; fourthly, the scavenging period Z indicated as 3—4, during which the pressure p in the explosion chamber rises to the pressure p_1 of the scavenging air, and at the end of which the nozzle valve is closed; and fifthly, the fuel charging period 4—5, at the end of which both the air and fuel valves are closed, the charge exploded, and a new cycle initiated.

The explosion period is of known magnitude and depends primarily upon the thermal content of the explosive mixture. I have found that optimum conditions are maintained when a mixture having a heat content of 400 to 450 kg. cal. per cubic meter is employed, the explosion period of such gas being equal to or greater than 0.06 second. The "saddle" can, of course, be controlled, and is generally made to amount to about 0.01 second. The charging time indicated in Fig. 2 as 4—5 may also be determined experimentally and amounts to about 0.13 second. If now, each combustion chamber is to be operated at 60 cycles per minute, there is available one second for each cycle. Of this second, there has been allotted, according to the example taken, 0.06 second for the explosion, 0.01 second for the "saddle" and 0.13 second for the charging. There thus remains 0.8 second for the expansion of the exploded gases and the scavenging of the residual gases remaining in the combustion chamber. The present invention is concerned primarily with the splitting or apportioning of this residual period of the explosion cycle in such manner that a stable operation of the turbine is assured while at the same time a high efficiency is obtained.

The scavenging period 3—4 is indicated as Z in Fig. 2. The amount of gas escaping from the chamber a per unit of time rises during this period with the ratio

$$\frac{p}{p_o}$$

until, upon reaching the critical pressure relationship, such amount attains its highest value. In the case of a uniformly cylindrical nozzle this critical pressure relationship is expressed by the fraction

$$\frac{1}{0.55}.$$

When this relationship is reached the rate at which the gas is forced out of the chamber cannot be increased even by further increasing this pressure ratio. It therefore follows that the more quickly this pressure ratio is reached within the scavenging period the more quickly is the maximum rate of gas discharge reached, and consequently the shorter the period in which the residual gases in the chamber are expelled. This ratio applies, however, only to a cylindrical nozzle. With expansion nozzles, of the De Laval type, the pressure relation

$$\frac{p}{p_o}$$

is expressed by the known formula:

$$\frac{p}{p_o}=\frac{1}{0.55+(1-0.55)\sqrt{\frac{q-1}{q}}}$$

where

$$q=\frac{F}{f},$$

the expansion ratio of the nozzle, F=the outlet area of the nozzle, and f=the minimum cross-section of the nozzle (Fig. 3).

The graph of this formula is shown in Fig. 4 where the relationship between the values

$$\frac{p}{p_o}$$

and p (the latter based on the assumption of an exhaust pressure $p_o=1.06$) on one hand and

$$q=\frac{F}{f}$$

on the other, is indicated. It is clear from the graph that the greater the expansion ratio of the nozzle the smaller is the pressure ratio

$$\frac{p}{p_o},$$

and consequently the smaller is the necessary scavenging air pressure, and the more rapidly will the chamber therefor be freed of residual combustion gases.

The value for

$$q=\frac{F}{f}$$

cannot be arbitrarily fixed. In the first place it determines in large measure the velocity at which the gases strike the turbine blades, and thus affects the speed of the turbine; it determines also the dimensions of the turbine rotor and the efficiency of the energy transference from the gases to the rotor. On the other hand, the ratio

$$q=\frac{F}{f}$$

determines the scavenging pressure to the extent that the latter must not be below the pressure p derived from the above formula, or from the graph of Fig. 4, if an unnecessarily prolonged scavenging period, and hence a reduced number of cycles and increased loss of heat, or else an incomplete scavenging of the explosion chamber and the consequent danger of pre-ignition, are to be avoided. In this way the magnitude of a number of the factors bearing on the operation of an explosion turbine may be calculated.

In accordance with my invention, the nozzle valve is held open during the charging of the air which effects scavenging of the explosion chamber for a period of time which is sufficiently long to insure proper scavenging. I have found that the duration of this period can be expressed in terms of the size of the explosion chamber and of the nozzle and that a distinct relationship exists between the minimum time which must be allowed for scavenging to insure substantially complete expulsion of the residual gases in the explosion chamber and avoidance of pre-ignition, and the ratio

$$\frac{f}{V},$$

where f and V represent the magnitudes indicated above. This relationship is of paramount importance and must be observed if a stable turbine operation is to be assured, and may be expressed as follows:

$$\frac{f}{V}Z=40$$

Z being the scavenging time in seconds (Fig. 2). This equation expresses mathematically the relation between the nozzle and the combustion chamber to insure substantially complete scavenging and avoidance of pre-ignition. As the other time divisions of the explosion cycle may be computed mathematically or fixed arbitrarily, the relation between the scavenging time, the chamber volume, and the minimum nozzle cross-section in effect states the interdependence of the same with the cycle or explosion frequency of the engine. Pre-ignition can be avoided on operation at the highest possible number of cycles only by operating with a scavenging air pressure which is not below the minimum determined by the nozzle ratio and by allowing for the scavenging a time interval which is not below about

$$40\frac{V}{f}.$$

Referring now to the example given above, wherein it was assumed that each chamber was to be operated at 60 cycles per minute and wherein it was found that 0.8 second was left for both the expansion and scavenging periods, the values

$$\frac{f}{V}$$

and Z may be determined as follows: It is known that

$$\frac{f}{V}$$

is a function of the expansion time T and may be represented as follows:

$$\frac{f}{V}=\int(T).*$$

For best efficiency the following equation must be observed:

$$\frac{f}{V}=40 \text{ to } 100.$$

Assuming

$$\frac{f}{V}=100$$

and substituting in the scavenging equation

$$\frac{f}{V}Z=40,$$

I obtain

$$100\,Z=40,$$
$$Z=0.4 \text{ sec.}$$

The value of T can be obtained from Equation *. If this should be greater than 0.4 sec., so that $Z+T>0.8$, then the number of cycles per minute must be reduced, or else

$$\frac{f}{V}$$

must be made greater than 100 and the heat economy of the turbine sacrificed. If T is less than 0.4 sec., say 0.2 sec., then either a lower value for

$$\frac{f}{V}$$

may be selected, with consequent increase in heat economy in the nozzle channel, or the number of cycles per minute may be increased, so that greater capacity per unit of machine weight may be obtained. In this way the expansion and scavenging periods are determined and also the ratio

$$\frac{f}{V}.$$

The actual value of f and V will obviously depend upon the size of the machine and the number of combustion chambers and can be determined mathematically.

The dimensions and speed of opening of the nozzle valve are obviously of great importance and increase in importance as the number of explosions cycles per minute is increased. I have found that a nozzle valve having a cross-section equal to about 3.5 f gives very satisfactory results; while with suitable mechanism the opening period may be reduced to 0.006 sec., whereby the whirling period in the nozzle channel is greatly reduced and the heat losses in such channel limited to about 10%.

As already indicated hereinabove, stability is a matter of primary importance to which any conflicting considerations of efficiency must yield, as a stable engine of a comparatively lower degree of efficiency is far preferable from a commercial standpoint to an unstable engine of higher efficiency. It is therefore obvious that in the construction of my engine, wherein the volume of the combustion chamber is V and the time allowed for scavenging Z, the smallest nozzle cross-section (f) must be of a size substantially corresponding to the formula

$$\frac{f}{V}Z=40.$$

As already explained, f is not an absolute size but is the minimum size of the smallest nozzle cross-section, and after this minimum has once been established it is obvious that from the standpoint of complete and efficient scavenging this cross-section may be increased if necessary. If now the efficiency formula

$$\frac{f}{V}=40 \text{ to } 100,$$

which calls for an optimum or maximum value for the smallest nozzle cross-section, calls in any particular instance for such a cross-section larger than that called for by the scavenging formula, such cross-section should be chosen as is called for by the efficiency formula. If, on the other hand, the efficiency formula calls for a smaller cross-section than that called for by the scavenging formula, the result of the scavenging formula must control.

I claim:

1. In combination, an explosion chamber, air and fuel charging valves at the inlet end of said chamber, an outlet valve at the outlet end of said chamber, a discharge element, a channel between said discharge element and the outlet end of said chamber, means for exploding a combustible mixture fed by said charging valves, said outlet valve being adapted to be opened a definite time after said explosion to discharge the combustion gases into said discharge element, said air valve being adapted to be opened when the pressure in said chamber is a definite amount above the counter pressure beyond said discharge element, means for holding said outlet valve open for a period sufficient to insure substantially complete scavenging of said chamber of the residual combustion gases, and means for closing said valve at the end of such period, said period, measured in seconds, being substantially 40 times the ratio of the volume of the explosion chamber, measured in cubic meters, to the minimum cross-sectional area of the discharge element, measured in square centimeters.

2. In combination, an explosion chamber, air and fuel charging valves at the inlet end of said chamber, an outlet valve at the outlet end of said chamber, a discharge element, a channel between said discharge element and the outlet end of said chamber, means for exploding a combustible mixture fed by said charging valves, said outlet valve being adapted to be opened a definite time after said explosion to discharge the combustion gases into said element, said air valve being adapted to be opened when the pressure in said chamber is a definite amount above the counter-pressure beyond said discharge element to charge air into such chamber at a pressure above the critical pressure, means for holding said outlet valve open for a period sufficient to insure substantially complete scavenging of said chamber of the residual combustion gases, and means for closing said valve at the end of such period, said period, measured in seconds, being at least 40 times the ratio of the volume of the explosion chamber, measured in cubic meters, to the minimum cross-sectional area of the discharge element, measured in square centimeters, said ratio being as closely as possible within the limits 1/100 to 1/40.

3. The improvement in the art of operating an

$$* \quad \frac{f}{V}=\frac{1}{T}\cdot\frac{10000}{1{,}65\sqrt{t_2+273}}\cdot\left[\left(\frac{p_2}{p_3}\right)^{\frac{1}{8{,}66}}-1\right]$$

where p_2 pressure in ats. at point 2 of Fig. 2.
t_2 temperature in °C. at point 2 of Fig. 2.
p_3 pressure in ats. at point 3 of Fig. 2.

explosion engine which comprises charging air and fuel into an explosion chamber forming part of such engine, exploding said air and fuel, discharging the resulting combustion gases from said chamber into a discharge element, and charging scavenging air into said chamber at a pressure above the critical pressure to drive out the residual combustion gases, said scavenging air being charged for a sufficiently long period to insure substantially complete scavenging of said chamber, said period measured in seconds being at least about 40 times the ratio of the volume of the explosion chamber, measured in cubic meters to the minimum cross-sectional area of the discharge element, measured in square centimeters.

4. The improvement in the art of operating an explosion engine which comprises charging air and fuel into an explosion chamber forming part of such turbine, exploding said air and fuel, discharging the resulting combustion gases from said chamber, into a discharge element, and charging scavenging air into said chamber at a pressure above the critical pressure to drive out the residual combustion gases, said scavenging air being charged for a sufficiently long period to insure substantially complete scavenging of said chamber, said period measured in seconds being at least about 40 times the ratio of the volume of the explosion chamber, measured in cubic meters, to the minimum cross-sectional area of the discharge element, measured in square centimeters, said ratio being as closely as possible within the limits 1/100 to 1/40.

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