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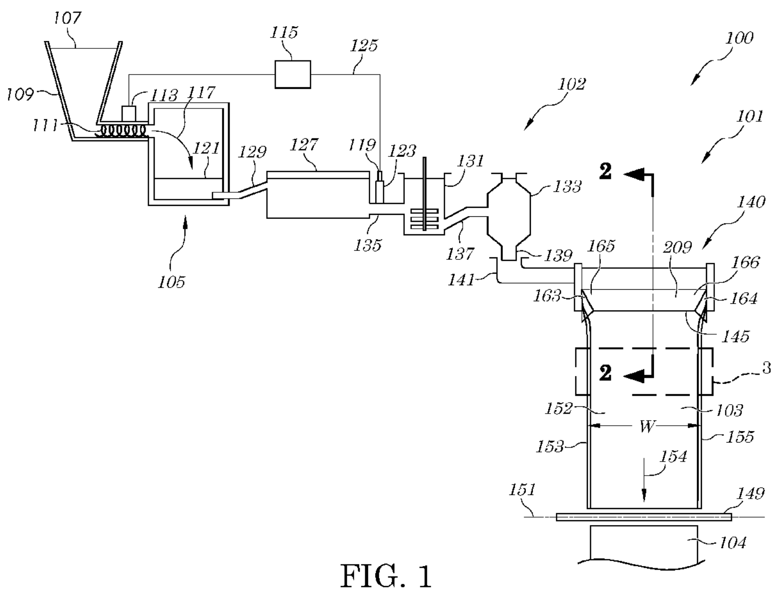

FIG. 1

(57) Abstract: A glass manufacturing apparatus includes a forming apparatus defining a travel path extending in a travel direction. The forming apparatus conveys a ribbon of glass-forming material along the travel path in the travel direction of the forming apparatus. The glass manufacturing apparatus includes a cooling tube extending substantially parallel to the travel path and extending across the travel direction. The cooling tube includes a plurality of orifices spaced apart along the cooling tube and facing the travel path. Methods of manufacturing glass can comprise flowing a coolant from an outlet of a conduit in a direction toward a target location of a flowing ribbon of molten material. Methods can also include changing a phase of the coolant while the coolant is flowing towards the target location. The change in phase can cool the target location.

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METHODS AND APPARATUS FOR PRODUCING A GLASS RIBBON

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. 62/896,699 filed on September 6, 2019 and U.S. Provisional Application Serial No. 62/868,187 filed on June 28, 2019 the content of which are relied upon and incorporated herein by reference in their entirety.

FIELD

[0001] The present disclosure relates generally to apparatus and methods for producing a glass ribbon and, more particularly, to apparatus and methods for cooling a glass ribbon.

BACKGROUND

[0002] It is known to manufacture molten material into a glass ribbon with a glass manufacturing apparatus. To increase the production capability of the glass manufacturing apparatus, a flow rate of the molten material can be increased. However, increasing the flow rate may necessitate an increase in cooling of the molten material to maintain a target cooling curve.

SUMMARY

[0003] The following presents a simplified summary of the disclosure to provide a basic understanding of some embodiments described in the detailed description.

[0004] Methods of manufacturing glass in accordance with embodiments of the disclosure can aid in increasing a flow rate of molten material in a glass manufacturing process and can inhibit (e.g., reduce, prevent, eliminate) problems associated with baggy warp. Baggy warp can occur when the viscosity of the molten material drawn from the forming device is too low such that a drawn ribbon of molten material cannot maintain its thickness, registration, and/or shape either under gravity, the force of pull rollers, or both. Embodiments of the disclosure can avoid baggy warp by aggressively cooling an outer portion of the streams of molten material (e.g., first stream, second stream) opposite the inner portion of the respective stream of molten material to increase an effective viscosity where the ribbon of molten material is drawn. Methods

of the embodiments of the disclosure can address baggy warp by allowing greater cooling rates (e.g., heat flux) and/or cooling capacity than would be possible using heat transfer, for example, by convection and/or radiation. Aggressive cooling of the glass ribbon can also facilitate processing of molten material with a low liquidus viscosity to a predetermined thickness. Further, directing the coolant toward a location on the ribbon of molten material positioned below the forming vessel can inhibit the crystallization of the molten material on the forming vessel. Additionally, directing the coolant toward a location above pull rollers can increase processing efficiency. Increased cooling capacity (e.g., above the pull rollers, below the forming device) can enable a reduction in a length of molten material travel path from when the ribbon of molten material is drawn from the forming vessel and when it can be handled.

[0005] Accordingly, a glass manufacturing apparatus is disclosed comprising a forming apparatus defining a travel path extending in a travel direction. The forming apparatus is configured to convey a ribbon of glass-forming material along the travel path in the travel direction of the forming apparatus. The glass manufacturing apparatus comprises a cooling tube extending substantially parallel to the travel path and extending across the travel direction. The cooling tube comprises a plurality of orifices spaced apart along the cooling tube and facing the travel path.

[0006] In some embodiments, the cooling tube extends linearly along a cooling axis.

[0007] In some embodiments, the cooling axis is substantially perpendicular to the travel direction.

[0008] In some embodiments, the glass manufacturing apparatus comprises a plurality of nozzles, wherein each nozzle of the plurality of nozzles is in fluid communication with a corresponding one or more orifices of the plurality of orifices, and each nozzle of the plurality of nozzles is configured to discharge atomized streams of fluid toward the travel path.

[0009] In some embodiments, a first nozzle orifice of a first nozzle of the plurality of nozzles comprises a first diameter and a second nozzle orifice of a second nozzle of the plurality of nozzles comprises a second diameter equal to the first diameter.

[0010] In some embodiments, the plurality of nozzles comprises a set of sequentially spaced nozzles comprising the first nozzle, the second nozzle spaced a first distance from the first nozzle, and a third nozzle of the plurality of nozzles spaced a second distance from the second nozzle, wherein the second nozzle is positioned in series between the first nozzle and the third nozzle, and the first distance is different than the second distance.

[0011] In some embodiments, a third nozzle orifice of the third nozzle comprises a third diameter that is different than the second diameter.

[0012] In some embodiments, the cooling tube comprises a plurality of cooling tubes, wherein a first set of the plurality of cooling tubes is positioned on a first side of the travel path, and a second set of the plurality of cooling tubes is positioned on a second side of the travel path.

[0013] In some embodiments, cooling tubes of the first set of the plurality of cooling tubes are sequentially spaced apart along the travel direction and cooling tubes of the second set of the plurality of cooling tubes are sequentially spaced apart along the travel direction.

[0014] In accordance with some embodiments, a glass manufacturing apparatus is described comprising a forming apparatus defining a travel path extending in a travel direction. The forming apparatus is configured to convey a ribbon of glass-forming material along the travel path in the travel direction of the forming apparatus. The glass manufacturing apparatus comprises a nozzle configured to discharge an atomized stream of fluid toward the travel path.

[0015] In some embodiments, the nozzle is configured to discharge one or more droplets of the atomized stream of fluid, the one or more droplets comprising a diameter within a range from about 0.5 micrometers to about 3 micrometers.

[0016] In some embodiments, the nozzle is configured to discharge the atomized stream of fluid within a spray angle range from about 0 degrees to about 90 degrees.

[0017] In some embodiments, the glass manufacturing apparatus comprises a cooling tube extending substantially parallel to the travel path and extending across the travel direction, the cooling tube comprising a plurality of orifices facing the travel path.

[0018] In some embodiments, a first cooling tube extends substantially parallel to the travel path and extends across the travel direction. The first cooling tube comprises a first orifice facing the travel path.

[0019] In some embodiments, the nozzle comprises a plurality of nozzles sequentially spaced across the travel direction.

[0020] In accordance with some embodiments, methods of producing a glass ribbon are disclosed comprising forming a ribbon of glass-forming material. Methods can comprise moving the ribbon of glass-forming material along a travel path in a travel direction. Methods can comprise converting a cooling fluid into one or more atomized streams of fluid. Methods can comprise converting a cooling fluid into one or more atomized streams of fluid. Methods can comprise directing the one or more atomized streams of fluid toward an area of the ribbon of glass-forming material. Methods can comprise cooling the area of the ribbon of glass-forming material by evaporating a portion of the one or more atomized streams of fluid without contacting the portion of the one or more atomized streams of fluid with the area of the ribbon of glass-forming material. Methods can comprise cooling the ribbon of glass-forming material into the glass ribbon.

[0021] In some embodiments, the directing the one or more atomized streams of fluid can comprise directing a first atomized stream of fluid toward a first side of the ribbon of glass-forming material and directing a second atomized stream of fluid toward a second side of the ribbon of glass-forming material.

[0022] In some embodiments, the directing the one or more atomized streams of fluid can comprise directing a third atomized stream of fluid toward the first side of the ribbon of glass-forming material downstream from the first atomized stream of fluid relative to the travel direction.

[0023] In some embodiments, the directing the one or more atomized streams of fluid toward the area of the ribbon of glass-forming material can comprise varying an amount of the one or more atomized streams of fluid directed toward the area.

[0024] In some embodiments, the cooling the area of the ribbon of glass-forming material can comprise attaining a substantially uniform temperature of the ribbon of glass-forming material along an axis perpendicular to the travel direction.

[0025] In still other embodiments, a method of manufacturing glass is disclosed, comprising flowing a coolant from an outlet of a conduit in a direction toward a target location of a flowing ribbon of molten material and changing a phase of the coolant while the coolant is flowing toward the target location, the change in phase cooling the target location. The coolant can comprise one or more of water, nitrogen, or carbon dioxide.

[0026] In some embodiments, a mass flow rate of the coolant flowing from the outlet can be in a range from about 1 gram per minute to about 200 grams per minute.

[0027] In some embodiments, the coolant flowing from the outlet can comprise solid particles with a median particle size in a range from about 5 micrometers to about 20 micrometers. For example, about 90% of the solid particles can comprise a size in a range from about 1 micrometer to about 100 micrometers.

[0028] In some embodiments, the coolant flowing from the outlet can comprise liquid droplets.

[0029] The method may further comprise heating the conduit. The method may further comprise moving the gas with a convective air current traveling along the ribbon of molten material. The convective air current can flow in a direction opposite a travel direction of the ribbon of molten material.

[0030] In some embodiments, the target location can be positioned below a forming vessel. For example, a minimum distance between the forming vessel and the target location can be about 1 meter or less.

[0031] The method may comprise pulling the molten material with pull rollers, wherein the target location is positioned between the forming vessel and the pull rollers.

[0032] A minimum distance between the outlet and the flowing ribbon of molten material can be in a range from about 100 millimeters to about 1 meter.

[0033] The conduit can comprise a nozzle comprising the outlet. For example, the nozzle can comprise a boiling nozzle or a shear nozzle. In some embodiments, the nozzle can comprise a diffuser.

[0034] In some embodiments, the conduit can comprise a plurality of conduits, the outlets of a first set of the plurality of conduits flowing the coolant toward a first surface of the ribbon of molten material, and the outlets of a second set of the plurality of conduits flowing the coolant toward a second surface of the ribbon of molten material opposite the first surface. The first set of the plurality of conduits can be arranged in a first row. The second set of the plurality of conduits can be arranged in a second row.

[0035] In some embodiments, the method may further comprise determining a deviation of a thickness of a portion of the ribbon of molten material from a predefined thickness, the cooling reducing the deviation of the thickness of the portion of the ribbon of molten material from the predefined thickness by increasing a viscosity of the portion of the ribbon of molten material.

[0036] 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. 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

[0037] These and other features, embodiments and advantages are better understood when the following detailed description is read with reference to the accompanying drawings, in which:

[0038] **FIG. 1** schematically illustrates example embodiments of a glass manufacturing apparatus in accordance with embodiments of the disclosure;

[0039] **FIG. 2** illustrates a perspective cross-sectional view of the glass manufacturing apparatus along line **2-2** of **FIG. 1** in accordance with embodiments of the disclosure;

[0040] **FIG. 3** illustrates an enlarged portion of the glass manufacturing apparatus taken at view **3** of **FIG. 1** in accordance with embodiments of the disclosure;

[0041] **FIG. 4** illustrates a side view of a plurality of cooling tubes of the glass manufacturing apparatus along line **4-4** of **FIG. 3** in accordance with embodiments of the disclosure;

[0042] **FIG. 5** illustrates a sectional view of a first cooling tube of the plurality of cooling tubes along line **5-5** of **FIG. 3** in accordance with embodiments of the disclosure;

[0043] **FIG. 6** illustrates a front view of the first cooling tube of the plurality of cooling tubes along line **6-6** of **FIG. 3** in accordance with embodiments of the disclosure;

[0044] **FIG. 7** illustrates an enlarged portion of additional embodiments of the glass manufacturing apparatus taken at view **3** of **FIG. 1** in accordance with embodiments of the disclosure; and

[0045] FIG. 8 illustrates a sectional view of additional embodiments of a first cooling tube of the plurality of cooling tubes along line **8-8** of **FIG. 7** in accordance with embodiments of the disclosure.

[0046] FIG. 9 schematically illustrates an example glass manufacturing apparatus in accordance with some embodiments of the disclosure;

[0047] FIG. 10 shows a cross-sectional view of a glass manufacturing apparatus taken along lines **10-10** of **FIG. 9** in accordance with some embodiments of the disclosure;

[0048] FIG. 11 is an enlarged view **6** of **FIG. 10**;

[0049] FIG. 12 illustrates another cross-sectional view of a glass manufacturing apparatus taken along lines **12-12** of **FIG. 10** in accordance with some embodiments of the disclosure;

[0050] FIG. 13 is a plot illustrating overall heat flux as a function of mass flow rate; and

[0051] FIG. 14 is a plot illustrating localization of heat flux as a function of mass flow rate.

DETAILED DESCRIPTION

[0052] Embodiments will now be described more fully hereinafter with reference to the accompanying drawings in which example embodiments are shown. Whenever possible, the same reference numerals are used throughout the drawings to refer to the same or like parts. However, this disclosure may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein.

[0053] The present disclosure relates to a glass manufacturing apparatus and methods for producing a glass ribbon. Methods and apparatus for producing a glass ribbon will now be described by way of example embodiments for producing a glass ribbon from a ribbon of glass-forming material. As schematically illustrated in **FIG. 1**, in some embodiments, an exemplary glass manufacturing apparatus **100** can comprise a glass melting and delivery apparatus **102** and a forming apparatus **101** comprising a forming vessel **140** designed to produce a ribbon of glass-forming material **103** from a quantity of molten material **121**. In some embodiments, the ribbon of glass-forming material **103** can comprise a central portion **152** positioned between opposite edge portions (e.g., edge beads) formed along a first outer edge **153** and a second outer edge **155** of the ribbon of glass-forming material **103**, wherein a thickness of the edge portions can be greater than a thickness of the central portion. Additionally, in some embodiments, a separated glass ribbon **104** can be separated from the ribbon of glass-forming material **103** along a separation path **151** by a glass separator **149** (e.g., scribe, score wheel, diamond tip, laser, etc.).

[0054] In some embodiments, the glass melting and delivery apparatus **102** can comprise a melting vessel **105** oriented to receive batch material **107** from a storage bin **109**. The batch material **107** can be introduced by a batch delivery device **111** powered by a motor **113**. In some embodiments, an optional controller **115** can be operated to activate the motor **113** to introduce a desired amount of batch material **107** into the melting vessel **105**, as indicated by arrow **117**. The melting vessel **105** can heat the batch material **107** to provide molten material **121**. In some embodiments, a melt probe **119** can be employed to measure a level of molten material **121** within a standpipe **123** and communicate the measured information to the controller **115** by way of a communication line **125**.

[0055] Additionally, in some embodiments, the glass melting and delivery apparatus **102** can comprise a first conditioning station comprising a fining vessel **127** located downstream from the melting vessel **105** and coupled to the melting vessel **105** by way of a first connecting conduit **129**. In some embodiments, molten material **121** can be gravity fed from the melting vessel **105** to the fining vessel **127** by way of the first connecting conduit **129**. For example, in some embodiments, gravity can drive the molten material **121** through an interior pathway of the first connecting conduit **129** from the melting vessel **105** to the fining vessel **127**. Additionally, in some embodiments, bubbles can be removed from the molten material **121** within the fining vessel **127** by various techniques.

[0056] In some embodiments, the glass melting and delivery apparatus **102** can further comprise a second conditioning station comprising a mixing chamber **131** that can be located downstream from the fining vessel **127**. The mixing chamber **131** can be employed to provide a homogenous composition of molten material **121**, thereby reducing or eliminating inhomogeneity that may otherwise exist within the molten material **121** exiting the fining vessel **127**. As shown, the fining vessel **127** can be coupled to the mixing chamber **131** by way of a second connecting conduit **135**. In some embodiments, molten material **121** can be gravity fed from the fining vessel **127** to the mixing chamber **131** by way of the second connecting conduit **135**. For example, in some embodiments, gravity can drive the molten material **121** through an interior pathway of the second connecting conduit **135** from the fining vessel **127** to the mixing chamber **131**.

[0057] Additionally, in some embodiments, the glass melting and delivery apparatus **102** can comprise a third conditioning station comprising a delivery chamber **133** that can be located downstream from the mixing chamber **131**. In some embodiments, the delivery chamber **133** can condition the molten material **121** to be fed into an inlet conduit **141**. For example, the delivery chamber **133** can function as an accumulator and/or flow controller to adjust and provide a consistent flow of molten material **121** to the inlet conduit **141**. As shown, the mixing chamber **131** can be coupled to the delivery chamber **133** by way of a third connecting conduit **137**. In some embodiments, molten material **121** can be gravity fed from the mixing chamber **131** to the delivery chamber **133** by way of the third connecting conduit **137**. For example, in some embodiments, gravity can drive the molten material **121** through an interior pathway of the third connecting conduit **137** from the mixing chamber **131** to the delivery chamber **133**. As further illustrated, in some embodiments, a delivery pipe **139** can be positioned to deliver molten material **121** to forming apparatus **101**, for example the inlet conduit **141** of the forming vessel **140**.

[0058] Forming apparatus **101** can comprise various embodiments of forming vessels in accordance with features of the disclosure, for example, a forming vessel with a wedge for fusion drawing the glass ribbon, a forming vessel with a slot to slot draw the glass ribbon, or a forming vessel provided with press rolls to press roll the glass ribbon from the forming vessel. In some embodiments, the forming apparatus **101** can comprise a sheet redraw, for example, with the forming apparatus **101** as part of a redraw process. For example, the glass ribbon **104**, which can comprise a thickness, may be heated up and redrawn to achieve a thinner glass ribbon **104** comprising a smaller thickness. By way of illustration, the forming vessel **140** shown and disclosed below can be provided to fusion draw molten material **121** off a bottom edge, defined as a root **145**, of a forming wedge **209** to produce the ribbon of glass-forming material **103**. For example, in some embodiments, the molten material **121** can be delivered from the inlet conduit **141** to the forming vessel **140**. The molten material **121** can then be formed into the ribbon of glass-forming material **103** based, in part, on the structure of the forming vessel **140**. For example, as shown, the molten material **121** can be drawn off the bottom edge (e.g., root **145)** of the forming vessel **140** along a draw path extending in a travel direction **154** of the glass manufacturing apparatus **100**. In some embodiments, edge directors **163**, **164** can direct the molten material **121** off the forming vessel **140** and define, in part, a width "**W**" of the ribbon of glass-forming material **103**. In some embodiments, the width "**W**" of the ribbon of glass-forming material **103** extends between the first outer edge **153** of the ribbon of glass-forming material **103** and the second outer edge **155** of the ribbon of glass-forming material **103**.

[0059] In some embodiments, the width "**W**" of the ribbon of glass-forming material **103**, which extends between the first outer edge **153** of the ribbon of glass-forming material **103** and the second outer edge **155** of the ribbon of glass-forming material **103**, can be greater than or equal to about 20 millimeters (mm), for example, greater than or equal to about 50 mm, for example, greater than or equal to about 100 mm, for example, greater than or equal to about 500 mm, for example, greater than or equal to about 1000 mm, for example, greater than or equal to about 2000 mm, for example, greater than or equal to about 3000 mm, for example, greater than or equal to about 4000 mm, although other widths less than or greater than the widths mentioned above can be provided in further embodiments. For example, in some embodiments, the width "**W**" of the ribbon of glass-forming material **103** can be within a range from about 20 mm to about 4000 mm, for example, within a range from about 50 mm to about 4000 mm, for example, within a range from about 100 mm to about 4000 mm, for example, within a range from about 500 mm to about 4000 mm, for example, within a range from about 1000 mm to about 4000 mm, for example, within a range from about 2000 mm to about 4000 mm, for example, within a range from about 3000 mm to about 4000 mm, for example, within a range from about 20 mm to about 3000 mm, for example, within a range from about 50 mm to about 3000 mm, for example, within a range from about 100 mm to about 3000 mm, for example, within a range from about 500 mm to about 3000 mm, for example, within a range from about 1000 mm to about 3000 mm, for example, within a range from about 2000 mm to about 3000 mm, for example, within a range from about 2000 mm to about 2500 mm, and all ranges and subranges therebetween.

[0060] FIG. 2 shows a cross-sectional perspective view of the forming apparatus **101** (e.g., forming vessel **140)** along line **2-2** of **FIG. 1**. In some embodiments, the forming vessel **140** can comprise a trough **201** oriented to receive the molten material **121** from the inlet conduit **141**. For illustrative purposes, cross-hatching of the molten material

121 is removed from **FIG. 2** for clarity. The forming vessel **140** can further comprise the forming wedge **209** comprising a pair of downwardly inclined converging surface portions **207**, **208** extending between opposed ends **165**, **166** (See **FIG. 1**) of the forming wedge **209**. The pair of downwardly inclined converging surface portions **207**, **208** of the forming wedge **209** can converge along the travel direction **154** to intersect along the root **145** of the forming vessel **140**. A draw plane **213** of the glass manufacturing apparatus **100** can extend through the root **145** along the travel direction **154**. In some embodiments, the ribbon of glass-forming material **103** can be drawn in the travel direction **154** along the draw plane **213**. As shown, the draw plane **213** can bisect the forming wedge **209** through the root **145** although, in some embodiments, the draw plane **213** can extend at other orientations relative to the root **145**. In some embodiments, the ribbon of glass-forming material **103** can move along a travel path **221** that may be co-planar with the draw plane **213** in the travel direction **154**.

[0061] Additionally, in some embodiments, the molten material **121** can flow in a direction **156** into and along the trough **201** of the forming vessel **140**. The molten material **121** can then overflow from the trough **201** by simultaneously flowing over corresponding weirs **203**, **204** and downward over the outer surfaces **205**, **206** of the corresponding weirs **203**, **204**. Respective streams of molten material **121** can then flow along the downwardly inclined converging surface portions **207**, **208** of the forming wedge **209** to be drawn off the root **145** of the forming vessel **140**, where the flows converge and fuse into the ribbon of glass-forming material **103**. The ribbon of glass-forming material **103** can then be drawn off the root **145** in the draw plane **213** along the travel direction **154**. In some embodiments, the ribbon of glass-forming material **103** comprises one or more states of material based on a vertical location of the ribbon of glass-forming material **103**. For example, at one location, the ribbon of glass-forming material **103** can comprise the viscous molten material **121**, and at another location, the ribbon of glass-forming material **103** can comprise an amorphous solid in a glassy state (e.g., a glass ribbon).

[0062] The ribbon of glass-forming material **103** comprises a first major surface **215** and a second major surface **216** facing opposite directions and defining a thickness "**T**" (e.g., average thickness) of the ribbon of glass-forming material **103**. In some embodiments, the thickness "**T**' of the ribbon of glass-forming material **103** can be less than or equal to about 2 millimeters (mm), less than or equal to about 1 millimeter, less than or equal to about 0.5 millimeters, for example, less than or equal to about 300 micrometers (μm), less than or equal to about 200 micrometers, or less than or equal to about 100 micrometers, although other thicknesses may be provided in further embodiments. For example, in some embodiments, the thickness "**T**" of the ribbon of glass-forming material **103** can be within a range from about 20 micrometers to about 200 micrometers, within a range from about 50 micrometers to about 750 micrometers, within a range from about 100 micrometers to about 700 micrometers, within a range from about 200 micrometers to about 600 micrometers, within a range from about 300 micrometers to about 500 micrometers, within a range from about 50 micrometers to about 500 micrometers, within a range from about 50 micrometers to about 700 micrometers, within a range from about 50 micrometers to about 600 micrometers, within a range from about 50 micrometers to about 500 micrometers, within a range from about 50 micrometers to about 400 micrometers, within a range from about 50 micrometers to about 300 micrometers, within a range from about 50 micrometers to about 200 micrometers, within a range from about 50 micrometers to about 100 micrometers, within a range from about 25 micrometers to about 125 micrometers, comprising all ranges and subranges of thicknesses therebetween. Exemplary molten materials, which may be free of lithia or not, can comprise soda lime molten material, aluminosilicate molten material, alkali-aluminosilicate molten material, borosilicate molten material, alkali-borosilicate molten material, alkali-alumniophosphosilicate molten material, or alkali-aluminoborosilicate glass molten material. In one or more embodiments, the molten material **121** may comprise, in mole percent (mol %): SiO_2 in a range from about 40 mol % to about 80%, Al_2O_3 in a range from about 10 mol % to about 30 mol %, B_2O_3 in a range from about 0 mol % to about 10 mol %, ZrO_2 in a range from about 0 mol% to about 5 mol %, P_2O_5 in a range from about 0 mol % to about 15 mol %, TiO_2 in a range from about 0 mol % to about 2 mol %, R_2O in a range from about 0 mol % to about 20 mol %, and RO in a range from 0 mol % to about 15 mol %. As used herein, R_2O can refer to an alkali metal oxide, for example, Li_2O, Na_2O, K_2O, Rb_2O, and Cs_2O. As used herein, RO can refer to MgO, CaO, SrO, BaO, and ZnO. In some embodiments, a molten material **121** may optionally further comprise in a range from about 0 mol % to about 2 mol %, any one or more of Na_2SO_4, NaCl, NaF, NaBr, K_2SO_4, KCl, KF, KBr, As_2O_3, Sb_2O_3, SnO_2, Fe_2O_3, MnO, MnO_2, MnO_3, Mn_2O_3, Mn_3O_4, Mn_2O_7. In some embodiments, the ribbon of glass-forming material **103**, the glass ribbon **106**, and/or glass sheets formed from the may be transparent, meaning that the ribbon of glass-forming material 103 and/or the glass ribbon **106** drawn from the molten material **121** can comprise an average light transmission over the optical wavelengths from 400 nanometers (nm) to 700 nm of about 85% or greater, about 86% or greater, about 87% or greater, about 88% or greater, about 89% or greater, about 90% or greater, about 91% or greater, or about 92% or greater.

[0063] In some embodiments, the glass separator **149** (see **FIG. 1**) can separate the glass ribbon **104** from the ribbon of glass-forming material **103** along the separation path **151** to provide a plurality of separated glass ribbons **104** (i.e., a plurality of sheets of glass). According to other embodiments, a longer portion of the glass ribbon **104** may be coiled onto a storage roll. The separated glass ribbon can then be processed into a desired application, e.g., a display application. For example, the separated glass ribbon can be used in a wide range of display applications, comprising liquid crystal displays (LCDs), electrophoretic displays (EPD), organic light emitting diode displays (OLEDs), plasma display panels (PDPs), touch sensors, photovoltaics, and other electronic displays.

[0064] **FIG. 3** illustrates an enlarged view of a portion of the ribbon of glass-forming material **103** at view **3** of **FIG. 1**. In some embodiments, the glass manufacturing apparatus **100** can comprise a cooling apparatus **301** for cooling the ribbon of glass-forming material **103**. For example, the ribbon of glass-forming material **103** can be conveyed from the forming apparatus **101** (e.g., illustrated in **FIGS. 1-2**) along the travel path **221** in the travel direction **154**. The cooling apparatus **301** can be located downstream from the forming apparatus **101** (e.g., illustrated in **FIG. 1**) relative to the travel direction **154**. For example, the cooling apparatus **301** can comprise a cooling tube extending substantially parallel to the travel path **221** and extending across the travel direction **154**. In some embodiments, the cooling tube can comprise a plurality of cooling tubes **303**.

[0065] The cooling apparatus **301** can comprise a fluid source **305** that can deliver a cooling fluid (e.g., water) to the plurality of cooling tubes **303**. The cooling apparatus **301** can comprise a gas source **307** that can deliver a compressed gas (e.g., air) to the plurality of cooling tubes **303**. The cooling fluid and the compressed gas can be mixed and discharged as an atomized stream of fluid from the plurality of cooling tubes **303**

toward the ribbon of glass-forming material **103**. In some embodiments, due to the relatively high temperatures adjacent to the ribbon of glass-forming material **103**, the atomized stream of fluid can at least partially evaporate. For example, an air temperature adjacent to the ribbon of glass-forming material **103** can be within a range from about 315° Celsius to about 593° Celsius. The evaporation of a portion of the atomized stream of fluid can cause a cooling of the air and, thus, a cooling of the ribbon of glass-forming material **103**.

[0066] In some embodiments, the fluid source **305** can be coupled to the plurality of cooling tubes **303**. For example, the plurality of cooling tubes **303** can comprise a first cooling tube **309**, a second cooling tube **311**, and a third cooling tube **313**. The fluid source **305** can be coupled to the first cooling tube **309** via a first fluid line **315** through which the cooling fluid can flow to the first cooling tube **309**. The fluid source **305** can be coupled to the second cooling tube **311** via a second fluid line **317** through which the cooling fluid can flow to the second cooling tube **311**. The fluid source **305** can be coupled to the third cooling tube **313** via a third fluid line **319** through which the cooling fluid can flow to the third cooling tube **313**. In some embodiments, the fluid lines **315**, **317**, **319** can comprise a conduit (e.g., a tube, a pipe, etc.) that may be substantially hollow and through which the cooling fluid can be conveyed. In some embodiments, the fluid source **305** can be coupled to a purifier **321** that can purify the cooling fluid from the fluid source **305**. For example, the purifier **321** can remove unwanted materials, for example, impurities, particulates, chemicals, etc. that may be present in the cooling fluid supplied from the fluid source **305**. The purifier **321** can be coupled to the fluid source **305** at an inlet of the purifier **321**, and the purifier **321** may be coupled to the first fluid line **315**, the second fluid line **317**, and the third fluid line **319** at an outlet of the purifier **321**. In some embodiments, the purifier **321** can purify the cooling fluid from the fluid source **305** and deliver the purified cooling fluid to the first cooling tube **309** (e.g., via the first fluid line **315**), the second cooling tube **311** (e.g., via the second fluid line **317**), and the third cooling tube **313** (e.g., via the third fluid line **319**).

[0067] In some embodiments, the gas source **307** can be coupled to the plurality of cooling tubes **303**. For example, the gas source **307** can be coupled to the first cooling tube **309** via a first gas line **323** through which the compressed gas can flow to the first cooling tube **309**. The gas source **307** can be coupled to the second cooling tube **311**

via a second gas line **325** through which the compressed gas can flow to the second cooling tube **311**. The gas source **307** can be coupled to the third cooling tube **313** via a third gas line **327** through which the compressed gas can flow to the third cooling tube **313**. In some embodiments, the gas lines **323**, **325**, **327** can comprise a conduit (e.g., a tube, a pipe, etc.) that may be substantially hollow and through which the compressed gas can be conveyed. In some embodiments, the cooling apparatus **301** can comprise one or more valves **329**. For example, the valves **329** can be coupled to one or more of the first fluid line **315**, the second fluid line **317**, the third fluid line **319**, the first gas line **323**, the second gas line **325**, or the third gas line **327**. The valves **329** can be selectively opened and closed to control the flow of cooling fluid and/or compressed gas through the lines and to the first cooling tube **309**, the second cooling tube **311**, and/or the third cooling tube **313**.

[0068] While **FIG. 3** illustrates the plurality of cooling tubes **303** comprising three cooling tubes (e.g., the first cooling tube **309**, the second cooling tube **311**, and the third cooling tube **313**), the plurality of cooling tubes **303** can comprise greater than or less than three cooling tubes. In some embodiments, the first cooling tube **309**, the second cooling tube **311**, and the third cooling tube **313** may be substantially identical in structure and function. As such, a description herein of the first cooling tube **309** and associated components attached to the first cooling tube **309** may be substantially identical to other cooling tubes of the plurality of cooling tubes **303**. In some embodiments, the first cooling tube **309** can extend substantially parallel to the travel path **221** and can extend across the travel direction **154**. In some embodiments, by extending across the travel direction **154**, the first cooling tube **309** can extend substantially perpendicular to the travel direction **154**. For example, in some embodiments, the first cooling tube **309** can extend linearly along a first cooling axis **331**. The first cooling axis **331** can be substantially perpendicular to the travel direction **154**. The first cooling tube **309** is not limited to such an orientation, however, and in some embodiments, the first cooling tube **309** can extend across the travel direction **154** by forming an angle relative to the travel direction **154** that may be greater than or less than 90 degrees relative to the travel direction. In some embodiments, the first cooling tube **309** can comprise a substantially hollow conduit (e.g., pipe, duct, hose, etc.) through which the cooling fluid and the compressed gas can travel. As will be described herein, the first cooling tube **309** can comprise a plurality of orifices that may be spaced apart along the first cooling tube **309**, with an atomized stream of fluid (e.g., comprising the cooling fluid and the compressed gas) being discharged through the orifices toward the ribbon of glass-forming material **103**. In addition, or in the alternative, in some embodiments, the plurality of cooling tubes **303** can be rotated about their axes. For example, the first cooling tube **309** can be rotated about the first cooling axis **331**, such that the first cooling tube **309** can direct the atomized stream of fluid upwardly and/or downwardly.

[0069] Referring to **FIG. 4**, a side view of the plurality of cooling tubes **303** along line **4-4** of **FIG. 3** is illustrated. In some embodiments, the plurality of cooling tubes **303** may be positioned on opposing sides of the travel path **221**. For example, a first set **401** of the plurality of cooling tubes **303** can be positioned on a first side **405** of the travel path **221**, while a second set **403** of the plurality of cooling tubes **303** can be positioned on a second side **407** of the travel path **221**. In some embodiments, the first set **401** can comprise the first cooling tube **309**, the second cooling tube **311**, and the third cooling tube **313** (e.g., illustrated in **FIG. 3**). In some embodiments, the second set **403** can comprise a fourth cooling tube **411**, a fifth cooling tube **413**, and a sixth cooling tube **415**. The second cooling tube **311**, the third cooling tube **313**, the fourth cooling tube **411**, the fifth cooling tube **413**, and the sixth cooling tube **415** may be substantially identical to the first cooling tube **309**. In some embodiments, a plurality of nozzles **416** can be attached to the cooling tubes **309**, **311**, **313**, **411**, **413**, **415**, and atomized streams of fluid **419** can be discharged from the cooling tubes **309**, **311**, **313**, **411**, **413**, **415** (e.g., through the plurality of nozzles **416**) toward the travel path **221** along which the ribbon of glass-forming material **103** travels.

[0070] In some embodiments, the first set **401** of the plurality of cooling tubes **303** and the second set **403** of the plurality of cooling tubes **303** can be spaced apart along the travel direction **154**. For example, the cooling tubes **309**, **311**, **313** of the first set **401** of the plurality of cooling tubes **303** may be sequentially spaced apart along the travel direction **154**. In some embodiments, the second cooling tube **311** can be spaced apart from the first cooling tube **309** along the travel direction **154** such that the second cooling tube **311** may be positioned downstream from the first cooling tube **309**. The third cooling tube **313** can be spaced apart from the second cooling tube **311** along the travel direction **154** such that the third cooling tube **313** may be positioned downstream from the second cooling tube **311**. In some embodiments, the cooling tubes **411**, **413**,

415 of the second set **403** of the plurality of cooling tubes **303** may be sequentially spaced apart along the travel direction **154**. For example, the fifth cooling tube **413** can be spaced apart from the fourth cooling tube **411** along the travel direction **154** such that the fifth cooling tube **413** may be positioned downstream from the fourth cooling tube **411**. The sixth cooling tube **415** can be spaced apart from the fifth cooling tube **413** along the travel direction **154** such that the sixth cooling tube **415** may be positioned downstream from the fifth cooling tube **413**. In some embodiments, the cooling tubes **309**, **311**, **313**, **411**, **413**, **415** of the first set **401** and the second set **403** can be positioned on opposing sides of the travel path **221** at matching elevations. For example, the first cooling tube **309** and the fourth cooling tube **411** can be arranged as a first row **421** at a first elevation, in which a first elevational axis **423** that may be perpendicular to the travel path **221** can intersect the first cooling tube **309** and the fourth cooling tube **411**. The second cooling tube **311** and the fifth cooling tube **413** can be arranged as a second row **425** at a second elevation, wherein a second elevational axis **427** that may be perpendicular to the travel path **221** can intersect the second cooling tube **311** and the fifth cooling tube **413**. The third cooling tube **313** and the sixth cooling tube **415** can be arranged as a third row **429** at a third elevation, wherein a third elevational axis **431** that may be perpendicular to the travel path **221** can intersect the third cooling tube **313** and the sixth cooling tube **415**.

[0071] In some embodiments, the cooling tubes **309**, **311**, **313**, **411**, **413**, **415** of the first set **401** and the second set **403** of the plurality of cooling tubes **303** are not limited to being arranged in rows (e.g., the first row **421**, the second row **425**, the third row **429**) with opposing cooling tubes at matching elevations. Rather, in some embodiments, the cooling tubes **309**, **311**, **313** of the first set **401** can be staggered relative to the cooling tubes **411**, **413**, **415** of the second set **403**. For example, in some embodiments, the first elevational axis **423** may intersect one cooling tube (e.g., the first cooling tube **309** or the fourth cooling tube **411**) but not another cooling tube (e.g., the other of the first cooling tube **309** or the fourth cooling tube **411**). In addition, or in the alternative, in some embodiments, the second elevational axis **427** may intersect one cooling tube (e.g., the second cooling tube **311** or the fifth cooling tube **413**), but not another cooling tube. In addition, or in the alternative, in some embodiments, the third elevational axis **431** may intersect one cooling tube (e.g., the third cooling tube **313** or the sixth cooling tube **415**), but not another cooling tube. As such, in some embodiments, an axis perpendicular to the travel path **221** can intersect zero cooling tubes, one cooling tube, or two cooling tubes. While the first set **401** and the second set **403** are illustrated as comprising the same number of cooling tubes (e.g., three cooling tubes in the first set **401** and three cooling tubes in the second set **403**), the first set **401** and the second set **403** may comprise a different number of cooling tubes, for example, with the first set **401** comprising more cooling tubes or fewer cooling tubes than the second set **403**.

[0072] In some embodiments, methods of producing the glass ribbon **104** can comprise directing the one or more atomized streams of fluid **419** toward an area **443** of the ribbon of glass-forming material **103**. For example, directing the one or more atomized streams of fluid **419** can comprise directing a first atomized stream of fluid **445** toward the first side **405** of the ribbon of glass-forming material **103** and directing a second atomized stream of fluid **447** toward the second side **407** of the ribbon of glass-forming material **103**. In some embodiments, the first atomized stream of fluid **445** and the second atomized stream of fluid **447** can be directed at opposing sides (e.g., the first side **405** and the second side **407**) of the ribbon of glass-forming material **103** at the same elevation along the first elevational axis **423**. The first atomized stream of fluid **445** and the second atomized stream of fluid **447** can therefore cool the ribbon of glass-forming material **103** at the first elevation.

[0073] In some embodiments, directing the one or more atomized streams of fluid **419** can comprise directing a third atomized stream of fluid **449** toward the first side **405** of the ribbon of glass-forming material **103** downstream from the first atomized stream of fluid **445** relative to the travel direction **154**. For example, the first atomized stream of fluid **445** can be directed toward the first side **405** of the ribbon of glass-forming material **103** along the first elevational axis **423** while the third atomized stream of fluid **449** can be directed toward the first side **405** of the ribbon of glass-forming material **103** along the second elevational axis **427**. The second elevational axis **427** may be spaced a distance apart from the first elevational axis **423** downstream from the first elevational axis **423** relative to the travel direction **154**. The third atomized stream of fluid **449** can therefore be directed toward the first side **405** of the ribbon of glass-forming material **103** downstream from the first atomized stream of fluid **445** relative to the travel direction **154**. In some embodiments, by directing the one or more atomized streams of fluid **419**, **445**, **447**, **449** toward a plurality of locations of the ribbon of glass-forming material **103**, for example, the first side **405**, the second side **407**, and at a plurality of elevations (e.g., along elevational axes **423**, **427**, **431**) relative to the travel direction **154**, a temperature of the ribbon of glass-forming material **103** can be controlled at a plurality of locations. In some embodiments, additional atomized streams of fluid can be directed toward the second side **407** of the ribbon of glass-forming material **103** along additional elevations. For example, additional atomized streams of fluid can be directed toward the second side **407** at locations downstream from the second atomized stream of fluid **447** relative to the travel direction **154**, for example, along the second elevational axis **427**, the third elevational axis **431**, etc. Similarly, additional atomized streams of fluid can be directed toward the first side **405** of the ribbon of glass-forming material **103** downstream from the third atomized stream of fluid **449** relative to the travel direction **154**, for example, along the third elevational axis **431**.

[0074] Referring to **FIG. 5**, a sectional illustration of the first cooling tube **309** along line **5-5** of **FIG. 3** is illustrated. In some embodiments, the first cooling tube **309** can be substantially hollow and may comprise one or more chambers for delivering cooling fluid and compressed gas to a first nozzle **501**. For example, the first cooling tube **309** can comprise a first chamber **503** and a second chamber **505**. The first chamber **503** and the second chamber **505** can extend along a length of the first cooling tube **309**. In some embodiments, the first chamber **503** can be coupled to the first gas line **323** (e.g., illustrated in **FIG. 3**). The first chamber **503** can be in fluid communication with the first gas line **323**, such that the first cooling tube **309** can receive compressed gas **507** within the first chamber **503** from the first gas line **323**. In some embodiments, the second chamber **505** can be coupled to the first fluid line **315** (e.g., illustrated in **FIG. 3**). The second chamber **505** can be in fluid communication with the first fluid line **315**, such that the first cooling tube **309** can receive cooling fluid **509** within the second chamber **505** from the first fluid line **315**.

[0075] In some embodiments, the first cooling tube **309** can comprise a first orifice **513** and a second orifice **515** facing the travel path **221**. For example, by facing the travel path **221**, an axis perpendicular to the travel path **221** can extend from the travel path **221** toward the first cooling tube **309** and may intersect the first orifice **513** prior to intersecting another portion of the first cooling tube **309**. In some embodiments, by facing the travel path **221**, another axis perpendicular to the travel path **221** can extend from the travel path **221** toward the first cooling tube **309** and may intersect the second orifice **515** prior to intersecting another portion of the first cooling tube **309**. In some embodiments, the first orifice **513** and the second orifice **515** can be in fluid communication with the first chamber **503** and the second chamber **505**, respectively. For example, the first orifice **513** can be in fluid communication with the first chamber **503** via a first passageway that extends between the first orifice **513** and the first chamber **503**. The second orifice **515** can be in fluid communication with the second chamber **505** via a second passageway that extends between the second orifice **515** and the second chamber **505**. In some embodiments, the compressed gas **507** can be delivered to the first orifice **513** from the first chamber **503**, while the cooling fluid **509** can be delivered to the second orifice **515** from the second chamber **505**.

[0076] In some embodiments, one or more nozzles of the plurality of nozzles **416** (e.g., illustrated in **FIG. 4**) can be attached to the first cooling tube **309** and may be in fluid communication with the first orifice **513** and the second orifice **515** in the first cooling tube **309**. The one or more nozzles can discharge atomized streams of fluid toward the travel path **221**. The one or more nozzles can be attached to the first cooling tube **309** in a substantially identical manner. For example, a first nozzle **501** of the plurality of nozzles **416** can be attached to the first cooling tube **309** and may be in fluid communication with the first orifice **513** and the second orifice **515**. The first nozzle **501** can be attached to the first cooling tube **309** in several ways. For example, in some embodiments, the first nozzle **501** can be attached via threading, wherein one of the first nozzle **501** or the first cooling tube **309** comprises a male threaded portion while the other of the first nozzle **501** or the first cooling tube **309** comprises a female threaded portion. The first nozzle **501** can be threaded onto the first cooling tube **309** to reduce the likelihood of inadvertent detachment of the first nozzle **501** from the first cooling tube **309**. The first nozzle **501** and the first cooling tube **309** are not limited to a threading engagement, and in some embodiments, the first nozzle **501** can be attached to the first cooling tube **309** via a mechanical fastener (e.g., adhesive, locking mechanism, etc.). In some embodiments, the first nozzle **501** can be formed with the first cooling tube **309**, for example, wherein the first nozzle **501** and the first cooling tube **309** comprise a unitary structure. It will be appreciated that while the first nozzle **501** can be attached to the first cooling tube **309** in several ways, the first nozzle **501** can receive the compressed gas **507** and the cooling fluid **509** from the first cooling tube **309** and discharge the first atomized stream of fluid **445** toward the travel path **221**.

[0077] In some embodiments, the first nozzle **501** may be substantially hollow and may define a first mixing chamber **523**. The first mixing chamber **523** may be surrounded by one or more walls of the first nozzle **501**. The first mixing chamber **523** can be in fluid communication with the first orifice **513** and the second orifice **515** of the first cooling tube **309**, such that the first mixing chamber **523** can receive the compressed gas **507** from the first orifice **513** and the cooling fluid **509** from the second orifice **515**. In some embodiments, the compressed gas **507** can flow from the first chamber **503** in the first cooling tube **309**, through the first orifice **513**, and into the first mixing chamber **523**. The cooling fluid **509** can flow from the second chamber **505** in the first cooling tube **309**, through the second orifice **515**, and into the first mixing chamber **523**. In some embodiments, the first nozzle **501** can comprise a first nozzle orifice **525** defined at an end of the first nozzle **501** opposite the first cooling tube **309**. The first nozzle orifice **525** can be oriented to face the travel path **221**. In some embodiments, the first nozzle orifice **525** may be in fluid communication with the first mixing chamber **523**. For example, the first nozzle orifice **525** can receive a mixture of the compressed gas **507** and the cooling fluid **509** from the first mixing chamber **523** and discharge the mixture of the compressed gas **507** and the cooling fluid **509** as the first atomized stream of fluid **445** from the first nozzle orifice **525** toward the travel path **221**.

[0078] In some embodiments, the first nozzle **501** can discharge one or more droplets **531** of the first atomized stream of fluid **445**. For example, the first nozzle **501** can convert the mixture of the compressed gas **507** and the cooling fluid **509** via an atomization process into the first atomized stream of fluid **445** comprising the one or more droplets **531**. In some embodiments, the atomization process can reduce the cooling fluid **509** from a liquid form into the one or more droplets **531**. The one or more droplets **531** can comprise a diameter that may be within a range from about 0.5 micrometers to about 3 micrometers. In some embodiments, the first mixing chamber **523** can receive the mixture of the compressed gas **507** and the cooling fluid **509**. The first mixing chamber **523** may be maintained at a higher pressure than ambient environment, such that the mixture of the compressed gas **507** and the cooling fluid **509** can flow through the first nozzle orifice **525** and may be discharged from the first nozzle **501**. In some embodiments, the first nozzle **501** can discharge the first atomized stream of fluid **445** within a spray angle **535** range from about 0 degrees to about 180 degrees, or within a spray angle **535** range from about 0 degrees to about 90 degrees, or within a spray angle **535** range from about 20 degrees to about 90 degrees. The spray angle **535** can be varied in several ways. For example, a cross-sectional size (e.g., diameter) of the first nozzle orifice **525** can be altered, which can correspondingly alter the spray angle **535**.

[0079] In some embodiments, a portion of the first atomized stream of fluid **445** can evaporate prior to reaching the travel path **221**. For example, the first atomized stream of fluid **445** can exit the first nozzle orifice **525** and may travel along a discharge direction **539** toward the travel path **221**. In some embodiments, as the first atomized stream of fluid **445** travels along the discharge direction **539**, a portion of the first atomized stream of fluid **445** can evaporate. For example, an ambient temperature surrounding the first nozzle **501** may be high enough (e.g., within a range from about 315° Celsius to about 593° Celsius) to cause at least some of the one or more droplets **531** to evaporate after being discharged from the first nozzle orifice **525** but before reaching the ribbon of glass-forming material **103** traveling along the travel path **221**. The first nozzle **501** can be spaced a discharge distance **541** from the travel path **221**. In some embodiments, a density of the one or more droplets **531** of the first atomized stream of fluid **445** can be greater from the first nozzle orifice **525** to a midpoint of the discharge distance **541** (e.g., about halfway between an end of the first nozzle **501** and the ribbon of glass-forming material **103**) than from the midpoint of the discharge distance **541** to the ribbon of glass-forming material **103**. This may be due, in part, to some of the one or more droplets **531** evaporating while traveling along the discharge direction **539**. In some embodiments, the portion of the first atomized stream of fluid **445** that evaporates prior to reaching the travel path **221** can comprise all of the first atomized stream of fluid **445**, such that none of the one or more droplets **531** reach the travel path **221** to contact the ribbon of glass-forming material **103**. In some embodiments, the portion of the first atomized stream of fluid **445** that evaporates prior to reaching the travel path **221** can comprise less than all of the first atomized stream of fluid **445**. For example, some of the first atomized stream of fluid **445** may not evaporate prior to reaching the travel path **221** and contacting the ribbon of glass-forming material **103**, in which case some of the one or more droplets **531** may contact the ribbon of glass-forming material **103**. However, the amount of the one or more droplets **531** that do not evaporate but, rather, reach the travel path **221** and contact the ribbon of glass-forming material **103** may be small enough so as not to affect the quality of the ribbon of glass-forming material **103**.

[0080] The evaporation of the portion of the first atomized stream of fluid **445** yields several benefits. For example, when the portion of the first atomized stream of fluid **445** evaporates, the one or more droplets **531** may change from a liquid to a gas, which can cause a reduction in air temperature. In some embodiments, when the portion of the first atomized stream of fluid **445** evaporates, the air temperature adjacent to the ribbon of glass-forming material **103** traveling along the travel path **221** may be reduced, which can cause the ribbon of glass-forming material **103** adjacent to the first atomized stream of fluid **445** to cool. Due to the glass manufacturing apparatus **100** comprising a plurality of nozzles that are attached to the cooling tubes, the temperature of the ribbon of glass-forming material **103** along a direction that may be perpendicular to the travel direction **154** can be cooled. In some embodiments, a dehumidifier may be provided to reduce humidity adjacent to the glass-forming material **103** to counteract a rise in humidity as a result of the evaporation of the atomized streams of fluid. In addition, due to the portion of the first atomized stream of fluid **445** evaporating prior to contacting the ribbon of glass-forming material **103** (e.g., wherein the portion comprises some or all of the first atomized stream of fluid **445**) contact between the one or more droplets **531** and the ribbon of glass-forming material **103** may be limited.

[0081] In some embodiments, methods of producing the glass ribbon **104** can comprise converting the cooling fluid **509** into the one or more atomized streams of fluid **419** (e.g., illustrated in **FIG. 4**). For example, the cooling fluid **509** can be supplied to the second chamber **505** of the first cooling tube **309** via the first fluid line **315** (e.g., illustrated in **FIG. 3**). The cooling fluid **509** can be mixed with the compressed gas **507** in the first mixing chamber **523** of the first nozzle **501**. In some embodiments, the mixture of the cooling fluid **509** and the compressed gas **507** can form the first atomized stream of fluid **445** of the one or more atomized streams of fluid **419** upon being discharged from the first nozzle orifice **525** of the first nozzle **501**. In some embodiments, methods of producing the glass ribbon **104** can comprise cooling the ribbon of glass-forming material **103** by evaporating a portion of the one or more atomized streams of fluid **419** (e.g., illustrated in **FIG. 4**) without contacting the portion of the one or more atomized streams of fluid **419** with the area **443** of the ribbon of glass-forming material **103**. For example, the one or more atomized streams of fluid **419** can evaporate as the atomized stream travels along the discharge direction **539** toward the ribbon of glass-forming material **103**. At least some of the one or more droplets **531** may evaporate due to the high temperature of the ambient air surrounding the ribbon of glass-forming material **103**. In some embodiments, the evaporation of the one or more droplets **531** can cause a reduction in air temperature near the area **443** of the ribbon of glass-forming material **103**. This reduction in air temperature can cause a corresponding decrease in temperature of the area **443** of the ribbon of glass-forming material **103**. In some embodiments, methods of producing the glass ribbon **104** can comprise cooling the ribbon of glass-forming material **103** into the glass ribbon **104**. For example, downstream from a location where the one or more atomized streams of fluid **419** are directed toward the ribbon of glass-forming material **103**, the ribbon of glass-forming material **103** can be separated (e.g., illustrated in **FIG. 1**) and/or cooled into the glass ribbon **104**.

[0082] Referring to **FIG. 6**, a front view of the first cooling tube **309** along line **6-6** of **FIG. 3** is illustrated. It will be appreciated that each of the plurality of cooling tubes **303** (e.g., illustrated in **FIG. 3**) may be substantially similar in structure and function to the first cooling tube **309** illustrated in **FIGS. 5-6**. For example, the first cooling tube **309** can comprise a plurality of orifices **601** spaced apart along the first cooling tube **309** and facing the travel path **221** (e.g., illustrated in **FIGS. 3-5**). In some embodiments, while one nozzle was illustrated in **FIG. 5**, the nozzle (e.g., the first nozzle **501**) can comprise a plurality of nozzles **609** sequentially spaced across the travel direction **154** (e.g., illustrated in **FIG. 5**) and in fluid communication with the plurality of orifices **601**. For example, in some embodiments, the plurality of orifices **601** can comprise the first orifice **513**, the second orifice **515**, a third orifice **603**, a fourth orifice **605**, etc. The first orifice **513**, the second orifice **515**, the third orifice **603**, and the fourth orifice **605** are illustrated with dashed lines due to being obstructed from view by the nozzles (e.g., the first nozzle **501** and a second nozzle **613**). The first cooling tube **309** can comprise additional orifices that may be in fluid communication with the plurality of nozzles **609** that may be attached to the first cooling tube **309**, though, the additional orifices are obstructed from view by the nozzles. In some embodiments, the first orifice **513** and the second orifice **515** can be spaced apart from the third orifice **603** and the fourth orifice **605**. The first orifice **513** and the second orifice **515** can be in fluid communication with the first nozzle **501**, while the third orifice **603** and the fourth orifice **605** may be in fluid communication with the second nozzle **613**. The third orifice **603** and the fourth orifice **605** may be similar in structure and function to the first orifice **513** and the second orifice **515** (e.g., also illustrated in **FIG. 5**), in which the first orifice **513** and the third orifice **603** can receive compressed gas **507** from the first chamber **503** (e.g., illustrated in **FIG. 5**) while the second orifice **515** and the fourth orifice **605** can receive cooling fluid **509** from the second chamber **505** (e.g., illustrated in **FIG. 5**).

[0083] In some embodiments, the plurality of nozzles **609** can be in fluid communication with the plurality of orifices **601**, with the plurality of nozzles **609** configured to discharge atomized streams of fluid toward the travel path **221**. For example, each nozzle of the plurality of nozzles **609** can be in fluid communication with a corresponding one or more orifices of the plurality of orifices **601**. In some embodiments, each nozzle of the plurality of nozzles **609** can discharge the atomized streams of fluid toward the travel path **221** (e.g., illustrated in **FIG. 5**). In some embodiments, the plurality of nozzles **609** can comprise the first nozzle **501**, the second nozzle **613**, and a third nozzle **615**. In some embodiments, the first nozzle orifice **525** of the first nozzle **501** of the plurality of nozzles **609** can comprise a first diameter **616**. In some embodiments, a second nozzle orifice **617** of the second nozzle **613** of the plurality of nozzles **609** can comprise a second diameter **619** that may be equal to the first diameter **616**. In some embodiments, the plurality of nozzles **609** can comprise a set of sequentially spaced nozzles comprising the first nozzle **501** and the second nozzle **613** spaced a first distance **621** from the first nozzle **501**. In some embodiments, the first nozzle **501** and the second nozzle **613** may be sequentially spaced with no intervening nozzles positioned between the first nozzle **501** and the second nozzle **613**.

[0084] In some embodiments, the third nozzle **615** of the plurality of nozzles **609** can be spaced a second distance **633** from the second nozzle **613**, with the second nozzle **613** positioned in series between the first nozzle **501** and the third nozzle **615**, and the first distance **621** different than the second distance **633**. For example, the second nozzle **613** and the third nozzle **615** can be sequentially spaced with no intervening nozzles positioned between the second nozzle **613** and the third nozzle **615**. In some embodiments, by being positioned in series, the second nozzle **613** may be positioned between the first nozzle **501** and the third nozzle **615**, wherein an axis can intersect the first nozzle **501**, the second nozzle **613**, the third nozzle **615**, and the other nozzles (e.g., the plurality of nozzles **609**). In some embodiments, the first distance **621** may be different than the second distance **633**. For example, the first distance **621** may be less than the second distance **633**, such that the first nozzle **501** and the second nozzle **613** can be positioned closer together than the second nozzle **613** and the third nozzle **615**. In some embodiments, a third nozzle orifice **629** of the third nozzle **615** can comprise a third diameter **631**, wherein the third diameter **631** may be different than the first diameter **616** and/or the second diameter **619**. For example, in some embodiments, the first diameter **616** and the second diameter **619** may be larger than the third diameter **631**.

[0085] In some embodiments, a spacing between adjacent nozzles of the plurality of nozzles **609** may be non-constant. For example, the plurality of nozzles **609** can comprise an inner group of nozzles **639**, a first outer group of nozzles **641**, and a second outer group of nozzles **643**. The inner group of nozzles **639** can be positioned toward a center of the first cooling tube **309** while the first outer group of nozzles **641** and the second outer group of nozzles **643** may be positioned toward the ends of the first cooling tube **309**. In some embodiments, the first outer group of nozzles **641** can comprise the first nozzle **501** and the second nozzle **613**. The inner group of nozzles **639** can be positioned between the first outer group of nozzles **641** and the second outer group of nozzles **643**. A diameter of the nozzle orifices of the first outer group of nozzles **641** (e.g., the first nozzle orifice **525** of the first nozzle **501** and the second nozzle orifice **617** of the second nozzle **613**) and the second outer group of nozzles **643** may be larger than a diameter of the nozzle orifices (e.g., the third nozzle orifice **629** of the third nozzle **615**) of the inner group of nozzles **639**.

[0086] The larger diameter of the nozzle orifices of the first outer group of nozzles **641** and the second outer group of nozzles **643** may be due, in part, to varying cooling requirements across the ribbon of glass-forming material **103**. For example, with brief reference to **FIG. 1**, the central portion **152** of the ribbon of glass-forming material **103** may comprise a thickness that may be less than a thickness of edge portions formed along the first outer edge **153** and the second outer edge **155** of the ribbon of glass-forming material **103**. In some embodiments, cooling of the central portion **152** may be achieved with a smaller atomized stream of fluid than cooling of the first outer edge **153** and the second outer edge **155** that comprise edge portions. To accommodate the varying cooling rates due to thickness disparities across the ribbon of glass-forming material **103**, the first outer group of nozzles **641** and the second outer group of nozzles **643** may provide a larger atomized stream of fluid than the inner group of nozzles **639**. For example, the first outer group of nozzles **641** and the second outer group of nozzles **643** may comprise nozzle orifices with larger diameters than the diameters of the nozzle orifices of the inner group of nozzles **639**. The larger diameters can allow for a larger atomized stream of fluid to be directed from the first outer group of nozzles **641** and the second outer group of nozzles **643**. The larger streams can lead to greater evaporation of droplets, which can thus cause greater cooling of the ribbon of glass-forming material **103** near the first outer group of nozzles **641** and the second outer group of nozzles **643**. In some embodiments, the cooling of the ribbon of glass-forming material **103** can further be controlled based on the spacing between adjacent nozzles. For example, a spacing between adjacent nozzles within the inner group of nozzles **639** may be less than a spacing between adjacent nozzles within the first outer group of nozzles **641** and/or the second outer group of nozzles **643**. The reduced spacing between the inner group of nozzles **639** can allow for a greater number of nozzles to be provided as part of the inner group of nozzles **639**, which can allow for more controlled cooling of the central portion **152** of the ribbon of glass-forming material **103**.

[0087] Referring to **FIGS. 4** and **6**, in some embodiments, directing the one or more atomized streams of fluid **419** toward the area **443** of the ribbon of glass-forming material **103** can comprise varying an amount of the one or more atomized streams of fluid **419** directed toward the area **443** along an axis **647** perpendicular to the travel direction **154**. For example, the nozzle orifices of the plurality of nozzles **609** can be varied in size, which can vary the amount of the one or more atomized streams of fluid **419** that may be directed toward the ribbon of glass-forming material **103**. In some embodiments, larger nozzle orifices can yield larger atomized streams of fluid while smaller nozzle orifices can yield smaller atomized streams of fluid. In addition, or in the alternative, a spacing between adjacent nozzles of the plurality of nozzles **609** along the axis **647** can be varied, with some nozzles positioned closer together than other nozzles. In some embodiments, cooling the area **443** of the ribbon of glass-forming material **103** can comprise attaining a substantially uniform temperature of the ribbon of glass-forming material **103** along the axis **647** perpendicular to the travel direction **154**. For example, edges **153**, **155** (e.g., illustrated in **FIG. 1**) of the ribbon of glass-forming material **103** may be thicker than the central portion **152** of the ribbon of glass-forming material **103**. To achieve more controlled and uniform cooling of the ribbon of glass-forming material **103**, larger atomized streams of fluid may be directed toward the edges **153**, **155** than the central portion **152**. Greater cooling can therefore be achieved near the edges **153**, **155** to accommodate for the increased thickness of the ribbon of glass-forming material **103**, wherein the greater cooling at the edges **153**, **155** can yield a substantially uniform temperature of the ribbon of glass-forming material **103**.

[0088] Referring to **FIG.** 7, further embodiments of a cooling apparatus **701** are illustrated. The cooling apparatus **701** can be similar in some respects to the cooling apparatus **301** illustrated and described relative to **FIGS. 3-6**. For example, the cooling apparatus **701** can comprise the fluid source **305**, the gas source **307**, the purifier **321**, and the plurality of cooling tubes **303** (e.g., the first cooling tube **309**, the second cooling tube **311**, the third cooling tube **313**, etc.). In some embodiments, the cooling apparatus **701** can comprise an atomizer **703** coupled to and in fluid communication with the gas source **307** and the purifier **321**. The atomizer **703** can receive the compressed gas from the gas source **307** and the cooling fluid from the purifier **321**. The atomizer **703** can comprise a chamber within which the compressed gas and the cooling fluid may mix to form an atomized stream of fluid. In some embodiments, the process of converting the mixture of compressed gas and cooling fluid into the atomized stream of fluid may be similar to the embodiments of **FIGS. 5-6**, wherein the mixing occurs within the first nozzle **501**. However, the formation of the atomized stream of fluid is not limited to occurring within the first nozzle **501**, and in some embodiments, the atomized stream of fluid can be generated upstream from the first nozzle **501**, for example, at the atomizer **703**. In some embodiments, a first atomization line **705** can be coupled to the atomizer **703** and the first cooling tube **309**, such that a first atomized stream of fluid can be delivered from the atomizer **703**, through the first atomization line **705**, and to the first cooling tube **309**. In some embodiments, a second atomization line **707** can be coupled to the atomizer **703** and the second cooling tube **311**, such that a second atomized stream of fluid can be delivered from the atomizer **703**, through the second atomization line **707**, and to the second cooling tube **311**. In some embodiments, a third atomization line **709** can be coupled to the atomizer **703** and the third cooling tube **313**, such that a third atomized stream of fluid can be delivered from the atomizer **703**, through the third atomization line **709**, and to the third cooling tube **313**. The atomized streams of fluid can be discharged from the plurality of cooling tubes **303** toward the ribbon of glass-forming material **103**. In some embodiments, the cooling apparatus **701** can comprise one or more valves, for example, the valves **329** of the cooling apparatus **301** illustrated in **FIG. 3**. The valves **329** can be coupled to one or more of the first atomization line **705**, the second atomization line **707**, or the third atomization line **709**. The valves **329** can be selectively opened and closed to control the flow of the mixture of compressed gas and cooling fluid through the lines **705**, **707**, **709** and to the first cooling tube **309**, the second cooling tube **311**, and/or the third cooling tube **313**.

[0089] FIG. 8 illustrates a sectional view of the first cooling tube **309** along line **8-8** of **FIG.** 7. In some embodiments, the first cooling tube **309** can be substantially hollow and may comprise a chamber **801** for delivering a first atomized stream of fluid **803** to the first nozzle **501**. The chamber **801** can extend along a length of the first cooling tube **309**. In some embodiments, the chamber **801** can be coupled to the first atomization line **705**, for example, with the chamber **801** in fluid communication with the first atomization line **705** and configured to receive the first atomized stream of fluid **803** from the first atomization line **705**. In some embodiments, the first cooling tube **309** can comprise an orifice **805** facing the travel path **221**. The orifice **805** can be in fluid communication with the chamber **801**, for example, via a passageway that extends between the chamber **801** and the orifice **805**. In some embodiments, the first atomized stream of fluid **803** can be delivered to the orifice **805** from the chamber **801**. The first atomized stream of fluid **803** can pass through the orifice **805** and may be received within the first mixing chamber **523** of the first nozzle **501**. In some embodiments, the first atomized stream of fluid **803** can be discharged from the first nozzle orifice **525** of the first nozzle **501** in the discharge direction **539** toward the travel path **221**. Similar to the embodiments of **FIG. 5**, a portion of the one or more droplets **531** of the first atomized stream of fluid **803** can evaporate prior to contacting the area **443** of the ribbon of glass-forming material **103**, thus cooling the ribbon of glass-forming material **103**.

[0090] In some embodiments, the glass manufacturing apparatus **100** can provide several benefits associated with cooling the ribbon of glass-forming material **103** that travels along the travel path **221**. For example, the plurality of cooling tubes **303** can be positioned on opposing sides of the ribbon of glass-forming material **103** and spaced apart along the travel direction **154** of the glass manufacturing apparatus **100**. In addition, the plurality of cooling tubes **303** can extend substantially perpendicular to the travel direction **154** along a width of the ribbon of glass-forming material **103**. The plurality of cooling tubes **303** can direct atomized streams of fluid toward the ribbon of glass-forming material **103**. In some embodiments, a portion of the atomized streams of fluid can evaporate prior to contacting the ribbon of glass-forming material **103**. The evaporation can reduce an air temperature adjacent to the ribbon of glass-forming material **103**, which can likewise cool the ribbon of glass-forming material **103**. In addition, by evaporating the portion of the atomized streams of fluid, a number of droplets contacting the ribbon of glass-forming material **103** may be limited, thus reducing a risk of contaminating the ribbon of glass-forming material **103**. The plurality of cooling tubes **303** can therefore cool the ribbon of glass-forming material **103** at a plurality of locations, for example, along the travel direction **154**, perpendicular to the travel direction **154**, and on opposing sides of the ribbon of glass-forming material **103**. The cooling of the ribbon of glass-forming material **103** can be achieved with a reduced risk of contamination, since the atomized streams of fluid are limited from contacting the ribbon of glass-forming material **103**. By providing more efficient cooling of the ribbon of glass-forming material **103**, production rates can be increased.

[0091] FIGS. 9-12 illustrate another embodiment of the glass manufacturing apparatus of **FIG. 1**. As described herein below, a coolant directed toward the ribbon of molten material can undergo a phase change, for example, from a liquid or a solid to a gas. Methods of manufacturing glass in accordance with embodiments of the disclosure can inhibit (e.g., reduce, prevent, eliminate) problems associated with baggy warp. Providing a coolant that undergoes a phase change can absorb a large quantity of heat as it undergoes the phase change (e.g., latent heat, enthalpy of vaporization, enthalpy of sublimation). Additionally, providing a coolant that undergoes a phase change can absorb heat when it is heated to a temperature where it undergoes the phase change to a gas as well as when it is heated as a gas afterward. This increased cooling capacity can enable processing of molten material comprising a lower liquidus viscosity to a predetermined thickness (e.g., from 300 micrometers to about 5 millimeters) than would otherwise be possible. Further, directing the coolant toward a location on the ribbon of molten material positioned below the forming vessel can inhibit the incidence of devitrification (e.g., crystallization) on the forming vessel. As well, directing the coolant toward a location above the pull rollers can provide increased processing efficiency (e.g., reduced time, reduced space). For example, increased cooling capacity (e.g., above the pull rollers, below the forming device) can enable a reduction in the time between when the ribbon of molten material is drawn from the forming vessel and when it can undergo subsequent processing. Additionally, increased cooling capacity (e.g., above the pull rollers, below the forming device) can enable a reduction in a length of molten material travel path from when the ribbon of molten material is drawn from the forming vessel and when it can be handled (e.g., by pull rollers, for subsequent processing).

[0092] Additional features of embodiments of the disclosure can provide further technical benefits. For example, providing a mass flow rate of the coolant in a range from about 1 gram per minute (g/min) to about 200 g/min can enable increased cooling rates and/or cooling capacity without damaging the surface(s) of the ribbon of molten material being cooled. Also, providing a coolant comprising a small median particle size (e.g., 5 micrometers to about 20 micrometers) can inhibit (e.g., reduce, prevent, eliminate) the incidence of surface damage because it decreases the likelihood that a particle will impact a surface of the ribbon of molten material instead of and/or before undergoing a phase transition while still increasing the cooling rate and/or cooling capacity. Likewise, providing a coolant comprising a controlled, narrow particle size distribution (e.g., about 90% of the particles comprise a size in a range from about 1 micrometer to about 100 micrometers) can decrease (e.g., reduce) the likelihood that a particle will impact a surface of the ribbon of molten material instead of and/or before undergoing a phase transition while still increasing the cooling rate and/or cooling capacity. Either of the above particle size relationships can be enabled by heating the conduit (e.g., outlet of the conduit, nozzle) because such heating can inhibit (e.g., reduce, prevent, eliminate) agglomeration of particles. Additionally, positioning the nozzle near the ribbon of molten material (e.g., within a range from about 100 millimeters to about 1 meter) can decrease (e.g., reduce) the velocity of the coolant exiting the conduit, which can inhibit (e.g., reduce, decrease, eliminate) the incidence of surface defects. Providing a convective air current traveling along the ribbon of molten material can decrease (e.g., reduce) the likelihood that a particle will impact a surface of the ribbon of molten material instead of and/or before undergoing a phase transition because the convective air current can redirect (e.g., carry away) such particles. Also, such a convective air current can direct (e.g., remove) the coolant after it undergoes a phase transition. Providing a coolant that undergoes a phase transition to a gas can decrease (e.g., reduce, eliminate) surface damage to the flowing ribbon.

[0093] **FIG. 10** shows a cross-sectional perspective view of the glass manufacturing apparatus **100** along line **10-10** of **FIG. 9**, according to various embodiments of the disclosure. As shown and described, the forming vessel **140** can include a trough **201** oriented to receive the molten material **121** from the inlet conduit **141**. The forming vessel **140** can further include the forming wedge **209** including a pair of downwardly inclined converging surface portions **207, 208** extending between opposed ends **165, 166** (see **FIG. 9**) of the forming wedge **209**. The pair of downwardly inclined converging surface portions **207, 208** of the forming wedge **209** can converge along the travel direction **154** to intersect along a bottom edge of the forming wedge **209** to define the root **145** of the forming vessel **140**. A draw plane **213** of the glass manufacturing apparatus **100** can extend through the root **145** along the travel direction **154**. In some embodiments, the ribbon of glass-forming material **103** can be drawn in the travel direction **154** along the draw plane **213**. As shown, the draw plane **213** can bisect the forming wedge **209** through the root **145** although, in some embodiments, the draw plane **213** can extend at other orientations relative to the root **145**.

[0094] Additionally, in some embodiments, the molten material **121** flows into the trough **201** of the forming vessel **140** and then overflows from the trough **201** by simultaneously flowing over weirs **203, 204** and downward over the outer surfaces **205, 206** of the weirs **203, 204**. Respective streams **211, 212** of molten material **121** flow along corresponding downwardly inclined converging surface portions **207, 208** of the forming wedge **209** to be drawn off the root **145** of the forming vessel **140**, where the streams **211, 212** of molten material **121** converge and fuse into the ribbon of glass-forming material **103**. The ribbon of glass-forming material **103** can then be drawn off the root **145** in the draw plane **213** along the travel direction **154**.

[0095] In some embodiments, although not shown, the forming vessel **140** can comprise a pipe oriented to receive the molten material **121** from the inlet conduit **141**. In some embodiments, the pipe can comprise a slot through which molten material **121** can flow. For example, the slot can comprise an elongated slot that extends along an axis of the pipe at the top of the pipe. In some embodiments, a first wall can be attached to the pipe at a first peripheral location and a second wall can be attached to the pipe at a second peripheral location. The first wall and the second wall can comprise a pair of downwardly inclined converging surface portions. The first wall and the second wall can also at least partially define a hollow region within the forming vessel. In some embodiments, a pipe wall comprising the pipe, the first wall, and/or the second wall can comprise a thickness in a range from about 0.5 mm to about 10 mm, from about 0.5 mm to about 7 mm, from about 0.5 mm to about 3 mm, from about 1 mm to about 10 mm, from about 1 mm to about 7 mm, from about 3 mm to about 10 mm, from about 3 mm to about 7 mm, or any range or subrange therebetween. A thickness in the above range can result in overall reduced material costs compared to embodiments comprising thicker walls.

[0096] In some embodiments, the ribbon of glass-forming material **103** can cool to become a glass ribbon **106** below a glass transition line **167**. In some embodiments, the glass separator **149** (see **FIG. 9**) can then separate the glass sheet **104** from the glass ribbon **106** along the separation path **151**. As illustrated, in some embodiments, the separation path **151** can extend along the width "**W**" of the ribbon of glass-forming material **103** and/or the glass ribbon **106** between the first outer edge **153** and the second outer edge **155**. Additionally, in some embodiments, the separation path **151** can extend perpendicular to the travel direction **154** of the ribbon of glass-forming material **103**. Moreover, in some embodiments, the travel direction **154** can define a direction along which the ribbon of glass-forming material **103** can be fusion drawn from the forming vessel **140**. In some embodiments, the ribbon of glass-forming material **103** can include a speed as it traverses along travel direction **154** of about 1 millimeters per second (mm/s) or more, about 10 mm/s or more, about 50 mm/s or more, about 100 mm/s or more, or about 500 mm/s or more, for example, in a range from about 1 mm/s to about 500 mm/s, from about 10 mm/s to about 500 mm/s, from about 50 mm/s to about 500 mm/s, from about 100 mm/s to about 500 mm/s, or any range or subrange therebetween.

[0097] As shown in **FIGS. 10-11**, in some embodiments, the ribbon of glass-forming material **103** is drawn from the root **145** with a first major surface **215** of the ribbon of glass-forming material **103** and a second major surface **216** of the ribbon of glass-forming material **103** facing opposite directions and defining an average thickness **"T"** of the ribbon of glass-forming material **103**. In some embodiments, the average thickness **"T"** of the central portion **152** of the ribbon of glass-forming material **103**

and/or the glass ribbon **106** can be about 2 mm or less, about 1 mm or less, about 500 micrometers (μm) or less, about 300 μm or less, about 200 μm or less, or about 100 μm or less, although other thicknesses may be provided in further embodiments. For example, in some embodiments, the average thickness **"T"** of the ribbon of glass-forming material **103** and/or the glass ribbon **106** can be in a range from about 50 μm to about 750 μm, from about 100 μm to about 700 μm, from about 200 μm to about 600 μm, from about 300 μm to about 500 μm, from about 50 μm to about 500 μm, from about 50 μm to about 700 μm, from about 50 μm to about 600 μm, from about 50 μm to about 500 μm, from about 50 μm to about 400 μm, from about 50 μm to about 300 μm, from about 50 μm to about 200 μm, or from about 50 μm to about 100 μm, or any range or subrange therebetween.

[0098] Also, as shown in **FIG. 9**, the glass manufacturing apparatus **100** may comprise two pairs of edge rollers (e.g., a first pair of edge rollers **171a** contacting the first outer edge **153** and a second pair of edge rollers **171b** contacting the second outer edge **155**). Additionally, the glass manufacturing apparatus **100** may comprise two pairs of pull rollers (e.g., a first pair of pull rollers **173a** contacting a first edge portion comprising the first outer edge **153** and a second pair of pull rollers **173b** contacting a second edge portion comprising the second outer edge **155**). As used herein, "upstream" and "downstream" are terms used to describe relations based on the travel direction **154**. For example, in some embodiments, the two pairs of edge rollers may be located downstream from the forming vessel **140**. In some embodiments, the two pairs of pull rollers may be located downstream from the forming vessel **140** as shown in **FIG. 9**. In further embodiments, the two pairs of pull rollers may be located downstream from the two pairs of edge rollers **171a, 171b**. For example, as shown, the two pairs of pull rollers **173a, 173b** may be located downstream from the two pairs of edge rollers **171a, 171b** and downstream from the forming vessel **140**. Although not shown, in some embodiments, the two pairs of pull rollers **173a, 173b** may be provided without edge rollers **171a, 171b**. In some embodiments, the two pairs of pull rollers **173a, 173b** can exert a pulling force in the travel direction **154** to obtain a predetermined thickness (e.g., average thickness **"T"**) of the ribbon of glass-forming material **103**, which can be within the thickness range discussed above.

[0099] As shown schematically in **FIGS. 9-12**, the glass manufacturing apparatus **100** can comprise a cooling apparatus **175**. For example, as shown in **FIG. 10**, the cooling apparatus **175** may comprise a first cooling apparatus **218a** and/or a second cooling apparatus **218b**. As shown, in some embodiments, the cooling apparatus **175** may comprise both the first cooling apparatus **218a** and the second cooling apparatus **218b** with the draw plane **213** positioned between the first cooling apparatus **218a** the second cooling apparatus **218b**. Although two cooling apparatuses **218a, 218b** are shown, a single cooling apparatus or more than two cooling apparatuses may be provided in further embodiments. **FIG. 3** is an enlarged view taken at view **3** of **FIG. 10**, and **FIG. 12** is a cross-section taken along line **12-12** of **FIG. 10**. Both **FIGS. 11-12** discuss features of the first cooling apparatus **218a**. The first cooling apparatus **218a** will be described more fully with the understanding that such description can also apply to one or more other cooling apparatus such as the second cooling apparatus **218b**.

[00100] As shown in **FIGS. 10-11**, in some embodiments, the first cooling apparatus **218a** can comprise a conduit **219a**. As shown in **FIG. 11**, coolant flowing out of the conduit **219a** can be directed by the conduit **219a** in a flow direction **353**. As shown, the conduit **219a** can comprise a flow segment with a length **357** in the flow direction **353**. In some embodiments, the length **357** of the flow segment of the conduit **219a** can be about 0.01 meters (m) or more, about 0.1 m or more, about 0.5 m or more, about 10 m or less, about 5 m or less, or about 1 m or less. In some embodiments, the length **357** of the flow segment of the conduit **219a** can be in a range from 0.01 m to about 10 m, from about 0.01 m to about 5 m, from about 0.01 m to about 1 m from 0.1 m to about 10 m, from about 0.1 m to about 5 m, from about 0.1 m to about 1 m, from about 0.5 m to about 10 m, from about 0.5 m to about 5 m, from about 0.5 m to about 1 m, or any range or subrange therebetween.

[00101] As shown, the flow segment of the conduit **219a** can comprise a first width **342** in a direction substantially perpendicular to the flow direction **353**. As used herein, the first width **342** is a maximum dimension of an inner surface **355** of the flow segment of the conduit **219a** in a cross-section perpendicular to the flow direction **353**. If the inner surface is a circular cylindrical surface, the maximum dimension would be the diameter of the circular cylindrical surface in a cross-section perpendicular to the flow direction. In some embodiments, as shown in **FIG. 11**, the first width **342** may be substantially the same along the length **357** of the flow segment of the conduit **219a**. In some embodiments, although not shown, the first width **342** of the flow segment of the conduit **219a** may increase (e.g., monotonically increase) along the length **357** of the flow segment of the conduit **219a**. In other embodiments, although not shown, the first width **342** of the flow segment of the conduit **219a** may decrease (e.g., monotonically decrease) along the length of the flow segment of the conduit **219a**.

[00102] The flow segment of the conduit **219a** comprises a maximum width. As used herein, a maximum width of the flow segment of the conduit **219a** is the greatest value of the maximum dimension of the inner surface **355** of the flow segment of the conduit **219a** in a cross-section perpendicular to the flow direction at every point along the length of the flow segment of the conduit **219a**. In some embodiments, the first width **342** and/or the maximum width of the flow segment of the conduit **219a** may be about 0.1 mm or more, 0.4 mm or more, about 1 mm or more, about 3 mm or more, about 10 mm or more, about 20 mm or more, about 50 mm or more, about 5 m or less, or about 1 m or less. In some embodiments, the first width **342** and/or the maximum width of the flow segment of the conduit **219a** may be in a range from about 0.1 mm to about 5 m, 0.1 mm to about 1 m, from about 0.1 mm to about 5 m, 0.4 mm to about 1 m, from about 1 mm to about 5 m, from about 1 mm to about 1 m, from about 3 mm to about 5 m, from about 3 mm to about 1 m, from about 10 mm to about 5 m, from about 10 mm to about 1 m, from about 20 mm to about 5 m, from about 20 mm to about 1 m, from about 50 mm to about 5 m, from about 50 mm to about 1 m, or any range or subrange therebetween.

[00103] As shown in **FIGS. 10-11**, the conduit **219a** of the first cooling apparatus **218a** can be in fluid communication with a coolant source **251a**. In some embodiments, the coolant source **251a** can comprise a pump, a cannister, a cartridge, a boiler, a compressor, and/or a pressure vessel. In some embodiments, the coolant source **251a** may store the coolant in a gas phase. In some embodiments, the coolant source **251a** may store the coolant in a liquid phase. In some embodiments, the coolant source **251a** may store the coolant in a solid phase.

[00104] As shown in **FIG. 11**, the conduit **219a** can comprise an outlet **343a**. In some embodiments, as shown, the conduit **219a** can comprise a nozzle **217a**. In some embodiments, as shown, the nozzle **217a** may be provided in addition to the flow segment wherein the nozzle **217a** may be attached to an end of the flow segment. As shown, the nozzle **217a** can comprise an outlet **346a** comprising the outlet **343a** of the conduit **219a**. In further embodiments, as shown, the outlet **346a** of the nozzle **217a** can comprise a second width **344**, and the nozzle **217a** can comprise an inlet **341a**

comprising the first width **342** that is different from the second width **344**. In even further embodiments, as shown, the second width **344** can be greater than the first width **342**. In even further embodiments, the nozzle **217a** can comprise an inlet **341a** where the width (e.g., first width **342**, cross-section) starts to increase along a direction toward the draw plane **213**. In some embodiments, although not shown, the outlet of the nozzle may comprise substantially the same cross-section as another portion (e.g., the rest of) the conduit. In some embodiments, the nozzle **217a** can comprise a length **347** in the flow direction **353**. In some embodiments, the length **347** of the nozzle **217a** may be less than the second width **344** of the outlet **346a**. In some embodiments, the length **347** of the nozzle **217a** can be within any of the ranges discussed above with regards to the length **357** of the conduit **219a**.

[00105] In some embodiments, as shown in **FIGS. 11**, the nozzle **217a** can comprise a diffuser. Without wishing to be bound by theory, a diffuser can decrease (e.g., reduce) the velocity of coolant in the nozzle **217a**, which can inhibit (e.g., reduce, decrease, eliminate) the chance that the coolant contacts a surface of the ribbon of glass-forming material **103**. Additionally, without wishing to be bound by theory, a diffuser can decrease the temperature of the coolant flowing through the diffuser when the coolant comprises a negative Joule-Thomson coefficient. In some embodiments, an atomizer may be positioned between the coolant source and the nozzle to generate particles (e.g., liquid droplets, solid particles).

[00106] In some embodiments, the nozzle **217a** can comprise a boiling nozzle. Without wishing to be bound theory, a boiling nozzle may generate particles (e.g., liquid droplets, solid particles) using the kinetic energy (e.g., acceleration) of the coolant to separate a coolant stream into particles. In some embodiments, portions of a coolant stream may undergo a phase transformation to a gas (e.g., “boil”) when accelerated by a boiling nozzle. In some embodiments, portions of a coolant stream may separate from one another based on the surface tension of the coolant as the coolant stream is thinned during acceleration in the nozzle.

[00107] In some embodiments, the nozzle **217a** can comprise a shear nozzle. In further embodiments, a shear nozzle may generate particles (e.g., liquid droplets, solid particles) from a single coolant stream. In even further embodiments, the shear nozzle can induce a rotary fluid motion that can cause the coolant stream to separate into particles based on the shear forces introduce therein. In further embodiments, a shear nozzle can form particles (e.g., liquid droplets, solid particles) by combining a coolant and another fluid (e.g., gas). In even further embodiments, the coolant may be circumscribed by another fluid within the shear nozzle. Without wishing to be bound by theory, shearing between the coolant and the another fluid can produce particles of coolant.

[00108] In some embodiments, the conduit **219a** (e.g., nozzle **217a** and/or flow segment of the conduit **219a**) can comprise a thermally conductive material. In further embodiments, the conduit **219a** (e.g., nozzle **217a** and/or flow segment of the conduit **219a**) can comprise a material comprising a thermal conductivity of about 20 Watts per meter Kelvin (W/mK) or more, about 50 W/mK or more, about 100 W/mK or more, about 1000 W/mK or less, about 500 W/mK or less, or about 300 W/mK or less. In further embodiments, the conduit **219a** (e.g., nozzle **217a** and/or flow segment of the conduit **219a**) can comprise a material comprising a thermal conductivity in a range from about 20 W/mK to about 1000 W/mK, from about 20 W/mK to about 500 W/mK, from about 20 W/mK to about 200 W/mK, from about 50 W/mK to about 1000 W/mK, from about 50 W/mK to about 500 W/mK, from about 50 W/mK to about 200 W/mK, from about 100 W/mK to about 1000 W/mK, from about 100 W/mK to about 500 W/mK, from about 100 W/mK to about 200 W/mK, or any range or subrange therebetween. For example, silicon nitride comprises a thermal conductivity of about 20 W/mK, bronze comprises a thermal conductivity of about 26 W/mK, platinum comprises a thermal conductivity of about 55 W/mK, silicon carbide comprises a thermal conductivity of 60 W/mK, and gold comprises a thermal conductivity of about 310 W/mK. Providing a material that is thermally conductive (e.g., about 20 W/mK or more) can inhibit (e.g., reduce, prevent, eliminate) thermal fluctuation and/or thermal gradients along the length **357 or 347** of the flow segment of the conduit **219a** and/or nozzle **217a** of the conduit **219a** respectively. In further embodiments, this can inhibit (e.g., reduce, prevent, eliminate) agglomeration of coolant, which can lead to larger particle sizes that might otherwise impact (e.g., mar) the surface of the ribbon of glass-forming material **103**. In some embodiments, the conduit **219a** and/or nozzle **217a** can comprise one or more of a thermally conductive ceramic or a metal. Exemplary embodiments of thermally conductive ceramics can comprise one or more of silicon nitride, alumina, or silicon carbide. Exemplary embodiments of thermally conductive metals can comprise copper alloys (e.g., bronze, brass), iron, steel alloys, platinum,

platinum alloys, nickel, tin, copper, tungsten, molybdenum, aluminum, gold, and/or silver. In some embodiments, the conduit **219a** and/or nozzle **217a** can comprise an electrically insulating material (e.g., comprising a resistivity of about 10,000 Ω/m or more, and/or comprising a conductivity of about 0.0001 S/m or less).

[00109] In some embodiments, the conduit **219a** (e.g., nozzle **217a** and/or flow segment of the conduit **219a**) can comprise a polygonal (e.g., triangular, quadrilateral, pentagonal, hexagonal, etc.) cross-section taken perpendicular to the flow direction **353**. In some embodiments, the conduit **219a** (e.g., nozzle **217a** and/or flow segment of the conduit **219a**) can comprise a curvilinear (e.g., elliptical, circular) cross-section taken perpendicular to the flow direction **353**. In some embodiments, the conduit **219a** (e.g., nozzle **217a** and/or flow segment of the conduit **219a**) can comprise a cross-section taken perpendicular to the flow direction **353** comprising a combination of polygonal and curvilinear shapes.

[00110] In some embodiments, as shown in **FIGS. 10-12**, the first cooling apparatus **218a** can comprise a heater (e.g., electric heater **227a**). In further embodiments, as shown, the heater (e.g., electric heater **227a**) can be configured to heat the first cooling apparatus **218a** adjacent to the outlet **343a, 346a**. In some embodiments, the heater can be attached to conduit **219a** or spaced from the conduit **219a** while heating the conduit adjacent the outlet **343a, 346a**. In further embodiments, as shown, the heater (e.g., electric heater **227a**) can heat the nozzle **217a** of the first cooling apparatus **218a**. In some embodiments, the heater may be attached to the nozzle **217a** to heat the nozzle although the heater may be spaced from the nozzle **217a** in further embodiments. In some embodiments, the heater (e.g., electric heater **227a**) can circumscribe the nozzle **217a** and/or conduit **219a**. Providing the heater (e.g., electric heater **227a**) can maintain the nozzle **217a** and/or the flow segment of the conduit **219a** at a predetermined temperature, which can inhibit (e.g., reduce, prevent, eliminate) agglomeration of coolant, which can lead to larger particle sizes that might otherwise impact the surface of the ribbon of glass-forming material **103**.

[00111] In some embodiments, although not shown, the heater may comprise a heating conduit through which a heated fluid (e.g., air, steam, super critical carbon dioxide) circulates. In some embodiments, as shown in **FIGS. 10-12**, the heater may comprise an electric heater **227a**. The electric heater **227a** may comprise a metal or a refractory material (e.g., ceramic). Exemplary embodiments of metals can include chromium, molybdenum, tungsten, platinum, platinum, rhodium, iridium, osmium, palladium, ruthenium, gold, and combinations (e.g., alloys) thereof. Additional exemplary embodiments of metals (e.g., alloys) can include nickel-chromium alloys (e.g., nichrome), iron-chromium-aluminum alloys, or platinum alloys as described above. Exemplary embodiments of ceramics can include silicon carbide, chromium disilicide ($CrSi_2$), molybdenum disilicide ($MoSi_2$), tungsten disilicide (WSi_2), alumina, barium titanate, lead titanate, lanthanum chromite, zirconia, yttrium oxide, or combinations thereof. In some embodiments, the electric heater **227a** can comprise platinum or a platinum alloy. In some embodiments, the electric heater **227a** can comprise silicon carbide. In some embodiments, the electric heater **227a** can comprise molybdenum disilicide.

[00112] As shown in **FIGS. 11-12**, the heater (e.g., electric heater **227a**) can be connected to a power source **229a** via leads **224a**. As used herein, the power source **229a** may be any device capable of creating an electric potential difference. In some embodiments, the power source **229a** may comprise a battery, a capacitor, a fuel cell, or a generator. In some embodiments, the power source **229a** may comprise a commercially available power supply unit, for example, a programmable power supply unit, an uninterruptible power supply unit, a switched-mode power supply unit, and/or a linear regulator power supply unit.

[00113] As shown in **FIGS. 10-12**, the outlet **343a** of the conduit **219a** and/or the outlet **346a** of the nozzle **217a** can face a surface (e.g., first major surface **213a**) of the ribbon of glass-forming material **103**. In some embodiments, a minimum distance **349** between the outlet **343a or 346a** and the ribbon of glass-forming material **103** (e.g., first major surface **213a**) can be about 100 mm or more, about 200 mm or more, about 500 mm or more, about 1 m or less, about 800 mm or less, or about 500 mm or less. In some embodiments, a minimum distance **349** between the outlet **343a or 346a** and the ribbon of glass-forming material **103** (e.g., first major surface **213a**) can be in a range from about 100 mm to about 1 m, from about 200 mm to about 1 m, from about 500 mm to about 1 m, from about 100 mm to about 800 mm, from about 200 mm to about 800 mm, from about 500 mm to about 800 mm, from about 100 mm to about 500 mm, from about 200 mm to about 500 mm, or any range or subrange therebetween.

[00114] In some embodiments, the coolant may undergo a phase change between the outlet **343a** of the conduit **219a** and/or the outlet **346a** of the nozzle **217a** and the ribbon of glass-forming material **103**. In further embodiments, substantially all of the coolant may undergo a phase after flowing from the outlet **343a** of the conduit **219a** and/or the outlet **346a** of the nozzle **217a**. In further embodiments, substantially all of the coolant may undergo a phase change within a distance from the ribbon of glass-forming material **103** that can be within any of the ranges discussed above for minimum distance **349**. In further embodiments, substantially none of the coolant impacts the flowing ribbon of molten material.

[00115] In some embodiments, as shown in **FIGS. 10-12**, the outlet **343a** of the conduit **219a** and/or the outlet **346a** of the nozzle **217a** can be positioned below the forming vessel **140** such that the nozzle **217a** is positioned downstream in the travel direction **154** relative to the forming vessel **140**. The outlet **343a** of the conduit **219a** and/or the outlet **346a** of the nozzle **217a** is designed to direct coolant from the outlet in the flow direction **353** to a target location **351a**. Throughout the disclosure, the target location is defined as a location impinged by a central axis **350** of the coolant flow as it flows from the outlet. Referring to **FIG. 11**, the target location **351a** on the ribbon of glass-forming material **103** is defined as a location impinged by the central axis **350** of the coolant flow as it flows from the outlet **343a or 346a**. A length of the central axis **350** is defined as the minimum distance between the outlet **343a, 346a** and the ribbon of glass-forming material **103**. In some embodiments, a minimum distance **349** between the outlet **343a or 346a** and the target location **351a** can comprise the length of the central axis **310** and can be about 1 mm or more, about 10 mm, or more, about 100 mm or more, about 1 m or less, about 500 mm or less, or about 200 mm or less. In some embodiments, the minimum distance **349** can be in a range from about 1 mm to about 1 m, from about 10 mm to about 1 m, from about 100 mm to about 1 m, from about 1 mm to about 500 mm, from about 10 mm to about 500 mm, from about 100 mm to about 500 mm, from about 1 mm to about 200 mm, from about 10 mm to about 200 mm, from about 100 mm to about 200 mm, or any range or subrange therebetween.

[00116] In some embodiments, as shown, the outlet **343a** of the conduit **219a** and/or the outlet **346a** of the nozzle **217a** can be positioned upstream in the travel direction **154** relative to the pairs of pull rollers **173a, 173b**. As further illustrated, the target location **351a** can be positioned upstream in the travel direction **154** relative to the pairs of pull rollers **173a, 173b**.

[00117] In further embodiments, as shown, the outlet **343a** of the conduit **219a** and/or the outlet **346a** of the nozzle **217a** can be positioned between the forming vessel **140** and the pairs of pull rollers **173a, 173b**. That is, the outlet **343a** of the conduit **219a** and/or the outlet **346a** of the nozzle **217a** can be positioned downstream in the travel direction **154** relative to the forming vessel **140** and upstream in the travel direction **154** relative to the pairs of pull rollers **173a, 173b**. In further embodiments, as shown, the target location **351a** can be positioned between the forming vessel **140** and the pairs of pull rollers **173a, 173b**. That is, the target location **351a** can be positioned downstream in the travel direction **154** relative to the forming vessel **140** and upstream in the travel direction **154** relative to the pairs of pull rollers **173a, 173b**.

[00118] In further embodiments, as shown, the outlet **343a** of the conduit **219a** and/or the outlet **346a** of the nozzle **217a** can be positioned above the pairs of edge rollers **171a, 171b**. That is, the outlet **343a** of the conduit **219a** and/or the outlet **346a** of the nozzle **217a** can be positioned upstream in the travel direction **154** relative to the pairs of edge rollers **171a, 171b**. In further embodiments, the target location **351a** can be positioned above the pairs of edge rollers **171a, 171b**. That is, the target location **351a** can be positioned upstream in the travel direction **154** relative to the pairs of edge rollers **171a, 171b**.

[00119] In some embodiments, the first cooling apparatus can comprise a plurality of conduits although a single conduit may be provided in further embodiments. If a plurality of conduits are provided, as shown in **FIG. 12**, the plurality of conduits **219a-c** may comprise the illustrated three conduits although two conduits or more than three conduits may be provided in further embodiments. In further embodiments, as shown, each conduit **219a-c** can be connected to a respective coolant source **251a-c**. In further embodiments, although not shown, one or more conduits may be connected to the same fluid source. In further embodiments, one or more of the conduits **219a-c** may comprise a nozzle. In even further embodiments, as shown, each conduit **219a-c** can comprise a respective nozzle **217a-c**. In further embodiments, one or more of the conduits **219a-c** may be associated with a heater (e.g., electric heaters **227a-c**). In even further embodiments, as shown, each conduit **219a-c** can be associated with a respective heater (e.g., electric heaters **227a-c**). In still further embodiments, as shown, each electric heater **227a-c** may be provided in an electric circuit with a corresponding power source

229a-c and leads **224a-c**. In still further embodiments, although not shown, a plurality of the electric heaters **227a-c** may be powered by a common power source.

[00120] As shown in **FIG. 10**, the plurality of conduits, if provided, may comprise a first set of conduits (e.g., conduits **219a-c**, see **FIG. 12**). The first set of conduits **219a-c** can provide a plurality of target locations **351a-c** with each target location of the plurality of target locations associated with a corresponding conduit of the first set of conduits. As further illustrated in **FIG. 10**, the plurality of conduits can also comprise a second set of conduits (e.g., second conduits **220a**) that, in some embodiments, may mirror the first set of conduits **219a-c** illustrated in **FIG. 12**. The second set of conduits **220a** can provide a second set of target locations (e.g., **352a** in **FIG. 10**) that, in some embodiments, may mirror the first set of target locations **351a-c** illustrated in **FIG. 12**. Each target location of the second set of target locations (e.g., **352a** in **FIG. 10**) can be associated with a corresponding conduit of the second set of conduits (e.g., conduits **220a**). In some embodiments, as shown, the first set (e.g., conduits **219a-c**) and corresponding first set of target locations **351a-c** can be arranged in a first row. In further embodiments, as shown, the first row may extend along a direction **451** of the width **W** of the ribbon of glass-forming material **103**. In further embodiments, although not shown, the first row may extend along the travel direction **154** of the ribbon of glass-forming material **103** or in a matrix of rows and columns of conduits and corresponding target locations can extend in the direction **451** of the width and in the travel direction **154**. In some embodiments, as shown, the outlets of the first set (e.g., first cooling apparatus **218a**) of the plurality of conduits can face a first surface (e.g., first major surface **213a**) of the ribbon of glass-forming material **103**. In further embodiments, as shown in **FIG. 10**, the outlets (e.g., outlet **232a**) of the second set (e.g., second cooling apparatus **218b**) of the plurality of conduits can face a second surface (e.g., second major surface **213b**) of the ribbon of glass-forming material **103** opposite the first surface (e.g., first major surface **213a**) of t the ribbon of glass-forming material **103** the ribbon of glass-forming material **103**. In some embodiments, the second set of conduits (e.g., conduits **220a**) and corresponding second set of target locations (e.g., target locations **352a**) can be arranged in a second row or matrix similar or identical to the row or matrix of conduits **219a-c** and target locations **351a-c** illustrated in **FIG. 12** and discussed above.

[00121] As shown in **FIGS. 10-12**, the first cooling apparatus **218a** can be configured to flow a coolant from the outlet **343a** of the conduit **219a** (e.g., the outlet **346a** of the nozzle **217a**). In some embodiments, as shown, the coolant can flow from the outlet **343a or 346a** as coolant particles **223**. In some embodiments, the coolant can flow from the outlet **343a or 346a** as a solid particle. In further embodiments, the coolant flowing from the outlet **343a or 346a** can comprise solid particles with a median particle size of about 5 µm or more, about 10 µm or more, about 20 µm or less, or about 10 µm or less. In further embodiments, the coolant flowing from the outlet **343a or 346a** can comprise solid particles with a median particle size in a range from about 5 µm to about 20 µm, from about 5 µm to about 10 µm, from about 10 µm to about 20 µm, or any range or subrange therebetween. In some embodiments, the coolant flowing from the outlet **343a or 346a** can comprise solid particles and about 90% of the solid particles can comprise a size in a range from about 1 µm to about 100 µm, from about 5 µm to about 100 µm, from about 10 µm to about 100 µm, from about 1 µm to about 75 µm, from about 5 µm to about 75 µm, from about 10 µm to about 75 µm, from about 1 µm to about 50 µm, from about 5 µm to about 50 µm, from about 10 µm to about 50 µm, from about 1 µm to about 20 µm, from about 5 µm to about 20 µm, from about 10 µm to about 20 µm, or any range or subrange therebetween.

[00122] In some embodiments, the coolant can flow from the outlet **343a or 346a** as a liquid. In further embodiments, the coolant may flow from the outlet **303a or 346a** as a liquid particle (e.g., atomized liquid). In further embodiments, the coolant flowing from the outlet **343a or 346a** can comprise liquid particles with a median particle size of about 5 µm or more, about 10 µm or more, about 20 µm or less, or about 10 µm or less. In further embodiments, the coolant flowing from the outlet **343a or 346a** can comprise liquid particles with a median particle size in a range from about 5 µm to about 20 µm, from about 5 µm to about 10 µm, from about 10 µm to about 20 µm, or any range or subrange therebetween. In some embodiments, the coolant flowing from the outlet **343a or 346a** can comprise liquid particles and about 90% of the liquid particles can comprise a size in a range from about 1 µm to about 100 µm, from about 5 µm to about 100 µm, from about 10 µm to about 100 µm, from about 1 µm to about 75 µm, from about 5 µm to about 75 µm, from about 10 µm to about 75 µm, from about 1 µm to about 50 µm, from about 5 µm to about 50 µm, from about 10 µm to about 50 μm, from about 1 μm to about 20 μm, from about 5 μm to about 20 μm, from about 10 μm to about 20 μm, or any range or subrange therebetween.

[00123] Providing coolant particles **223** with a small median particle size (e.g., from about 5 μm to about 20 μm) can decrease (e.g., reduce, prevent, eliminate) the incidence of surface damage because it decreases the likelihood that a particle will impact a surface of the ribbon of molten material instead of and/or before undergoing a phase transition while still increasing the cooling rate and/or cooling capacity. Further, providing a coolant that undergoes a phase change to a gas can decrease (e.g., reduce, eliminate) the change of surface damage (e.g., increased roughness) to the flowing ribbon. Likewise, providing a coolant comprising a controlled, narrow particle size distribution (e.g., about 90% of the particles comprise a size in a range from about 1 micrometer to about 100 micrometers) can decrease (e.g., reduce, eliminate) the likelihood that a particle will impact a surface of the ribbon of molten material instead of and/or before undergoing a phase transition while still increasing the cooling rate and/or cooling capacity. Either of the above particle size relationships can be enabled by heating the conduit (e.g., outlet of the conduit, nozzle) because such heating can inhibit (e.g., reduce, prevent, eliminate) agglomeration of particles.

[00124] In some embodiments, the coolant can be configured to undergo a phase transition, such as to a gas **225**, after it flows from the outlet **343a** of the conduit **219a** and/or the outlet of the nozzle **217a,** as shown in **FIGS. 10-12**. In some embodiments, the coolant may undergo a phase transformation from a solid to a gas (e.g., sublimation, melting followed by vaporization). In some embodiments, the coolant may undergo a phase change from a liquid to a gas (e.g., vaporization). In some embodiments, the coolant can absorb a thermal energy from the phase change of about 0.1 kilojoules per kilogram (kj/kg) or more, about 1 kj/kg or more, about 10 kj/kg or more, about 100 kj/kg or more, about 500 kj/kg or more, about 5,000 kj/kg or less, or about 600 kj/kg or less. In some embodiments, the coolant can absorb a thermal energy from the phase change in a range from about 0.1 kj/kg to about 5,000 kj/kg, from about 1 kj/kg to about 5,000 kj/kg, from about 10 kj/kg to about 5,000 kj/kg, from about 100 kj/kg to about 5,000 kj/kg, from about 500 kj/kg to about 5,000 kj/kg, from about 0.1 kj/kg to about 600 kj/kg, from about 1 kj/kg to about 600 kj/kg, from about 10 kj/kg to about 600 kj/kg, from about 100 kj/kg to about 600 kj/kg, from about 500 kj/kg to about 600 kj/kg, or any range or subrange therebetween. For example, nitrogen comprises a latent heat of vaporization about 0.2 kj/kg, carbon dioxide comprises a latent heat of sublimation of about 570 kj/kg, and water comprises a latent heat of vaporization of about 2,300 kj/kg.

[00125] The coolant can absorb thermal energy thereby cooling the ribbon of glass-forming material **103**. The coolant can absorb thermal energy as it is heated from an initial temperature when it flows from the outlet **343a or 346a** to a second temperature when it undergoes a phase transformation. The coolant can absorb thermal energy when it undergoes a phase transformation, for example, to a gas **225**. The coolant can absorb thermal energy when it is heated from a second temperature when it underwent the phase transformation to a final temperature. Without wishing to be bound by theory, the amount of thermal energy absorbed by a material when it is heated from a first temperature to a second temperature without undergoing a phase change is proportional to the heat capacity of the material. In some embodiments, the coolant can comprise a heat capacity at a temperature from about 300 Kelvin (K) to about 500 K of about 1 kilojoules per kilogram Kelvin (kj/kgK) or more, about 2 kj/kgK or more, about 3 kj/kgK or more, about 5 kj/kgK or less, or about 4 kj/kgK or less. In some embodiments, the coolant can comprise a heat capacity at a temperature from about 300 K to about 500 K in a range from about 1 kj/kgK to about 5 kj/kgK, from about 2 kj/kgK to about 5 kj/kgK, from about 3 kj/kgK to about 5 kj/kgK, from about 1 kj/kgK to about 4 kj/kgK, 2 kj/kgK to about 4 kj/kgK, from about 3 kj/kgK to about 4 kj/kgK, or any range or subrange therebetween. For example, nitrogen comprises a heat capacity of about 1 kj/kgK, carbon dioxide comprises a heat capacity of about 1 kj/kgK, and water comprises a heat capacity of about 4 kj/kgK.

[00126] In some embodiments, the coolant can comprise one or more of water, nitrogen, and carbon dioxide. In some embodiments, the coolant can be a compound with hydrogen bonding. Without wishing to be bound by theory, compounds with hydrogen bonding in a solid and/or liquid can be associated with higher latent heat of vaporization, fusion, and/or sublimation than similar compounds without hydrogen bonding. In further embodiments, the coolant can comprise ammonia, water, or an organic alcohol (e.g., methanol, ethanol, propanol, butanol, pentanol, hexanol). In some embodiments, the coolant can comprise an alkane (e.g., methane, ethane, propane, butane, pentane, hexane).

[00127] In some embodiments, the coolant can be flowed from the conduit without a propellant. In some embodiments, the coolant can be flowed from the conduit with a propellant. In further embodiments, the propellant can comprise a carrier gas. In even further embodiments, the carrier gas may comprise the same material as the coolant in the gas phase. In even further embodiments, the carrier gas can comprise one or more of air, nitrogen, helium, argon, xenon, carbon dioxide, or oxygen.

[00128] In some embodiments, as shown in **FIG. 10**, a convective air current **231, 241** may be generated from a fan **233a, 243a** or other device designed to drive an air current. In further embodiments, as shown, a portion of the convective air current **231, 241** can travel along the ribbon of glass-forming material **103**. In even further embodiments, as shown, a portion of the convective air current **231** can travel along the ribbon of glass-forming material **103** in a direction opposite a travel direction **154** of the ribbon of glass-forming material **103**. In even further embodiments, as shown, the convective air current **241** can travel along the ribbon of glass-forming material **103** in the travel direction **154** of the ribbon of glass-forming material **103**. In even further embodiments, although not shown, the convective air current can travel across to the travel direction **154** of the ribbon of glass-forming material **103** (e.g., in the direction **451** or directional component of the width "**W**"). As shown, the portion of the convective air current **231** associated with the first major surface **213a** can travel in an opposite direction than the portion of the convective air current **241** associated with the second major surface **213b**. Although not shown, the portions of the convective air currents **231, 241** traveling along the ribbon of glass-forming material **103** can travel in the same direction. For example, the fans **233a, 243a** or other device can provide that the portions of the convective air currents **231, 241** traveling along the ribbon of glass-forming material **103** both flow in the travel direction **154** or both flow in a direction opposite the travel direction **154**.

[00129] In some embodiments, as shown in **FIGS. 10 and 12**, the convective air current **231, 241**, in addition or alternative to the fans **233a, 243a**, can be promoted by one or more vacuum sources **237a, 237b**. The vacuum sources **237a, 237b** as well as the fans **233a, 243a** can help remove the gas **225** from the vicinity of the ribbon of glass-forming material **103**.

[00130] The glass manufacturing apparatus **100** of the embodiments of the disclosure can be used in methods of manufacturing glass. Methods can comprise flowing a ribbon of glass-forming material **103** in a travel direction **154**, as shown in **FIGS. 10-11**. As shown, methods can comprise flowing a coolant from an outlet **343a** of a conduit **219a** in a flow direction **353** toward a target location **351a** of the ribbon of glass-forming material **103**. The coolant can comprise any of the materials described above for the coolant, for example, one or more of water, nitrogen, or carbon dioxide. In some embodiments, as described above and shown in **FIGS. 10-12** the outlet **343a** of the conduit **219a** can comprise a nozzle **217a**. In further embodiments, the nozzle **217a** can comprise a diffuser. In further embodiments, the nozzle **217a** can comprise a boiling nozzle. In further embodiments, the nozzle **217a** can comprise a shear nozzle. In some embodiments, a minimum distance **349** between the outlet **343a** of the conduit **219a** and the ribbon of glass-forming material **103** can be within the ranges discussed above, for example, in a range from about 100 mm to about 1 m. As described above, the coolant flowing from the outlet **343a** of the conduit **219a** can comprise a liquid and/or a solid. In some embodiments, the coolant flowing from the outlet **343a** of the conduit **219a** can comprise coolant particles **223**. In further embodiments, the particles of coolant can comprise a median particle size within the ranges discussed above, for example, in a range from about 5 μm to about 20 μm. In even further embodiments, the particles can comprise solid particles of coolant. In further embodiments, about 90% of the particles can comprise a size within the ranges discussed above, for example, from about 1 μm to about 100 μm. In even further embodiments, the particles can comprise solid particles of coolant. Methods can also comprise heating the conduit **219a**, for example with a heater (e.g., electric heater **227a)**, as discussed above.

[00131] In some embodiments, as shown in **FIGS. 10-11**, a minimum distance **359** between the outlet **343a** of the conduit **219a** and the forming vessel **140** can be about 1 mm or more, about 10 mm, or more, about 100 mm or more, about 1 m or less, about 500 mm or less, or about 200 mm or less. In some embodiments, a minimum distance **359** between the outlet **343a** of the conduit **219a** and the forming vessel **140** can be in a range from about 1 mm to about 1 m, from about 10 mm to about 1 m, from about 100 mm to about 1 m, from about 1 mm to about 500 mm, from about 10 mm to about 500 mm, from about 100 mm to about 500 mm, from about 1 mm to about 200 mm, from about 10 mm to about 200 mm, from about 100 mm to about 200 mm, or any range or subrange therebetween.

[00132] In some embodiments, coolant can flow from the outlet **343a** of the conduit **219a** at a mass flow rate of about 1 gram per minute (g/min) or more, about 10 g/min or more, about 50 g/min or more, about 200 g/min or less, about 100 g/min or less, or about 50 g/min or less. In some embodiments, the coolant can flow from the outlet **343a** of the conduit **219a** at a mass flow rate in a range from about 1 g/min to about 200 g/min, from about 1 g/min to about 100 g/min, from about 1 g/min to about 50 g/min, from about 10 g/min to about 200 g/min, from about 10 g/min to about 100 g/min, from about 10 g/min to about 50 g/min, from about 50 g/min to about 200 g/min, from about 50 g/min to about 100 g/min, or any range or subrange therebetween. Providing a mass flow rate of the coolant within the above ranges can enable increased cooling rates and/or cooling capacity without damaging the surface(s) of the ribbon of molten material being cooled.

[00133] In some embodiments, as discussed above and shown in **FIGS. 10-11**, the target location **351a** can be positioned below the forming vessel **140**. In further embodiments, a minimum distance **345** between the forming vessel **140** and the target location **351a** can be within any of the ranges discussed above with regards to minimum distance **359**, for example, about 1 meter (m) or less. In some embodiments, as discussed above and shown in **FIG. 10**, the method can further comprise pulling the molten material **121** (e.g., ribbon of glass-forming material **103**) with pairs of pull rollers **173a, 173b**. In further embodiments, as shown, the target location **351a** can be positioned between the forming vessel **140** and the pairs of pull rollers **173a, 173b**.

[00134] Methods can also comprise changing a phase of the coolant while the coolant is flowing toward the target location **351a** wherein the change in phase cools the target location **351a**. In some embodiments, changing a phase of the coolant can comprise changing the phase of the coolant to a gas **225** while the coolant is flowing toward the target location **351a** wherein the change in phase cools the target location **351a**. In some embodiments, a substantial portion (e.g., substantially the entire) quantity of coolant emitted from the outlet of the conduit changes phase before reaching the ribbon of glass-forming material **103**. Changing phase such that a substantial portion of the coolant fails to contact the ribbon of glass-forming material **103** can decrease (e.g., reduce) an impact force that the coolant may impose on the ribbon that might otherwise occur without the phase change. As such, the change in phase of the coolant can provide the beneficial effect of providing cooling of the target location without damaging the ribbon that might otherwise occur if the coolant were to impact the ribbon prior to the phase change to the gas. In some embodiments, the coolant (e.g., the change in phase of the coolant) can cool portions of the flowing ribbon adjacent to the target location in addition to cooling the portion of the flowing ribbon comprising the target location. In some embodiments, as shown in **FIGS. 10 and 12**, methods can further comprise moving the gas **225** with a convective air current **231, 241** travelling along the ribbon of glass-forming material **103**.

[00135] Methods can further comprise determining a deviation of a thickness (e.g., average thickness **"T"** of a portion (e.g., target location **351a**) of the ribbon of glass-forming material **103** from a predefined thickness. In some embodiments, the thickness of the portion may be greater than the predetermined thickness. Methods can further comprise cooling the portion (e.g., target location **351a**) of the ribbon of glass-forming material **103** by flowing coolant from an outlet **343a** of a conduit **219a** toward the portion (e.g., target location **351a**). In some embodiments, a phase change of coolant can cool the portion (e.g., target location **351a**). In further embodiments, a phase change of coolant to a gas can cool the portion (e.g., target location **351a**). In some embodiments, the cooling can decrease (e.g., reduce, eliminate) the deviation of the thickness of the portion (e.g., target location **351a**) of the ribbon of glass-forming material **103** by increasing a viscosity of the portion (e.g., target location **351a**) of the ribbon of glass-forming material **103**.

EXAMPLES

[00136] Various embodiments will be further clarified by the following examples. The overall heat flux as a function of mass flow rate is reported in **FIG. 13**. The thermal gradient as a function of mass flow rate is reported in **FIG. 14**. The data reported in **FIGS. 13-14** were obtained by flowing solid carbon dioxide from a nozzle comprising a 1 mm width at the outlet towards a first surface of a 110 mm by 56 mm by 6 mm sheet of stainless steel within a chamber maintained at 1000°C. Temperatures were recorded using thermocouples with a minimum spacing of 0.7 mm.

[00137] As used with regards to **FIG. 13**, overall heat flux is the change in temperature per time unit multiplied by the mass of the sheet and the heat capacity of the sheet divided by the surface area of the sheet. The horizontal axis **901** (e.g., x-axis) is a mass flow rate of carbon dioxide in grams per minute (g/min). The vertical axis **903** (e.g., y-axis) is an overall heat flux in kilowatts per meter^2 (kW/m^2). The first horizontal line **905** represents the maximum heat flux obtainable using radiative cooling and/or convection currents of gas along the surface of the sheet at a temperature in a range from about 800°C to about 900°C, which can correspond to a target location with a minimum distance from the forming vessel in a range from about 130 mm to about 650 mm. The second horizontal line **907** represents the maximum heat flux obtainable using radiative cooling and/or convection currents of gas along the surface of the sheet at a temperature in a range from about 1000°C to about 1100°C, which can correspond to a target location with a minimum distance from the forming vessel of about 100 mm or less. The data presented in **FIG. 13** shows that overall heat flux increases as the mass flow rate increases until about 200 g/min beyond which the overall heat flux plateaus at about 60 kW/m^2. Without wishing to be bound by theory, heat flux increases as the temperature difference between a surface and a convective flow increases; however, boundary layers and/or transition regions can limit the ability of additional cooling to further increase heat flux. As such, it can be beneficial to use a mass flow rate less than 200 g/min where the overall heat flux plateaus. Limiting the coolant mass flow rate to 200 g/min can obtain the maximum overall heat flux while avoiding unnecessary forces against the ribbon of glass-forming material **103** that may result in damage to the ribbon without further increase in heat flux. An overall heat flux greater than the first horizontal line **905** is obtained for the lowest mass flow rate tested (e.g., about 30 g/min). An overall heat flux greater than the second horizontal line **907** can be obtained for a mass flow rate of about 90 g/min or more.

[00138] As used with regards to **FIG. 14**, localization of heat flux is the variation in temperature across the surface of the sheet multiplied by the thermal conductivity of the sheet. The horizontal axis **1001** (e.g., x-axis) is a mass flow rate of carbon dioxide in grams per minute (g/min). The vertical axis **1003** (e.g., y-axis) is a measured of the localization of heat flux in kilowatts per $meter^2$ (kW/m^2). The first horizontal line **1005** represents the maximum heat flux obtainable using radiative cooling and/or convection currents of gas along the surface of the sheet at a temperature in a range from about 800°C to about 900°C, which can correspond to a target location with a minimum distance from the forming vessel in a range from about 130 mm to about 650 mm. The second horizontal line **1007** represent the maximum heat flux obtainable using radiative cooling and/or convection currents of gas along the surface of the sheet at a temperature in a range from about 1000°C to about 1100°C, which can correspond to a target location with a minimum distance from the forming vessel of about 100 mm or less. All data plotted in **FIG. 14** comprise localization of heat flux values greater than that of the first horizontal line **1005** and the second horizontal line **1007**. However, the localization of heat flux decreases as the mass flow rate increases. **FIG. 14** demonstrates that, in embodiments where the coolant is used for localized thickness control, a smaller coolant mass flow rate can provide more localized temperature control and thus morel localized thickness control.

[00139] The surface roughness for different glass manufacturing apparatuses is reported in Table 1. As used herein, "surface roughness" means the Ra surface roughness, which is an arithmetical mean of the absolute deviations of a surface profile from an average position in a direction normal to the surface of the test area. Unless otherwise indicated, all surface roughness values are the measured average roughness (Ra) for an 80 μm by 80 μm test area using atomic force microscopy (AFM). Example A is a ribbon of molten material that was not exposed to a coolant in accordance with the embodiments of the disclosure. Example B is a ribbon of molten material that was exposed to a carbon dioxide coolant flowed from a heated nozzle at the end of a conduit at about 80 g/min, which produced an overall heat flux of about 30 kW/m^2. Example C is a ribbon of molten material that was exposed to carbon dioxide coolant flowed from a heated nozzle at the end of a conduit at a coolant mass flow rate of about 120 g/min, which produced an overall heat flux of about 43 kW/m^2. Example D is a ribbon of molten material that was exposed to carbon dioxide coolant as in Example C except that the nozzle was not heated. Table 1 shows that Example A and Example B have the same surface roughness. As such, the carbon dioxide coolant did not damage the surface of the ribbon of molten material. When the coolant mass flow rate was increased, Example C comprises a slightly greater surface roughness. However, when the nozzle was not heated, the surface roughness doubled. In Example D, larger agglomerations of carbon dioxide particles were observed. As such, heating the nozzle inhibits (e.g., reduces, eliminates, prevents) agglomeration of coolant particles, which may otherwise increase the surface roughness of the ribbon of molten material if the nozzle was not heated.

Table 1: Surface Roughness

Example	Surface Roughness (Ra) (nm)
A	0.2
B	0.2
C	0.3
D	0.6

[00140] Methods of manufacturing glass in accordance with embodiments of the disclosure can decrease (e.g., reduce, prevent, eliminate) problems associated with baggy warp. Embodiments of the disclosure can avoid baggy warp by aggressively cooling an outer portion of the streams of molten material (e.g., first stream, second stream) opposite the inner portion of the respective stream of molten material to increase an effective viscosity where the ribbon of molten material is drawn. Methods of the embodiments of the disclosure can address the baggy warp problem by allowing greater cooling rates (e.g., heat flux) and/or cooling capacity than would be possible using heat transfer by convection and/or radiation. Providing a coolant that undergoes a phase change can absorb a large quantity of heat as it undergoes the phase change (e.g., latent heat, enthalpy of vaporization, enthalpy of sublimation). Additionally, providing a coolant that undergoes a phase change can absorb heat when it is heated to a temperature where it undergoes the phase change as well as when it is heated as a gas afterwards. This increased cooling capacity can enable processing of molten material comprising a lower liquidus viscosity to a predetermined thickness (e.g., from 300 micrometers to about 5 millimeters) than would otherwise be possible. In addition, providing a coolant that undergoes a phase change to a gas can avoid surface damage to the flowing ribbon of molten material that may otherwise occur if a solid or liquid were permitted to impact the flowing ribbon.

[00141] The positioning of the target location can provide further technical benefits. For example, directing the coolant toward a target location positioned below the forming vessel can decrease (e.g., reduce, eliminate, prevent) the incidence of devitrification (e.g., crystallization) of the molten material on the forming vessel. As well, directing the coolant toward a target location above the pull rollers can provide increased processing efficiency (e.g., reduced time, reduced space). For example, increased cooling capacity (e.g., above the pull rollers, below the forming device) can enable a reduction in the time between when the ribbon of molten material is drawn from the forming vessel and when it can undergo subsequent processing. Additionally, increased cooling capacity (e.g., above the pull rollers, below the forming device) can enable a reduction in a length of molten material travel path from when the ribbon of molten material is drawn from the forming vessel and when it can be handled (e.g., by pull rollers, for subsequent processing).

[00142] Additional features of embodiments of the disclosure can provide further technical benefits. For example, providing a mass flow rate of the coolant in a range from about 1 gram per minute to about 200 grams per minute can enable increased cooling rates and/or cooling capacity without damaging the surface(s) of the ribbon of molten material being cooled. Also, providing a coolant comprising a small median particle size (e.g., 5 micrometers to about 20 micrometers) can decrease (e.g., reduce, prevent, eliminate) the incidence of surface damage because it decreases the likelihood that a particle will impact a surface of the ribbon of molten material instead of and/or before undergoing a phase transition (e.g., to a gas) while still increasing the cooling rate and/or cooling capacity. Likewise, providing a coolant comprising a controlled, narrow particle size distribution (e.g., about 90% of the particles comprise a size in a range from about 1 micrometer to about 100 micrometers) can decrease (e.g., reduce, eliminate) the likelihood that a particle will impact a surface of the ribbon of molten material instead of and/or before undergoing a phase transition (e.g., to a gas) while still increasing the cooling rate and/or cooling capacity. Either of the above particle size relationships can be enabled by heating the conduit (e.g., outlet of the conduit, nozzle) because such heating can inhibit (e.g., reduce, prevent, eliminate) agglomeration of particles. Additionally, positioning the nozzle near the ribbon of molten material (e.g., within a range from about 100 millimeters to about 1 meter) can decrease (e.g., reduce) the velocity of the coolant exiting the conduit, which can decrease (e.g., reduce, eliminate) the incidence of surface defects. Providing a convective air current traveling along the ribbon of molten material can decrease (e.g., reduce, eliminate) the likelihood that a particle will impact a surface of the ribbon of molten material instead of and/or before undergoing a phase transition (e.g., to a gas) because the convective air current can redirect (e.g., carry away) such particles. Also, such a convective air current can direct (e.g., remove) the coolant after it undergoes a phase transition (e.g., to a gas) and thereby create room for additional coolant to undergo a phase change to provide continued cooling of the ribbon.

[00143] As used herein, the terms “the,” “a,” or “an,” mean “at least one,” and should not be limited to “only one” unless explicitly indicated to the contrary. Thus, for example, reference to “a component” comprises embodiments having two or more such components unless the context clearly indicates otherwise.

[00144] 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. When the term “about” is used in describing a value or an endpoint of a range, the disclosure should be understood to comprise the specific value or endpoint referred to. If a numerical value or endpoint of a range in the specification recites “about,” the numerical value or endpoint of a range is intended to comprise two embodiments: one modified by “about,” and one not modified by “about.” 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.

[00145] 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, as defined above, “substantially similar” is intended to denote that two values are equal or approximately equal. In some embodiments, “substantially similar” may denote values within about 10% of each other, for example within about 5% of each other, or within about 2% of each other.

[00146] 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.

[00147] It should be understood that while various embodiments have been described in detail relative to certain illustrative and specific examples thereof, the present disclosure should not be considered limited to such, as numerous modifications and combinations of the disclosed features are possible without departing from the scope of the following claims.

What is claimed is:

1. A glass manufacturing apparatus, comprising:

a forming apparatus defining a travel path extending in a travel direction, the forming apparatus configured to convey a ribbon of glass-forming material along the travel path in the travel direction; and

a cooling tube extending substantially parallel to the travel path and extending across the travel direction, the cooling tube comprising a plurality of orifices spaced apart along the cooling tube and facing the travel path.

2. The glass manufacturing apparatus of claim 1, wherein the cooling tube extends linearly along a cooling axis.

3. The glass manufacturing apparatus of claim 2, wherein the cooling axis is substantially perpendicular to the travel direction.

4. The glass manufacturing apparatus of any one of claims 1-3, further comprising a plurality of nozzles, each nozzle of the plurality of nozzles in fluid communication with a corresponding one or more orifices of the plurality of orifices, and each nozzle of the plurality of nozzles configured to discharge atomized streams of fluid toward the travel path.

5. The glass manufacturing apparatus of claim 4, wherein a first nozzle orifice of a first nozzle of the plurality of nozzles comprises a first diameter and a second nozzle orifice of a second nozzle of the plurality of nozzles comprises a second diameter equal to the first diameter.

6. The glass manufacturing apparatus of claim 5, wherein the plurality of nozzles comprises a set of sequentially spaced nozzles comprising the first nozzle, the second nozzle spaced a first distance from the first nozzle, and a third nozzle of the plurality of nozzles spaced a second distance from the second nozzle, the second nozzle positioned in series between the first nozzle and the third nozzle, and the first distance is different than the second distance.

7. The glass manufacturing apparatus of claim 6, wherein a third nozzle orifice of the third nozzle comprises a third diameter different than the second diameter.

8. The glass manufacturing apparatus of any one of claims 1-7, wherein the cooling tube comprises a plurality of cooling tubes, a first set of the plurality of cooling tubes positioned on a first side of the travel path, and a second set of the plurality of cooling tubes positioned on a second side of the travel path.

9. The glass manufacturing apparatus of claim 8, wherein cooling tubes of the first set of the plurality of cooling tubes are sequentially spaced apart along the travel direction and cooling tubes of the second set of the plurality of cooling tubes are sequentially spaced apart along the travel direction.

10. A method of producing a glass ribbon, comprising:

forming a ribbon of glass-forming material;

moving the ribbon of glass-forming material along a travel path in a travel direction;

converting a cooling fluid into one or more atomized streams of fluid;

directing the one or more atomized streams of fluid toward an area of the ribbon of glass-forming material;

cooling the area of the ribbon of glass-forming material by evaporating a portion of the one or more atomized streams of fluid without contacting the portion of the one or more atomized streams of fluid with the area of the ribbon of glass-forming material; and

cooling the ribbon of glass-forming material into the glass ribbon.

11. The method of claim 10, wherein the directing the one or more atomized streams of fluid comprises directing a first atomized stream of fluid toward a first side of the ribbon of glass-forming material and directing a second atomized stream of fluid toward a second side of the ribbon of glass-forming material.

12. The method of claim 11, wherein the directing the one or more atomized streams of fluid comprises directing a third atomized stream of fluid toward the first side of the ribbon of glass-forming material downstream from the first atomized stream of fluid relative to the travel direction.

13. The method of any one of claims 10-12, wherein the directing the one or more atomized streams of fluid toward the area of the ribbon of glass-forming material comprises varying an amount of the one or more atomized streams of fluid directed toward the area.

14. The method of any one of claims 10-13, wherein the cooling the area of the ribbon of glass-forming material comprises attaining a substantially uniform temperature of the ribbon of glass-forming material along an axis perpendicular to the travel direction.

15. A method of manufacturing glass comprising:

flowing a coolant from an outlet of a conduit in a direction toward a target location of a flowing ribbon of molten material; and

changing a phase of the coolant while the coolant is flowing toward the target location, the change in phase cooling the target location.

16. The method of claim 15, wherein the coolant comprises one or more of water, nitrogen, or carbon dioxide.

17. The method of any one of claims 15-16, wherein a mass flow rate of the coolant flowing from the outlet is in a range from about 1 gram per minute to about 200 grams per minute.

18. The method of any one of claims 15-17, wherein the coolant flowing from the outlet comprises solid particles with a median particle size in a range from about 5 micrometers to about 20 micrometers.

19. The method of claim 18, wherein about 90% of the solid particles comprise a size in a range from about 1 micrometer to about 100 micrometers.

20. The method of any one of claims 15-16, wherein the coolant flowing from the outlet comprises liquid droplets.

21. The method of any one of claims 15-20, further comprising heating the conduit.

22. The method of any one of claims 15-21, further comprising moving the gas with a convective air current traveling along the ribbon of molten material.

23. The method of claim 22, wherein the convective air current flows in a direction opposite a travel direction of the ribbon of molten material.

24. The method of any one of claims 15-23, wherein the target location is positioned below a forming vessel.

25. The method of claim 24, wherein a minimum distance between the forming vessel and the target location is about 1 meter or less.

26. The method of any one of claims 24-25, further comprising pulling the molten material with pull rollers, the target location positioned between the forming vessel and the pull rollers.

27. The method of any one of claims 15-26, wherein a minimum distance between the outlet and the flowing ribbon of molten material is in a range from about 100 millimeters to about 1 meter.

28. The method of any one of claims 15-27, wherein the conduit comprises a nozzle comprising the outlet.

29. The method of claim 28, wherein the nozzle comprises a boiling nozzle.

30. The method of claim 28, wherein the nozzle comprises a shear nozzle.

31. The method of claim 28, wherein the nozzle comprises a diffuser.

32. The method of any one of claims 15-31, wherein the conduit comprises a plurality of conduits, the outlets of a first set of the plurality of conduits flowing the coolant toward a first surface of the ribbon of molten material, and the outlets of a second set of the plurality of conduits flowing the coolant toward a second surface of the ribbon of molten material opposite the first surface.

33. The method of claim 32, wherein the first set of the plurality of conduits is arranged in a first row.

34. The method of any one of claims 32-33, wherein the second set of the plurality of conduits is arranged in a second row.

35. The method of any one of claims 15-34, further comprising determining a deviation of a thickness of a portion of the ribbon of molten material from a predefined thickness, the cooling reducing the deviation of the thickness of the portion of the ribbon of molten material from the predefined thickness by increasing a viscosity of the portion of the ribbon of molten material.

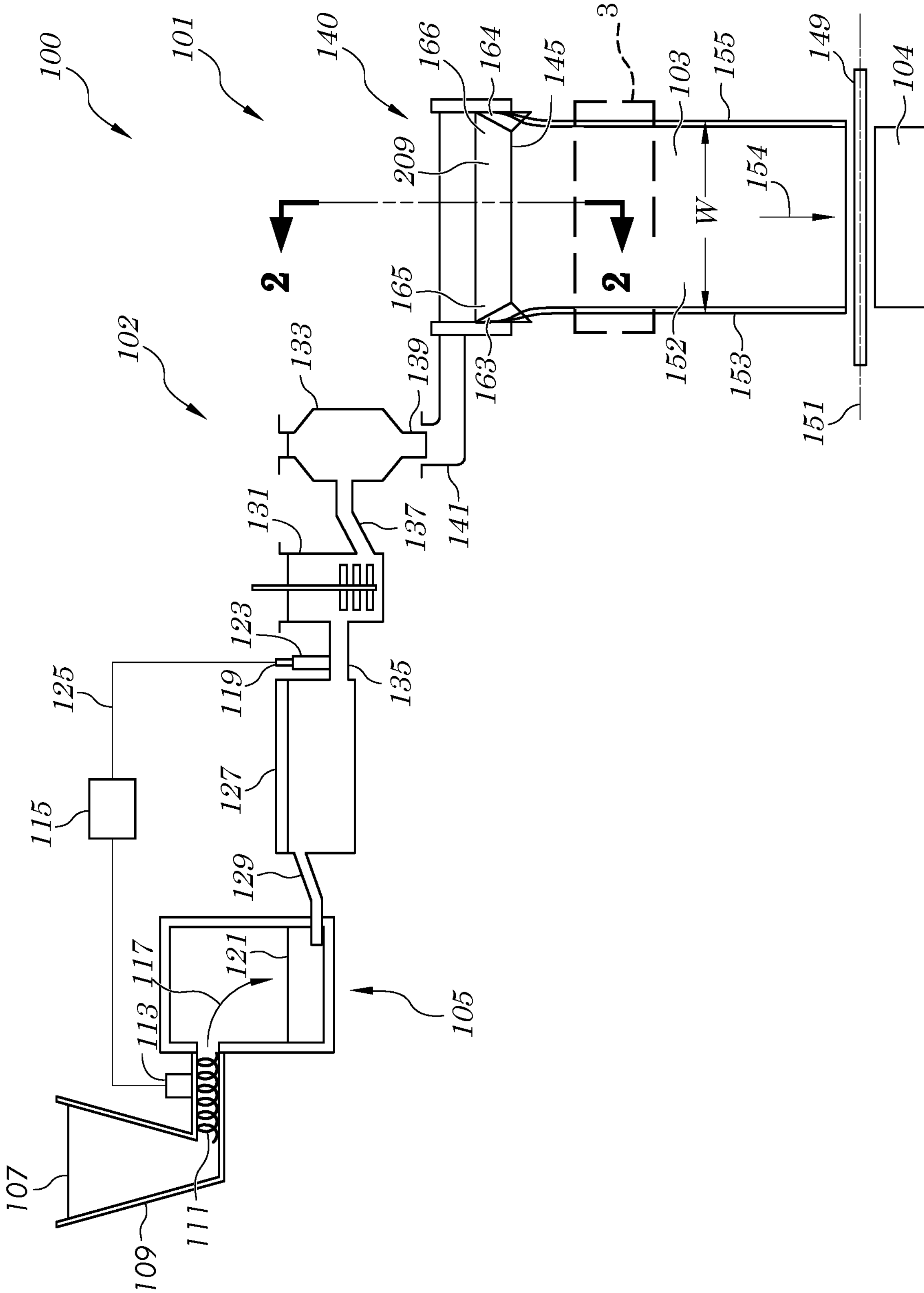
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FIG. 1

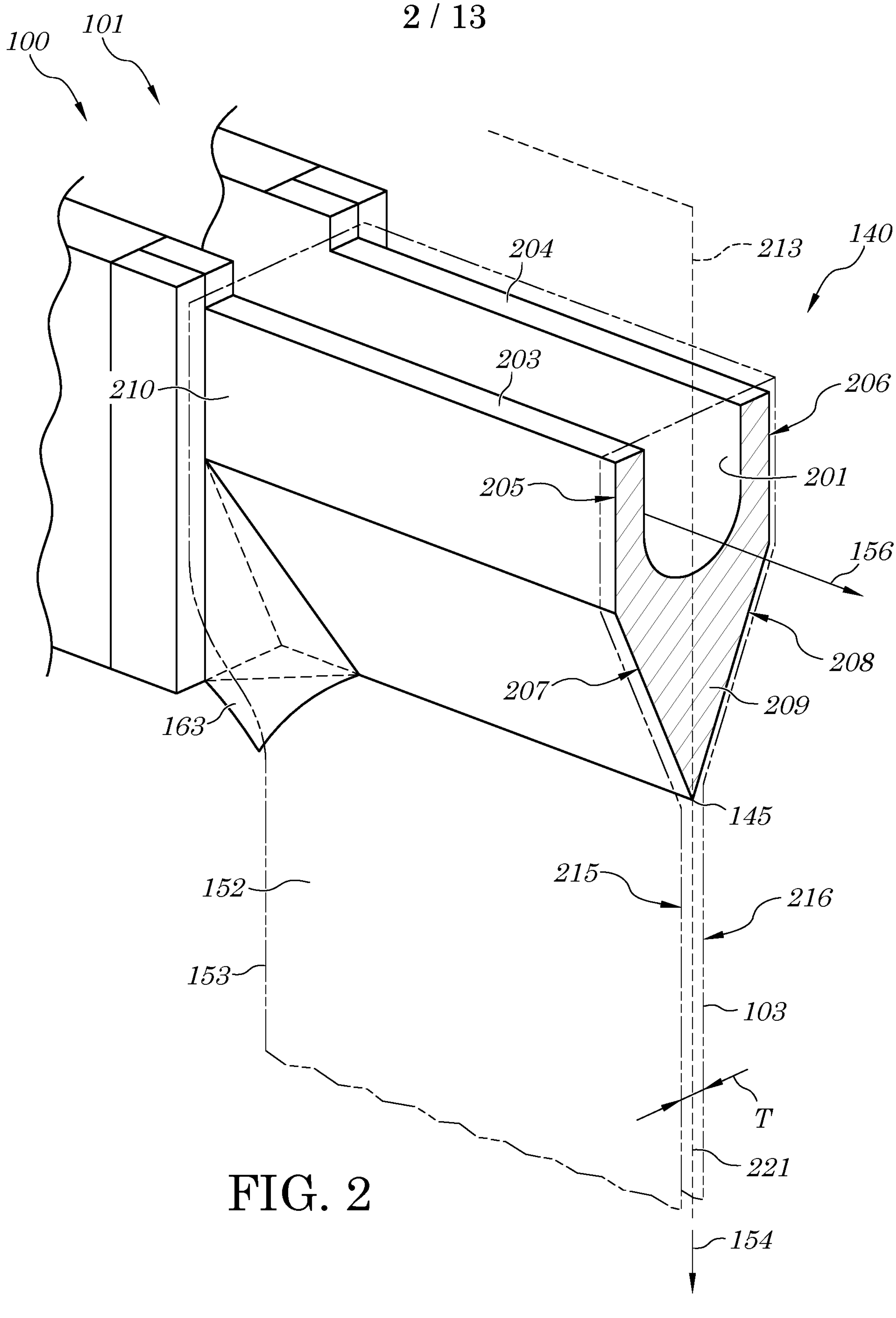
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FIG. 2

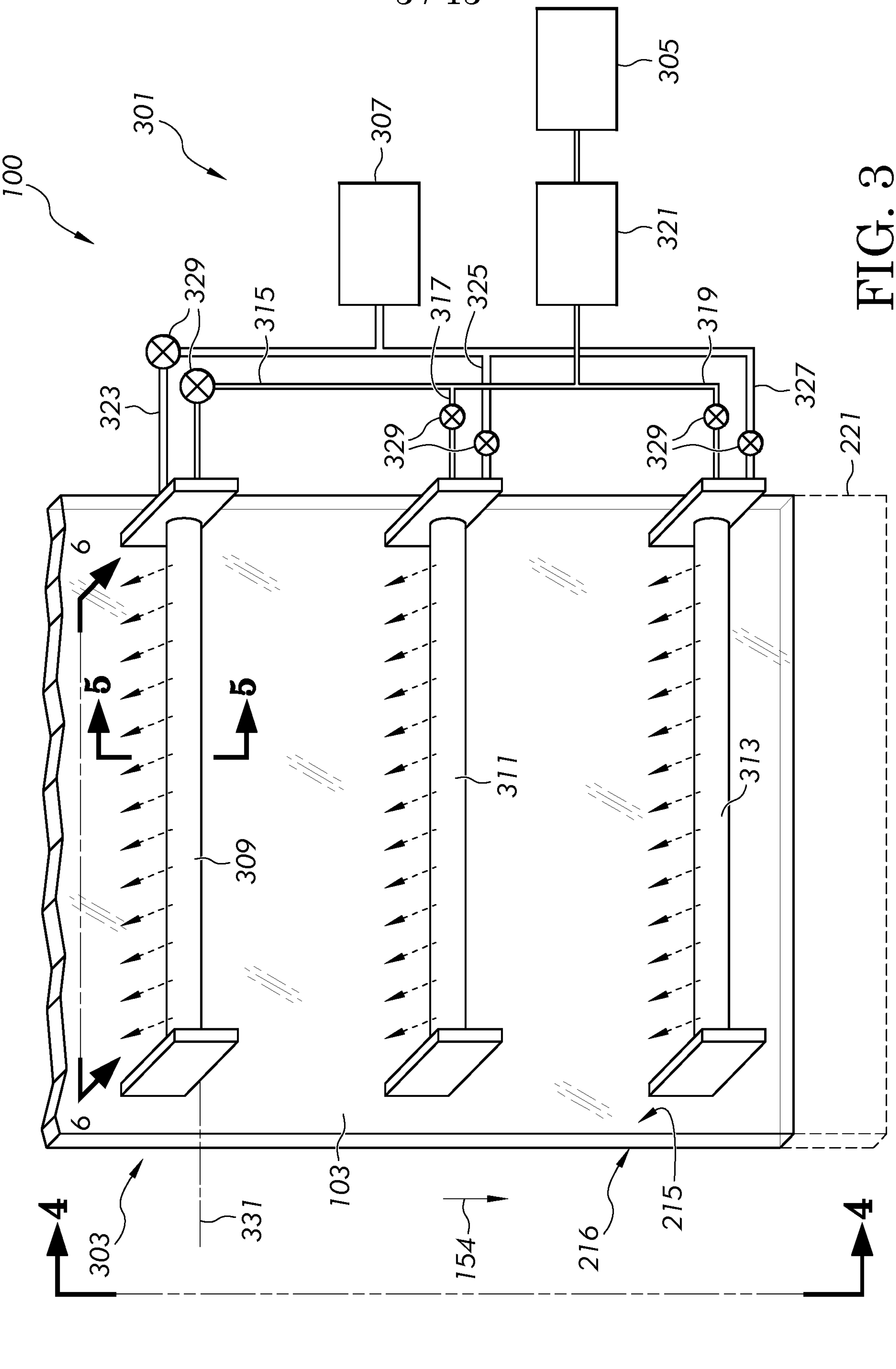
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FIG. 3

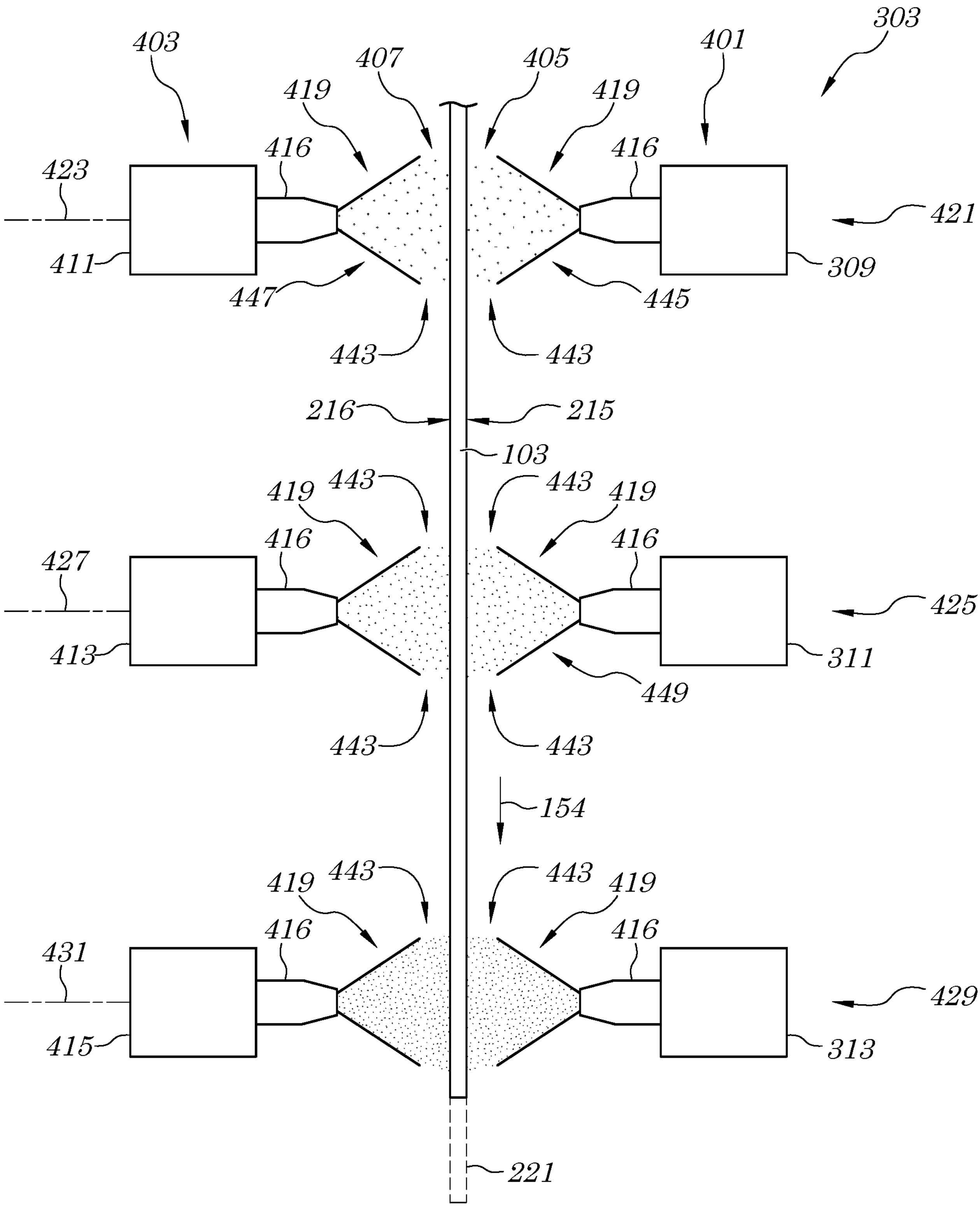
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FIG. 4

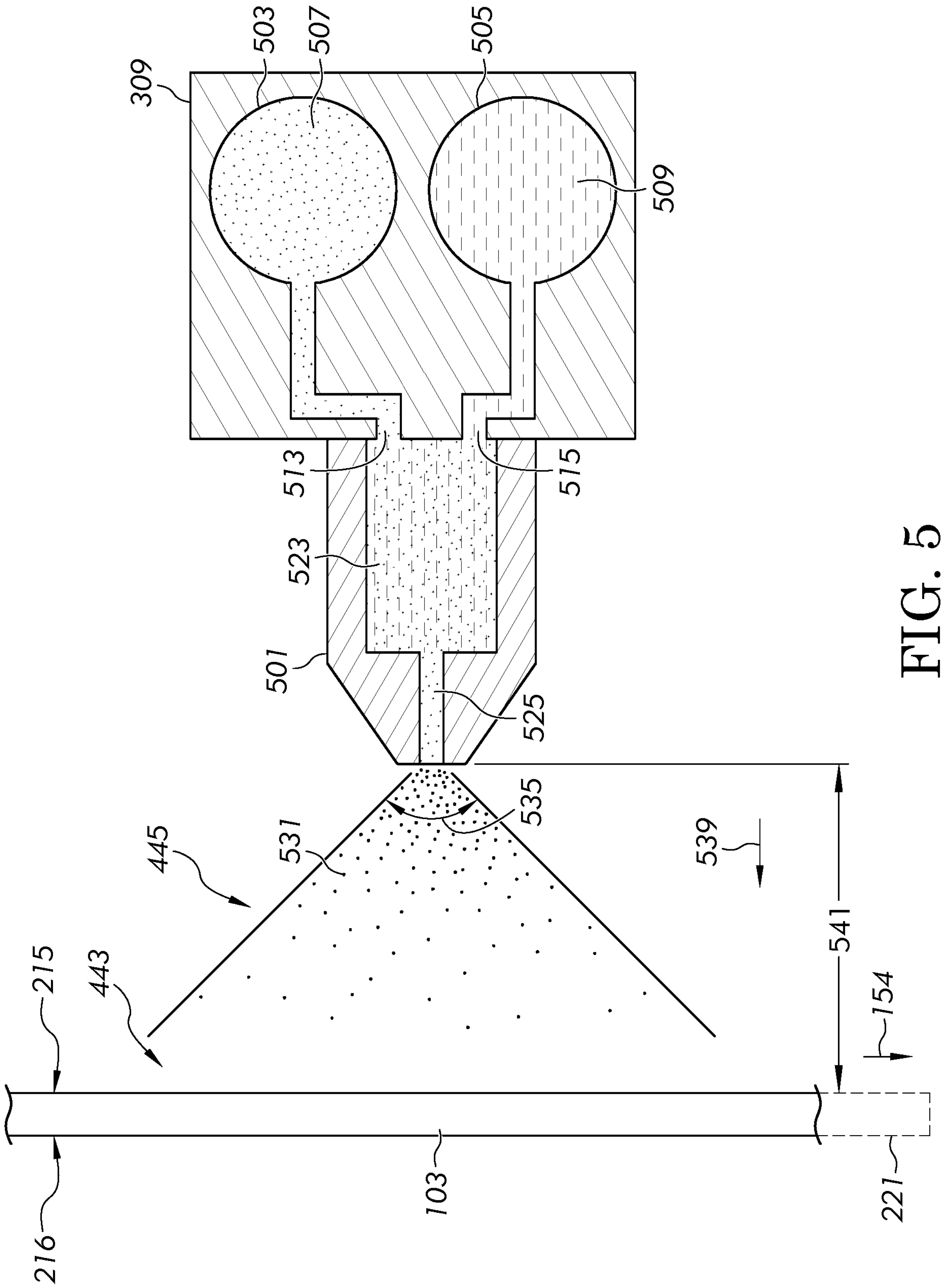
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FIG. 5

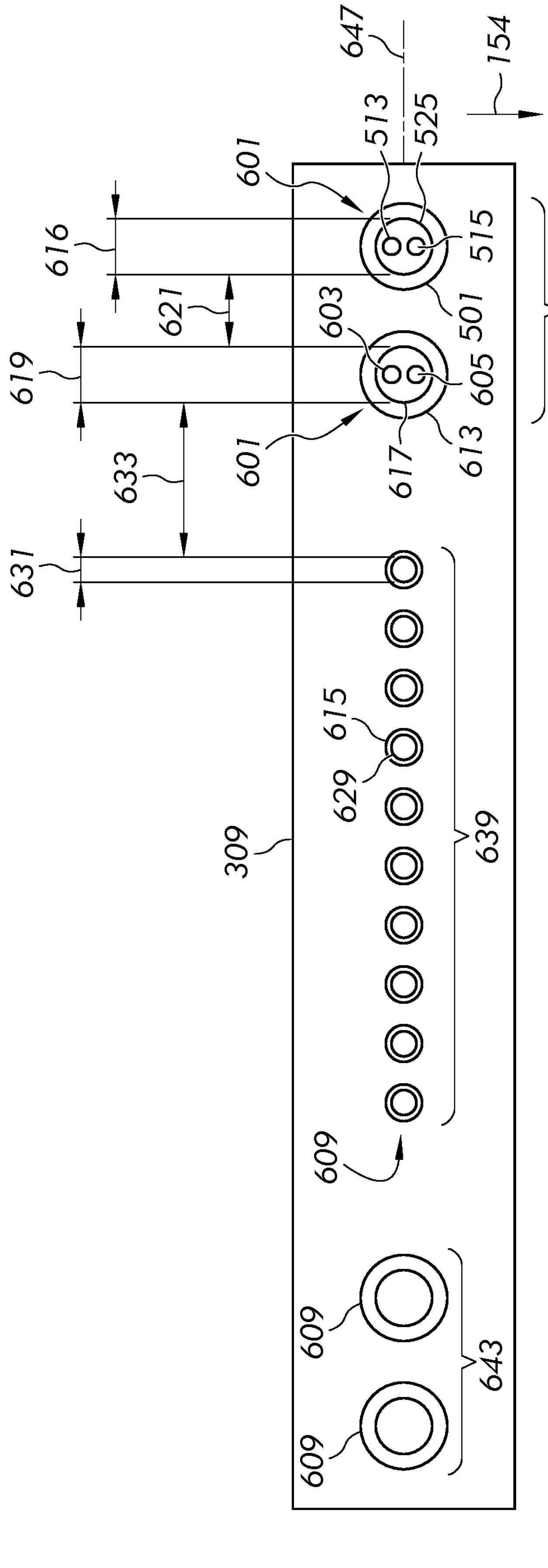
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FIG. 6

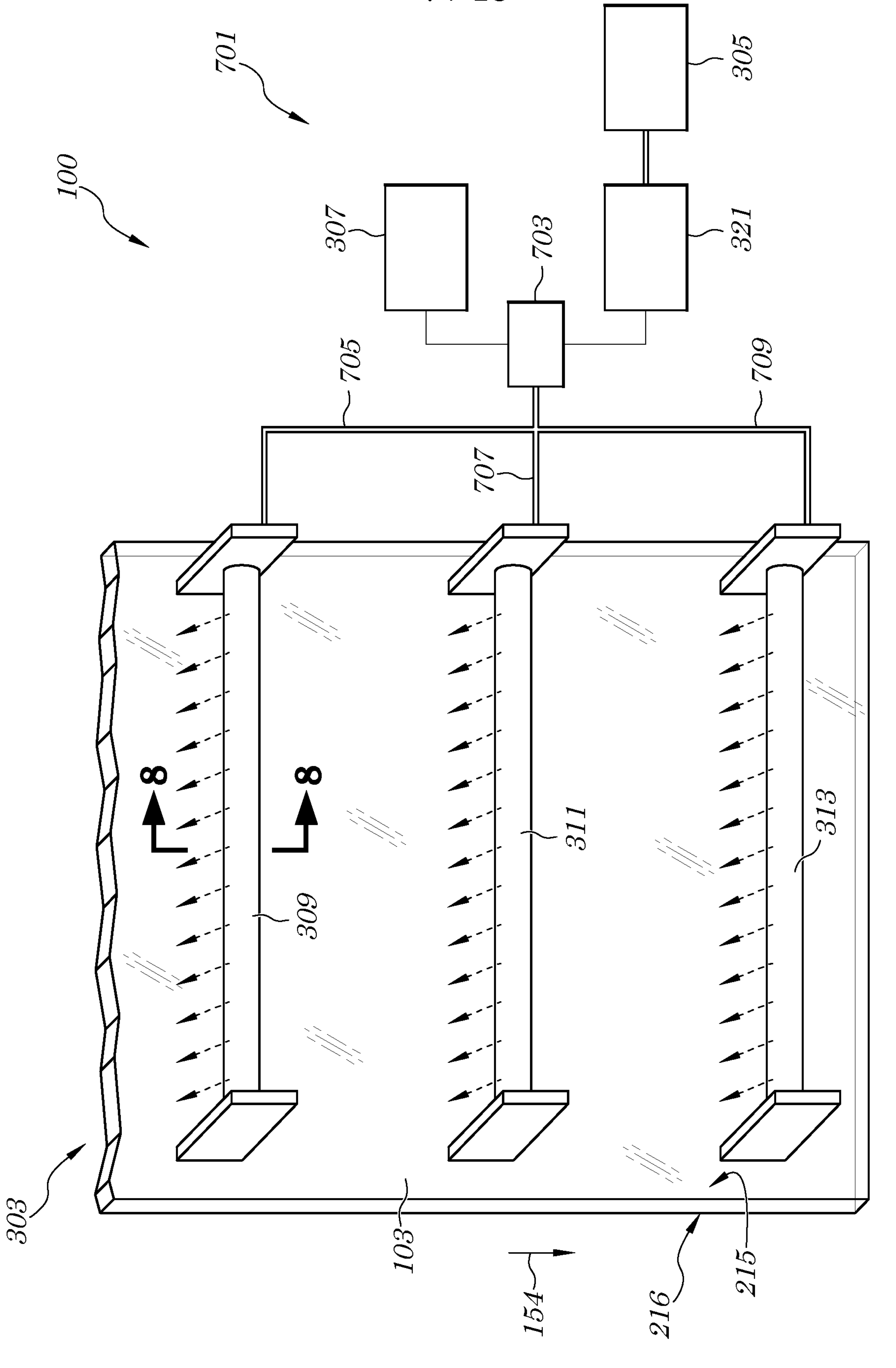
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FIG. 7

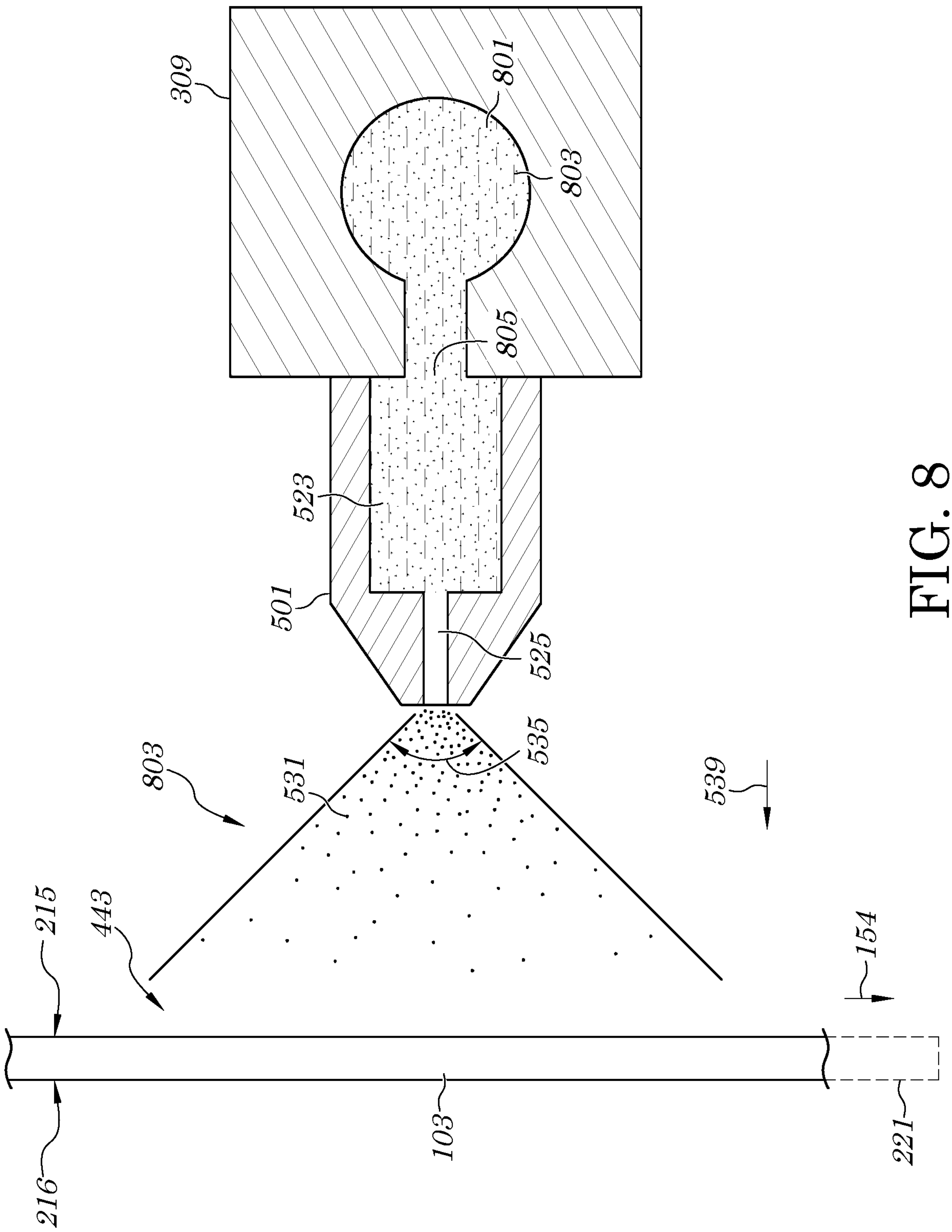
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FIG. 8

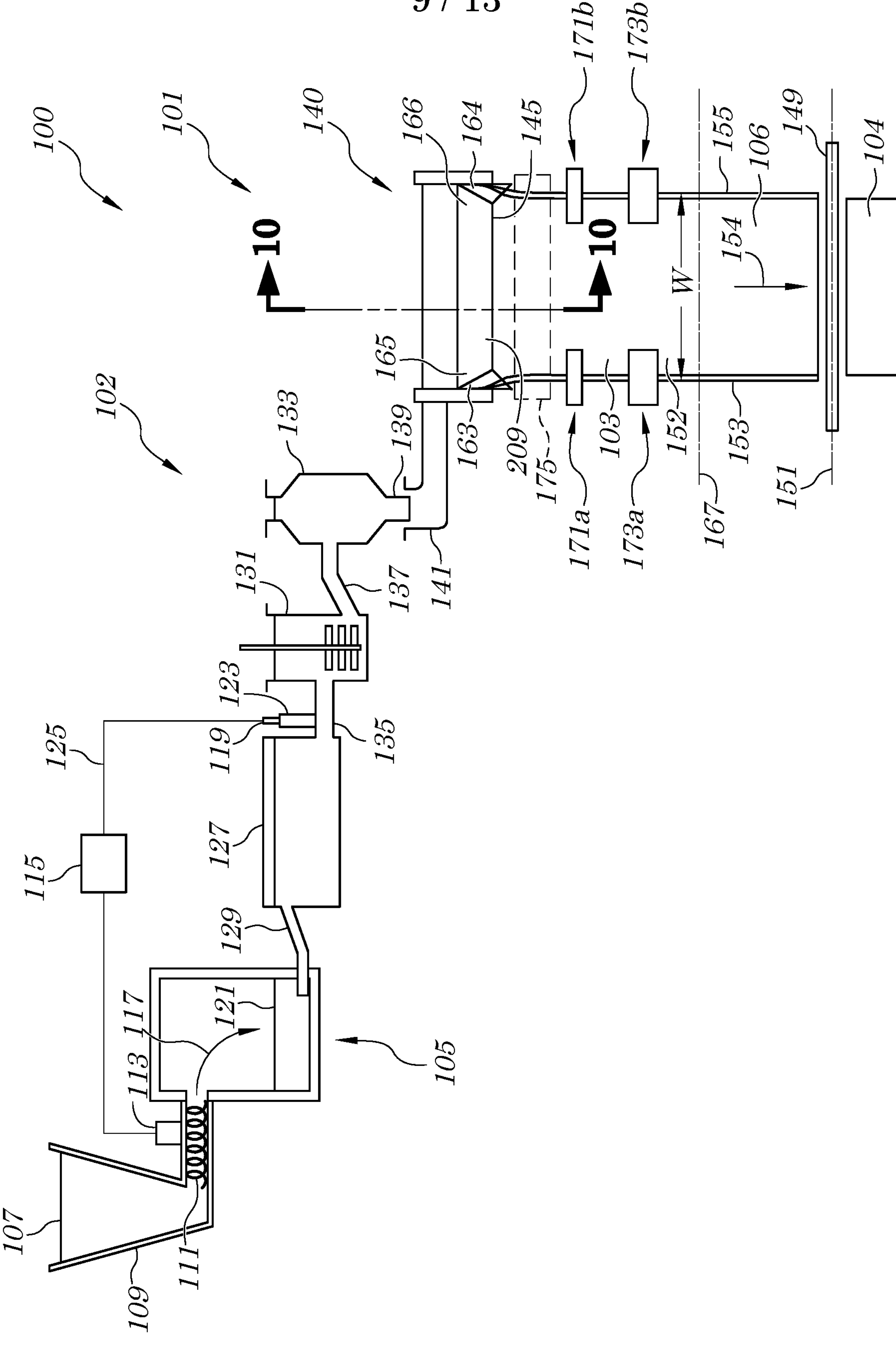
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FIG. 9

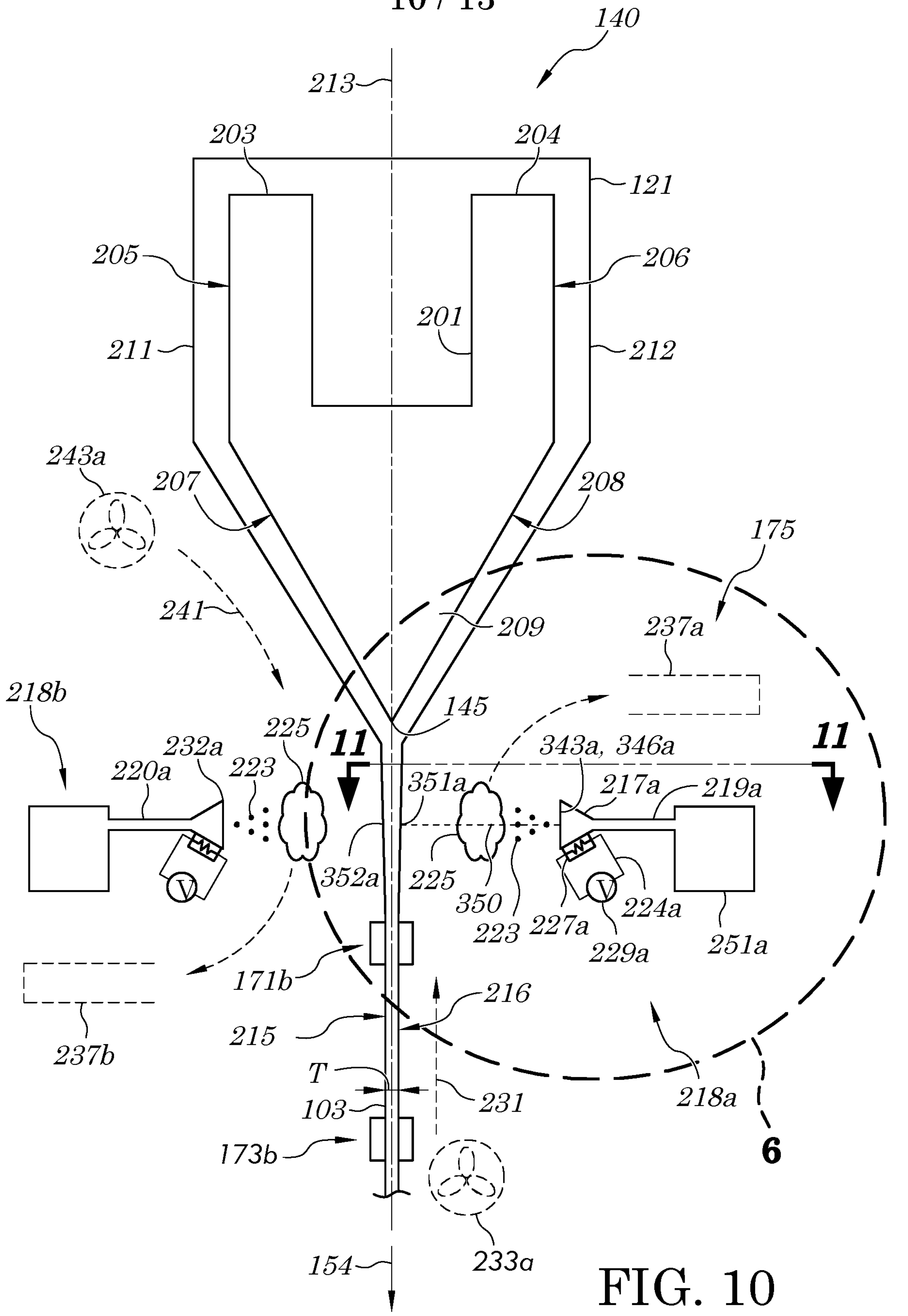
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FIG. 10

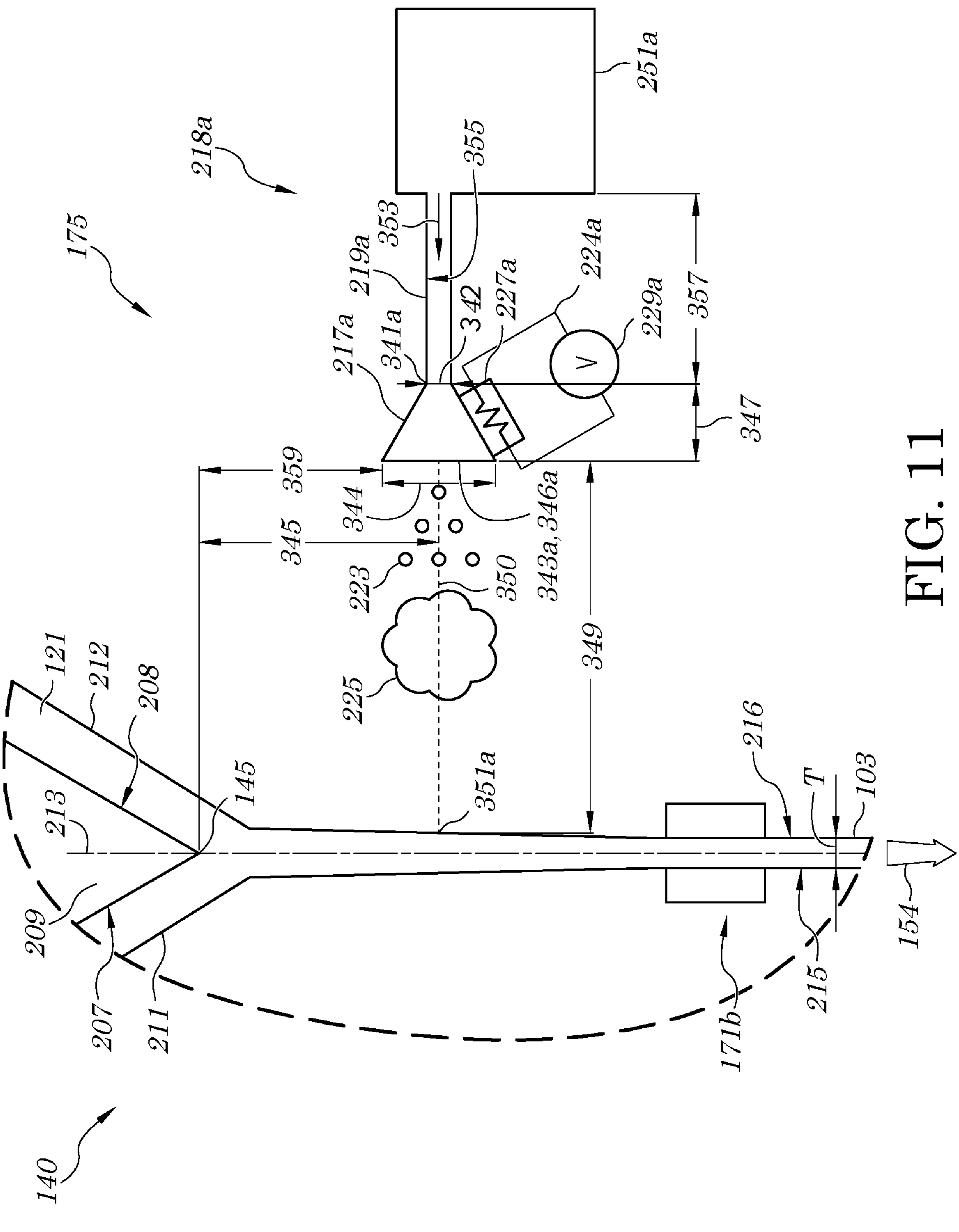
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FIG. 11

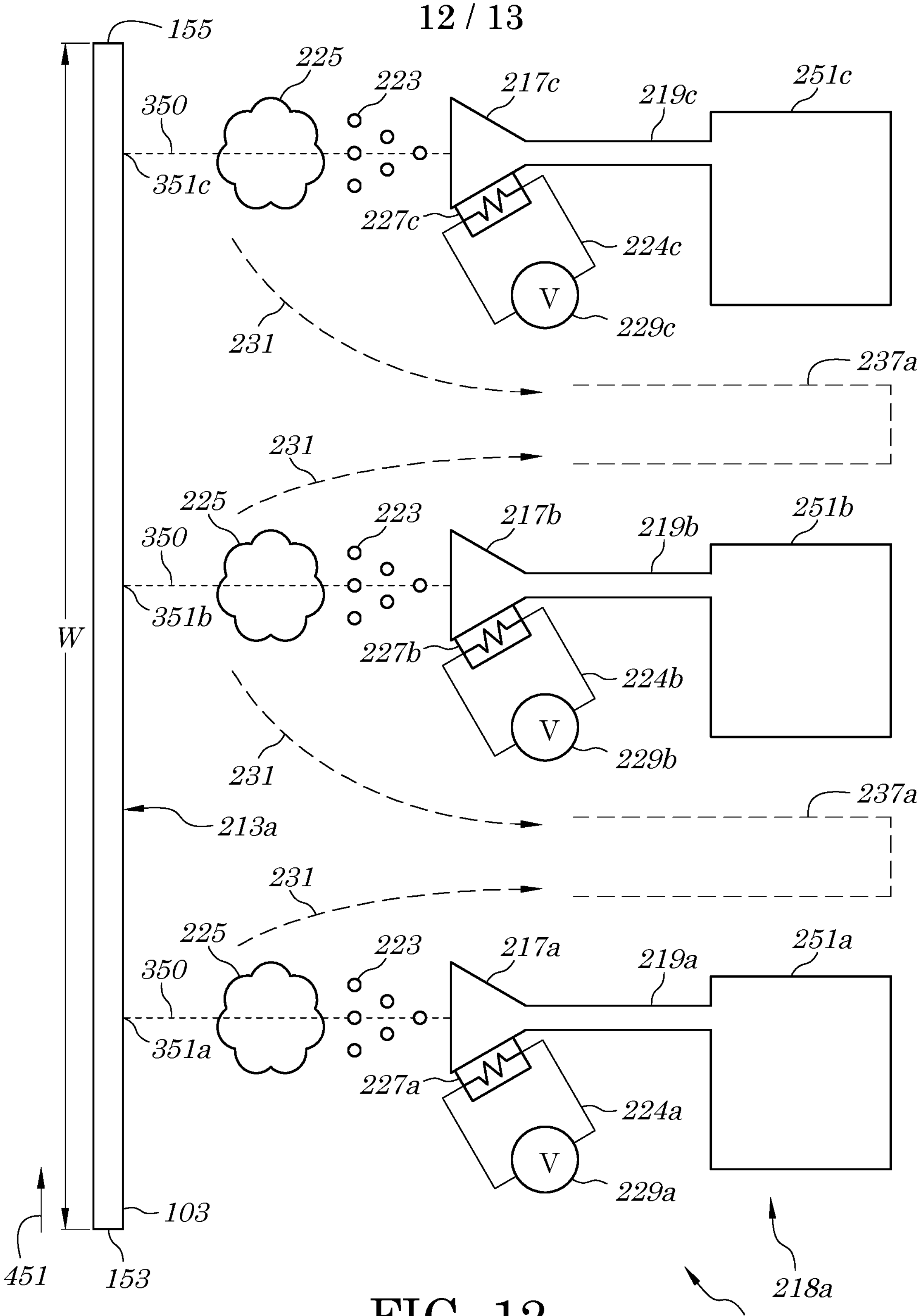
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FIG. 12

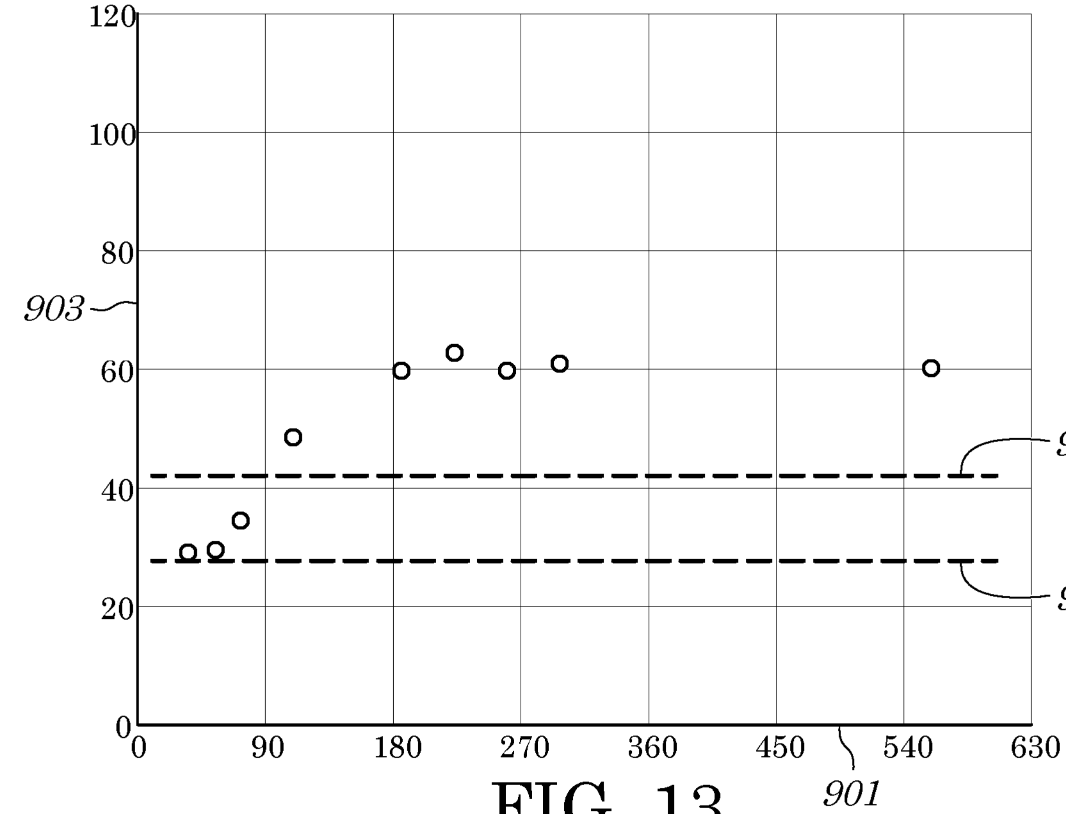
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FIG. 13

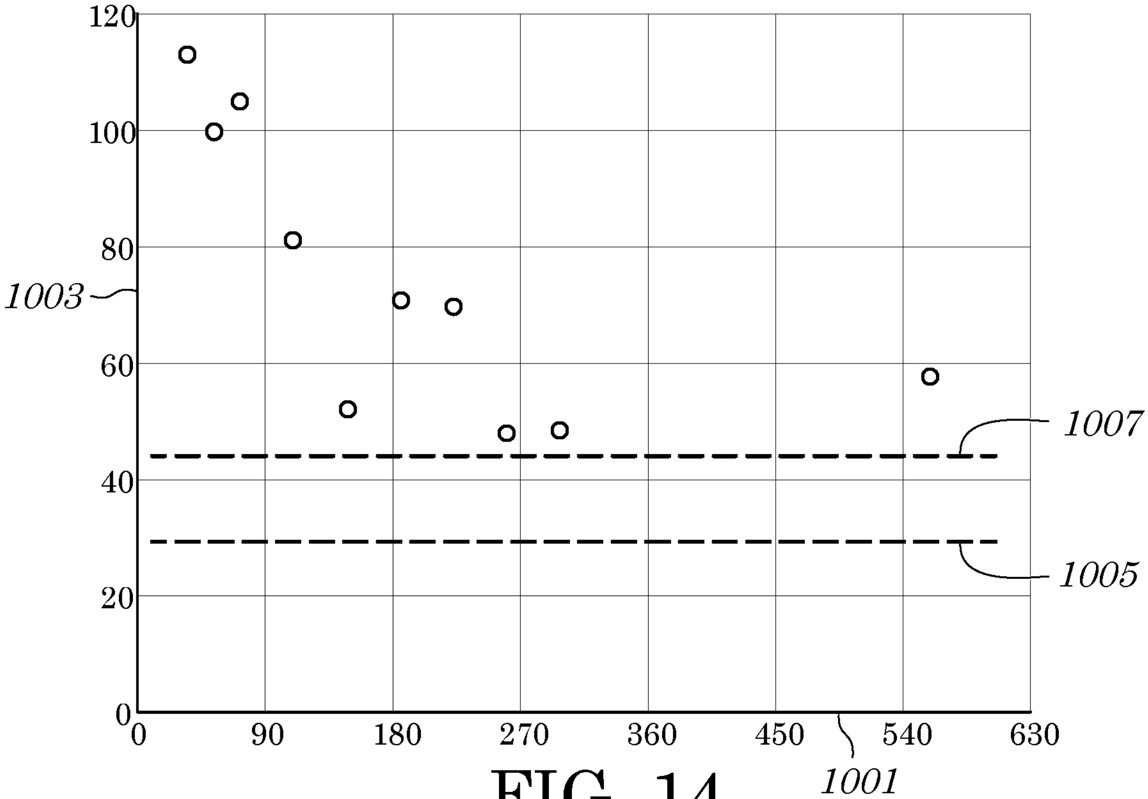
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FIG. 14

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2020/039751

A. CLASSIFICATION OF SUBJECT MATTER

C03B 17/06(2006.01)i, C03B 35/14(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 17/06; C03B 18/04; C03B 18/18; C03B 27/02; C03B 27/04; C03B 33/02; F28D 5/00; C03B 35/14

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, forming apparatus, cooling tube, nozzles

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2011-0289969 A1 (DELIA, ROBERT et al.) 01 December 2011 See paragraphs [0041], [0043]; claims 1, 10; figures 1, 2.	1-7
Y		10-13,15-17,20
Y	US 5931981 A (MCMASTER, RONALD A. et al.) 03 August 1999 See columns 1-3; claim 1.	10-13,15-17,20
A	US 2012-0247154 A1 (ABRAMOV, ANATOLI ANATOLYEVICH et al.) 04 October 2012 See the entire document.	1-7,10-13,15-17,20
A	WO 2012-174353 A2 (CORNING INCORPORATED) 20 December 2012 See the entire document.	1-7,10-13,15-17,20
A	US 2012-0060536 A1 (AHONEN, SAMPO et al.) 15 March 2012 See the entire document.	1-7,10-13,15-17,20

☐ 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	Date of mailing of the international search report
21 October 2020 (21.10.2020)	**21 October 2020 (21.10.2020)**

Name and mailing address of the ISA/KR
International Application Division
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea
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Telephone No. +82-42-481-3326

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2020/039751

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.: 9, 19, 23, 25, 29-31, 33
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 9, 19, 23, 25, 29-31, 33 are not clear because they refer to multiple dependent claims respectively, which do not comply with PCT Rule 6.4(a).

3. ☒ Claims Nos.: 8, 14, 18, 21-22, 24, 26-28, 32, 34-35
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required addtional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		WO 2012-174353 A3	18/04/2013
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		CN 102803520 B	31/12/2014
		EP 2443262 A1	25/04/2012
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		WO 2011-004061 A1	13/01/2011