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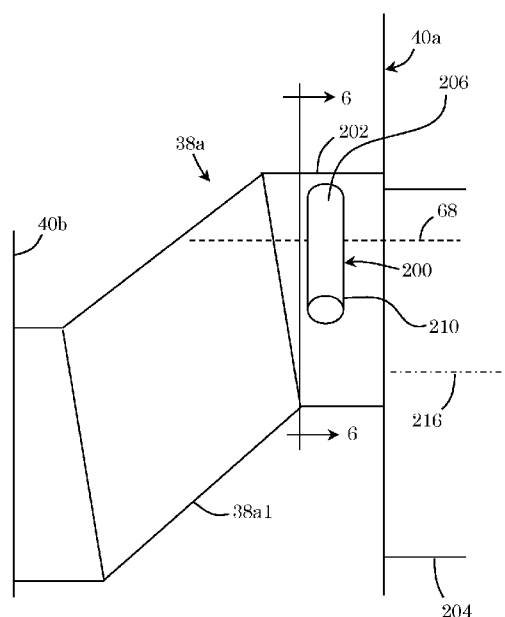


FIG. 5

(57) Abstract: A method of manufacturing a glass article includes flow-
ing molten glass through a first vessel to a downstream second vessel,
the molten glass flowing through a conduit connecting the first vessel to
the second vessel, the first vessel and the conduit defining a continuous
free volume above a free surface of the molten glass extending into at
least a portion of the conduit. The method further includes venting a first
atmosphere contained in the free volume to a second atmosphere external
to the first vessel through a vent tube connected to the conduit proximate
a top of the conduit and above the free surface, the vent tube extending
downward from the conduit to a distal end of the vent tube along a longi-
tudinal axis at an angle relative to horizontal and providing fluid com-
munication between the first atmosphere and the second atmosphere.

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METHOD FOR FORMING A GLASS ARTICLE

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. 63/064,642 filed on August 12, 2020, the content of which is relied upon and incorporated herein by reference in its entirety.

FIELD

[0002] The present disclosure relates to a method for forming a glass article, and more particularly a method of venting a vessel holding or conveying molten glass during the article manufacture.

TECHNICAL BACKGROUND

[0003] Fining molten glass during a glass manufacturing process aids in removing dissolved gases from the molten glass, helping to yield a bubble-free glass product. The temperature of the molten glass is raised to a temperature greater than the melting temperature causing one or more fining agents in the molten glass to release oxygen. The oxygen combines with melting-related gases and bubbles of the resultant gas mixture rise a surface of the molten glass. The bubbles pop and the released gases fill a free volume of the fining vessel. These gases must be removed from the fining vessel. However, venting directly from the fining vessel through a top of the fining vessel risks condensate particles dropping from the vent tube into the molten glass below, either spontaneously or when the vent tube is cleaned to remove the condensate.

SUMMARY

[0004] In accordance with the present disclosure, a method of manufacturing a glass article is disclosed comprising flowing a molten material through a first vessel to a second vessel downstream from the first vessel, the molten material flowing through a conduit connecting the first vessel to the second vessel, the first vessel and the conduit defining a continuous free volume above a free surface of the molten material, the free volume extending into at least a portion of the conduit. The method further comprises

venting a first atmosphere contained in the free volume to a second atmosphere external to the first vessel through a vent tube comprising a proximal end, a distal end opposite the proximal end, and a passage extending between the proximal end and the distal end, the proximal end connected to the conduit proximate a top of the conduit and above the free surface, the vent tube extending downward and away from the conduit along a longitudinal axis at an angle α relative to horizontal and providing fluid communication between the first atmosphere and the second atmosphere.

[0005] The vent tube can be straight, without bends or kinks, between the proximal end and the distal end. The proximal end is attached to the first vessel.

[0006] In various embodiments, the angle α is in a range from greater than 0° to less than 90° , for example in a range from about 3° to about 80° , from about 3° to about 40° , from about 3° to about 20° , or from about 3° to about 10° .

[0007] In some embodiments, the method may further comprise heating the vent tube during the venting. The heating can comprise establishing an electrical current in a heating element. The heating element can comprise a wall of the vent tube or be one or more individual discrete heating elements arranged adjacent to the vent tube wall.

[0008] When the vent tube wall is the heating element, the heating can comprise establishing an electrical current between a first electrical flange connected to the vent tube and a second electrical flange connected to at least one of the first vessel or the conduit.

[0009] In various embodiments, the first vessel can be a fining vessel.

[0010] In various embodiments, the second vessel can be a mixing vessel.

[0011] The method may further comprise flowing the molten material to a forming body and forming the molten material into a glass ribbon. In some embodiments, the forming can comprise drawing the molten material downward from the forming body.

[0012] In some embodiments, a first portion of the conduit can extend horizontally from the first vessel, and the vent tube can be connected to the first portion. In some embodiments, a second portion of the conduit extends downward relative to horizontal. The second portion can be located downstream from the first portion relative to the direction of flow of molten glass through the conduit. The second portion can be attached to the first portion. In some embodiments, the conduit may comprise a first section and a second section, wherein the first conduit portion and the second conduit portion comprise the first conduit section. The conduit may still further comprise a

second section coupled to the first conduit section (e.g., the second conduit portion) by a glass seal.

[0013] The method may still further comprise flowing a cover gas into the free volume through a gas delivery pipe connected to the first vessel. The gas can comprise an inert gas. The gas can comprise oxygen. The gas can be a mixture of an inert gas and oxygen. The gas can be a humidified gas.

[0014] The method may further comprise heating the conduit while flowing the molten material through the conduit. In some embodiments, a thickness of a wall of the conduit varies along a length of the conduit. To wit, in a cross-section of the conduit orthogonal to a longitudinal axis of the conduit, a thickness of the wall of the conduit in a first portion of the cross-section is different than a thickness of the wall of the conduit in a second portion of the cross-section. In some embodiments, a circumferential thickness of the wall of the conduit can vary along a length of the conduit. In some embodiments, the thickness may vary both as a function of circumference and length. In other embodiments, a method of manufacturing a glass article is described, comprising flowing a molten material from a first vessel through a conduit connected to the first vessel, the first vessel and the conduit defining a continuous free volume above a free surface of the molten material, the free volume extending into a portion of the conduit.

[0015] The method may further comprise venting a first atmosphere contained in the free volume to a second atmosphere external to the first vessel through a vent tube comprising a proximal end and a distal end opposite the proximal end, the proximal end connected to the conduit proximate a top of the conduit and above the free surface, the vent tube extending downward along a longitudinal axis at an angle α relative to horizontal and providing fluid communication between the first atmosphere and the second atmosphere.

[0016] The method may still further comprise heating the vent tube while the flowing the molten material, the heating removing condensate accumulated on an interior surface of the vent tube. The heating can comprise establishing an electrical current in a heating element, for example in a wall of the vent tube wherein the vent tube is the heating element. For example, the heating may comprise establishing an electrical current between a first electrical flange connected to the vent tube and a second electrical flange connected to at least one of the first vessel or the conduit

[0017] The method may still further comprise flowing the molten material to a forming body, the forming body forming the molten material into the glass article. In some embodiments, the glass article can be a glass ribbon. The forming may comprise drawing the molten material downward from the forming body.

[0018] In some embodiments, the first vessel can be a fining vessel.

[0019] In some embodiments, the second vessel can be a mixing apparatus.

[0020] In some embodiments, at least a first portion of the conduit extends downward relative to horizontal. For example, in some embodiments, a first portion of the conduit extends horizontally from the first vessel and the vent tube is connected to the first portion of the conduit. In some embodiments, a second portion of the conduit extends downward from the first portion of the conduit.

[0021] In some embodiments, the conduit may comprise a first section and a second section, wherein the first section is coupled to the second section by a glass seal.

[0022] In some embodiments, the method may further comprise flowing a gas into the free volume through a gas delivery pipe. The gas delivery pipe may be connected to the first vessel. In some embodiments, the cover gas may comprise an inert gas, for example nitrogen. The cover gas may be a low-oxygen gas comprising less than about 1.5% by volume oxygen O₂, for example, in a range from about 0.075% by volume to about 1.5% by volume. In some embodiments, the cover gas may be a humidified gas. In some embodiments the cover gas may be a dry gas.

[0023] Additional features and advantages of the embodiments disclosed herein will be set forth in the detailed description that follows, and in part will be clear to those skilled in the art from that description or recognized by practicing the embodiments described herein, including the detailed description which follows, the claims, as well as the appended drawings.

[0024] It is to be understood that both the foregoing general description and the following detailed description present embodiments intended to provide an overview or framework for understanding the nature and character of the embodiments disclosed herein. The accompanying drawings are included to provide further understanding and are incorporated into and constitute a part of this specification. The drawings illustrate various embodiments of the disclosure, and together with the description explain the principles and operations thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

- [0025] FIG. 1 is a schematic view of an exemplary glass making apparatus;
- [0026] FIG. 2 is a schematic view of an exemplary connecting conduit extending between a fining vessel and a mixing apparatus;
- [0027] FIG. 3 is a side cross-sectional view of an exemplary fining vessel illustrating a gas delivery tube configured to provide a cover gas to a free volume of the fining vessel;
- [0028] FIG. 4 is a detailed cross-sectional view of a portion of an exemplary gas delivery tube;
- [0029] FIG. 5 is a portion of the exemplary connecting conduit of FIG. 2 illustrating a vent tube extending therefrom;
- [0030] FIG. 6 is a view of the connecting conduit of FIG. 5 looking back along line 6-6 of FIG. 5
- [0031] FIG. 7 is a cross-sectional side view of another embodiment of a connecting conduit with a domed portion proximate a fining vessel to which the connecting conduit is attached;
- [0032] FIG. 8 is a view of the connecting conduit of FIG. 7 taken looking back along line 8-8 of FIG. 7 showing a vent tube extending from the domed portion;
- [0033] FIG. 9 is a schematic view of an exemplary electrical flange located at a distal end of the vent tube shown in FIG. 6;
- [0034] FIG. 10 is a schematic view of an embodiment of a vessel including a vent tube with a thickened end portion at the attachment point to the vessel; and
- [0035] FIG. 11 is a cross-sectional view of the thickened portion of the vent tube.

DETAILED DESCRIPTION

[0036] Reference will now be made in detail to embodiments of the present disclosure, examples of which are illustrated in the accompanying drawings. Whenever possible, the same reference numerals will be used throughout the drawings to refer to the same or like parts. However, this disclosure can be embodied in many different forms and should not be construed as limited to the embodiments set forth herein.

[0037] As used herein, the term “about” means that amounts, sizes, formulations, parameters, and other quantities and characteristics are not and need not be exact, but may be approximate and/or larger or smaller, as desired, reflecting tolerances,

conversion factors, rounding off, measurement error and the like, and other factors known to those of skill in the art.

[0038] Ranges can be expressed herein as from “about” one particular value, and/or to “about” another particular value. When such a range is expressed, another embodiment includes from the one particular value to the other particular value. Similarly, when values are expressed as approximations by use of the antecedent “about,” it will be understood that the particular value forms another embodiment. It will be further understood that the endpoints of each of the ranges are significant both in relation to the other endpoint, and independently of the other endpoint.

[0039] Directional terms as used herein - for example up, down, right, left, front, back, top, bottom - are made only with reference to the figures as drawn and are not intended to imply absolute orientation.

[0040] Unless otherwise expressly stated, it is in no way intended that any method set forth herein be construed as requiring that its steps be performed in a specific order, nor that with any apparatus, specific orientations be required. Accordingly, where a method claim does not actually recite an order to be followed by its steps, or that any apparatus claim does not actually recite an order or orientation to individual components, or it is not otherwise specifically stated in the claims or description that the steps are to be limited to a specific order, or that a specific order or orientation to components of an apparatus is not recited, it is in no way intended that an order or orientation be inferred in any respect. This holds for any possible non-express basis for interpretation, including matters of logic with respect to arrangement of steps, operational flow, order of components, or orientation of components; plain meaning derived from grammatical organization or punctuation, and; the number or type of embodiments described in the specification.

[0041] As used herein, the singular forms “a,” “an” and “the” include plural references unless the context clearly dictates otherwise. Thus, for example, reference to “a” component includes aspects having two or more such components, unless the context clearly indicates otherwise.

[0042] The word “exemplary,” “example,” or various forms thereof are used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as “exemplary” or as an “example” should not be construed as preferred or advantageous over other aspects or designs. Furthermore, examples are provided solely

for purposes of clarity and understanding and are not meant to limit or restrict the disclosed subject matter or relevant portions of this disclosure in any manner.

[0043] As used herein, the terms “comprising” and “including”, and variations thereof, shall be construed as synonymous and open-ended, unless otherwise indicated. A list of elements following the transitional phrases comprising or including is a non-exclusive list, such that elements in addition to those specifically recited in the list may also be present.

[0044] The terms “substantial,” “substantially,” and variations thereof as used herein are intended to note that a described feature is equal or approximately equal to a value or description. For example, a “substantially planar” surface is intended to denote a surface that is planar or approximately planar. Moreover, “substantially” is intended to denote that two values are equal or approximately equal. In some embodiments, “substantially” may denote values within about 10% of each other, such as within about 5% of each other, or within about 2% of each other.

[0045] As used herein, the term “electrically connected,” “electrically connecting,” and variations thereof, mean connected by way of an electrical conductor not including a molten material (e.g., molten glass). A first element electrically connected to a second element can include additional elements between the first element and the second element such that the additional elements are also electrically connected to the first element and the second element. That is, a first element electrically connected to a second element is not to be construed as precluding the presence of additional conducting elements in the connection. Typically, such electrical conductors can comprise metallic wiring or cabling, bus bars, and the like, but are not limited thereto. The electrical connection may further include other components, including but not limited to electrical connectors (e.g., plugs, tabs, lugs, bolts, etc.) that facilitate connection between components, electrical control devices such as electrical current and/or voltage controllers, electrical current and/or voltage measurement devices, and the like.

[0046] As used herein, “refractory” refers to non-metallic materials having chemical and physical properties making them applicable for structures, or as components of systems, that are exposed to environments above 538°C.

[0047] Shown in FIG. 1 is an exemplary glass manufacturing apparatus **10**. In some embodiments, the glass manufacturing apparatus **10** can comprise a glass melting furnace **12** including a melting vessel **14**. In addition to melting vessel **14**, glass

melting furnace **12** can optionally include one or more additional components such as heating elements (e.g., combustion burners and/or electrodes) configured to heat raw material and convert the raw material into molten glass. For example, melting vessel **14** may be an electrically boosted melting vessel, wherein energy is added to the raw material through both combustion burners and by direct heating, wherein an electrical current is passed through the raw material, the electrical current thereby adding energy via Joule heating of the raw material.

[0048] In further embodiments, glass melting furnace **12** can include other thermal management devices (e.g., isolation components) that reduce heat loss from the melting vessel. In still further embodiments, glass melting furnace **12** can include electronic and/or electromechanical devices that facilitate melting of the raw material into a glass melt. Glass melting furnace **12** can include support structures (e.g., support chassis, support member, etc.) or other components.

[0049] Melting vessel **14** can be formed from a refractory material, such as a refractory ceramic material, for example a refractory ceramic material comprising alumina or zirconia, although the refractory ceramic material can comprise other refractory materials, such as yttrium (e.g., yttria, yttria-stabilized zirconia, yttrium phosphate), zircon (ZrSiO_4) or alumina-zirconia-silica or even chrome oxide, used either alternatively or in any combination. In some examples, melting vessel **14** may be constructed from refractory ceramic bricks.

[0050] In some embodiments, glass melting furnace **12** can be incorporated as a component of a glass manufacturing apparatus configured to fabricate a glass article, for example a glass ribbon, although in further embodiments, the glass manufacturing apparatus can be configured to form other glass articles without limitation, such as glass rods, glass tubes, glass envelopes (for example, glass envelopes for lighting devices, e.g., light bulbs) and glass lenses, although many other glass articles are contemplated. In some examples, the melting furnace may be included in a glass manufacturing apparatus comprising a slot draw apparatus, a float bath apparatus, a down-draw apparatus (e.g., a fusion down draw apparatus), an up-draw apparatus, a pressing apparatus, a rolling apparatus, a tube drawing apparatus or any other glass manufacturing apparatus that would benefit from the present disclosure. By way of example, FIG. 1 schematically illustrates glass melting furnace **12** as a component of a fusion down-draw style glass manufacturing apparatus **10** for fusion drawing a glass ribbon for subsequent processing into individual glass sheets or for rolling the glass

ribbon onto a spool. As used herein, fusion drawing comprises flowing molten glass over both side surfaces of a forming body, wherein the resulting two streams of molten material join, or “fuse,” at the bottom of the forming body.

[0051] Glass melting furnace **12** can optionally include an upstream glass manufacturing apparatus **16** positioned upstream of melting vessel **14**. In some examples, a portion of, or the entire upstream glass manufacturing apparatus **16**, can be incorporated as part of the glass melting furnace **12**.

[0052] As shown in the embodiment illustrated in FIG. 1, upstream glass manufacturing apparatus **16** can include a raw material storage bin **18**, a raw material delivery device **20** and a motor **22** connected to raw material delivery device **20**. Raw material storage bin **18** can be configured to store a quantity of raw material **24** that can be fed into melting vessel **14** of glass melting furnace **12** through one or more feed ports, as indicated by arrow **26**. Raw material **24** typically comprises one or more glass forming metal oxides and one or more modifying agents. In some examples, raw material delivery device **20** can be powered by motor **22** to deliver a predetermined amount of raw material **24** from raw material storage bin **18** to melting vessel **14**. In further examples, motor **22** can power raw material delivery device **20** to introduce raw material **24** at a controlled rate based on a level of molten material ((hereinafter “molten glass”) sensed downstream from melting vessel **14** relative to a flow direction of the molten glass. As used herein, the term molten glass refers to any molten material (“melt”), which, when cooled, can become a glass or glass-ceramic (e.g., ceramic phase particles embedded in a glass phase matrix). Raw material **24** in melting vessel **14** can thereafter be heated to form molten glass **28**. Typically, in an initial melting step, raw material is added to the melting vessel as particulate, for example as various “sands.” Raw material **24** can also include scrap glass (i.e., cullet) from previous melting and/or forming operations. Combustion burners are typically used to begin the melting process. In an electrically boosted melting process, once the electrical resistance of the raw material is sufficiently reduced, electric boost can begin by developing an electrical potential between electrodes positioned in contact with the raw material, thereby establishing an electrical current through the raw material, the raw material typically entering, or in, a molten state.

[0053] Glass manufacturing apparatus **10** can also optionally include a downstream glass manufacturing apparatus **30** positioned downstream of glass melting furnace **12** relative to a flow direction of molten glass **28**. In some examples, a portion of

downstream glass manufacturing apparatus **30** may be incorporated as part of glass melting furnace **12**. However, in some instances, first connecting conduit **32** discussed below, or other portions of the downstream glass manufacturing apparatus **30**, can be incorporated as part of the glass melting furnace **12**.

[0054] Downstream glass manufacturing apparatus **30** can include a first conditioning chamber, such as fining vessel **34**, located downstream from melting vessel **14** and coupled to melting vessel **14** by way of the above-referenced first connecting conduit **32**. In some examples, molten glass **28** may be gravity fed from melting vessel **14** to fining vessel **34** by first connecting conduit **32**. For instance, gravity may drive molten glass **28** through an interior pathway of first connecting conduit **32** from melting vessel **14** to fining vessel **34**. Accordingly, first connecting conduit **32** provides a flow path for molten glass **28** from melting vessel **14** to fining vessel **34**. It should be understood, however, that other conditioning chambers may be positioned downstream of melting vessel **14**, for example between melting vessel **14** and fining vessel **34**. In some embodiments, a conditioning chamber can be employed between the melting vessel and the fining vessel. For example, molten glass from a primary melting vessel can be further heated in a secondary melting (conditioning) vessel or cooled in the secondary melting vessel to a temperature lower than the temperature of the molten glass in the primary melting vessel (melting vessel **14**) before entering fining vessel **34**.

[0055] As described previously, bubbles may be removed from molten glass **28** by various techniques. For example, raw material **24** may include multivalent compounds (i.e. fining agents) such as tin oxide that, when heated, undergo a chemical reduction reaction and release oxygen. Other suitable fining agents include without limitation, oxides of arsenic, antimony, iron, and cerium, although the use of arsenic and antimony oxides may be discouraged for environmental reasons in some applications as arsenic and antimony elements are biologically toxic. Fining vessel **34** is heated, for example to a temperature greater than the melting vessel temperature or the molten glass therein, thereby heating the fining agent. Oxygen produced by the temperature-induced chemical reduction of one or more fining agents included in the molten glass enters pre-existing bubbles in the molten glass, causing them to increase in size. The enlarged gas bubbles with increased buoyancy rise to a free surface of the molten glass within the fining vessel and are vented from the fining vessel as described in greater detail farther below.

[0056] The downstream glass manufacturing apparatus **30** can further include another conditioning chamber, such as mixing apparatus **36**, for example a stirring vessel, for mixing the molten glass that flows downstream from fining vessel **34**. Mixing apparatus **36** can be used to provide a homogenous molten glass composition, thereby reducing chemical or thermal inhomogeneities that may exist in the molten glass exiting the fining vessel. As shown, fining vessel **34** may be coupled to mixing apparatus **36** by way of a second connecting conduit **38**. In some embodiments, molten glass **28** can be gravity fed from fining vessel **34** to mixing apparatus **36** by way of second connecting conduit **38**. For instance, gravity may drive molten glass **28** through an interior pathway of second connecting conduit **38** from fining vessel **34** to mixing apparatus **36**. Typically, the molten glass within mixing apparatus **36** includes a free surface, with a free volume extending between the free surface and a top of the mixing apparatus. As used herein, “free surface” refers to the interface between the molten glass and a gaseous atmosphere above the molten glass, i.e., the surface of the molten glass. While mixing apparatus **36** is shown downstream of fining vessel **34** relative to a flow direction of molten glass **28**, mixing apparatus **36** may be positioned upstream from fining vessel **34** in other embodiments. In some embodiments, downstream glass manufacturing apparatus **30** may include multiple mixing apparatus, for example a mixing apparatus upstream from fining vessel **34** and a mixing apparatus downstream from fining vessel **34**. These mixing apparatus may be of the same design, or they may be of a different design from one another. In some embodiments, one or more of the vessels and/or conduits comprising downstream glass manufacturing apparatus **30** can include static mixing vanes positioned therein to promote mixing and subsequent homogenization of the molten glass.

[0057] Heating of fining vessel **34**, mixing apparatus **36**, and other metallic components of the glass manufacturing apparatus, including but not limited to first connecting conduit **32**, and second connecting conduit **38** can occur through direct heating. That is, electrical flange assemblies **40** may be attached to the various metallic components, wherein the flange assemblies **40** are in electrical communication with one or more electrical power sources configured to supply an electrical current to the electrical flange assemblies **40**. The electrical current passes through walls of the metallic components (e.g., vessels, conduits) between the flange assemblies **40**, thereby heating the walls of the metallic components by Joule heating, and subsequently heating the

molten material **28** flowing therethrough. A more detailed discussion of the flange assemblies is provided farther below.

[0058] In some embodiments, second connecting conduit **38** can include more than one section. For example, as shown in FIG. 2, second connecting conduit **38** can include a first conduit section **38a** comprising a proximal end **42**, a distal end **44** opposite proximal end **42**, and a passage **46** extending between proximal and distal ends **42**, **44**. Proximal end **42** is connected to fining vessel **34**. Second connecting conduit **38** may further include a second conduit section **38b** comprising a proximal end **48**, a distal end **50**, and a passage **52** extending between proximal and distal ends **48**, **50**. Proximal end **48** may be connected to mixing apparatus **36** (e.g., a mixing vessel). First conduit section **38a** can be rigidly joined to an exit of fining vessel **34** at proximal end **42** of first conduit section **38a** by welding. Similarly, second conduit section **38b** can be rigidly joined to an inlet of mixing apparatus **36** at proximal end **48** of second conduit section **38b** by welding. Additionally, distal end **44** of first conduit section **38a** can be coupled to distal end **50** of second conduit section **38b**. For example, in various embodiments, first conduit section **38a** may include a first electrical flange assembly **40a** attached to distal end **44** and second conduit section **38b** may include a second electrical flange assembly **40b** attached to distal end **50**, wherein first conduit section **38a** and second conduit section **38b** are arranged such that a gap **54** is formed between first electrical flange assembly **40a** and second electrical flange assembly **40b**. Gap **54** can be, for example, in a range from about 1 mm to about 1 cm. As molten glass **28** is conveyed through first and second conduit sections **38a**, **38b**, the molten glass can seep into gap **54**. Exposure of the molten glass in the gap to the cooler environment outside the gap cools the molten glass therein, whereupon the viscosity of the molten glass increases, blocking the gap and preventing further leakage of molten glass. Such blockage is referred to as a “glass seal.” The glass seal can accommodate small misalignment or movement of the coupled components, such as during temperature changes, and may electrically isolate first conduit section **38a** from second conduit section **38b** and allow independent direct heating.

[0059] First and second electrical flange assemblies **40a**, **40b** are configured to allow an electrical current to enter or leave the respective first or second conduit sections **38a**, **38b**. For example, in some embodiments, fining vessel **34** may include a third electrical flange assembly **40c** positioned at or proximate to the junction between proximal end **42** of first conduit section **38a** and fining vessel **34**. Accordingly, first electrical flange

assembly **40a** and third electrical flange assembly **40c** can be electrically connected to an electrical power source **56a** capable of supplying an electrical current to first conduit section **38a** through first and third electrical flange assemblies **40a** and **40c**. The supplied electrical current can thereby heat the first conduit section **38a** as a function of the electrical resistance of the wall(s) of the first connecting conduit portion by direct heating. While first electrical power source **56a** is shown in direct connection to electrical flange assemblies **40a** and **40c**, in further embodiments, first electrical power source **56a** can be in indirect electrical connection. For example, first electrical power source **56a** can comprise a transformer wherein one side of the transformer windings (e.g., primary winding) can be electrically connected to the electrical service for the facility housing the glass manufacturing apparatus, and the other side of the transformer windings (e.g., secondary winding) can be electrically connected to the first and third electrical flange assemblies **40a**, **40c** through winding taps. Electrical flange assemblies **40a-40c** each include a body portion **58** that encircles and attaches to the respective conduit or vessel portion to which it is attached, and one or more electrode portions **60** that extend from the body portion and provide an attachment point for electrical power cables or bus bars that supply the electrical current to the flange assemblies. While not shown, in various embodiments, the electrical flange assemblies may include one or more rings (e.g., concentric rings) of different materials, different thicknesses, and/or different radial widths to control the distribution of electrical current around the flange assembly and into the respective conduit or vessel.

[0060] While fining vessel **34** is typically arranged such that its length is horizontal or substantially horizontal (e.g., within 10° of horizontal), as seen in FIG. 2, first conduit section **38a** may include a first conduit portion **38a1** arranged horizontally or substantially horizontally, and a second conduit portion **38a2** that slopes downward from first conduit portion **38a1** (e.g., relative to horizontal) at an angle β along a longitudinal axis **62** of the section. As described herein, axes that extend in a downward direction relative to horizontal and a local direction of molten glass flow (e.g., direction **63**) will be considered to extend at a negative angle and axes that extend in an upward direction relative to horizontal and a local direction of molten glass flow (e.g., direction **63**) will be considered to extend at a positive angle. Accordingly, longitudinal axis **62** may form a negative angle β relative to horizontal axis **64**. The downward slope of conduit portion **38a2** positions second conduit section **38b**, coupled

via glass seal **66** to first conduit section **38a**, entirely below a plane defined by free surface **68** of molten glass **28** in fining vessel **34**. To wit, in operation, molten glass **28** conveyed through fining vessel **34** is maintained at a level such that free surface **68** of the molten glass in fining vessel **34** forms a “free volume” **70** within the fining vessel defined between the free surface **68** of molten glass **28** and fining vessel **34**. Free volume **70** is free of molten glass and contains a first atmosphere **72** that provides space for accumulation of volatile gases and other materials that may be released from the molten glass. For example, certain constituents of the molten glass, e.g., boron, can readily evaporate from the free surface of the molten glass. Additionally, various gases generated during the melting process may be released from the free surface. As described herein below, this first atmosphere can be vented to a second atmosphere **74** external to the fining vessel (e.g., an ambient atmosphere surrounding the glass making apparatus **10**). Moreover, free volume **70** is continuous within at least a portion of first conduit section **38a** (e.g., proximate fining vessel **34**) and also includes first atmosphere **72**. The level (vertical position) of free surface **68** of the molten material is referred to as the “glass line,” which term may be used interchangeably with molten glass level herein. The glass line may be thought of as the level to which the molten glass wets the inside surface of the conduit inside wall surface.

[0061] Positioning second conduit section **38b** below the glass line, and in particular below the minimum expected glass line, can minimize trapping of gases contained in first atmosphere **72** into the molten glass. Second conduit section **38b** is positioned sufficiently below the glass line that normal excursions of the glass line up or down will not result in a free volume within second conduit section **38b**.

[0062] As further shown in FIG. 2, additional flange assemblies may be provided. For example, a fourth electrical flange assembly **40d** may be attached to second conduit section **38b** downstream of second electrical flange assembly **40b**, wherein second electrical flange assembly **40b** and fourth electrical flange assembly **40d** are electrically connected to a second electrical power source **56b**. Electrical current supplied by second electrical power source **56b** is passed through the wall of second conduit section **38b** via second electrical flange assembly **40b** and fourth electrical flange assembly **40d**. Similarly, a fifth electrical flange assembly **40e** may be attached to mixing apparatus **36** and electrically connected to a third electrical power source **56c**, wherein electrical flange assemblies **40d** and **40e** supply an electrical current through portions of second conduit section **38b** and mixing apparatus **36** via third electrical power source

56c. Other electrical flange assemblies **40** may be provided on mixing apparatus **36** and fining vessel **34**. In some embodiments, a plurality of flange assemblies **40** and a plurality of electrical power sources **56** may be provided on fining vessel **34** and other components of the downstream glass manufacturing apparatus **30** and can define a plurality of individually controlled heating zones. Each heating zone may be provided with an electrical current of the same or differing electrical current magnitude and phase as necessary to obtain a predetermined temperature within the individual temperature zone. For example, in some embodiments, it may be desirable to cool the molten glass flowing through second connecting conduit **38** before entering mixing apparatus **36**. Accordingly the electrical current in first conduit section **38a** may be controlled to have a magnitude less than the magnitude of the current in second conduit section **38b** such that a temperature of second conduit section **38b** is cooler than a temperature of first conduit section **38a**, thereby cooling the molten glass as the molten glass flows through first and second conduit sections **38a** and **38b**.

[0063] Returning to FIG. 1, downstream glass manufacturing apparatus **30** can further include another conditioning chamber such as delivery vessel **80** located downstream from mixing apparatus **36**. Delivery vessel **80** can condition molten glass **28** to be fed into a downstream forming device. For instance, delivery vessel **80** can act as an accumulator and/or flow controller to adjust and provide a consistent flow of molten glass **28** to forming body **82** by way of exit conduit **84**. The molten glass within delivery vessel **80** can, in some embodiments, include a free surface, wherein a free volume extends upward from the free surface to a top of the delivery vessel. As shown, mixing apparatus **36** can be coupled to delivery vessel **80** by way of third connecting conduit **86**. In some examples, molten glass **28** can be gravity fed from mixing apparatus **36** to delivery vessel **80** by way of third connecting conduit **86**. For instance, gravity can drive molten glass **28** through an interior pathway of third connecting conduit **86** from mixing apparatus **36** to delivery vessel **80**.

[0064] Downstream glass manufacturing apparatus **30** can still further include forming apparatus **88** comprising the above-referenced forming body **82**, including inlet conduit **90**. Exit conduit **84** can be positioned to deliver molten glass **28** from delivery vessel **80** to inlet conduit **90** of forming apparatus **88**. Forming body **82** in a fusion down-draw glass making apparatus can comprise a trough **92** positioned in an upper surface of the forming body, and converging forming surfaces **94** (only one surface shown) that converge in a draw direction along a bottom edge (root) **96** of the forming body wherein

the converging surfaces define the root. Molten glass delivered to forming body trough **92** via delivery vessel **80**, exit conduit **84** and inlet conduit **90** overflows the walls of forming body trough **92** and descends along the converging forming surfaces **94** as separate flows of molten glass. The separate flows of molten glass join below and along root **96** to produce a single ribbon **98** of molten glass that is drawn along a draw plane in a draw direction **100** from root **96** by applying a downward tension to the ribbon, such as by gravity and/or pulling roll assemblies (not shown), to control the dimensions of the ribbon as the molten glass cools and a viscosity of the molten glass increases. Accordingly, ribbon **98** goes through a viscoelastic transition to an elastic state and acquires mechanical properties that give ribbon **98** stable dimensional characteristics. The resultant glass ribbon **98** may in some embodiments be separated into individual glass sheets **102** by a glass separation apparatus (not shown), while in further embodiments, the glass ribbon may be wound onto spools and stored for further processing.

[0065] Components of downstream glass manufacturing apparatus **30**, including any of connecting conduits **32**, **38**, **86**, fining vessel **34**, mixing apparatus **36**, delivery vessel **80**, exit conduit **84**, or inlet conduit **90** may be formed from a precious metal. Suitable precious metals include platinum group metals selected from the group consisting of platinum, iridium, rhodium, osmium, ruthenium and palladium, or alloys thereof. For example, downstream components of the glass manufacturing apparatus may be formed from a platinum-rhodium alloy including from about 70% to about 90% by weight platinum and about 10% to about 30% by weight rhodium. However, other suitable metals for forming downstream components of the glass manufacturing apparatus can include molybdenum, rhenium, tantalum, titanium, tungsten and alloys thereof.

[0066] Although elements of the glass manufacturing apparatus **10** are shown and described as fusion downdraw glass making elements, principles of the present disclosure can be applied to a wide variety of glass making processes. For example, melting vessels according to embodiments of the present disclosure can be used in such diverse glass making processes as fusion processes, slot draw processes, rolling processes, pressing processes, float processes, tube drawing processes, and so forth.

[0067] As described above, bubbles are removed from the molten material in fining vessel **34**. These bubbles include, without limitation, those formed from trapped gases within the granular pile of raw materials and/or cullet introduced to the melting system as those materials melt, bubbles generated, for example, from the chemical dissolution

or reactions of the raw materials throughout the melting process, and bubbles generated from reactions with other materials in the process, such as refractory or metallic components. Bubbles may contain, for example, such gases as oxygen, nitrogen, water vapor, argon, sulfur dioxide, and carbon dioxide. Additionally, in various embodiments, gases may be intentionally introduced into the fining vessel (e.g., into free volume 70) through a gas supply pipe 104 to aid the fining process (see FIG. 3). Such deliberately introduced gases can include nitrogen, helium, or other inert gases or combinations thereof. Water may be introduced in the form of vapor and may be combined with the inert gases (e.g., humidified gas). Still further, the high temperatures present in parts of the fining vessel (approaching or exceeding 1700°C in some instances) can cause vaporization of one or more constituents of the molten glass, e.g., boron, sodium, and/or tin.

[0068] In accordance with embodiments described herein, a cover gas 106 can be injected into free volume 70 above free surface 68 via fining vessel gas supply tube 104. In some embodiments, cover gas 106 can be a humidified cover gas. Humidified cover gas 106 comprises water vapor and oxygen (O₂) and can further comprise a non-combustible carrier gas. As used herein a non-combustible carrier gas does not include hydrocarbons and/or is not formed as a by-product of combustion during the glass making process, and may comprise, for example, an inert gas such as nitrogen, although in further embodiments, the carrier gas may be another inert gas, for example a noble gas such as helium, neon, argon, krypton, xenon, etc., or combinations of any of the preceding inert gases. For example, in embodiments, neither the carrier gas, nor any component of the humidified gas in general, originates from a submerged combustion burner in the glass making process (e.g., melting vessel) that relies on the combustion of a fuel, for example natural gas, as a source of humidity (e.g., water vapor).

[0069] The average oxygen (O₂) content of humidified cover gas 106 should be equal to or greater than the oxygen content in the bubbles to ensure no outward diffusion of oxygen from the bubbles. That is, the partial pressure of oxygen in the atmosphere outside the bubbles should at least be equal to the partial pressure of oxygen inside the bubbles. Outward diffusion of oxygen from the bubbles into the surrounding atmosphere can lead to bubble shrinkage and subsequent bubble wall thickness. Thickened bubble walls can prolong bubble popping for a time sufficient to allow the bubbles to become re-entrained within the molten glass flow. Thus, in some

embodiments, the partial pressure of oxygen within the humidified gas can be greater than the partial pressure of oxygen in the bubbles to ensure bubble expansion.

[0070] The average oxygen content of oxygen in humidified cover gas **106** can, for example, be in a range from about 10% to about 90% by volume, for example in a range from about 15% to about 90% by volume, in a range from about 20% to about 90% by volume, in a range from about 30% to about 90% by volume, in a range from about 40% to about 90% by volume, in a range from about 50% to about 90% by volume, in a range from about 60% to about 90% by volume, in a range from about 70% to about 90% by volume, in a range from about 80% to about 90% by volume, in a range from about 10% to about 80% by volume, in a range from about 10% to about 70% by volume, in a range from about 10% by volume to about 60% by volume, in a range from about 10% by volume to about 50% by volume, in a range from about 10% by volume to about 40% by volume, in a range from about 10% by volume to about 30% by volume, or in a range from about 10% by volume to about 20% by volume, including all ranges and sub-ranges therebetween. In some embodiments, humidified cover gas **106** can comprise air.

[0071] In some embodiments, the presence of water vapor as a surfactant can counter the effect of a lower partial pressure of oxygen outside the bubble wall than inside the bubble wall. It should be understood, therefore, that a goal is to prevent bubble shrinkage, which can thicken the bubble wall and prolong bubble persistence (delay bubble popping). Accordingly, the amount of oxygen and water vapor can be adjusted to prevent bubble shrinkage, which, in some embodiments can result in a partial pressure of oxygen outside the bubble that is less than the partial pressure of oxygen inside the bubble.

[0072] A dew point of humidified cover gas **106** can be in a range from about 41°C to about 92°C, for example in a range from about 60°C to about 92°C. The remainder of the humidified cover gas can be the inert carrier gas.

[0073] A flow rate of humidified cover gas **106** can be in a range from greater than 0 to about 80 standard liters per minute (slpm), for example in a range from about 10 slpm to about 80 slpm, in a range from about 20 slpm to about 80 slpm, in a range from about 30 slpm to about 80 slpm, such as in a range from about 40 slpm to about 80 slpm, in a range from about 50 slpm to about 80 slpm, in a range from about 60 slpm to about 80 slpm, in a range from about 70 slpm to about 80 slpm, in a range from about 10 slpm to

about 70 slpm, in a range from about 10 slpm to about 60 slpm, in a range from about 10 slpm to about 50 slpm, in a range from about 10 slpm to about 40 slpm, in a range from about 10 slpm to about 30 slpm, or in a range from about 10 slpm to about 20 slpm.

[0074] In some embodiments, fining vessel gas supply tube **104** may be heated, thereby heating the humidified cover gas supplied to fining vessel **34**. For example, fining vessel gas supply tube **104** and thereby humidified cover gas **106** may be heated by one or more heating elements **107** such as external electrical resistance heating element(s) **108**, although in further embodiments, fining vessel gas supply tube **104** may be direct heated by establishing an electric current directly within the fining vessel gas supply tube in a manner similar to the method of heating fining vessel **34**. For example, fining vessel gas supply tube **104** may include one or more electrical flange assemblies **40** in electrical communication with an electrical power source as described in respect of fining vessel **34**.

[0075] In accordance with other embodiments described herein, a dry cover gas **106** can be injected into free volume **70** above free surface **68** via fining vessel gas supply tube **104**. Dry cover gas **106** can, in various embodiments, comprise a relative humidity equal to or less than about 1%, for example equal to or less than about 0.5%, equal to or less than about 0.1%, or equal to or less than about 0.05%, such as zero percent (0%), and can further comprise inert gas, for example nitrogen, although in further embodiments, the inert gas may be a noble gas such as helium, neon, argon, krypton, xenon, etc., or combinations of any of the preceding inert gases.

[0076] The average oxygen (O₂) content of dry cover gas **106** supplied to fining vessel **34** should be less than the oxygen content in the bubbles to ensure outward diffusion of oxygen from the bubbles. That is, the partial pressure of oxygen in the cover gas outside the bubbles should be less than the partial pressure of oxygen within the bubbles. For example, in various embodiments, dry cover gas **106** supplied to fining vessel **34** may comprise an O₂ content equal to or less than 0.2% by volume, for example in a range from about 0.05 by volume to about 0.2% by volume, such as in a range from about 0.075% by volume to about 1.5% by volume. There should be sufficient oxygen in the cover gas to prevent reduction of the platinum-comprising walls of the fining vessel due to a high nitrogen concentration in the cover gas. However, the concentration of oxygen should be sufficiently low to prevent damaging oxidation of the platinum-comprising walls at high temperatures. Accordingly, in

various embodiments, dry cover gas **106** can be a majority nitrogen gas (>50% by volume) comprising oxygen in a range from about 0.05% by volume to about 0.2% by volume and comprising a relative humidity equal to or less than about 0.5%. In other embodiments, dry cover gas **106** can be a majority nitrogen gas comprising oxygen in a range from about 0.075% by volume to about 0.15% by volume and comprising a relative humidity equal to or less than about 0.1%. In still other embodiments, dry cover gas **106** can be a majority nitrogen gas comprising oxygen in a range from about 0.075% by volume to about 0.15% by volume and comprising a relative humidity equal to or less than about 0.05%. In some embodiments, dry cover gas **106** may comprise N₂ in a concentration equal to or greater than 78% by volume, for example equal to or greater than about 85% by volume, equal to or greater than about 90% by volume, equal to or greater than about 95% by volume, equal to or greater than about 98% by volume, or equal to or greater than about 99.8 % by volume.

[0077] The low oxygen, low humidity atmosphere provided to free volume **70** via dry cover gas **106** can produce a net flow of gas and/or vapor from inside bubbles on the surface of molten glass **28** within fining vessel **34** across the bubble membrane into free volume **70**, where, as previously stated, the released gas and/or vapor (e.g., water vapor) can exit free volume **70** through a vent. The release of gas and/or vapor that diffuses from the bubbles across the bubble membranes can result in shrinkage of the bubbles. Shrinkage may make the bubbles too small to be re-entrained into the flow of molten glass, allowing the bubbles more time to pop. In some embodiments, such shrinkage can result in complete collapse of the bubbles.

[0078] A flow rate of cover gas **106** can be in a range from equal to or greater than about 1 (one) turnover per minute to equal to or less than about 1 turnover per hour, including all ranges and subranges therebetween. As used herein, “turnover” means a flow rate equivalent to the volume of the free volume per unit time. As an example, for a one-liter volume, one turnover per minute means a gas flow rate equal to one liter per minute. A gas supplied to a four-liter volume at a rate of two turnovers per minute means a flow rate of eight liters per minute. The flow rate selected will depend on the size of the free volume supplied with the cover gas. The flow rate of cover gas can be, for example, in a range from about 0.02 turnovers per minute to about 1 turnover per minute, in a range from about 0.05 turnovers per minute to about 1 turnover per minute, in a range from about 0.1 turnovers per minute to about 1 turnover per minute, in a range from about 0.5 turnovers per minute to about 1 turnover per

minute, or in a range from about 0.8 turnovers per minute to about 1 turnover per minute, and including all ranges and subranges therebetween.

[0079] In some embodiments, a non-reactive gas, for example a noble gas such as argon, krypton, neon, or xenon, or another non-reactive gas, can be added to cover gas **106** at a predetermined concentration, for example a cover gas injected into the free volume in the finer or other vessel (e.g., mixing apparatus **36**), as an aid to identifying a source of blisters in a finished glass article resulting from the glass manufacturing process. That is, bubbles in the molten glass can be tagged with a detectable quantity of a non-reactive gas as a means of determining a location for the bubble formation. For example, a specific first non-reactive gas (hereinafter “tag” gas) can be added to cover gas **106** supplied to fining vessel **34**, for example a gas mixing chamber in fluid communication with the respective vessel gas supply tube (e.g., fining vessel gas supply tube **104**). Suitable tag gases can include, but are not limited to, argon, krypton, neon, helium, and xenon.

[0080] Blisters (bubbles) found in a finished glass article can be analyzed, for example by mass spectrometry, to determine if the first tag gas is present in the blisters at a concentration consistent with the concentration of the first tag gas added to the cover gas supplied to fining vessel **34**, thereby identifying the source of blisters as the fining vessel. However, a tag gas concentration found in blisters inconsistent with the concentration of the tag gas supplied to fining vessel **34** may indicate the source of the blisters is not the fining vessel. Similarly, a second tag gas different from the first tag gas can be added to a cover gas supplied to a different vessel, for example mixing apparatus **36**. An analysis of blisters in the glass article can then be used to determine the number of blisters containing the first tag gas, if any, and/or the number of blisters containing the second tag gas, if any, thereby providing better identification and quantification of the source of blisters. If, for example the second tag gas is found, but not the first tag gas, then the source of blisters may be inferred to come from the vessel into which the second tag gas was injected. The presence of both the first tag gas and the second tag gas in a bubble may indicate the bubble survived transportation between several vessels and reside on the surface of the molten glass in both vessels.

[0081] The tag gas or gases are typically not the majority gas comprising the cover gas. For example, if the majority gas (>50%) comprising cover gas **106** is N₂, the cover gas may comprise less than 50% tag gas, wherein the tag gas is different than the majority gas.

[0082] FIGS. 3 and 4 depict a lower portion of an exemplary fining vessel gas supply tube **104**, shown penetrating a wall **120** of fining vessel **34** above free surface **68** of molten glass **28** in FIG. 3 and in cross-section in FIG. 4. Fining vessel gas supply tube **104** can extend through a reinforcing sleeve **122** where the fining vessel gas supply tube **104** penetrates fining vessel wall **120**. In addition, reinforcing plate or plates **124** are depicted in FIG. 4 encircling reinforcing sleeve **122** and located above and/or below fining vessel wall **120** and attached thereto. Reinforcing plates **124**, reinforcing sleeve **122**, and fining vessel wall **120** can be attached to each other, such as by welding. For example, reinforcing plates **124** can be welded to fining vessel wall **120** and to reinforcing sleeve **122**. In addition, in embodiments, reinforcing sleeve **122** can be welded to fining vessel gas supply tube **104**. Reinforcing plates **124** and reinforcing sleeve **122** provide additional thickness to the fining vessel wall and to fining vessel gas supply tube **104** where the fining vessel gas supply tube penetrates the fining vessel, since all can be formed of thin sheets of a platinum alloy and easily deformed as the metal expands during initial heating up of the system. The additional thickness can provide greater strength to the gas supply tube where the gas supply tube penetrates the fining vessel wall and may reduce heating at the region of penetration by reducing electrical current (decreasing electrical resistance) through the junction in instances where the gas supply tube is direct heated.

[0083] Fining vessel gas supply tube **104** can comprise a closed bottom **126** and an exhaust port **128** located on the side wall of the fining vessel gas supply tube **104** near the bottom of the fining vessel gas supply tube and oriented such that cover gas **106** is exhausted from the fining vessel gas supply tube **104** in a direction substantially parallel with a flow direction **130** of the molten glass in fining vessel **34** (e.g., oriented in a downstream direction). Substantially parallel flow of cover gas **106** and molten glass **28** minimizes or eliminates direct impingement of the cover gas exhausted from the gas supply tube onto the surface of the molten glass and subsequent cooling of molten glass surface. Such cooling could cause viscosity inhomogeneities in the molten glass that could manifest as defects in the finished product. In addition, a side-ported fining vessel gas supply tube **104** can reduce the probability that condensates, such as glass constituents like easily volatilized boron, can accumulate in the exhaust port and eventually drop into the molten glass below.

[0084] As a consequence of the processes described above, first atmosphere **72** contained within free volume **70** and extending along a length of fining vessel **34** and at

least a portion of first conduit section **38a** can include any one or more of the preceding gases and vapors, and this atmosphere should be vented from the fining vessel. Typically, venting of fining vessel **34** has occurred through a vent tube extending from a top of the fining vessel. However, such a configuration can produce unwanted results. For example, volatile materials evaporating from the molten glass can condense on interior surfaces of the vent tube. If a sufficient amount of condensate accumulates, the condensate can break off and fall into the molten glass below, thereby contaminating the molten glass. Moreover, a straight vent tube extending from the top of the fining vessel is difficult to clean without dislodging condensate that, again, can fall through the vent tube and contaminate the molten glass below. Past efforts to mitigate contamination have included forming a bend in the vent pipe so the vent pipe, while initially rising vertically from the fining vessel, bends sharply so dislodged condensate will not fall into the fining vessel. However, such sharp bends make cleaning the vent pipe beyond the bend (e.g., between the bend and the fining vessel, difficult from outside the fining vessel, as cleaning tools are unable to reach from the vent tube exit to beyond the bend.

[0085] To overcome the preceding issues, embodiments of an improved venting apparatus are described. Accordingly, in some embodiments, a diameter of first conduit section **38a** can be enlarged compared to conventional connecting conduits. Referring to FIGS. 5 and 6, a large-diameter conduit can provide an increased free volume **70**, thereby enabling placement of vent tube **200** at a location proximate the top **202** of first conduit section **38a** but sufficiently above the free surface of molten glass **28** to prevent ingress of molten glass **28** into vent tube **200**. For example, the inlet of vent tube **200** may be positioned at least 2.5 cm above the glass line. Referring to the cross-sectional view of FIG. 6, shown looking along line **6-6** of FIG. 5, in various embodiments, the connection between vent tube **200** and first conduit section **38a** can be positioned within an angular range from about 5° to about 60° relative to vertical, for example in a range from about 10° to about 45°, wherein a position of 0° refers to a connection at the vertical top of first conduit section **38a** (i.e., 12 o'clock position).

[0086] In some embodiments, the top of first conduit section **38a** can be higher than the top of fining vessel **34** relative to the bottom **204** of fining vessel **34**. Vent tube **200** can be a straight vent tube extending from proximal end **206** downward along central longitudinal axis **208** at a negative angle α relative to horizontal and terminating at

distal end **210**, the vent tube defining a passage **212** therethrough (see FIG. 11). As shown, no portion of vent tube **200** extends upward from proximal end **206**, either vertically or at any positive angle above horizontal. Angle α can be in a range from greater than 0° to less than 90° , such as in a range from about 3° to about 80° , from about 3° to about 40° , from about 3° to about 20° , or from about 3° to about 10° . Thus, vent tube **200** provides fluid communication between free volume **70** proximate the top of first conduit section **38a** and further provides sufficient distance between free surface **68** of molten glass **28** and the bottom of proximal end **206** of vent tube **200** to accommodate upward excursions of the glass line without blocking the vent tube. First atmosphere **72** remains in fluid communication with the second, external atmosphere **74** through vent tube **200** during operation of the glass manufacturing apparatus. At the same time, vent tube **200** provides access through the entire length of the vent tube from outside second conduit **38** (e.g., first conduit section **38a**), thereby facilitating easy cleanout without the risk of particulate dropping into molten glass **28**.

[0087] Referring to FIG. 7, in other embodiments, it may be unnecessary to enlarge the entirety of first conduit section **38a**. Instead, a portion of first conduit section **38a** can be enlarged upward, creating a large, domed portion **214** above free surface **68** of molten glass **28** within first conduit section **38a**. Domed portion **214** can, in some embodiments, extend above fining vessel **34**. That is, the top of domed portion **214** can extend vertically upward a greater distance **d1** from the bottom of fining vessel **34** than the distance **d2** of the top of fining vessel **34**. As previously described, vent tube **200** can be a straight vent tube connected to domed portion **214** at proximal end **206** and extending from proximal end **206** downward along central longitudinal axis **208** at a negative angle α relative to horizontal, vent tube **200** terminating at distal end **210**. As before, no portion of vent tube **200** extends upward from proximal end **206**, either vertically or at any positive angle above horizontal. Angle α can be in a range from greater than 0° to less than 90° , such as in a range from about 3° to about 80° , from about 3° to about 40° , from about 3° to about 20° , or from about 3° to about 10° .

[0088] The large, upwardly extending domed portion **214** allows sufficient distance between free surface **68** of molten glass **28** and the bottom of proximal end **206** of vent tube **200** to accommodate upward excursions of the glass line during operation of the glass manufacturing apparatus. In other words, free volume **70** of fining vessel **34** extends into first conduit section **38a** and the inlet of vent tube **200** is positioned on first

conduit section **38a** (e.g., domed portion **214**) such that proximal end **206** of vent tube **200** is positioned above the expected maximum height of the glass line to prevent an upward excursion of the molten glass from blocking the vent tube during operation of the glass manufacturing apparatus. For example, the inlet of vent tube **200** may be positioned at least 2.5 cm above the glass line.

[0089] Although fining vessel **34** is shown having a circular cross-section in a plane orthogonal to central longitudinal axis **216** of the fining vessel, in further embodiments, fining vessel **34** may comprise a non-circular cross-sectional shape, for example an oblong cross-sectional shape. Similarly, vent tube **200** can have a non-circular cross-sectional shape.

[0090] In a manner similar to the arrangements shown in FIG. 6, seen looking back along line **6-6** of FIG. 5, in some embodiments, shown in FIG. 8 looking back along line **8-8** of FIG. 7, vent tube **200** can comprise an electrical flange **220**. Electrical flange **220** is configured to extend completely around vent tube **200** at or near distal end **210** and may include an extended portion **222**, e.g., an electrode portion, that functions as a connection point for an electrical cable, bus bar, or other electrical conductor. Electrical flange **220** may comprise a single, homogeneous piece and may comprise, for example a platinum-containing material, such as a platinum-rhodium alloy. In any of the preceding embodiments, vent tube **200** can be fitted with electrical flange **220** at distal end **210**, wherein an electrical power supply can provide an electrical current between electrical flange **220** and either one or both of first electrical flange assembly **40a** and/or third electrical flange assembly **40c**. In some embodiments, the electrical power supply can comprise an additional secondary winding, or a tap from a single secondary winding, of first electrical power source **56a**. Accordingly, vent tube **200** can be direct heated by an electrical current in a wall of the vent tube. To wit, the vent tube may serve as a heating element. As shown in FIGS. 10 and 11, in various embodiments, the wall of vent tube **200** at and/or near proximal end **206**, where vent tube **200** attaches to first conduit section **38a**, can be made thicker than the wall at distal end **118**, or thicker than the vent tube wall at an intermediate position between proximal end **206** and distal end **210**. For example, proximal end **206** may comprise multiple layers.

[0091] FIG. 11 illustrates an embodiment of proximal end **206** comprising a first, inner layer **224** and a second, outer layer **226**. Inner layer **224** can be the vent tube itself that extends from proximal end **206** to distal end **210**, wherein second layer **226** is a

cladding layer disposed over the vent tube at proximal end **206**. In such fabrication practices, second layer **226** can be attached to vent tube **200** by welding. A thick proximal end can strengthen the attachment region of vent tube **200** where the vent tube is attached to fining vessel **34** and can aid in controlling electrical current passing through the attachment point, thereby avoiding hot spots that may degrade the connection. Accordingly, in some embodiments the thickened portion of proximal end **206** may vary in thickness circumferentially as necessary to distribute the electrical current evenly around the circumference of the vent tube at proximal end **206**. Similarly, a region of first conduit section **38a** at the attachment of vent tube **200** may also be thickened relative to regions farther displaced from the vent tube, both to strengthen the connection point and to aid in distribution of the electrical current. The wall of connecting conduit **38** at the attachment point of vent tube **200** may also be thickened, such as by the attachment, for example by welding, of reinforcement plate(s) **228**. In some embodiments, distal end **210** of vent tube **200** where electrical flange **220** is joined to the vent tube may be thickened in a manner similar to proximal end **206** by attaching sleeve around the vent tube at distal end **210**.

[0092] In further embodiments, vent tube **200** can be heated by radiant and/or conductive heat from a separate heating element, e.g., a heating coil, positioned proximate the vent tube. For example, in some embodiments, a heating element can be coiled around but spaced apart from the vent tube. In some embodiments, a plurality of heating elements can be positioned at various locations around a circumference of vent tube **200**. To maintain a temperature of the vent tube, vent tube **200** may be surrounded by, e.g., encased in, a thermal insulating material (not shown), for example a ceramic insulating material.

[0093] It will be apparent to those skilled in the art that various modifications and variations can be made to embodiments of the present disclosure without departing from the spirit and scope of the disclosure. Thus, it is intended that the present disclosure cover such modifications and variations provided they come within the scope of the appended claims and their equivalents.

What is claimed is:

1. A method of manufacturing a glass article, comprising:
 flowing a molten material through a first vessel to a second vessel downstream from the first vessel, the molten material flowing through a conduit connecting the first vessel to the second vessel, the first vessel and the conduit defining a continuous free volume above a free surface of the molten material, the free volume extending into at least a portion of the conduit; and
 venting a first atmosphere contained in the free volume to a second atmosphere external to the first vessel through a vent tube comprising a proximal end, a distal end opposite the proximal end, and a passage extending between the proximal end and the distal end, the proximal end connected to the conduit proximate a top of the conduit and above the free surface, the vent tube extending downward and away from the conduit along a longitudinal axis at an angle α relative to horizontal and providing fluid communication between the first atmosphere and the second atmosphere.
2. The method of claim 1, wherein the vent tube is straight between the proximal end and the distal end.
3. The method of claim 1 or claim 2, wherein the angle α is in a range from greater than 0° to less than 90° .
4. The method of claim 3, wherein the angle α is in a range from about 3° to about 10° .
5. The method of any one of claims 1 to 4, further comprising heating the vent tube during the venting.
6. The method of claim 5, wherein the heating comprises establishing an electrical current in a heating element.
7. The method of claim 6, wherein the heating element comprises a wall of the vent tube.

8. The method of claim 5, wherein the heating comprises establishing an electrical current between a first electrical flange connected to the vent tube and a second electrical flange connected to at least one of the first vessel or the conduit.
9. The method of any one of claims 1 to 8, wherein the first vessel is a fining vessel.
10. The method of claim 9, wherein the second vessel is a mixing vessel.
11. The method of any one of claims 1 to 10, further comprising, flowing the molten material to a forming body and forming the molten material into a glass ribbon.
12. The method of claim 11, wherein the forming comprises drawing the molten material downward from the forming body.
13. The method of any one of claims 1 to 12, wherein a first portion of the conduit extends horizontally from the first vessel and the vent tube is connected to the first portion of the conduit.
14. The method of claim 13, wherein at least a second portion of the conduit extends downward relative to the first portion of the conduit.
15. The method of any one of claims 1 to 14, further comprising flowing a cover gas into the free volume through a gas delivery pipe connected to the first vessel.
16. The method of any one of claims 1 to 15, further comprising heating the conduit while flowing the molten material through the conduit.
17. The method of any one of claims 1 to 16, wherein a thickness of a wall of the conduit varies along a length of the conduit.
18. The method of any one of claims 1 to 16, wherein, in a cross-section of the conduit orthogonal to a longitudinal axis of the conduit, a thickness of a wall of the conduit in a first

portion of the cross-section is different than a thickness of the wall of the conduit in a second portion of the cross-section.

19. A method of manufacturing a glass article, comprising:

flowing a molten material from a first vessel through a conduit connected to the first vessel, the first vessel and the conduit defining a continuous free volume above a free surface of the molten material, the free volume extending into a portion of the conduit;

venting a first atmosphere contained in the free volume to a second atmosphere external to the first vessel through a vent tube comprising a proximal end and a distal end opposite the proximal end, the proximal end connected to the conduit proximate a top of the conduit and above the free surface, the vent tube extending downward along a longitudinal axis at an angle α relative to horizontal and providing fluid communication between the first atmosphere and the second atmosphere; and

heating the vent tube while the flowing the molten material, the heating removing condensate accumulated on an interior surface of the vent tube.

20. The method of claim 19, further comprising flowing the molten material to a forming body, the forming body forming the molten material into the glass article.

21. The method of claim 20, wherein the glass article is a glass ribbon.

22. The method of any one of claims 19 to 21, wherein the heating comprises establishing an electrical current in a heating element.

23. The method of claim 22, wherein the heating element comprises a wall of the vent tube.

24. The method of any one of claims 19 to 21, wherein the heating comprises establishing an electrical current between a first electrical flange connected to the vent tube and a second electrical flange connected to at least one of the first vessel or the conduit.

25. The method of any one of claims 19 to 24, wherein the first vessel is a fining vessel.

26. The method of claim 25, wherein the second vessel is a mixing vessel.
27. The method of any one of claims 19 to 26, further comprising flowing the molten material to a forming body and forming the molten material into a glass ribbon.
28. The method of claim 27, wherein the forming comprises drawing the molten material downward from the forming body.
29. The method of any one of claims 19 to 28, wherein at least a first portion of the conduit extends downward relative to horizontal.
30. The method of claim 29, wherein a second portion of the conduit extends horizontally from the first vessel, the vent tube connected to the second portion of the conduit.
31. The method of any one of claims 19 to 30, further comprising flowing a cover gas into the free volume through a gas delivery pipe.
32. The method of claim 31, wherein the gas delivery pipe is connected to the first vessel.

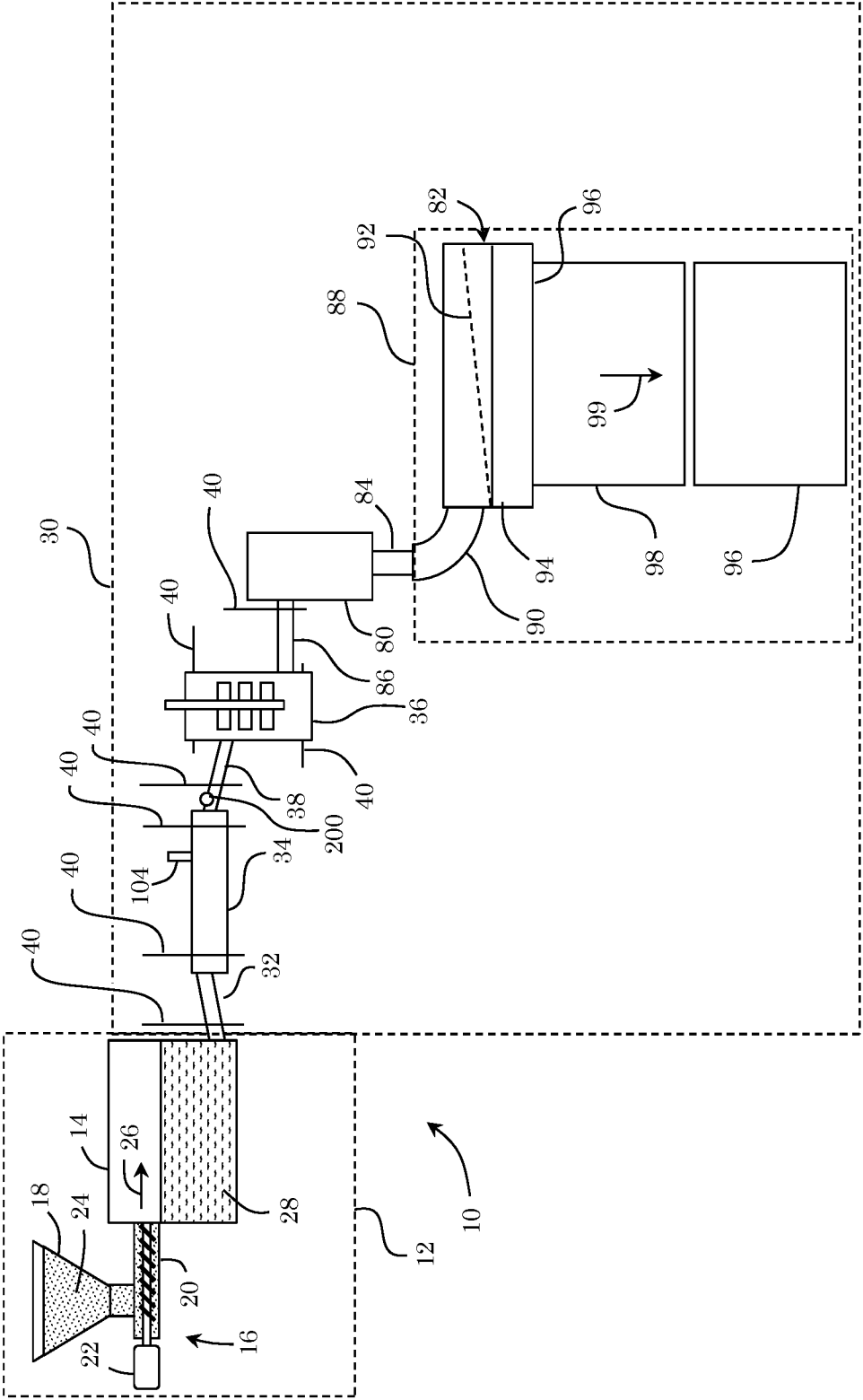


FIG. 1

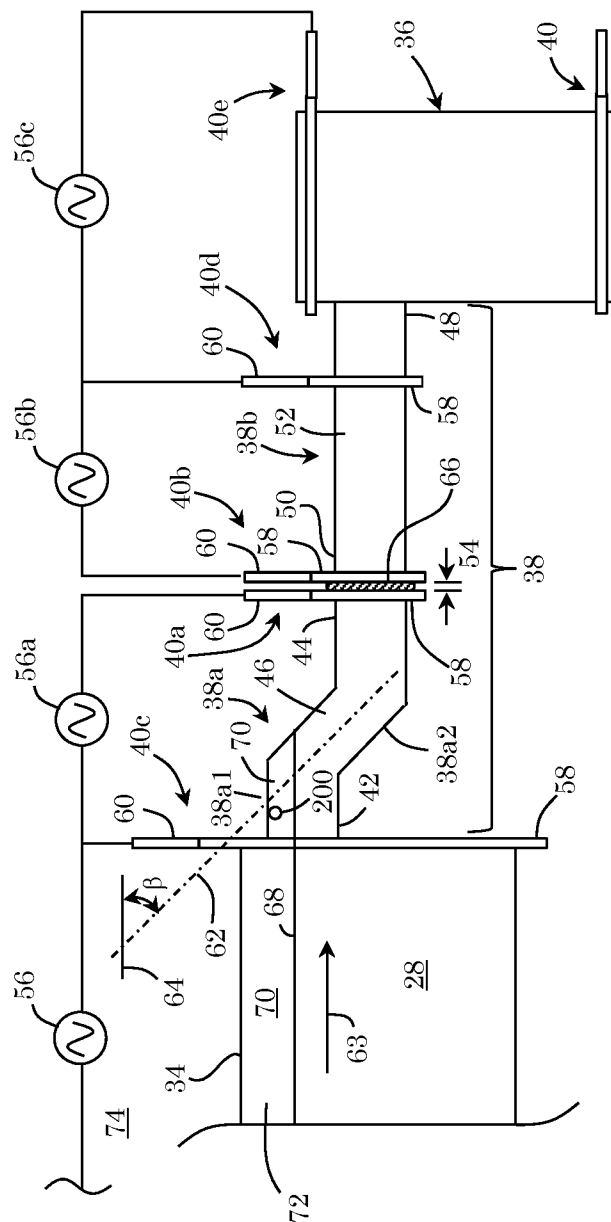


FIG. 2

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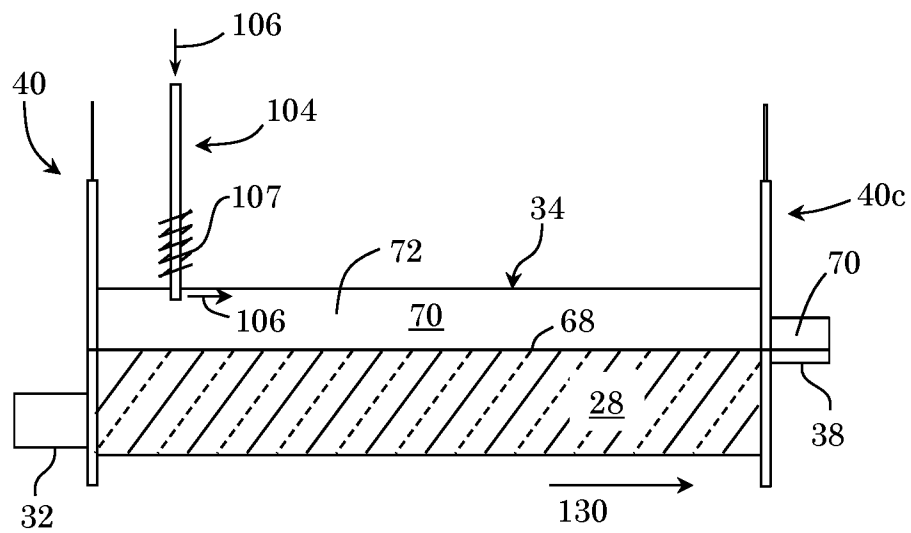


FIG. 3

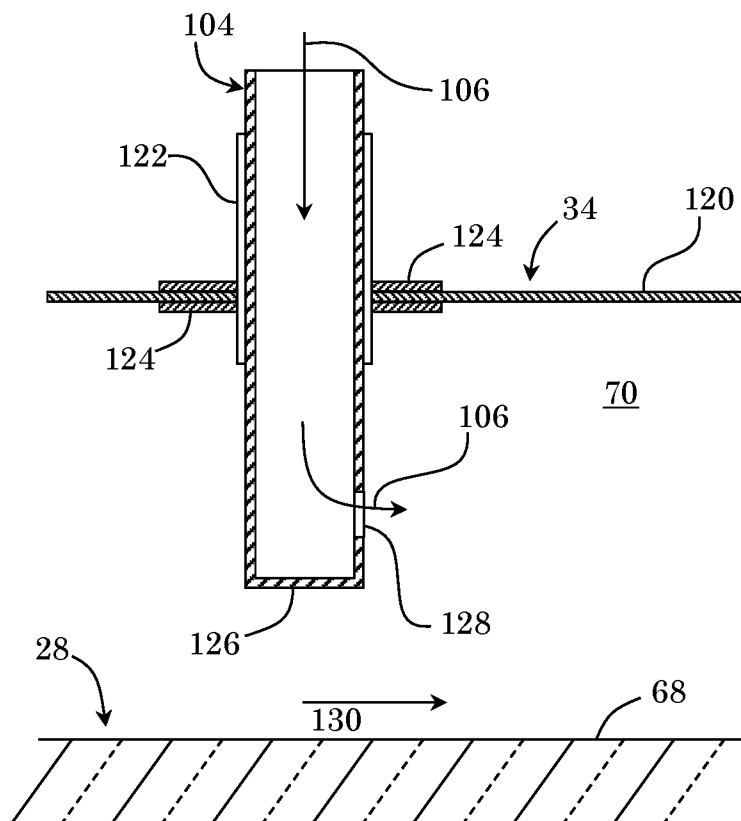


FIG. 4

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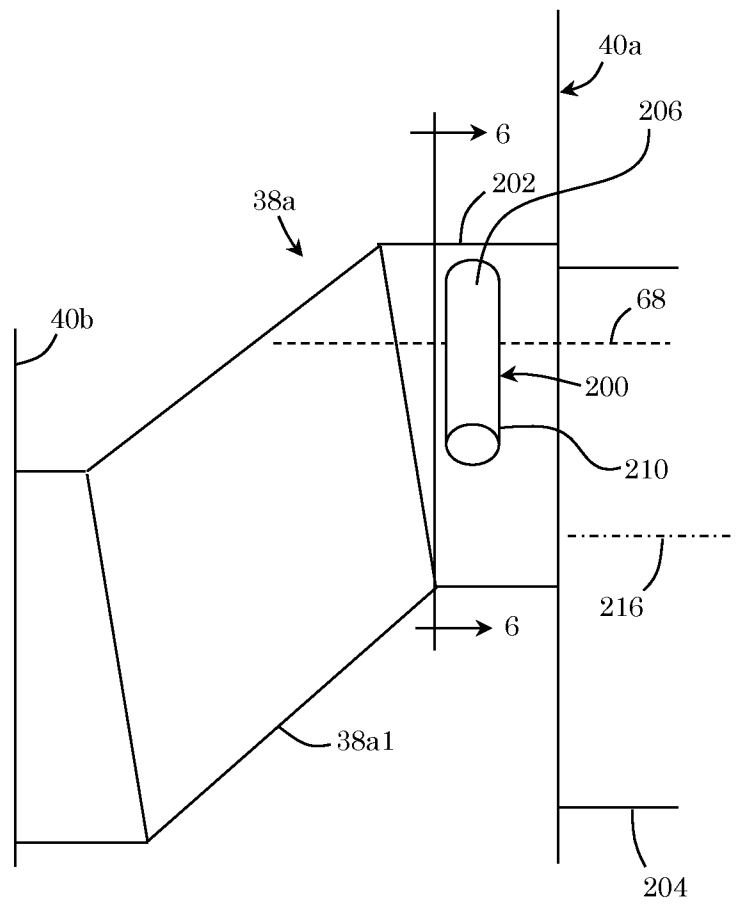


FIG. 5

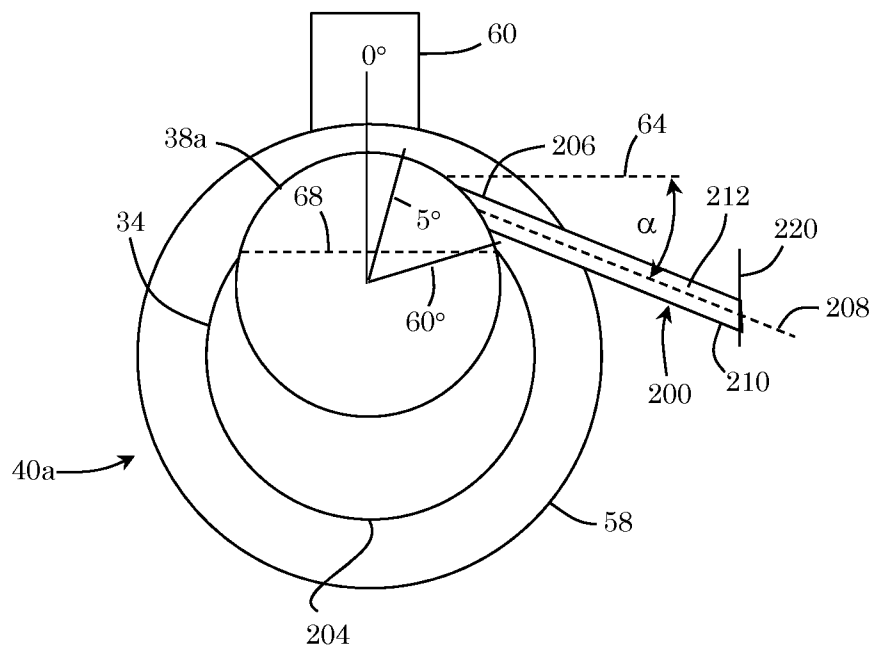


FIG. 6

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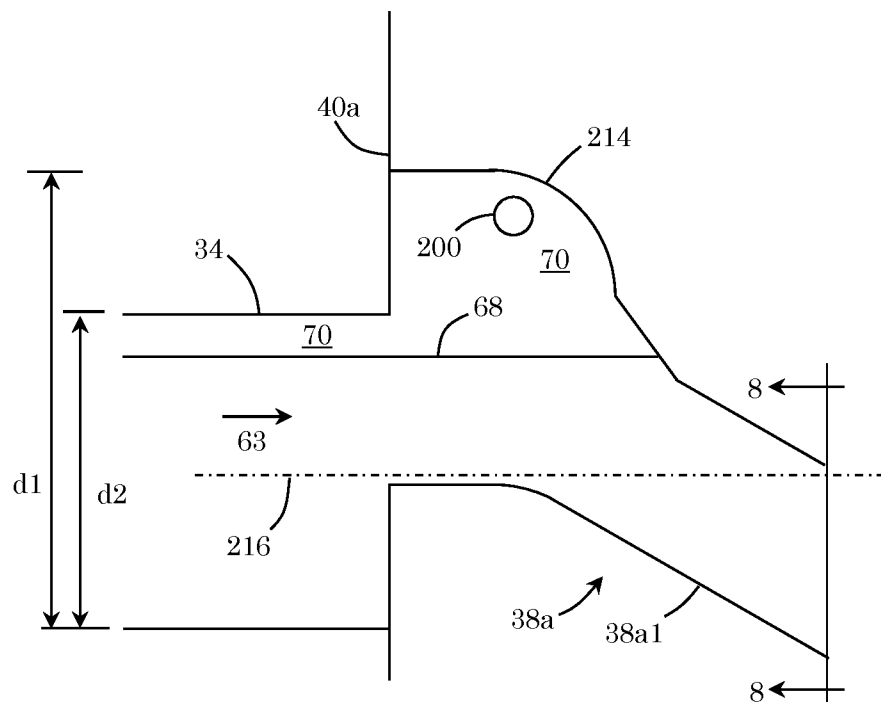


FIG. 7

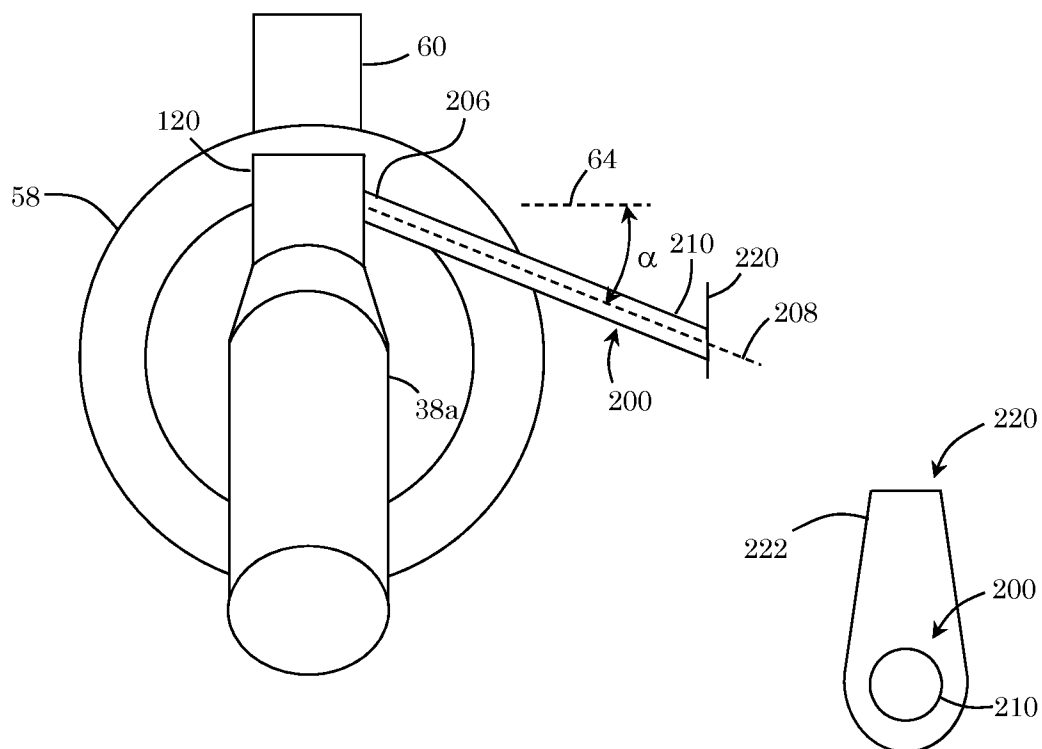


FIG. 8

FIG. 9

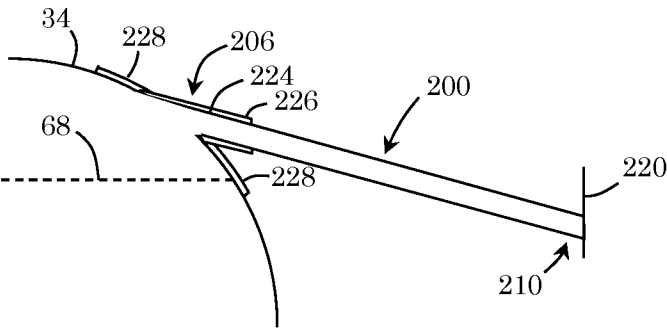


FIG. 10

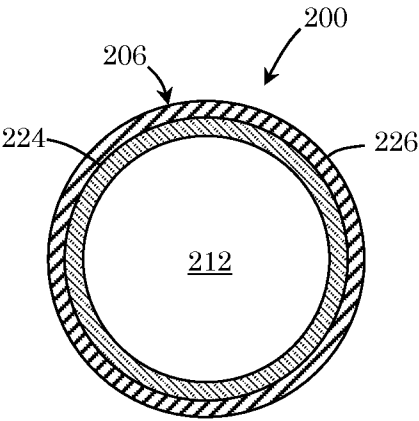


FIG. 11

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2021/044260

A. CLASSIFICATION OF SUBJECT MATTER C03B 5/20(2006.01)i 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 5/20(2006.01); C03B 13/00(2006.01); C03B 5/167(2006.01); C03B 5/18(2006.01); C03B 5/187(2006.01); C03B 5/225(2006.01); C03B 5/235(2006.01); C03B 5/26(2006.01); C03B 7/00(2006.01) Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Korean utility models and applications for utility models Japanese utility models and applications for utility models Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) eKOMPASS(KIPO internal) & Keywords: glass, vent tube, vessel, conduit		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2020-009143 A1 (NIPPON ELECTRIC GLASS CO., LTD.) 09 January 2020 (2020-01-09) paragraphs [0040], [0059], [0080]; claims 1, 3, 8-10; figures 1-2, 13-18	1-4,19-24
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A	JP 2015-199639 A (AVANSTRATE INC.) 12 November 2015 (2015-11-12) the whole document	1-4,19-24
☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "D" document cited by the applicant in the international application "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 24 November 2021		Date of mailing of the international search report 24 November 2021
Name and mailing address of the ISA/KR Korean Intellectual Property Office 189 Cheongsa-ro, Seo-gu, Daejeon 35208, Republic of Korea Facsimile No. +82-42-481-8578		Authorized officer Jung, Da Won Telephone No. +82-42-481-5373

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2021/044260

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☒ Claims Nos.: **6-8, 10, 12, 14, 26, 28, 30, 32**
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

Claims 6-8, 10, 12, 14, 26, 28, 30, 32 refer to a multiple dependent claim which does not comply with PCT Rule 6.4(a).
3. ☒ Claims Nos.: **5, 9, 11, 13, 15-18, 25, 27, 29, 31**
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/US2021/044260

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