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D E S C R I P T I O N

FLUID TREATMENT APPARATUS AND METHOD

This invention pertains generally to apparatuses and methods for treating a substrate with a fluid, i.e., a liquid or a gas.

In the fabrication of a variety of devices such as, for example, printed circuit boards, various fluid treatments are applied to corresponding substrates, including rinsing, drying, chemical etching and electrolytic processing. These fluid treatments have been carried out using dip tanks and various configurations of spray nozzles and fluid jet injectors.

Dip tanks, while useful, are disadvantageous because they require an undesirably large amount of time for mounting and unmounting substrates to and from racks or baskets which are submerged within the dip tanks. In addition, mass transfer within a dip tank is typically effected via diffusion, which is often too slow a process to be economic. For example, when used for substrate rinsing, a dip tank quickly becomes heavily laden with the material to be removed from a substrate, which reduces the diffusion rate within the dip tank, and thereby slows rinsing. In fact, dip tanks often become so heavily laden with removed material that further rinsing becomes impossible.

Spray nozzles are disadvantageous because, among other reasons, they serve to atomize a fluid, resulting in the evaporation of the fluid. As a consequence, undesirable chemical emissions are exacerbated and re-use of the fluid is precluded, both of which are uneconomic. In addition, because the sprays produced by spray nozzles typically fail to achieve fluid bearing action on the substrates being processed, these substrates must be transported to and from the sprays by

rollers and guides positioned between the spray nozzles and the substrates. However, the presence of these rollers and guides is undesirable because, among other reasons, they produce nonuniformities in the spray action which results in, for example, nonuniform rinsing and etching. Moreover, because sprays quickly lose momentum, they often fail to achieve efficient fluid treatment of specific substrate areas, which limits processing rate and throughput. For example, sprays are often inefficient or ineffective in rinsing or drying specific substrate areas, such as the interiors of holes in substrates, because whatever fluid reaches such areas tends to be retained on or in these areas (a phenomenon called dragout), with relatively little fresh fluid reaching these areas. Moreover, sprays often re-deposit or re-position, rather than remove, debris on the substrate, which then requires the use of additional sprays. Consequently, the use of sprays often requires the use of an undesirably large amount of processing area, which is also uneconomic. While attempts have been made to orient sprays to achieve directionality and thereby overcome some of the above-mentioned disadvantages, these attempts have typically been accompanied by a torque being imposed upon the substrate by the directed spray. This results in instabilities in the motion of the substrate, often causing jamming of the substrate in the corresponding processing equipment, resulting in damage to the substrate or equipment, which is undesirable and counterproductive.

The use of fluid jets in the fluid treatment of substrates is potentially advantageous because fluid jets exhibit directionality and therefore, in principle, are capable of overcoming the disadvantages of sprays. However, previous configurations of fluid jets have failed to overcome the problem of dragout, particularly in the case of substrates with holes. Moreover, these previous fluid jet configurations have also imposed torques on substrates, resulting in undesirable and counterproductive instabilities in the motions of substrates.



Thus, those engaged in the development of fluid treatment apparatuses and methods have long sought, thus far without success, fluid jet configurations which: (1) overcome the problem of dragout, particularly in the case of substrates with holes; (2) avoid imposing torques on substrates; and (3) substantially reduce the need for rollers and guides for transporting substrates, thereby substantially reducing the interference caused by such rollers and guides.

The invention involves a fluid treatment apparatus, and corresponding fluid treatment method, which substantially overcomes the problem of dragout, which avoids imposing torques on substrates and substantially reduces the need for rollers and guides for transporting substrates. In one embodiment of the inventive apparatus, at least one row of fluid jet injectors penetrates a surface of the apparatus, over which a substrate to be processed is transported via rollers positioned at the entrance edge and exit edge of the apparatus surface. The substrate is transported in a direction which is substantially parallel to an axis associated with the apparatus surface, extending from the entrance edge to the exit edge, and the row of fluid jet injectors is aligned transversely to this axis. During its transport, the substrate is positioned close enough to the apparatus surface so that the fluid jets emitted by the fluid jet injectors become immersed in a layer of spent fluid covering the surface, and therefore the emitted fluid jets constitute submerged fluid jets. Significantly, the row of fluid jet injectors is positioned closer to the entrance edge of the apparatus surface than to the exit edge. As a result, the resistance to fluid flow toward the exit edge, through the relatively long portion of the layer of spent fluid, is greater than the resistance to fluid flow toward the entrance edge, through the relatively short portion of the layer of spent fluid. Consequently, after the fluid jets emitted by the fluid jet injectors impinge upon the substrate, more than half the fluid associated with the fluid jets flows countercurrently toward the entrance edge, where it is vented via, for example, drain

holes in the apparatus surface. Thus, dragout is substantially eliminated because fluid impinged upon the substrate is more readily removed after impingement, allowing fresh fluid to reach the substrate. In addition, the countercurrent flow prevents removed debris from being re-deposited or re-positioned on any portion of the substrate which has been impinged upon by the fluid jets. Moreover, the spent fluid layer and submerged fluid jets achieve a fluid bearing action on the substrate, reducing the need for rollers and guides, other than the rollers at the entrance edge and exit edge of the apparatus surface.

It must be noted that the substantial elimination of dragout via the invention enables the inventive fluid treatment apparatus to fluid treat substrates more efficiently than was previously possible. Thus, for example, the length of the inventive apparatus can now be much shorter than was previously possible, which is highly advantageous.

To avoid a torque on a substrate which might be imposed by the use of one row of fluid jets, the inventive apparatus preferably includes two surfaces, with each containing one or more rows of fluid jet injectors, between which a substrate to be processed is transported. Here, the fluid jets which impinge upon the upper and lower surfaces of the substrate substantially balance each other, thereby substantially eliminating torques.

In another embodiment of the invention, intended to even more completely eliminate dragout in substrates with holes, the inventive apparatus again includes two surfaces, with each surface containing one or more rows of fluid jet injectors, between which a substrate is to be transported. Each row of fluid jet injectors on one surface is aligned with a corresponding row of fluid jet injectors on the other surface. However, the fluid jet injectors of a row on one surface are offset relative to the fluid jet injectors of the corresponding row on the other surface so that if one were to



project the former fluid jet injectors onto the latter surface, the former fluid jet injectors would be interdigitated with the latter fluid jet injectors. This interdigitation of the fluid jet injectors ensures that the fluid jets which penetrate the holes in the substrate are unopposed by counteracting fluid jets.

In yet another embodiment of the invention, the above-described countercurrent flow is achieved by providing at least two rows of fluid jet injectors on an apparatus surface over which a substrate is to be transported. Significantly, at least the second row of fluid jet injectors is inclined toward the entrance edge of the surface. As a result, the fluid jets emanating from the second row of fluid jet injectors induce more than half the fluid associated with the fluid jets emanating from the first row of fluid jet injectors to flow toward the entrance edge of the apparatus surface, after impingement upon the substrate.

The invention is described with reference to the accompanying drawings, wherein:

Fig. 1 is an isometric view of a first embodiment of the inventive apparatus;

Fig. 2 is an end view of the embodiment shown in Fig. 1;

Fig. 3 is a top view of the embodiment shown in Fig. 1;

Fig. 4 is a top view of a second embodiment of the inventive apparatus;

Fig. 5 is a front view of the second embodiment of Fig. 4;

Fig. 6 is an isometric view of a third embodiment of the inventive apparatus;

Fig. 7 is an end view of the embodiment shown in Fig. 6;



Fig. 8 is a top view of the embodiment shown in Fig. 6; and

Fig. 9 is a front view of the embodiment shown in Fig. 6.

The invention involves a fluid treatment apparatus, and a corresponding fluid treatment method, which substantially overcomes the problem of dragout, which avoids imposing torques on substrates and substantially reduces the need for rollers and guides for transporting substrates. These goals are achieved, in accordance with the invention, by employing a new configuration of fluid jet injectors in the inventive apparatus, producing a new configuration of fluid jets which impinge upon substrates undergoing fluid treatment, as more fully described below.

With reference to Figs. 1 and 2, a first embodiment of the inventive fluid treatment apparatus 10 includes at least one plenum housing 20 made, for example, of stainless steel, which contains a plenum chamber 30 into which a fluid is fed under pressure via a feed tube 40. The plenum housing 20 is topped by a connected injector plate 50 made, for example, of aluminum. Significantly, at least one row 60 of at least two, spaced-apart, drilled holes extends from the plenum chamber 30 to the surface 52 of the injector plate 50, which holes serve as fluid jet injectors.

As shown more clearly in Fig. 1, the inventive apparatus 10 also includes rollers 80 and 90 which serve to transport a substrate 100, e.g., a printed circuit board substrate, at a distance, H, from the surface 52, from an entrance edge 54 to an exit edge 56 of the surface 52. This transport of the substrate 100 occurs along a direction which is substantially parallel to an imaginary axis 110 associated with the surface 52, which axis is oriented transversely to the entrance and exit edges 54 and 56, and extends from the entrance edge 54 to the exit edge 56, and beyond.

While not shown in Figs. 1 or 2, the inventive apparatus 10 preferably also includes side walls in flush contact with the flat end faces of the plenum housing 20, which side walls serve to confine the fluid emitted by the fluid jet injectors.

With reference now to Fig. 3, the at least one row 60 of fluid jet injectors includes the fluid jet injectors 60-1, 60-2, 60-3, etc., with the row 60 being inclined transversely to the imaginary axis 110. Preferably, each of the fluid jet injectors is of equal diameter, D , which ranges from about 5 mils (0.005 inches) to about $6.25 \times 10^3 \mu\text{m}$ (about 250 mils) (0.25 inches)). Fluid jet injectors having diameters smaller than about 125 μm (about 5 mils) are undesirable because they are difficult to fabricate. On the other hand, fluid jet injectors having diameters greater than about $625 \times 10^3 \mu\text{m}$ (about 250 mils) are undesirable because they require an undesirably large amount of pump pressure to produce fluid jets.

With reference to Fig. 2, the drilled holes which constitute the fluid jet injectors are preferably all of equal length, L . In this regard, the ratio L/D preferably ranges from about 0.5 to about 40. Ratios less than about 0.5 are undesirable because they result in poorly developed fluid jets. Ratios greater than about 40 are undesirable because the corresponding fluid jet injectors are difficult to fabricate and require an undesirably large amount of pump energy to achieve a useful flow rate.

With reference once again to Fig. 3, the fluid jet injectors are preferably equidistantly spaced, with the center-to-center spacing between adjacent fluid jet injectors being denoted by S . The ratio S/D is necessarily greater than one (a ratio $S/D=1$ implies the fluid jet injectors are touching) but is preferably equal to or less than about 20. Ratios greater than about 20 are undesirable because after the corresponding fluid jets impinge upon the substrate 100, it has been found that the resulting fluid flows separate from the surface of the

substrate 100 and form a region of recirculating fluid, which permits undesirable re-deposition of debris or spent fluid.

With reference to Fig. 1, as noted above, the fluid jets injected by the fluid jet injectors are to be submerged fluid jets, i.e., the fluid jets are to be injected into a layer of spent fluid covering the surface 52 and substantially filling the space between the surface 52 and the substrate 100. Such submerged fluid jets are achieved, in accordance with the invention, by bringing the substrate 100 into proximity with the surface 52 so that the ratio H/D ranges from about 0.2 to about 15. Ratios smaller than about 0.2 are undesirable because the substrate 100 is then so close to the surface 52 that the substrate is likely to become jammed against the surface 52. On the other hand, ratios greater than about 15 are undesirable because the substrate 100 is then so far from the fluid jet injectors that the corresponding fluid jets lose an undesirably large amount of momentum before impinging upon the substrate 100.

It should be noted that the spent fluid layer and fluid jets achieve a fluid bearing action on the substrate 100. As a consequence, the need for rollers and guides between the entrance edge 54 and the exit edge 56 for transporting the substrate 100 is eliminated.

Because the fluid jet injectors are preferably all of equal diameter, D , and are all connected to the same plenum chamber 30, the fluid supplied to each of the fluid jet injectors is necessarily the same, and the speed of the fluid jets emanating from the fluid jet injectors is necessarily also the same. If the kinematic viscosity of the supplied fluid is denoted by ν and the speed of the fluid jets at the fluid jet injectors is denoted by V , then the Reynolds number associated with each of the fluid jets, defined as the ratio $V \cdot D / \nu$, preferably ranges from about 50 to about 30,000. Reynolds numbers less than about 50 are undesirable because the corresponding fluid jets have undesirably small momenta. On

the other hand, Reynolds numbers greater than about 30,000 are undesirable because the achievement of such high Reynolds numbers requires undesirably high plenum pressures.

In accordance with the invention, and as noted above, the row 60 of fluid jet injectors is positioned closer to the entrance edge 54 (see Fig. 3) of the surface 52 than the exit edge 56. As a result, in the operation of the apparatus 10, the resistance to fluid flow from the row 60 toward the exit edge 56, through the relatively long portion of the layer of spent fluid covering the surface 52, is relatively high. By contrast, the resistance to fluid flow from the row 60 toward the entrance edge 54, through the relatively short portion of the layer of spent fluid covering the surface 52, is relatively low. Consequently, after the fluid jets emitted by the row 60 of fluid jet injectors impinge upon the substrate 100, more than half the fluid associated with the fluid jets flows countercurrently toward the entrance edge 54. Thus, undesirable dragout and re-positioning of debris is substantially reduced or eliminated.

Although not shown in the drawings, the injector plate 50 preferably includes a row of drain holes positioned adjacent the entrance edge 54, aligned transversely to the imaginary axis 110. These drain holes permit ready venting of the above-described countercurrently flowing fluid. Moreover, if a pump is used to pump fluid out of the drain holes, then the countercurrent flow is enhanced.

Preferably, although not shown in the drawings, the injector plate 50 also includes a row of drain holes positioned adjacent the exit edge 56, aligned transversely to the imaginary axis 110. These additional drain holes serve to vent the relatively small amount of fluid which flows toward the exit edge.

As shown in Figs. 2 and 3, the first embodiment of the inventive apparatus 10 preferably includes a second row 70 of

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fluid jet injectors, penetrating the surface 52, aligned transversely to the imaginary axis 110. Significantly, this second row 70 of fluid jet injectors, which includes fluid jet injectors 70-1, 70-2, 70-3, etc., is positioned between the row 60 of fluid jet injectors and the exit edge 56, and is preferably equidistantly positioned between the entrance edge 54 and the exit edge 56. By virtue of the presence of the fluid jets emitted by the second row 70, the above-described countercurrent flow associated with the fluid emitted by the first row 60 is enhanced.

To avoid imposing a torque on the substrate 100, and as depicted in Figs. 1 and 2, the first embodiment of the inventive apparatus 10 preferably includes a second plenum housing 120, containing a plenum chamber 130 into which fluid is fed under pressure via a feed tube 140. An injector plate 150 is mounted on the plenum housing 120, with rows 160 and 170 of fluid jet injectors extending from the plenum chamber 130 to the surface 152 of the injector plate 150. The fluid jets emitted by the rows 160 and 170, which impinge upon the upper surface of the substrate 100, serve to counterbalance the fluid jets emitted by the rows 60 and 70, which impinge upon the lower surface of the substrate 100. As a result, undesirable torques on the substrate 100 are avoided.

With reference now to Figs. 1, 4 and 5, a second embodiment of the inventive apparatus 10 is generally similar to the first embodiment. This second embodiment definitely includes both the plenum housing 20 and the plenum housing 120, and the surfaces 52 and 152 define a channel having an entrance adjacent the entrance edges 54 and 154 and an exit adjacent the exit edges 56 and 156. This channel is characterized by an axis which is oriented transversely to the entrance and exit edges 54, 154, 56 and 156, and extends from the entrance of the channel to the exit of the channel.

In connection with the second embodiment, the substrate 100 is transported via rollers 80 and 90 through the above-defined

channel in a direction which is substantially parallel to the channel axis. This transport occurs at a distance, H_1 , above the surface 52 and at a distance, H_2 , below the surface 152. The distances H_1 and H_2 need not be the same.

As shown in Figs. 4 and 5, the second embodiment includes at least one row 60, and preferably two rows 60 and 70, of fluid jet injectors penetrating the surface 52. The fluid jet injectors of the rows 60 and 70 are of equal diameter, D_1 , and the fluid jets which they emit exit the fluid jet injectors with fluid speed V_1 . The fluid in these fluid jets is characterized by a kinematic viscosity ν_1 . Preferably, the row 60 is positioned closer to the entrance edge 54 than to the exit edge 56, for the reason discussed above.

The second embodiment also includes at least one row 160, and preferably two rows 160 and 170, of fluid jet injectors penetrating the surface 152. The fluid jet injectors of the rows 160 and 170 are of equal diameter D_2 , and the fluid jets which they emit exit the fluid jet injectors with fluid speed V_2 . The fluid in these fluid jets is characterized by a kinematic viscosity ν_2 . The diameter D_2 is not necessarily equal to the diameter D_1 , the kinematic viscosity ν_2 is not necessarily equal to the kinematic viscosity ν_1 , and the fluid speed V_2 is not necessarily equal to the fluid speed V_1 .

In the second embodiment, like the first embodiment, the ratios H_1/D_1 , H_2/D_2 , $V_1 \cdot D_1/\nu_1$ and $V_2 \cdot D_2/\nu_2$ fall within the ranges given above, for the reasons given above.

As shown more clearly in Fig. 4, the second embodiment differs from the first embodiment in that the row 160 is shifted relative to the row 60 so that if the row 160 were to be projected onto the surface 52 (as depicted in Fig. 4), the fluid jet injectors of the row 160 would be interdigitated with the fluid jet injectors of the row 60. The row 170 is similarly shifted relative to the row 70. The purpose of these shifts is to ensure that fluid jets which penetrate holes in

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the substrate 100 are unopposed by counteracting fluid jets, which substantially eliminated dragout in such hole.

The amount of the above-described shift, denoted S_y , is chosen so that the ratio S_y/S is greater than 0 but less than 1. Ratios equal to 0 and 1 imply an absence of interdigitation.

It should be noted that the second embodiment has been found to be particularly useful in rinsing substrates having holes.

With reference now to Figs. 6, 7, 8 and 9, a third embodiment of the inventive apparatus is generally similar to the first and second embodiments, and is characterized by a coordinate system x, y, z , as pictured in Fig. 6. As shown, the x -axis is parallel to the axis 110 associated with the surface 52, here referred to as the transport axis. The y -axis lies in a least-squares-fit planar approximation to the surface 52 and is perpendicular to the x -axis. The z -axis is perpendicular to both the x -axis and the y -axis.

The third embodiment differs from the second embodiment in that each of the fluid jet injectors in row 70 is inclined toward the entrance edge 54. Moreover, each of these fluid jet injectors forms an angle, θ , with the z -axis, as measured in the counterclockwise direction in a plane defined by the z -axis and x -axis, which is greater than 0 degrees but less than 90 degrees. Such an inclination, and range of angles, θ , enhance the countercurrent flow associated with the fluid emitted by the fluid jet injectors in the row 60, discussed above.

Preferably, the fluid jet injectors in the row 70 are also inclined toward the y -axis. Moreover, each such inclined fluid jet injector forms an angle, ϕ , with the z -axis, as measured in the clockwise direction in a plane defined by the z -axis and the y -axis, which is greater than 0 degrees but less than 90 degrees. This y -axis inclination is advantageous because it induces the fluid emitted by the fluid jet injectors in the

row 60, after impingement upon the substrate 100, to flow laterally in the direction of the y-axis, which also serves to eliminate dragout.

As shown in Figs. 7 and 8, the third embodiment also includes a row 72 of fluid jet injectors penetrating the surface 52. This third row is advantageous because the corresponding fluid jets serve to stabilize the motions of substrates, particularly relatively thin substrates.

As also shown in Figs. 7 and 8, the surface 54 is penetrated by rows 160, 170 and 172 of fluid jet injectors, which mirror the rows 60, 70 and 72 penetrating the surface 52.

It should be noted that the third embodiment has been found to be particularly advantageous in drying substrates with holes.

Example 1

Rinsing of circuit boards was compared using a standard spray rinse vs. the invention apparatus. The comparison looked at conveyor length used for rinsing, electricity usage, flow rate of rinse water used, and resultant ionic contamination on the circuit boards.

For both parts of the experiment, one or two DSM (double spray modules), horizontally conveyORIZED wet processing equipment built by Chemcut in State College, Pennsylvania, were used in a countercurrent rinse configuration. For the standard spray rinsing tests, two modules were used in series, with the spent waste water of the second module cascading to the first module and then to waste treatment. Each module had solid cylindrical "squeegee" type rollers at its entrance and exit and had its own pump supplying the sprays. For the invention apparatus rinsing tests, a single module was fitted with four pairs of the apparatus having the preferred embodiment for rinsing as shown in Figures 4 and 5.

Each apparatus pair for the rinsing embodiment was characterized by two surfaces with an entrance-to-exit length of $2.87 \times 10^{-2}\text{m}$ (1.13"). Two rows, each containing 327 7.62×10^{-4} (0.030") dia. injectors, were placed in both the upper and lower surfaces at distances from the entrance edge of the device of, respectively, $1.08 \times 10^{-2}\text{m}$ (0.425") and $1.76 \times 10^{-2}\text{m}$ (0.692"). The injectors were made by drilling holes through $1.27 \times 10^{-2}\text{m}$ (0.5") thick polycarbonate plastic. Center-to-center spacing of the 7.62×10^{-4} (0.030") dia. injector holes within each of the four rows was $2.29 \times 10^{-3}\text{m}$ (0.090"). The injectors in the first and second rows in the upper surface were positioned so that their projection onto the lower surface was centered between the injectors in the first and second rows in the lower surface, respectively. The y-position of the injectors in the second row in each surface was offset from the y-position of the injectors in the respective adjacent first row by $1.73 \times 10^{-3}\text{m}$ (0.068"). A 10 degree beveling of the first $4.06 \times 10^{-3}\text{m}$ (0.16") of the upper and lower surfaces served as a guide for the substrates. Two rows of drain holes were included with diameters of $3.63 \times 10^{-3}\text{m}$ (0.143") and spaced center-to-center within a row $4.88 \times 10^{-3}\text{m}$ (0.192") apart were placed with centers spaced $5.59 \times 10^{-3}\text{m}$ (0.220") and $5.61 \times 10^{-3}\text{m}$ (0.221") from the entrance and exit edges, respectively. The distance, H1, of the lower surface from the bottom of the substrate was $2.54 \times 10^{-3}\text{m}$ (0.10") and the distance, H2, of the upper surface of the device from the top of the substrate was $6.35 \times 10^{-3}\text{m}$ (0.25"). The rinsing fluid, water, having a viscosity, ν , of $10^{-8}\text{m}^2/\text{s}$ (0.01 cm²/sec), was passed through each of the injectors with a velocity V of 302 cm/sec, giving a Reynolds number, Re, of about 2300.

Each apparatus pair had at its entrance and exit side a pair of solid cylindrical "squeegee" conveyor rollers and was provided with a pump and sump. The water was re-circulated from each respective sump to the respective apparatus, after which the water would fall back into the sump. At the same time, incoming water caused the sump water to cascade

continuously to the stage preceding and finally to waste treatment. By "stage preceding", it is meant the stage through which the circuit board would travel immediately prior to the current stage. The water cascaded from stage to stage in the opposite direction to the direction of circuit board travel. This arrangement of water cascade direction relative to product travel direction, is known as "countercurrent rinsing" in the art, is the most efficient in terms of both overall water usage and cleanliness of the final rinse, and was used in both the spray and invention apparatus tests.

Each run consisted of ten circuit boards measuring $0.254 \times 0.381 \times 1.52 \times 10^{-3} \text{ m}$ ($10 \times 15 \times 0.060$ inches) and having a mixture of $1.27 \times 10^{-3} \text{ m}$ and $4.57 \times 10^{-4} \text{ m}$ (0.050 inch and 0.018 inch) diameter holes. There were copper traces on epoxy dielectric on the surface. The circuit boards were run at 3.05 m per minute (120 inches per minute) through a microetch chamber, followed by the rinse, and air dried. The microetch consisted of approx. 40 g/l sodium persulfate and 40 g/l sulfuric acid dissolved in water. Resultant contamination was measured using an Omega ionograph meter which had been calibrated to give conductivity readings in equivalent NaCl contamination in micrograms/square inch of circuit board.

Water usage was measured with a float-type see-through flowmeter, and power usage was determined with a hand-held current meter.

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Results

Fluid	Water	Ionic	Conveyor	Electrical
Delivery	usage	contamination	length	Usage
Device	m ³ /min (gal/min)	on product μg/m ² (micro g/sq.in.) (NaCl equivalent)	m (feet)	Kilowatts

Spray	1.89x10 ⁻²	9.03x10 ⁻⁴	3.12	2.7
(2-stage)	(5)	(1.4)	(4)	

Invention

Apparatus	3.79x10 ⁻³	1.10x10 ⁻³	6.1x10 ⁻¹	1.6
(4-stage)	(1)	(1.7)	(2)	

As can be seen from the data, the invention showed an essentially equivalent contamination level while using 40% less electricity (four smaller pumps feeding the apparatuses of the invention used less electricity than the two larger pumps feeding the sprays) and generating 80% less water waste by volume, all in 50% less conveyor space than the standard spray system. As far as water usage is concerned, let it be noted that theoretically a four-stage spray rinse could use just as small an amount of water as a four-stage rinse incorporating the invention apparatus. However, such a four-stage spray rinse would occupy four times as much conveyor space and would consume three and one-third times as much electricity as the invention apparatus.

Example 2

Drying of circuit boards was compared using the invention apparatus versus two state-of-the art dryers. Comparison results were measured for both high and normal aspect-ratio thru-holes in terms of electricity usage and conveyor length.

The state-of-the-art dryer used as a basis of comparison for hi-aspect ratio thru-holes was a SHD ("small hole dryer") built by International Supplies of Parma, Italy. Circuit boards run through this machine were approximately $7.62 \times 10^{-3}\text{m}$ (0.300 inches) thick and $0.61 \times 0.71 \text{ m}$ (24x28 inches) in width and length with thousands of approx. $3.81 \times 10^{-4}\text{m}$ (approx. 0.015 inch) dia. thru-holes. The dryer used four "push-pull" slotted manifolds run by a turbine blower that forced pressurized air against one side of the circuit board and suction to the opposing side. The push-pull was alternated so that the pressure side alternated up, down, up and then down. Following the forced-air slotted blowers were two heated fan blowers that recirculated hot air. When the circuit boards were conveyed through this configuration at 1 meter/minute, many of the thru-holes were still wet, leading to unwanted stains that were deleterious in subsequent processes. A single pair of the invention apparatuses with the preferred drying embodiment as shown in Figures 6-9 were installed with a turbine blower feeding each side.

The apparatus pair for the drying embodiment was characterized by two surfaces with an entrance-to-exit length of $5.7 \times 10^{-2}\text{m}$ (2.25"). Three rows, each containing $171 \times 1.09 \times 10^{-3}\text{m}$ (0.043") dia. injectors, were placed in both the upper and lower surfaces at distances from the entrance edge of the device of, respectively, $1.27 \times 10^{-2}\text{m}$ (0.500"), $1.65 \times 10^{-2}\text{m}$ (0.650"), and $2.86 \times 10^{-2}\text{m}$ (1.125"). The injectors in the upper and lower surfaces, respectively, were made by drilling holes through $7.62 \times 10^{-3}\text{m}$ (0.3") and $1.27 \times 10^{-2}\text{m}$ (0.5") thick aluminum metal. Center-to-center spacing of the $1.09 \times 10^{-3}\text{m}$ (0.043") dia. injector holes within each of the four rows was $3.81 \times 10^{-3}\text{m}$ (0.150"). The injectors in the first, second and third rows in the upper surface were positioned so that their vertical projection onto the lower surface was centered between the injectors in the first, second, and third rows in the lower surface, respectively. The y-position of the injectors in the second and third rows in each surface was offset from the y-position of the injectors in the adjacent

first row by $1.27 \times 10^{-3}\text{m}$ (0.050") and $2.54 \times 10^{-3}\text{m}$ (0.100"), respectively. An 18 degree beveling of the first $9.53 \times 10^{-3}\text{m}$ (0.375") of the upper and lower surfaces served as a guide for the substrates. The injectors in the upper and lower surfaces were drilled at a 15degree angle so that jets issuing from them were tilted towards the entrance of the device. The distance, H1, of the lower surface from the bottom of the substrate was $1.27 \times 10^{-3}\text{m}$ (0.050") and the distance, H2, of the upper surface of the device from the top of the substrate was $6.35 \times 10^{-3}\text{m}$ (0.250"). The drying fluid was air having a viscosity, ν , of $1.7 \times 10^{-7}\text{m}^2/\text{s}$ (0.17 cm^2/sec), and was passed through each of the injectors with a velocity V of 9000 cm/sec , giving a Reynolds number, Re, of about 5800.

With the invention installed, at 1 meter/min conveyor speed, and with the two heated blowers off, all of the thru-holes were dry.

The state-of-the-art dryer used as a basis of comparison for normal aspect-ratio thru-holes was a "TMDM" dryer built by Chemcut of State College, Pennsylvania. Circuit boards run through this machine were approximately $1.52 \times 10^{-3}\text{m}$ (0.060 inch) thick and $0.254 \times 0.381\text{m}$ (10x15 inches) in width and length. The dryer used several different blowers and manifolds and also used a heated rinse with the intent to allow the water retained on the panel to dry more rapidly. When panels were sent through this machine at 2 meters/minute they dried sufficiently, but when they were sent through at 3 meters/minute they still had wet spots. In comparison, the same drying apparatus pair used in the hi-aspect ratio tests above dried the panels completely at 3 meters/minute conveyor speed.

To qualitatively test the amount of air venting from the entrance of the device vs. from the exit, a strip of paper was held vertically immediately before and behind the apparatus. Using this method, it was noted that a strong positive flow of air issued from the device entrance, but that a neutral if not

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slightly negative flow of air was issuing from the device exit. In other words, it appeared that air was actually being sucked into the exit side of the device, probably due to Bernoulli effects. From these observations, it is clear that the invention produces an exceptionally good countercurrent flow of air against the travelling substrate, which is also advantageous to efficient drying.

A summary of the drying comparison follows:

	Conveyor length m (feet)	Electrical Usage Kilowatt
Low aspect-ratio		
State-of-the art	1.02×10^{-1} (4)	10
Invention Apparatus	1.27×10^{-2} (0.5)	4
High aspect-ratio		
State-of-the art	1.4×10^{-1} (5.5)	>15
Invention Apparatus	1.27×10^{-2} (0.5)	4

As can be seen, all other things being equal, the invention is very economical in terms of both conveyor space and electrical usage. The fact that heated air is not needed is also a plus since this reduces the risk of oxidation of the copper traces on the circuit boards.

C L A I M S



1. Fluid treatment apparatus, comprising:

at least a first surface, of finite dimensions, including an entrance edge and an exit edge and characterized by an axis extending from said entrance edge to said exit edge;

means for transporting a substrate over said surface at a predetermined distance, H , from said surface, from said entrance edge to said exit edge along a direction which is substantially parallel to said axis, characterized in that

said apparatus further comprises at least a first row of at least two, spaced-apart fluid jet injectors, said first row being aligned transversely to said axis, said at least two fluid jet injectors penetrating said surface and serving to produce a first row of at least two fluid jets which impinge upon said substrate, each of said fluid jet injectors being characterized by a diameter, D , with the ratio H/D ranging from about 0.2 to about 15, and said first row of fluid jet injectors being positioned closer to said entrance edge than to said exit edge, whereby after said first row of fluid jets is impinged upon said substrate, more than half the fluid associated with said first row of fluid jets flows in a direction substantially opposite to the direction of transport of said substrate.

2. The fluid treatment apparatus of claim 1, wherein each of said fluid jets is characterized by a fluid speed, V , at said fluid jet injectors, and the fluid of said fluid jets is characterized by a kinematic viscosity, ν , and wherein a Reynolds number associated with each of said fluid jets, defined as the ratio $V \cdot D / \nu$, ranges from about 50 to about 30,000.

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3. The fluid treatment apparatus of claim 1 or 2, further comprising at least a second row of at least two, spaced-apart fluid jet injectors, said second row being aligned transversely to said axis, the fluid jet injectors of said second row also penetrating said surface and also serving to produce a second row of at least two fluid jets which impinge upon said substrate, said second row being positioned between said first row and said exit edge.
4. The fluid treatment apparatus of claim 3, wherein said second row of fluid jet injectors is positioned equidistantly between said entrance edge and said exit edge.
5. The fluid treatment apparatus of any one of claims 1 to 4, further comprising at least a first row of at least two, spaced-apart drain holes which penetrate said surface, said first row of drain holes being aligned transversely to said axis and being positioned between said entrance edge and said first row of fluid jet injectors.
6. The fluid treatment apparatus of claim 5, further comprising means for pumping fluid out of said first row of drain holes.
7. The fluid treatment apparatus of claim 5, further comprising at least a second row of at least two, spaced-apart drain holes, said second row of drain holes being aligned transversely to said axis and being positioned between said first row of fluid jet injectors and said exit edge.
8. Fluid treatment apparatus, comprising:

first and second spaced-apart surfaces, each having finite dimensions, defining a channel therebetween having

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an entrance, an exit and an axis extending from said entrance to said exit;

means for transporting a substrate through said channel, between said first and second surfaces, in a direction substantially parallel to said axis, from said entrance to said exit, characterized in that

said apparatus further comprises at least a first row of at least two, spaced-apart fluid jet injectors, said first row being aligned transversely to said axis, the fluid jet injectors of said first row penetrating said first surface and serving to produce a first row of at least two, spaced-apart fluid jets which impinge upon a lower surface of said substrate,

at least a second row of at least two, spaced-apart fluid jet injectors, said second row being aligned transversely to said axis, the fluid jet injectors of said second row penetrating said second surface and serving to produce a second row of at least two, spaced-apart fluid jets which impinge upon an upper surface of said substrate, said second row of fluid jet injectors being positioned relative to said first row of fluid jet injectors so that if said second row of fluid jet injectors were to be projected onto said first surface, the fluid jet injectors of said second row would be substantially interdigitated with the fluid jet injectors of said first row.

9. The fluid treatment apparatus of claim 8, wherein each of the fluid jet injectors of said first row is characterized by a first diameter, D_1 , and each of the fluid jet injectors of said second row is characterized by a second diameter, D_2 , and wherein said means serves to transport said substrate through said channel at a first distance, H_1 , from said first surface and at a second distance, H_2 , from said second surface, and wherein





- the ratio $H1/D1$ ranges from about 0.2 to about 15 and the ratio $H2/D2$ ranges from about 0.2 to about 15.
10. The fluid treatment apparatus of claim 9, wherein each of the fluid jets of said first row of fluid jets is characterized by a fluid speed, $V1$, at the first row of fluid jet injectors and each of the fluid jets of said second row of fluid jets is characterized by a fluid speed, $V2$, at the second row of fluid jet injectors, the fluid associated with each of the fluid jets of said first row of fluid jets is characterized by a kinematic viscosity, $\nu1$ and the fluid associated with each of the fluid jets of said second row of fluid jets is characterized by a kinematic viscosity, $\nu2$, and each of the fluid jets of said first row and said second row of fluid jets is characterized by a Reynolds number, defined as the ratio $V1 \cdot D1 / \nu1$ and $V2 \cdot D2 / \nu2$, respectively, which ranges from about 50 to about 30,000.
11. The fluid treatment apparatus of any one of claims 8 to 10, wherein each of said first and second rows of fluid jet injectors is positioned closer to said entrance than to said exit.
12. The fluid treatment apparatus of any one of claims 8 to 11, further comprising a third row of at least two, spaced-apart fluid jet injectors, said third row being aligned transversely to said axis, the fluid jet injectors of said third row penetrating said first surface and serving to produce a third row of at least two fluid jets which impinge upon a lower surface of said substrate, said third row of fluid jet injectors being positioned between said first row of fluid jet injectors and said exit.
13. The fluid treatment apparatus of claim 12, further comprising a fourth row of at least two, spaced-apart fluid jet injectors, said fourth row being aligned





transversely to said axis, the fluid jet injectors of said fourth row penetrating said second surface and serving to produce a fourth row of at least two fluid jets which impinge upon an upper surface of said substrate, said fourth row being positioned between said second row of fluid jet injectors and said exit, and said fourth row being positioned relative to said third row so that if the fluid jet injectors of said fourth row were to be projected onto said first surface, the fluid jet injectors of said fourth row would be substantially interdigitated with the fluid jet injectors of said third row.

14. Fluid treatment apparatus, according to any one of claims 8 to 13, further comprising:

a coordinate system including an x-axis which is parallel to said axis extending from the entrance to the exit, a y-axis which lies in a least-squares-fit planar approximation to said first surface and is perpendicular to said x-axis, and a z-axis which is perpendicular to both said x-axis and said y-axis; characterized in that

said second row of fluid jet injectors is positioned at a greater x-coordinate location than said first row of fluid jet injectors, and at least each of the fluid jet injectors of said second row of fluid jet injectors being inclined toward said entrance edge with each forming an angle with said z-axis, as measured in the counterclockwise direction in a plane defined by said z-axis and said x-axis, which angle is greater than 0 degrees but less than 90 degrees, whereby after said first row of fluid jets is impinged upon said substrate, more than half the fluid associated with said first row of fluid jets flows in a direction substantially opposite to the direction of transport of said substrate.





15. The fluid treatment apparatus of claim 14; wherein each of the fluid jet injectors of said second row of fluid jet injectors is also inclined toward said y-axis, each of the inclined fluid jet injectors forming an angle with said z-axis, as measured in the clockwise direction in a plane defined by said z-axis and said y-axis, which is greater than 0 degrees but less than 90 degrees.

16. A method for treating a substrate with a fluid, comprising the steps of:

transporting said substrate over a surface, of finite dimensions, including an entrance edge and an exit edge and characterized by an axis extending from said entrance edge to said exit edge, said transporting being carried out at a distance, H, from said surface, from said entrance edge to said exit edge, along a direction which is substantially parallel to said axis; and

impinging at least a first row of at least two fluid jets according to claim 1 or 2 upon said substrate.

17. The method of claim 16, further comprising the step of impinging at least a second row of at least two fluid jets upon said substrate, emanating from a second row of at least two, spaced-apart fluid jet injectors, said second row of fluid jet injectors being aligned transversely to said axis and penetrating said surface, and therefore said second row of fluid jets is aligned transversely to said axis, said second row of fluid jet injectors being positioned between said first row of fluid jet injectors and said exit edge and the areas of impingement of said second row of fluid jets upon said substrate being between the areas of impingement of said first row of fluid jets upon said substrate and said exit edge.





18. A method of treating a substrate with a fluid, comprising the steps of:

transporting a substrate between first and second spaced-apart surfaces, according to claim 8 and preferably having a coordinate system according to claim 14 or 15 and

impinging at least a first row of at least two fluid jets according to any one of claims 9 to 11 upon a lower surface of said substrate, said first row of fluid jets emanating from a first row of at least two fluid jet injectors which penetrate said first surface, and impinging at least a second row of at least two fluid jets according to any one of claims 9 to 11 upon an upper surface of said substrate, said second row of fluid jets emanating from a second row of at least two fluid jet injectors which penetrate said second surface, said second row of fluid jets being positioned relative to said first row of fluid jets so that if said second row of fluid jets were to be projected onto said first surface, said second row of fluid jets would be substantially interdigitated with said first row of fluid jets.

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