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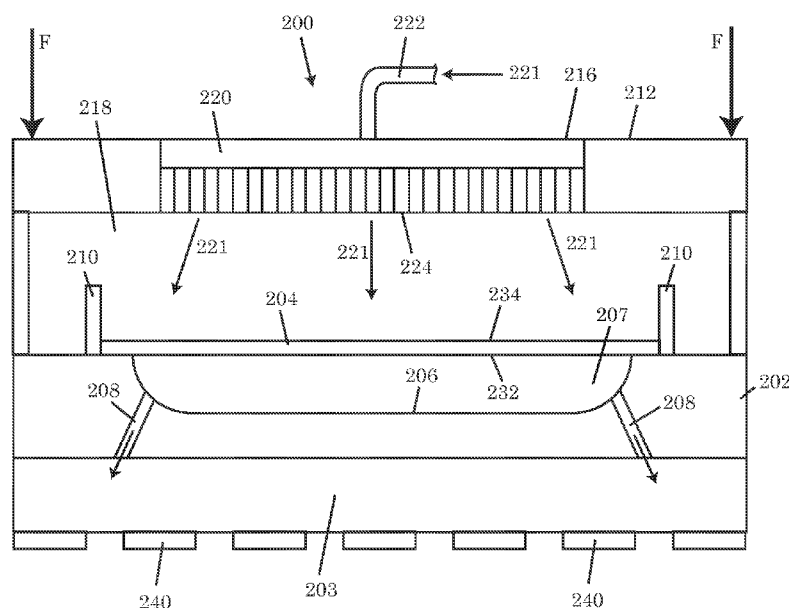
(54) **Title:** METHOD OF FORMING A 3D GLASS ARTICLE FROM A 2D GLASS SHEET

FIG. 2A

(57) **Abstract:** A method of forming a 3D glass article from a 2D glass sheet includes placing the 2D glass sheet on a mold having a mold surface with a 3D surface profile corresponding to that of the 3D glass article. The 2D glass sheet is heated to a first temperature selected from a temperature range corresponding to a glass viscosity of 10^7 Poise to 10^{11} Poise. A pressurized gas heated to a second temperature in the temperature range is applied to a first surface of the 2D glass sheet to conform the 2D glass sheet to the mold surface and form the 3D glass article.

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METHOD OF FORMING A 3D GLASS ARTICLE FROM A 2D GLASS SHEET

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Application Serial No. 61/447146 filed on February 28, 2011 and U.S. Provisional Application Serial No. 61/483095 filed on May 6, 2011 the content of which is relied upon and incorporated herein by reference in its entirety.

TECHNICAL FIELD

[0002] The present invention relates generally to a method of thermally reforming two-dimensional (2D) glass sheets into three-dimensional (3D) glass articles.

BACKGROUND

[0003] There is a large demand for 3D glass covers for portable electronic devices such as laptops, tablets, and smart phones. A particularly desirable 3D glass cover has a combination of a 2D surface, for interaction with a display, and a 3D surface, for wrapping around the edge of the display. The 3D surface may be an undevelopable surface, i.e., a surface that cannot be unfolded or unrolled onto a plane without distortion, and may include any combination of bends, corners, and curves. The bends may be tight and steep. The curves may be irregular. Such 3D glass covers are complex and difficult to make with precision.

[0004] Thermal reforming has been used to form 3D glass articles from 2D glass sheets. Thermal reforming involves heating a 2D glass sheet to a forming temperature and then reforming the 2D glass sheet into a 3D shape. Where the reforming is done by sagging or pressing the 2D glass sheet against a mold, it is desirable to keep the temperature of the glass below the

softening point of the glass to maintain a good glass surface quality and to avoid a reaction between the glass and the mold. Below the softening point, the glass has a high viscosity and requires a high pressure to be reformed into complex shapes such as bends, corners, and curves. In traditional glass thermal reforming a plunger is used to apply the needed high pressure. The plunger contacts the glass and presses the glass against the mold.

[0005] To achieve a 3D glass article with a uniform thickness, the gap between the plunger surface and the mold surface must be uniform while the plunger presses the glass against the mold. FIG. 1A shows an example of a uniform gap between a plunger surface 100 and a mold surface 102. However, it is usually the case that the gap between the plunger surface and the mold surface is not uniform due to small errors in mold machining and alignment errors between the mold and plunger. FIG. 1B shows a non-uniform gap (e.g., at 103) between the plunger surface 100 and mold surface 102 due to misalignment of the plunger with the mold. FIG. 1C shows a non-uniform gap (e.g., at 105) between the plunger surface 100 and mold surface 102 due to machining errors in the mold surface 102.

[0006] Non-uniform gaps result in over-pressing in some areas of the glass and under-pressing in other areas of the glass. Over-pressing will create glass thinning that will show up as a noticeable optical distortion in the 3D glass article. Under-pressing will create wrinkles in the 3D glass article, particularly at complex areas of the glass article including bends, corners, and curves. Small machining errors, e.g., on the order of 10 microns, can result in non-uniform gaps that would produce over-pressing and/or under-pressing. Unavoidable thermal expansion of the plunger surface, mold surface, glass, or other equipment involved in the forming can also affect uniformity of the gap.

[0007] During pressing, the plunger also stretches the glass so that the thickness of the glass between the plunger surface and mold surface changes. Therefore, even if the gap between the plunger surface and the mold surface are perfect, the stretching of the glass would result in a 3D glass article having a non-uniform thickness. The mold surface or the plunger surface may be designed to compensate for the expected change in glass thickness as a result of stretching. However, this will result in a non-uniform gap between the plunger surface and mold surface, which as noted above will result in over-pressing in some areas of the glass and under-pressing in other areas of the glass.

SUMMARY

[0008] In one aspect of the present invention, a method of forming a 3D glass article from a 2D glass sheet comprises placing the 2D glass sheet on a mold having a mold surface with a 3D surface profile corresponding to that of the 3D glass article, heating the 2D glass sheet to a first temperature in a temperature range corresponding to a glass viscosity of 10^7 Poise to 10^{11} Poise, and applying a pressurized gas heated to a second temperature in the temperature range to a first surface of the 2D glass sheet to conform the 2D glass sheet to the mold surface and form the 3D glass article.

[0009] In one embodiment, the method further includes applying vacuum to a second surface of the 2D glass sheet to conform the 2D glass sheet to the mold surface prior to or simultaneously with at least a portion of the applying the pressurized gas step.

[0010] In one embodiment, the method further includes providing the mold and applying a contour correction to the mold surface to compensate for a potential error in forming a portion of the 3D glass article.

[0011] In one embodiment, the pressurized gas is uniformly applied to the first surface of the 2D glass sheet in the applying the pressurized gas step.

[0012] In another embodiment, the pressurized gas is differentially applied to the first surface of the 2D glass sheet in the applying the pressurized gas step.

[0013] In one embodiment, the method further comprises applying a burst of pressurized gas at a third temperature greater than the first temperature to a selected area of the 2D glass sheet during the applying the pressurized gas step.

[0014] In one embodiment, a pressure of the pressurized gas is in a range from 10 psi to 20 psi.

[0015] In one embodiment, the pressurized gas is applied through a sealed pressure chamber and a sealing pressure of the sealed pressure chamber is selected to be greater than a pressure of the pressurized gas or the pressurized gas is applied through a non-sealed pressure chamber in the applying the pressurized gas step.

[0016] In one embodiment, the 2D glass sheet is preferentially heated on the mold so that a temperature of the mold is lower than the first temperature in the heating the 2D glass sheet step.

[0017] In one embodiment, in the heating the 2D glass sheet step, the mold surface has a 2D area and a 3D area and the 2D glass sheet is preferentially heated on the mold such that a temperature of a first portion of the 2D glass sheet corresponding to the 2D area of the mold is at the first temperature, a temperature of a second portion of the 2D glass sheet corresponding to the 3D area of the mold is higher than the

first temperature, and a temperature of the mold is lower than the first temperature.

[0018] In one embodiment, the method further comprises applying vacuum to a second surface of the 2D glass sheet to partially conform the 2D glass sheet to the mold surface prior to the applying the pressurized gas step.

[0019] In one embodiment, the method further includes cooling the 3D glass article by applying a pressurized gas to the 3D glass article at a fourth temperature lower than the second temperature.

[0020] In one embodiment, during the cooling the 3D glass article step, the fourth temperature is adjusted to match a temperature of the mold.

[0021] In another embodiment, the method further includes cooling the 3D glass article and at least one of machining the 3D glass article to a final dimension, annealing the 3D glass article, and strengthening the 3D glass article by ion-exchange.

[0022] In another aspect of the present invention, an apparatus for forming a 3D glass article from a 2D glass sheet comprises a mold capable of supporting the 2D glass sheet, the mold having a mold surface with a 3D surface profile corresponding to that of the 3D glass article, means for directing a pressurized gas towards the mold surface, and means for providing heat in a vicinity of the mold.

[0023] In one embodiment, the mold surface defines a mold cavity and the mold includes one or more ports for applying vacuum to or exhausting gas from the mold cavity.

[0024] In one embodiment, the means for directing a pressurized gas comprises a bonnet having a plenum. The plenum

has a plenum chamber for receiving the pressurized gas and a gas grille mounted adjacent to the plenum chamber for directing the pressurized gas in the plenum chamber towards the mold surface.

[0025] In one embodiment, the gas grille is configured and positioned to distribute the pressurized gas uniformly across the mold surface.

[0026] In one embodiment, the gas grille is configured and positioned to distribute the pressurized gas differentially across the mold surface.

[0027] In one embodiment, the means of directing a pressurized gas further includes a sealable pressure chamber between the bonnet and the mold.

[0028] It is to be understood that both the foregoing general description and the following detailed description are exemplary of the invention and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention and are incorporated in and constitute a part of this specification. The drawings illustrate various embodiments of the invention and together with the description serve to explain the principles and operation of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0029] The following is a description of the figures in the accompanying drawings. The figures are not necessarily to scale, and certain features and certain views of the figures may be shown exaggerated in scale or in schematic in the interest of clarity and conciseness.

[0030] FIG. 1A is a schematic of a uniform gap between a plunger and mold.

[0031] FIG. 1B is a schematic of a non-uniform gap between a plunger and mold.

[0032] FIG. 1C is a schematic of a non-uniform gap between a plunger and mold.

[0033] FIG. 2A is a cross-section of an apparatus for forming a 3D glass article from a 2D glass sheet.

[0034] FIG. 2B is a cross-section of an apparatus for forming a 3D glass article from a 2D glass sheet.

[0035] FIG. 2C is a cross-section of an apparatus for forming a 3D glass article from a 2D glass sheet.

[0036] FIG. 3A is a perspective view of a 3D glass article formed from an oversized 2D glass sheet.

[0037] FIG. 3B is a perspective view of a 3D glass article formed from a machined 2D preform.

[0038] FIG. 4 is a schematic of a continuous system for forming 3D glass articles from 2D glass sheets.

DETAILED DESCRIPTION

[0039] Additional features and advantages of the invention will be set forth in the detailed description that follows and, in part, will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein.

[0040] The present invention involves forming a 3D glass article from a 2D glass sheet using hot pressurized gas. The hot pressurized gas is used to apply pressure to the 2D glass sheet in order to fully conform the 2D glass sheet to a 3D surface of a mold, thereby forming the 3D glass article. The hot pressurized gas may be applied uniformly to the glass or may be applied differentially, e.g., only or in greater concentration to areas of the glass needing high forming pressure, such as areas of the glass that will include bends, corners, and curves. In general, the process of forming the 3D glass article includes placing the 2D glass sheet on a mold, preheating the 2D glass sheet and mold

to a temperature where the glass viscosity is between 10^7 Poise and 10^{11} Poise, applying vacuum to partially form the 3D shape and seal the glass to the mold, applying hot pressurized gas to complete the 3D shape forming, and cooling the glass while controlling thermal gradients in the glass to minimize distortions in the glass.

[0041] FIG. 2A shows an apparatus 200 for forming a 3D glass article from a 2D glass sheet 204 according to the process described above. The apparatus 200 includes a mold 202 having a mold surface 206. The mold surface 206 has a 3D surface profile that corresponds to the 3D shape of the 3D glass article to be formed. The mold surface 206 is concave and defines a mold cavity 207. The 2D glass sheet 204 is placed on the mold 202 in a position to sag into the mold cavity 207 or against the mold surface 206. Ports or holes 208 are provided in the mold 202. The ports 208 run from the exterior of the mold 202 to the mold surface 206. In one embodiment, the ports 208 are located at the corners of the mold surface 206. In alternate embodiments, the ports 208 may be located at the corners and bottom of the mold surface 206 or just at the bottom of the mold surface 206. An advantage of locating the ports 208 at only the corners of the mold surface 206 will be described later. The ports 208 may serve as vacuum ports, to apply vacuum to the mold cavity 207, or exhaust ports, to withdraw gas trapped in the mold cavity 207. Alignment pins 210 may be provided on the mold 202 to assist in aligning the 2D glass sheet 204 with the mold cavity 207.

[0042] The mold 202 is made of a material that can withstand high temperatures, such as would be encountered while forming the 3D glass article from the 2D glass sheet. The mold material may be one that will not react with (or not stick to) the glass under the forming conditions, or the mold surface 206 may be coated with a coating material that will not react with (or not stick to) the glass under the forming conditions. In one embodiment, the mold 202 is made of a non-reactive carbon material, such as

graphite, and the mold surface 206 is highly polished to avoid introducing defects into the glass when the mold surface 206 is in contact with the glass. In another embodiment, the mold 202 is made of a dense ceramic material, such as silicon carbide, tungsten carbide, and silicon nitride, and the mold surface 206 is coated with a non-reactive carbon material, such as graphite. In another embodiment, the mold 202 is made of a superalloy, such as Inconel 718, a nickel-chromium alloy, and the mold surface 206 is coated with a hard ceramic material, such as titanium aluminum nitride. In one embodiment, the mold surface 206, with or without a coating material, has a surface roughness of $R_a < 10$ nm. Use of a carbon material for the mold 202 or use of a carbon coating material for the mold surface 206 will require that the forming of the 3D glass article is carried out in an inert atmosphere.

[0043] A bonnet 212 is mounted on top of the mold 202. The bonnet 212 has a plenum 216. When the bonnet 212 is mounted on the top of the mold 202 as shown, a pressure chamber 218 is formed between the mold 202 and plenum 216. The plenum 216 includes a plenum chamber 220, which is connected via a conduit 222 to a source of hot pressurized gas 221 (the source is not shown). The gas is preferably an inert gas, such as nitrogen. The plenum 216 includes a gas grille 224, which is mounted below the plenum chamber 220 and positioned above the mold 202. The gas grille 224 is a perforated plate and includes holes through which gas in the plenum chamber 220 can be directed into the pressure chamber 218 and towards the mold surface 206. The bonnet 212 and gas grille 224 should be made of materials that would not generate contaminants under the conditions in which the 2D glass sheet 204 will be reformed into a 3D glass article. The bonnet 212 and gas grille 224 may be made of the same materials as the mold 202, except that it would not be necessary for the surfaces of the bonnet 212 and gas grille 224 to be highly polished since the glass sheet will not come into contact with the surfaces of the bonnet 212 and gas grille 224 during reforming of the glass sheet.

[0044] In one embodiment, the pressure chamber 218 between the bonnet 212 and the mold 202 is sealed before delivering hot pressurized gas 221 into the pressure chamber 218 through the plenum 216. The pressure chamber 218 may be sealed by applying a force F to the bonnet 212 so that the bonnet 212 clamps down on the top of the mold 202. A ram, or other device capable of applying a force, may be used for this purpose. To maintain the pressure chamber 218 in a sealed condition, the sealing pressure due to application of the force F should be greater than the pressure of the hot pressurized gas 221 delivered into the pressure chamber 218.

[0045] In FIG. 2A, the gas grille 224 occupies the entire bottom of the plenum chamber 220 and directs hot pressurized gas across the entire top surface 234 of the 2D glass sheet 204 on the mold 202. If the distribution and sizes of the holes in the gas grille 224 are uniform, the hot pressurized gas 221 will be directed substantially uniformly across the entire surface of the 2D glass sheet 204. FIG. 2B shows an alternative arrangement where a gas grille 228 is located at an edge of a plenum chamber 230 and allows for differential application of the hot pressurized gas 221 to the top surface 234 of the 2D glass sheet 204. The gas grille 228 may be annular in shape. Alternatively, a plurality of gas grilles arranged along the edge of the plenum chamber 230 may be used. In the arrangement shown in FIG. 2B, the gas grille 228 will direct hot pressurized gas to the periphery of the 2D glass sheet 204. This periphery may be where high forming pressure is needed, e.g., where bends, corners, or curves will be formed. In general, where the gas grille is located on the plenum will determine the focus of the hot pressurized gas delivered through the gas grille, and the location of the gas grille as well as the size and spacing of the holes in the gas grille may be tailored to the 3D shape to be formed using the mold surface 206. A gas grille such as shown in FIG. 2B that directs hot pressurized gas to a selected area of a 2D glass

sheet on a mold or that directs hot pressurized gas differentially across a 2D glass sheet on a mold may be referred to as a directional gas grille.

[0046] In one embodiment, the pressure chamber 218 is not sealed prior to delivering hot pressurized gas 221 into the pressure chamber 218. A directional gas grille, such as gas grille 208 in FIG. 2B, is positioned within a small distance from the 2D glass sheet 204. This small distance is preferably less than 5 mm. The small distance allows for a directional jet applied through the directional gas grille to be confined to the desired area of the 2D glass sheet 204 requiring high pressure forming. The high velocity of the directional jet is used to create point or line pressure in the desired area of the 2D glass sheet. Because the pressure chamber 218 is not sealed in this case, the equilibrium pressure in the pressure chamber 218 is not established. Thus, only the desired area of the 2D glass sheet 204 will receive the high velocity gas jet pressure.

[0047] The mold 202 is placed on a vacuum chuck 203 in one embodiment, as illustrated in FIG. 2A. One or more heaters 240 are arranged below the vacuum chuck 203 to heat the mold 202 and the 2D glass sheet 204 placed on the mold 202. If the vacuum chuck 203 is not used, the one or more heaters 240 may simply be arranged below the mold 202. In another embodiment, one or more heaters may be arranged in the pressure chamber 218 to heat the mold 202 and the 2D glass sheet 204. The heaters in the pressure chamber 218 may be in addition to or in lieu of the heaters 240 arranged below the mold 202 or vacuum chuck 203. The heaters could be mid-infrared (mid-IR) heaters, such as Hereaus Noblelight mid-IR heaters. Mid-IR heaters can be used to preferentially heat the 2D glass sheet 204 on the mold 202 such that the mold 202 is at a lower temperature compared to the glass, e.g., 100°C to 200°C lower, prior to and while reforming the 2D glass sheet 204 into the 3D glass article. Other types of

heaters besides mid-IR heaters, such as resistive-type heaters, may also be used.

[0048] In one embodiment, the 2D glass sheet 204 is thin, e.g., has a thickness in a range from 0.3 mm to 1.5 mm. In one embodiment, the 2D glass sheet 204 is an ion-exchangeable glass. Ion-exchangeable glasses are alkali-containing glasses with small alkali ions, such as Li^+ , Na^+ , or both. These small alkali ions can be exchanged for larger alkali ions, such as K^+ , during an ion-exchange process. Examples of suitable ion-exchangeable alkali-containing glasses are alkali-aluminosilicate glasses. Examples of these glasses are described in U.S. Patent No. 7,666,511 (Ellison et al.; 23 February 2010) and U.S. Patent Application Publication Nos. US 2009/0142568 A1 (Dejneka et al.; 4 June 2009), US 2009/0215607 (Dejneka et al.; 27 August 2009), US 2009/0220761 (Dejneka et al.; 3 September 2009), and US 2010/0035038 A1 (Barefoot et al.; 11 February 2010). These alkali-aluminosilicate glasses can be ion-exchanged at relatively low temperatures and to a depth of at least 30 microns. An example of a suitable ion-exchangeable glass is GORILLA glass, which is available from Corning Incorporated, NY, under code 2317. A process for strengthening glass by ion-exchange is described in, for example, U.S. Patent No. 5,674,790 (Araujo; 7 October 1997).

[0049] To form the 3D glass article, the 2D glass sheet 204 is placed on the mold 202 as shown in FIG. 2A. The alignment pins 210 may be used to precisely locate the 2D glass sheet 204 on the mold 202. After placing the 2D glass sheet 204 on the mold 202, the 2D glass sheet 204 and mold 202 are heated. In one embodiment, at least the 2D glass sheet 204 is heated to a forming temperature in a temperature range corresponding to a glass viscosity range of 10^7 Poise to 10^{11} Poise. In one embodiment, the 2D glass sheet 204 and mold 202 are heated such that they are both at the same temperature by the time the forming of the 2D glass sheet 204 into the 3D glass article

starts. For this type of heating, the mold 202 may be made of a non-reactive carbon material such as graphite or of a dense ceramic material coated with a carbon coating material. The heating would need to take place in an inert atmosphere. In another embodiment, the 2D glass sheet 204 is preferentially heated while on the mold 202 so that the temperature of the mold 202 is lower than that of the 2D glass sheet 204, e.g., the temperature of the mold 202 may be 100°C to 200°C lower than the temperature of the 2D glass sheet 204. A mid-IR heater may be used for this preferential heating. For this preferential heating, the mold 202 may be made of a superalloy with a hard ceramic coating. With this material, the preferential heating can take place in a non-inert atmosphere.

[0050] After heating the 2D glass sheet 204 and mold 202, vacuum is applied to the mold cavity 207 to draw the bottom surface 232 of the 2D glass sheet against the mold surface 206 and seal the glass to the mold surface 202. Before vacuum is applied, the 2D glass sheet 204 may already have started sagging against the mold surface 206 due to gravity. The vacuum applied may be in a range of 2 to 10 in-Hg in one embodiment. Hot pressurized gas 221 is applied to the top surface 234 of the partially-shaped 2D glass sheet 204 through the plenum 216 and pressure chamber 218. The hot pressurized gas 221 provides the pressure needed to fully conform the 2D glass sheet 204 to the mold surface 206, thereby completely forming the 3D glass article. The temperature of the hot pressurized gas is in the previously mentioned temperature range corresponding to a glass viscosity range of 10^7 Poise to 10^{11} Poise. The temperature of the hot pressurized gas may be the same as or may be different from the temperature of the 2D glass sheet. In one embodiment, the temperature of the hot pressurized gas is within 80°C of the temperature of the 2D glass sheet. The temperature of the hot pressurized gas may be the same as, or higher than or lower than the temperature of the 2D glass sheet. Bursts of hot pressurized gas at a temperature higher than the temperature of the 2D glass

sheet may be selectively applied to the 2D glass sheet, as will be further explained below. The gas grille 224 may be designed such that the bursts of hot pressurized gas are directionally applied, i.e., only to areas of the 2D glass sheet where the bursts are needed. FIG. 2C shows a 3D glass article 205 formed from the 2D glass sheet 204 by pressure from the hot pressurized gas. Typical gas pressure required to form a 3D shape is comparable to plunger pressure used in contact forming. Depending on the 3D shape to be formed and the glass viscosity, this pressure may be in the range of 10 psi to 20 psi. For example, forming a dish shape having bends with radiuses less than 5 mm from a 1.0-mm thick glass at a glass viscosity of approximately 10^9 Poise would require about 20 psi.

[0051] Prior to applying the hot pressurized gas 221 to the 2D glass sheet 204, the pressure chamber 218 may be sealed, as already described above. The pressure chamber 218 may be sealed before, during, or after heating the 2D glass sheet 204 if the 2D glass sheet 204 is heated by conduction and radiation from the mold 202. Alternatively, if the pressure chamber 218 is to be sealed, the pressure chamber 218 should be sealed after heating the 2D glass sheet 204 if the 2D glass sheet 204 is heated directly on the mold 202 using radiative heaters. The vacuum can be applied to the mold cavity 207 a few seconds before the hot pressurized gas 221 is applied to the glass sheet. The vacuum can be maintained partially or through the entire duration of applying the hot pressurized gas 221 to the glass sheet, in which case the vacuum can help maintain the position of the glass sheet on the mold surface 206 so that the glass sheet does not move when the hot pressurized gas 221 is being applied. If the starting 2D glass sheet 204 is larger than the mold cavity 207 so that it covers the mold cavity 207, then the 2D glass sheet may be formed into the 3D glass article without use of vacuum. While forming with or without vacuum, the ports 208 in the mold 202 are used to exhaust gas trapped in the mold cavity 207.

[0052] After forming the 3D glass article 205, the flow of hot pressurized gas 221 to the pressure chamber 218 is stopped or replaced with flow of colder pressurized gas. Then, the 3D glass article 205 is cooled to below the strain point of the glass using or not using colder pressurized gas. The colder pressurized gas may assist in more rapid cooling of the 3D glass article 205. In one embodiment, when the colder pressurized gas is used in cooling the 3D glass article 205, the temperature of the colder pressurized gas is selected from a temperature range corresponding to the glass transition temperature plus or minus 10°C. In another embodiment, when the colder pressurized gas is used in cooling the 3D glass article 205, the temperature of the colder pressurized gas is adjusted to match the temperature of the mold 202 during the cooling. This may be achieved by monitoring the temperature of the mold 202 with sensors such as thermocouples and using the output of the sensors to adjust the temperature of the colder pressurized gas. The pressure of the colder pressurized gas may be less than or the same as the pressure of the hot pressurized gas. The cooling of the 3D glass article is such that the temperature difference (ΔT) across the thickness of the glass article, along the length of the glass article, and along width of the glass article is minimized. Preferably, ΔT is less than 10°C across the thickness of the glass article and along the length and width of the glass article. The lower the ΔT during cooling, the lower the stress in the glass article. If high stress is generated in the glass article during cooling, the glass article will warp in response to stress. As such, it is desirable to avoid generating high stress in the glass article during cooling. The 3D glass article 205 can be cooled convectively by applying controlled-temperature gas flow on both sides of the 3D glass article 205. Colder pressurized gas, as described above, can be applied to the top surface 236 of the 3D glass article 205 through the plenum 216 and pressure chamber 218, and controlled-temperature gas flow, which may have similar characteristics to the colder pressurized gas, can be applied to the bottom surface 238 of the

3D glass article 205 through the ports 208 in the mold 202. The pressure of the gas supplied through the ports 208 may be such that a net force is created that lifts the 3D glass article 205 from the mold 202 during the cooling. The mold 202 cools at a much slower rate than the glass due to the mold 202 having a larger thermal mass than the glass. This slow cooling of the mold 202 can generate a large ΔT across the thickness of the glass. Lifting the glass from the mold 202 during the cooling helps avoid this large ΔT .

[0053] Cooling may be followed by annealing of the 3D glass article 205, and annealing of the 3D glass article 205 may be followed by an ion-exchange process involving the 3D glass article 205. The 2D glass sheet 204 used in forming the 3D glass article may be an oversized sheet that will be machined to final dimensions after being formed into the 3D glass article 205. In this case, the machining can be carried out prior to the ion-exchange process. FIG. 3A shows an example of a 3D glass article 300 formed from an oversized glass sheet 302. The 3D glass article 300 would need to be extracted from the oversized sheet and then edge-finished by suitable machining processes. Alternatively, the 2D glass sheet 204 may be a machined 2D preform that needs to be precisely aligned on the mold 202 and that will not be machined after being formed into the 3D glass article. The machined preform will have been edge-contoured and edge-finished to the precise shape and size needed for forming the 3D glass article. FIG. 3B shows an example of a 3D glass article 304 formed from a machined preform. The 3D glass article 304 does not require additional edge-finishing.

[0054] Gentle contours can be formed at high glass viscosities, e.g., 10^9 Poise to 10^{11} Poise, while tight bends and sharp corners require much lower viscosities, e.g., between 10^7 Poise and $10^{8.2}$ Poise. The lower viscosities allow the glass to better conform to the mold. However, it is challenging to achieve good glass surface cosmetics at low viscosities because it is

easier to imprint defects on the glass surface. Forming at low viscosities can cause glass reboil, which generates orange peel. The vacuum or exhaust ports in the mold surface are easily imprinted in the glass at lower glass viscosities. On the other hand, it is easier to achieve good surface cosmetics high glass viscosities. Thus, to achieve both good glass surface cosmetics and tight dimensional tolerances in the 3D glass article, the pressure applied to the glass by the hot pressurized gas, the glass viscosity, and the location at which the pressure of the hot pressurized gas is applied to the glass will have to be optimized. There are several options for obtaining tight dimensional tolerances while maintaining good glass surface cosmetics.

[0055] One option is to use contour correction in the mold. For example, for forming 3D shapes with tight bends, the mold can be designed with walls at a tighter bend radius and steeper sidewall tangent angle than the final shape. For example, if the sidewall tangent angle of a dish to be formed is 60° , and if it is desired to form the dish at log viscosity of 9.5P to maintain good glass surface cosmetics, then the forming process may produce a dish with sidewall tangent angle of 46° , i.e. 14° less than the desired angle, if the mold contour is not corrected. To increase the sidewall tangent angle, without lowering glass viscosity, the mold contour can be compensated to increase the sidewall tangent angle by the difference between the ideal shape and the measured angle on the formed article. In the above example, the compensated mold would have a sidewall tangent angle of 74° . It is possible to do this contour correction and achieve a glass article with uniform thickness because there is no gap between a plunger and mold to worry about, since the pressure needed to form the shape is being provided by hot pressurized gas.

[0056] Another option is to use a high degree of polish on the mold that would allow for lowering the glass viscosity without

creating defects on the glass surface. The mold surface can be made to have a surface roughness of $R_a < 10\text{nm}$ and can be made to be non-sticky or non-reactive. For example, a glassy graphite coating may be used on the mold surface. Also, the vacuum or exhaust ports (218 in FIG. 2A) can be placed in the corner of the mold only, i.e., at the location where glass would touch the mold last during the pressure forming.

[0057] Another option is to use a directional plenum, such as shown in FIG. 2B, where the pressure of hot gas is directed towards complex areas, e.g., areas including bends or corners, of the glass. Pressurized gas burst at temperatures of 20°C to 50°C greater than the temperature of the glass can be applied as a directional puff to preferentially raise the glass temperature and lower the glass viscosity in the complex areas.

[0058] Another option is to use a cold mold/hot glass arrangement, where the mold is 100°C to 200°C cooler than the glass being formed.

[0059] Yet another option is to use small heaters above a 3D area (i.e., the area to be formed into a 3D shape including any combination of bends, corners, and curves) of the glass sheet. For example, the glass in the 3D area may be heated $10\text{--}30^\circ\text{C}$ higher than the glass in the 2D area (i.e., the remaining area that will not be formed into a 3D shape) of the glass sheet. This can be combined with use of directional jets as described above.

[0060] Another option is to have heaters in the mold to heat a 3D area (i.e., the area to be used in forming the 3D area of the glass sheet) of the mold to a temperature higher than that of a 2D area of the mold. The 3D area of the mold may be heated to a temperature of $10\text{--}30^\circ\text{C}$ more than the temperature of the 2D area (or flat area) of the mold. This can be combined with use of directional jets as described above.

[0061] Another option is to have radiant heaters above and near the 3D area of the glass sheet to apply radiant heating to the 3D area of the glass sheet, thus preferentially softening the small area of the glass sheet that needs to be made into a 3D shape while maintaining the 2D area of the glass sheet relatively colder. Keeping the 2D area colder than the 3D area allows for maintaining the pristine surface finish in the 2D area.

[0062] FIG. 4 shows a continuous system 400 for forming 3D glass articles from 2D glass sheets. The system 400 includes a forming station 402. The forming station 402 includes the apparatus 200 (in FIG. 2A-2C). The system 400 includes a preheating station 404 upstream of the forming station 402. Molds 202 carrying 2D glass sheets 204 are preheated at the preheating station 404. The molds 202 are transported along the preheating station 404 to the forming station 402 on a conveyor 406. The preheating station 404 includes heaters 408 for heating the 2D glass sheets 204 carried by the molds 202. The heaters 408 may be mid-IR heaters, as described above, or other types of heaters capable of delivering heat to the 2D glass sheets and mold 202. The system 400 includes a cooling station 410 downstream of the forming station 402. 3D glass articles 205 formed at the forming station 402 are carried to the cooling station 410 and allowed to cool down to a temperature at which they can be removed from the mold without distortion of the shape (i.e., glass temperature is below the transition temperature of the glass). Active cooling can be applied to the molds in cooling station 410 so that the molds are cooled from the bottom by a heat transfer fluid or gas, allowing the mold temperature to match the air temperature above the glass to minimize the delta T across the glass thickness. Initial cooling of the 3D glass articles 205 may also occur at the forming station 402. The molds 202 are transported along the cooling station 410 on a conveyor 412. The system 400 may also include an annealing station 414 downstream of the cooling station 410. The annealing station 414 may include a hot air bearing 416, and the 3D glass articles may be annealed by

floating on the hot air bearing 416. Pick-up devices are used to pick up the 3D glass articles 205 from the molds 202 and place the 3D glass articles 205 on the hot air bearing 416.

[0063] While the invention has been described with respect to a limited number of embodiments, those skilled in the art, having benefit of this disclosure, will appreciate that other embodiments can be devised which do not depart from the scope of the invention as disclosed herein. Accordingly, the scope of the invention should be limited only by the attached claims.

CLAIMS

1. A method of forming a 3D glass article from a 2D glass sheet, comprising:
 - (a) placing the 2D glass sheet on a mold having a mold surface with a 3D surface profile corresponding to that of the 3D glass article;
 - (b) heating the 2D glass sheet to a first temperature in a temperature range corresponding to a glass viscosity of 10^7 Poise to 10^{11} Poise; and
 - (c) applying a pressurized gas heated to a second temperature in the temperature range to a first surface of the 2D glass sheet to conform the 2D glass sheet to the mold surface and form the 3D glass article.
2. A method according to claim 1, further comprising:
 - (d) applying vacuum to a second surface of the 2D glass sheet to conform the 2D glass sheet to the mold surface prior to step (c) or simultaneously with at least a portion of step (c).
3. A method according to claim 1, further comprising:
 - (e) providing the mold; and
 - (f) applying a contour correction to the mold surface to compensate for a potential error in forming a portion of the 3D glass article.
4. A method according to claim 1, wherein in step (c), the pressurized gas is uniformly applied to the first surface of the 2D glass sheet.
5. A method according to claim 1, wherein in step (c), the pressurized gas is differentially applied to the first surface of the 2D glass sheet.

6. A method according to claim 1, further comprising:
 - (g) applying a burst of pressurized gas at a third temperature greater than the first temperature to a selected area of the 2D glass sheet during step (c).
7. A method according to claim 1, wherein a pressure of the pressurized gas is in a range from 10 psi to 20 psi.
8. A method according to claim 1, wherein in step (c), the pressurized gas is applied through a sealed pressure chamber and a sealing pressure of the sealed pressure chamber is selected to be greater than a pressure of the pressurized gas or the pressurized gas is applied through a non-sealed pressure chamber.
9. A method according to claim 1, wherein in step (b), the 2D glass sheet is preferentially heated on the mold so that a temperature of the mold is lower than the first temperature.
10. A method according to claim 1, wherein in step (b), the mold surface has a 2D area and a 3D area and the 2D glass sheet is preferentially heated on the mold such that (i) a temperature of a first portion of the 2D glass sheet corresponding to the 2D area of the mold is at the first temperature, (ii) a temperature of a second portion of the 2D glass sheet corresponding to the 3D area of the mold surface is higher than the first temperature, and (iii) a temperature of the mold is lower than the first temperature.
11. A method according to claim 10, further comprising:
 - (h) applying vacuum to a second surface of the 2D glass sheet to partially conform the 2D glass sheet to the mold surface prior to step (c).
12. A method according to claim 1, further comprising:
 - (i) cooling the 3D glass article by applying a pressurized gas to the 3D glass article at a fourth temperature lower than the second temperature.

13. A method according to claim 12, wherein during step (h), the fourth temperature is adjusted to match a temperature of the mold.
14. A method according to claim 1, further comprising:
 - (j) cooling the 3D glass article; and
 - (k) at least one of machining the 3D glass article to a final dimension, annealing the 3D glass article, and strengthening the 3D glass article by ion-exchange.
15. An apparatus for forming a 3D glass article from a 2D glass sheet, comprising:
a mold capable of supporting the 2D glass sheet, the mold having a mold surface with a 3D surface profile corresponding to that of the 3D glass article;
means for directing a pressurized gas towards the mold surface; and
means for providing heat in a vicinity of the mold.
16. The apparatus of claim 15, wherein the mold surface defines a mold cavity, and wherein the mold comprises one or more ports for applying vacuum to or exhausting gas from the mold cavity.
17. The apparatus of claim 15, wherein the means for directing a pressurized gas comprises a bonnet having a plenum, the plenum having a plenum chamber for receiving the pressurized gas and a gas grille mounted adjacent to the plenum chamber for directing the pressurized gas in the plenum chamber towards the mold surface.
18. The apparatus of claim 17, wherein the gas grille is configured and positioned to distribute the pressurized gas uniformly across the mold surface.

19. The apparatus of claim 17, wherein the gas grille is configured and positioned to distribute the pressurized gas differentially across the mold surface.
20. The apparatus of claim 17, wherein the means for directing a pressurized gas further comprises a sealable pressure chamber between the bonnet and the mold.

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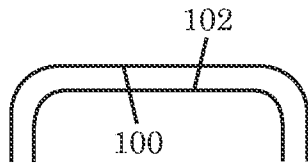


FIG. 1A

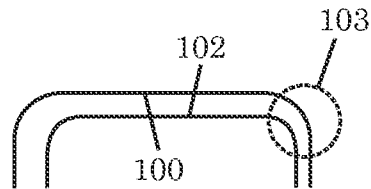


FIG. 1B

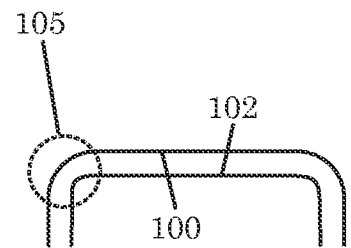


FIG. 1C

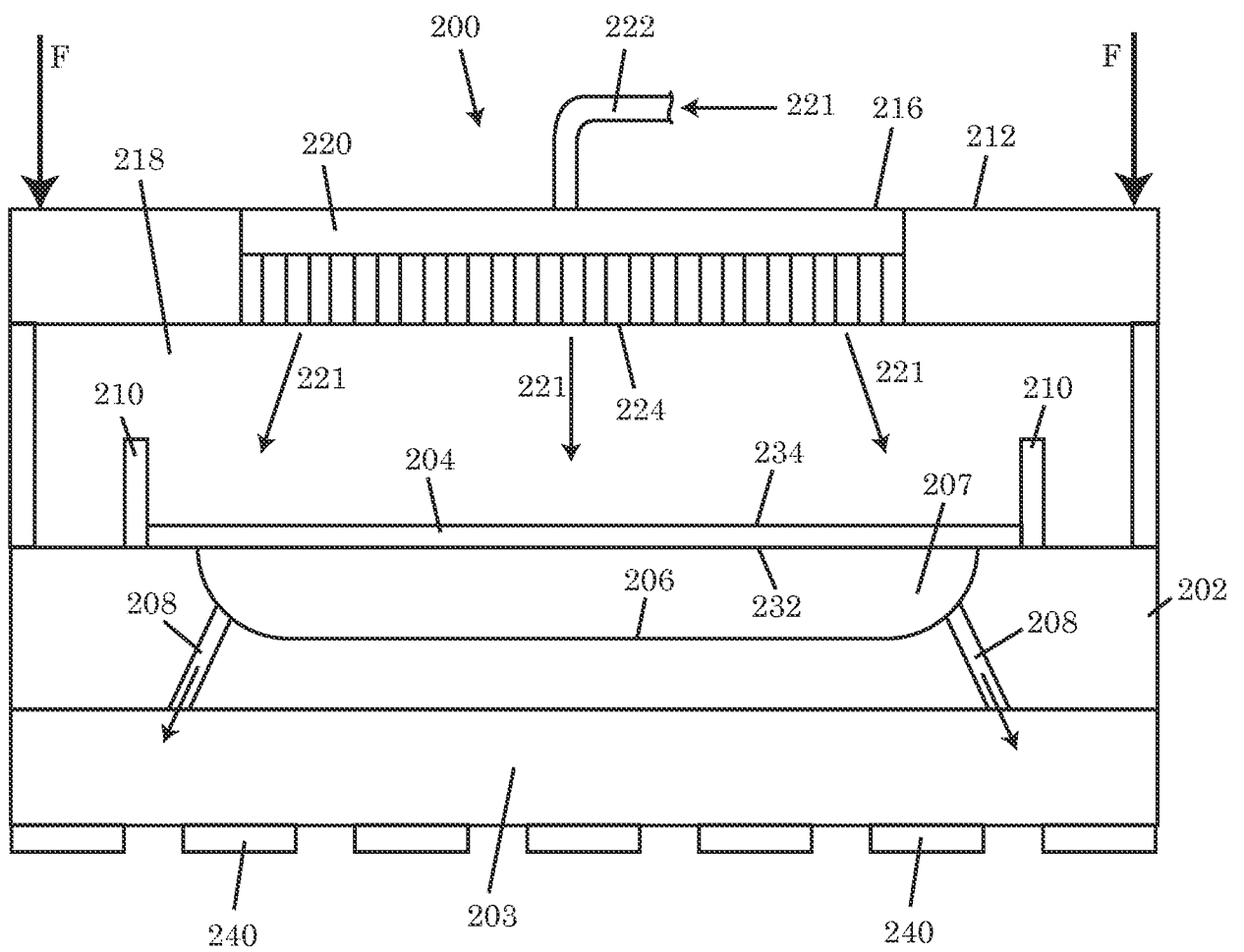


FIG. 2A

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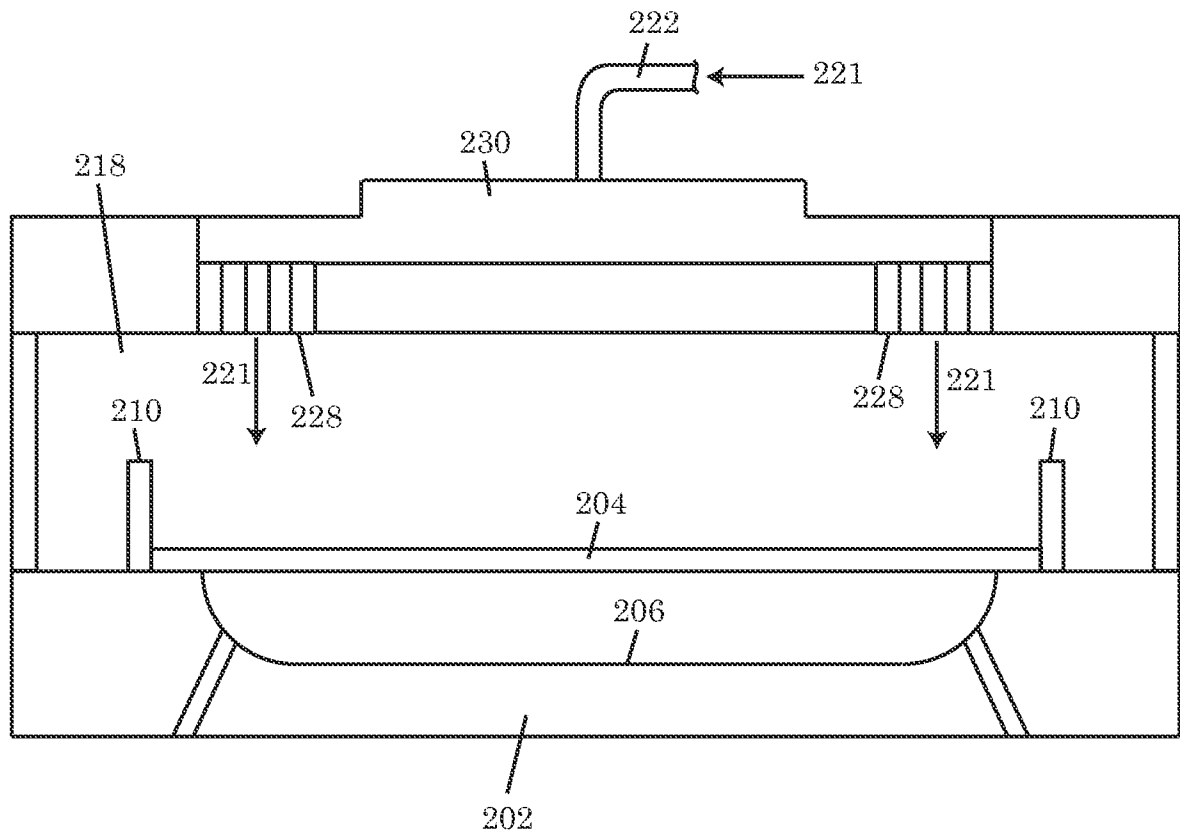


FIG. 2B

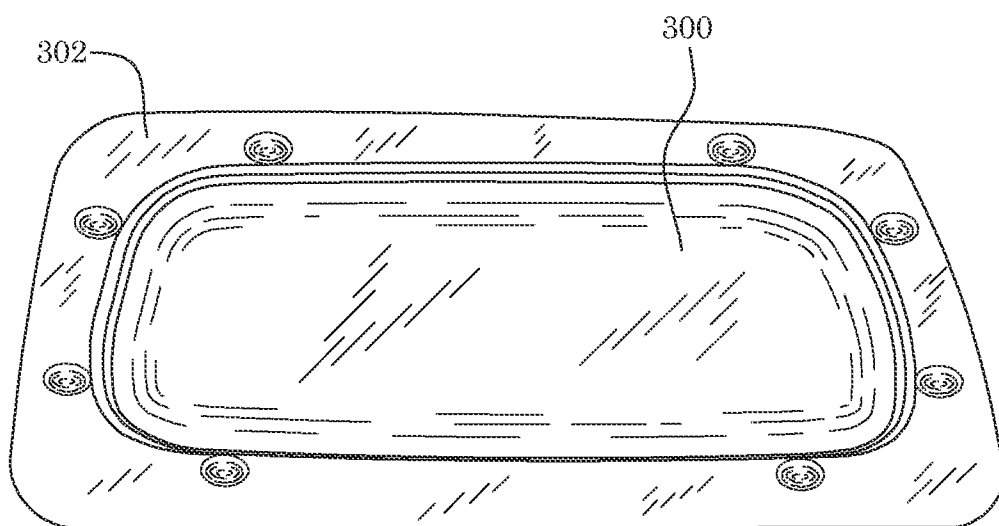


FIG. 3A

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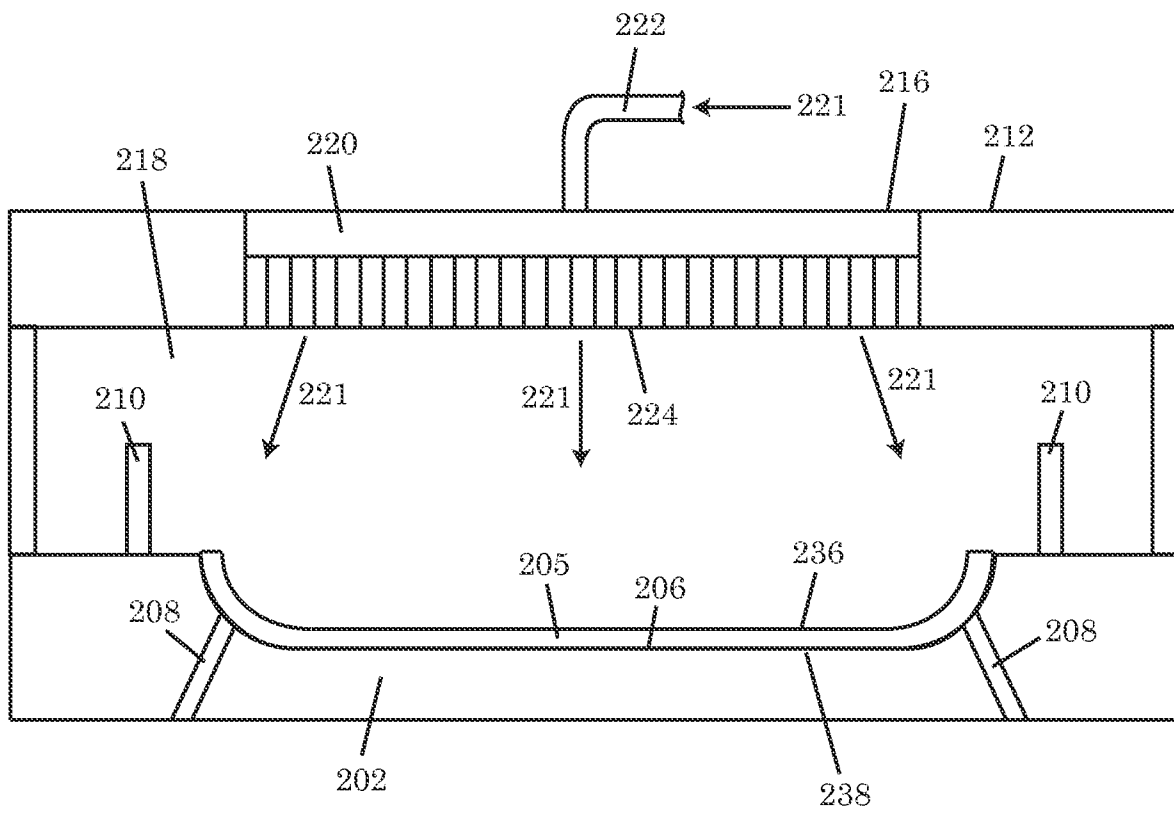


FIG. 2C

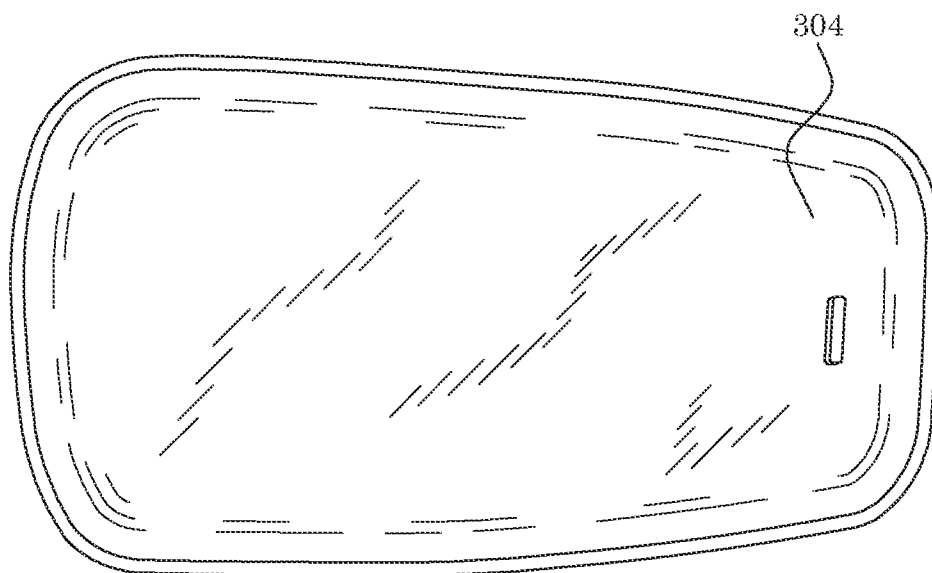


FIG. 3B

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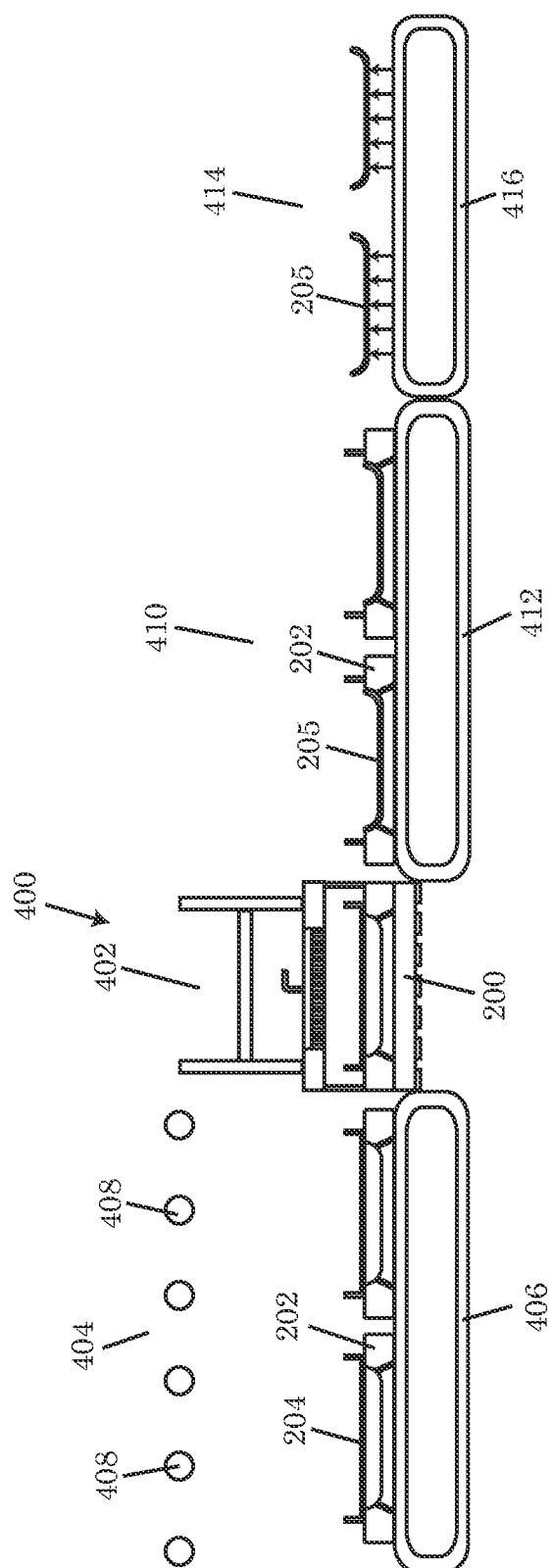


FIG. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2012/024934

A. CLASSIFICATION OF SUBJECT MATTER
INV. C03B23/035 C03B23/025
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)
C03B

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 practical, 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	EP 0 448 959 A1 (TAMGLASS OY [FI] TAMGLASS ENG OY [FI]) 2 October 1991 (1991-10-02) column 3, line 33 - column 12, line 35 figures 1,1a,2,3 claims 1-17	1-20
X	WO 93/06052 A1 (TAMGLASS ENG OY [FI]) 1 April 1993 (1993-04-01) the whole document	1-20
Y	DE 100 47 576 A1 (SCHOTT GLAS [DE]) 18 April 2002 (2002-04-18) paragraphs [0066] - [0081] figures 7a,7b claims 1-27	1-20
Y	US 4 233 050 A (COMPERATORE JOHN A ET AL) 11 November 1980 (1980-11-11) the whole document	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

24 April 2012

Date of mailing of the international search report

07/05/2012

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2012/024934

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