Nov. 12, 1968 A. M. MARKS 3,411,025

METHOD AND APPARATUS FOR PRODUCING CHARGED AEROSOLS

Filed March 11, 1965 4 Sheets-Sheet 1

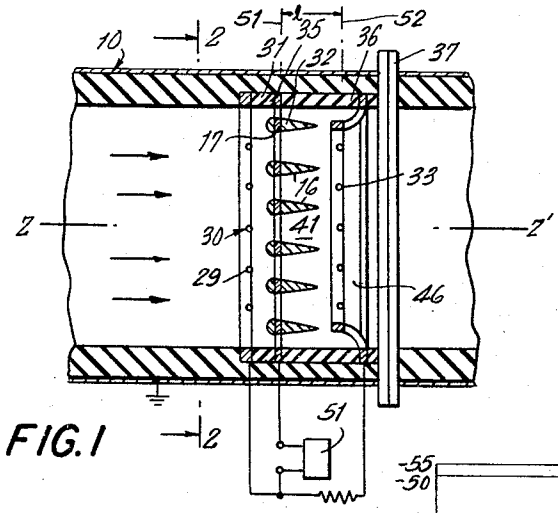

FIG. 1

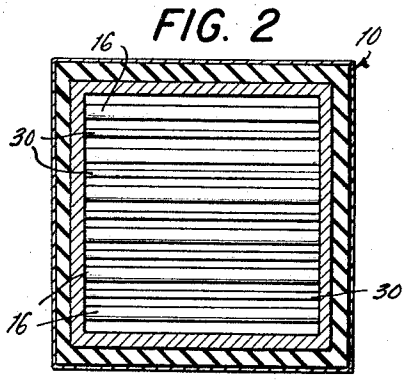

FIG. 2

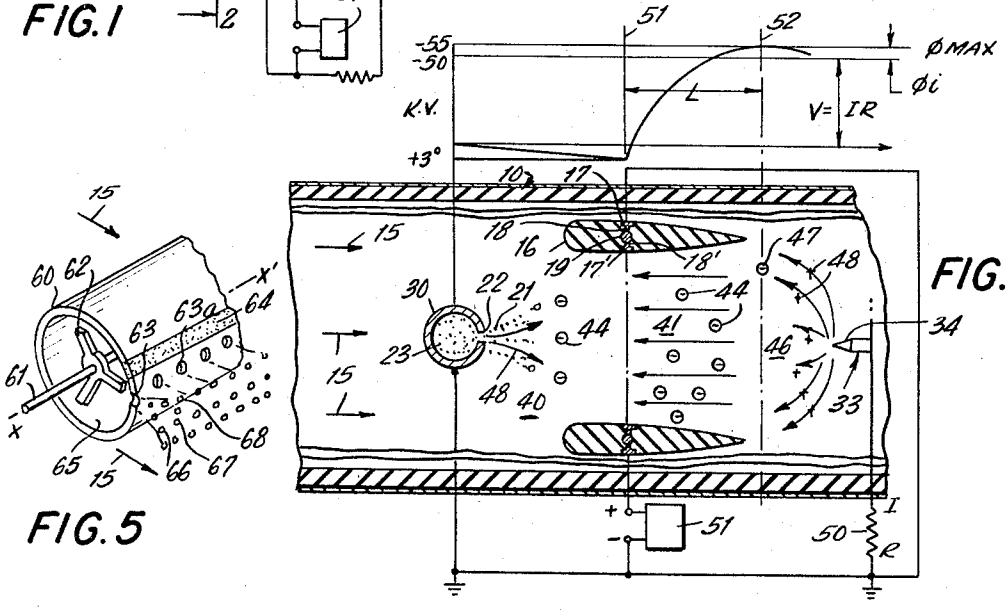

FIG. 3

FIG. 5

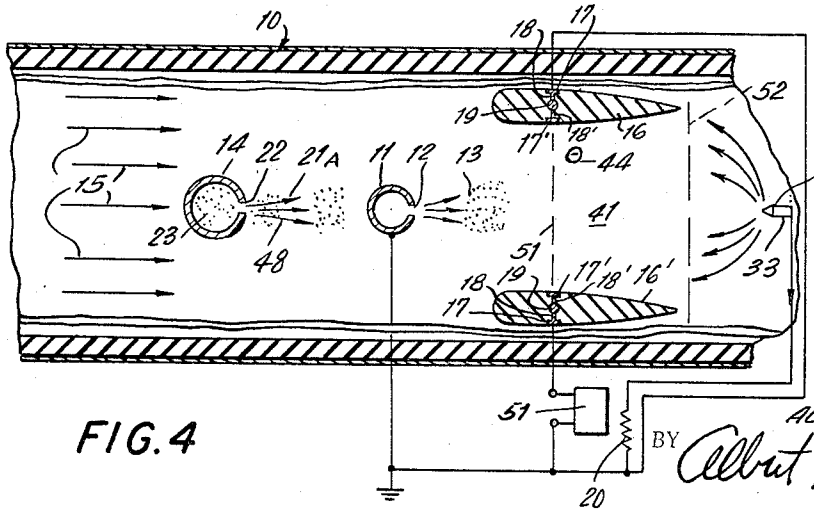

FIG. 4

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METHOD AND APPARATUS FOR PRODUCING CHARGED AEROSOLS

Filed March 11, 1965 4 Sheets-Sheet 2

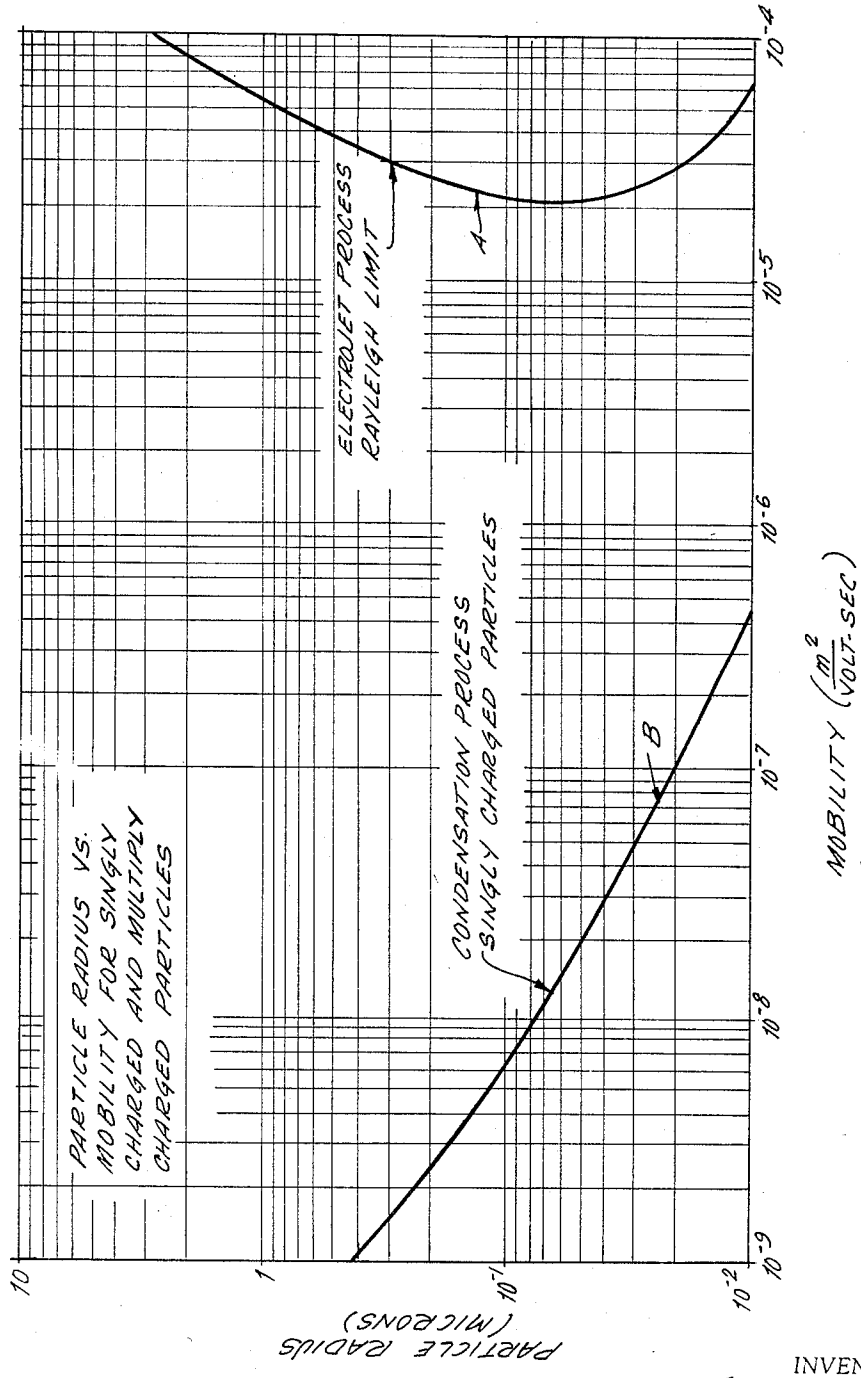

FIG. 6

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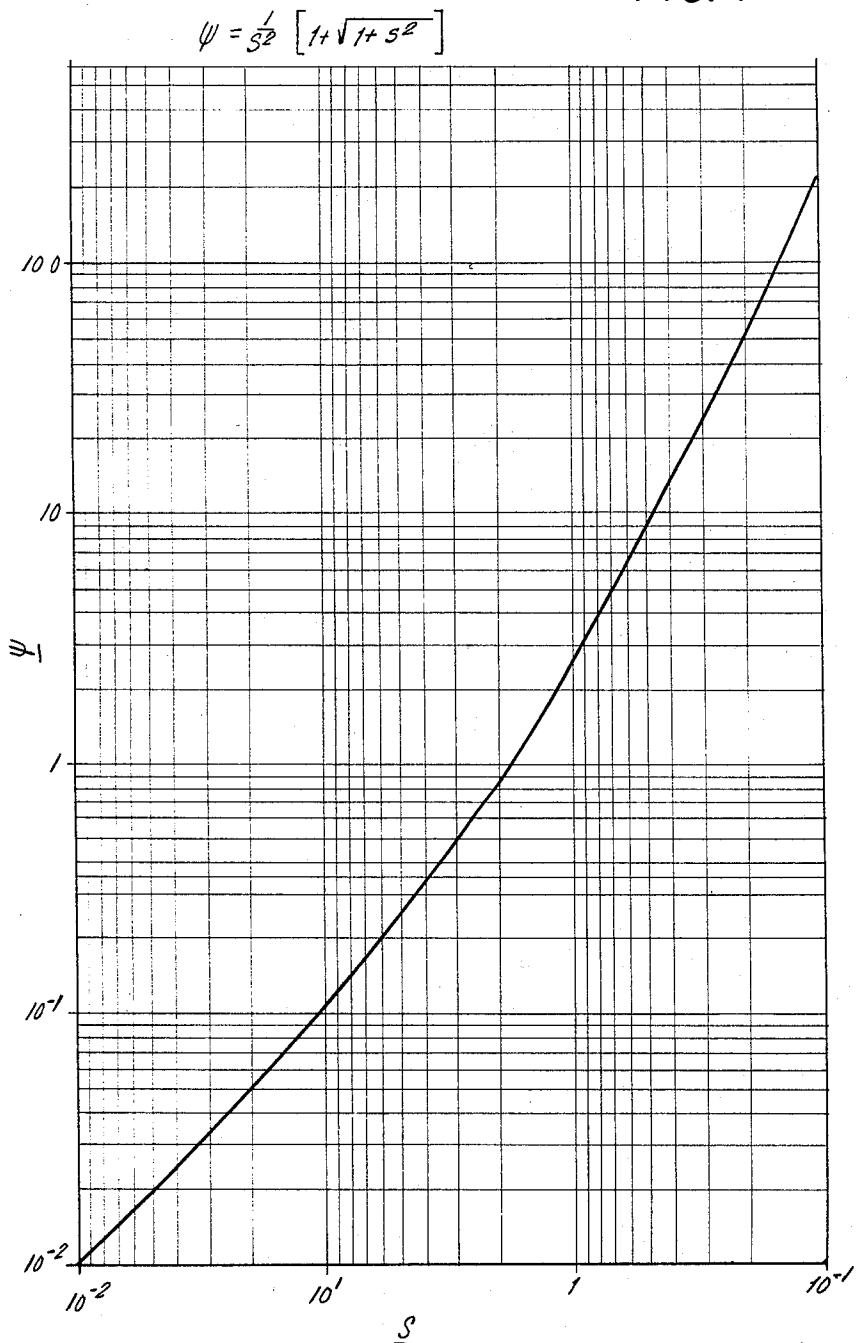
METHOD AND APPARATUS FOR PRODUCING CHARGED AEROSOLS

Filed March 11, 1965 4 Sheets-Sheet 3

FIG. 7



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Nov. 12, 1968 A. M. MARKS 3,411,025

METHOD AND APPARATUS FOR PRODUCING CHARGED AEROSOLS

Filed March 11, 1965 4 Sheets-Sheet 4

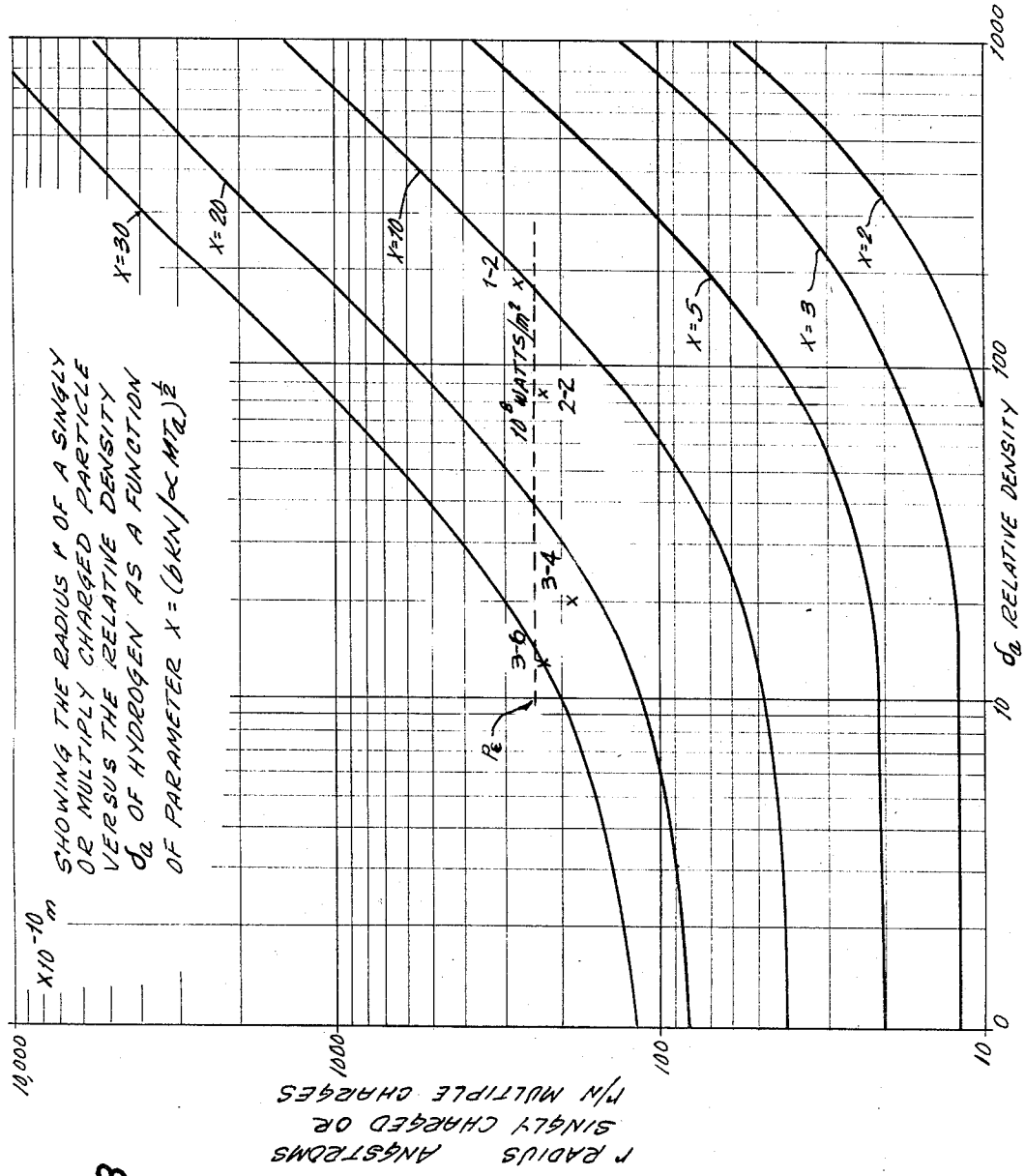

FIG. 8

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United States Patent Office 3,411,025
Patented Nov. 12, 1968

3,411,025

METHOD AND APPARATUS FOR PRODUCING CHARGED AEROSOLS

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Filed Mar. 11, 1965, Ser. No. 438,930
12 Claims. (Cl. 310—11)

ABSTRACT OF THE DISCLOSURE

A device to convert the heat kinetic power of a moving gas to electric power in which a moving gas under pressure containing a condensable vapor cools as it flows through ions in an electric field, the vapor condenses on the ions to form minute charged droplets and thereafter further condenses upon the droplets to form larger charged droplets which are passed through a conversion space having a repelling electric field. A collector electrode at the exit of the conversion space discharges the charged droplets, an electrical load is connected between the collector electrode and the ionizer. Various means for charging, forming, controlling and introducing the droplets are also disclosed.

This invention relates to a device for transducing the thermal and/or kinetic power of a moving charged aerosol gas to electric power and vice versa, with good aerodynamic and electrical efficiency.

In the conversion process, the charged particle is moving in a carrier gas against an electric field, which induces a slip velocity opposite to the velocity of the carrier gas. When the particle radius is small in relation to the electric charge per particle, a great number of charged particles may be present in a unit volume of gas and the charge density is large, but the slip velocity may then be a large fraction of the gas velocity. Excessive frictional power loss, and little or no power conversion may result. When the particle radius is large in relation to its electric charge, the slip velocity is small but there may be too few charged particles per unit volume and the charge density may be too small, and hence only a little power may be converted.

It has been shown that to efficiently and abundantly transduce power through the medium of a charged aerosol with negligible slip power loss, the charged particle must have an optimum radius in relation to its charge, and the number of charged particles per unit volume must be such as to provide the required charge density. The mathematical-physics of these relationships, set forth in U.S. Patent No. 2,638,555, has been substantially confirmed experimentally.

Definitions

The following terms employed herein are defined as follows:

The charge density of a charged aerosol is defined as the electric charge per unit volume of the charged aerosol.

The term "chafo" is an acronym for charged aerosol and formation.

Standard conditions for the gas are defined as 10^5 newtons/m.^{2} at 300° K.; or, approximately one atmosphere at 27° C.

Certain physical variables such as gas temperature and pressure are expressed relative to ambient conditions, using known physical laws.

Supersaturated vapor, as used herein, is a vapor in that condition in which it is capable of condensing upon an electrically neutral aerosol droplet.

A superheated vapor is one in which an electrically neutral droplet will evaporate. However, a supersaturated vapor tends to preferentially condense on ions or charged particles. A charged liquid particle may be stable in superheated vapor, where a neutral liquid particle will evaporate, provided the superheat is not too great.

The particle mobility is related to particle radius, particle charge, gas density and other physical parameters. Optimum values of these physical parameters for a charged aerosol gas to operate as an efficient power transducer are hereinafter derived.

Maximum electric field intensity necessary to operate the charged aerosol generator under the conditions of maximum power conversion occurs at just under the breakdown electric field for the charged aerosol gas under the conditions of operation.

The breakdown electric field in air under standard conditions is approximately 3×10^6 volts/m. The breakdown electric field strength of a gas is increased in approximately direct proportion to the gas density. The converted electric power increases as the square of the electric field intensity, and hence as the square of the gas density.

Mobility is defined as the velocity given to a charged particle or ion in a gas by a unit electric field intensity. It is expressed in the MKS system as the units m.^{2}/volt-sec. In air under standard conditions, negative ions or positive ions have a mobility of approximately 10^{-4} m.^{2}/volt-sec.

Under ambient conditions the application of the breakdown electric field intensity results in an ion velocity of about 300 m./sec. through the air. For power transducing devices, 300 m./sec. is a subsonic velocity within a suitable operating velocity range.

The "optimum mobility" of a charged aerosol particle is defined as that which results in a charged aerosol particle having an arbitrary negligibly small slip velocity, taken herein as 1% of the carrier gas velocity, under the near breakdown electric field intensity.

If an ion be placed under standard conditions in a gas stream moving at 300 m./sec. with an opposing electric field of maximum intensity, the forward motion of the gas is then equal to the slip velocity of the ion and the net velocity of the ion is zero; the kinetic power of the gas is lost in internal frictional heat; and no net power conversion results. Hence positive or negative free ions cannot be used for efficiently transducing heat-kinetic power to electric power.

Nor can unattached or free electrons be used as a power transducer between a moving gas and the electrical circuit, since their mobility is even greater than the mobility of a free ion.

For efficient power conversion the charged aerosol particles must have an "optimum mobility" which corresponds to an "optimum ratio of radius to electric charge." To use a still smaller mobility would not result in a useful improvement; the larger radius particle might result in fewer particles per unit volume and result in a smaller charge density. The optimum mobility of a charged aerosol particle depends on the choice of gas velocity. This velocity is usually chosen subsonic, not exceeding about 0.5 Mach to keep the gas friction power losses small. The gas velocity cannot be much less than 0.5 Mach to maintain a substantial electric current transport via the charged aerosol gas. As an example, under standard conditions and with subsonic gas velocity, the optimum mobility for the charged aerosol particle is 10^{-6} m.^{2}/volt-sec.

A mathematical-physics analysis will later set forth these relationships in detail, enabling the specification of optimum radius in relation to the electric charge under the various conditions of operation.

Objects

One of the objects of this invention is to provide an efficient charged aerosol power converter, which avoids one or more of the disadvantages and limitations of the methods and apparatus of the prior art.

An object of this invention is to provide an improved power transducer utilizing a charged aerosol of optimum characteristics suitable for employment as a generator, pump or thrustor.

Another object of this invention is to provide an improved jet pump by the use of charged aerosols of optimum characteristics.

An object of this invention is to provide new and improved methods and devices for producing charged aerosols having an optimum mobility.

An object of this invention is to efficiently produce a charged aerosol comprising charged liquid particles having an optimum ratio of radius to electric charge.

A further object of this invention is to minimize the frictional power loss due to the slip of the charged particles relative to the gas in a charged aerosol power transducer, by providing charged aerosol particles of optimum mobility.

Another object of this invention is to provide improved methods of forming and charging aerosols.

Another object of this invention is to modify the electrojet process so as to produce charged aerosol particles of optimum mobility.

Another object of this invention is an improved condensation process producing charged aerosol particles of optimum mobility.

Another object of the invention is to provide a method and apparatus in which condensation of vapor onto an ion continues, forming a singly charged droplet of increasing radius, until the mobility is decreased to a suitable optimum value.

Another object of the invention is to provide a method and apparatus in which multiply charged liquid particles acquire additional liquid from surrounding vapor to increase the particle radius and decrease the mobility to an optimum value.

A further object of this invention is to equalize the charging current produced by each unit area of a charging array.

This invention also concerns a new method and apparatus of introducing thermal jet power into a gas for increasing its kinetic power through the use of a charged aerosol jet.

For a better understanding of the present invention, together with other and further objects thereof, reference is made to the following description taken in connection with the accompanying drawings, in which similar reference characters indicate corresponding parts, in which:

FIGURE 1 is a cross-sectional view taken along the axis of flow of one form of a charged aerosol converter according to the present invention, showing an assembly of elements forming an airfoil array.

FIGURE 2 shows a cross-sectional view, taken on line 2—2 of FIGURE 1 normal to the axis of flow.

FIGURE 3 is a cross-sectional detail view similar to FIGURE 1 of another form of the charged aerosol converter, utilizing an improved condensation type charged aerosol formation and charging process.

FIGURE 4 is a longitudinal cross-sectional detail view of still another form of the charged aerosol converter, utilizing an improved combination of an electrojet type and condensation type charged aerosol forming and charging process.

FIGURE 5 is an enlarged fragmentary, somewhat isometric view of a charged aerosol formation and charging device, according to the present invention.

FIGURE 6 graphically represents the particle radius versus mobility for singly charged particles, and for multiply charged particles.

FIGURE 7 shows a graph of a mathematical function useful in calculating the optimum radius of a charged aerosol particle.

FIGURE 8 shows a graph of the optimum radius for singly charged particles versus relative gas density. The solid curves were calculated for different given values of relative breakdown electric intensity for the gas. The dashed curves correspond to different electric power densities.

Referring to the drawings and particularly to FIGURE 1, there is shown a conduit **10** containing the charged aerosol converter assembly. This assembly comprises: The chafo section **31**, for forming and charging the charged aerosol; the converter section **32** where the heat-kinetic power is transduced to electric power, or vice versa; and the collector section **33** where the charged aerosol is discharged and connected to the external load current.

The charged aerosol

A number of different processes may be employed to form and charge the aerosol. In the process hereinafter termed the "electrojet process", a fluid jet is emitted from an orifice into a gas stream in the presence of a strong electric field. The fluid is subject to electric forces, and to mechanical forces generated by the slip of the particle relative to the gas stream. The mechanical forces and the electrical forces tend to disrupt the fluid drop; the surface tension forces tend to keep the fluid drop together. The breakup into smaller charged droplets continues until an equilibrium condition between these contending forces is established. A charged aerosol is formed which comprises particles of the order of one micron in radius, with many charges on each particle.

The "electrojet process" is an efficient method for producing charged aerosol particles. However, if the ratio of the electric charge to the radius of the charged aerosol particles is large, then the mobility of such particles may be too large for them to act as an efficient power transducer.

In a process hereinafter referred to as the "condensation process," a gas containing a condensable vapor is directed through a nozzle and continuously expanded to decrease the temperature of the vapor in the presence of ions, whereupon the vapor condenses to form charged aerosol droplets suspended in the flowing gas stream. Effective condensation of the vapor onto a singly charged particle causes the charged liquid droplet to increase in radius. In this manner a charged aerosol may be formed having optimum mobility and capable of acting as an efficient power transducer.

However, charged aerosol particles produced by the condensation process may produce singly charged particles having radii so small that their slip and frictional power loss is excessive. Moreover, to obtain effective vapor condensation onto the charged particles, a large temperature drop was heretofore required which was obtained by a gas-vapor flow through a nozzle having a large expansion ratio. Gases flowing in nozzles having large expansion ratios are usually accompanied by excessive frictional power losses.

These difficulties with the condensation process are overcome by the present invention.

Accordingly to one form of this invention a suitable subsonic gas velocity is maintained with small proportionate flows of jets of condensable vapors. A large drop in temperature is obtained by conversion of the superheat of the jet into jet kinetic power imparted to the carrier gas.

According to another form of this invention, the condensable vapor is initially slightly superheated, and cools by mixing with the cooler carrier gas. In both cases the vapor condenses onto charged particles such as ions and liquid droplets.

The electric charge on the particle is predetermined by the process of formation. The "condensation process"

produces singly charged particles. The "electrojet process," except with ultra thin jets, produces multiply charged particles. Utilizing either method, the radius of the charged particle may be too small in relation to its charge, the mobility too large, and the slip velocity greater than 1% of the gas velocity; and hence efficient operating conditions may not be attained.

The problem solved herein is that of producing charged particles of such small mobility that they are capable of performing as an efficient thermal-kinetic-electric power transducer.

According to one form of this invention this result is achieved by the condensation of vapor onto the previously formed and charged particles, whether singly or multiply charged, causing the radius of the particles to increase and their mobility to decrease until it becomes optimum.

According to another form of the invention, there may be used an "electrojet process" employing ultrathin jets of liquid. These ultrathin liquid jets are mechanically disrupted by the gas into particles having an optimum radius for a few electric charges. The charge on each particle is controlled by the voltage applied to the jet. A charged aerosol results which is capable of efficient power transduction.

The converter section

The converter section **32** includes an airfoil array **16**. Each airfoil in the array has a streamlined cross section so that the airfoil array is in effect an array of slit-nozzles **41**. The charged aerosol-gas flows through these slit-nozzles and electrothermodynamic power conversion occurs. Each airfoil **16** has a conducting strip **17** on its upper and lower surface.

The conducting strips **17** apply an electric field to the chafo ionizer electrode **30** which is carried by the conduit **10** upstream of the airfoils **16**. The function of the chafo ionizer electrode **30** is to supply ions used as nuclei to form and charge the aerosol. The ionizer electrode **30** may be an array of points, wires or thin tubes. The conversion region of the nozzle **41** lies between the planes **51** and **52**, which are separated by a distance L. The collector electrode section **33** performs the function of discharging the charged aerosol at the end plane **52** of the conversion region of the nozzle **41**.

One form of collector electrode **33**, shown in FIGURE 3 is a plurality of thin tungsten wire "points" **34**, which function in a manner hereinafter described.

The chafo, converter and collector sections are mounted within the duct **10**, which is shown in FIGURE 2 as rectangular in section. The duct **10** may be suitably split with a flange joint generally indicated at **37** to enable the ready assembly of the transducer components within the duct.

The chafo section, the converter section, and the collector section are spaced and insulated from each other by the insulating spacers **35** and **36** respectively.

The chafo electrode **29** may be entirely fabricated of metal and connected directly to and supported within the metal duct **10** which may be at ground potential.

The converter section **32** comprises an array of airfoil elements **16** constructed of insulating material, for example, fused quartz. Each airfoil element **16** has conducting charging strips **17, 17'** therein just downstream of the thickest portion of the airfoil. If the voltage applied between the charging strips and the chafo electrode **29** were increased sufficiently; or if the electrode spacings were not everywhere equal, within the usual dimensional tolerances, then current density imbalance may occur. To avoid this it is sometimes preferred to utilize the balast resistor network hereinafter described. The conducting strips **17, 17'** are connected by balast resistors **18, 18'** (see FIGURE 3) to a common lead **19** within the airfoil element. A function of this structure is to equalize the current per unit cross section of the array. When the charging voltage is applied between the charging strips **17, 17'** and the chafo electrode **29**, little or no current will reach the charging strips. However, if more than a little (say 1%) of the current density of the power converter is diverted at any place to one of the charging strips **17, 17'**, then a voltage drop occurs in its balast resistor which limits such current. This tends to equalize the current density taken from each area of the array.

When the charging electrode **17** is at a suitable potential relative to the chafo electrode **29**, the aerosol formation and charging processes herein described occur in the chafo region **40**. For example, the electrode **17** may be at +3 kv. relative to the chafo electrode **29**, which may be at zero or ground potential.

The mobility of the charged particles **44** in the conversion region of the nozzles **41** must have approximately the optimum value. During the formation of the charged aerosol particles **44**, there exists only free electrons, negative ions, or charged particles of relatively large mobility. In the chafo region **40**, the ions or just-formed small charged aerosol particles have a mobility from 10 to 10^3 times greater than the larger charged aerosol particles in the conversion section of the nozzle **41**.

The collector section

The charged aerosol particles are discharged at the exit plane **52** of the conversion nozzzle space **41**. Since they now carry no charge, they are no longer affected by the electric field. In some cases these uncharged particles are unstable and evaporate to form a vapor in the carrier gas. The current flow in the discharge region is conducted by positive ions emitted from the point electrodes **33** which discharge the charged aerosol particles at the exit plane **52**. These positive ions traverse the region at the exit plane **52**. These positive ions traverse the region **46** rapidly because of their relatively large mobility. The charged particle **47** at the exit plane **52** of the conversion space **41** is shown as it is being discharged by a positive ion **48** from the point electrode **34** (see FIGURE 3).

In the conversion space **41**, the large space charge density causes a substantial increase of electric potential in the downstream direction. On the other hand, in the charging region **40** and in the discharging region **46**, there is little electric potential buildup due to space charge density. Charge density in coulombs/m.^{3} is equal to current density in amps./m.^{2} divided by velocity in m./sec. Except for slight leakage currents, the current is the same across each of the regions **40, 41** and **46**. However, the mobilities and velocities of the ions in the regions **40** and **46** are large, compared to the conversion region **41** where the charged aerosol particles in the carrier gas have a relatively small velocity. It follows that the charge densities are small in the charging region **40** and discharging region **46**; and that the charge density is large in the conversion region **41**. Hence there are small potential gradients in the regions **40** and **46**, but there is a large potential gradient between entrance plane **51** and the exit plane **52** of the conversion region **41**.

Ions are emitted from the point electrode **34** to discharge the charged aerosol at the exit plane **52**. The space charge of the negatively charged aerosol in the conversion space **41** results in a large negative potential, ϕ_{max} at the exit plane **52**. For example, referring to FIGURE 3, $\phi_{max}=-53$ kv. The current I produces a potential difference $\phi=IR$ across the load resistor **50**, which has a resistance R, and a potential difference $\phi_1=(\phi_{max}-\phi)$ between the collector point and the potential due to the charged aerosol at the plane **52**. The potential difference ϕ_1 is of the order of 3 kv., causing an ion current emission from point **34** sufficient to continuously discharge the charged aerosol moving across the exit plane **52**. Most of the generated potential difference ϕ appears across the load since $\phi_1 << \phi$. In this example $\phi=-50$ kv.

The charged aerosol particle

By supersaturated vapor, there is herein meant a vapor in that condition in which it is capable of condensing upon an electrically neutral aerosol droplet. A superheated vapor is one in which an electrically neutral droplet will evaporate.

Under superheated conditions electrically neutral liquid droplets evaporate. However, charged aerosol particles form by condensation from a vapor onto a charged ion or droplet even under superheated vapor conditions. Hence the electrically charged aerosol particles are more stable than electrically neutral particles. Consequently charged aerosol particles may form and grow in the chafo region and exist in the conversion space, all in slightly superheated vapor; then evaporate to again form vapor dispersed in the gas stream, after being discharged in the collector region.

Alternatively, it may be preferred to operate the chafo region and the conversion region in the supercooled vapor state to increase the electric breakdown strength of the charged aerosol gas. Superheated vapor may then be subsequently introduced into the stream after passing the collector region to evaporate the neutralized liquid droplets.

The potential at the charging electrode **17** is maintained by a potential source **51** which is connected between the grounded chafo electrode **30** and the electrode **17**. The current required to maintain the charging voltage at the charging electrode is negligible compared to the current emitted by the chafo electrode **30** and collected by the collector electrode **34**. This is because the electrons or negative ions emitted from the chafo electrode, for the most part, never reach the charging electrode **17**. Instead, these ions or electrons are captured by the condensing vapor and form charged aerosol droplets of very small mobility and which are, therefore, carried by the gas stream into the conversion region **41**. In the conversion region, the charged aerosol particles react with their own space charge field, and the field provided by the charging electrodes, and power is extracted from the charged aerosol-gas by a decrease in velocity or temperature or both. Thereafter the charged aerosol particles are discharged at the end plane **52** of the conversion space **41**, for example, as shown at **47**, by positive ions of large mobility such as **48** emitted from the point source **34**.

The corona electrode

The chafo corona electrode **29** may be a hollow needle, not shown, or one or more thin tubes **30** having a series of minute holes **22** therein. The very small holes required may be drilled by an electron beam technique. Within the tube **30** there is maintained a superheated vapor **23**. The superheat is at a suitable temperature above that of the gas stream **15**. The tube **30** provides a jet of vapor indicated by the arrow **48** whose kinetic power is added to the gas stream **15**. In certain devices, according to this invention, the kinetic power of the jet equals the friction power loss plus the converted electric power. Ions from the corona field form about the tube **30**. These ions form nuclei on which to condense vapor in the jet **48** forming the required charged aerosol droplets **44**.

The gas stream **15** is preferably operated at subsonic velocity. A large expansion of the carrier gas stream **15** is not required to produce the condensation. Instead, vapor condensation onto charged ions or droplets is produced by a temperature drop caused by the conversion of the thermal power of the superheated vapor **23** into the kinetic power of the jet streams **48**, which provides additional kinetic power to the gas stream **15**. Only a small proportion of the gas mass, of the order of 10^{-3} parts, is required to provide sufficient liquid for the charged aerosol droplets. Hence a large temperature drop may occur in the vapor jets **48**, which constitutes only a small proportion of the flow, with little change in the temperature and pressure of the main flow and little effect on the overall thermodynamic efficiency.

The charged aerosol jet pump

The charged aerosol jet constitutes a novel jet pump which efficiently transfers its kinetic power to the gas stream without the inefficiencies normally due to turbulence. No ordinary jet pump does this. In the ordinary jet pump, the mixing of a jet with a slower gas stream is accompanied by boundary turbulence, and the transfer of kinetic power from the jet to the gas is accompanied by excessive frictional power loss.

However, with the present invention, the supersaturated vapor in the jet condenses upon ions forming charged particles of small mobility, intermixing with, and entrapping the gas. The kinetic power of the charged aerosol jet is efficiently transferred to the gas stream without the usual turbulence. Therefore, the charged aerosol jet pump has a greater efficiency than obtainable with an ordinary jet pump. In this invention, the charged aerosol jet pump may be used to advantage to provide additional power to the gas stream.

The jet aerosol transducer

The operation of the device shown in FIGURE 3 is as follows: The superheated vapor is introduced at a temperature and pressure such that, on passing through the holes, high velocity jets of electrically supersaturated vapor are formed whose temperature and pressure is about the same as the temperautre of the flowing gas **15**. Very small liquid drops **21** are first formed around the ions produced by the corona field about the pipe electrode **30**. These charged drops initially have a radius smaller than that required for their operation as an efficient power transducer. However, as the vapor jets mix with the charged droplets, additional vapor is condensed thereon in the liquid state, thereby increasing the radius of these charged drops. FIGURES 3 and 4 show charged drops **21** having a small radius when first formed close to the openings **22**. Exposed to the supersaturated vapor **23** from the jet **48** the charged droplets increase in radius until just prior to entering the conversion space. With the increase in radius, and with no additional charges added, the larger droplets **44** perform as efficient power transducers in the conversion space **41** and are discharged at the exit plane **52** by the electrode **34**. External means (not shown) are provided for causing a flow of gas **15** through the conduit **10**. The gas **15** preferably has a low molecular weight and a high electrical breakdown.

The velocities of the gas **15** in the duct **10** is preferably subsonic. Suitable velocities range between 300 to 500 m./sec. This corresponds to 0.3 to 0.6 Mach for a low molecular gas such as hydrogen or helium. As an example of a low molecular weight gas composition having large electric breakdown characteristic we may employ the following range of compositions:

TABLE I.—COMPOSITION OF THE CHARGED AEROSOL-GAS

Gas	Symbol	Parts by Weight	Molecular Weight
Hydrogen	H_2	0-50	2
Helium	He	0-50	4
Condensable Vapor and Aerosol Droplets		10^{-3}-20	
Electron or Ion Scavenger-gas or Vapor		1-20	
Total		100	

The condensable vapors have the common characteristic that they condense about ions or charged droplets to form charged particles suitable for the practice of this invention. Examples are: steam, organic vapors such as an alcohol, a ketone, formamide, metal vapors such as mercury, salt vapors such as mercurous chloride.

The electron or ion "scavenger" gas or vapor is optional. Well known gases or vapors having an affinity for electrons or ions are water, oxygen, halogens, sulphur hexafluoride, diphenyl chloride, carbon tetrachloride, etc.

The scavenger gas should be non-reactive with the condensable vapor employed or may be identical therewith. For example, the scavenger gas may also be a condensable vapor such as water or alcohol. As another example, diphenyl chloride having appreciable vapor pressure at the operating temperature may be employed to form a charged aerosol droplet, and the vapor will also act as a scavenger gas. Water vapor is similarly useful. In other cases the scavenger gas is different from the condensable vapor, for example water vapor and chlorine gas.

The charged aerosol droplets produced by the electrojet process may have too large a mobility because for a given charge the radius of the charged particles was too small.

This invention provides a soltuion to this problem by providing a supersaturated vapor in the vicinity of a charged aerosol particle which may be initially formed by the electrojet. The supersaturated vapor condenses onto the charged aerosol particle and increases its radius until a charged particle having the optimum mobility is attained.

In the condensation process, as previously practiced, the gas entering the converter contained unsaturated superheated vapor or a carrier gas with vapor. Upon expansion of the gas in the nozzle, the vapor was strongly cooled and became supersaturated and condensed upon ions present to form charged aerosol droplets.

With steam normally considered to be in the condition of superheat, condensation will nevertheless occur upon charged ions or charged aerosol droplets. For example, in superheated steam at about 5 atmospheres pressure, the condensation upon ions or charged droplets is more rapid as the degree of superheat is decreased from say +60° C. towards saturation or 0° C. superheat. The greater the superheat the smaller are the charged particles produced, and the mobility of these particles may be too great for useful power conversion. Therefore, it will be generally preferred to work under conditions of slight superheat, saturation or supersaturation such that effective condensation occurs to produce charged particles of the required small mobility.

The improved condensation techniques described herein differ from the condensation technique above described in that the required supersaturated vapor is provided by the vapor jet issuing from orifices in the immediate vicinity of the ions produced by the corona, while the main gas stream may contain the vapor under slightly undersaturated conditions. The gas **15** which is moving at subsonic velocity undergoes only change in velocity and/or temperature in the airfoil section **16** corresponding to the power converted. No temperature drop is employed without a corresponding extraction of electric power.

Electrojet condensation power converter

FIGURE 4 shows a detail view of a power converter according to this invention, for a combined electrojet-condensation process. In this figure the tube **11** is preferably made of "micro" tubing, of the order of 0.1 mm. I.D. and 0.2 mm. O.D., having orifices **12** of the oder of 0.02 mm. in the tube wall in a line parallel to the tube axis. The tube **11** is connected to a source of liquid (not shown) under pressure, which is emitted in jets of liquid through the holes **12**. These liquid jets form a spray of charged liquid particles **13** under the influence of the electric field and the gas flow.

A second tube **14**, mounted upstream from the tube **11**, carries a superheated vapor. The vapor is expelled through a plurality of holes **22** in tube **14**. The diameters of the tube **14** and the holes **22** which emit the vapor may be larger than the corresponding diameters of tube **11** and holes **12**. The vapor jets **21** issuing from openings **22** in the tube **14** have a velocity somewhat greater than the velocity of the gas stream **15**.

Electrodes **17**, **17'** positioned downstream from tubes **11** are mounted on the airfoils **16**, **16'**. The charged aerosol particles are entrained in the gas flow between the airfoils **16**, **16'**. One or more collector electrodes **33** are mounted downstream from the exit plane **52** and connected to a load **20**.

The operation of the device as shown in FIGURE 4 is as follows: Tube **14** which contains a superheated vapor, emits a jet **21** of supersaturated vapor into the gas stream **15** at a velocity somewhat greater than the gas velocity. The superheated vapor jet **21** from tube **14** decreases in temperature and in enthalpy which is efficiently converted into kinetic power, and transfered to the total gas-vapor-aerosol flow in the duct **10**. The jet **21** is in a supersaturated state, and deposits liquid on charged ions or droplets in the chafo region **40**, further downstream.

Utilizing the electrojet process, tube **11** discharges a liquid jet of small diameter which breaks up immediately into small charged aerosol particles **13**. With the electrojet process, as the electric field intensity is increased, the charge increases and the radius of the charged particles decreases. When these charged particles are first formed, their radius is too small in relation to their charge. However, according to this invention, the supersaturated vapor jet **21** deposits additional liquid on each charged particle, increasing the radius. The final radius of the charged particles at the entrance plane **51** of the conversion space **41** may be controlled by a number and diameter of orifices **16** per unit length of the tube **14**, and the temperature and pressure of the superheated vapor **23** in the tube **14**, as well as the temperature, pressure and velocity of the flowing gas **15**, as well as other factors known to control the charged aerosol produced by the electrojet process at **13**. A suitable choice of these control factors enables an optimum ratio of radius to electric charge to be attained.

The charging electrodes

Referring to the charging electrode **17**, **17'** shown in FIGURE 3, it is neccesary to maintain a uniform ion emission from the corona field created about electrode **30**. Variations in the distance of electrode **30** from the electrode **17** induce a greater current discharge from portions of the electrode **30** closest to the electrode **17**. To produce a balanced or uniform emission from the entire length of the corona electrode **30**, it is preferred to utilize a plurality of spaced resistive strips **18**, **18'** attached to central electrode **19** within the insulating airfoil section **16**.

As an example, the corona electrode emits 30 microamperes/mm. of length, the leakage current to electrode **17** is 0.1 microampere/mm., the resistors **18**, **18'** have a resistance of 10^{10} ohms/mm. length of the airfoil section, and the potential difference between the charging electrode **17** and the electrode **30** is 2 kv.; then, the potential difference across the resistors **18**, **18'** is 1 kv., and the total potential difference from the electrode **30** to the common lead **19** is 3 kv. Any increase in current through resistors **18**, **18'** over any portion of the length of the airfoil, produces a greater potential difference locally across one of the resistors. This tends to reduce the potential difference between the charging electrodes **17**, **17'** and the electrode **30**, and thus decreases local current emission. Thus, while the resistors **18**, **18'** have negligible power dissipation, they self-regulate and make uniform the emission of ion current per unit length from the corona about the electrode **30**.

The resistors **18**, **18'** may comprise a continuous strip placed between the outer conducting strips **17** and the lead conductor **19**. The resistors **18** may have a resistance per unit length. This simplifies the construction. Alternative to a fixed resistance we may employ a non-linear ballast resistor.

The resistance of the ballast resistor **18** is a function of the current. A voltage drop is thereby produced which is a non-linear function of the current. Ballast resistors are known in the art in which the resistance drop is for

example in proportion to the fifth power of the current. This tends to produce a more sharply limited maximum current through the resistor and produces better regulation.

At the discharge end of the conversion space, the discharge current emitted from the collector points **34** is also self-regulating. If the charged aerosol which passes the exit plane were not neutralized by the local positive ion point source, then the charge density would increase with a buildup of space potential at the exit plane, and cause an increase in the potential difference between the exit plane and the collector points, and an increase in the ion emission from the nearest collector point. This effect tends to insure the uniform and complete discharge of the charged aerosol passing across the exit plane by the collector points.

FIGURE 5 shows another form of aerosol formation and charging device which, for example, may be employed in lieu of the tube type **30** charging electrode **17, 17'** in FIGURE 3 or in lieu of the tube **12** and charging electrodes **17, 17'** in FIGURE 4.

In FIGURE 5 an insulating cylindrical tube **60** or airfoil (not shown) has an axis X–X', along which is placed a thin wire, such as a tungsten wire **61**. The wire may be coaxially supported within the tube **60** by, for example, spiders **62**. Along the outer surface of the tube **60** and along the line parallel to the axis X–XX' there are a series of minute holes **63, 63*a***, etc. On the outer surface of the tube **60** there is a conducting strip **64** which serves the function of a charging electrode. The interior of the tube **60** contains a superheated vapor **65**. Upon issuing from the holes **63** the vapor is supercooled. The vapor **65** along with charged ions issues from the internal corona produced by the wire **61**, through the holes **63, 63*a***, etc. forming a wedge shaped beam **66** of charged liquid particles **67**.

The operation of the device will be understood from previous descriptions in connection with the operation of the corresponding structures shown in FIGURES 3 and 4. The advantage of the device shown in FIGURE 5 is that the charging electrode and the wire **61** which provides ions by corona discharge, are all contained within a single simple structure and the ions are thus intermingled within the shortest distance and most concentrated manner possible within the emerging superheated jets.

The holes **63, 63*a*** can vary in diameter from 1–100 A. microns and may be spaced from each other in any suitable manner, to provide the required mass flow of charged liquid particles relative to the mass flow of the carrier gas **15**. The charged aerosol particles **67, 68** quickly disperse by mutual repulsion and intermix intimately with the carrier gas **15**. The conducting charging strips **64** may be a metal strip deposited in the form of a plating upon the outer surface of the insulating tube **60**. The connection to the conducting strip **64** is to the potential source **51** (see FIGURES 3 and 4) and the wire **61** is grounded.

An advantage of this device shown in FIGURE 5 is that the airfoils **16** downstream of the chafo device no longer require conducting strips and may be constructed entirely of insulating material. This greatly simplifies the construction and is a particular advantage when the entire assembly must be miniaturized.

In FIGURE 6 the curve A is for the electrojet process only; not the combined electrojet-condensation technique described herein in connection with FIGURE 4. The curves A and B are calculated for ambient conditions.

In FIGURE 6 curve A shows mobility versus particle radius calculated for the electrojet process. Curve A was calculated for larger diameter liquid jets by equating the surface tension forces tending to hold the drop together to the electric forces tending to tear the drop apart. This limiting condition is called the Raleigh limit. The corresponding mobility was calculated from the Stokes Cunningham or Millikan equation. These calculations show a minimum mobility of about 10^{-5} m.^{2}/volt-sec. This mobility is too large for efficient power transduction.

However, using the electrojet process, with ultrathin jets of liquid issuing from very small holes, large particles with a single charge having an optimum mobility can be produced. Since tubes with such small holes are difficult to make, it is preferred to employ another process according to this invention, in which the condensation process is combined with the electrojet process to produce particles of optimum mobility. The effect is to displace the curve A to the left so that the mobility is now less than 10^{-6} m.^{2}/volt-sec.

Curve B in FIGURE 6 refers to singly charged particles commonly produced using the condensation method. Under certain conditions of operation, as previously practiced, for example with single charges in superheated steam, the radius of the charged particle which is formed may be smaller than that shown on the graph and the mobility is decreased to less than 10^{-6} m.^{2}/volt-sec.

With the novel condensation process of this invention, the radius of the charged particle is increased and the mobility is decreased to less than 10^{-6}m.^{2}/volt-sec.

In this example, utilizing the improved condensation process and the device of FIGURE 3, with water vapor and air; with a current density of 10 amps/m.^{2}; a velocity of 300 m./sec.; a gas density of about 9 times ambient, or 11.6 kg./m.^{3}; the charge density in the conversion space is 0.033 coulombs/m.^{2}; the length L of the conversion space is about 7.4 mm. and the converted power density is 1 megawatt/m.^{2}.

This data is summarized in the following table:

TABLE II.—OPERATING CHARACTERISTICS OF A CHARGED AEROSOL GENERATOR WITH A WATER-AIR AEROSOL

Variable	Symbol	Value	Units
Potential	ϕ	100,000	Volts.
Power Density Converted	p	10^6	Watts/m.^{2}
Charge Density	ρ	3.3×10^{-2}	Coulombs/m.^{3}
Velocity of Gas-Aerosol	U	300	m./sec.
Density of Gas-Aerosol	δ	11.6	Kg./m.^{3}
Length of Conversion Space	L	7.4×10^{-3}	M.
Particle Radius	r	2×10^{-8}	M.
Charges per Particle	N	1	
Charge per Particle	Ne	1.6×10^{-19}	Coulombs.

The values in Table II are illustrative only and not limiting.

The principles may be applied to design charged aerosol generators having multiple stages in which power is extracted successively from a gas stream. Using the example of Table II, and with 50 such multiple stages per meter length of the converter, the power conversion concentration is 50 megawatts/m.^{3}.

Similar results may be obtained with the combined electrojet-condensation process shown in FIGURE 4. However, in this case the number of charges and the radius of the particle are each greater, but their ratio is the same as in the previous case.

In the electrojet methods, as heretobefore practiced, liquid jets having a diameter of the order of 100 microns, were utilized, and it was primarily the electrical forces which caused the disruption of the jet into charged particles having radii of the order of 1 micron, averaging about 12,600 charges per particle.

The particle radius and charge is determined by the well known Raleigh limit, which requires an electric potential difference between the jet orifice and the charging electrode of the order of 2,000 volts.

Curve A in FIGURE 6 shows that the mobility of the charged particles produced solely by electrical disruption, greatly exceeds the optimum due to the presence of too many charges upon the particle.

In another process according to this invention, ultrathin liquid jets of the order of 1 micron in diameter are employed. These ultrathin jets require little or no electric force to break up into particles of the order of 0.5 micron in radius. The ultrathin jets are disrupted by the

mechanical forces between the jet and the flowing gas stream, and the surface tension of the jet itself.

Under these circumstances, a small potential difference of the order of one hundred volts applied between the ultra thin jet orifice and the charging electrode, will introduce a controlled small number of charges; thus forming charged aerosol particles of optimum mobility.

The advantage of this technique is that no vapor need be employed. The particles are instantaneously charged and formed and have the optimum mobility without the requirement for further accretion of condensed vapor.

The ultrathin electrojet method may be used with other power conversion devices such as that shown in FIGURE 3. In the case of FIGURE 3 a liquid is substituted for the superheated vapor within the tube **30**.

Any of the devices disclosed herein may be used for producing charged aerosol particles for other applications. In certain cases the collector electrodes may be omitted. For example, positive and negative aerosol forming devices may be arranged to mutually discharge each other. In other uses, the ground may be used as the collector electrode and the other electrode potentials arranged accordingly. Positive charged aerosols may be used instead of negative charged aerosols without departing from the scope of the invention.

Table of symbols

$a_1=1.74\ \lambda_1/r_1=552$

b=Relative breakdown electric intensity for any gas relative to hydrogen under standard conditions.

b_1=Breakdown electric intensity for hydrogen under standard conditions.

b_0=Breakdown electric intensity for air under standard conditions=3.08×10^6 volts/m.

b_g=Relative breakdown electric intensity for any gas relative to air under standard conditions.

c_1=Sonic velocity for hydrogen at standard conditions (meters/sec.).

D=Molecular diameter (meter).

D_1=Molecular diameter of hydrogen (meters).

E_b=Electric breakdown field intensity (volts/meter).

e=Electronic charge=1.60×10^{-19} coulombs.

ϵ_0=Permittivity of empty space=8.85×10^{-12}.

$f=(D/D_1)^2$=molecular cross section relative to hydrogen.

γ=Surface tension of liquid drop newtons/m.

K=Relative electric breakdown field intensity for any moving aerosol. This value is normalized with respect to breakdown field intensity for the gas component of the aerosol taken at static standard conditions.

$k=v/E$; mobility (meters^2/volt-sec.).

M=Mach number.

m=Molecular weight of gas.

N=Number of electronic charges per particle.

N_0=Avogadro's number (particles/mole).

P_e=Pressure of the gas relative to standard conditions.

q_0=Charge to mass ratio=q_p/M_p coulombs/kg.

q_p=Charge per particle coulombs.

r=Radius (meters).

$r_1=[0.87eb_1\lambda_1/6\pi\mu_1c_1]^{1/2}=3.91\times10^{-10}$ meters.

$r_s=r_1X$ (meters).

$S=(1.74\lambda/r_s)$.

T_a=Relative temperature=$T/300$.

u=Carrier gas velocity (meters/sec.).

v=Relative slip velocity (meters/sec.).

$\propto$=Slippage coefficient=KE_b/u.

δ_a=Relative gas density.

μ=viscosity (newton-sec./m.^{2}).

λ=Mean free path (meters).

λ_1=Mean free path for hydrogen at standard conditions.

$X=[bNK/\propto MT_a]^{1/2}$.

$\psi=(1/S^2)(1+\sqrt{1+S^2})$.

Standard conditions

$T_0=300°$ K.

$P_0=10^5$ newtons/m.^{2}.

Mathematical-physics analysis

A mathematical-physics analysis follows, in which radius r of the charged droplet for efficient power transduction between the moving gas and the electric field is determined as a function of various operating parameters.

The "mobility" k of a charged particle moved with a velocity v through a gas by an electric field of intensity E is, by definition:

$$k=v/E \tag{1}$$

The Stokes-Cunningham equation is:

$$k=(Ne/\pi\mu r)(1+0.87\lambda/r) \tag{2}$$

To determine r under the various conditions of operation substitutions for k, μ and λ must be made in (2), which is then solved for r and simplified.

For efficient power transduction the slip velocity v must be a small fraction $\propto$ of the carrier gas velocity u. Let $v=\propto U$, and arbitrarily set $\propto=0.01$. Set the electric field intensity to incipient breakdown $E=E_b$. Then the mobility k of a charged particle or radius r is:

$$k=\propto u/E_b \tag{3}$$

The gas velocity u may be expressed in terms of M the Mach No. of the gas; the sonic velocity c_1 of hydrogen gas H_2 at standard conditions, the absolute temperature T_a, and m the atomic or molecular weight of the gas:

$$u=\sqrt{2}c_1M\sqrt{T_a/m} \tag{4}$$

The electric breakdown voltage E_b is given by:

$$E_b=b_1bK\delta_a \tag{5}$$

The mobility k may be expressed in terms of the operating conditions, by substituting (4) and (5) into (3):

$$k=\propto(\sqrt{2}c_1/b_1)(\propto M/bK\delta_a)(T_a/m)^{1/2} \tag{6}$$

According to the kinetic theory of gases the viscosity μ may be expressed in terms of μ_1 the viscosity of H_2 under standard conditions:

$$\mu=(\mu_1/\sqrt{2})(\sqrt{m}T_a/f) \tag{7}$$

While Sutherland's formula is more accurate, formula (7) is sufficiently accurate and is preferred because the derivations hereinafter are simpler.

According to the kinetic theory of gases, the mean free path λ may be expressed in terms of λ_1:

$$\lambda=(1/4\pi N_oD^2)(1/\delta_a)$$
$$=(1/4\pi N_0D_1^2)(1/f\delta_a)=(\lambda_1/f\delta_a) \tag{8}$$

In (2) let:

$$r_s=r\ll\lambda \tag{9}$$

Then (2) may be readily solved for r_s:

$$r_s=(0.87Ne\lambda/6\pi\mu k)^{1/2} \tag{10}$$

Multiplying by r, and using substitutions (10) and S, Equation 2 may be written:

$$r^2-(2r_s/S)r-r_s^2=0 \tag{11}$$

Solving (11) for r and simplifying:

$$r=r_sS[(1/S^2)(1+\sqrt{1+S^2})] \tag{12}$$

Let

$$\psi=(1/S^2)(1+\sqrt{1+S^2}) \tag{13}$$

A plot of ψ versus S is shown graphically in FIGURE 6.

To evaluate r_s in terms of standard conditions for hydrogen gas H_2, substitute for k, μ and λ from (6), (7) and (8) respectively into (10) and simplify:

$$r_s=\{[0.87e\lambda_1b_1/6\pi\mu_1c_1][bNK/\propto MT_a]\}^{1/2} \tag{14}$$

Let

$$X=[bNK/\propto MT_a]^{1/2} \tag{15}$$

where X is an operating parameter. Also let:

$$r_1=[0.87eb_1\lambda_1/6\pi\mu_1c_1]^{1/2} \tag{16}$$

Making substitutions (15) and (16) into (14):

$$r_s=r_1X \tag{17}$$

Evaluate S in terms of standard conditions for hydrogen

gas H_2 using (8) and (17) for λ and r_s respectively, and then simplify using a_1:

$$S=1.74\lambda r_s=(1.74\lambda_1/r_1)/f\delta_a X=a_1/f\delta_a X \quad (18)$$

Equation 12 may be written in terms of (13), (16), (17) and (18):

$$r=r_1\times S\psi=(1.74\lambda_1/f)(\psi/\delta_a) \quad (19)$$

The following data for the viscosity μ, the mean free path λ, the sonic velocity c_1, and the breakdown electric intensity relative to air, b_g for 1 atmos. pressure at the given temperatures, were obtained from literature references for hydrogen gas.

Viscosities are usually given in poise or centipoise. 1 poise=1 dyne sec./cm.^{2}. Since the MKS unit system is used herein, the viscosity must be expressed in newtons-sec./m.^{2}. To convert poises to newtons-sec./m.^{2}, multiply poises by 10^{-1}.

Applying conditions (30) to general equation (19):

$$r=r_1X=r_1(bNK/\propto MT_a)^{1/2} \text{ for } X\geqq 1 \quad (31)$$

Hence, for small values of δ_a, r is approximately independent of molecular diameter and gas density.

Case II

$$\begin{cases}\psi=2/S^2\\ \psi=2/S^2\end{cases} \quad (32)$$

Applying conditions (32) in general Equation 19:

$$r=(2r_1^2/1.74\lambda_1)fX^2\delta_a=1420\times 10^{-10}fX^2\delta_a(m) \quad (33)$$

Restrictions A

$$\begin{cases}\propto=10^{-2} & (34)\\ MT_a=1 & (35)\end{cases}$$

TABLE III.—PHYSICAL CONSTANTS OF HYDROGEN GAS UNDER VARIOUS CONDITIONS

Parameter	Symbol	Value	Units	Temp., ° K.
Viscosity	μ	8.7×10^{-6}	Newton-sec./m.^{2}	288.0
Mean Free Path	λ	1.18×10^{-7}	M	288.0
Sonic Velocity	c	1269.5	M/sec	273.1
Breakdown Electric Intensity Relative to Air	b_g	0.65		

This data has been converted to standard conditions in Table IV.

The values of u_1, λ_1, c_1 and b_1 are computed using:

μ varies as $\sqrt{T_a}$ from (7) (20)

λ varies as $1/\delta_a$, or as T_a/p_a from (8) (21)

c varies as $\sqrt{T_a}$ (22)

The breakdown electric intensity for hydrogen gas under standard conditions is:

$$b_1=b_g b_o; \text{ where } b_g=0.65 \quad (23)$$

Restriction (34) follows from the definition of "optimum mobility." Restriction (35) is a reasonable choice that facilitates calculation:

$$\begin{cases}0.1<M<1\\ 10>T_a>1\\ 3000°\text{ K}>T>300°\text{ K}\end{cases} \quad (36)$$

With restrictions A, (15) becomes:

$$X=10(bK)^{1/4}\text{ N}^{1/4} \quad (37)$$

TABLE IV.—PHYSICAL CONSTANTS FOR HYDROGEN GAS FOR STANDARD CONDITIONS

Parameter	Symbol	Value	Units
Viscosity	μ_1	8.89×10^{-6}	Newton-sec./m.^{2}.
Mean Free Path	λ_1	1.24×10^{-7}	Meters.
Sonic Velocity	c_1	1.33×10^{3}	Meters/sec.
Breakdown Electric Field Intensity	b_1	2.00×10^{6}	Volts/m.

The value of r_1 is computed using the data of Table IV in (16).

$$r_1=3.91\times10^{-10} \text{ meters} \quad (24)$$

Having λ_1 from Table IV, and r_1 from (24), the value of a_1 is:

$$a_1=1.74\lambda_1/r_1=552 \quad (25)$$

Evaluating S in (18) from (25):

$$S=552/f\delta_a X \quad (26)$$

Evaluating r by putting the value of λ_1 from Table IV into (19):

$$r=(2.16\times10^{-7}/f)(\psi/\delta_a)\text{ (meters)} \quad (27)$$

The radius of the singly charged particle may be expressed in terms of angstroms:

$$r_{A.}=(2160/f)(\psi/\delta_a) \quad (28)$$

For hydrogen gas $f=1$ and (28) becomes:

$$r_{A.}=2160\psi/\delta_a \quad (29)$$

In the following S is given by Equation (26):

Case I

$$\begin{cases}S\gg 1\delta_a \text{ small}\\ \psi=1/S\end{cases} \quad (30)$$

From (37) the values of X may be computed for corresponding values of bK:

$$\begin{cases}X=10, 20, 30\\ bK=1, 4, 9\end{cases} \quad (38)$$

Case I with restrictions A

From (31) and (37):

$$r=10r_1(bK)^{1/4}\text{ N}^{1/4} \quad (39)$$

$$r_{A.}=39.1(bK)^{1/4}\text{ N}^{1/4}\text{ (Angstroms)} \quad (40)$$

Case II with restrictions A

From (33) and (37):

$$r_{A.}=14.2fn(bK\delta_a)\text{ (Angstroms)} \quad (41)$$

For hydrogen gas, with singly charged particles:

$$r_{A.}=14.2bK\delta_a \quad (42)$$

Case II, Formulae 41 and 42, are useful approximations only for $\delta_a>100$. Values of S usually fall between the extremes of Cases I and II. In most cases it is, therefore, best to use Equation 19.

Case I, Formula 31, may be used for values of relative density less than 5; and Case II, Formula 33, may be used for values of relative density of 100 or more.

The following Table V which shows (r/N) versus δ_a was computed from the general Formula 28 for hydrogen as a carrier gas for the various given values of the operating parameter X.

TABLE V.—RELATIVE DENSITY VERSUS THE RADIUS OF A SINGLY CHARGED PARTICLE

X	bK	δ_a	S	ψ	r_A.
2		1	276		7.82
		10	27.6		7.82
		100	2.76	0.518	11.2
		500	0.552	6.5	28.1
		1,000	0.276	26.7	57.7
3		1	184		11.7
		10	18.4		11.7
		100	1.84	0.913	19.7
		333	0.552	6.5	42.3
		1,000	0.184	59.7	129
5		1	110		19.6
		10	11		19.6
		110	1.0	2.42	47.4
		552	0.20	50.5	197
		1,000	0.11	172	372
10	1	1.00	55.2		40.0
		5.52	10.0	0.110	43
		10.00	5.52	0.185	47
		27.60	2.0	0.833	65
		55.2	1.0	2.414	95
		100.00	0.552	6.5	140
		1,000.00	0.5552	658	1,420
20	4	1.00	27.6		80
		2.86	10	0.110	86
		10.00	2.76	0.518	112
		20.00	1.38	1.42	153
		27.60	1.00	2.414	189
		35.0	0.789	3.65	225
		55.20	0.5	8.47	332
		100.00	0.276	26.7	556
		1,000.00	0.0276	2,620	5,660
30	9	1	18.4		120
		1.84	10	0.110	130
		10.0	1.84	0.913	197
		18.4	1.	2.414	283
		36.8	0.5	8.47	498
		55.2	0.333	18.5	723
		100	0.184	59.7	1,290
		500	0.0368		6,380

In FIGURE 8 there is shown radius r of a singly charged particle versus relative density δ_a, computed for values of $X=10$, 20 and 30 corresponding to values for $bK=1$, 4 and 9 respectively.

The dashed line p_e on FIGURE 8 is for a power density of 10^8 watts/m.^{2} utilizing a hydrogen water aerosol. For Composition No. 1, a hydrogen water aerosol; b, the molecular weight relative to air is 0.07, the electrical breakdown field intensity relative to hydrogen is 1.0, and K, the electrical breakdown strength of the charged aerosol relative to the carrier gas is taken as 1.0. For composition No. 2 which is composition No. 1 inhibited with a scavenger gas corresponding values are 0.07, 2.0 and 1.0. For Composition No. 3 which is the same as Composition No. 2 but supercooled, the corresponding values are 0.07, 2.0 and 3.0.

TABLE VI.—OPERATING PARAMETERS FOR CHARGED AEROSOLS OF VARIOUS COMPOSITIONS

$\eta_k=1$	$\eta_t=0.10$	
Electric Power Density p_e	10^8 watts/m.^{2}	
Column	1	2
Gas-Aerosol Composition	Velocity U, m./sec.	Relative Density, δ_a
1	235	190
2	302	89
3	470	24
$\eta_k=0.25$	$\eta_t=0.04$	
Column	3	4
1	409	144
2	523	67
3	817	20
$\eta_k=0.10$	$\eta_t=0.10$	
Column	5	6
1	590	120
2	756	55
3	1,180	14

The data is plotted and points from this data are plotted and numbered according to the composition number and column number. From this, there is obtained, for a power density of 10^8 watts/m.^{2}, a mean optimum singly charged particle radius of 300 A. to 400 A.

The molecular cross section f relative to hydrogen gas is computed in Table VII by solving Equation (7) for f and using data on viscosity normalized to a temperature of 300° K for the various carrier gases.

TABLE VII.—RELATIVE MOLECULAR CROSS SECTION OF VARIOUS CARRIER GASES—VISCOSITIES OF GASES ARE NORMALIZED TO 300° K.

Carrier Gas	Viscosity newton, sec./m.^{2}	μ/μ_1	f
He	1.87×10^{-5}	2.24	0.635
H_2	0.84×10^{-5}	1.00	1.00
Steam	2.60×10^{-5}	3.00	1.6
Air	1.7×10^{-5}	2.05	1.85
Mercury	2.23×10^{-5}	2.65	3.78

Case 1 above shows the particle radius is independent of cross section for small values of relative density δ_a. However, Case II shows that for larger values of relative density δ_a the relative molecular cross section is an important factor in computing the radius of the charged particle.

For example, for steam in which δ_a exceeds 100, the radius r in FIGURE 7 must be multiplied by 1.6. However, the Table VII shows that helium has a cross section of 0.635 compared to hydrogen. Therefore, radius r for helium for values of relative density exceeding 100 is only 62.5% of that shown in FIGURE 7. Helium is, therefore, the preferred carrier gas where for efficient operation, charged particles of the smallest radius are required. Hydrogen, however, may be preferred when other factors are considered.

The following table summarizes the limits on the operating parameters:

TABLE VIII.—LIMITS ON OPERATING PARAMETERS

Parameter	Symbol	Units	Minimum	Maximum
Slip Factor	M		0.01	0.09
Temperature	T_a	$T_a=1\cong300°$ K.	0.5	10
Mach No.	M		0.1	0.8
Relative Breakdown Electric Intensity of Gas.	b		1	3
Relative Breakdown Electric Strength of Aerosol.	K		1	3
Number of Charges per particle.	N		1	10
Relative Molecular Radius.	f		1	5
Relative Gas Density	δ_a		1	1,000

To compute charge per particle, and charge to mass ratio for a water drop produced by electrical disruption, the Raleigh limit for the maximum charge for a stable sphere of radius r is used:

$$q_{p\max}=8\pi\epsilon_0{}^{1/2}\gamma^{1/2}r^{3/2} \text{ coulombs/drop} \quad (43)$$

γ, the surface tension of water is 0.073 newtons/m. Hence for a water the charge to mass ratio is:

$$q_0=4.8\ r^{-3/2} \text{ coulombs/kg.} \quad (44)$$

The number of electrons per drop is given by:

$$N=1.26\times10^4\ r^{3/2} \quad (45)$$

In Equations 44 and 45 r is expressed in microns.

The number of charges on a multiply charged particle having a radius of 1μ for the charged particle to have the "optimum" mobility may be computed from FIGURE 7: $r/N=350$ A. per electron charge or 28 electron charges per drop of 1μ radius.

According to Equation 45, upon disrupting a sphere to a radius of 1μ or 10^4 A., approximately 1.26×10^4 charges remain on the particle. In such case $r/N=0.81$ A. per electric charge, which is too small. FIGURE 7 shows that to achieve optimum mobility it is required that: $rN\cong350$.

However, the electrojet process, modified to use ultrathin jets which are charged to a controlled low voltage,

provides the 28 charges on a 1μ radius droplet required to achieve optimum mobility.

The above analysis has been presented for the optimum mobility conditions defined by the slip factor $\alpha=0.01$; or for a charged particle having a slip velocity of 1% of the velocity of the carrier gas with an electric field intensity near breakdown.

An important feature of this invention is the establishment of a useful operating range by control of the parameter X. For $X=10$, 20 or 30 a particle radius of about 350 A. is required for a power density of 10^8 watts/m.^{2}. However, charged particles having much smaller radii may be used if the parameter X is decreased to 5, 3 or 2.

To decrease the parameter X, there may be employed a slip factor increased to 10%; smaller values of breakdown electric field intensity to $bK=1$, and larger values of MT_a to 2.5 may be employed.

FIGURE 8 shows curves marked $X=5$, 3 or 2 in which the charged particle radii is much decreased.

The following is an example of operating parameters for which $X=2$:

Hydrogen gas as a carrier	$f=1$
Slip factor 10%	$\alpha=0.10$
Mach No.	$M=0.5$

Certain liquids such as water, alcohol, etc. are known to be molecular electric dipoles; that is, have an electric dipole moment. The ion first attaches to one of these molecular dipoles, and then other molecular dipoles quickly attach. When the charged liquid droplets are brought into an electrical field, the molecular dipoles are oriented; the charged liquid drop increases in free energy, decreases in entropy, and decreases in temperature. The orientation of the molecular dipoles in a charged water drop decreases its absolute temperature about 36%; whereupon the oriented dipole molecules lose their ability to re-evaporate. Vapor molecules striking the charged aerosol droplets are captured, become oriented in the electrical field. The charged aerosol droplets thus continue to grow.

The electric field intensity increases from the charging space to the conversion space. As the charged aerosol liquid droplet traverses the conversion space in a generator, the repelling electric field intensity decreases. The radius of the charged droplet stops growing and reaches equilibrium at optimum mobility. The particles have an optimum mobility during their traverse of the conversion space. Beyond this point the electric field intensity decreases further until it is zero at the collector plane, the molecular dipoles in the liquid drop disorient, the temperature of the charged drop increases, and the drop becomes smaller in radius as it evaporates. Hence ions from the collector preferably discharge the charged aerosol particles just before they start to evaporate. Upon discharge, the molecular dipoles are disoriented, the neutral droplets suddenly increase in temperature and rapid evaporation of the droplet occurs. The droplet liquid returns to the vapor phase within the carrier stream.

The condition of the carrier gas and contained vapor is now the same at the exit as at the entrance to the electrical converter device. Hence electrical converter devices may be placed one after the other in the gas stream and by staging, additional power may then be extracted from the carrier gas.

In the case of a pump, the power from the electrical circuit is transduced, producing an increase in pressure and temperature of the moving gas. In a pump, an accelerating electric field is applied to the charged droplet in an electrical converter section similar to that previously described. In this case the electric field intensity increases from a minimum at the entrance to the conversion space, to a maximum at the collector electrodes, and the charged aerosol particles continue to grow until discharged at the collector plane, after which they may evaporate as described above. Staging may also be used to increase the buildup of pressure and temperature differentials.

Summarizing, an optimum range of particle radius has been set forth. The corresponding parameters have been established. Various methods of accomplishing suitable ranges of electric charge and particle radius have been set forth. These comprise the several modifications of the condensation method, electrojet method and a combined condensation electrojet technique.

The parameters of operation may be chosen in accordance with the operational requirements; the methods of charging and forming the aerosol may be chosen from amongst the various methods disclosed herein; and the device may be constructed according to any of the various devices illustrated and described herein, all without departing from the scope of this invention.

Having thus fully described the invention, what is claimed as new to be secured by Letters Patent of the United States is:

1. A device to convert the heat kinetic power of a moving gas to electric power output comprising a conduit, a moving gas under presure in said conduit, means comprising a tube having a plurality of nozzle-like holes therein within the conduit to emit supercooled vapor jets into the gas at a temperature pressure and velocity somewhat greater than that of the gas, ionizer means within the conduit to form ions in an electric field in the region of the supercooled vapor, whereby the vapor will condense upon said ions to form minute charged droplets, and whereby the vapor will further condense upon the said minute charged droplets to form a charged aerosol having larger droplets, a conversion space having a repelling electric field to convert the heat kinetic power of the charged aerosol gas to electric power, a collector electrode at the exit of the conversion space to discharge the charged droplets, and an electrical load to receive the output electric power connected between the collector electrode and the ionizer.

2. A device to convert the heat kinetic power of a moving gas to electric power comprising a conduit, a moving gas in said conduit said gas containing a condensable vapor having a low mean molecular weight, high electrical breakdown, a velocity of the order of 300 to 1000 m./sec., and a pressure exceeding one atmosphere, means within the conduit comprising a tube having a plurality of nozzle-like holes therein to emit jets of supercooled vapor into the gas at a temperature pressure and velocity somewhat greater than that of the gas, ionizer means within the conduit to form ions in an electric field in the region of the supercooled vapor, whereby minute charged droplets will condense upon said ions, and whereby the vapor will further condense upon the charged droplets to form a charged aerosol having larger droplets, a conversion space having a repelling electric field to convert the heat kinetic power of the charged aerosol gas to electric power, a collector electrode at the exit of the conversion space to discharge the charged droplets, and an electrical load to receive the output electric power connected between the collector electrode and the ionizer.

3. A device to convert the heat kinetic power of a moving gas to electric power comprising a conduit, a moving gas under pressure in said conduit, a condensable vapor in the gas, means comprising a first tube within the conduit connected to a source of conductive liquid under pressure and having a plurality of spaced openings therein to eject liquid jets, means to apply an electric field to said jets, whereby said jets form minute charged droplets, a second tube carried within the conduit upstream of the first tube, said second tube being connected to a source of superheated vapor under pressure and having a plurality of spaced openings therein whereby supercooled vapor issues from the said second tube at a

velocity approximating the velocity of the gas, whereby the supercooled vapor will condense upon the minute charged droplets to form a charged aerosol having larger droplets, a conversion space having a repelling electric field to convert the heat kinetic power of the charged aerosol gas to electric power, a collector electrode at the exit of the conversion space to discharge the charged droplets, and an electrical load to receive the output electric power connected between the collector electrode and the liquid source.

4. A device according to claim 3 in which the tube openings are of the order of 1 to 10 microns in diameter.

5. A device to convert the heat kinetic power of the moving gas to electric power comprising a conduit, a moving gas under pressure in said conduit, a condensable vapor in the gas, means comprising first tube electrodes within the conduit having a plurality of spaced openings to emit a supercooled vapor jet into the gas stream at a temperature, pressure and velocity somewhat greater than that of the gas, means within the conduit comprising a plurality of spaced insulating airfoil members having conductive strips thereon and disposed downstream of the tube electrode, a source of electrical potential connected between said strips and said tube electrodes to form ions in an electric field in the region of the vapor, whereby the vapor will condense upon ions to form minute charged droplets, second tubes within the conduit upstream of the first tubes, said second tubes being connected to a source of superheated vapor and having a plurality of spaced openings therein whereby supercooled vapor issues from the said second tubes at a velocity approximating the velocity of the gas, whereby the supercooled vapor will condense upon the said minute charged droplets to form a charged areosol having larger droplets, a conversion space between said airfoil members having a repelling electric field to convert the heat kinetic power of the charged aerosol gas to electric power, a collector electrode at the exit of the conversion space to discharge the charged droplets, and an electrical load to receive the output electric power connected between the collector electrode and the first tube electrodes.

6. A device to convert the heat kinetic power of a moving gas to electric power comprising a conduit, a moving gas under pressure in said conduit, a vapor in the gas, pipe electrodes within the conduit having a plurality of spaced openings to emit a supercooled vapor into the gas stream at a temperature, pressure and velocity somewhat greater than that of the gas, a plurality of spaced insulating airfoil members within the conduit and disposed downstream of the pipe electrodes, conductive strips on said airfoil members, a central electrode within the airfoil members, a resistive strip between each of the conductive strips and the central electrode, and a source of electrical potential connected between said strips and said pipe electrodes, whereby ions are formed in an electric field in the region of the vapor which condenses upon said ions to form minute charged droplets, second tubes within the conduit upstream of the first tube, said second tubes having a plurality of spaced openings and connected to a source of superheated vapor, whereby supercooled vapor issues from the said second tubes at approximately the velocity of the gas and condenses upon the said minute charged droplets to form larger charged droplets, a conversion space between said airfoil members having a repelling electric field to convert the heat kinetic power of the charged aerosol gas to electric power, collector electrodes at the exit of the conversion space to discharge the charged droplets, and an electrical load to receive the output electric power connected between the collector electrodes and the pipe electrodes.

7. A device according to claim 6 in which the resistance comprises non-linear ballast resistors.

8. A device to convert the heat kinetic power of a moving gas to electric power comprising a conduit, a moving source of gas under pressure in said conduit, a vapor in the gas, means comprising dielectric tube disposed normal to the longitudinal axis of the conduit, said tube connected to a source of superheated vapor, said tube having a plurality of spaced openings to emit supercooled vapor jets, an axial conducting wire electrode within the tubes, a charging strip on the outer surface of the tube adjacent the openings therein, a source of electrical potential difference connected between the axial wire electrode and the strip whereby ions are produced within the vapor jets from the openings, said vapor condensing upon the ions to form minute charged droplets, a second tube upstream of the first tube, said second tube being connected to a source of superheated vapor and having a plurality of spaced openings therein whereby supercooled vapor is issued from the said second tube at approximately the velocity of the gas and condenses upon the minute charged droplets to form a charged aerosol having larger droplets, a conversion space having a repelling electric field to convert the heat kinetic power of the charged aerosol gas to electric power, a collector electrode at the exit of the conversion space to discharge the charged droplets, and an electrical load to receive the output electric power connected between the collector electrode and the wire electrode.

9. The method of converting the heat-kinetic power of a moving gas into electrical power comprising the steps of passing a non-conducting gas at subsonic velocity through a conduit, introducing a supercooled vapor into the gas, maintaining a conducting liquid under pressure in a tube placed within the conduit, forming a small diameter charged jet from said liquid in an electric field within said moving gas, whereby said jet breaks up into minute charged droplets and whereby the vapor condenses upon the minute charged droplets to form a charged aerosol gas having charged droplets of larger radius, and of approximately optimum mobility, directing said charged aerosol gas of optimum mobility against a repelling electric field and thereafter neutralizing the charge on the aerosol by collector means downstream from the repelling electric field, and supplying the output electric power to an electrical load connected between the collector means and the conducting liquid.

10. A device for producing and charging an aerosol comprising a dielectric tube, a source of superheated vapor at a temperature and pressure substantially above that of the gas on the exterior of the tube, a plurality of openings along the tube to emit supercooled jets, an axial conducting wire electrode within the tube, a charging strip on the outer surface thereof adjacent the openings therein, a source of electrical potential difference connected between the axial wire and the strips, whereby ions are produced within the vapor jets from the openings said vapor condensing upon the ions to form minute charged droplets in the gas constituting a charged aerosol gas.

11. A device for producing and charging a charged aerosol gas comprising a dielectric tube, a source of superheated vapor at a temperature and pressure substantially above that of the gas on the exterior of the tube, a plurality of openings along the tube to emit supercooled jets, an axial conducting wire electrode within the tube, a charging strip on the outer surface thereof adjacent the openings therein, a source of electric potential difference connected between the axial wire and the strips, whereby ions are produced within the vapor jets from the openings, said vapor condensing upon the ions to form minute charged droplets in the gas, a second tube upstream of the jets of said first tube, said second tube being connected to a source of superheated vapor having a temperature and pressure substantially greater than that of the gas, and having a plurality of spaced openings thereon whereby supercooled vapor issues from the said second tube and condenses upon the minute charged droplets to form a charged aerosol having larger droplets, constituting a charged aerosol gas.

12. The method of converting the heat kinetic power

of a moving gas into electrical power comprising the steps of passing a non-conducting gas through a conduit, introducing a supercooled vapor produced from jets issuing at a somewhat greater pressure temperature and velocity than the gas from the orifices in an upstream pipe, said upstream pipe being supplied with superheated vapor under substantially greater temperature and pressure than that of the moving gas into said gas, introducing ions into the supercooled vapor from a corona within the supercooled vapor to form minute charged droplets, increasing the radius of the minute charged droplets by condensation of the vapor thereon to form larger charged droplets of approximately optimum mobility, passing said larger charged

droplets through a repelling electric field, discharging the larger charged droplets by collector means, and supplying electrical power to a load connected between the collector means and the ionizer means.

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