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Bratkowski et al.
[11] 3,821,507
[45] June 28, 1974

[54] CIRCUIT INTERRUPTERS UTILIZING SUPERSONIC FLOW

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[73] Assignee: **Westinghouse Electric Corporation**, Pittsburgh, Pa.

[22] Filed: **Nov. 14, 1972**

[21] Appl. No.: **306,509**

Related U.S. Application Data

[63] Continuation of Ser. No. 7,074, Jan. 30, 1970, abandoned.

[52] **U.S. Cl.** .... **200/148 R**, 200/148 C
[51] **Int. Cl.** **H01h 33/80**
[58] **Field of Search** .... 200/148 R, 148 B, 148 C

[56] **References Cited**

UNITED STATES PATENTS

2,284,840	6/1942	Paul	200/148 C
2,367,934	1/1945	Flurscheim	200/148 R
2,399,412	4/1946	Webb	200/148 R
2,481,996	9/1949	Grunewald et al.	200/148 C
2,486,127	10/1949	Davies	200/148 C
2,761,935	9/1956	Prince	200/148 C
3,133,176	5/1964	Schneider	200/148 B
3,270,173	8/1966	Barkan	200/148 B

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[57] **ABSTRACT**

A circuit interrupter uses transonic or supersonic flow of an interrupting medium, such as air or other gas to interrupt direct or alternating currents. The interrupter is provided with a supersonic nozzle and an arc chute constructed to take advantage of high speed flow to remove ionized gases quickly and of directed expansion which stretches the arc core and length to interrupt the arc. The nozzle promotes supersonic flow of the interrupting medium into the arc path, and the arc chute provides smooth flow and continuous expansion of the arc gases, thereby increasing the interrupting ability of the breaker.

17 Claims, 32 Drawing Figures

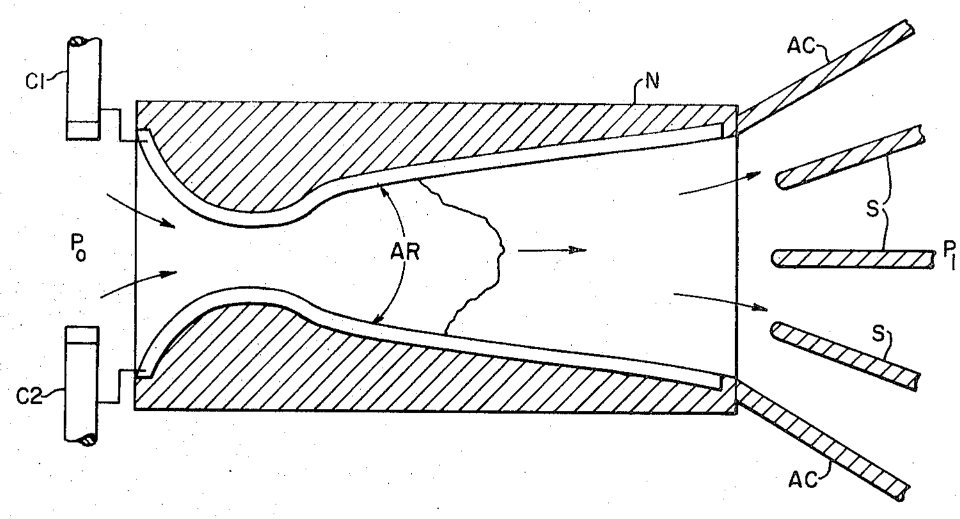

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FIG.1.

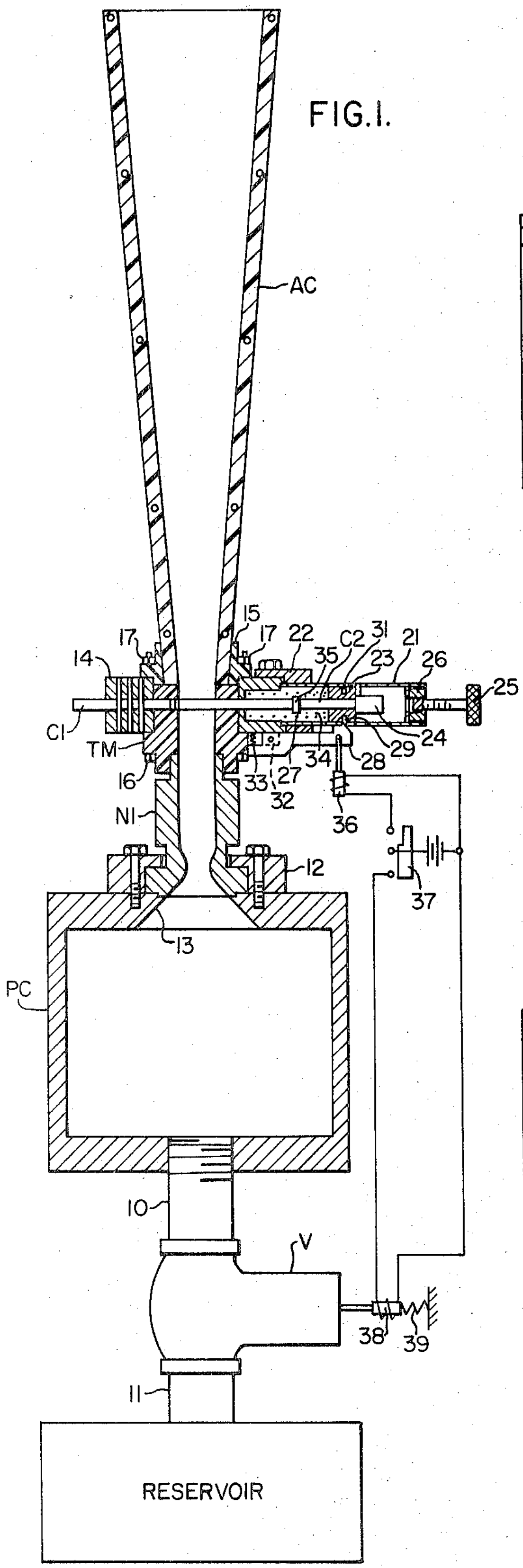


FIG.2.

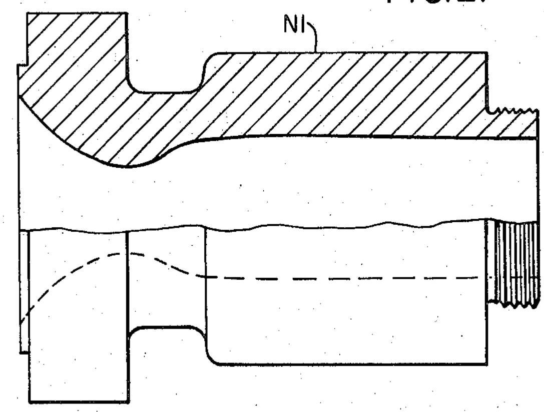
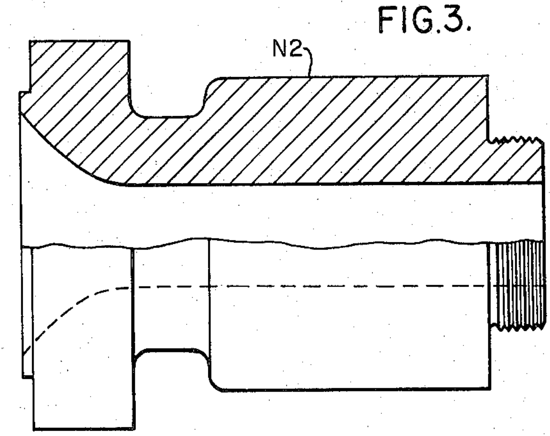


FIG.3.



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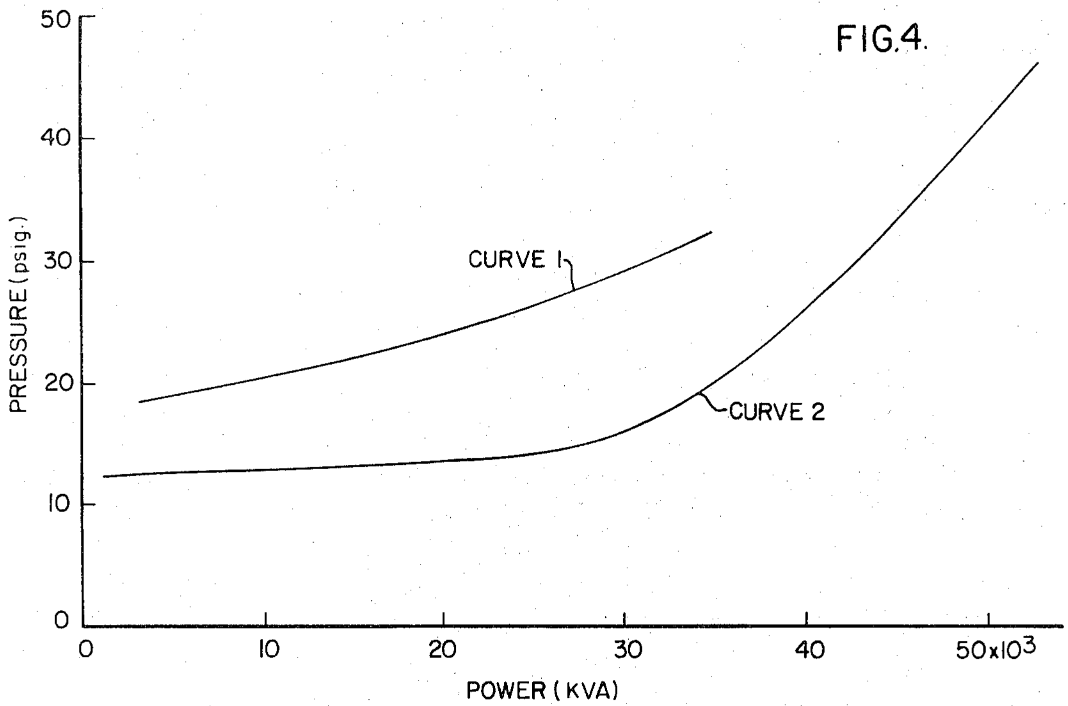


FIG. 4.

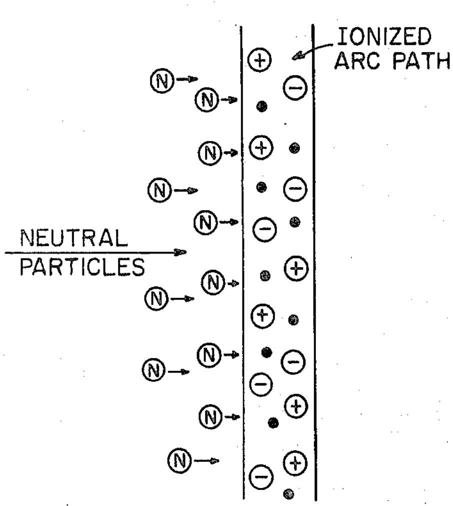


FIG. 5.

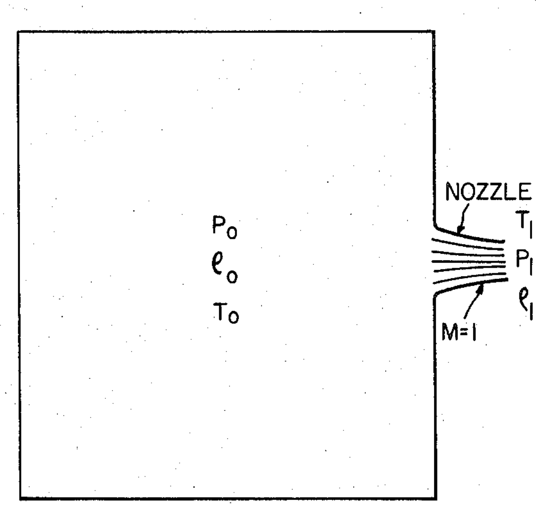


FIG. 6.

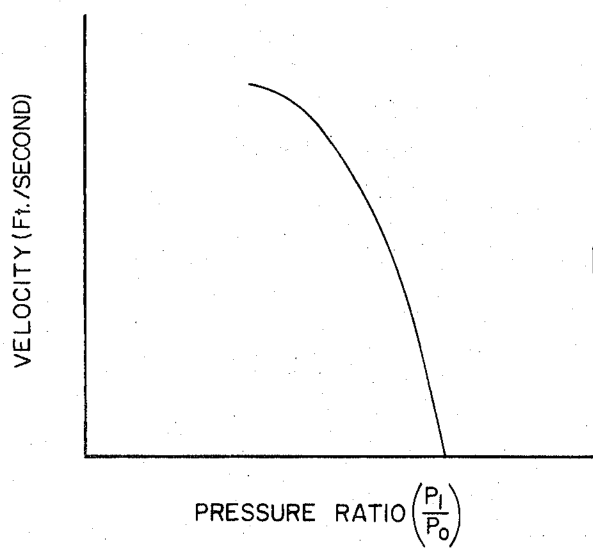


FIG. 7.

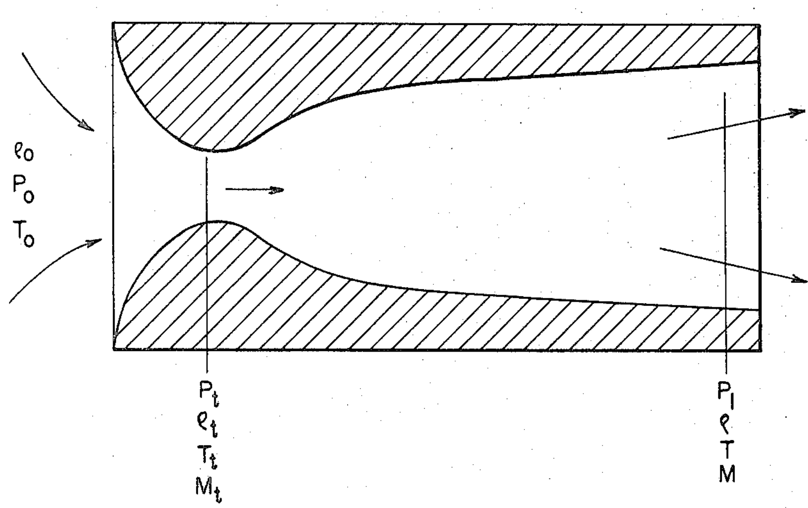


FIG. 8.

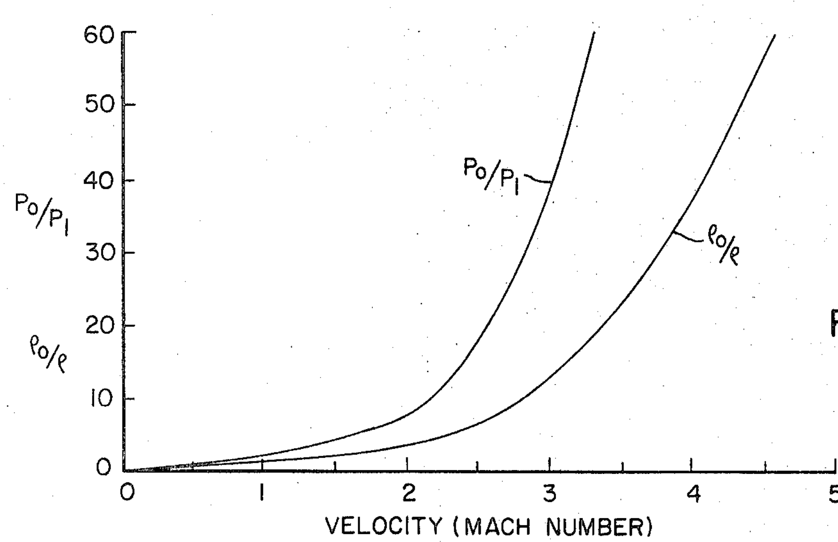


FIG. 9.

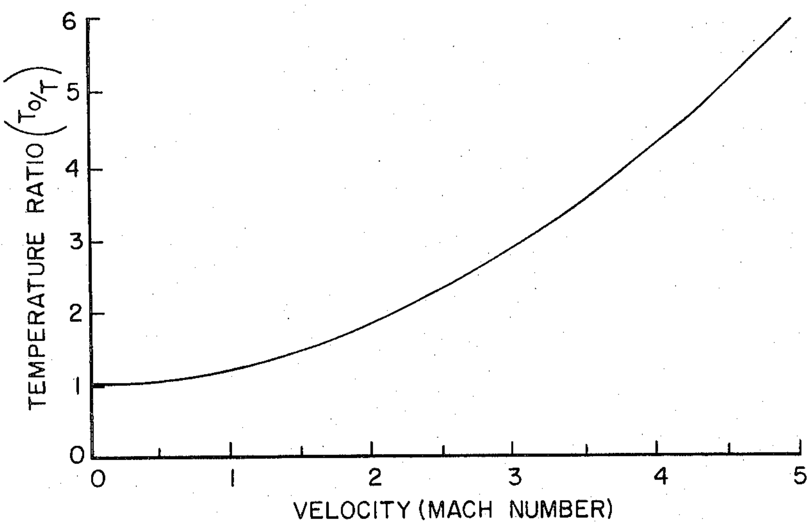
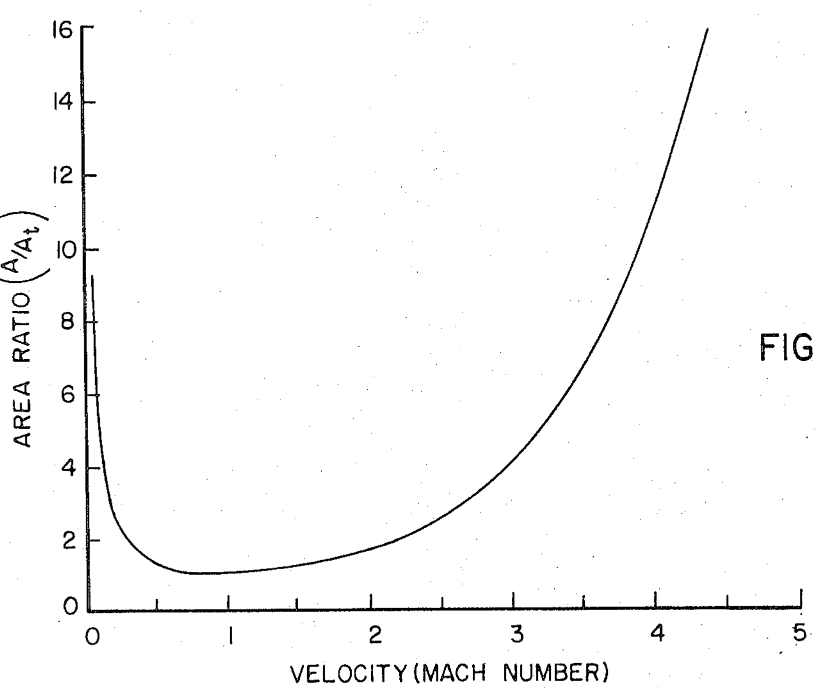

6
5
4
3
2
1
0
TEMPERATURE RATIO (To/T)
0
1
2
3
4
5
VELOCITY (MACH NUMBER)

FIG. 10.


16
14
12
10
8
6
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2
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AREA RATIO (A/At)
0
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2
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VELOCITY (MACH NUMBER)

FIG. 11.

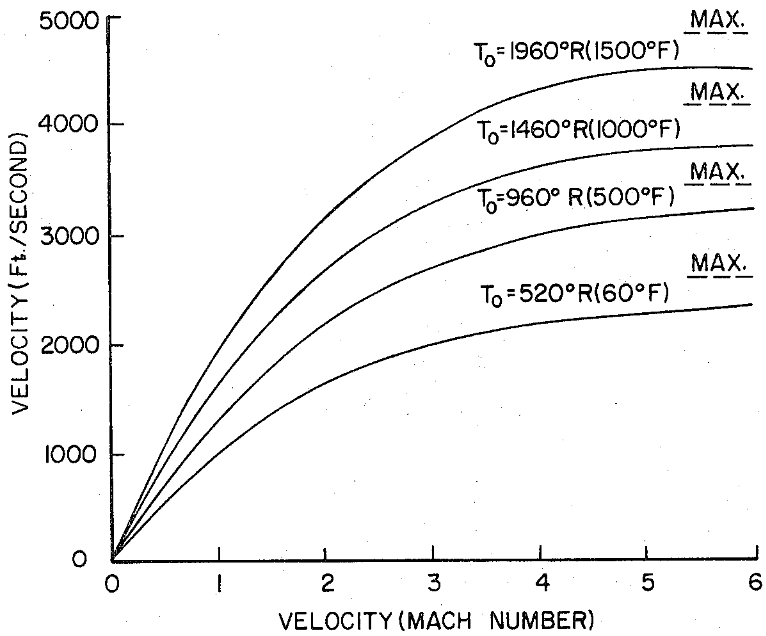


FIG. 12.

FIG. 13.

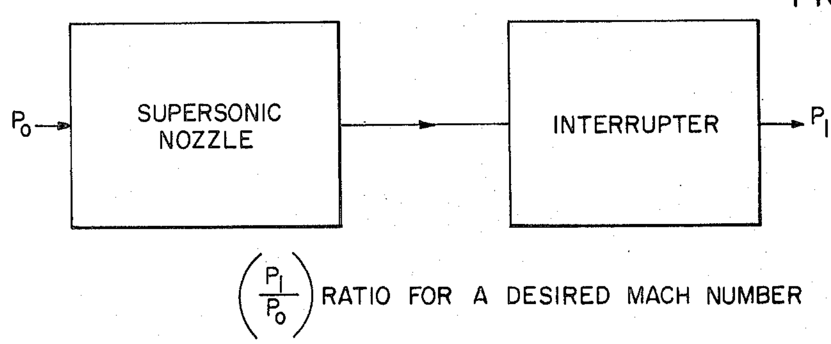
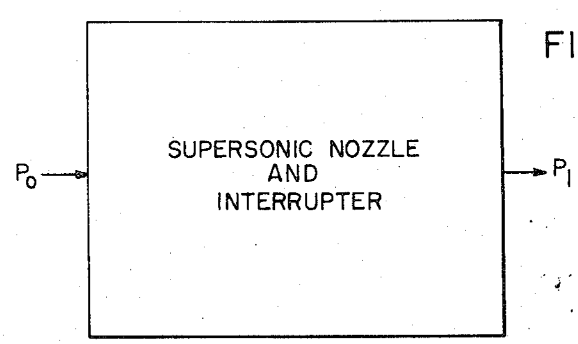


FIG. 13A.



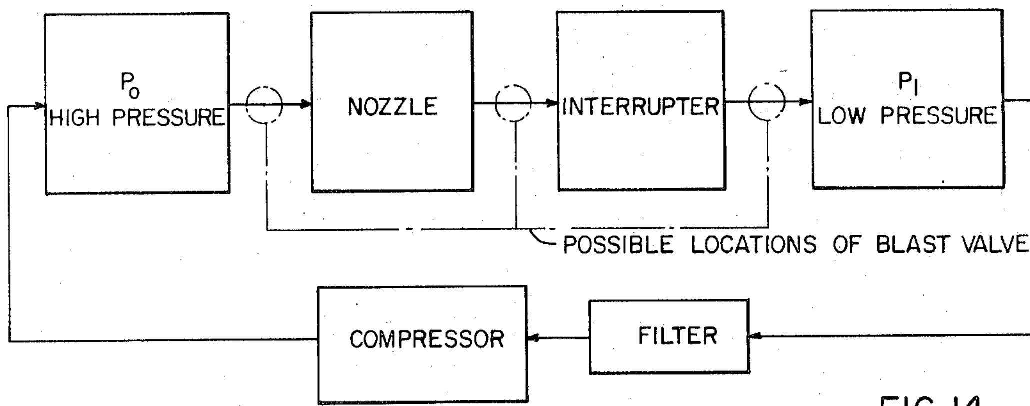


FIG. 14.

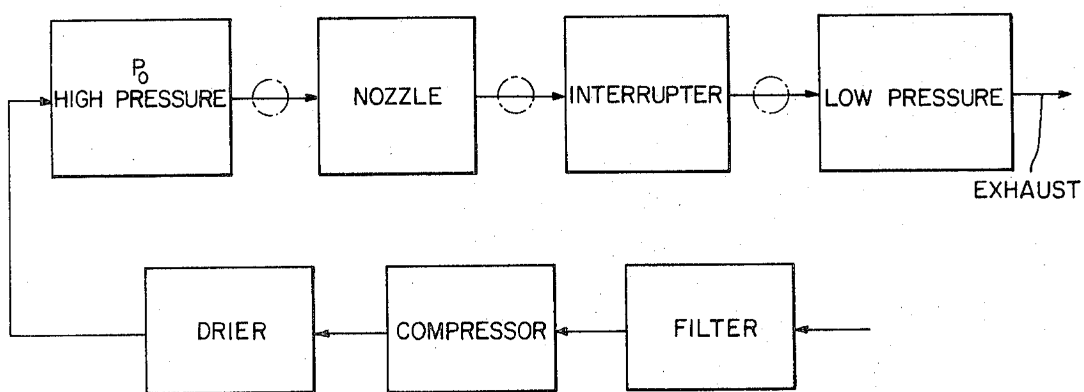


FIG. 14A.

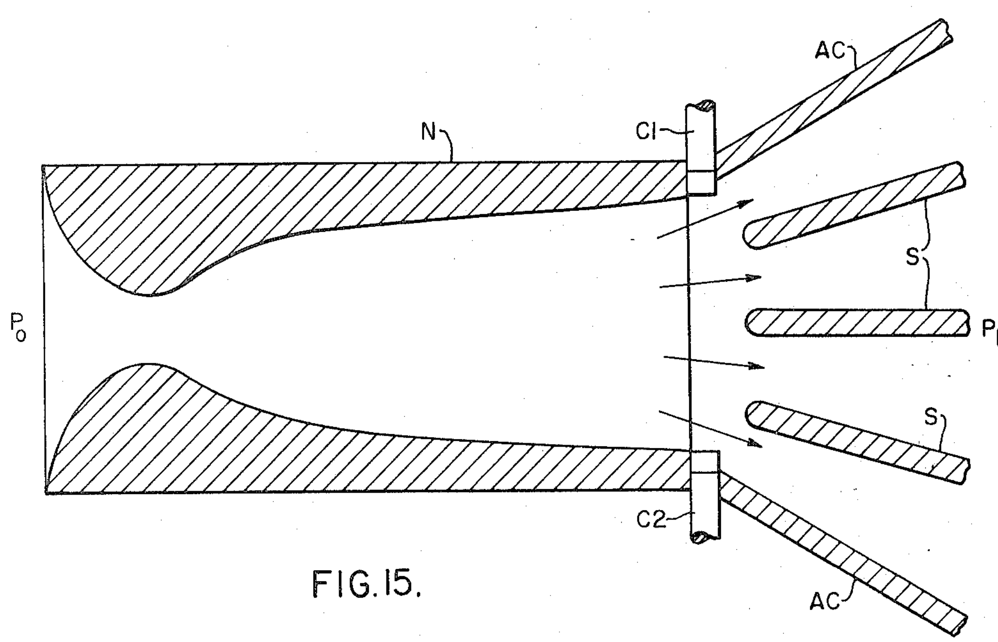


FIG. 15.

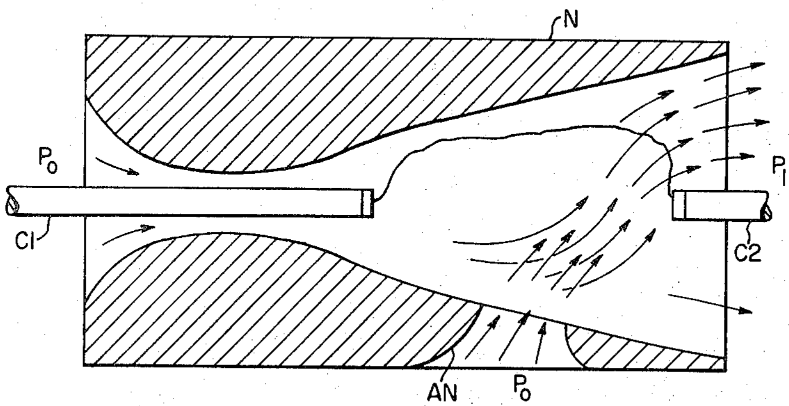
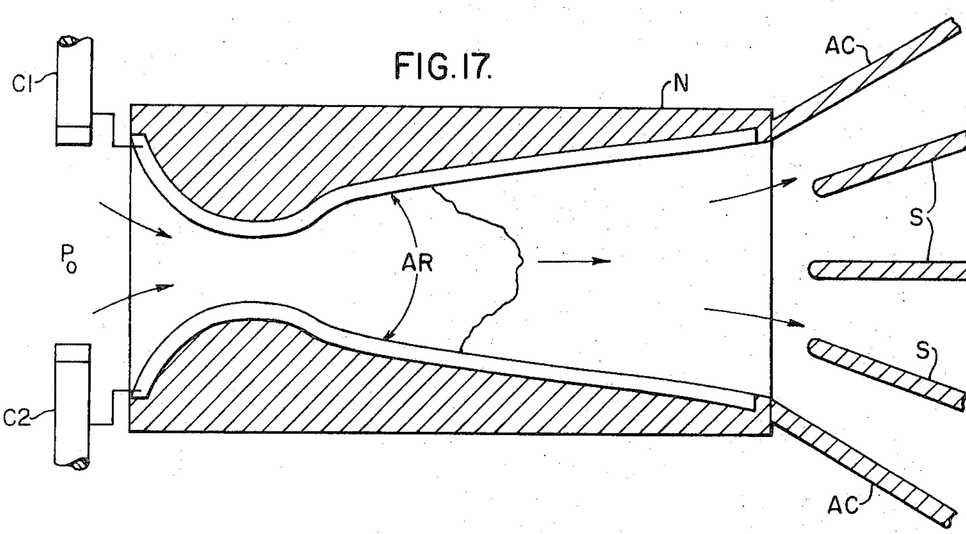


FIG. 16.

FIG. 17.



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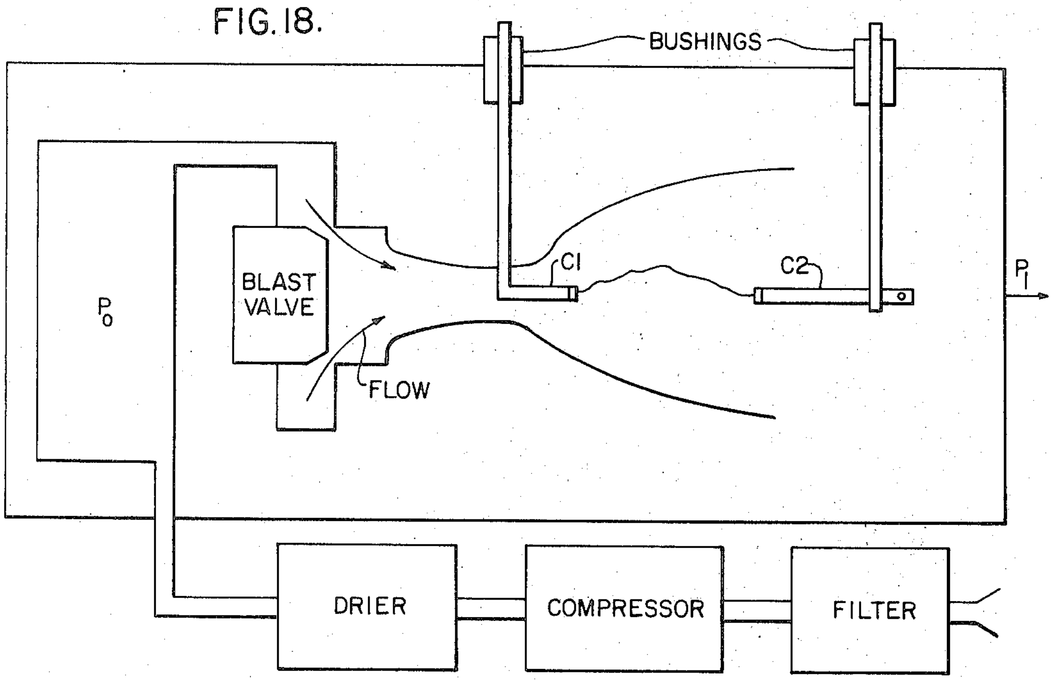

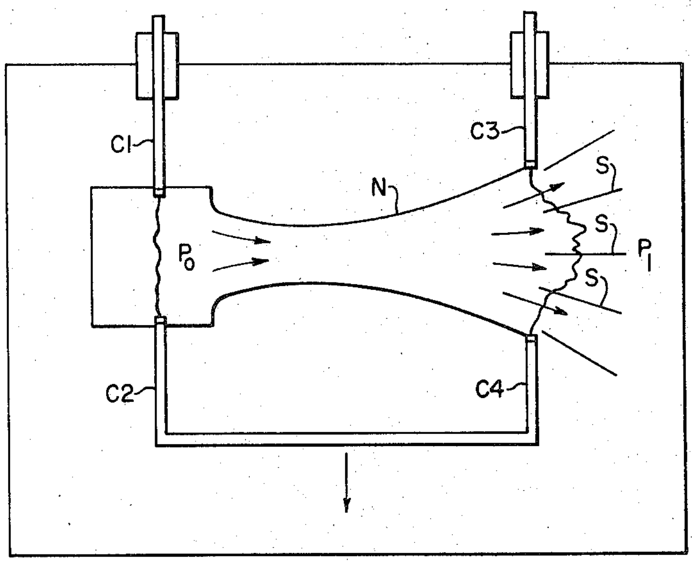

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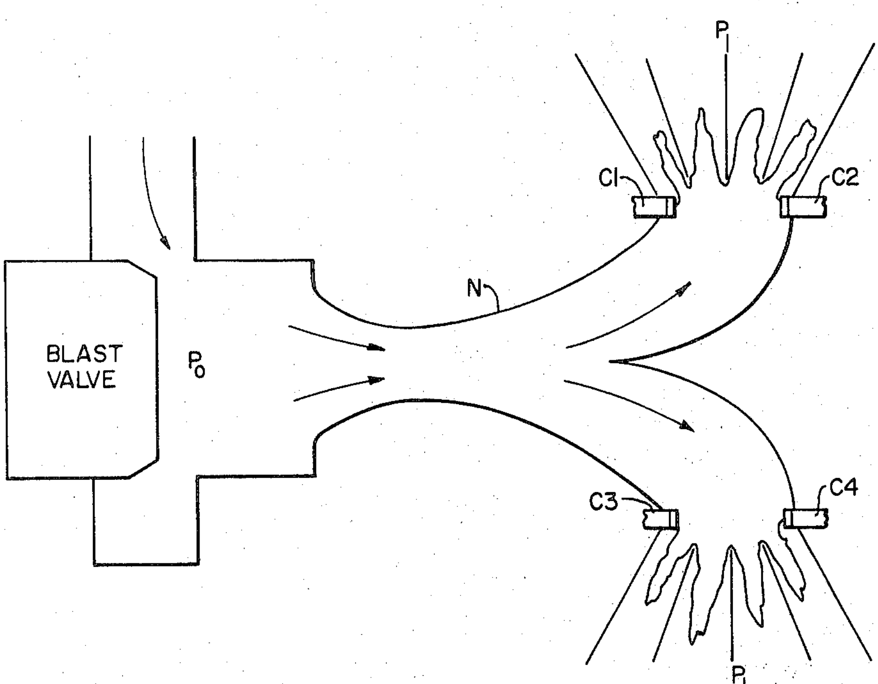
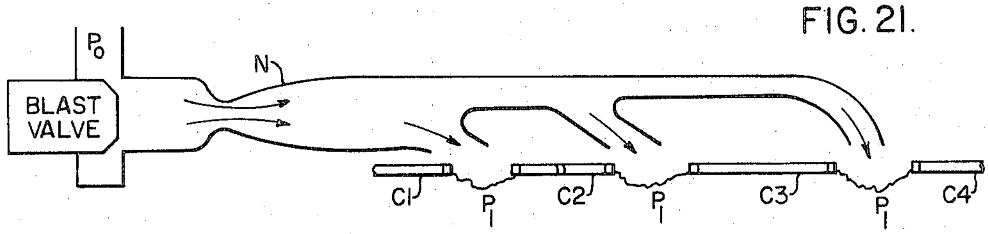


FIG. 20.

FIG. 21.



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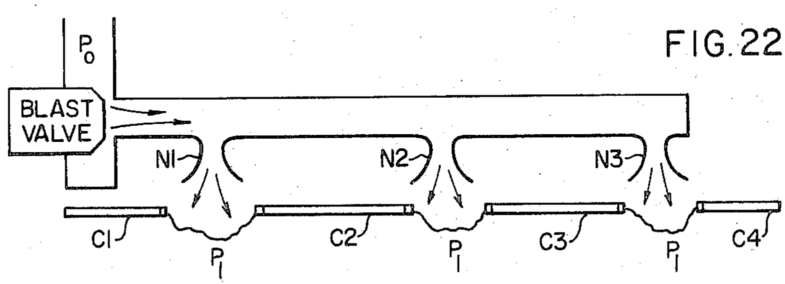
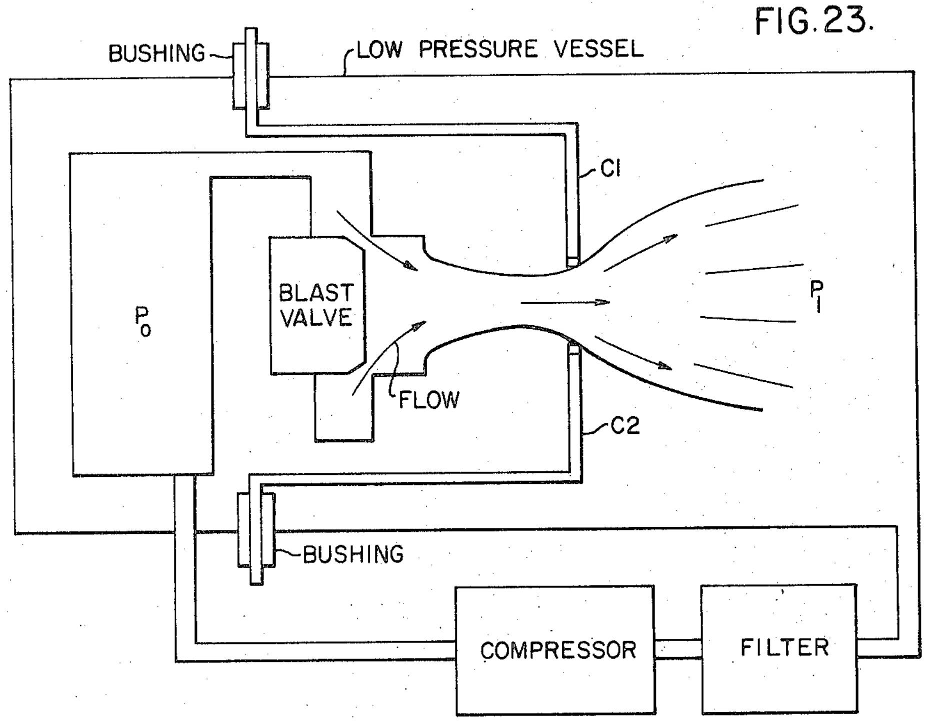
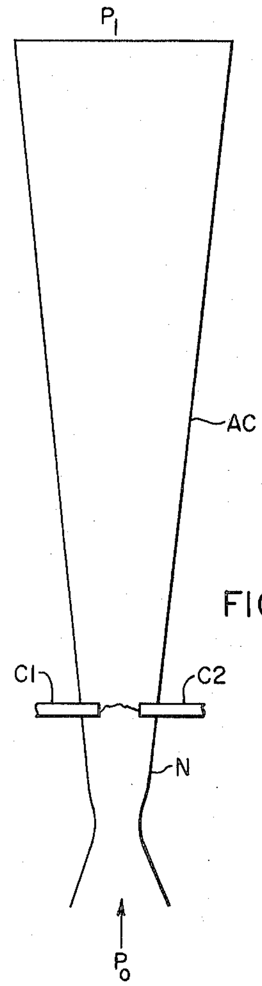


FIG. 23.





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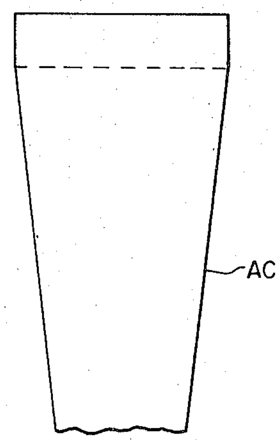

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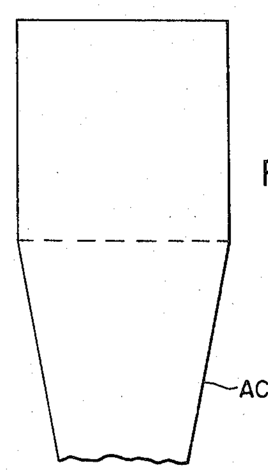

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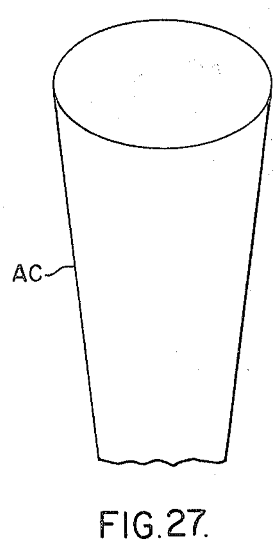
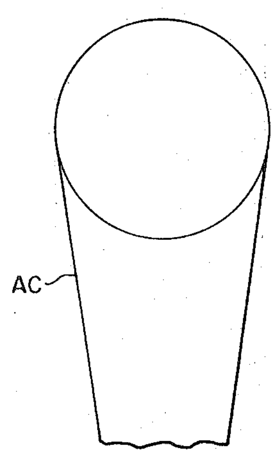


FIG. 27.



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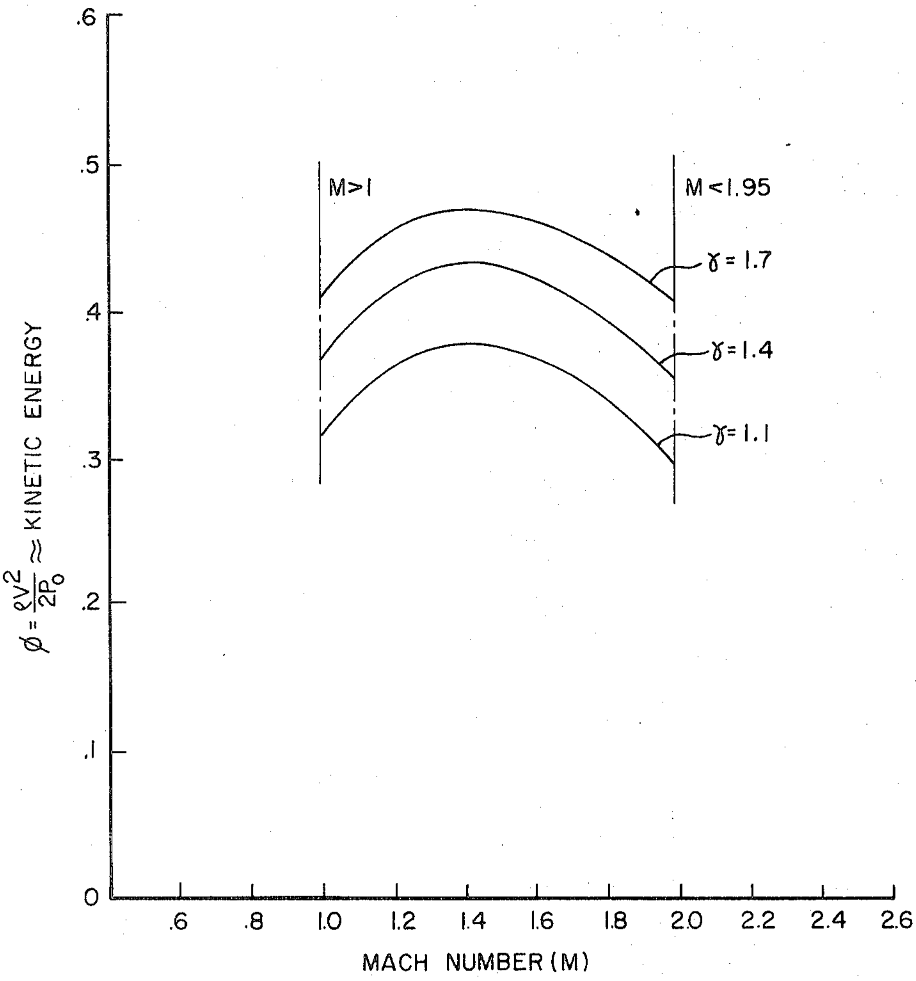

FIG. 29.

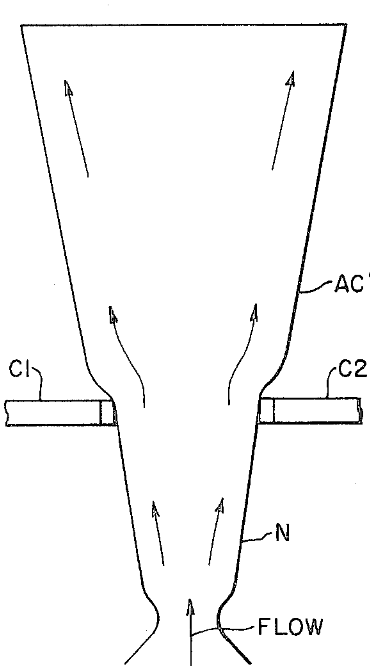

FIG. 30.

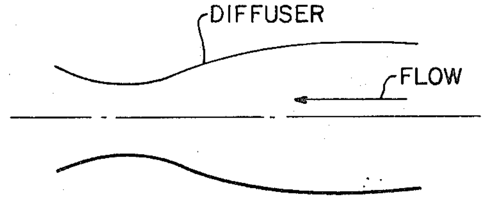

FIG. 31.

CIRCUIT INTERRUPTERS UTILIZING SUPERSONIC FLOW

This is a continuation of application Ser. No. 7,074 filed Jan. 30, 1970.

BACKGROUND OF THE INVENTION

This invention relates, generally, to gas blast circuit interrupters, and, more particularly, to improved interrupting structures involving improved flow systems for efficiently directing the gas at and through the arc for effecting the extinction thereof and for removing the ionized gases while promoting deionization and arc extinction.

The process of interrupting an electrical circuit is essentially that of introducing insulation at some point in the circuit so that the current will cease to flow. Opening a knife switch or cutting a wire are examples in which the insulation at the break is air. Other insulating materials, such as oil, or sulfur hexafluoride SF_6 gas, can also be used. However, in many instances such a simple circuit breaker is not adequate. The voltage generated may be high enough to maintain an arc across the gap in the circuit. How well the circuit breaker performs its function is dependent upon the efficiency of the interrupter.

The present invention is particularly concerned with a circuit interrupter of a new type which uses transonic of supersonic flow of a fluid to interrupt direct or alternating currents. The use of such a flow system permits the breaker to interrupt larger voltages and currents than an equivalent-sized circuit breaker of the types currently being produced.

Some of the more important advantages of the present invention are:

1. The new circuit breaker of the present invention is able to interrupt larger currents and voltages for the same size breaker than heretofore.
2. The interrupting efficiency of the improved circuit breaker of the present invention is better than that of other breakers of prior art construction.
3. Since the circuit breaker of the present invention is smaller in size for a larger rating, the manufacturing cost is less than for equivalent breakers presently being produced.

Circuit breakers are used to interrupt both direct and alternating currents. The general method of interrupting a direct current is to raise the voltage required to maintain the arc above the normal voltage supplied by the circuit. This is usually accomplished simply by lengthening the arc as the contacts are separated. A strong magnetic field is frequently employed to speed up this lengthening, and barriers or arc splitters are placed so as to increase the effective length of the arc.

The extinguishing of arcs in alternating current circuits is fundamentally easier than in direct current circuits because the alternating current, in reversing direction, must approach and pass through zero current twice each cycle. These repeated current-zero moments are ideal for circuit interruption. During this time, the arc gases are mixed with un-ionized gases, the dielectric strength of the interrupting medium is recovered and the arc is extinguished. Once the arc has been extinguished, the current can than flow only if the arc is re-ignited. The problem of arc interruption then becomes merely one of preventing arc re-ignition. Thus, the proper functioning of an alternating current interrupter depends upon two factors, namely the dielectric strength of the medium between the separated contacts and, additionally, the conductance of the arc. These are major factors in circuit interruption.

When moderate currents are interrupted, the arc loses its conducting ability rapidly, and the opening of the circuit depends only upon the recovery by the conducting arc space of adequate dielectric strength. However, when large currents and voltages are interrupted, the rate of loss of conductance may be the most important factor in determining the maximum interrupting ability of a given circuit breaker. There are many cases were both factors cannot clearly be separated, but are overlapping. The extinguishing of an arc is often described as a race, beginning at current zero at which time the arc has lost conductance, between the deionizing process trying to restore the dielectric strength of the arc space and the rapidly rising recovery voltage across the circuit breaker contacts which is attempting to break down the gap and start the current flowing again.

Under favorable conditions, where the circuit capacitance is small and damping resistance is negligible, the voltage across the contacts will rise rapidly — within a matter of microseconds — and overshoot to a peak about twice the normal voltage crest. With such limited time for deionization of the arc space, the interruption of a high voltage arc is quite difficult. However, since there is always some capacitance in a circuit, the time for deionization is longer.

The novel circuit interrupter construction of the present invention is particularly concerned with the principle of deionizing the arc space in a much shorter time and the more rapid expulsion of ionized gases than is presently being done. One of the most important factors in deionizing an arc space is the flow and stirring or mixing action of the gas. This flow causes intermingling of the hot ionized arc gases and the surrounding cool un-ionized gas. This action speeds up the diffusion process, and rapid recovery of breakdown strength results from this deionization and cooling.

Present circuit interrupters utilize subsonic or sonic flow conditions. The circuit interrupter of the present invention is particularly concerned with transonic or supersonic flow of the fluid into an arc between separating circuit breaker contacts. Accordingly, it is a general purpose of the present invention to provide an improved circuit interrupter of the gas-blast type in which the gas velocity attains sonic, transonic and supersonic velocities.

SUMMARY OF THE INVENTION

In accordance with one embodiment of the invention, a circuit interrupter is provided with a flow system comprising a supersonic nozzle and an arc chute constructed to take advantage of high speed flow to remove ionized gases quickly and of directed expansion which strethces the arc core and length to interrupt the arc. The nozzle promotes supersonic flow of the interrupting medium into the arc path, and the arc chute provides smooth flow and continuous expansion of the arc gases, thereby increasing the interrupting ability of the breaker.

BRIEF DESCRIPTION OF THE DRAWINGS

Further objects and advantages will readily become apparent upon reading the following specification, taken in conjunction with the drawings, in which:

FIG. **1** is a side elevational view, partly in vertical section, of a circuit interrupter embodying principles of the present invention, the contact structure being illustrated in the closed-circuit position;

FIGS. **2** and **3** illustrate, respectively, a supersonic and a sonic nozzle selectively employed in the interrupter shown in FIG. **1** for test purposes;

FIG. **4** is a graph illustrating the improved performance of the circuit interrupter of the invention over that of prior art construction, the ordnance being expressed in psig and the abscissa in power (KVA);

FIG. **5** illustrates diagrammatically certain flow conditions;

FIG. **6** diagrammatically represents a sonic nozzle;

FIG. **7** illustrates graphically the relationship between the velocity in feet per second and the pressure ratio for sonic flow conditions;

FIG. **8** represents diagrammatically a supersonic flow nozzle;

FIG. **9** graphically illustrates the ratio of stagnation to static pressure and density against Mach number for air;

FIG. **10** graphically represents the ratio of stagnation to static temperature versus Mach number for air;

FIG. **11** graphically represents the area ratio versus Mach number for a supersonic nozzle using air;

FIG. **12** graphically represents the variation of velocity with Mach number for air for a given stagnation temperature;

FIGS. **13** and **13A** represent, in two different block forms the basic units of a supersonic circuit breaker;

FIGS. **14** and **14A** graphically represent, in block form a closed flow system and an open flow system, respectively;

FIG. **15** represents schematically a supersonic nozzle with coacting splitters and contacts utilizing a cross-blast construction;

FIG. **16** illustrates diagrammatically a modified type of axial-flow interrupter with the possibility of utilizing an auxiliary nozzle;

FIG. **17** illustrates a modified type of nozzle utilizing arc runners extending therethrough;

FIG. **18** illustrates a modified-type of flow system in which the arc is drawn axially of the nozzle;

FIG. **19** illustrates a modified-type of contact and nozzle arrangement in which a serially-related arc establishes the requisite pressure for the transonic and supersonic velocity;

FIG. **20** illustrates a modified-type of construction utilizing a multi-break arrangement employing a single nozzle;

FIG. **21** illustrates diagrammatically a modified arrangement utilizing a plurality of serially-related arcs;

FIG. **22** illustrates diagrammatically another serial-16-related break arrangement utilizing a cross-blast construction;

FIG. **23** illustrates diagrammatically a circulating flow system utilizing a cross-blast type of contact arrangement;

FIG. **24** shows diagrammatically an expansion section after the contacts which will compensate for the sudden introduction of energy into the interrupting medium due to the arc and allow it to expand in such a manner as to maximize the deionization rate, and therefore obtain a more efficient circuit interrupter;

FIGS. **25–28** illustrate modified-types of arc chute constructions with different cross-sectional configurations;

FIG. **29** graphically illustrates the kinetic energy versus Mach number for three gases;

FIG. **30** is a diagrammatic view of a supersonic nozzle and a supersonic arc chute, and

FIG. **31** is a diagrammatic view of a diffuser.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

This application discloses interrupter structures which use improved sonic, transonic and supersonic flow of an interrupting medium to enhance the interrupting ability of a circuit breaker. There are many advantages of transonic and supersonic flow for circuit breaker interruption. However, several of the most important advantages of supersonic flow over the subsonic flow, which is present in prior circuit breakers are (1) the temperature of the interrupting medium at the interrupting break is drastically reduced and (2) the velocity is considerably higher. The combined effect of reduced temperature and increased velocity greatly speeds up the process of deionization.

The constructions shown herein are examples of the inventive concept and are not intended to limit the scope of the invention. It is understood that many variations are possible which will not depart from the basic spirit of the invention. As an example, air and SF_6 are referred to in the description, but other media such as H_2, CO_2, etc. could also be used.

This specification describes, first, circuit breaker interruption theory that shows the advantages that can be obtained from supersonic flow; second, supersonic flow theory, and third, a few of the many possible supersonic circuit breaker structure configurations.

I. CIRCUIT BREAKER INTERRUPTION THEORY

Deionization of the arced space is fundamental to the arc quenching process in a circuit interrupter. Several important factors which promote rapid loss of electrical conductance of the arc path are (1) cooling, (2) diffusion, and (3) high velocity.

1. Cooling

Cooling or low temperature promotes deionization by (a) slowing down ionizing processes, (b) speeding up recombination.

a. Thermal ionization is the principal source of ionization in an electric arc. It has been defined as the ionizing action of molecular collisions, radiation, and electron collisions occurring in gases at high temperatures. Thermal ionization can be approximately described by equation (1).

$$(X^2/1 - X^2)\, p = CT^{2.5}\, \epsilon\, (-eV_i/KT) \qquad (1)$$

where

X is the fraction of ionized atoms
p is the pressure
C is a proportionality constant
T is the absolute temperature
eV_i is the ionization energy
K is Boltzmann's constant
$\epsilon = 2.718$

From this equation, it can be seen that a sizable reduction is ionization can be obtained by reducing the tempersture. Supersonic flow drastically reduces the fluid temperature, thus producing a large reduction in ionization.

b. Dionization may also be speeded up by recombination. Deionization by recombination means the recombining of the negative ions with the positive ions forming neutral atoms or molecules. The rate of recombination is given by equation (2).

$dn/dt \approx \alpha_r N^2$ (Const. N^2/T 3.5) (2)

where

dn/dt is the rate of recombination

α_r is the recombination coefficient

N represents the charge density of either sign (±)

The recombination coefficient varies as the minus 7/2 power of the absolute temperature ($T^{-7/2}$). Therefore, a reduced temperature substantially aids deionization by speeding up the rate of ion recombination, dn/dt. With supersonic flow, the temperature is much lower than that for subsonic or sonic flow. Thus, the higher flow yields a much lower temperature which, in turn, speeds up the rate of ion recombination.

2. Diffusion

One of the most important ways in which deionization is accomplished is by diffusion. Wherever a concentration gradient of ions exists, there will be a flow of ions from regions of high concentration to regions of lower concentration. Thus, diffusion produces a deionizing effect in highly concentrated regions. The net quantity of particles diffusing into an area per unit of time is described by equation (3).

$$q = -D\,(dn/dx),\ \text{where } D \approx T^{3/2}/p \qquad (3)$$

where

q is net quantity of particles diffusing into an area per unit time

D is the diffusion coefficient

dn/dx is the concentration gradient.

For supersonic flow, the pressure and temperature are greatly reduced. It is noted from equation (3) that diffusion is a function of temperature and pressure. Thus, with increased velocity a lower pressure is obtained and a larger diffusion coefficient is realized. Therefore, the high velocity will increase diffusion and aid measurably in deionization.

The diffusion coefficient can also be expressed in terms of mean free path L and average velocity $\overline{C}$. From this relationship, the effects of supersonic flow are more easily seen.

$$D = L\overline{C}/3 \qquad (3a)$$

In the supersonic flow regions, L, the mean free path, can be made large and $\overline{C}$ is large. Thus, the diffusion coefficient D becomes larger and the deionization process is greatly speeded up.

3. Velocity

Increased velocity of the interrupting medium obviously helps speed up deionization in that the ionized path will be diluted or swept away at a much faster rate. The conditions just before interruption are shown in FIG. 5. The particles of the interrupting medium, entering the arc path at current zero, have a higher velocity and thus a higher kinetic energy. Therefore, collisions with the ionized particles are more severe, sweeping them away at a higher rate. This can be seen from the following:

$$\Sigma \tfrac{1}{2} M_i V^2 = KE \qquad (4)$$

where M_i is mass and V is velocity and KE = Kinetic Energy

As the Mach number is increased, the kinetic energy also increases up to Mach 1.44. Beyond this the available kinetic energy decreases. A curve of $\rho V^2/2P_o$ vs. Mach number is plotted for different gases in FIG. 29. This curve essentially shows how the kinetic energy changes with Mach number. Furthermore, it shows a peak at the same place for all gases which obey the gas laws. However, the total kinetic energy available is different for different gases. The curves show how the kinetic energy changes for K values ranging from 1.1 to 1.7, where γ equals $^CP/^CV$.

Increasing the velocity for the same mass flow rate increases the kinetic energy for sweeping away the ionized particles. Since the heated gases are being swept away at a faster rate, the condition of "clogging" or slowing down of the flow is reduced. In many instances, clogging occurs because the arced gases cannot be removed quickly enough, thus reducing the operating capacity of the breaker. Thus, the insertion of a properly constructed nozzle and arc chute into the flow system of a cuicuit breaker is beneficial because (1) the increased velocity improves the displacement capabilities of the medium, and (2) the increased velocity decreases the temperature of the medium which, in turn, speeds up the diffusion process and slows down the ionization process.

II. SUPERSONIC FLOW THEORY

Before describing supersonic flow, it might be well to point out some of the limitations of subsonic flow. The velocity of the fluid emerging from the throat of the nozzle attached to a reservoir, shown in FIG. 6, increases as the pressure ratio (p_1/p_o) decreases until a certain critical ratio is reached. For air this ratio is 0.528. If the pressure ratio is reduced below the value of 0.528, the velocity at the exit will no longer continue to increase. The velocity at the throat is actually equal to the speed of sound for air under the given throat conditions and cannot increase above that value. The effect of the lowered pressure cannot be transmitted "upstream" for the stream is traveling with the speed of the pressure impulse. The pressure as it emerges from the throat is therefore just equal to the critical pressure (0.528 for air) regardless of the pressure in the region into which it is expanding. The effects of pressure ratio on the velocity in the "sonic" nozzle are shown in FIG. 7. When developing the flow system for circuit interruption, supersonic flow theory is used as a first approximation. Once the properties of the ionized gases are known, a more exacting modified supersonic flow theory can be used. If the fluid at the point of measurement has undergone only isentropic changes, its stagnation pressure may be assumed to be the reservoir pressure p_o. A measurement of the static pressure p_1 then determines the Mach number or:

$$p_o/p_1 = (1 + [-1/2]M^2)\ (\gamma)/\gamma - 1 \qquad (5)$$

where

p_o = reservoir pressure

p_1 = static pressure at a point in the flow

M = Mach number

γ is the ratio of specific heats for the fluid in question. For sonic flow for air, $C_p/C_v = \gamma = 1.4$, then $p_1/p_o = 0.528$ which is the critical pressure ratio for conventional nozzles.

A schematic of a supersonic flow nozzle is shown in FIG. **8.** If the pressure ratio is decreased below the critical ratio in this design, the fluid, after passing through the throat at the velocity of sound, will continue to increase in velocity as it expands and will emerge from the nozzle as a supersonic stream. The relation between the pressure, density, and absolute temperature at any point in the nozzle for supersonic flow is given by equations (5), (6) and (7), respectively. They are plotted vs Mach number (ratio of velocity to that of the sonic velocity) for air in FIGS. **9** and **10.**

$$p_o/p_1 = (1 + [\gamma - 1/2]M^2)\ (1/\gamma - 1) \quad (6)$$

$$T_o/T_1 = 1 + (\gamma - 1)/(2)\ M^2 \quad (7)$$

It is noted from equation (7) that at Mach 2, or twice the speed of sound, the temperature is drastically reduced. For air, if the reservoir temperature was 70°F., the temperature at Mach 2 would be −165°F. As previously mentioned, a lower temperature will permit a breaker to interrupt an electrical arc more efficiently.

The sonic velocity for a fluid is given by equation (8).

$$V_{sonic} = \sqrt{2\gamma RT_o/(\gamma + 1)} \quad (8)$$

For air,

$$V_{sonic} = 44.73 \quad \sqrt{T_o} \quad (8a)$$

where R is the gas constant. It can be seen that the maximum velocity at the throat for a particular gas is dependent on the stagnation temperature T_o and the type of gas.

The mass flow rate in pounds per second is given by equation (9).

$$m = 203.6\sqrt{\frac{\gamma}{\gamma+1}}\left(1+\frac{\gamma-1}{2}\right)^{-\frac{1}{\gamma-1}}\frac{A_t g p_o}{\sqrt{RT_o}} \quad (9)$$

It is noted from equation (9) that the maximum velocity is dependent upon temperature and type of gas. There is also a limit to maximum velocity that can be obtained. However, the limitation does not apply to mass flow rate as is shown by equation (9). For air, equation (9) reduces to the following:

$$m = 76.6\ \frac{A_t P_o}{\sqrt{T_o}}\ \text{sec} \quad (9a)$$

It is noted that the mass flow rate for a particular gas can be increased by either increasing the throat area, the stagnation pressure, or decreasing the stagnation temperature. Mass flow rate m varies directly with p_o the tank pressure, and A_t the throat area, and inversely as the square root of tank temperature T_o.

Velocity is an important factor in circuit interruption. It can be seen from equations (10) and (11) that the velocity of the gas at the exit does not increase directly with Mach numbers, but approaches very close to an asymptotic limit.

It was shown previously that the Mach number continues to increase as the area ratio of the divergent section increases provided the needed low pressure ratio is maintained. The velocity varies as shown by equation (10).

$$V = \sqrt{\gamma RT_o}\sqrt{\frac{M^2}{1+\frac{\gamma-1}{2}M^2}} \quad (10)$$

For very large values of M, equation (10) approaches equation (11).

$$V_{max.} = \sqrt{(2/-1)\ \gamma\ RT_o} \quad (11)$$

For Air

$$V_{max.} = 109.7\ \sqrt{T_o} \quad (11a)$$

Velocity vs Mach number is plotted in FIG. **12** for air. It is noted that the temperature and type of gas are the most important parameters in attaining high velocities in a nozzle.

It should be noted at this point that the advantages of using fluids other than air (different γ and R) to attain higher velocities should be considered. The velocities of other fluids are given in the following table:

TABLE I

Type of Gas	Ratio of Specific Heats, γ	Molecular Weight Wm	Universal Gas Constant R	Velocity of Sound at T = 520°R	V_{max} for T_o = 520°R
Carbon Dioxide CO_2	1.3	44	1,130	875	2,257
Air N_2 and O_2	1.4	29	1,714	1,118	2,498
Hydrogen H_2	1.4	2	24,860	4,260	9,513
Helium He	1.67	4	12,430	3,285	5,676
Neon, Ne	1.67	20.2	2,461	1,460	2,526
Argon, A	1.67	40	1,243	1,040	1,795
Oxygen, O_2	1.3977	32	1,554	1,062	2,383
Nitrogen, N_2	1.41	28	1,772	1,140	2,517

It should also be noted that when selecting a gas or fluid for interruption, the maximum velocity, dielectric strength and affinity to take on electrons must be considered.

The area ratio needed to achieve a given Mach number is given by equation (12).

$$\frac{A}{A_t} = \frac{1}{M}\left[\frac{1+\frac{\gamma-1}{2}M^2}{\frac{\gamma+1}{2}}\right]^{\frac{1}{2}\left(\frac{\gamma+1}{\gamma-1}\right)} \quad (12)$$

where

A is the area in question for a given Mach number

A_t is the area of the throat.

FIG. **11** shows a plot of area ratios vs. Mach number for air. Of course the pressure ratio across the nozzle must be equal to or less than that required to give the desired Mach number.

While area ratio is the criterion governing the Mach number of the flow in the nozzle at any point, it is necessary that the shape of the nozzle between the throat and that point conform to a certain definite form if the flow is to emerge uniform across its cross section. The most common method for determining the correct shape has been developed from the "method of characteristics" and is sometimes called "the method of numbers". The method was originally described by Prandtl and Busemann and has been enlarged upon and made applicable to engineering usage by other authors. The equations of motion assume such a form that they may be solved graphically, in a step-by-step process. This method was used in determining the dimensions of nozzles utilized in a prototype breaker hereinafter described. In a practical circuit breaker, it may be necessary to use a supersonic diffuser D such as shown in FIG. **32**, in order to keep the sound to a reasonable level.

III. CIRCUIT BREAKER CONFIGURATIONS

Possible circuit breaker configurations will be described next. There are of course an infinite number of configurations which are possible. Basically all that is needed is a supersonic nozzle, an interrupter structure, and the required pressure ratio across the nozzle.

FIGS. **13** and **13A** show the basic units. The nozzle and interrupter can be one unit, as shown in FIG. **13A**, or separate units, as shown in FIG. **13.** The pressure ratio can be obtained by increasing P_o, or decreasing P_1, or a combination of both. The pressure P_o can be obtained by means of a compressor.

FIGS. **14** and **14A** show schematics of a closed and an open fluid system, respectively, each using a compressor. The pressure P_o could also be obtained by means of self-generated pressure due to thermal heating by an auxiliary arc, or by means of a puffer. A puffer is comprised of a piston and cylinder which is actuated to compress the gas and force it into the arc.

Note that when a device such as a compressor is used to produce high pressure, a blast valve is needed. however, when the pressure is obtained by a self-generated means or a puffer no blast valve is required. The exhaust pressure, P_1, can also be lowered by a vacuum pump.

The interrupter can take many forms, such as cross-blast, axial-flow, axial-flow with cross-blast, etc. An example of a cross-blast interrupter is shown in FIG. **15.** In this case the supersonic nozzle N exhausts into an arc chute AC containing splitters S with the contacts C1 and C2 being drawn apart between the nozzle and the splitters. The nozzle can be circular, square, rectangular, or any other suitable cross section.

An axial flow nozzle N is shown in FIG. **16.** If desired, an auxiliary nozzle AN may be provided to increase the mass flow of the interrupting medium directed through the arc.

FIG. **17** shows diagrammatically an arrangement where the contacts C1 and C2 are drawn apart outside the nozzle N and the arc runs into the nozzle on conducting runners AR.

Another circuit breaker scheme is shown in FIG. **23.** This is a closed system and is suitable for use with an interrupting medium such as SF_6, to conserve the medium.

FIG. **18** shows an open system which can be used with air or any other suitable fluid, which is relatively inexpensive.

FIG. **19** shows a self-generated pressure arrangement utilizing a double break. The pressure P_o is produced by the arc drawn between contacts C1 and C2. The medium flows through nozzle N to interrupt the arc between contacts C3 and C4.

Arrangements using more than one break or multi-breaks can be utilized. FIGS. **20** and **21** show schemes in which more than one break is fed by the same nozzle. FIG. **22** shows a structure in which three nozzles N1, N2 and N3 are fed by one blast valve.

As previously stated, the process of interrupting an electric circuit is essentially that of introducing insulation at some point in the circuit so that the current will cease to flow. In fluid breakers, such as those using compressed air or sulfur hexafluoride, the fluid as blown around and through the arc and the arc is extinguished. Other breakers, such as magnetic or oil breakers, also use a flow interrupter of some type. An efficient breaker must remove the ionized gases as quickly and as efficiently as possible, thus restoring the dielectric strength of the gas between the contacts and interrupting the current.

A study of prior breakers has shown that improvements in flow systems can result in an increased capacity of the breaker. Orifices, obstructions, expansions and contractions are but a few of the flow conditions which must be considered for the most efficient breaker. The flow system is like a chain; each link or each part of the flow system — tank, valve, orifice, nozzle, contacts, are chute and splitters are links in the flow chain — the weakest link determines the overall capacity of the breaker.

A circuit breaker of the cross-blast type shown diagrammatically in FIG. **24** takes advantage of high-speed flow to remove ionized gases quickly, and of directed expansion to interrupt the arc. High-speed flow is obtained by providing a supersonic nozzle N as previously descirbed, and directed expansion is obtained by making the arc chute AC a continuation of the nozzle N to provide for smooth flow and continuous expansion of the arced gases. The expansion angle of the arc chute is greater than the expansion angle of the nozzle in order to take care of increased expansion caused by arc heat. The arc chute may be either generally rectangular, square, elliptical or circular in cross section as shown in FIGS. **25, 26, 27** and **28,** respectively, with progressively increasing cross sectional areas between the entrance end of the chute adjacent the nozzle and the exit or outer end of the chute.

The arc chute used in a prototype breaker hereinafter described was constructed as a two-dimensional plane flow nozzle. The computation of flows of a frictionless incompressible fluid around general two-dimensional boundaries presents problems of some mathematical difficulty. The additional condition that the density of the fluid may vary will complicate the problem under certain conditions. However, in those cases were the velocities in the flow field are everywhere greater than the local speed of sound, a fundamental simplification occurs, permitting again the use of the "method of characteristics".

This simplification, applied to a two-dimensional flow field in which the velocity is everywhere supersonic, permits the flow field to be represented approximately by a number of small adjacent quadrilateral flow fields in each of which the velocity and pressure are constant. These quadrilaterals must be separated by lines representing waves in the flow. Changes in velocity and pressure through any wave can be computed. By increasing the number of small areas into which the complete flow field is divided, the accuracy of this approximate solution can be increased. Such an analysis is applied throughout the entire length of the nozzle from entrance to exit resulting in a complete profile of a two-dimensional plane flow nozzle.

FIG. **1** shows a prototype circuit breaker embodying principles of the present invention. Basically the breaker comprises a reservoir R, a valve V, a plenum chamber PC, a supersonic nozzle N**1**, a contact piece or transition member TM, contact members C1 and C2 and an arc chute AC. The valve V may be an electrically operated valve of a type well known in the art. The valve is connected through a pipe **10** to the plenum chamber and through a pipe **11** to the reservoir R containing air, or other suitable interrupting medium, under pressure maintained by a compressor (not shown).

In order to insure a well established pressure head in the plenum chamber PC, the valve V is controlled to open a short time before the contacts are separated during an interruption. Starting the flow in the system before "contacts part" is standard procedure on most breakers. Although a plenum chamber is used in the present breaker to avoid turbulent conditions in the nozzle, the plenum chamber can be eliminated by providing a blast valve which will give uniform flow into the nozzle.

The nozzle N**1** is devised to give a Mach number of 1.44. It is shown in more detail in FIG. **2.** A similar nozzle N**2,** devised to give Mach 1.0, is shown in FIG. **3.** Each nozzle may be held on the plenum chamber PC by means of a sectionalized clamping ring **12.** Thus, the nozzles may be interchanged for test purposes. The orifice **13** of the plenum chamber is well blended into the entrance of each nozzle to assure smooth flow into the nozzle.

The stationary contact member C1 and the movable contact member C2 extend through the transition member TM which supports the arc chute AC on the nozzle N**1.** The member TM is screwed onto the nozzle, the upper end of which is threaded as shown in FIG. **2.** The member TM is preferably composed of polytetrafluoroethylene which is sold under the trade name "Teflon".

Likewise, the arc chute AC is preferably composed of Teflon. The arc chute and a support ring **14** are held on the member TM by a holder **15** attached to the member TM by bolts **16** and nuts **17.** Thus, the arc chute may be interchanged with other arc chutes. Since the nozzles are interchangeable, the effects of various nozzle and arc chute configurations upon the arc interrupting ability of the breaker can be studied. The arc chute is constructed to provide smooth flow and continuous expansion of the arced gases. The expansion angles takes into consideration the fluid dynamic characteristics of the expanding gases and closely approximates the maximum Prandel-Meyer angle for a change in velocity from M = 1, to M = 1.44, as explained in ELEMENTS OF GAS DYNAMICS, by H.W. Liepmann and A. Roshko, John Wiley and Sons, Inc. This was done to keep the arc chute to a minimum length.

However, a supersonic arc chute constructed as the chute AC' shown in FIG. **30,** would be more efficient. In the chute illustrated in FIG. **1,** the expansion is carried out in only one direction, the other being held constant. As hereinbefore described and shown in FIGS. **25** to **28,** the chute can be constructed for multiple direction expansion.

In the prototype breaker herein described, the transition member has one-dimensional expansion of flow, the arc chute has two-dimensional expansion and the nozzle has symmetrical three-dimensional expansion, one-dimensional flow or motion takes place in a tube of constant area. Expansion only takes place in the x direction. Two-dimensional flow involves expansion in two directions only (x, y). Three-dimensional flow involves expansion in directions given by three coordinates x, y, z.

The movable contact member C2 is slidably disposed in the transition member TM and inside a plunger tube **21** attached to the support ring **14** by a bracket **22.** The outer end of the contact C2 is carried by a guide **23** slidably disposed inside the tube **21.** An enlarged portion **24** on the contact C2 is engaged by the guide **23.**

In the present structure the movable contact is actuated to the closed position by a cocking screw **25** which is screwed into an insert **26** in the outer end of the tube **21** to engage the end portion **24** of the contact C2. The contact C2 is held closed against the force of an accelerating spring **27** by a tripping latch **28** having a projection **29** disposed in a groove **31** in the guide **23.** The latch **28** is pivotally mounted on a support **32** attached to the support ring **14** and is biased to the closed position by a spring **33.** Contact pressure between contacts C1 and C2 is maintained by a spring **34** disposed between a collar **35** on the contact member C2 and the guide **23.** The screw **25** is returned to the position shown after the contacts are closed in order to permit them to be opened when the latch **28** is released.

The tripping latch **28** is released by means of a solenoid **36,** the energization of which is controlled by a controller contact **37.** The contact **27** is so constructed that solenoid **38** is energized slightly before the solenoid **36.** The solenoid **38** opens the valve V against the force of a spring **39.** In this manner the interrupting medium is admitted to the plenum chamber PC a short time before the contacts C1 and C2 are separated to draw an arc. The contacts C1 and C2 are connected to a power source by conductors (not shown). It will be understood that closing and tripping mechanisms of a type well known in the art may be provided in place of those shown.

The results of tests made on the prototype breaker are shown in FIG. **4.** Curve **1** is for a prior breaker and curve **2** is for the new breaker herein described. These curves show that with a pressure of 20 psig the new breaker interrupted over three times the power (KVA).

Therefore, a new concept of arc interruption has been evolved, this concept being that with the proper choice of expansion gradient, temperature, density and velocity of an interrupting medium, forces are brought to bear on the arc which are greater than the electrical forces sustaining it. As herein before described, this imbalance can be created with smaller component parts than those required heretofore.

Since numerous changes may be made in the above-described constructions, and different embodiments of the invention may be made without departing from the spirit and scope thereof, it is intended that all subject matter contained in the foregoing description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

We claim as our invention:

1. A gaseous-type circuit-interrupter comprising a nozzle structure having an entrance portion, throat portion, supersonic region and a downstream portion, means for establishing an arc at a location within said supersonic region, said entrance portion of said nozzle receiving a gas under pressure, said throat portion maintaining a sonic flow of said gas, and said supersonic region and downstream portion maintaining supersonic flow of gas during the interruption of said arc.

2. The combination according to claim 1, wherein the kinetic energy of the gas within said supersonic region varies in the range from Mach 1 to Mach 2.

3. The combination according to claim 1, wherein the kinetic energy of the gas within said supersonic region is maximized.

4. The combination according to claim 1, wherein means defining an aspirating opening is provided into the supersonic region.

5. The combination according to claim 1, wherein a pair of spaced divergent arc-horns is provided along the side-walls of the supersonic region.

6. The combination according to claim 1, wherein a plurality of serially-related breaks are provided within said supersonic region.

7. The combination according to claim 1, wherein a plurality of spaced arc-splitters are provided within the downstream portion.

8. The combination according to claim 1, wherein means defining an enclosure is provided about the downstream portion.

9. The combination according to claim 1, wherein the arc is established transversely of the flow of pressurized gas, whereby a cross-blast action is achieved.

10. The combination according to claim 1, wherein contact-means are provided to establish an arc longitudinally within the supersonic region.

11. The combination according to claim 1, wherein the means for etablishing a pressurized gas constitutes a serially-related arc.

12. A gaseous-type circuit-interrupter comprising a nozzle structure having an entrance portion, throat portion, supersonic region and a downstream portion, means for extablishing a plurality of arcs at a location within said supersonic region, said entrance portion of said nozzle receiving a gas under pressure, said throat portion maintaining sonic flow of said gas, and said supersonic region and downstream portion maintaining a supersonic flow of gas during the interruption of said plurality of arcs.

13. The combination according to claim 1, wherein the supersonic region is defined by a rectangularly-shaped arc-chute.

14. The combination according to claim 1, wherein the supersonic region is defined by a circularly-shaped divergent arc-chute.

15. The combination according to claim 1, wherein the supersonic region is defined by a square-shaped arc-chute.

16. The combination according to claim 1, wherein the supersonic region is defined by an oval-shaped arc-chute.

17. The combination according to claim 7, wherein the arc is established within the supersonic region immediately adjacent to said plurality of splitter plates.

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