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F. FRUENGEL ET AL
METHOD AND APPARATUS FOR HIGH-SPEED PHOTOGRAPHY
OF GAS FLOW PHENOMENA

3,197,675

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2 Sheets-Sheet 1

FIG. 1

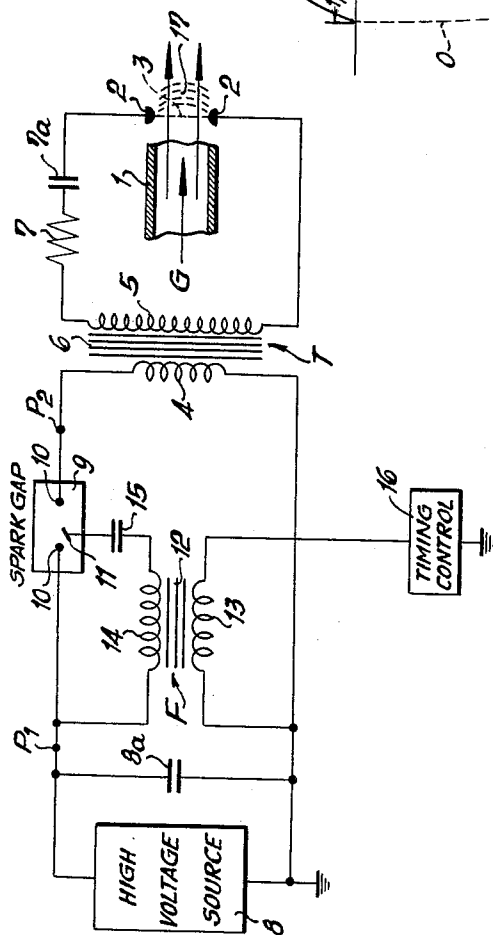


FIG. 2

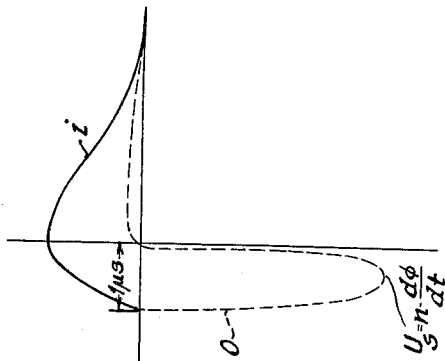


FIG. 1b

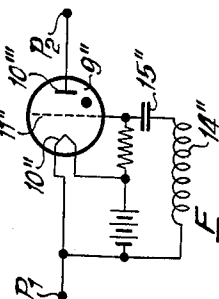
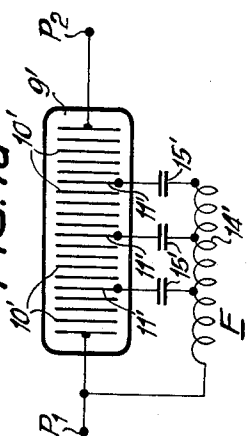


FIG. 1a



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FIG. 3

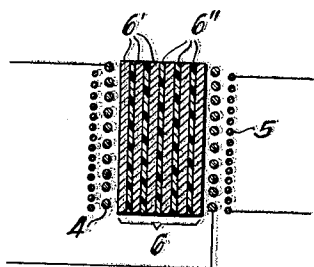


FIG. 3a

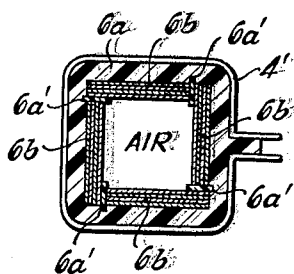
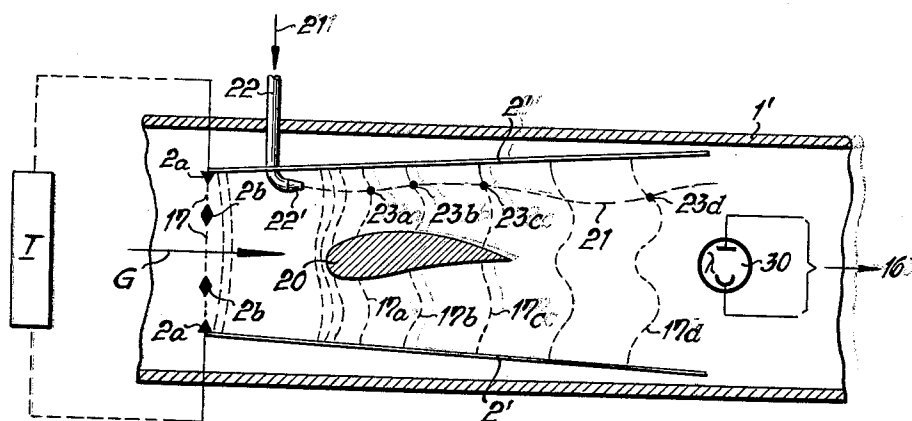


FIG. 4



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METHOD AND APPARATUS FOR HIGH-SPEED
PHOTOGRAPHY OF GAS FLOW PHENOMENA

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19 Claims. (Cl. 315-111)

The present invention concerns an apparatus for high speed photography of gas flow phenomena.

In this field of photography gas is caused to flow through a channel or out of a channel under various flow conditions and at varying speeds, suitable spark gap electrodes being arranged across the stream of gas and a photographic apparatus of generally known type being arranged to produce pictures of spark phenomena appearing between the spark electrodes and a portion of the gas stream beyond these spark electrodes in the direction of flow of the gas. For obtaining pictures illustrating gas flow phenomena a sequence of high frequency pulses is applied to the spark gap electrodes with the result that the spark plasma existing along the path of each individual spark is carried along by the gas stream and the light emission of each consecutive spark illuminates the plasma of the preceding sparks traveling with the gas stream. Consequently, the photographic picture shows an array of consecutive illuminated plasma lines each of which is derived from the theoretically straight original path of the spark and carried away and possibly distorted depending upon the particular flow conditions existing in the gas stream in the photographed area.

While arrangements are known for carrying out high speed photography of gas flow phenomena of the type described above in which the distance between the spark electrodes or, in other words, the size of the spark gap is comparatively small, it has not been possible up to now to produce such photographs in which the distance between the spark gap electrodes, the spark frequency and the electric energy of the spark discharges is greatly increased.

It is therefore a main object of the present invention to provide for an apparatus capable of producing spark path photographs from discharges between electrodes at least 8 inches apart, involving energies up to 40 megawatts at a rate of up to 50,000 discharges per second, at voltages rating up to 250 kilovolts and with pulse durations of the order of 1 microsecond or less.

Further objects of the invention will become apparent from the following description.

With above objects in view the invention provides in an apparatus for high speed photography of gas flow phenomena including channel means for delivering a stream of gas, in combination, spark gap means located in the area of the channel means for directing spark discharges across the stream of gas; pulse transformer means having components consisting of a primary coil, a secondary coil and an open, laminated ferrous metal core, said secondary coil being connected in the circuit with said spark gap means, said components being dimensioned to determine a coupling factor of so small a value that the output current is substantially the first differential of an input pulse current applied to said primary coil; and pulse input means in the circuit with said primary coil for applying thereto pulse sequences of predetermined frequency at predetermined pulse durations.

The novel features which are considered as characteristic for the invention are set forth in particular in the appended claims. The invention itself, however, both as to its construction and its method of operation, together with additional objects and advantages thereof, will be best understood from the following description of specific

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embodiments when read in connection with the accompanying drawings, in which:

FIG. 1 is a schematic circuit diagram illustrating one embodiment of the invention;

FIGS. 1a and 1b illustrate alternatives of a component of the arrangement of FIG. 1;

FIG. 2 is a graph illustrating the relation between an input pulse and an output pulse;

FIG. 3 is a schematic illustration, partly in axial section of an impulse transformer forming part of the arrangement according to FIG. 1;

FIG. 3a is a diagrammatic end view of an alternative type of impulse transformer; and

FIG. 4 diagrammatically illustrates the installation and operation of an embodiment of the invention in a wind tunnel.

Referring now to FIG. 1 a portion of a channel 1 is illustrated through which, by means not shown, a stream of gas G can be forced to flow in the direction of the arrows. Within the channel 1 or adjacent to its delivery opening a pair of spark electrodes 2 is arranged defining between themselves a spark gap 3. A pulse transformer T is provided which is composed mainly of a primary coil 4, a secondary coil 5, and an open, laminated core 6. Details of this transformer will be described further below with reference to FIG. 3. The spark gap electrodes 2 are connected in circuit with the secondary coil 5 with the interposition of an attenuating resistor 7, or of a current-time limiting condenser 7a.

For applying energizing pulses to the primary coil 4 a supply and control circuit is provided which is preferably of the type known under the trade name "Strobokin." In the illustrated example, this supply and control circuit comprises a source of high voltage electrical energy 8 connected in circuit with the primary coil 4, but with the interposition of a spark gap device 9 which serves as a switching device. Under ordinary circumstances the spark gap device 9 is in a non-conductive condition so that the circuit between the source 8 (or a charge condenser 8a charged by source 8) and the primary coil 4 is interrupted between the spark electrodes 10. However, whenever a suitable potential is applied to the auxiliary or igniting electrode 11 in the spark gap device 9 a break-down of the spark gap occurs and energy from the source 8 (or from condenser 8a) is applied to the primary coil 4 as an input pulse. An auxiliary circuit is provided for determining the duration of such input pulses and for timing their sequence. For this purpose, the auxiliary circuit comprises a second transformer F having a core 12, a primary coil 13 and a secondary coil 14. The secondary coil 14 is connected between one of the electrodes 10 and the auxiliary or igniting electrode 11 across a condenser 15. The primary coil 13 is connected in circuit with a timing control device 16 which is capable of energizing the primary coil 13 for predetermined duration and at predetermined intervals.

Whenever an energizing pulse is applied from the timing control device 16 to the transformer F the igniting electrode 11 renders the spark gap device 9 conductive, so that an input pulse from the source 8 is applied to the primary coil 4 with the result that an output pulse is applied from the secondary coil 5 to the spark gap electrodes 2, so as to produce a spark discharge across the gap 3.

The arrangement of FIG. 1 is only an example, particularly as far as the spark gap device 9 is concerned.

The three-electrode spark gap device 9 may be replaced, as shown in FIG. 1a, by a quenched spark gap device 9' which operates in a similar manner. It comprises a plurality of stacked, but closely spaced plate electrodes 10', some of which (marked 11') are igniting electrodes and connected via one or several condensers 15', respec-

tively, to tapping points of the secondary 14' of the transformer F. Normally the circuit between source 8 (or condenser 8a) and the primary coil 4 is interrupted between the first and last electrode (end plates) 10'. Upon application of igniting potential to electrodes 11' the spark gap device 9' breaks down and an impulse is applied to transformer T.

A second, although more expensive alternative is illustrated by FIG. 1b. In this case a high-emission hydrogen thyatron 9'' is connected between the circuit points P₁ and P₂ in the manner shown. The thyatron 9'' may have a vessel of ceramic material and a plane cathode 10''. The grid 11'' acts as ignitor, and cathode 10'' and anode 10''' act in a manner similar to the spark electrodes 10 when igniting potential is applied to grid 11'' from secondary 14'' via condenser 15''.

As is intimated in FIG. 1 by phantom lines 17 the spark plasma existing originally along a comparatively straight path between the electrodes 2 across gap 3 will be carried along the gas stream G in the direction of the arrows and, upon production of a sequence of spark discharges a picture of a series of more or less distorted curves will be obtained which illustrate in a generally known manner the flow conditions in the gas stream.

In order to obtain pictures of this nature, which can be evaluated and interpreted precisely and in accordance to a preselected scale, it is of extreme importance to use in the sequence of spark discharges a great constancy of the pulse frequency and great precision in timing the start of the consecutive discharges. On the other hand, in order to reduce to a minimum any possible disturbance of the gas flow by the spark discharges it is also necessary that the amount of energy comprised in the individual spark discharges is as small as possible, yet sufficient for producing a sufficient intensity of light for producing a satisfactory photograph. Therefore, the individual voltage impulses must be as brief as possible which will also result in a very sharp line picture of the illuminated spark plasma curves.

A supply and control circuit of the type described above, and particularly the type known under the trade name "Strobokin" makes it possible to produce pulse sequences, under the control of electronic or crystal devices, at frequencies of up to 140,000 sparks per second. The discharge pulses derived from the spark gap device 9 have a duration of the order of 1 microsecond and are transformed by the pulse transformer T to a very high voltage.

It is important to note that an optimal condition is obtained if the charging energy $\frac{1}{2}CE^2$ (in Joules) of the condenser 8a is selected or predetermined to match the parameters of the iron core 6 of transformer T in such a manner that the energy (in Joules) required for magnetizing the core 6 to full saturation is nearly equal, for every discharge of the condenser 8a, to its charging energy.

FIG. 2 will serve to illustrate the function of the pulse transformer T. Assuming that the input pulse applied to the input coil 4 has approximately the form of the curve *i* of FIG. 2, with a comparatively steep rise up to maximum potential with a following more gradual decay, then an output pulse represented by the dotted curve *o* of FIG. 2 can be obtained, provided that the number of turns of the secondary coil 5 and all the other parameters of the transformer T are so chosen, for the purpose of keeping the coupling factor very small, that the output current is substantially the first differential of an input pulse current applied to the primary coil 4. Since the output pulse can be calculated by the equation

$$U_s = n \frac{d\Phi}{dt}$$

wherein *n* represents the number of turns of the secondary coil 5 evidently the desired results can be obtained.

FIG. 3 illustrates diagrammatically in greater detail a

desirable structure of the pulse transformer T according to the invention. As can be seen, the transformer has the above mentioned input coil 4 and the output coil 5 and an open laminated core 6. This core 6 is composed of very thin laminations 6' of ferrous metal preferably of a material of high permeability and having also a high saturation point, e.g., of 20,000 gauss, for instance that known by the trade name "Hypersil" with interspaced layers 6'' of insulating material, preferably consisting of a material known by the trade name "Hostaphane" or a high quality paper having a dielectric strength of 600,000 v./cm. or more.

FIG. 3a illustrates another suitable core construction for the pulse transformer. In this case an input or primary winding 4' is separated by a layer 6a of the above recommended insulating material from a hollow core assembly composed of four stacks 6b of laminated ferrous metal of the above described type, with insulating layers 6a', e.g., of hard paper, interposed between consecutive or adjoining stacks. The secondary winding is suitably arranged although not visible in FIG. 3a. This construction is particularly suitable for transformers of comparatively large size.

It has been found that in an arrangement according to the invention as described above, and arranged in association with a wind tunnel sparks of a length ranging between 8 inches and 20 inches are produced by utilizing a pulse transformer as described and capable of handling energies up to 40 megawatts and discharge sequences amounting to 50,000 discharges per second, controlled to have durations between 0.3 and 1 microsecond, with voltages rating up to 250 kilovolts. Controlled ultra-rapid spark discharges at 5,000 to 300,000 discharges per second have been fed into the primary coil 4 of the pulse transformer T as described. At a voltage of approximately 5 kilovolts per turn, the thin laminated low loss, high permeability sheet core is charged to magnetic saturation values in approximately .2 microsecond. The result is a steep voltage step-up at the secondary coil 5, which at 75 turns, for example, produces a no-load voltage of 300 kilovolts.

If the electric energy applied to charge the condenser 8a is equivalent to the magnetic energy required to saturate core 6 (or 6b), then the curve illustrating the charging will correspond to the curve in FIG. 2, the rise being nearly linear without any oscillatory deviations or noticeable change of the angle of inclination. Experience shows that every kilogram of a satisfactory ferrous core may consume up to .2 Joule of energy so that, e.g., for a pulse of 8 Joules energy a core mass of the order of 40 kilograms would be desirable.

Due to the short spark discharge time no picture blur results even at a gas flow of several Machs. Although the spark luminance is sufficient for high speed photography, practical experience shows that its low energy does not cause thermodynamic disturbances of the observed gas flow. The lowest possible spark rate where no de-ionization occurs is 5,000 sparks per second at a spacing of 1 mm. between sparks, corresponding to a gas current velocity of 5 meters per second, whereas the maximum spark rate of 300,000 sparks per second at a spacing of 10 mm. between consecutive sparks corresponds to a gas current velocity of 3 kilometers per second, i.e., approximately Mach 9. Also patterns of explosion and detonation shock waves and their subsequent eddy currents can be traced by the above outline spark method.

In addition for obtaining still better and more valuable photographs, it has been found advantageous to introduce a second different gas into the gas stream G of FIG. 1, the second gas being so chosen that the spark discharge will produce therein a color different from the color produced by the spark discharge in the main gas stream. In this case, color photos are to be taken. Under these circumstances the resulting two-color picture of gas discharges furnishes not only, for evaluation of the photo-

graph, abscissa data in the direction of the movement of the gas stream but also ordinate points in transverse direction.

FIG. 4 will illustrate a most useful application of the invention incorporating the above discussed features. For this purpose only a comparatively large size wind tunnel 1' is shown which corresponds to channel 1 of FIG. 1. The electrodes 2a correspond to electrodes 2. The rest of the circuitry of FIG. 1 is omitted from FIG. 4. The main electrodes 2a are supplemented by electrode wires 2' extending in lengthwise direction of tunnel 1', but need not be parallel with each other. When discharge occurs the spark will primarily travel along a substantially straight path 17 between the main electrodes 2a which may be pointed. If desired, the path 17 may be more positively predetermined by auxiliary electrodes 2b arranged along the desired path without being part of a circuit, serving only as "stepping stones."

An air foil 20 may be mounted in the tunnel 1' between the electrode wires 2' shown. The latter should be very clean and are preferably made of silver or nickel.

When a series of spark discharges is produced between the main electrodes 2a and a flow of gas G is caused through the tunnel 1' in the direction of the arrow, then a sequence of luminous spark path lines will appear in the area of the tunnel beyond the main electrodes 2a, as the gas stream G carries them along, and the opposite ends of these spark path lines travel along the wire electrodes 2' which give them a "footing." Where the gas stream is interrupted or split by the air foil 20 the spark path lines will also travel along the flanks of the air foil 20 as indicated by a few illustrations of randomly selected lines 17a, 17b, 17c, the actual spacing between consecutive spark path lines being much closer and, in view of the known frequency of, or time interval between, the sparks, the spacing between consecutive lines as they appear in the picture is an accurate, scaled indication of the speed of the gas stream at the respective point. Distortions of the spark path lines show all existing disturbances or variations of the gas flow due to the air foil, also the flow conditions in the boundary layer adjacent to the contour of the air foil 20. The material of the air foil (or any other object placed in the path of the gas stream) may be conductive or non-conductive. In the latter case the spark path lines will curve around the air foil until they have substantially passed its remote end. If the air foil (or other object) is made of metal it must be very clean and have a low electron work function as for instance silver, aluminum, stainless steel. Using a metal object favors observation of flow conditions in the boundary layer next to the contour thereof, while using a non-conductive object favors observation of the phenomena in the space surrounding the object.

Sometimes it may be desirable, for obtaining a perfect spark path line picture, to stop the sequence of sparks, e.g., when the first produced spark path line has traveled to a certain position, e.g., 17d. For this purpose a control device, e.g., a photocell 30 may be mounted adjustably in an area of the tunnel 1' remote from the main electrodes 2a and connected in a circuit of conventional type for its operation and with the timing control 16 (FIG. 1) for terminating the operation thereof in response to pick-up of illumination furnished by the foremost luminous spark path line 17d.

The above mentioned injection of a second gas of different spark color characteristics into the main gas stream G can be effected, as shown in FIG. 4, through a duct 22 ending in at least one nozzle 22' so that a narrow stream 21 of this second gas will travel from such nozzle with the main gas stream and will be distorted in transverse direction of the tunnel in the same manner as the main gas stream. This would result in the picture, if a color photograph is taken, in a colored (or differently colored) sequence of points 23a, 23b, 23c, 23d on the respective spark path lines 17a, 17b, 17c, 17d (and, of

course, on all other interspaced spark path lines not shown in FIG. 4). Thus, while the axial distances of e.g. points 23a, 23b, 23c, 23d from the line 17 can be evaluated as abscissae of a flow diagram furnished by the photograph, the transverse distances of these points from an axial reference line parallel with the wall of the tunnel 1' can be evaluated as the respective ordinates. Of course, also the nozzle 22' is preferably adjustable within the tunnel 1'.

It will be understood that each of the elements described above, or two or more together, may also find a useful application in other types of apparatus for high-speed photography differing from the types described above.

While the invention has been illustrated and described as embodied in the apparatus for high-speed photography of gas flow phenomena based on controlled spark discharges, it is not intended to be limited to the details shown, since various modifications and structural changes may be made without departing in any way from the spirit of the present invention.

Without further analysis, the foregoing will so fully reveal the gist of the present invention that others can by applying current knowledge readily adapt it for various applications without omitting features that, from the standpoint of prior art, fairly constitute essential characteristics of the generic and specific aspects of this invention and, therefore, such adaptations should and are intended to be comprehended within the meaning and range of equivalence of the following claims.

What is claimed as new and desired to be secured by Letters Patent is:

1. In an apparatus for high-speed photography of gas flow phenomena, including channel means of substantial width for delivering a stream of gas along a predetermined path at a gas stream velocity of between 5 and 3,000 meters per second, in combination, spark gap means of a substantial gap size located across the path of the gas stream produced by the channel means for directing spark discharges across said stream of gas; pulse transformer means comprising components consisting of a primary coil, a secondary coil and open, laminated ferrous metal core means, said secondary coil being connected in circuit with said spark gap means, said components being dimensioned to determine a coupling factor of so small a value that the output current is substantially the first differential of an input pulse current applied to said primary coil and therefore adapted to produce a brief, high voltage spark discharge in said spark gap means; and pulse input means in circuit with said primary coil for applying thereto pulse sequences of a frequency of between 5,000 and 300,000 pulses per second while said gas stream is moving at said gas stream velocity of between 5 and 3,000 meters per second and very short pulse duration.

2. An apparatus as claimed in claim 1, wherein said pulse input means include a source of high voltage and switching means changeable between non-conductive and conductive condition and connected between said source and said primary coil, and timing control means for rendering said switching means periodically conductive at a predetermined frequency and for uniform predetermined periods of time.

3. An apparatus as claimed in claim 2, wherein said switching means is a spark gap arrangement including a second pulse transformer and a spark gap device including at least one igniting electrode and capacitor means in circuit with the output of said second pulse transformer for igniting said spark gap device upon application of an energizing pulse to the input of said second pulse transformer, said input being connected in circuit with said timing control means for being energized thereby.

4. An apparatus as claimed in claim 3, wherein said spark gap device has a deionization time of between 1 and 10 microseconds.

5. An apparatus as claimed in claim 3, wherein said spark gap device is of the quenched spark gap type.

6. In apparatus for high-speed photography of gas flow phenomena including channel means for delivering a stream of gas along a predetermined path at a gas stream velocity of between 5 and 3,000 meters per second, in combination, spark gap means positioned across the path of the gas stream produced by said channel means for directing spark discharges across said stream of gas;

pulse input means for providing pulse sequences of a frequency between 5,000 and 300,000 pulses per second and very short pulse duration; and

pulse providing means coupling said pulse input means to said spark gap means for causing between 5,000 and 300,000 very short spark discharges per second while said gas stream is moving at said gas stream velocity of between 5 and 3,000 meters per second, the energy of said spark discharges being small enough to create minimum gas flow disturbance but sufficient to provide light for photographing the gas stream.

7. An apparatus as claimed in claim 6, wherein said pulse providing means includes pulse transformer means having core means and said core means of said pulse transformer means comprise a plurality of thin laminations of ferrous metal and a corresponding number of layers of thin insulating material interposed between said laminations.

8. An apparatus as claimed in claim 7, wherein said ferrous metal has an extremely small energy loss characteristic in a magnetization cycle and a high permeability μ of at least 500, and wherein said insulating material has a dielectric strength of at least 600 kv./cm.

9. An apparatus as claimed in claim 6, wherein said pulse providing means includes pulse transformer means having core means and said core means of said pulse transformer means comprises a plurality of stacks of thin laminations of ferrous metal arranged to form a polygon surrounding a hollow inner space, one end of each of said stacks being located adjacent to one end of another stack, respectively, with insulating material interposed between adjacent ends of said stacks.

10. An apparatus as claimed in claim 9, wherein said ferrous metal has an extremely small energy loss characteristic in a magnetization cycle and a high permeability μ of at least 500, and wherein said insulating material has a dielectric strength of at least 600 kv./cm.

11. An apparatus as claimed in claim 6, wherein said pulse providing means includes pulse transformer means having a secondary coil, and impedance means including an auxiliary capacitor connected in series between said secondary coil of said pulse transformer means and said spark gap means for limiting the current flow across the latter to a period of time corresponding to a predetermined amount of ampere-seconds.

12. An apparatus as claimed in claim 6, wherein said spark gap means comprise at least one pair of main spark electrodes and auxiliary electrodes connected with said

main spark electrodes, respectively, each of said auxiliary electrodes comprising an elongated conductor extending substantially in the direction of said stream of gas.

13. An apparatus as claimed in claim 6, including means for introducing into the channel means at least two different gases simultaneously for obtaining two-color pictures of spark discharges depending upon the different colors characteristic of the reaction of said different gases to spark discharges therethrough.

14. An apparatus as claimed in claim 6, wherein said channel means is a wind tunnel arrangement including a test object mounted in said gas stream, and wherein said spark gap means are mounted within said wind tunnel at a distance from said object in direction opposite to said gas stream.

15. An apparatus as claimed in claim 14, wherein said spark gap means comprise at least one pair of main spark electrodes comprising an elongated conductor extending main spark electrodes, respectively, each of said auxiliary electrodes comprising an elongated conductor extending substantially in the direction of said stream of gas.

16. An apparatus as claimed in claim 14, wherein said object is made of electrically non-conductive material.

17. An apparatus as claimed in claim 14, wherein said object is made of conductive material having a clean surface and having a low electron work function.

18. An apparatus as claimed in claim 14, including means comprising at least one nozzle located within said wind tunnel for introducing into said gas stream a second gas for obtaining pictures of at least two colors depending upon the different color characteristic of the reaction of said gas stream and, in contrast thereto, of said second gas to spark discharges therethrough.

19. An apparatus as claimed in claim 6, further comprising timing control means included in said pulse input means for controlling the pulse sequence provided by said pulse input means, and a control device for automatically terminating said pulse sequence which controls said spark discharge, said control device comprising photoelectric means mounted at a predetermined distance remote from said spark gap means in direction of said gas stream and responsive to illumination by said spark discharges across said gas stream, said control means being connected to said timing control means for stopping the operation of the latter upon response to said illumination.

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