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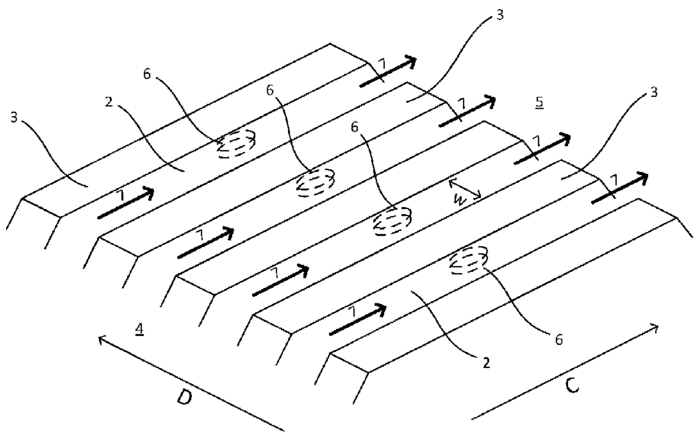

FIG. 7

(57) **Abstract**: A droplet ejection apparatus, such as an inkjet printhead, having improved productivity that includes: an array of elongate fluid chambers (2), with each chamber communicating with a nozzle (6), the array extending in an array direction; a common fluid inlet manifold (4); a common fluid outlet manifold (5); and a fluid supply that generates a through-flow of fluid from the common fluid inlet manifold, through each chamber in the array and into the common fluid outlet manifold; the two walls defining each chamber are formed from piezoelectric material so as to effect droplet ejection from the nozzle; this ejection flow occurs simultaneously with the through flow, which may have a larger value than the maximum ejection flow; each nozzle may be elongate parallel to the length of its chamber and/or may have an outlet with an area conferring advantages in terms of productivity and temperature control.

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DROPLET DEPOSITION APPARATUS AND METHOD FOR DEPOSITING DROPLETS OF FLUID

The present invention relates to droplet deposition apparatus and methods for depositing droplets of fluid. It may find particularly beneficial application in a droplet deposition apparatus comprising an array of elongate fluid chambers, each chamber communicating with an orifice for droplet ejection, with a common fluid inlet manifold and with a common fluid outlet manifold, together with means for generating a fluid flow into said inlet manifold, through each chamber in the array and into said outlet manifold.

Examples of such droplet deposition apparatus are provided by WO 00/38928, from which Figures 1, 2, 3 and 4 are taken. Figure 1, for example illustrates a “pagewide” printhead 10, having two rows of nozzles 20, 30 (each having a circular profile) that extend (in the direction indicated by arrow 100) the width of a piece of paper and which allow ink to be deposited across the entire width of a page in a single pass. Ejection of ink from a nozzle is achieved by the application of an electrical signal to actuation means associated with a fluid chamber communicating with that nozzle, as is known e.g. from EP-A-0 277 703, EP-A-0 278 590 and, more particularly, WO 98/52763 and WO 99/19147. To simplify manufacture and increase yield, the "pagewide" row(s) of nozzles may be made up of a number of modules, one of which is shown at 40, each module having associated fluid chambers and actuation means and being connected to associated drive circuitry (integrated circuit ("chip") 50) by means e.g. of a flexible circuit 60. Ink supply to and from the printhead is via respective bores (not shown) in endcaps 90.

Figure 2 is a perspective view of the printhead of Figure 1 from the rear and with endcaps 90 removed to reveal the supporting structure 200 of the printhead incorporating ink flow passages 210,220,230 extending the width of the printhead. Via a bore in one of the endcaps 90 (omitted from the views of Figures 1 and 2), ink enters the printhead and the ink supply passage 220, as shown at 215 in Figure 2. As it flows along the passage, it is drawn off into respective ink chambers, as illustrated in Figure 3, which is a sectional view of the printhead taken perpendicular to the direction of extension of the nozzle rows. From passage 220, ink flows into first and second parallel rows of ink chambers (indicated at 300 and 310 respectively) via aperture 320 formed in structure 200 (shown shaded). Having flowed through the first and second rows of ink chambers, ink exits via apertures 330 and 340 to join the ink flow along respective first and second ink outlet passages 210,230, as indicated at 235. These join at a common ink outlet (not shown) formed in the end-cap and which may be located at the opposite or same end of the printhead to that in which the inlet bore is formed.

Further detail of the chambers and nozzles of the particular printhead shown in Figures 1 to 3 is given in Figure 4, which is a sectional view taken along a fluid chamber of a module 40. The fluid chambers take the form of channels, 11, machined or otherwise formed in a base component 860 of piezoelectric material so as to define piezoelectric channel walls which are subsequently coated with electrodes, thereby to form channel wall actuators, as known e.g. from EP-A-0 277 703. Each channel half is closed along a length 600,610 by respective sections 820,830 of a cover component 620 which is also formed with ports 630,640,650 that communicate with fluid manifolds 210,220,230 respectively. A break in the electrodes at 810 allows the channel walls in either half of the channel to be operated independently by means of electrical signals applied via electrical inputs (flexible circuits 60).Ink ejection from each channel half is via openings 840,850 that communicate the channel with the opposite surface of the piezoelectric base component to that in which the channel is formed. Nozzles 870,880 for ink ejection are subsequently formed in a nozzle plate 890 attached to the piezoelectric component.

Those skilled in the art will appreciate that a variety of alternative fluids may be deposited by droplet deposition apparatus: droplets of ink may travel to, for example, a paper or other substrate, such as ceramic tiling, to form an image, as is the case in inkjet printing applications; alternatively, droplets of fluid may be used to build structures, for example electrically active fluids may be deposited onto a substrate such as a circuit board so as to enable prototyping of electrical devices, or polymer containing fluids or molten polymer may be deposited in successive layers so as to produce a prototype model of an object (as in 3D printing). Droplet deposition apparatus suitable for such alternative fluids may be provided with modules that are similar in construction to standard inkjet printheads, with some adaptations made to handle the specific fluid in question.

Figures 5 and 6 are exploded perspective views of a printhead employing a similar double-ended side-shooter construction to that of Figures 1 to 4, but taken from WO 01/12442. As may be seen, two rows of channels spaced relatively to one another in the media feed direction are used, with each row extending the width of a page in a direction transverse to the media feed direction.

The two rows of channels are formed in respective strips of piezoelectric material 110a, 110b, which are bonded to a planar surface 120 of substrate 86. Electrodes are provided on the walls of the channels, so that electrical signals may be selectively applied to the walls. The channel walls thus act as actuator members and may cause droplet ejection. Substrate 86 is formed with conductive tracks 192 which are electrically connected to the respective channel wall electrodes, (for example by solder bonds), and which extend to the edge of the substrate where respective drive circuitry (integrated circuits 84a, 84b) for each row of channels is located.

As may also be seen from Figures 5 and 6, a cover member 130 is bonded to the tops of the channel walls so as to create closed, "active" channel lengths which may contain pressure waves that allow for droplet ejection. Nozzle holes, each having a circular profile, are formed in cover member 130, which communicate with the channels to enable ejection of droplets.

The substrate 86 is also provided with ports 88, 90 and 92, which communicate to inlet and outlet manifolds. As with the construction described with reference to Figures 1 to 4, an inlet manifold may be provided in between two outlet manifolds, with the inlet manifold thus supplying ink to the channels via ports 90, and ink being removed from the two rows of channels to respective outlet manifolds via ports 88 and 92. As Figure 6 illustrates, the conductive tracks 192 may be diverted around the ports 88, 90 and 92.

The printheads disclosed in WO 00/38928 and WO 01/12442 may therefore be considered examples of droplet deposition apparatus that include an array of elongate fluid chambers, with each chamber communicating with an orifice for droplet ejection, with a common fluid inlet manifold and with a common fluid outlet manifold, together with means for generating a fluid flow into said inlet manifold, through each chamber in the array and into said outlet manifold.

The present invention relates to improvements in such droplet deposition apparatus.

Increase in process productivity in droplet deposition processes, such as printing applications and industrial deposition is a key driver in many industrial sectors. This demand for increased productivity may often be satisfied by increasing the frequency at which drops are ejected from the nozzle, or alternatively by increasing the size of each fluid drop.

A further approach to increase productivity is to increase the nozzle or orifice count (more nozzles deliver more ink) which can be achieved by producing a printhead having a higher density of nozzles in the array direction, or by using multiple suitably aligned droplet deposition modules (such as printheads) to address the substrate.

Depending on the particular application, these approaches may be combined so as to further increase productivity. However, while each of these approaches may – depending on the circumstances – be used to increase productivity there may in each case be real compromises to be considered. There may also be physical limitations on the increases in productivity that are available for a particular approach.

For example, increases in orifice density may be limited by a minimum size to which the actuating elements or the fluid chambers may be manufactured. In printheads such as those shown in Figures 1 to 5, there may be a limit on the density to which the channels may be sawn into the piezoelectric material. Further, increases in orifice density may impinge on the size of the actuating elements (particularly where the footprint of the device remains constant) and as a consequence the actuating element may be less powerful and thus the capability of the device compromised to some extent.

As noted above, multiple droplet ejection modules (such as printheads) may also be used to increase productivity. Droplet deposition apparatus including multiple modules may lessen the impact of restrictions on the minimum size of actuating elements, but the cost for the device may be prohibitive, given that it includes multiple high-cost droplet deposition modules.

Further, in some cases it may be appropriate to use droplet deposition modules with larger footprints in order to increase productivity. This may clearly relieve some of the limitations on the size of the actuating elements; however, the larger footprint may come at the cost of decreased resolution. Depending on the particular application, such a decrease in resolution may not be acceptable.

The present invention may ameliorate some of these problems. In some particular embodiments it may increase the productivity of droplet deposition apparatus, while in others different improvements may be experienced in addition or instead.

Thus, in accordance with a first aspect of the present invention there is provided droplet ejection apparatus comprising: an array of elongate fluid chambers, each chamber communicating with an orifice for droplet ejection, the array extending in an array direction; a common fluid inlet manifold; a common fluid outlet manifold; and means for generating a through-flow of fluid (Q_{TF}) from said common fluid inlet manifold, through each chamber in said array and into said common fluid outlet manifold; wherein each of said fluid chambers communicates at one longitudinal end with said common fluid inlet manifold and at the opposing longitudinal end with said common fluid outlet manifold; wherein each chamber is associated with at least one piezoelectric actuator for effecting droplet ejection from said orifice, resulting in an ejection flow of fluid from said chamber and out of said orifice, said ejection flow occurring simultaneously with said through flow, said ejection flow having a maximum value Q_E; wherein each of said orifices is elongate in a direction parallel to the longitudinal axis of the respective one of said fluid chambers.

The elongation of the orifice parallel to the longitudinal axis of the respective fluid chamber may enable the orifice size to be increased without unduly impacting upon the orifice density in the array direction. In addition, or otherwise, increasing the orifice size through elongation of the orifice parallel to the longitudinal axis may enable the nozzle inlet to be spaced apart from the walls of the fluid chamber. This may enable the apparatus to be manufactured more easily as it provides more tolerance of errors in positioning the orifice relative to the chamber. Further, the spacing may avoid or reduce damage to the walls during formation of the orifice, particularly where the orifices are formed by ablation. The increased size of the orifice may allow the orifice to eject fluid droplets of increased volume, thus increasing the productivity of the apparatus.

There may be further advantages to this specific orientation of the orifice. For example, since the fluid chamber communicates at one longitudinal end with said common fluid inlet manifold and at the opposing longitudinal end with said common fluid outlet manifold, the through flow may be directed along its longitudinal length. Thus, the through flow and the direction of elongation of the orifice may be aligned. This may lead to particularly efficient removal of detritus, such as air bubbles and dust particles, from the vicinity of the orifice during use of the apparatus. Such removal of detritus may reduce the incidence of orifice blockages during use, thus improving the reliability of the apparatus.

Further, this orientation of the orifice may result in acoustic waves (which may be generated by the piezoelectric actuators during use of the apparatus) being present in the vicinity of the orifice for a longer period of time than with a circular orifice. Typically, such acoustic waves will be generated at each of the longitudinal ends of the chamber following actuation of the piezoelectric actuator and travel inwards towards the orifice. As the orifice is thus elongate in the direction of travel of the acoustic wave they may be present at the orifice for a relatively longer period of time, thus improving the efficiency of ejection.

Preferably, for each of said orifices, the aspect ratio of the outlet may be smaller than that of the inlet. The Applicant has found that orifices that are elongate parallel to the longitudinal axis, while having certain advantages as discussed above, may in certain circumstances, experience lower directional accuracy than a circular orifice. However, the Applicant has also found that such problems with directional accuracy may be corrected by shaping the outlet of the orifices appropriately. Suitably, therefore, the aspect ratio of the outlet for each orifice may be smaller than that of the inlet. Such an arrangement may still benefit from the advantages of elongation described above, since the inlet may be elongate in the longitudinal direction. Preferably, the outlet for each orifice may have an aspect ratio of between 1.0 and 1.2 and, in certain embodiments, the outlet for each orifice may have an aspect ratio of approximately 1.0. It may also be appropriate that each orifice is tapered so that the area of the nozzle outlet (as well as the aspect ratio) is less than that of the nozzle inlet.

Suitably, the major dimension of the inlet for each of said orifices may be aligned with longitudinal axis of the fluid chamber. Optionally, the major dimension of the outlet may also be aligned with longitudinal axis of the fluid chamber.

In addition, or otherwise, the outlet and inlet of said orifices may be approximately elliptical and, suitably, the major axes of said ellipses may be aligned with the longitudinal axis of the fluid chamber. Preferably, the outlet of each of said orifices may be approximately circular.

Preferably, each of said fluid chambers has a width w in said array direction, thus defining a theoretical circular area $A_T = \frac{1}{4}\pi w^2$, the orifice outlet for each chamber having an area A_n, wherein $0.48A_T > A_n > 0.2A_T$.

It has been found that the through flow acts to cool the apparatus and in particular the actuator. In addition, the ejection flow may also act to cool the apparatus (specifically in the vicinity of the actuator) as heat transferred is to the fluid and then removed from the apparatus with the ejected droplets. It would therefore be expected that, with increasing orifice area, the cooling of the apparatus would improve as the size of the droplets being ejected would increase and thus more fluid would be removed from the chamber by means of ejection. However, the Applicant has found that, surprisingly, orifices with larger areas do not necessarily provide more efficient cooling and that, orifices with areas in this particular range provide more effective cooling of the apparatus and, in particular, of the piezoelectric actuators, than apparatus with orifices having larger areas. This cooling effect is typically provided with only modest values for the through-flow.

More preferably, the value of said through-flow is such that $Q_{TF} > 0.25Q_E$. The use of a through-flow in this range, with orifices as defined above, may allow the apparatus, and particularly the actuator, to be cooled to an extent such that the fluid passing through the chambers is typically heated only by 2 degrees or less. This indicates a temperature differential that may significantly improve the useable lifetime of the apparatus.

In this regard it should be appreciated that a small rise in the temperature of the fluid may indicate a substantial increase in the temperature of the apparatus, and in particular the actuator. Estimates for the lifetime of the apparatus may be based on the Arrhenius model, where chemical attack of the components is the dominant factor in the failure of the apparatus. Therefore, it will be appreciated that the lifetime of the apparatus may be sensitive to even smaller temperature differences.

It should further be appreciated that a large temperature differential may lead to undesirable effects on droplet ejection characteristics. It has been found by the Applicant that such characteristics are sensitive to the rheology of the fluid, which may be significantly influenced by even small changes in temperature.

Still more preferably, the value of said through-flow is such that $Q_{TF} > Q_E$. This may lead to significant increases in the reliability of the apparatus: as more fluid is passing the orifice than flowing through it, even during maximal ejection, the through-flow is particularly effective at scouring away detritus from the vicinity of the nozzle.

Alternatively, each of said fluid chambers has a width *w* in said array direction, thus defining a theoretical circular area $A_T = \frac{1}{4}\pi w^2$, the orifice outlet for each chamber having an area A_n, and wherein $0.80A_T > A_n > 0.20A_T$ and $Q_{TF} > 4Q_E$.

The Applicant has found that, with a through-flow in this range, apparatus with orifices having areas up to $0.80A_T$ will typically have similar temperature differentials to apparatus with orifices having significantly smaller areas. Specifically, the temperature differential experienced within the apparatus with the larger orifices (those with areas up to up to $0.80A_T$) will typically be within 0.2 degrees of temperature differential experienced in apparatus with the smaller orifices (those with areas greater than $0.20A_T$). As 0.2 degrees is generally considered to be within the normal range of variation, it may – depending on the circumstances – be neglected, with the performance of the two apparatus in terms of lifetime and droplet characteristics being substantially the same.

Suitably, the longitudinal axes of said fluid chambers are parallel to a channel extension direction. Preferably, this channel extension direction is perpendicular to said array direction.

According to a second aspect of the present invention there is provided droplet ejection apparatus comprising: an array of elongate fluid chambers, each chamber communicating with an orifice for droplet ejection, the array extending in an array direction; a common fluid inlet manifold; a common fluid outlet manifold; and means for generating a through-flow of fluid (Q_{TF}) from said common fluid inlet manifold, through each chamber in said array and into said common fluid outlet manifold; wherein each of said fluid chambers communicates at one end with said common fluid inlet manifold and at the opposing end with said common fluid outlet manifold; wherein each chamber is associated with at least one piezoelectric actuator for effecting droplet ejection from said orifice, resulting in an ejection flow of fluid from said chamber and out of said orifice, said ejection flow occurring simultaneously with said through flow, said ejection flow having a maximum value Q_E; wherein each of said fluid chambers has a width *w* in said array direction, thus defining a theoretical circular area $A_T = \frac{1}{4}\pi w^2$, the orifice outlet for each chamber having an area A_n, wherein $0.48A_T > A_n > 0.20A_T$.

As discussed in detail above, orifices having areas in the range $0.48A_T > A_n > 0.20A_T$ range may provide a particularly small temperature differential between fluid at the inlet manifold and fluid at the outlet manifold. This may correspond to particularly efficient cooling of the apparatus and, in particular, of the piezoelectric actuators, without requiring large values for the through-flow. Such effects do not necessarily rely upon the elongation of the orifice described above.

Preferably, the value of Q_{TF} is sufficient to ensure that the temperature of fluid returned to said outlet common manifold is substantially maintained within 0.2 degrees of the fluid entering the chambers from the common inlet manifold.

According to a further aspect of the present invention there is provided droplet ejection apparatus comprising: an array of elongate fluid chambers, each chamber communicating with an orifice for droplet ejection, the array extending in an array direction; a common fluid inlet manifold; a common fluid outlet manifold; and means for generating a through-flow of fluid (Q_{TF}) from said common fluid inlet manifold, through each chamber in said array and into said common fluid outlet manifold; wherein each of said fluid chambers communicates at one end with said common fluid inlet manifold and at the opposing end with said common fluid outlet manifold; wherein each chamber is associated with at least one piezoelectric actuator for effecting droplet ejection from said orifice, resulting in an ejection flow of fluid from said chamber and out of said orifice, said ejection flow occurring simultaneously with said through flow, said ejection flow having a maximum value Q_E; wherein each of said fluid chambers has a width *w* in said array direction, thus defining a theoretical circular area $A_T = \frac{1}{4}\pi w^2$, the orifice outlet for each chamber having an area A_n, and wherein $0.80A_T > A_n. > 0.20A_T$ and $Q_{TF} > 4Q_E$.

As discussed above, the Applicant has found that, with a through-flow defined in the range $Q_{TF} > 4Q_E$, apparatus with orifices having areas up to $0.80A_T$ will typically have similar temperature differentials to apparatus with orifices having significantly smaller areas. Specifically, the temperature differential experienced within the apparatus with the larger orifices (those with areas up to up to $0.80A_T$) will typically be within 0.2 degrees of temperature differential experienced in apparatus with the smaller orifices (those with areas greater than $0.20A_T$). As 0.2 degrees is generally considered to be within the normal range of variation, it may – depending on the circumstances – be neglected, with the performance of the two apparatus in terms of lifetime and droplet characteristics being substantially the same.

According to a still further aspect of the present invention there is provided droplet ejection apparatus comprising: an array of elongate fluid chambers, each chamber communicating with an orifice for droplet ejection, the array extending in an array direction; a common fluid inlet manifold; a common fluid outlet manifold; and means for generating a through-flow of fluid (Q_{TF}) from said common fluid inlet manifold, through each chamber in said array and into said common fluid outlet manifold; wherein each of said fluid chambers communicates at one end with said common fluid inlet manifold and at the opposing end with said common fluid outlet manifold; wherein each chamber is associated with at least one piezoelectric actuator for effecting droplet ejection from said orifice, resulting in an ejection flow of fluid from said chamber and out of said orifice, said ejection flow occurring simultaneously with said through flow, said ejection flow having a maximum value Q_E; wherein said orifices are provided in an orifice plate, having a thickness of *t* microns, each orifice being tapered so as to define a taper angle θ; wherein each of said fluid chambers has a width of *w* microns in said array direction, thus defining a practical circular area $A_P = \frac{1}{4}\pi(w-e-2t\cdot \tan\theta)^2$, with *e* taking the value 10 microns, the orifice outlet for each chamber having an area A_n , wherein $3A_P > A_n > 1.25A_P$.

This value of *e* may correspond to the accuracy of the process by which the chambers and orifices are formed.

In embodiments, the taper angle θ may take a value between 5 and 15° and preferably may take a value between 10 and 12°. It should be appreciated that reference to a taper angle should not be understood to imply that the orifice will necessary have the same taper at all points. Therefore, suitably, the taper angle θ may correspond to the average taper angle for the orifice.

According to a still further aspect of the present invention there is provided droplet ejection apparatus comprising: an array of elongate fluid chambers, each chamber communicating with an orifice for droplet ejection, the array extending in an array direction; a common fluid inlet manifold; a common fluid outlet manifold; and means for generating a through-flow of fluid (Q_{TF}) from said common fluid inlet manifold, through each chamber in said array and into said common fluid outlet manifold; wherein each of said fluid chambers communicates at one end with said common fluid inlet manifold and at the opposing end with said common fluid outlet manifold; wherein each chamber is associated with at least one piezoelectric actuator for effecting droplet ejection from said orifice, resulting in an ejection flow of fluid from said chamber and out of said orifice, said ejection flow occurring simultaneously with said through flow, said ejection flow having a maximum value Q_E; wherein said orifices are provided in an orifice plate, having a thickness of *t* microns, each orifice being tapered so as to define a taper angle θ; wherein each of said fluid chambers has a width of *w* microns in said array direction, thus defining a theoretical circular area $A_P = \frac{1}{4}\pi(w-e-2t\cdot \tan\theta)^2$, with *e* taking a value between 5 and 10 microns, the orifice outlet for each chamber having an area A_n , wherein $5A_P > A_n > 1.25A_P$, and $Q_{TF} > 4Q_E$.

This value of *e* may correspond to the accuracy of the process by which the chambers and orifices are formed.

In embodiments, the taper angle θ may take a value between 5 and 15° and preferably may take a value between 10 and 12°.

According to yet a further aspect of the present invention there is provided droplet ejection apparatus comprising: an array of elongate fluid chambers, each chamber communicating with an orifice for droplet ejection, the array extending in an array direction; a common fluid inlet manifold; a common fluid outlet manifold; and means for generating a through-flow of fluid (Q_{TF}) from said common fluid inlet manifold, through each chamber in said array and into said common fluid outlet manifold; wherein each of said fluid chambers communicates at one end with said common fluid inlet manifold and at the opposing end with said common fluid outlet manifold; wherein each chamber is associated with at least one piezoelectric actuator for effecting droplet ejection from said orifice, resulting in an ejection flow of fluid from said chamber and out of said orifice, said ejection flow occurring simultaneously with said through flow, said ejection flow having a maximum value Q_E; wherein the orifice outlet for each chamber has an area A_n wherein $1600\ \mu m^2 > A_n > 650\ \mu m^2$.

According to yet a further aspect of the present invention there is provided droplet ejection apparatus comprising: an array of elongate fluid chambers, each chamber communicating with an orifice for droplet ejection, the array extending in an array direction; a common fluid inlet manifold; a common fluid outlet manifold; and means for generating a through-flow of fluid (Q_{TF}) from said common fluid inlet manifold, through each chamber in said array and into said common fluid outlet manifold; wherein each of said fluid chambers communicates at one end with said common fluid inlet manifold and at the opposing end with said common fluid outlet manifold; wherein each chamber is associated with at least one piezoelectric actuator for effecting droplet ejection from said orifice, resulting in an ejection flow of fluid from said chamber and out of said orifice, said ejection flow occurring simultaneously with said through flow, said ejection flow having a maximum value Q_E; wherein the orifice outlet for each chamber has an area A_n and wherein $2700\ \mu m^2 > A_n > 650\ \mu m^2$ and $Q_{TF} > 4Q_E$.

According to a still further aspect of the present invention there is provided a method for depositing droplets of fluid comprising the steps of: providing an apparatus according to any one of the preceding claims; operating said apparatus so as to provide said through-flow and said ejection-flow.

Preferably, in each of the aspects presented above, each of the orifices is tapered so that the area of the orifice outlet is less than the area of the orifice inlet. Optionally, the orifice inlet may be contained wholly within the fluid chamber, so that it does not overlap the chamber walls. The orifice inlet may be defined in a surface that faces towards the corresponding fluid chamber. This surface may enclose the top of the corresponding fluid chamber. The orifice outlet may be defined in an opposing surface, which may be parallel to the surface in which the orifice inlet is defined.

Preferably, the orifices may be provided in an orifice plate. This orifice plate may comprise two substantially planar opposing surfaces. One of these surfaces may provide the inlets of said orifices, while the other provides the outlets of said orifices. The surface in which the inlets are defined may enclose the tops of the array of fluid chambers.

Preferably, each of said elongate chambers is defined between two elongate chamber walls, with the top edges of said chamber walls together providing a substantially planar surface, said orifice plate being attached to said surface. Each chamber wall may comprise piezoelectric material and, optionally, this piezoelectric material may be poled so that the chamber wall will deform in response to an actuation signal so as to assume a chevron shape. Specifically, when actuated, the wall will have a chevron shape when viewed along the length of the chamber. This may be achieved by dividing the chamber wall into two halves along its length, with one half being poled in one direction and the other half being poled in the opposite direction.

In order to effect droplet ejection, the two chamber walls may both be actuated simultaneously. Electrodes may be formed on the two sides of the chamber walls which face towards the two chambers separated by the wall. Where the chamber walls comprise piezoelectric material, they may deform in shear mode. The electrodes and the direction poling of the piezoelectric material of the walls may be arranged to achieve this.

The chamber may have a width of, for example, between 20 and 150 microns, between 30 and 130 microns, between 40 and 110 microns, between 50 and 90 microns, or between 60 and 70 microns.

The apparatus may be actuable to eject droplets with a speed *v*, where *v* is between 2 and 20m/s, between 3 and 18 m/s, between 4 and 16m/s, or between 5 and 14m/s.

Embodiments of the invention will now be described with reference to the accompanying drawings, in which:

Figure 1 illustrates a prior art inkjet printer;

Figure 2 is a perspective view of the printhead of Figure 1 from the rear with endcaps removed to reveal the flow of ink through the printhead;

Figure 3 is a sectional view of the printhead of Figures 1 and 2, taken perpendicular to the direction of extension of the nozzle rows;

Figure 4 is a sectional view of the inkjet printer of Figures 1 to 3 taken along a fluid chamber of a module;

Figures 5 illustrates a further example of a prior art printhead, employing a similar double-ended side-shooter construction to that of Figures 1 to 4;

Figure 6 is an exploded perspective view of the printhead of Figure 5, which shows the conductive tracks used to apply electrical signals to the actuator elements;

Figure 7 shows an exploded perspective view of a printhead according to a first embodiment of the present invention, which has nozzles elongated in the chamber extension direction;

Figure 8 is a perspective view along the length of a chamber of an inkjet printhead and shows the dimensions of a tapered nozzle relative to the dimensions of the fluid chamber of the printhead;

Figure 9 shows the results of a series of tests carried out on printheads of differing nozzle areas, for different value of through-flow, the printheads ejecting droplets with a speed of 6m/s;

Figure 10 shows the results of a similar series of tests to those whose results are shown in Figure 9, but with printheads ejecting droplets with a speed of 12m/s.

Figure 11 shows the results of tests of directional accuracy in the direction perpendicular to the longitudinal axes of fluid chambers of a series of printheads with nozzle outlets having different aspect ratio values, the printheads all having nozzle inlets with an aspect ratio of 1.8;

Figure 12 shows the results of tests of directional accuracy in the direction parallel to the longitudinal axis of the fluid chambers, for the same series of printheads whose result are shown in Figure 11;

Figure 13 plots the ratio of the values shown in Figure 11 to the values shown in Figure 12 against the values of the nozzle outlet aspect ratio for each of the series of printheads whose results are shown in Figures 11 and 12;

Figure 14 is a plan view of a series of further embodiments according to the present invention, where alternative nozzle geometries to those shown in Figure 7 are utilised; and

Figure 15 is a plan view of a series of still further embodiments according to the present invention, where alternative chamber geometries to those shown in Figure 7 are utilised.

The present invention may be embodied in an inkjet printer. Figure 7 therefore illustrates an exploded view of an inkjet printhead within an inkjet printer according to a first embodiment of the present invention. As may be seen from the figure, the inkjet printhead includes a single array of fluid chambers (2), each defined between a pair of elongate chamber walls (3). Each of the fluid chambers (2) is elongate in a channel extension direction (C), with the chamber walls (3) also being elongate in this direction. The array extends in an array direction (D), which is perpendicular to the chamber extension direction (C). As shown in Figure 7 by arrows 7, during use of the apparatus fluid enters each chamber at one longitudinal end of the chamber from a common inlet manifold (4), flows along the length of the chamber past the orifice (6), which is provided towards the middle of the chamber with respect its longitudinal ends, and leaves the chamber at its other longitudinal end to return to a common outlet manifold (5). There may also be provided one or more fluid conduits to recirculate ink from the common outlet manifold to the common inlet manifold (not shown).

The inkjet printer may have a similar structural features to those described above with reference to Figures 1 to 6, such as providing two arrays of ports in the surface of a substrate which communicate respectively with the common inlet and common outlet manifolds. The manifolds may also be provided within a single substantially cylindrical housing, as shown in Figures 1 to 3.

In order to provide the flow (7) through the chambers (2), an ink supply system may apply a constant first pressure to the ink in the common inlet manifold (4), whilst simultaneously applying a constant second, lower pressure to the ink in the common outlet manifold (5). Such constant pressures may be provided by reservoirs vertically offset with respect to the orifices, as is know from WO 00/38928, or simply by respective fluid pressurizers. As also know from WO 00/38928, the fluid supply system may impose a negative pressure (with respect to atmospheric pressure) at the nozzles (6). Those skilled in the art will recognise that this may require the difference in value between the first and second pressures to be negative. This negative pressure may prevent the weeping of fluid from the nozzles (6) during non-ejection periods.

The chamber walls (3) may be formed from piezoelectric material, as described above with reference to Figures 1 to 6, with electrodes (not shown) being formed on part of the chambers walls so that actuation signals may be applied to the chamber walls. However, those skilled in the art will recognise that alternative piezoelectric actuators may be utilised, with the chambers being defined in a non-piezoelectric material. For example, the chambers may be defined in a non-piezoelectric material using a photolithographic process, with piezoelectric actuators being provided within these chambers at an earlier or later stage, as desired.

As indicated in Figure 7, the opposing faces of the chamber walls (3) defining each chamber are separated by a width w, so that the chamber (2) may be said to have a width equal to w. Using circular nozzles (6), as with the constructions of Figures 1 to 6, the theoretical maximum area that a nozzle could take whilst still remaining within the chamber would therefore be equal to a value $A_T=\frac{1}{4}\pi w^2$.

It will be appreciated that, since this width defines the extent of the fluid chambers (2), where the chamber walls (3) include one or more coating layers (for example an electrode and/or a passivation layer), the width should be measured from the outermost coating layer of one wall to the outermost coating layer of the other wall.

In practice, however, it may not possible to reliably form a circular nozzle having this theoretical maximum area, as this would require the nozzle (6) to match exactly the width and shape of the chamber (2) with one hundred percent accuracy. It may therefore be necessary to take account of common sources of manufacturing error so as to determine a practically achievable maximum area for the nozzle.

A first source of such errors is the process by which the nozzles (6) themselves are formed. It is common to use an optical process to define the shape and size of the nozzles (6); for example, photo-lithography may be used form a complete nozzle plate (8) from a photoresist material, or the photoresist may serve as a negative to define the shape of nozzle bores, with a metal nozzle plate (8) being electroformed around photoresist posts, as known from WO 2005/014292. Equally, the nozzles (6) may be ablated directly within a nozzle plate (8), which may be formed from a metal, a polymer, or combinations of the two. Although such optical processes are relatively accurate, they will still introduce an uncertainty of the order of several microns.

A further source of manufacturing errors is the process by which the chambers (2) are formed. For example, this may, as described above with reference to Figures 1 to 6, include sawing channels in strips of piezoelectric material, but may also include moulding and sintering of piezoelectric material, or, where a non-piezoelectric material is utilised to define the channels an optical method may be used. There will be uncertainty not only in the size and shape of the chambers (2), but also in the spacing of each chamber within the array.

Furthermore, the combination of the two processes, specifically the registration or alignment of each nozzle with respect to its corresponding chamber will also introduce uncertainty into the manufacturing process.

Taken in combination, these errors may be of the order of 10 microns. It will therefore typically be necessary for the edges of the nozzle (6) to nominally be spaced a distance of 5 microns from the respective chamber walls (3). This is especially the case where the process utilised for nozzle formation may cause damage to the chamber walls. For example, where laser ablation is used to form the nozzles, scorching of the walls and their overlying layers may occur.

While processes have been proposed that reduce the incidence of such damage (such as those disclosed in WO 2012/017248), these may only protect the interior walls of the chamber and may not protect the top edges of the chamber walls, including any coating layers. As is discussed in WO 2012/017248, damage to the coating layers, such as the electrode and passivation layers may significantly impact upon the performance of the apparatus: damage to the electrode layer may cause the chamber to have lower activity than other chambers within the array, or even to be altogether inactive; damage to the passivation layer may lead to chemical attack of the underlying layers, which may impact upon the lifespan of the apparatus. Thus, even where protective processes such as those taught in WO 2012/017248 are available it may nonetheless be important to space the nozzle inlet (6b) from the chamber walls.

While the size of the nozzle inlet (6b) may be related to the dimensions of the chamber, it has been found that the size of the nozzle outlet (6a) may be related to the productivity of the apparatus. Specifically, for a given nozzle inlet (6b), the area of the nozzle outlet (6a) is believed to be a limiting factor of the size of the droplets ejected by the apparatus.

However, as it has been found to be desirable in some circumstances to form the nozzle with a taper (this may result in improved stability of the fluid meniscus at the nozzle) the area of the nozzle outlet (6a) may in turn be related to the area of the nozzle inlet (6b) and, specifically, it may be smaller than the area of the nozzle inlet (6b). Nonetheless, the Applicant has identified certain ways in which the size of the nozzle outlet (6a) may be optimized, which apply even with these restrictions.

Figure 8, which is a perspective view along the length of a chamber (2) of an inkjet printhead, shows the dimensions of such a tapered nozzle (6) relative to the dimensions of the fluid chamber (2). As may be seen, the inlet of the nozzle communicates with a fluid chamber of width w. The nozzle tapers towards its outlet, which is formed in an opposing surface of a nozzle plate.

As may be seen from Figure 8, the width of the nozzle inlet (6b) is taken to be w-e, where e is a value chosen to substantially increase the likelihood that the nozzle inlet (6b) will lie wholly within the width of the chamber (2). The value of e is therefore chosen so as to take into account the various sources of errors in nozzle (6) and chamber (2) formation discussed above and may thus take a suitable value, such as 10, 7, or 5 microns.

The width of the nozzle outlet (6a) is then smaller still, as a result of the taper of the nozzle, which is defined by an angle θ. As shown in Figure 8, the taper angle θ may be defined at the point where a line parallel to the array direction and passing through the centre of the nozzle inlet (6b) intersects with the perimeter of the nozzle inlet. As also shown in Figure 8, the taper angle may be defined with respect to a direction that is perpendicular to both the array direction and the chamber extension direction. In a typical inkjet printhead, the taper angle for the nozzle may be between 5 and 15 degrees and in some cases may be between 10 and 12 degrees.

As further shown by Figure 8, the nozzle plate (8) in which the nozzles (6) are formed has a thickness of t. In a typical inkjet printhead, the thickness of the nozzle plate (8) may be in the region of 50 to 150 microns, though those skilled in the art will appreciate that a number of other values may be appropriate.

As is clear from the diagram in Figure 8, the difference in width between the nozzle inlet (6b) and the nozzle outlet (6a) is $2t \cdot \tan \theta$, so that the nozzle inlet (6b) has a width of $(w\text{-}e\text{-}2t \cdot \tan \theta)$. The nozzle outlet (6a) therefore has an area defined by the following relationship:

$$A_P = \tfrac{1}{4}\pi(w-e-2t \cdot \tan \theta)^2$$

Thus, where it is desired that the nozzle inlet (6b) is contained within the width of the fluid chamber, the maximum value that a circular nozzle outlet (6a) may in practice take may be A_P, as defined in this equation. Those skilled in the art will appreciate that, where different portions of a nozzle have different taper angles, that the average value of the taper angles may be used within the formula above, given that this represents only an approximation of the design constraints.

For a typical droplet deposition apparatus, specifically an inkjet printhead, this practical maximum area for a circular nozzle may be in the region of 530 square microns. This is based on a chamber width w of 65 microns, taking account of a coating layer of 5 microns on each chamber wall (the spacing between the chamber walls themselves thus being 75 microns).

By contrast, the theoretical maximum value for a circular nozzle in such an apparatus ($A_T = \tfrac{1}{4}\pi w^2$) may therefore be calculated to be about 3320 square microns based on these values, which is clearly considerably larger than the value of A_P.

Returning to the embodiment of Figure 7, as noted above, the nozzles are elongated in the chamber extension direction (C). Therefore, their areas relative to both the theoretical maximum and practical maximum values are increased, as these maximum values are based on circular nozzles. As noted above, the increased area of the nozzles, specifically of the nozzle outlets (6a), may lead to an increase in the volume of each droplet ejected, thus increasing the productivity of the printhead. More, because the nozzles are elongate in the same direction as the flow of fluid through the chamber, the flow through the chamber is able to scour detritus away from the vicinity of the nozzle particularly effectively. This may lead to improvements in the reliability of the printhead. This improvement in reliability may also be experienced with nozzles that are not in excess of the practical maximum area A_P., though it will be appreciated that such printheads would not necessarily benefit from improvements in productivity.

In order to have an appreciable effect on the productivity of the printhead it has been found that it will typically be necessary to increase the area of each nozzle by 25%. This may impose a lower limit of $1.25A_P$ on the area of nozzles, in order to improve the productivity of the printhead. This lower limit may correspond, in the inkjet printhead described above, to approximately 650 square microns.

Further, as the area of the nozzles (6) is increased and thus more ink is ejected from the chamber (2), it is expected that the chambers will be cooled more effectively. Heat from the apparatus, and in particular the actuator elements (3) will be transferred to the ink during use, with the ejection of this fluid thus acting to remove heat from the chamber (2) in the vicinity of the actuator elements (3). Thus, as the area of the nozzles (6) is increased, and thus the amount of flow through the nozzles (6) in the form of droplets is also increased, the rate at which heat is transferred away from the actuator should increase, thus resulting in improved cooling of the apparatus in addition to improved productivity.

In order to quantify this cooling effect, tests were carried out for a series of printheads, with the different printheads each having nozzles (6) of a specific area. The behaviour of each of these printheads was tested at different rates of flow through the chambers (2). The results of these experiments are shown in Figure 9.

The chambers (2) of the printheads had the same typical value for the chamber width discussed above, namely a chamber width *w* of 65 microns. The practical maximum value for the nozzle outlet (6a) was taken to be 530 square microns, also as discussed above.

The printheads included an array of elongate chambers (2), each defined between a pair of elongate piezoelectric chamber walls (3), as depicted in Figure 7, with a flow along the length of each chamber being provided during use from a common inlet manifold (4) to a common outlet manifold (5). This through-flow occurs simultaneously with ejection of droplets from the nozzle (6), which, although droplets are of course discreet volumes of fluid may be considered equivalent to a further, ejection flow. For each printhead, the difference in temperature between ink at the inlet manifold (4) and ink at the outlet manifold (5) was measured, for various values of flow through the chambers (2).

The rates of through-flow for the printheads are shown on the abscissa of Figure 9. The rates of flow for the printheads are expressed relative to the maximum flow through the nozzle (6) owing to ejection. This corresponds to the chambers printing droplets at maximum ejection frequency, with the printhead imparting a speed of 6m/s to each droplet. A value of 1 on the abscissa therefore corresponds to the flow through each chamber and to the outlet manifold being equal to the maximum ejection flow. As the ejection-flow and through-flow occur simultaneously, during maximum ejection there would be an equal amount of fluid returning to the outlet manifold as being ejected from the nozzle (6).

The values shown on the ordinate of Figure 9 represent the difference in temperature (ΔT) in degrees Celsius between ink at the inlet manifold and ink at the outlet manifold. This temperature differential may be used to indicate the cooling effect within the printhead in question.

Each line on the graph of Figure 9 thus represents a different printhead, with a respective nozzle outlet area. The legend for the graph therefore shows these respective nozzle areas for the chambers using the dimensionless quantity area ratio (AR), which is the ratio of the nozzle area in question to the practical maximum nozzle area (A_p). As noted above, the value of the practical maximum nozzle area (A_p) was 530 square microns.

As may be seen from Table 1 below, the increase in nozzle area leads to an increase in productivity, as expected. The table sets out the measured value of the droplet volume for each area ratio (AR) value.

AR value	**Droplet volume (pl)**
1.00	42
1.76	76
2.00	88
3.00	166
4.00	223
5.00	280

<u>Table 1</u>

While this increase in productivity (through an increase in the volume of droplets) was expected, it was surprisingly found that the larger nozzle areas do not remove heat most effectively from the chamber, as may be seen from Figure 9. In fact, at modest values of through-flow, they perform significantly worse than nozzles with areas of $3A_P$ or less.

It is also expected that the amount of through-flow in the chambers will also act to improve the cooling of the chambers. It is therefore particularly surprising that nozzles having larger areas have worse performance at similar through-flow values, since the through-flow values are relative to the ejection flow, and thus the same through-flow value for a larger nozzle area corresponds to a far greater amount of flow in absolute terms.

The results do however indicate that effectiveness of cooling decreases substantially for nozzles (6) having an area of greater than $3A_P$. Thus, the results indicate that nozzles (6) having areas less than $3A_P$ may be particularly efficient at cooling the apparatus. Accordingly, apparatus with nozzles (6) having areas in the range 1.25 A_P -3 A_P may afford improvements in productivity whilst also allowing the apparatus to be cooled particularly effectively. This range of areas may also be expressed in terms of the theoretical maximum area for the chamber – A_T – which, based on the chamber width value of 65 microns is calculated (according to the formula $A_T=\frac{1}{4}\pi w^2$) to be about 3320 square microns. Therefore, the range for the nozzle outlet (6a) area may be restated as $0.48A_T > A_n > 0.20A_T$. Alternatively, in terms of absolute values, this range may be stated as $1600\ \mu m^2 > A_n > 650\ \mu m^2$.

It will be appreciated that, while the test results shown in Figure 9 appear to indicate a point of inflection at $3A_P$, there may be some uncertainty in this value. Therefore, advantageous upper limits for the nozzle area may take values less than $3A_P$, such as 2.5, 2.6, 2.7, 2.8, or 2.9 A_P, which correspond respectively to 0.40, 0.42, 0.43, 0.45, and 0.46 A_T, or absolute values of approximately 1330, 1380, 1430, 1487, and 1540 square microns. Equally, advantageous upper limits may take values greater than $3A_P$, such as 3.1, 3.2, 3.3, 3.4, or 3.5 A_P, which correspond respectively to 0.50, 0.51, 0.53, 0.54 and 0.56 A_T, or absolute values of approximately 1650, 1700, 1750, 1810, and 1860 square microns.

Similarly, while for productivity reasons a lower limit of 1.25 A_P may be appropriate, in some situations a relatively larger lower limit may be appropriate so as to provide an appreciable improvement in productivity. Thus, lower limits of 1.30, 1.35, 1.40, 1.45 and 1.50 A_P may be desirable, which correspond respectively to 0.21, 0.22, 0.22, 0.23, and 0.24 A_T, or absolute values of 690, 720, 740, 770, and 800 square microns.

As may be seen from Figure 9, as the amount of through-flow is increased the difference between the different printheads decreases. In particular, as the through-flow exceeds a value of 4 times the ejection flow, the thermal differential experienced in the $5A_P$ printhead (corresponding to $0.8A_T$ or approximately 2655 square microns) is within 0.2 degrees of the value for the thermal differential experienced in the other printheads. As 0.2 degrees is generally considered to be within the normal range of variation, it may – depending on the circumstances – be neglected, with the performance of the two apparatus in terms of lifetime and droplet characteristics being substantially the same.

Figure 10 illustrates the results of a further set of similar tests, but with the printheads ejecting droplets with speeds of 12m/s. The same pattern of less efficient cooling for larger nozzle areas as that shown in Figure 9 may also be seen in Figure 10.

It is believed that the worsening in the cooling provided by printheads with larger nozzle areas is a result of a higher actuation voltage being required in order to eject the correspondingly larger droplets. Specifically, in order to achieve the same velocity of ejection for a larger droplet a larger amount of energy is required to overcome the relatively larger inertia of the droplet. This larger amount of energy may therefore result in increased heating of the ink within the chamber. For typical values of through-flow this heating effect appears to dominate the increased flow of heat out of the chamber (2) owing to the larger ejection flow.

It may therefore be appreciated that similar effects should be expected with a number of nozzle geometries, and not necessarily with elongate nozzles.

More particularly, whereas there may be advantages associated with elongation of the nozzle inlet (6b), the above-described effects are linked primarily to the area – as opposed to the shape – of the nozzle outlet (6a). It may therefore be particularly advantageous to provide arrangements where the nozzle inlet (6b) is elongate in a direction parallel to the longitudinal axis of the respective one of the fluid chambers and where the nozzle outlet (6a) has an area that lies in one of the ranges discussed above, which provide benefits in terms of providing improved productivity with desirable levels of temperature control.

More particularly still, the Applicant has discovered that it may be advantageous to provide nozzles where the inlet (6b) is elongate (specifically, in a direction parallel to the longitudinal axis of the respective one of the fluid chambers) and has an aspect ratio greater than that of the nozzle outlet (6a). Figures 11 to 13 therefore show the results of tests carried out with a series of printheads, with a range of values for the aspect ratio of the nozzle outlets, but all having nozzle inlets with the same aspect ratio of 1.8. Both the nozzle outlets and inlets were approximately elliptical in shape.

Each point on the graphs corresponds to the results from a particular printhead (note therefore that for each of the values 1.0 and 1.4 for the aspect ratio of the nozzle outlet, two printheads were tested).

Figure 11 shows the error in the landing position in the X-direction (perpendicular to the longitudinal axis of the fluid chamber) of droplets produced by the printheads against the corresponding value of the nozzle outlet aspect ratio for the printheads. Specifically, the error values are the 3-sigma values, measured in microns. As noted above, the aspect ratio of the nozzle inlet was kept the same for all printheads at 1.8.

As may be seen from the graph, there is a clear trend of increasing droplet landing error in the X-direction with increasing values of nozzle outlet aspect ratio (note that both printheads with nozzle outlet aspect ratio values of 1.4 were recorded as having substantially the same drop landing error in the X-direction). It may therefore be understood that, as the aspect ratio of the nozzle outlet decreases – and so the nozzle outlet becomes more circular – the landing error in the X-direction also decreases.

Figure 12 shows the error in the landing position in the Y direction (parallel to the longitudinal axis of the fluid chamber) of droplets produced by the printheads against the corresponding value of the nozzle outlet aspect ratio for the printheads. Again, the error values are the 3-sigma values, measured in microns and the aspect ratio of the nozzle inlet was kept the same for all printheads at 1.8.

In contrast to the trend shown in Figure 11, the landing errors in the Y-direction remain roughly constant for all of the values of nozzle outlet aspect ratio tested. The data therefore imply that making the nozzle outlet more circular does not have a significant effect on the landing error in the Y-direction.

Figure 13 shows the ratio of errors in the X-direction to the Y-direction against the value of the nozzle outlet aspect ratio. As may be seen from the graph, there is a very clear trend of decreasing error ratio value for decreasing nozzle outlet aspect ratio values. It may therefore be understood that the directional accuracy of the apparatus improves as the nozzle outlet is made more circular.

The data shown in Figures 11 to 13 therefore clearly suggest that a nozzle having a lower aspect ratio for the nozzle outlet than for the nozzle inlet may have improved accuracy of droplet placement. In addition, if the nozzle inlet is elongated in the direction of the longitudinal axis of the fluid chamber, it may also provide the benefits in terms of manufacturing and operation discussed further above.

The graphs also suggest that a nozzle having an approximately circular nozzle outlet (corresponding to an aspect ratio of 1.0) has a particularly high level of accuracy of droplet placement. Therefore, it may be particularly beneficial to provide a nozzle that has a nozzle inlet that is elongate in the longitudinal direction of the fluid chamber (and specifically an elliptical nozzle inlet, with the major axis of the ellipse aligned with the longitudinal axis of the chamber) and a nozzle outlet that is approximately circular. In addition, the nozzle outlet has an area that lies in one of the ranges discussed above, which provide benefits in terms of providing improved productivity with desirable levels of temperature control.

It may also be noted that the difference in accuracy between the nozzle outlet with aspect ratio 1.0 and the nozzle outlet with aspect ratio 1.2 is small. Therefore, similar advantages in terms of accuracy may be experienced for an orifice having an aspect ratio of between 1.0 and 1.2.

Figures 14 and 15 display still further embodiments with alternative geometries for the nozzle and also for the chamber, which may experience similar improvements in productivity to those discussed with reference to Figures 9 and 10, in combination with good thermal control.

Figure 14(a), for example, provides circular nozzles whose inlets (20a) have diameters that are larger than the width (w) of the chamber (11) with which they communicate, in contrast to the embodiments described above, for example with reference to Figure 7. Such a nozzle may be manufactured by an “ex-situ” process, where the nozzles are formed in a nozzle plate component prior to being attached to the edges of the chamber walls to enclose the chambers. In this way, there is little risk that the nozzle formation process will damage the chamber walls.

Although the nozzle inlet (20a) has a larger width than the chamber (11) with which it communicates and therefore has an area larger than the theoretical maximum $A_T=\frac{1}{4}\pi w^2$ quoted above, the nozzle outlet (20b) nonetheless has an area that lies in one of the ranges discussed above, which provide benefits in terms of providing improved productivity with desirable levels of temperature control. For example, the nozzle outlet (20b) may have an area defined in the range $0.48A_T > A_n > 0.20A_T$, or alternatively, in terms of absolute values, $1600\ \mu m^2 > A_n > 650\ \mu m^2$.

Figure 14(b) illustrates a similar embodiment to Figure 14(a), but with nozzles that are elongate in the same direction as the fluid chambers. This may provide improvements in reliability as discussed above.

Figure 14(c) shows a further embodiment where the outlets (20b) of the nozzles are elongate, whereas the inlets (20a) are circular. As with the embodiment of Figure 14(a), the diameters of the inlets (20a) are larger than the widths of the chambers (11).

Figure 15(a) illustrates a still further embodiment, where the chamber walls are tapered along their lengths, with the direction of the taper alternating between neighbouring chamber walls. This results in chambers (11) that have a substantially constant width, but which do not lie parallel to one another. More specifically, the length of each chamber is angularly offset with respect to the array direction, with the sense of the angular offset alternating between neighbouring chambers (11).

Figure 15(b) illustrates a still further embodiment, where, as with the embodiment of Figure 14(a) circular nozzles are provided. However, in this embodiment the chamber includes a portion in the vicinity of the nozzle having a relatively larger width than the remainder of the chamber. Specifically, the portion of the chamber in the vicinity of chamber follows a similar profile to the nozzle itself, which may assist in ensuring that the inlet is confined between the chamber walls.

Those skilled in the art will appreciate that the foregoing teaching may be applied to a wide range of droplet deposition apparatus, rather than being specific to printers. Thus, disclosure with regard to printers and/or printheads should be understood, unless otherwise stated, to apply more generally to droplet deposition apparatus. Specifically, disclosure with regard to printheads should be understood, unless stated otherwise, to apply to other droplet deposition apparatus, which comprise: an array of elongate fluid chambers , where each chamber communicates with an orifice for droplet ejection, and the array extends in an array direction; a common fluid inlet manifold; a common fluid outlet manifold; and means for generating a through-flow of fluid from said common fluid inlet manifold, through each chamber in said array and into said common fluid outlet manifold.

CLAIMS

1. Droplet ejection apparatus comprising:
an array of elongate fluid chambers, each chamber communicating with an orifice for droplet ejection, the array extending in an array direction;
a common fluid inlet manifold;
a common fluid outlet manifold; and
means for generating a through-flow of fluid (Q_{TF}) from said common fluid inlet manifold, through each chamber in said array and into said common fluid outlet manifold;
wherein each of said fluid chambers communicates at one longitudinal end with said common fluid inlet manifold and at the opposing longitudinal end with said common fluid outlet manifold;
wherein each chamber is associated with at least one piezoelectric actuator for effecting droplet ejection from said orifice, resulting in an ejection flow of fluid from said chamber and out of said orifice, said ejection flow occurring simultaneously with said through flow, said ejection flow having a maximum value Q_E;
wherein each of said orifices is elongate in a direction parallel to the longitudinal axis of the respective one of said fluid chambers.

2. Apparatus according to Claim 1, wherein actuation of each of said piezoelectric actuators generates acoustic waves at each of the longitudinal ends of the respective chamber, said acoustic waves thereafter travelling towards said orifice.

3. Apparatus according to Claim 1 or Claim 2, wherein for each of said orifices the aspect ratio of the outlet is smaller than that of the inlet.

4. Apparatus according to Claim 3, wherein the outlet of each of said orifices is approximately circular.

5. Apparatus according to any one of claims 1 to 4, wherein each of said fluid chambers has a width w in said array direction, thus defining a theoretical circular area $A_T = \frac{1}{4}\pi w^2$, the orifice outlet for each chamber having an area A_n, wherein $0.48A_T > A_n > 0.2A_T$

6. Apparatus according to Claim 5, wherein the value of Q_{TF} is sufficient to ensure that the temperature of fluid returned to said outlet common manifold is substantially maintained within 2°C of the fluid entering the chambers from the common inlet manifold.

7. Apparatus according to Claim 5 or Claim 6, wherein the amount of said through-flow is such that $Q_{TF} > 0.25Q_E$. and preferably wherein $Q_{TF} > Q_E$.

8. Apparatus according to any one of claims 1 to 4, wherein each of said fluid chambers has a width *w* in said array direction, thus defining a theoretical circular area $A_T = \frac{1}{4}\pi w^2$, the orifice outlet for each chamber having an area A_n, and wherein $0.80A_T > A_n > 0.20A_T$ and $Q_{TF} > 4Q_E$.

9. Droplet ejection apparatus comprising:
an array of elongate fluid chambers, each chamber communicating with an orifice for droplet ejection, the array extending in an array direction;
a common fluid inlet manifold;
a common fluid outlet manifold; and
means for generating a through-flow of fluid (Q_{TF}) from said common fluid inlet manifold, through each chamber in said array and into said common fluid outlet manifold;
wherein each of said fluid chambers communicates at one end longitudinal end with said common fluid inlet manifold and at the opposing longitudinal end with said common fluid outlet manifold;
wherein each chamber is associated with at least one piezoelectric actuator for effecting droplet ejection from said orifice, resulting in an ejection flow of fluid from said chamber and out of said orifice, said ejection flow occurring simultaneously with said through flow, said ejection flow having a maximum value Q_E;
wherein each of said fluid chambers has a width *w* in said array direction, thus defining a theoretical circular area $A_T = \frac{1}{4}\pi w^2$, the orifice outlet for each chamber having an area A_n, wherein $0.48A_T > A_n > 0.20A_T$.

10. Droplet ejection apparatus comprising:
an array of elongate fluid chambers, each chamber communicating with an orifice for droplet ejection, the array extending in an array direction;
a common fluid inlet manifold;
a common fluid outlet manifold; and
means for generating a through-flow of fluid (Q_{TF}) from said common fluid inlet manifold, through each chamber in said array and into said common fluid outlet manifold;
wherein each of said fluid chambers communicates at one end longitudinal end with said common fluid inlet manifold and at the opposing longitudinal end with said common fluid outlet manifold;
wherein each chamber is associated with at least one piezoelectric actuator for effecting droplet ejection from said orifice, resulting in an ejection flow of fluid from said chamber and out of said orifice, said ejection flow occurring simultaneously with said through flow, said ejection flow having a maximum value Q_E;
wherein said orifices are provided in an orifice plate, having a thickness of *t* microns, each orifice being tapered so as to define a taper angle θ;
wherein each of said fluid chambers has a width of *w* microns in said array direction, thus defining a practical circular area $A_P = \frac{1}{4}\pi(w\text{-}e\text{-}2t \cdot \tan\theta)^2$, with *e* taking a value between 5 and 10 microns, the orifice outlet for each chamber having an area A_n , wherein $3A_P > A_n > 1.25A_P$.

11. Droplet ejection apparatus comprising:
an array of elongate fluid chambers, each chamber communicating with an orifice for droplet ejection, the array extending in an array direction;
a common fluid inlet manifold;
a common fluid outlet manifold; and
means for generating a through-flow of fluid (Q_{TF}) from said common fluid inlet manifold, through each chamber in said array and into said common fluid outlet manifold;
wherein each of said fluid chambers communicates at one end with said common fluid inlet manifold and at the opposing end with said common fluid outlet manifold;
wherein each chamber is associated with at least one piezoelectric actuator for effecting droplet ejection from said orifice, resulting in an ejection flow of fluid from said chamber and out of said orifice, said ejection flow occurring simultaneously with said through flow, said ejection flow having a maximum value Q_E;

wherein the orifice outlet for each chamber has an area A_n wherein 1600 μm^2 > A_n > 650 μm^2.

12. Apparatus according to any one of claims 9 to 11, wherein the value of Q_{TF} is sufficient to ensure that the temperature of fluid returned to said outlet common manifold is substantially maintained within 2°C of the fluid entering the chambers from the common inlet manifold.

13. Apparatus according to any one of claims 9 to 12, wherein the amount of said through-flow is such that $Q_{TF} > 0.25Q_E$. and preferably wherein $Q_{TF} > Q_E$.

14. Droplet ejection apparatus comprising:
an array of elongate fluid chambers, each chamber communicating with an orifice for droplet ejection, the array extending in an array direction;
a common fluid inlet manifold;
a common fluid outlet manifold; and
means for generating a through-flow of fluid (Q_{TF}) from said common fluid inlet manifold, through each chamber in said array and into said common fluid outlet manifold;
wherein each of said fluid chambers communicates at one end with said common fluid inlet manifold and at the opposing end with said common fluid outlet manifold;
wherein each chamber is associated with at least one piezoelectric actuator for effecting droplet ejection from said orifice, resulting in an ejection flow of fluid from said chamber and out of said orifice, said ejection flow occurring simultaneously with said through flow, said ejection flow having a maximum value Q_E;
wherein each of said fluid chambers has a width w in said array direction, thus defining a theoretical circular area $A_T = \frac{1}{4}\pi w^2$, the orifice outlet for each chamber having an area A_n, and wherein $0.80A_T > A_n > 0.20A_T$ and $Q_{TF} > 4Q_E$.

15. Droplet ejection apparatus comprising:
an array of elongate fluid chambers, each chamber communicating with an orifice for droplet ejection, the array extending in an array direction;
a common fluid inlet manifold;
a common fluid outlet manifold; and
means for generating a through-flow of fluid (Q_{TF}) from said common fluid inlet manifold, through each chamber in said array and into said common fluid outlet manifold;
wherein each of said fluid chambers communicates at one end with said common fluid inlet manifold and at the opposing end with said common fluid outlet manifold;
wherein each chamber is associated with at least one piezoelectric actuator for effecting droplet ejection from said orifice, resulting in an ejection flow of fluid from said chamber and out of said orifice, said ejection flow occurring simultaneously with said through flow, said ejection flow having a maximum value Q_E;
wherein said orifices are provided in an orifice plate, having a thickness of *t* microns, each orifice being tapered so as to define a taper angle θ;
wherein each of said fluid chambers has a width of *w* microns in said array direction, thus defining a theoretical circular area $A_P= \frac{1}{4}\pi(w-e-2t\cdot \tan\theta)^2$, with *e* taking a value between 5 and 10 microns, the orifice outlet for each chamber having an area A_n , wherein $5A_P > A_n > 1.25A_P$, and $Q_{TF} > 4Q_E$.

16. Droplet ejection apparatus comprising:
an array of elongate fluid chambers, each chamber communicating with an orifice for droplet ejection, the array extending in an array direction;
a common fluid inlet manifold;
a common fluid outlet manifold; and
means for generating a through-flow of fluid (Q_{TF}) from said common fluid inlet manifold, through each chamber in said array and into said common fluid outlet manifold;
wherein each of said fluid chambers communicates at one end with said common fluid inlet manifold and at the opposing end with said common fluid outlet manifold;
wherein each chamber is associated with at least one piezoelectric actuator for effecting droplet ejection from said orifice, resulting in an ejection flow of fluid from said chamber and out of said orifice, said ejection flow occurring simultaneously with said through flow, said ejection flow having a maximum value Q_E;
wherein the orifice outlet for each chamber has an area A_n and wherein $2700\ \mu m^2 > A_n > 650\ \mu m^2$ and $Q_{TF} > 4Q_E$.

17. Apparatus according to any preceding claim, wherein said orifices are provided in an orifice plate.

18. Apparatus according to Claim 17, wherein each of said elongate chambers is defined between two elongate chamber walls, with the top edges of said chamber walls together providing a substantially planar surface, said orifice plate being attached to said surface.

19. Apparatus according to any one of claims 1 to 16, wherein each of said elongate chambers is defined between two elongate chamber walls.

20. Apparatus according to Claim 18 or Claim 19, wherein each of said piezoelectric actuators extends along the length of a corresponding chamber.

21. Apparatus according to Claim 20, wherein each of said piezoelectric actuators extends substantially from the first end of the chamber to the second end of the chamber.

22. Apparatus according to any one of claims 18 to 21, wherein said chamber walls comprise piezoelectric material, each of said piezoelectric actuators comprising a corresponding one of said chamber walls.

23. Apparatus according to any preceding claim, wherein the longitudinal axes of said fluid chambers are parallel to a channel extension direction and preferably wherein said channel extension direction is perpendicular to said array direction.

24. Apparatus according to any preceding claim, wherein each of said orifices is tapered so that the area of the nozzle outlet is less than the area of the nozzle inlet.

25. Method for depositing droplets of fluid comprising the steps of:
providing an apparatus according to any one of the preceding claims;
operating said apparatus so as to provide said through-flow and said ejection-flow.

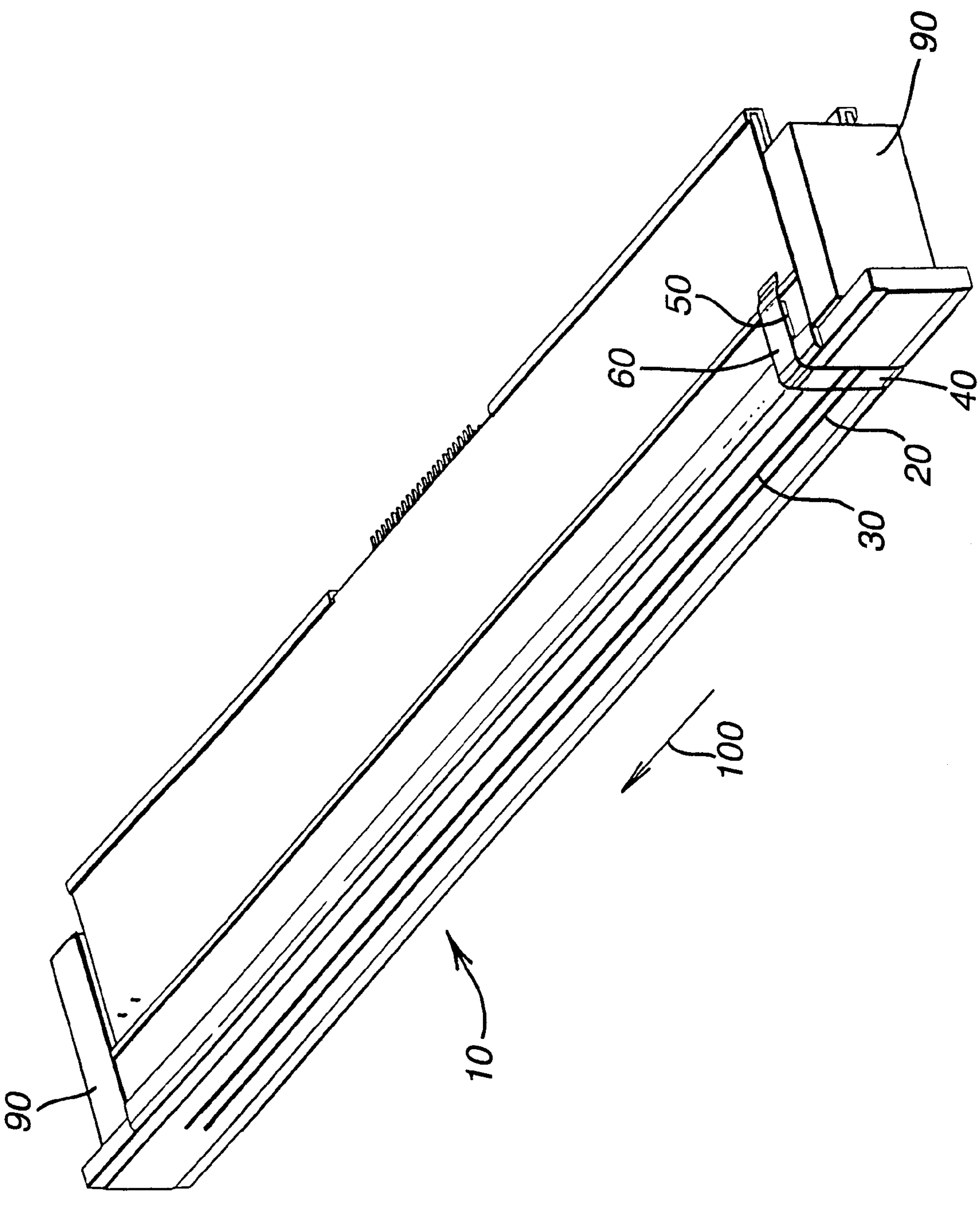

FIG. 1

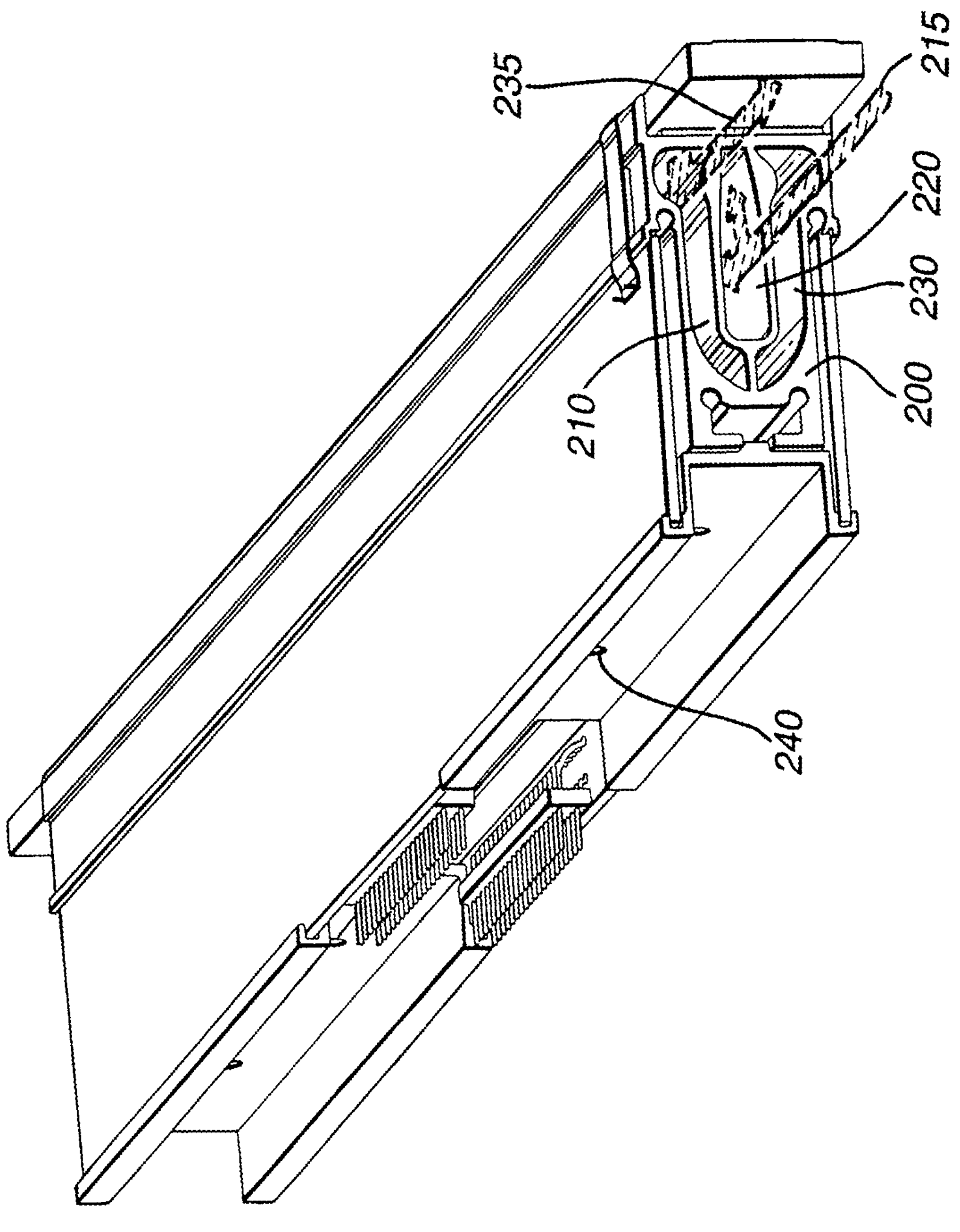

FIG. 2

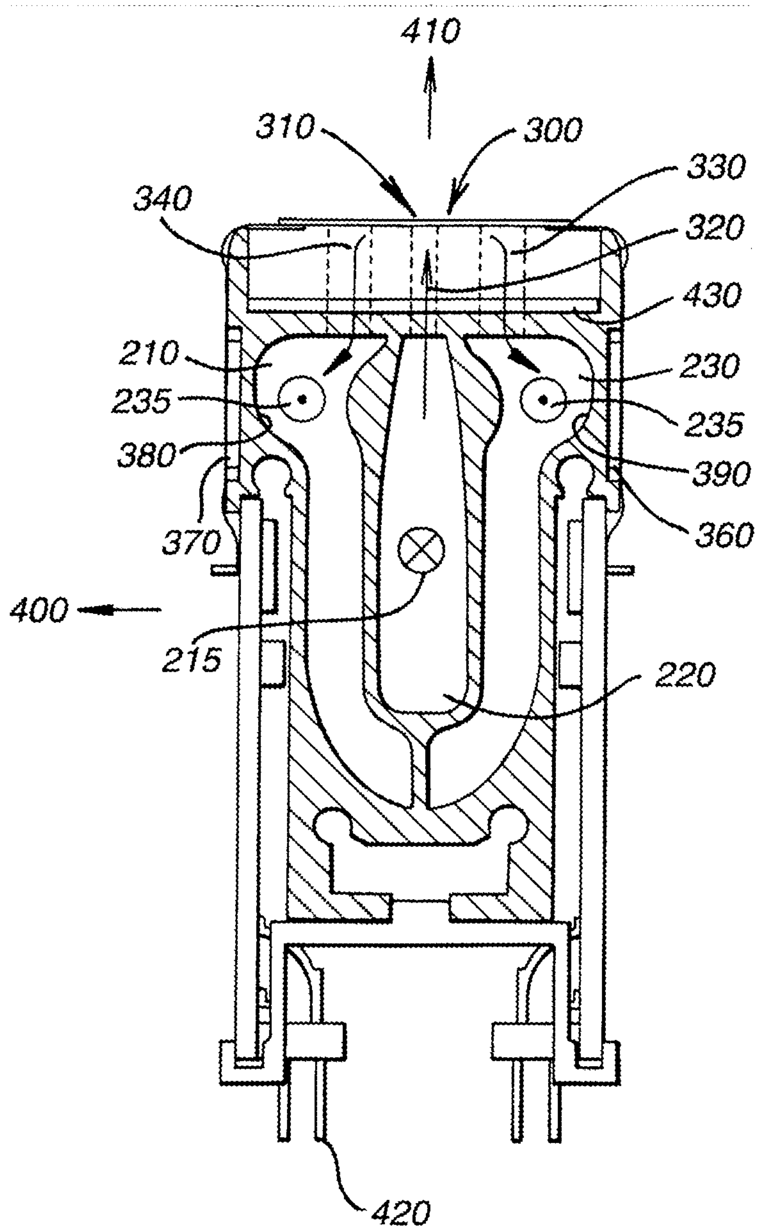
410
310
300
330
340
320
430
210
230
235
235
380
390
370
360
400
215
220
420

FIG. 3

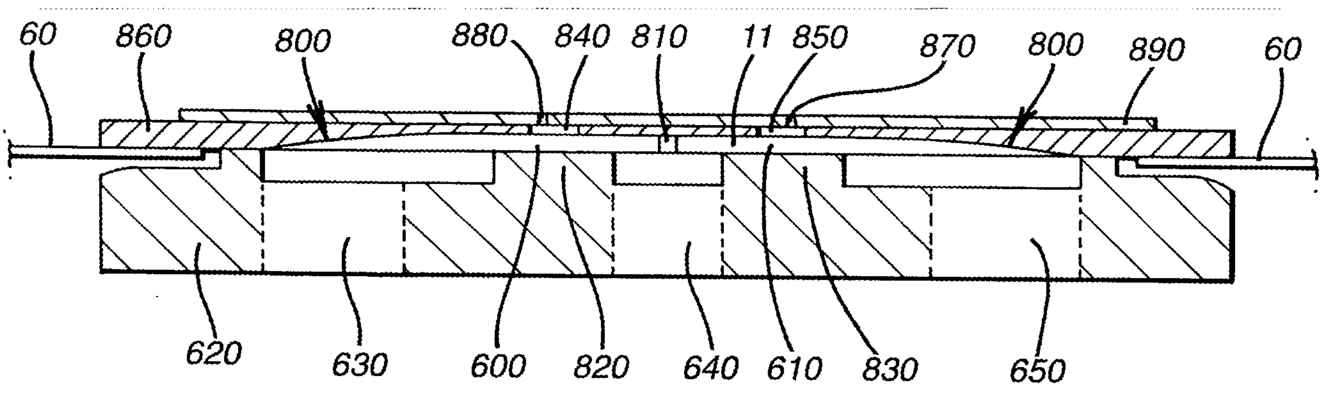
60
860
800
880
840
810
11
850
870
800
890
60
620
630
600
820
640
610
830
650

FIG. 4

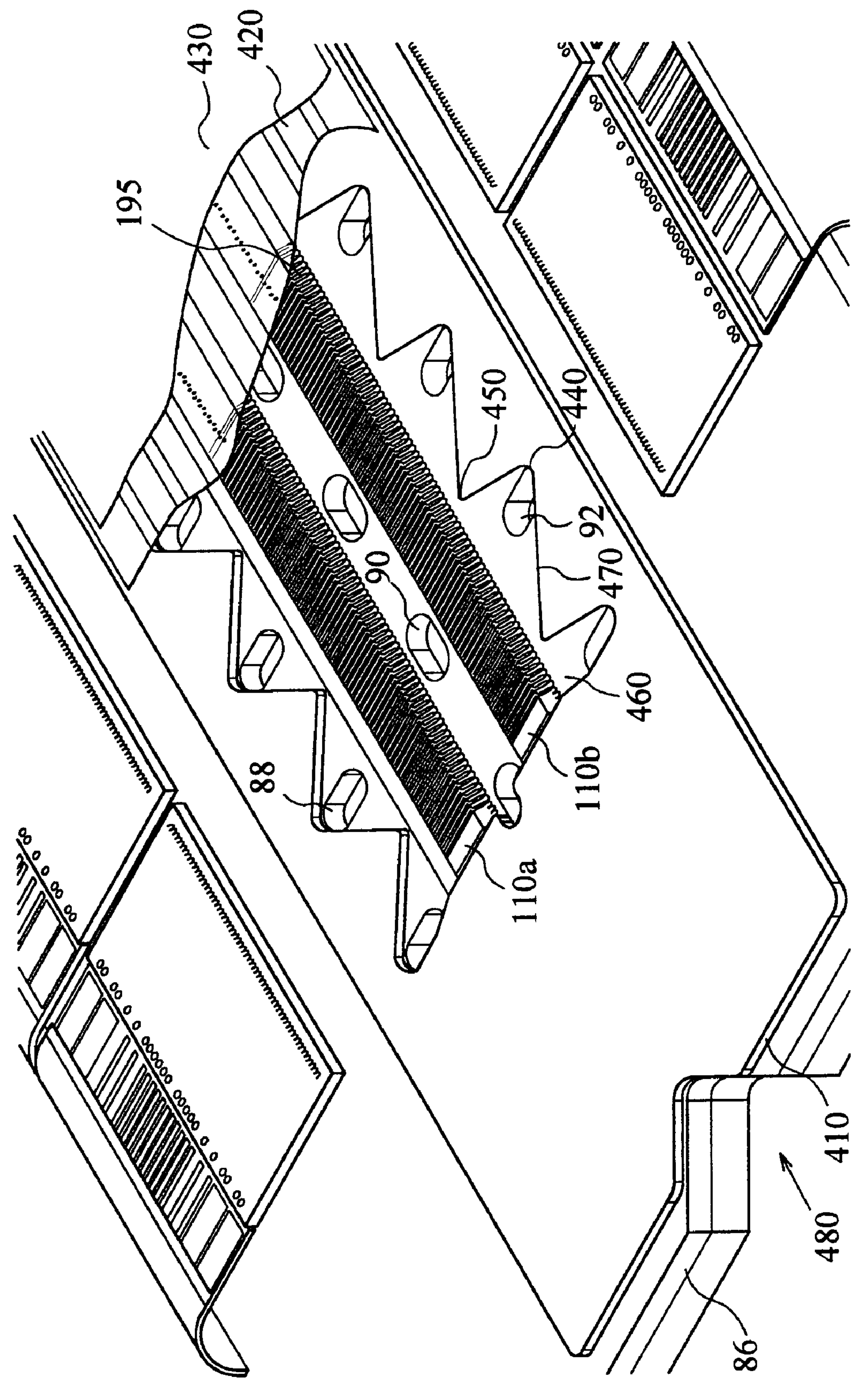

FIG. 5

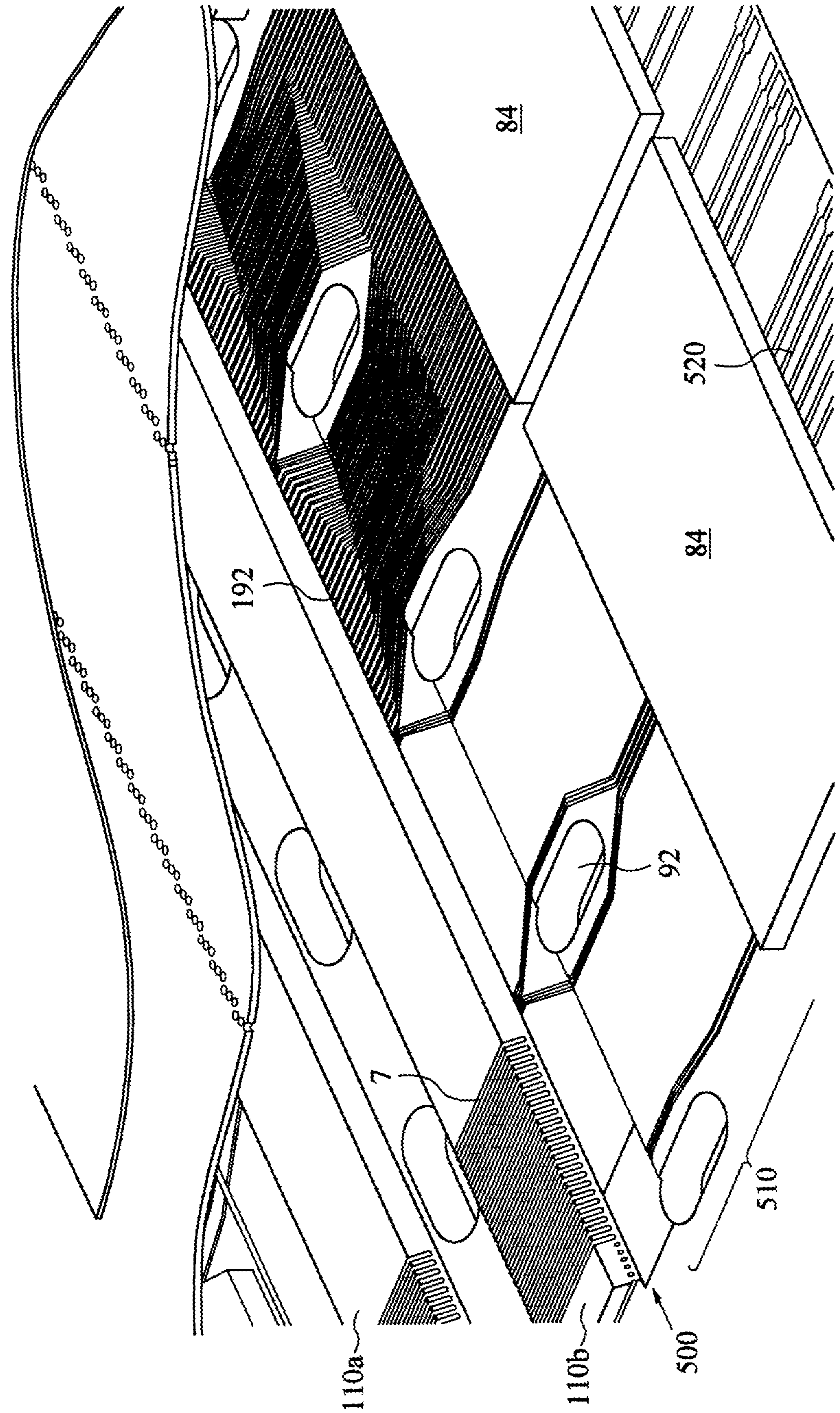

FIG. 6

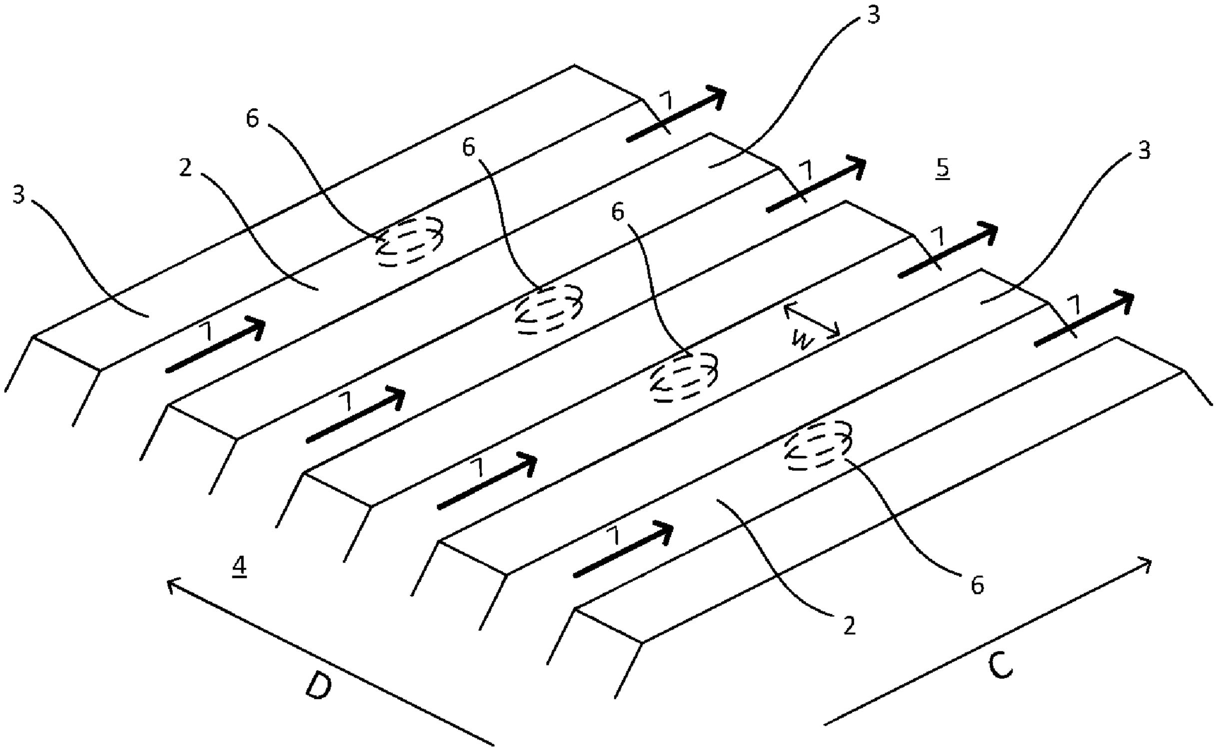

FIG. 7

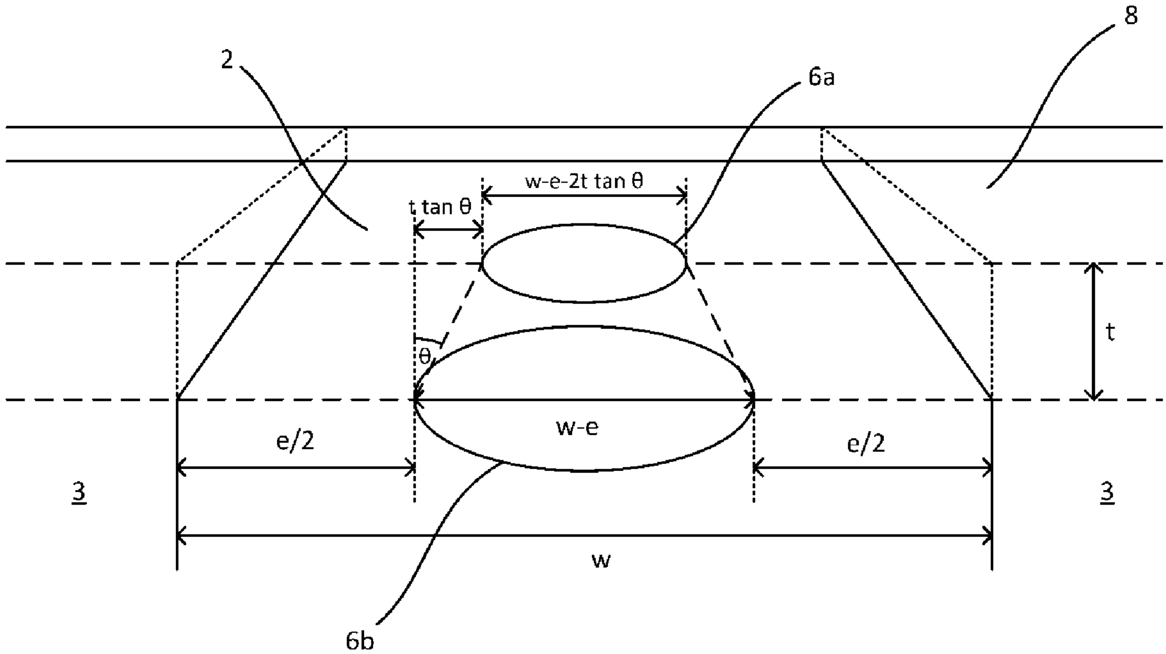

FIG. 8

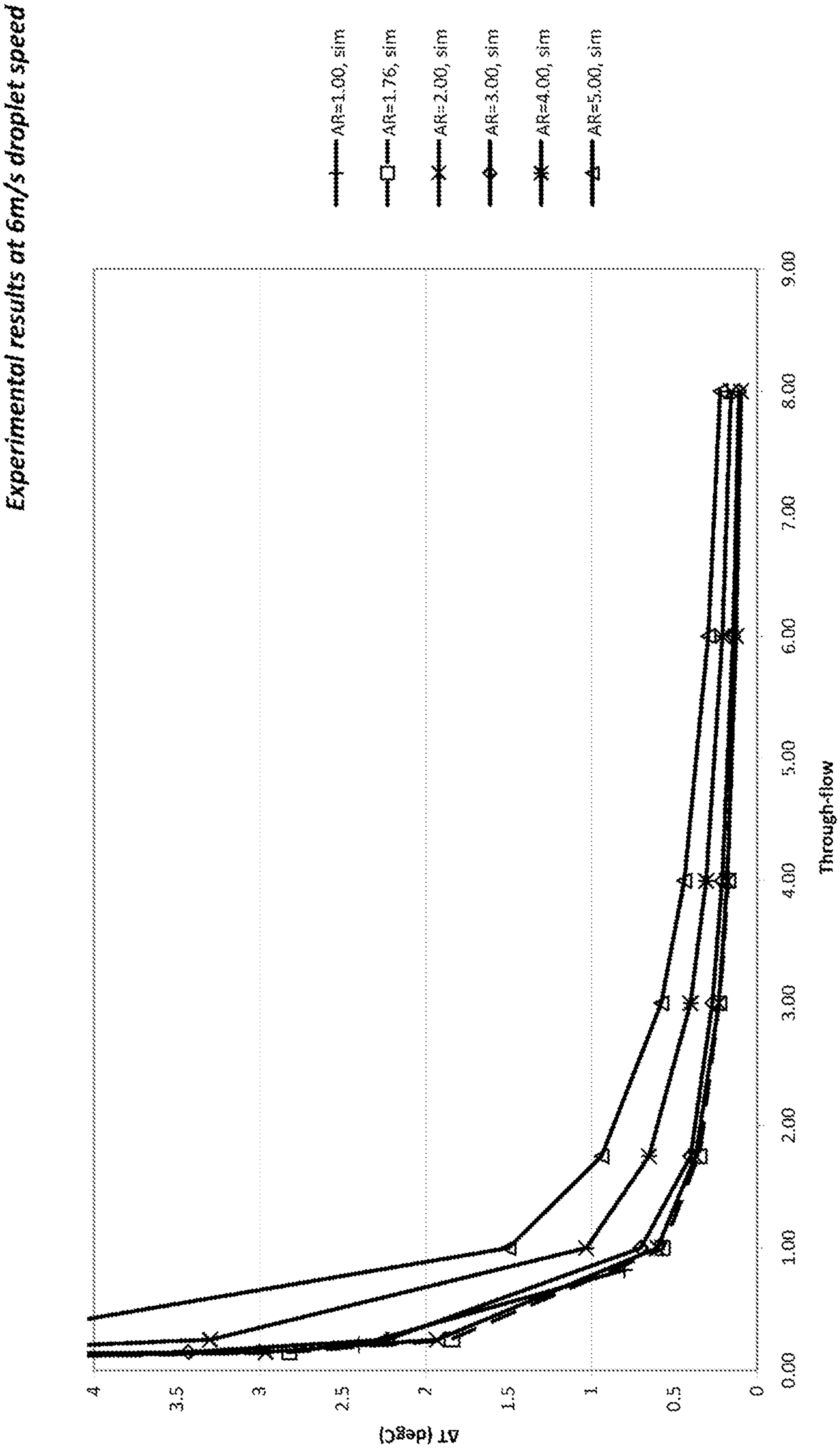
Experimental results at 6m/s droplet speed
AR=1.00, sim
AR=1.76, sim
AR=2.00, sim
AR=3.00, sim
AR=4.00, sim
AR=5.00, sim
ΔT (degC)
0
0.5
1
1.5
2
2.5
3
3.5
4
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
Through-flow

FIG. 9

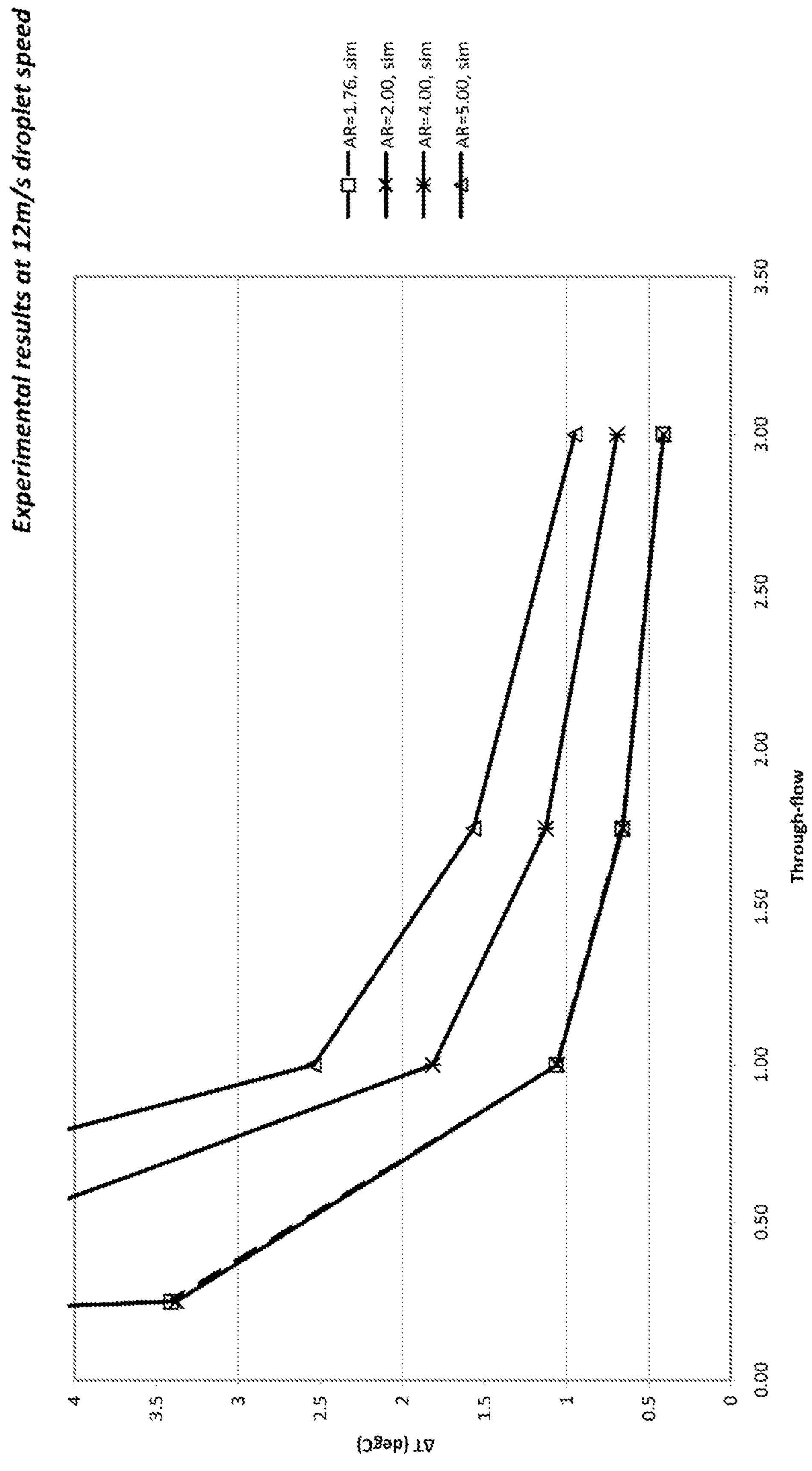
Experimental results at 12m/s droplet speed
AR=1.76, sim
AR=2.00, sim
AR=4.00, sim
AR=5.00, sim
ΔT (degC)
Through-flow
0
0.5
1
1.5
2
2.5
3
3.5
4
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50

FIG. 10

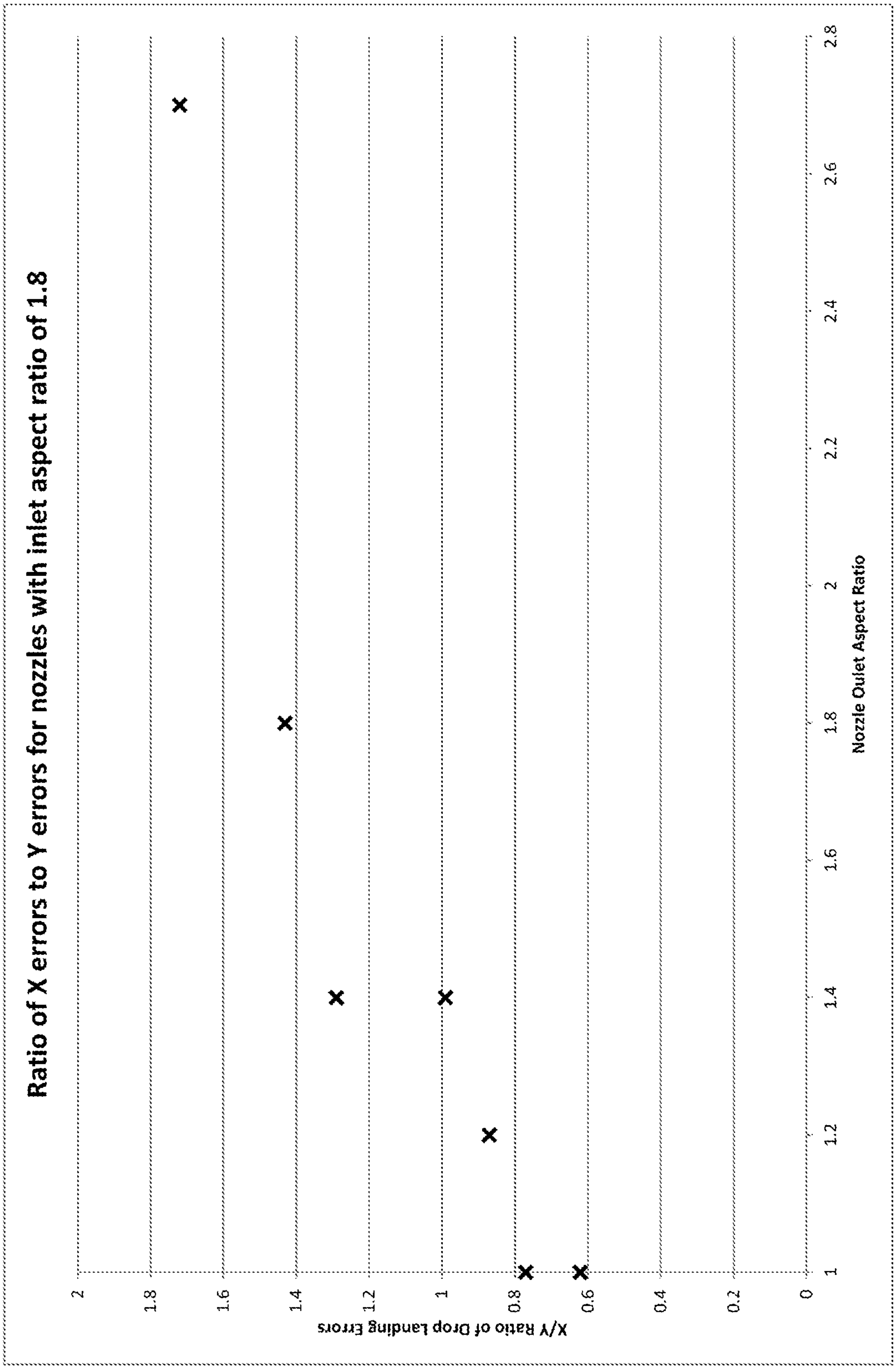
Ratio of X errors to Y errors for nozzles with inlet aspect ratio of 1.8
X/Y Ratio of Drop Landing Errors
Nozzle Oulet Aspect Ratio
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8

FIG. 11

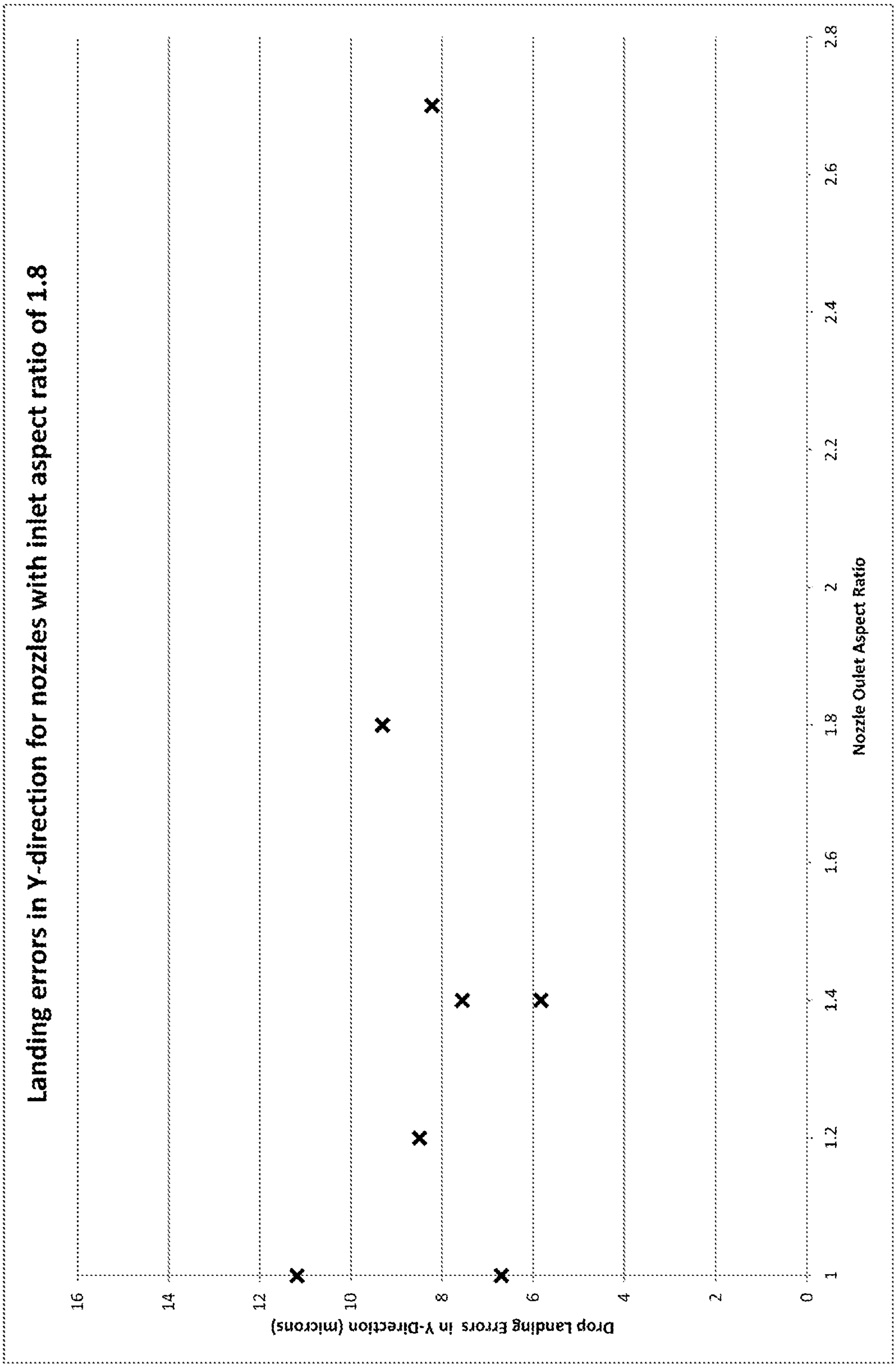
Landing errors in Y-direction for nozzles with inlet aspect ratio of 1.8
Drop Landing Errors in Y-Direction (microns)
0
2
4
6
8
10
12
14
16
Nozzle Oulet Aspect Ratio
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8

FIG. 12

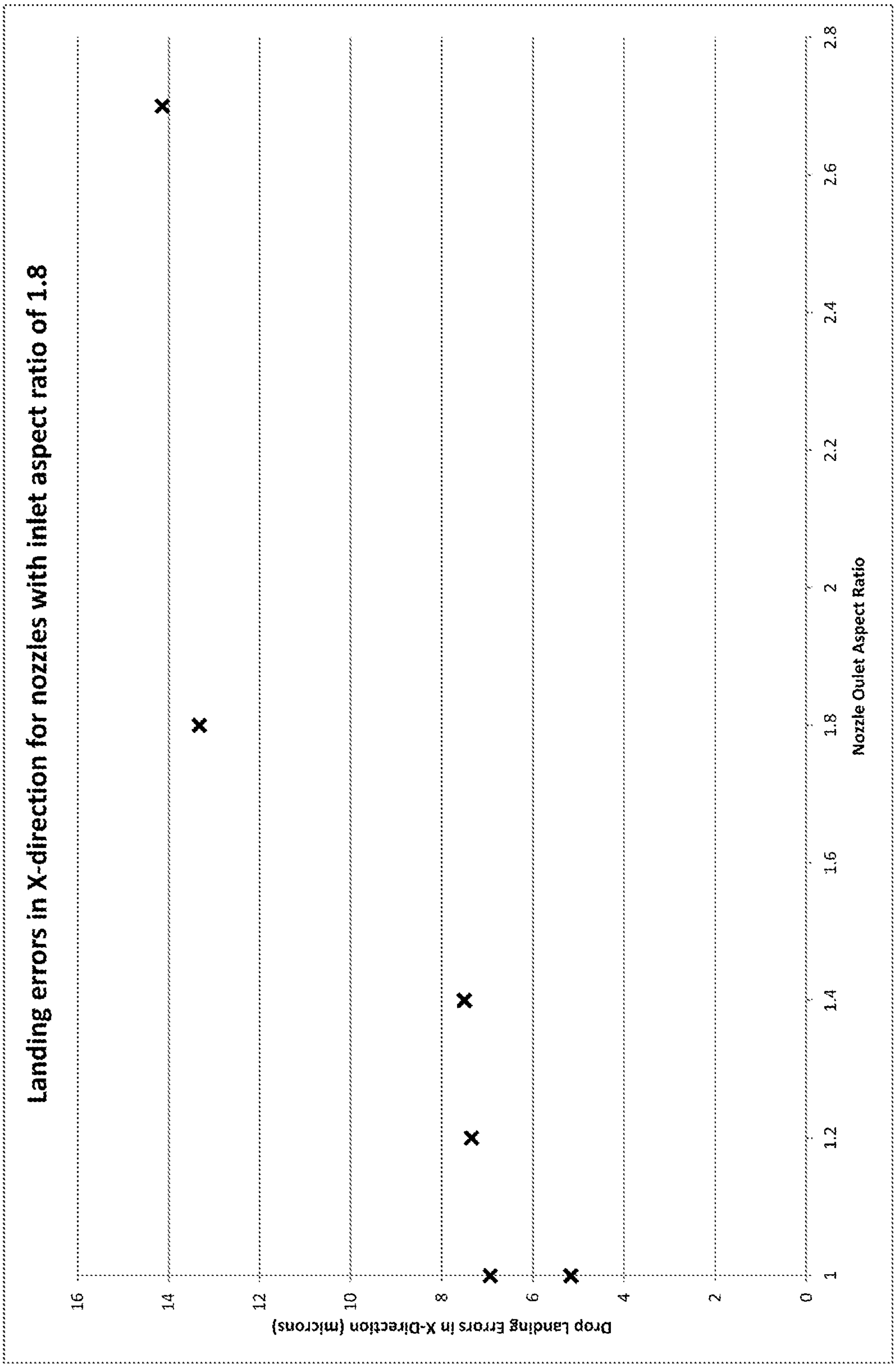
Landing errors in X-direction for nozzles with inlet aspect ratio of 1.8
Drop Landing Errors in X-Direction (microns)
Nozzle Oulet Aspect Ratio
0
2
4
6
8
10
12
14
16
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8

FIG. 13

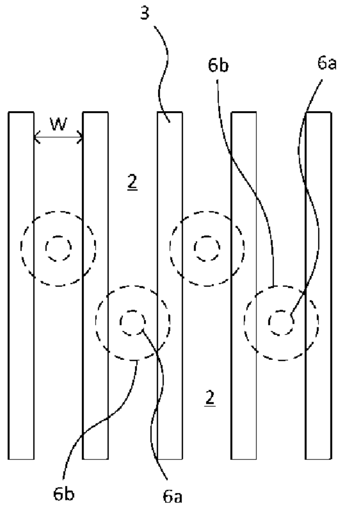

FIG. 14(A)

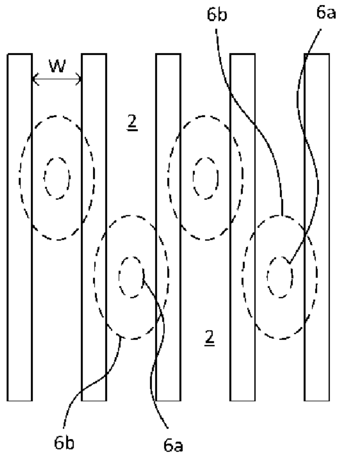

FIG. 14(B)

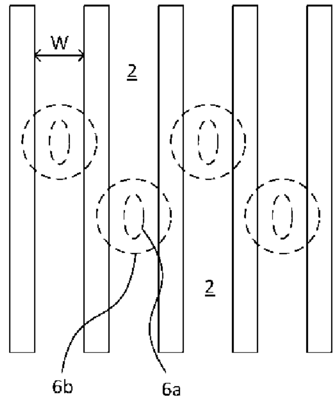

FIG. 14(C)

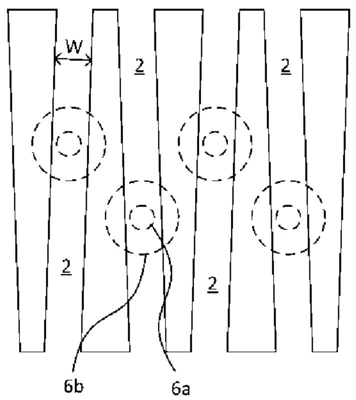

FIG. 15(A)

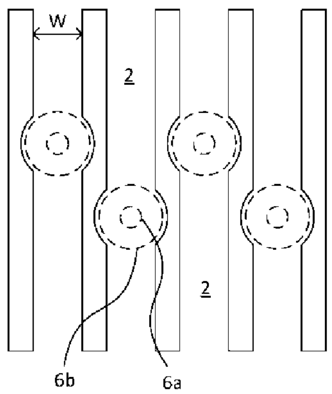

FIG. 15(B)

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2013/052146

A. CLASSIFICATION OF SUBJECT MATTER
INV. B41J2/14
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B41J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 2009/040250 A1 (SUZUKI ISAO [JP]) 12 February 2009 (2009-02-12) paragraphs [0103], [0106], [0117] - [0124] figures 13,14,16	6,11,12, 25 1-5, 7-10, 13-24
Y	US 2002/140774 A1 (MIKI MOTOHARU [JP] ET AL) 3 October 2002 (2002-10-03) paragraphs [0051] - [0062] figure 1	1-4, 17-24
Y	EP 0 595 654 A2 (CITIZEN WATCH CO LTD [JP]) 4 May 1994 (1994-05-04) column 15, line 56 - column 16, line 22 column 15, lines 26-27 column 12, line 11 - column 13, line 29 figure 17	5,9,10, 14,15

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 November 2013	22/11/2013

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Bonnin, David

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2013/052146

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 00/38928 A1 (XAAR TECH LTD [GB]; DIXON MICHAEL JOHN [GB]; TEMPLE STEVE [GB]; MANNIN) 6 July 2000 (2000-07-06) page 11, line 30 - page 13, line 21 page 14, lines 1-30 figures 5,6 -----	7,8, 13-16

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2013/052146

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