



Europäisches Patentamt
European Patent Office
Office européen des brevets



Publication number: **0 437 062 A2**

(12)

EUROPEAN PATENT APPLICATION

(21) Application number: **90313723.0**

(51) Int. Cl.⁵: **B41J 2/06**

(22) Date of filing: **14.12.90**

(30) Priority: **15.12.89 US 451080**

(43) Date of publication of application:
17.07.91 Bulletin 91/29

(84) Designated Contracting States:
DE FR GB IT NL

(71) Applicant: **TEKTRONIX, INC.**
Howard Vollum Park 14150 S.W. Karl Braun
Drive P.O. Box 500
Beaverton Oregon 97077 (US)

(72) Inventor: **Roy, Joy**
14468 SW Scarlett Place
Tigard, Oregon 97224 (US)
Inventor: **Schoening, Susan C.**
2247 NW Irving Street
Portland, Oregon 97210 (US)
Inventor: **Le, Hue P.**
9301 SW Sagert Street, Apt. 154
Tualatin, Oregon 97062 (US)

(74) Representative: **Lawrence, Malcolm Graham**
et al
Hepworth, Lawrence, Bryer & Bizley Gate
House South West Gate
Harlow Essex CM20 1JN (GB)

(54) **Method and apparatus for printing with a drop-on-demand ink jet print head using an electric field.**

(57) A drop-on-demand ink jet has an ink chamber coupled to a source of ink, and an ink drop orifice with an outlet. An acoustic driver produces a pressure wave in the ink and causes the ink to pass outwardly through the ink drop orifice and outlet. A high voltage electric field is oriented to accelerate ink drops along a path from the outlet to print medium. The electric field is time invariant and is the only electric field present along the path during drop formation and acceleration. The size of the ink drops may be varied, such as by driving the acoustic driver with varying drive signals. One preferred form of acoustic drive signal comprises of individual or combinations of plural bipolar drive pulses. The combination of energy imparted by the acoustic driver and the electric field accelerates small and large drops such that the time for the drops to travel to the print medium is substantially the same. The ink jet printer of the present invention may be used to print with a wide variety of inks, including phase change inks.

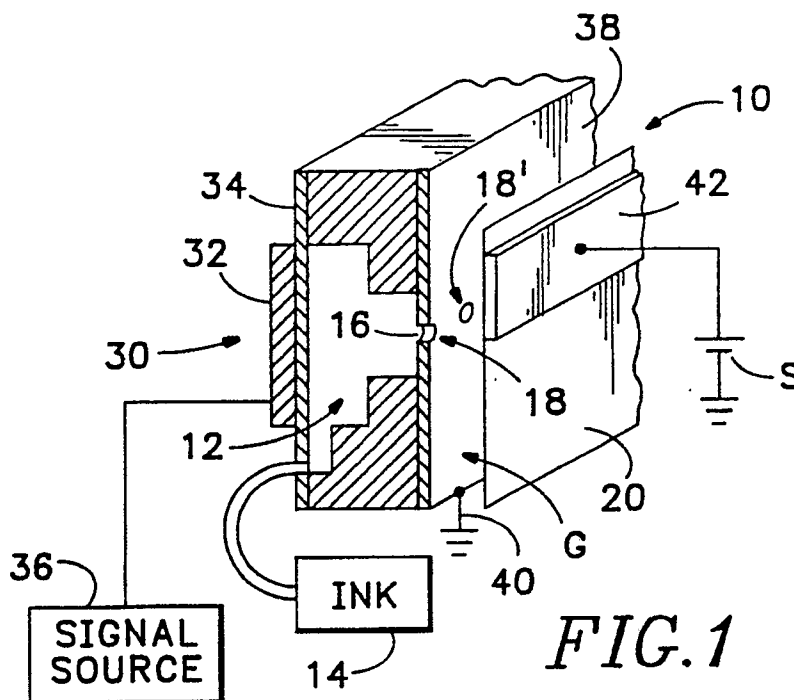


FIG. 1

EP 0 437 062 A2

METHOD AND APPARATUS FOR PRINTING WITH A DROP-ON-DEMAND INK JET PRINT HEAD USING AN ELECTRIC FIELD

The present invention relates to printing with a drop-on-demand ink jet print head using an electric field which remains time invariant during ink drop ejection and travel of the drops toward print medium. In addition to other applications, the present invention is particularly useful in grey scale or half-tone printing in which ink drop size is selectively varied during printing.

Ink jet printers, and in particular drop-on-demand ink jet printers having print heads with acoustic drivers for ink drop formation are well known in the art. The principle behind an impulse ink jet of this type is the generation of a pressure wave in an ink chamber and subsequent emission of ink droplets from the ink chamber through a nozzle orifice as a result of the pressure wave. A wide variety of acoustic drivers are employed in ink jet print heads of this type. For example, the drivers may consist of a transducer formed by a piezoceramic material bonded to a thin diaphragm. In response to an applied voltage, the diaphragm displaces ink in the ink chamber and causes a pressure wave and the flow of ink through one or more nozzles. Piezoelectric drivers may be of any suitable shape such as circular, polygonal, cylindrical, annular-cylindrical, etc. In addition, piezoelectric drivers may be operated in various modes of deflection, such as in the bending mode, shear mode, and longitudinal mode. Other types of acoustic drivers for generating pressure waves in ink include heater-bubble source drivers (so called bubble or thermal ink jets) and electromagnet-solenoid drivers. In general, it is desirable in an ink jet print head to employ a geometry that permits multiple nozzles to be positioned in a densely packed array with each nozzle being driven by an associated acoustic driver.

The prior art has also recognized that advantages may arise from printing with ink drops of selectively varying volume. For example, drop volume can be selected to provide optimum spot optical density to effectively produce high resolution printing. Also, by using only larger drops, a draft-mode print quality can be chosen. Such printers are also useful in applications requiring half-tone images, such as involving the control of color saturation, hue and lightness.

U.S. Patent No. 4,513,299 of Lee, et al. describes one approach for achieving variations in ink drop size. In this approach, an electromechanical transducer is coupled to an ink chamber and is driven by one or more electrical drive signals of the same polarity which are each separated by a fixed time delay. This time delay is short with respect to the drop-on-demand drop production rate. Each electrical drive signal ejects a predetermined volume of ink with the ejected volumes of ink merging to form a single drop.

An increase in the number of electrical drive signals between the formation and ejection of a drop causes an increase in the drop volume. This patent mentions that the various sized drops travel at a constant velocity to the print medium. This patent also recognizes that, because the print head is moving at a constant velocity during printing, any variation in drop velocity would cause displacement of the drops on the print medium from their desired position, and would degrade the print quality. However, inasmuch as all of the energy for drop formation and ejection results from the drive pulse supplied to the transducer, the variation in drop size is somewhat limited, the velocity of individual drops is limited, and some variation in the travel time to paper would tend to occur. In addition, the capacity of the ink jet to produce large ink spots using a large number of successive pulses limits the maximum rate. U.S. Patent No. 4,491,851 of Mizuno, et al. illustrates another approach in which successive drive pulses are used to generate ink drops of varying sizes.

U.S. Patent No. 4,561,025 of Tsuzuki describes another printer for printing half-tone images with ink drops or dots of varying sizes. The diameter of each dot is controlled by controlling the energy content of the driving pulse which causes the dot, for example, by varying the amplitude or pulse width of the driving pulse.

U.S. Patent No. 4,563,689 of Murakimi, et al. discloses still another approach for achieving half-tone printing. In this approach, a preceding pulse is applied to an electromechanical transducer prior to a main pulse. The preceding pulse is described as a voltage pulse that is applied to a piezoelectric transducer in order to oscillate ink in the nozzle. The preceding pulse controls the position of the ink meniscus in the nozzle and thereby the ink drop size. In Figures 4 and 8, of this patent, the preceding and main pulses are of the same polarity. In Figures 9 and 11, of this patent, these pulses are of opposite polarity. This patent also mentions the control of ink drop size by changing the voltage and/or the pulse width of the preceding pulse and the time interval between the application of the preceding pulse and the main pulse.

Although these approaches for achieving half-tone or grey scale printing are known, they suffer from a number of drawbacks. For example, drops of various sizes which are accelerated solely by energy pulses applied to a piezoceramic transducer tend to travel at varying velocities and reach the media at varying times. This can result in distortions in the resulting print because ink jet print heads typically scan the print medium, and thus are moving, or the print medium is moved, during printing. In addition,

the range of ink drop sizes and ink drop repetition rates is limited in a number of these designs.

Relatively complex drive circuitry has also been used to insert time delays in the application of drive signals applied to transducers to compensate for variations in travel time to the print medium. However, this approach adds to the costs of such systems and can limit the maximum drop repetition rate of an ink jet.

Electric fields have also been employed in connection with ink jet print heads.

For example, U.S. Patent No. 3,060,429 of Winston discloses an ink jet print head having a nozzle which is supplied with ink under sufficient pressure to form a convex meniscus at the end of the nozzle, but which is insufficient to produce a flow of ink out of the nozzle. An electrostatic field is established between the nozzle and a conductive platen. This electric field draws drops of ink from the nozzle toward strips of paper or other print medium placed against the platen. Drop ejection is interrupted by reducing the strength of the electric field. In one embodiment described in this patent, an anode or valving plate with an aperture is positioned between the nozzle and platen. By varying the voltage applied to the valving plate, the ink jet is controlled to interrupt the flow of ink toward the print medium. In still other embodiments, deflecting electrodes are used to apply a field in a direction transverse to the direction of travel of ink drops toward the print medium so as to deflect or alter the travel path of the ink drops.

In designs of this type, relatively complex circuits are required to switch high electric fields to accomplish drop-on-demand printing and to provide deflection voltages in examples wherein deflection plates are used. Also, the electric fields are typically switched individually for each ink jet orifice in an array, further adding to the complexity of these designs. In addition, there is a tendency for ink jet print heads of this type to drool, due to an attempt to maintain ink pressure at a level which is only slightly below the level required for printing. In addition, designs of this type lack the advantages of ink jet print heads in which acoustic drive mechanisms are used in drop formation and ejection.

U.S. Patent No. 4,710,784 of Nakayama describes an ink jet print head which includes an array of electrically conductive printing electrodes impregnated with ink. When a particular print electrode is not being utilized for printing, an electrical field of a first strength is established between such electrode and the print medium and printing does not occur. To cause printing from this electrode, a switch is operated to increase the strength of the field between the electrode and the print electrode. By increasing the length of the time period of application of the higher electric field, the volume of ink in a drop is increased.

Although utilizing an electric field, the approach of the Nakayama patent adds to the circuit complexities

by varying an electric field to accomplish drop ejection. Also, the Nakayama approach requires the individual switching of electric fields associated with each ink jet orifice. In addition, the benefits achieved by using acoustic drive mechanisms for generating pressure pulses in ink are not present in the Nakayama approach.

U.S. Patent No. 4,403,223 of Tsuzuki, et al. describes a drop-on-demand type ink jet printer in which a driving pulse is applied to a piezoelectric transducer to cause the ejection of a drop of ink from a nozzle. The drop size is varied by controlling the energy content of the applied driving pulse for purposes of achieving half-tone printing. The ejected ink drops pass between charging electrodes and are charged by a voltage which is applied as the drops are ejected from the nozzle. This charging voltage varies as a function of the energy content of the driving pulses. In the embodiment of Fig. 10 of this patent, the charged ink drops pass between deflection plates which generate a field oriented transversely to the direction of drop travel for purposes of altering the flight path of the drops. In the Fig. 1 form of the apparatus, the charged drops pass between a pair of plates 40 and a pair of plates 60, with the deflection plates positioned between plates 60 and plates 40. The plates 40 and 60 establish an electric field oriented in the direction of travel of the ink drops for purposes of accelerating the drops.

The Tsuzuki, et al. patent requires relatively complex driving circuits inasmuch as the charging voltage is varied with variations in the driving pulse. In addition, the use of deflection voltages also adds to the complexities of this device.

Although these prior art devices are known, a need exists for an improved ink jet printer which is capable of operating at a relatively high ink drop repetition rate. A need also exists for such an ink jet print head which is capable of effectively achieving half-tone or grey scale printing using a wide range of ink drop sizes and without requiring complex field switching or time delay circuitry.

A drop-on-demand ink jet is described of the type having an ink chamber coupled to a source of ink, an ink drop forming orifice with an outlet, and in which the ink drop orifice is coupled to the ink chamber. An acoustic driver is used to produce a pressure wave in the ink to cause the ink to pass outwardly through the ink drop orifice and the outlet. A high voltage electric field is established and oriented to accelerate ink drops along a path from the outlet to print medium spaced from the outlet. The acoustic driver causes ink to pass from the outlet and into the electric field whereupon the electric field pulls the ink from the outlet, assists in breaking off the ink passing from the outlet to form an ink drop, and assists in accelerating the ink drop toward the print medium. The electric field remains time invariant during ink drop formation and

drop acceleration. Preferably only one time invariant electric field is present along the path of ink drop travel. The electric field may be established by one or more electrodes with the field being oriented to accelerate the drops in a common direction toward the print medium.

An ink jet of this type operated with an electric field in general is capable of producing a larger range of ink drop sizes, and in particular small size ink drops, than can be achieved by operating the ink jet without the electric field. In addition, the ink jet of the present invention is simplified. For example, circuit complexities associated with varying an electric field during operation of an ink jet printer are eliminated. In addition, the electric field allows stable and uniform operation of an ink jet printer at a higher drop repetition rate than the case without the electric field.

In accordance with another aspect of the present invention, an acoustic driver may be operated to selectively vary the volume of ink that emerges from the outlet into the electric field. As a result, the volume of ink in the ink drops traveling along the path toward the print medium is varied. It has been found that an acoustic driver imparts more energy to larger drops than smaller drops and tends to cause the larger drops to travel faster toward the print medium. In addition, the electric field tends to accelerate smaller drops more than larger drops. As a result, the combined effect from the use of an electric field and an acoustic driver is to cause the various volume ink drops to take substantially the same amount of time to travel to the print medium. As a result, distortions in the resulting printed image are minimized and an effective approach for achieving grey scale or half-tone printing is achieved.

As another aspect of the present invention, at least one bipolar electric pulse, with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period, may be applied to acoustic drivers of the ink jet printer. The volume of the ink in the ink drops is varied by selectively varying the duration of the wait period, varying the duration or pulse width of the ejection pulse component, varying the amplitude of the ejection pulse component, varying the ratio of the pulse width of the ejection pulse component to the pulse width of the refill pulse component, varying the ratio of the amplitude of the ejection pulse component to the amplitude of the refill pulse component, and by combinations of the above techniques.

In another approach for varying the volume of ink in the ink drops, a plurality of bipolar pulses are used to form the drops, with the number of pulses used to form an individual drop controlling the volume of ink in the drop. Each of these bipolar electric pulses are separated from one another by a time period which is insufficient to permit the breaking off of an ink drop at the orifice outlet until a selected number of the bipolar

drive pulses have been applied. In one specific approach, these bipolar electric pulses are separated from one another by a time period of at least about two times the duration of an individual bipolar electric pulse. More specifically, the bipolar electric pulses which are applied to form a single drop may be separated from one another by a time period of from about 40 microseconds to about 100 microseconds.

Alternatively, the acoustic drivers may be driven by unipolar electric pulses with the amplitude and pulse width of the unipolar pulses being varied to vary the volume of ink in the ink drops. In addition, strings or packets of successive drive pulses may be used to vary the volume of ink in the ink drops.

The drop-on-demand ink jet printer may comprise an array of plural ink jets, each with an orifice or nozzle outlet. In a preferred approach, a common electric field is established downstream (closer to the print medium) of the orifice outlets and is oriented in the direction of travel of ink drops ejected from the outlets. As ink passes from the respective outlets in response to drive pulses applied to acoustic drivers associated with the outlets, the electric field pulls the ink passing from the outlets, assists in breaking off of the ink passing from the outlets to form ink drops, and accelerates the ink drops toward the print medium.

The present invention is useable with a wide variety of inks, including inks with a resistivity of from about 10^{-4} ohm-cm to 10^{-11} ohm-cm. In addition, the inks may be of the phase change type as well as the type which is liquid at room temperature.

The magnitude of the electric field typically ranges from about 750 kilovolts per millimeter to the breakdown voltage across the gap between the electrodes which produce the field. The present invention works for both positive and negative electric fields, however, a negative field appears to produce marginally improved results. The strength of the electric field, although remaining time invariant during drop formation and acceleration, may be varied from a first level for a first type of print medium to a second level for a second type of print medium. For example, if the print medium is mylar positioned between the electrodes forming the electric field, the electric field is typically higher than if the print medium is paper.

It is accordingly one object of the present invention to provide an ink jet print head which is capable of reliably and efficiently operating to provide grey scale or half-tone printing.

Another object of the present invention is to increase the range of drop sizes available from an ink jet printer.

A further object of the present invention is to provide an ink jet printer which is capable of stable operation at relatively high drop repetition rates.

Another object of the present invention is to reduce the drive voltages required to generate ink drops and to permit the operation of an ink jet print

head in response to a wide range of drive wave forms.

Still another object of the present invention is to eliminate the complexities associated with establishing time varying electric fields during printing by an ink jet printer.

These and other objects, features and advantages of the present invention will become apparent with reference to the following description and drawings.

FIG. 1 is a schematic illustration, partially in section, of one form of ink jet printer in accordance with the present invention with print medium positioned between an electric field generating electrode and an ink jet print head.

FIG. 2 is a schematic illustration of the process of ink drop formation by an ink jet printer of the present invention.

FIG. 3 illustrates one suitable form of a drive signal for an acoustic driver of an ink jet printer in accordance with the present invention.

FIG. 4 is a schematic illustration of an alternative form of drive signal for an acoustic driver of an ink jet printer of the present invention.

FIG. 5 is a schematic illustration of various ink spot sizes printed by an ink jet printer operated in accordance with the present invention.

FIG. 6 is a schematic illustration, partially in section, of an ink jet printer in accordance with the present invention with an electric field generating electrode positioned between the print medium and the ink jet print head.

With reference to FIG. 1, a drop-on-demand ink jet 10 is illustrated with an ink chamber 12 coupled to a source of ink 14. The ink jet 10 has an orifice 16 coupled to or in communication with the ink chamber 12. The orifice 16 has an outlet 18 through which ink passes during ink drop formation. The ink drops travel in a first direction along a path from the outlet toward print medium 20, which is spaced from the outlet 18 by a gap G. A typical ink jet printer includes a plurality of ink chambers each coupled to one or more respective orifices and orifice outlets. In FIG. 1, a second orifice 18' is indicated.

An acoustic drive mechanism 30 is utilized for generating a pressure wave in the ink to cause ink to pass outwardly through the ink drop orifice and outlet. The illustrated acoustic drive mechanism comprises piezoceramic material 32 bonded to a thin diaphragm 34 which overlies and closes one side of the ink chamber 12. The driver 30 bends in response to signals from a signal source 36 and causes pressure waves in the ink.

It should be noted that the invention has particular applicability and benefits when piezoelectric drivers are used in ink drop formation. One preferred form of an ink jet print head using this type of driver is described in detail in our co-pending European Application No 90 311977.4.

This particular patent application is incorporated herein by reference and is owned by the Assignee of the present application. However, it is also possible to use other forms of ink jet printers and acoustic drivers in conjunction with the present invention. For example, bubble jets having a heater for generating bubbles which cause a pressure wave in ink for generating ink drops may be used. Also, electromagnet-solenoid drivers, as well as other shapes of piezoelectric drivers (e.g., circular, polygonal, cylindrical, annular-cylindrical, etc.) may be used. In addition, various modes of deflection of piezoelectric drivers may also be used, such as bending mode, shear mode, and longitudinal mode.

Again, with reference to FIG. 1, a high voltage electric field is established and oriented to accelerate ink drops along the path of travel from the outlet 18 toward the print medium 20. As explained below, the electric field is constant or time invariant during drop formation and acceleration. In addition, this electric field is preferably the only electric field present along the path as the drops are formed and accelerated toward the print medium. This time invariant field may be established by two, three, or more electrodes with the field being oriented to accelerate the drops in a common direction toward the print medium may be used. As a result, circuitry for charging drops and for establishing fields oriented to deflect drops away from the print medium is eliminated.

In FIG. 1, the orifice 16 extends through an orifice plate 38 which is shown coupled to the electrical ground potential. A bar electrode 42 is positioned as shown with the print medium 20 between the electrode 42 and the orifice plate 38. The electrode 42 is coupled to a power source S such that an electric field is established between the orifice plate 38 and the electrode 42. This electric field is oriented in a direction which is orthogonal to the orifice plate 38 and thus parallel to the axes of the respective orifices 16. A field oriented in this direction accelerates ink drops along the path from the outlets 18, 18' etc. and toward the print medium.

The electric field, which is downstream of the orifice plate 38, is typically established at 750 volts per millimeter as a minimum with 2000 volts per millimeter being a typical preferred field. The field may be increased up to the breakdown voltage across the gap G, which typically occurs at about 3000-3500 volts per millimeter. Various types of electrodes may be used to establish the desired electric field. For example, a ring or cylindrical electrode or electrodes may be used between the orifices and print medium for establishing the desired electric field with the ink drops passing through the ring electrodes. As another example, as shown in FIG. 6, an electrode 42' may be positioned between the print medium 20 and the orifice plate 38. This type of electrode has an elongated slit 44 aligned with the orifice outlets 18, 18' through which ink drops

from the outlets travel to the print medium.

As is apparent from FIGS. 1 and 6, advantageously, although not necessarily, a common electric field is established for all of the ink jet orifices in an array. This further simplifies the present invention in that individualized fields and electrodes are not required for the various orifices and orifice outlets. As ink jet print heads become more and more compact, the spacing between individual orifice outlets is substantially reduced. By eliminating the need for individualized electric fields for the various ink jet outlets, the present invention is applicable to ink jet print heads with compact arrays of multiple nozzle orifices.

As previously mentioned, the electric field is time invariant or constant. That is, the electric field is not pulsed during operation of the ink jet nor is the magnitude of the electric field altered to charge individual ink drops or to adjust the acceleration applied to individual ink drops, depending, for example, upon their size.

However, it has been found desirable to adjust the magnitude of the electric field from a first level for one type of print medium to a second level for other types of print medium, particularly where the print medium is positioned between the electrodes. That is, various types of print medium may have differing electrical insulation characteristics. Therefore, when a particular print medium is used, the electric field is established for this type of print medium and maintained until another type of print medium is used at which time a different time invariant electric field may be established. As a specific example, if the print medium 20 of FIG. 1 is mylar, a typical electric field is 2.7 kilovolts per millimeter. In contrast, if the print medium is bond paper having a lower dielectric constant than mylar, the electric field is typically set at a lower level, such as about 2.5 kilovolts per millimeter. The electric field need not be adjusted for variations in the print medium, but optimization of printing results can be achieved in the FIG. 1 approach by increasing the electric field as the dielectric constant of the print medium increases.

FIGS. 2a, 2b, 2c and 2d illustrate a sequence of ink drop ejection for the ink jet print head 10 of FIG. 1. When the ink jet print head 10 is not being operated, the ink meniscus 50 is withdrawn inside the orifice plate 38 and within the orifice 16 as shown in FIG. 2a. This is due to a slight negative pressure typically maintained in the ink chamber 12 to prevent drooling of ink from the orifice outlet 18 at times when drop ejection is not desired. When the ink meniscus 50 is in this position, there is no electric field on the surface of the meniscus because the orifice plate 38 is maintained at the electrical ground potential in this embodiment of the invention. When a drop of ink is desired on the print medium, an electric pulse is applied from signal source 36 to the piezoelectric driver 30 which causes it to bend. As a result of this bending, an

acoustic or pressure wave is created in the ink near the orifice 16. Consequently, in response to this pressure wave, the ink meniscus 50 protrudes outside of the ink orifice outlet 18 as shown in FIG. 2b. The protruded ink meniscus 50 is subjected to the strong electric field established between the orifice outlet 18 and the common electrode 42. The electric field produces electrostatic forces on the surface of the meniscus 50 which are strongest at the meniscus tip. If the electrostatic force at the meniscus is sufficiently large, the tip is pulled toward the common electrode 42 and forms a narrow fluid filament of ink which is attached to apex of the protruding meniscus 50. FIG. 2c shows this phenomena of a long narrow liquid filament 52 attached to a hemisphere-like base of ink near the ink orifice outlet. The narrow liquid filament 52 breaks off from the meniscus tip as shown in FIG. 2d when the meniscus is pulled back inside of the orifice plate 38. This is believed to occur because, when the ink meniscus 50 is pulled back inside the ink orifice, the surface of the ink meniscus which includes the point of attachment to the filament 52 is not subjected to any electrostatic forces. Consequently, the high surface tension forces at the point of attachment of the filament 52 causes the filament to break off as shown in FIG. 2d. In FIG. 2c, the presence of a strong electrostatic force at the point of attachment of the filament 52 to the meniscus tip 50, opposes the forces of surface tension and thus minimizes break-off at undesired times.

The acoustic driver 30 may be operated to simply push the meniscus out from the orifice plate and pull the meniscus back within the orifice plate with the electric field breaking off the filament and accelerating the filament toward the print medium. When the drive mechanism is used solely for this purpose and not for imparting the initial velocity to the ink drop, lower drive energy is required for driver 30 and a more compact ink jet print head can be used. This is the preferred mode of operation for producing drops of the smallest sizes.

However, the preferred approach for producing large volume drops involves the operation of the driver 30 with sufficient energy to form the drop and impart an initial small forward velocity to the drop. As explained below, drops of various volumes may be generated for use in half-tone or grey scale printing. The energy from the drive mechanism primarily establishes the volume of the drop and also has a small influence on the initial velocity of the larger volume drops. Typical initial velocities as a result of the drive pulse range up to about 2 meters per second, depending upon the drop size. Larger volume drops are accelerated by the drive mechanism at a faster rate than smaller volume drops, with the smallest drops not being accelerated by the drive pulse. The electric field pulls the ink passing from the orifice outlet and accelerates these drops to typically from

about 10 to about 20 meters per second. It has been found that the constant electric field accelerates the smaller drops at a faster rate than the larger drops. In addition, as previously mentioned, the driver mechanism accelerates the large drops faster than the smaller drops. Therefore, the acoustic drive mechanism and electric field cooperate such that drops of various sizes require substantially the same amount of time to travel to the print medium.

In typical printing applications, the print medium is moved, the ink jet print head is moved to scan the print medium, or both the medium and ink jet print head move. Therefore, it is desirable not only to have a substantially constant travel time between the orifice plate and print medium, but also to have a much larger drop velocity in comparison to the relative media velocity, to minimize distortion in the resulting printed image. By a substantially constant travel time, it is meant that the drops of various sizes reach the print medium within about plus or minus fifteen microseconds of one another.

In addition to advantages in grey scale or half-tone printing, other advantages also exist as a result of the present invention. That is, lower voltages are required to drive the piezoceramic transducers because the transducers are not required to impart all of the velocity to the ink drops. That is, the electric field assists in accelerating the drops. In addition, it has been found that ink jet print heads which stably operate uniformly at a first maximum drop repetition rate without an electric field are capable of operating at a higher drop repetition rate in the presence of a time invariant field in accordance with the present invention. Ink jet print heads of the type shown in FIG. 1 have been operated at drop repetition rates of from up to eight kilohertz, with higher drop repetition rates being possible. Furthermore, ink drops of smaller sizes have been obtained using a drop-on-demand ink jet print head operating in the presence of an electric field than the case of the ink jet print head operating without such a field for a given drop repetition rate. It has been found for ink jet print heads tested up to this time, that the minimum drop sizes can be reduced by about twenty percent or more by the use of an electric field. In addition, the relatively high drop velocities achieved in the presence of an electric field permit greater versatility in the drive wave forms that can be used to drive acoustic drivers used in generating the drops at high drop repetition rates.

Although these other advantages exist, one of the principal advantages of the present invention relates to the effective achievement of half-tone or grey scale printing in a drop-on-demand ink jet printer when operated as described in the presence of an electric field. The phrase grey scale printing is synonymous with drop volume modulation or variation.

In general, the volume of ink contained in an individual ink drop is controlled by the diameter of the ink

jet orifice and by controlling the wave form used in driving the acoustic driver. By adjusting the wave form to increase the volume of ink and the amount of time the ink volume protrudes in front of the orifice outlet and in the region of the high electric field, larger ink drops can be achieved. Conversely, by reducing the volume of ink and the time the ink protrudes from the orifice outlet, the smaller the ink drops.

With reference to FIG. 4, a unipolar drive pulse is illustrated. Such a unipolar drive pulse can be generated in a conventional manner by signal generator 36 and applied to the acoustic drive mechanism 30. In a first approach for varying the volume of ink drops, an amplitude modulation approach, the amplitude of the pulse shown in FIG. 4 may be increased from V_0 to V_1 . This results in an increase in the volume of ink included in an ink drop. Conversely, if the voltage is reduced from V_0 to a lower level, the volume of ink in the ink drop is reduced. A pulse width modulation technique may also be used. For example, by increasing the duration or pulse width of the pulse illustrated in FIG. 4 from t_1 to t_2 to t_1 to t_3 , the volume of ink included in an ink drop is increased. In contrast, by decreasing the pulse width of the illustrated pulse, the volume of ink included in an ink drop is reduced. Combinations of amplitude and pulse width modulation approaches may also be used and different wave forms may be applied other than those shown in FIG. 4. For example, strings of pulses may be used with the number of pulses applied to the driver 30 between initial drop formation and break-off of the drop determining the volume of the ink drop.

One particularly advantageous drive signal for achieving grey scale printing is illustrated in FIG. 3. This particular drive signal is a bipolar electric pulse 60 with a refill pulse component 62 and an ejection pulse component 64. The components 62 and 64 are of voltages of opposite polarity. The pulse components 62, 64 are also separated by a wait time period X. The polarities of the components 62, 64 may be reversed from that shown in FIG. 3 depending upon the polarization of the piezoelectric driver mechanism 30. In operation, upon the application of the refill pulse component 62, the ink chamber 12 expands and draws ink into the chamber for refilling the chamber following the ejection of a drop. As the voltage falls toward 0 at the end of the refill pulse, the ink chamber begins to contract and moves the ink meniscus forwardly in the orifice 16 toward the orifice outlet 18. Upon the application of the ejection pulse component 64, the ink chamber is rapidly constricted to cause the ejection of a drop of ink. As the duration of the wait period increases, the ink meniscus moves closer to the orifice outlet 18 at the time the ejection pulse component 64 is applied. By increasing the duration of the wait period until the meniscus has moved forward to a position closest to the outlet 18 before the application of the drop ejection pulse, the volume of ink

included in an individual ink drop is increased. The volume is conversely reduced by shortening the wait period. The duration of the desired wait period for a given drop volume depends upon the characteristics of the particular ink jet being utilized and can be observed by monitoring the performance of the ink jet. In general, the wait period is less than about one-third of the time period of the natural or resonance frequency of the meniscus. Typical meniscus resonance time periods range from 50 microseconds to 160 microseconds, depending upon the ink jet configuration and the ink being used. In addition, by increasing the duration of the eject pulse component 64, or by increasing the amplitude of the eject pulse component the volume of the ink drops can be increased.

As a specific example, an ink jet print head of the type disclosed in the previously mentioned European Patent Application No 90 311977.4, was operated at a 4 kilohertz drop repetition rate. As shown in FIG. 5, various levels or volumes of ink in individual ink drops were achieved by altering the drive wave form of FIG. 3. The spots or dots FIG. 5 correspond to dots printed on mylar print medium which ranged in size from about 1.6 mils. to about 3.92 mils. If the ink is not melt ink, following fusing of the ink spots on the print medium, by the application of pressure, this variation in spot size is even greater, for example, from about 1.8 mils to about 5.5 mils. To achieve the level 1 dot size, the wait period X was set at 9 microseconds and the duration Y of the eject pulse component 64 was set at 3 microseconds. To achieve the level 2 dot size, X was set at 11 microseconds and Y was set at 5 microseconds. To achieve the level 3 dot size, X was set at 11 microseconds and Y at 9 microseconds. To achieve the level 4 dot size, X was set at 12 microseconds and Y was set at 11 microseconds. To achieve the level 5 dot size, X was set at 12 microseconds and Y was set at 15 microseconds. Finally, to achieve the level 6 dot size, X was set at 12 microseconds and Y was set at 20 microseconds. In each of these cases, the amplitude and pulse width of the refill pulse component was respectively five microseconds and forty volts. Also, the amplitude of the eject pulse component was forty volts. In addition, the electric field was 2.4 kilovolts per millimeter. By adjusting these component values of the bipolar drive pulses, the ink drop volumes and ink dot sizes are correspondingly adjusted. Similarly, by increasing the amplitude of the eject pulse component, either alone or in combination with an adjustment of the duration of the wait period and of the pulse width of the eject pulse component, variation in ink drop volume can also be achieved. As the amplitude of the eject pulse component 64 increases, the ratio of the amplitude of the eject pulse component to the refill pulse component increases as does the volume of ink included in the drops. Similarly, as the pulse width of the eject pulse component increases, the ratio of the pulse

width of the eject pulse component to the pulse width of the refill pulse component also increases as does the ink drop volume.

In addition, plural bipolar pulses of the type shown in FIG. 3 may be utilized to produce an individual ink drop. In general, by increasing the number of such bipolar pulses used in forming an ink drop, the volume of ink in the ink drop is increased. In effect, each bipolar pulse causes the protrusion of an additional amount of ink into the electric field and thus increases the volume of ink included in an ink drop before the ink drop separates. To cause separation of an individual ink drop formed in this manner, the time period between the bipolar pulses is increased. Drop break-off can also be accomplished by applying a pulse of higher energy after the desired number of bipolar pulses have been used to generate the drop of the desired size. However, the apparatus is simplified if all of the bipolar pulses have the same characteristics and the delay between individual bipolar pulses is simply adjusted to cause a drop to break off in the electric field.

As a specific example, a typical bipolar pulse of a string of such pulses, including the refill component, wait period component and eject component, has a duration of from about 20 microseconds to 40 microseconds. In addition, the typical time delay between individual bipolar pulses ranges from about 12 to about 30 microseconds. For an ink jet print head of the type shown in FIG. 1, if the time delay between individual pulses becomes greater than about 100 microseconds, the drops break off. Assuming a 20 microsecond duration bipolar pulse, then a suitable separation between the bipolar pulses is about 40 microseconds, that is about two times the duration of an individual bipolar pulse. As long as the time period between bipolar pulses is less than about 100 microseconds or the time at which drop break-off occurs, a successive bipolar pulse adds ink to the volume of an individual ink drop instead of generating a separate drop.

In one specific test, a single bipolar pulse produced an ink dot on Xerox® bond paper of 2 mils in diameter, a string of two such bipolar pulses of 20 microsecond duration separated by a 40 microseconds produced an ink dot of 3 mils in diameter on this print medium, and a string of three such bipolar pulses resulted in an ink dot of a diameter of 4 mils on the print medium. In this example, the amplitude of the refill component of the individual bipolar pulses was forty volts. Also, the wait period between the refill and eject components was five microseconds. In addition, the pulse width and amplitude of the eject pulse component of each bipolar drive pulse was, respectively, ten microseconds and forty volts. Also, the electric field was 1.6 kilovolts per millimeter.

The compounding of one or more bipolar pulses to produce an individual drop does reduce the

maximum drop repetition rate at which an ink jet printer can be operated. However, high drop repetition rates are still possible. For example, in the case above where up to three bipolar pulses were combined to produce the largest drop sizes, repetition rates of up to eight kilohertz have been achieved.

Finally, it should be noted that the present invention is applicable to ink jet printers using a wide variety of inks. For example, inks having a resistivity of from about 10^{-4} ohm-cm to about 10^{-11} ohm-cm would be suitable, with inks having a resistivity of about 10^{-6} ohm-cm to about 10^{-8} ohm-cm being more suitable. In general, higher resistivity inks are believed to produce better results, although the exact range of suitable resistivity has yet to be established. Inks that are liquid at room temperature, as well as inks of the phase change type which are solid at room temperature, may be used. One suitable phase change ink is disclosed in European Patent Application No 89 307777.6. Again, however, the present invention is not limited to particular types of ink.

In its broad aspect, the invention provides a method of operating a drop-on-demand ink jet of the type having an ink chamber coupled to a source of ink, an ink drop orifice with an outlet, the ink drop orifice being coupled to the ink chamber, acoustic drive means for producing a pressure wave in the ink to cause ink to pass outwardly through the ink drop orifice and outlet and in which ink drops travel in a first direction along a path from the outlet, toward print medium spaced from the outlet and method comprising establishing a high voltage electric field oriented to accelerate ink drops along the path from the outlet toward the print medium, operating the acoustic drive means to cause ink to pass from the outlet and into the electric field, the electric field pulling the ink passing from the outlet, the electric field assisting in breaking off of ink passing from the outlet to form an ink drop, and the electric field accelerating the ink drop toward the print medium, and maintaining the electric field time invariant (and preferably as the only electric field present along the path) during drop formation and acceleration.

The operating step conveniently comprises operating the acoustic drive means to selectively vary the volume of ink that emerges from the outlet into the electric field and thereby the volume of ink drops travelling along the path toward the print medium, the electric field accelerating the various volume ink drops such that drops of various sizes require substantially the same amount of time to travel to the print medium, whereby the various volume drops are used to accomplish grey scale or half-tone printing. In such method, the drive means may comprise a piezoelectric drive means for expanding and contracting the volume of the ink chamber, the operating step comprising the step of driving the driver with at least one bipolar electric pulse with refill and ejection pulse

components of voltages of opposite polarity which are separated by a wait period, the operating step including varying the duration of the wait period to vary the volume of the ink drops. Alternatively, the operating step may comprise the step of driving the driver with a bipolar electric pulse with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period, the operating step including varying the duration of the ejection pulse to vary the volume of the ink drops. In a further alternative, the operating step may comprise the step of driving the driver with a bipolar electric pulse with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period, the operating step including varying the duration of the wait period and the duration of the ejection pulse to vary the volume of the ink drops. In another alternative, the operating step comprises the step of driving the driver with at least one bipolar electric pulse with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period, the operating step including varying the amplitude of the ejection pulse to vary the volume of the ink drops. A further alternative comprises the step of driving the driver with at least one bipolar electric pulse with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period, the operating step including varying the ratio of the pulse duration of the ejection pulse component to the pulse width of the refill pulse component to vary the volume of ink drops or the step of driving the driver with at least one bipolar electric pulse with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period, the operating step including varying the ratio of the amplitude of the ejection pulse component to the amplitude of the refill pulse component to vary the volume of ink drops. At least one unipolar electric pulse may be used instead of a bipolar pulse, the operating step including the step of varying the duration of unipolar drive pulses to vary the volume of ink in the ink drops, the step of varying the amplitude of the unipolar drive pulses to vary the volume of ink in the ink drops, or the step of varying the duration and the amplitude of the unipolar drive pulses to vary the volume of ink in the ink drops. Alternatively, driving is effected with at least one bipolar electric pulse with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period, the operating step including the step of varying the number of bipolar pulses used to form the drops to vary the volume of ink in the ink drops.

Claims

1. A method of operating a drop-on-demand ink (10) jet of the type having an ink chamber (12) coupled

- to a source (14) of ink, an ink drop orifice (16) with an outlet (18), the ink drop orifice (16) being coupled to the ink chamber (12), acoustic drive means (32) for producing a pressure wave in the ink to cause ink to pass outwardly through the ink drop orifice (16) and outlet (18), and in which ink drops travel in a first direction along a path from the outlet (18), toward print medium (20) spaced from the outlet (18), the method comprising operating the acoustic drive means (32) to cause ink to pass from the outlet (18) and into a high voltage electric field oriented to accelerate ink drops along the path from the outlet (18) toward the print medium (20), the electric field pulling the ink passing from the outlet (18) and assisting in breaking off of ink passing from the outlet (18) to form an ink drop, and the electric field accelerating the so-formed ink drop toward the print medium (20) characterized in that the electric field is maintained time invariant and as the only electric field present along the path during drop formation and acceleration.
2. A method as claimed in Claim 1 in which the drop-on-demand ink jet (10) is capable of producing drops of a first minimum size without establishing the electric field, the method comprising the step of operating the drive means (30) with the electric field established such that the drop-on-demand ink jet (10) produces drops of a second minimum size smaller than the first minimum size.
 3. A method as claimed in Claim 1 or Claim 2 in which the drop-on-demand ink jet (10) is capable of operation with a substantially constant drop travel time from the outlet (18) to the print medium (20) up to a first maximum repetition rate without establishing the electric field, the method comprising the step of operating the drive means (30) with the electric field established such that the drop-on-demand ink jet (10) operates with a substantially constant drop travel time from the outlet (18) to the print medium (20) up to a second maximum repetition rate greater than the first maximum repetition rate.
 4. A method as claimed in any one of Claims 1 to 3 in which the acoustic drive means (30) is operated so as selectively to vary the volume of ink that emerges from the outlet (18) into the electric field and thereby the volume of ink drops traveling along the path toward the print medium (20), the electric field accelerating the various volume ink drops such that drops of various sizes require substantially the same amount of time to travel to the print medium, the various volume drops being used to accomplish grey scale or half-tone printing.
 5. A method as claimed in any preceding claim in which the drive means (30) comprises a piezoelectric drive means for expanding and contracting the volume of the ink chamber (12), the acoustic driver (30) being driven in one of the following ways :—
 - (i) the acoustic driver (30) is driven with at least one bipolar electric pulse with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period, the duration of the wait period being varied so as to vary the volume of the ink drops ;
 - (ii) the acoustic driver (30) is driven with a bipolar electric pulse with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period, the duration of the ejection pulse being varied so as to vary the volume of the ink drops ;
 - (iii) the acoustic driver (30) is driven with a bipolar electric pulse with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period the duration of the wait period and the duration of the ejection pulse being varied so as to vary the volume of the ink drops ;
 - (iv) the acoustic driver (30) is driven with at least one bipolar electric pulse with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period, the amplitude of the ejection pulse being varied so as to vary the volume of the ink drops ;
 - (v) the acoustic driver (30) is driven with at least one bipolar electric pulse with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period, the ratio of the pulse duration of the ejection pulse component to the pulse width of the refill pulse component being varied so as to vary the volume of ink drops ;
 - (vi) the acoustic driver (30) is driven with at least one bipolar electric pulse with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period, the ratio of the amplitude of the ejection pulse component to the amplitude of the refill pulse component being varied so as to vary the volume of ink drops ;
 - (vii) the acoustic driver (30) is driven with at least one bipolar electric pulse with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period, the number of bipolar pulses used to form the drops being varied so as to vary the volume of ink in the ink drops ;
 - (viii) the acoustic driver (30) is driven with at least one unipolar electric pulse, the duration

- of unipolar drive pulses being varied so as to vary the volume of ink in the ink drops ;
 (ix) the acoustic driver (30) is driven with at least one unipolar electric pulse, the amplitude of the unipolar drive pulses being varied so as to vary the volume of ink in the ink drops ;
 or
 (x) the acoustic driver (30) is driven with at least one unipolar electric pulse, the duration and the amplitude of the unipolar drive pulses being varied so as to vary the volume of ink in the ink drops.
6. A method as claimed in any preceding claim in which the ink is phase change ink.
 7. A method as claimed in any preceding claim in which the drop-on-demand ink jet (10) comprises an array of a plurality of ink drop orifices (16) each with an orifice outlet (18), the electric field being a common electric field downstream of the orifice outlets (18) and addressing them all, the array being operated in accordance with the steps of Claim 1.
 8. A method as claimed in any preceding claim wherein the ink is a phase change or other ink having a resistivity of from 10^{-4} ohm-cm to 10^{-11} ohm-cm.
 9. A method as claimed in Claim 8 wherein the ink has a resistivity of 10^{-6} ohm-cm to 10^{-8} ohm-cm.
 10. A method as claimed in any preceding claim wherein the electric field is established by an electrode (42) spaced from the ink drop orifice outlet (18) by a gap (G), the electric field being within the range of from about 750 volts per millimeter of the breakdown voltage across the gap (G).
 11. A method as claimed in any preceding claim wherein the drive means (30) comprises a piezoelectric drive means for expanding and contracting the volume of the ink chamber (12), the driver (30) being supplied with at least one bipolar electric pulse with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period and the number of bipolar pulses used to form the drops being varied so as to vary the volume of ink in the ink drops.
 12. A method as claimed in Claim 11 wherein the bipolar electric pulses are separated from each other by a time period which is insufficient to cause the breaking off of a drop at the orifice outlet (18) until a selected number of the bipolar drive pulses have been applied.
 13. A method as claimed in Claim 11 wherein the bipolar electric pulses are separated from each other by no more than about one hundred microseconds.
 14. A method as claimed in Claim 11 wherein the bipolar electric pulses are separated from one another by a time period of at least about two times the duration of an individual bipolar electric pulse.
 15. A method as claimed in Claim 11 wherein the bipolar electric pulses are separated from one another by a time period of from about forty to about one hundred microseconds.
 16. A method as claimed in any preceding claim wherein the electric field is established by electric field-generating means (42) whose output is adjustable to vary the strength of the electric field from a first level for a first type of print medium (20) to a second level for a second type of print medium (20).
 17. A drop-on-demand ink jet print head (10) for ejecting a drop of ink along a path of travel from the ink jet print head (10), across a gap (G), and to print medium (20), the ink jet print head (10) comprising an ink chamber (12) ; a member (38) defining an ink drop ejection orifice (16) in communication with the ink chamber (12), the ink drop orifice (16) having an outlet (18) ; acoustic drive means (30) for causing ink to pass from the outlet (18) ; and means (42) for establishing a high voltage electric field along at least a portion of the path for pulling ink passing from the outlet (18), for assisting in forming a drop of ink, and for accelerating the travel of ink drops to the print medium (20), the electric field being time invariant during drop formation and acceleration.
 18. A print head as claimed in Claim 17 and including means for selectively varying the volume of ink in the ink drops.
 19. A print head as claimed in Claim 17 or Claim 18 wherein the means (42) for establishing the high voltage electric field is so arranged as in use to establish an electric field oriented to accelerate ink drops towards the print medium (20) as the sole orientation of electric fields along the path.
 20. A print head as claimed in any one of Claims 17 to 19 and including means (32, 34) for passing a body of ink outwardly through the outlet (18) such that the electric field draws the body of ink into the configuration of a filament (52) and means for retracting a portion of the body of ink adjacent to the orifice (16) to sever the body of ink into a body

portion (52) outside the outlet (18) and a body portion (50) which is inside the orifice (16) thereby to form a drop of ink, the electric field causing the drop to accelerate across the gap (G) and toward the print medium (20).

5

passing from the outlets (18) in use, for assisting in forming drops of ink and for accelerating the travel of ink drops of the print medium (20), the electric field being time invariant during drop formation and acceleration.

21. A print head as claimed in any one of Claims 17 to 20 wherein the drive means (30) comprises a piezoelectric drive means for expanding and contracting the volume of the ink chamber (12), the drive means (30) including means (32) for driving the drive means with a bipolar electric drive pulse with refill and ejection pulse components of voltages of opposite polarity which are separated by a wait period as to vary the volume of ink in the ink drops.

10

15

22. A print head as claimed in any one of Claims 17 to 21 and comprising an array of orifices (16) and orifice outlets (18).

20

23. A print head as claimed in any one of Claims 17 to 22 wherein the means for establishing an electric field comprises means for establishing an electric field of a magnitude within the range from 750 volts per millimeter to the breakdown voltage across the gap (G).

25

24. A print head as claimed in any one of Claims 17 to 23 wherein the means for establishing an electric field includes an electrode (42) positioned with the print medium (20) between the electrode (42) and the orifice outlet (18), the print head (10) having an orifice plate (38) defining the orifice outlet (18), the orifice plate (38) being generally in a first plane, the electric field being established in a direction normal to the first plane and between the orifice plate (38) and the electrode (42), the apparatus including means for adjusting the strength of the electric field to a first level for a first type of print medium (20) and to a second level for a second type of print medium (20).

30

35

40

25. A print head as claimed in any one of Claims 17 to 24 and configured and arranged for ejecting a plurality of drops of ink along paths of travel from nozzles (16) in an array of nozzles of the print head (10), the paths extending from the print head nozzles, across a gap (G) and to print medium (20), the print head (10) comprising plural ink chambers (12); a member (38) which defines plural ink drop ejecting orifices (16), each orifice (16) being in communication with a respective associated ink chamber (12) and each of the orifices (16) having an outlet (18); acoustic drive means (30) for causing ink to pass from the outlets (18); and means (42) for establishing a common high voltage electric field for pulling ink

45

50

55

