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### Systems and methods for measuring the temperature of glass during tube conversion

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#### Abstract

A system for producing articles from glass tube includes a converter having a base with a plurality of processing stations and a turret moveable relative to the base. The turret indexes a plurality of holders for holding the glass tubes successively through the processing stations. The system further includes a thermal imaging system that includes a thermal imager coupled to the turret for movement with the turret. The thermal imaging system may also include a mirror coupled to the thermal imager and positioned to reflect infrared light from one of the plurality of holders to the thermal imager. The thermal imaging system may measure one or more characteristics of the glass tube during the conversion process. Processes for controlling the converter using the thermal imaging system to measure one or more process variables are also disclosed.

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## References Cited

### U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
713280	12/1901	Blair	65/282	C03B 23/095
3424570	12/1968	Couquelet	N/A	N/A
3482448	12/1968	Gaffard	N/A	N/A
3736118	12/1972	Heflich et al.	N/A	N/A
4092142	12/1977	Dichter	N/A	N/A
4142883	12/1978	Dichter	N/A	N/A
4303435	12/1980	Sleighter	N/A	N/A
4441908	12/1983	Zauner	65/243	C03B 23/112
4548633	12/1984	Nebelung	N/A	N/A
4615719	12/1985	Pauluk et al.	N/A	N/A
4688474	12/1986	Anderl	N/A	N/A
5196997	12/1992	Kurtzberg et al.	N/A	N/A
5583337	12/1995	Chan	N/A	N/A
5611834	12/1996	Walter et al.	N/A	N/A
6188079	12/2000	Juvinall et al.	N/A	N/A
6232583	12/2000	Uhm	N/A	N/A
7660642	12/2009	Tuszynski	N/A	N/A
8958058	12/2014	Bonin et al.	N/A	N/A
10773989	12/2019	Gaylo et al.	N/A	N/A
10968133	12/2020	Gaylo et al.	N/A	N/A
11186513	12/2020	Gaylo et al.	N/A	N/A
11339079	12/2021	Klingensmith et al.	N/A	N/A

11420893	12/2021	McEnroe	N/A	N/A
2003/0216887	12/2002	Shieh	N/A	N/A
2004/0143357	12/2003	Schwarm et al.	N/A	N/A
2006/0031024	12/2005	Mountassir	N/A	N/A
2006/0096319	12/2005	Dalstra	N/A	N/A
2007/0038657	12/2006	Denton et al.	N/A	N/A
2009/0037013	12/2008	Hendler et al.	N/A	N/A
2010/0060902	12/2009	Wornson et al.	N/A	N/A
2010/0082120	12/2009	Stephenson et al.	N/A	N/A
2010/0208242	12/2009	Martinez et al.	N/A	N/A
2011/0141264	12/2010	Holtkamp et al.	N/A	N/A
2011/0141265	12/2010	Holtkamp et al.	N/A	N/A
2012/0047955	12/2011	Belgum et al.	N/A	N/A
2014/0174127	12/2013	Dalstra	N/A	N/A
2014/0373574	12/2013	Moseler et al.	N/A	N/A
2015/0074982	12/2014	Adams et al.	N/A	N/A
2015/0076353	12/2014	Bathelet	N/A	N/A
2015/0142163	12/2014	Simon	N/A	N/A
2015/0203077	12/2014	Gokan	N/A	N/A
2016/0016841	12/2015	Frost et al.	N/A	N/A
2016/0214224	12/2015	Jing et al.	N/A	N/A
2018/0134603	12/2017	Inoue	N/A	N/A
2019/0195724	12/2018	Jo et al.	N/A	N/A
2020/0377402	12/2019	Gaylo et al.	N/A	N/A

#### FOREIGN PATENT DOCUMENTS

<b>Patent No.</b>	<b>Application Date</b>	<b>Country</b>	<b>CPC</b>
1685229	12/2004	CN	N/A
1872754	12/2005	CN	N/A
104591525	12/2014	CN	N/A
104843981	12/2014	CN	N/A
105271658	12/2015	CN	N/A
19902316	12/1999	DE	N/A
1725501	12/2007	EP	N/A
2873572	12/2014	EP	N/A
3287419	12/2017	EP	N/A
2241400	12/1990	GB	N/A
201900005600	12/2019	IT	N/A
52-121486	12/1976	JP	N/A
60-098340	12/1984	JP	N/A
S60-98340	12/1984	JP	N/A
05-072138	12/1992	JP	N/A
H05-72138	12/1992	JP	N/A
H10-249930	12/1997	JP	N/A
H11116249	12/1998	JP	N/A
2002049930	12/2001	JP	N/A
2004051405	12/2003	JP	C03B 23/092
2007002138	12/2006	JP	N/A

2009008340	12/2008	JP	N/A
2013079180	12/2012	JP	N/A
2014-114028	12/2013	JP	N/A
2014-129224	12/2013	JP	N/A
2014-184845	12/2013	JP	N/A
2014-208565	12/2013	JP	N/A
2015107636	12/2014	JP	N/A
2064458	12/1995	RU	N/A
2014/010578	12/2013	WO	N/A
2016042984	12/2015	WO	N/A
2016/171214	12/2015	WO	N/A

## OTHER PUBLICATIONS

JP-2004051405-A (Kondo) Feb. 19, 2004 (English language translation). [online] [retrieved Oct. 8, 2024]. Retrieved from: Clarivate Analytics. (Year: 2004). cited by examiner

Translation of Chinese Office Action dated Sep. 6, 2024, pertaining to CN Patent Application No. 202211081352.5, 4 pgs. cited by applicant

US Final Office Action dated Sep. 12, 2024, pertaining to U.S. Appl. No. 17/385,684, 50 pgs. cited by applicant

International Search Report & Written Opinion dated Aug. 30, 2022, for PCT/US2022/030493. pp. 1-15; European Patent Office. cited by applicant

Ambeg Glasbearbeitungsmaschinen—RP16, Glass Forming Machines, Vial forming machine RP 16 with automatic tube feeder [online] retrieved from the internet on Mar. 12, 2018. URL: <<http://www.ambeg.de/en/products/rp16.html>>. pp. 1-2. cited by applicant

Brazil Office Action dated Jul. 6, 2022, pertaining to BR Patent Application No. BR112019019945-4, 8 pgs. cited by applicant

Chinese Office Action mailed Oct. 21, 2021 in related Chinese Patent Application No. 201880020806.3, 13 pages. cited by applicant

Dean Butler, et al., Intelligent software sensors and process prediction for glass container forming processes based on multivariate statistical process control techniques, UKACC International Conference on Control, 2012, pp. 281-285. cited by applicant

International Search Report & Written Opinion dated Jun. 6, 2018, for PCT/US2018/023873 filed Mar. 22, 2018, pp. 1-13. cited by applicant

Japanese Office Action dated Nov. 17, 2021, pertaining to Application No. JP2019-552485 filed Nov. 12, 2021, 5 pgs. cited by applicant

Japanese Patent Application No. 2019-552485, Office Action dated Jun. 17, 2022, 9 pages (4 pages of English Translation and 5 pages of Original Document), Japanese Patent Office. cited by applicant

Keyence, The Original Green LED Incorporated Digital Micrometer.[online] retrieved from the internet on Mar. 12, 2018. URL: <[www.keyence.com](http://www.keyence.com)>. pp. 1-8. cited by applicant

Non-Final Office Action dated Mar. 10, 2020, for U.S. Appl. No. 15/928,837, filed Mar. 22, 2018. pp. 1-9. cited by applicant

RU 1st Office Action & Search Report dated Jul. 5, 2021, for RU Patent Application No. 2019131142. cited by applicant

Taiwanese Patent Application No. 107110012, Office Action dated Jul. 21, 2021, 3 page (English Translation Only); Taiwanese Patent Office. cited by applicant

TW 1st Office Action & Search Report dated Jul. 21, 2021, for TW Patent Application No. 107110012. cited by applicant

Japanese Office Action dated Nov. 27, 2024, pertaining to JP Patent Application No. 2023-142114, 12 pgs. cited by applicant

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## **Background/Summary**

CROSS-REFERENCE TO RELATED APPLICATIONS (1) The present application is a continuation of U.S. patent application Ser. No. 17/385,684 filed Jul. 26, 2021, entitled “Systems and Methods for Measuring the Temperature of Glass During Tube Conversion”, which is a continuation of U.S. patent application Ser. No. 16/994,465 filed Aug. 14, 2020, entitled “Systems and Methods for Measuring the Temperature of Glass During Tube Conversion”, which is a divisional of U.S. patent application Ser. No. 15/928,837 filed Mar. 22, 2018, entitled, “Systems and Methods for Measuring the Temperature of Glass During Tube Conversion”, which claims the benefit of priority to U.S. Provisional Application No. 62/476,408, filed Mar. 24, 2017, entitled “Systems and Methods for Measuring the Temperature of Glass During Tube Conversion,” the entire contents of all of which are hereby incorporated by reference herein.

## **BACKGROUND**

### **Field**

(1) The present specification generally relates to systems and methods for measuring the temperature of glass during conversion of glass tube to glass articles.

### **Technical Background**

(2) Glass tubing may be converted into other glass articles. For example, glass tubing may be converted into various glass containers for use in pharmaceutical applications including, without limitation, vials, syringes, ampoules, cartridges and other glass articles. The glass tubing may be converted, for example, in “converting machines.” Converting machines have been used for over 75 years, and are currently made by various commercial and internal equipment suppliers. These converting machines typically reform long glass tube lengths into a plurality of glass articles using steps which include flame working, rotating and stationary tool forming, thermal separation, or score and shock cutoff steps.

(3) In the current glass converting industry, the converting machines are run by operators and technicians with extensive experience. These operators and technicians learn the machine operations through experience and artisan-like training, and operational adjustments to burners and machine setup, for example, are typically performed solely by visual assessment of temperature and shape of the partially formed or totally formed glass articles. Operational practices and machine modifications are closely held by part makers, a practice which presents a substantial barrier to entry into the market for producing high end pharmaceutical articles for new producers.

(4) Accordingly, a need exists for alternative systems and methods for forming glass articles with tube conversion machines.

## **SUMMARY**

(5) Accordingly, a need exists for systems and methods for measuring the temperatures of glass tubes during glass tube conversion to produce glass articles.

(6) In one or more aspects of the present disclosure, a system for producing glass articles from glass tube may comprise a converter comprising a base having a plurality of processing stations spaced apart in a circuit and a turret moveable relative to the base, the turret having a plurality of holders extending from the turret towards the plurality of processing stations, the plurality of

holders spaced apart from one another, wherein the turret is operable to index each of the plurality of holders into proximity with each of the plurality of processing stations in succession. The system may further include a thermal imaging system comprising a thermal imager coupled to the turret for movement with the turret, wherein the thermal imager is positioned to capture infrared light emitted from the glass tube disposed in one of the plurality of holders.

(7) In embodiments, the thermal imager may be positioned to directly receive infrared light emitted by an outer surface of the glass tube. The thermal imaging system may further comprise at least one mirror oriented to reflect infrared light emitted from an inner surface of the glass tube to the thermal imager. The at least one mirror may be a stationary mirror coupled to the base and oriented to reflect infrared light emitted from an inner surface of the glass tube to the thermal imager.

(8) In some embodiments, the system may further comprise a mirror coupled to the thermal imager and oriented to reflect infrared light from the glass tube to the thermal imager. The mirror may be oriented to reflect infrared light emitted from an outer surface of the glass tube to the thermal imager. A reflective surface of the mirror may have a reflectance equal to or greater than 96% for light having wavelengths from 800 nanometers to 20 microns. In other embodiments, the mirror may be oriented to reflect infrared light emitted from an inner surface of the glass tube to the thermal imager.

(9) In embodiments, the system may include at least one supplemental mirror coupled to the thermal imager, wherein the mirror is oriented to reflect infrared light emitted from an outer surface of the glass tube to the thermal imager and the supplemental mirror is oriented to reflect infrared light emitted from an inner surface of the glass tube to the thermal imager. In other embodiments, the system may include at least one stationary mirror positioned vertically below one of the plurality of processing stations, the stationary mirror positioned to reflect infrared light emitted from an inner surface of the glass tube to the thermal imager when the thermal imager is indexed into position at the one of the plurality of processing stations by the turret.

(10) In some embodiments, the thermal imager may be an infrared camera configured to receive infrared light having wavelengths from 4 microns to 14 microns, or from 5 microns to 14 microns. In embodiments, the system may comprise a main turret and a secondary turret. The thermal imager may be coupled to the main turret for rotation with the main turret. The system may comprise a loading turret positioned above the main turret and rotatable relative to the main turret. In some embodiments, the thermal imaging system may include a plurality of thermal imagers.

(11) In some embodiments, the system may include a slip ring positioned above the turret and having a slip ring axis aligned with a central axis of the turret, the slip ring electrically coupling the thermal imager to a power source. The slip ring may operatively couple the thermal imager to a processor. An inner ring of the slip ring may include a central bore.

(12) In other embodiments, the system may further comprise a power source coupled to the turret for rotation with the turret, the power source electrically coupled to the thermal imager to provide power to the thermal imager. The system may also include a wireless communication device coupled to the turret, wherein the wireless communication device communicatively couples the thermal imager to a processor.

(13) In embodiments, the system may comprise a cooling system that includes a cooling fluid supply, a rotating union fluidly coupled to the cooling fluid supply and having a union axis aligned with the central axis of the turret, and a supply conduit extending from the rotating union to the thermal imaging system. The system may also include a cleaning system comprising at least one nozzle positioned to deliver a fluid to the lens of the thermal imager. The thermal imaging system may include a mirror coupled to the thermal imager and oriented to reflect infrared light from glass tube positioned in one of the plurality of holders to the thermal imager, and the cooling system may include at least one nozzle positioned to deliver a fluid to a reflective surface of the mirror.

(14) In some embodiments, the system may include at least one processor communicatively coupled to the thermal imager, at least one memory module communicatively coupled to the

processor, and machine readable instructions stored in the at least one memory module that cause the thermal imaging system to perform at least the following when executed by the at least one processor: receive thermal image information from the thermal imager, process the thermal image information, and determine a characteristic of a glass tube from the thermal image information. The characteristic may be at least one of a temperature of the glass tube, a temperature gradient through a thickness of the glass tube, a viscosity of the glass tube, a viscosity gradient through the thickness of the glass tube, a dimension of the glass tube, a temperature profile of the glass tube, a temperature profile of the glass tube as a function of time, a centerline of the glass tube, or combinations thereof.

(15) In embodiments, the system may further comprise machine readable instructions stored in the at least one memory module that, when executed by the at least one processor, cause the thermal imaging system to determine a temperature of the glass tube from the thermal image information, determine a viscosity of the glass tube from the thermal image information, or determine a dimension of the glass tube from the thermal image information.

(16) In some embodiments, the system may further include machine readable instructions stored in the at least one memory module that cause the thermal imaging system to perform at least the following when executed by the at least one processor: determine a first characteristic of the glass tube at a first processing station, determine a second characteristic of the glass tube at a second processing station positioned downstream of the first processing station, calculate a difference between the first characteristic and the second characteristic, and transmit an output representative of the difference between the first characteristic and the second characteristic.

(17) In some embodiments, the processor may be communicatively coupled to a control device, and the system may further comprise machine readable instructions stored in the at least one memory module that cause the thermal imaging system to perform at least the following when executed by the at least one processor: compare the characteristic of the glass tube to a set point characteristic, determine a controlled variable from comparison of the characteristic of the glass tube to the set point characteristic, and transmit a control signal representative of the controlled variable to the control device.

(18) In embodiments, at least one of the plurality of processing stations may comprise a heating station having at least one heating element and the control device is operatively coupled to the heating element to manipulate the heating of the glass tube by the heating element. The heating element may include a burner and the control device may be one or more of a fuel control valve, an oxygen control valve, or an air control valve. The controlled variable may be a mass flow rate of one or more of fuel gas, oxygen, or air. Alternatively, the controlled variable may be a position of one or more of the fuel control valve, the oxygen control valve, or the air control valve.

(19) In embodiments, at least one of the processing stations may be a cooling station having at least one cooling fluid control valve, wherein the control device is the cooling fluid control valve. In embodiments, at least one of the processing stations may be a forming station having one or more actuators that translate at least one forming tool into removable engagement with the glass tube, wherein the control device comprises the one or more actuators. The controlled variable may be a contact time of the at least one forming tool with the glass tube in the forming station.

(20) In some embodiments, the system may further include a dimensioning system. The dimensioning system may include at least one of a visual imaging system, a laser reflectometer, a laser gauge, or an optical micrometer. The dimensioning system may be positioned to capture measurement data of the glass tube upstream of the converter. Alternatively, in some embodiments, the dimensioning system may be positioned to capture measurement data of the glass tube at one of the plurality of processing stations. The system may further include machine readable instructions stored in the at least one memory module that cause the dimensioning system to perform at least the following when executed by the at least one processor: capture measurement data of the glass tube in the one of the plurality of processing stations, process the measurement data of the glass

tube, and determine a physical attribute of the glass tube from the measurement data of the glass tube. The physical attribute is one or more of a diameter, thickness, or glass mass per unit length of the glass tube.

(21) In some embodiments, the system may include machine readable instructions stored in the at least one memory module that cause the system to perform at least the following when executed by the at least one processor: receive the physical attribute of the glass tube from the dimensioning system, and determine a characteristic gradient across a thickness of the glass tube from the physical attribute and the characteristic. The characteristic gradient may be a temperature gradient or a viscosity gradient.

(22) In embodiments, the system may include machine readable instructions stored in the at least one memory module that cause the system to perform at least the following when executed by the at least one processor: compare the physical attribute of the glass tube to a set point physical attribute, and determine an adjustment to the controlled variable from comparison of the physical attribute of the glass tube to the set point physical attribute.

(23) In another aspect, a process for controlling a glass tube converter may comprise indexing a glass tube, which is removably coupled to a turret of the glass tube converter, through a plurality of processing stations of the glass tube converter, at least one of the plurality of processing stations comprising a control device. The process may further include capturing a thermal image of the glass tube using a thermal imaging system coupled to the turret of the glass tube converter, the thermal imaging system comprising at least a thermal imager oriented to capture infrared light from the glass tube. The process may further comprise processing the thermal image, determining a characteristic of the glass tube from the thermal image, comparing the characteristic of the glass tube to a set point, determining a controlled variable from comparison of the characteristic of the glass tube to the set point, and transmitting a control signal representative of the controlled variable to a control device.

(24) In some embodiments of the process, the at least one of the plurality of processing stations may comprise a heating station having at least one heating element and the control device may be operatively coupled to the heating element. The heating element may be a burner and the control device may be one or more of a fuel control valve, an oxygen control valve, or an air control valve, wherein the controlled variable may be a mass flow rate of one or more of fuel gas, oxygen, or air. The control device may be one or more of a fuel control valve, an oxygen control valve, or an air control valve, and the controlled variable may be a position of one or more of the fuel control valve, the oxygen control valve, or the air control valve.

(25) In embodiments of the process, the at least one of the processing stations may comprise a cooling station having at least one cooling fluid control valve, wherein the control device may be the cooling fluid control valve. In some embodiments of the process, the at least one of the processing stations comprises a forming station having one or more actuators that translate at least one forming tool into removable engagement with the glass tube, wherein the control device may be the one or more actuators. The controlled variable may be a contact time of the at least one forming tool with the glass tube in the forming station.

(26) In some embodiments, the converter may comprise a dimensioning system having at least one of a visual imaging system, laser reflectometer, laser gauge, or optical micrometer positioned to capture measurement data of the glass tube at one of the plurality of processing stations. The process may further comprise capturing the measurement data of the glass tube in the one of the plurality of processing stations, processing the measurement data of the glass tube, and determining a physical attribute of the glass tube from the measurement data of the glass tube. The physical attribute may be one or more of a diameter, thickness, or glass mass per unit length of the glass tube.

(27) In embodiments, the process may further comprise comparing the physical attribute of the glass tube to a set point physical attribute, and determining an adjustment to the controlled variable



from comparison of the physical attribute of the glass tube to the set point physical attribute. In other embodiments, the process may further comprise measuring a physical attribute of the glass tube, wherein the physical attribute may be one of a diameter, a thickness, or a mass per unit length of the glass tube, comparing the physical attribute of the glass tube to a set point physical attribute, and determining an adjustment to the controlled variable from comparison of the physical attribute of the glass tube to the set point physical attribute.

(28) It is to be understood that both the foregoing general description and the following detailed description describe various embodiments and are intended to provide an overview or framework for understanding the nature and character of the claimed subject matter. The accompanying drawings are included to provide a further understanding of the various embodiments, and are incorporated into and constitute a part of this specification. The drawings illustrate the various embodiments described herein, and together with the description serve to explain the principles and operations of the claimed subject matter.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

- (1) FIG. 1 schematically depicts an embodiment of a converter for producing glass articles from glass tube, according to one or more embodiments shown and described herein;
- (2) FIG. 2 schematically depicts a main turret, secondary turret, and feed turret of the glass tube converting machine of FIG. 1, according to one or more embodiments shown and described herein;
- (3) FIG. 3A schematically depicts a heating station of the converter of FIG. 1, according to one or more embodiments shown and described herein;
- (4) FIG. 3B schematically depicts a separating station of the converter of FIG. 1, according to one or more embodiments shown and described herein;
- (5) FIG. 3C schematically depicts a forming station of the converter of FIG. 1, according to one or more embodiments shown and described herein;
- (6) FIG. 3D schematically depicts another embodiment of a forming station of the converter of FIG. 1, according to one or more embodiments shown and described herein;
- (7) FIG. 3E schematically depicts a cooling station of the converter of FIG. 1, according to one or more embodiments shown and described herein;
- (8) FIG. 4 is a perspective view of a glass tube prior to conversion in the converter of FIG. 1, according to one or more embodiments shown and described herein;
- (9) FIG. 5 schematically depicts a thermal imaging system of the converter of FIG. 1, according to one or more embodiments shown and described herein;
- (10) FIG. 6 schematically depicts the thermal imaging system of FIG. 5, according to one or more embodiments shown and described herein;
- (11) FIG. 7A schematically depicts operation of a thermal imager of the thermal imaging system of FIG. 5, according to one or more embodiments shown and described herein;
- (12) FIG. 7B schematically depicts operation of the thermal imager and a stationary mirror of the thermal imaging system of FIG. 5, according to one or more embodiments shown and described herein;
- (13) FIG. 7C schematically depicts operation of the thermal imager and a mirror of the thermal imaging system of FIG. 5, according to one or more embodiments shown and described herein;
- (14) FIG. 7D schematically depicts alternative operation of the thermal imager and the mirror of the thermal imaging system of FIG. 7C, according to one or more embodiments shown and described herein;
- (15) FIG. 7E schematically depicts operation of the thermal imager, the mirror, and a supplemental mirror of the thermal imaging system of FIG. 5, according to one or more embodiments shown and described herein;

described herein;

(16) FIG. 7F schematically depicts operation of the thermal imager, the mirror, and a stationary mirror of the thermal imaging system of FIG. 5, according to one or more embodiments shown and described herein;

(17) FIG. 7G schematically depicts an alternative operation of the thermal imager, mirror, and supplemental mirror of the thermal imaging system of FIG. 7F, according to one or more embodiments shown and described herein;

(18) FIG. 8A schematically depicts another embodiment of a thermal imaging system of the converter of FIG. 1, according to one or more embodiments shown and described herein;

(19) FIG. 8B schematically depicts another embodiment of a thermal imaging system of the converter of FIG. 1, according to one or more embodiments shown and described herein;

(20) FIG. 9 schematically depicts another embodiment of a thermal imaging system of the converter of FIG. 1, according to one or more embodiments shown and described herein;

(21) FIG. 10 is a plot of relative temperature of a surface of a glass tube (y-axis) as a function of time (x-axis) for the converter 100 measured using the thermal imaging system of FIG. 9, according to one or more embodiments shown and described herein;

(22) FIG. 11A is an image depicting a glass tube in a heating station of the converter of FIG. 1 captured by the thermal imaging system of FIG. 9, according to one or more embodiments shown and described herein;

(23) FIG. 11B is an image depicting a glass tube in a separating station of the converter of FIG. 1 captured by the thermal imaging system of FIG. 9, according to one or more embodiments shown and described herein;

(24) FIG. 11C is an image depicting a glass tube in a forming station of the converter of FIG. 1 captured by the thermal imaging system of FIG. 9, according to one or more embodiments shown and described herein;

(25) FIG. 11D is an image depicting a glass tube in another forming station of the converter of FIG. 1 captured by the thermal imaging system of FIG. 9, according to one or more embodiments shown and described herein;

(26) FIG. 12 is an image depicting a side view and a top view of a glass tube in a single thermal image captured using the thermal imaging system of FIG. 9, according to one or more embodiments shown and described herein;

(27) FIG. 13 schematically depicts a control system for the converter of FIG. 1, according to one or more embodiments shown and described herein;

(28) FIG. 14 schematically depicts single feedback control method for the control system of FIG. 13, according to one or more embodiments shown and described herein;

(29) FIG. 15 schematically depicts a cascade control method for the control system of FIG. 13, according to one or more embodiments shown and described herein;

(30) FIG. 16 schematically depicts another single feedback control method for the control system of FIG. 13, according to one or more embodiments shown and described herein;

(31) FIG. 17 schematically depicts a cross-sectional view of a mirror of a thermal imaging system of the converter of FIG. 1, according to one or more embodiments shown and described herein;

(32) FIG. 18A schematically depicts a secondary turret of the converter of FIG. 1, the secondary turret having a thermal imaging system, according to one or more embodiments shown and described herein; and

(33) FIG. 18B schematically depicts another embodiment of a secondary turret of the converter of FIG. 1, the secondary turret having a thermal imaging system, according to one or more embodiments shown and described herein.

#### DETAILED DESCRIPTION

(34) Reference will now be made in detail to embodiments of systems and methods for controlling a tube converting processes, examples of which are illustrated in the accompanying drawings.

Whenever possible, the same reference numerals will be used throughout the drawings to refer to the same or like parts. One embodiment of a system for producing articles from glass tube is depicted in FIG. 1. In this embodiment, the system for producing glass articles from glass tube **102** includes a converter **100** and a thermal imaging system **120**. The converter **100** includes a base **104** having a plurality of processing stations **106** spaced apart in a circuit and a main turret **108** spaced apart from the base **104** and moveable relative to the base **104**. The main turret **108** includes a plurality of holders **130** extending from the main turret **108** towards the plurality of processing stations **106**. The plurality of holders **130** are spaced apart from one another, and each of the plurality of holders **130** is aligned with one of the plurality of processing stations **106**. The main turret **108** is operable to index each of the plurality of holders **130** into proximity with each of the plurality of processing stations **106** in succession. The thermal imaging system **120** may include a thermal imager **122**, which may be coupled to a portion of the main turret **108** for translation with the portion of the main turret **108**. The thermal imaging system **120** may also include a mirror **124** coupled to the thermal imager **122** and positioned to reflect infrared light from one of the plurality of holders **130** to the thermal imager **122**. Various embodiments of systems and methods for controlling tube converting processes will be described herein with specific reference to the appended drawings.

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

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

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

(38) Referring now to FIG. 1, a converter **100** for producing glass articles from a glass tube **102** is schematically depicted. The converter **100** may be used to convert glass tubes **102** into a plurality of glass articles, such as, but not limited to, vials, syringes, cartridges, ampoules, or other glass articles. The converter **100** includes a base **104** having a plurality of processing stations **106**, a main turret **108** positioned above the base **104** and rotatable relative to the base **104** about the central axis A, and a glass tube loading turret **110** positioned above the main turret **108** for feeding glass tube **102** to the main turret **108**. The converter **100** may also include a plurality of secondary processing stations **112** on the base **104** and a secondary turret **114**, which is rotatable relative to the base **104**. A thermal imaging system **120** is coupled to the main turret **108** for rotation with the main turret **108**. In embodiments, the thermal imaging system **120** includes a thermal imager **122** and a mirror **124**. A mounting apparatus **126** may be used to couple the thermal imaging system **120** to the main turret **108**. The thermal imaging system **120** may be utilized to capture thermal images of the glass tube **102** as the glass tube **102** is indexed with the main turret between processing stations **106**. From these thermal images, one or more temperatures or temperature profiles of the glass tube **102** may be extracted and used to study the converting process and/or incorporated into one or more process control methods for controlling the converter **100**.

(39) As schematically depicted in FIG. 1, the base **104** of the converter **100** is stationary and the processing stations **106** may be coupled to an upper portion **105** of the base **104**. The plurality of processing stations **106** are spaced apart from one another and arranged in a main circuit **116**. In one or more embodiments, the main circuit **116** may be circular so that the main turret **108** may index a glass tube **102** through the plurality of processing stations **106** by rotation of the main turret **108** about the central axis A. The type and/or shape of the article to be made from the glass tube **102** may influence the number of processing stations **106** coupled to the base **104**. The number of processing stations **106** of the main turret **108** may be from 14 processing stations **106** to 32 processing stations **106**. Although the converter **100** and converting process are described herein in the context of a converter **100** having sixteen processing stations **106** in the main circuit **116**, it is understood that the converter **100** may have more or less than sixteen processing stations **106** in the main circuit **116**. The processing stations **106** may include, by way of example and without limitation, one or more heating, forming, polishing, cooling, separating, piercing, measuring, feeding, or discharge stations or other processing stations for producing the glass articles from the glass tubes **102**. The type and/or shape of the article to be made from the glass tube **102** may also influence the type of processing stations **106** and/or order of processing stations **106** of the converter **100**.

(40) The main turret **108** may be positioned above the base **104** and may be rotatably coupled to the base **104** so that the main turret **108** is rotatable about the central axis A relative to the base **104**. A drive motor (not shown) may be utilized to rotate the main turret **108** relative to the base **104**. The main turret **108** includes a plurality of holders **130**, which are configured to removably secure each glass tube **102** to the main turret **108**. The holders **130** may be clamps, chucks, or other holding devices, or combinations of holding devices. The holders **130** may orient each glass tube **102** so that the glass tube **102** is generally parallel to the central axis A of the main turret **108** and generally perpendicular to the upper portion **105** of the base **104**. Although the converter **100** is described in this specification in the context of a vertically oriented converter **100**, it should be understood that the converter **100** may be oriented horizontally or at an angle. Each of the holders **130** extend from a bottom portion **109** of the main turret **108** in a direction towards the base **104** (i.e., in the -Z direction relative to the coordinate axis in FIG. 1), and each holder **130** is oriented to position the glass tube **102** in or proximate to each of the successive processing stations **106** of the main circuit **116** of the base **104** as the main turret **108** is indexed about the central axis A. Vertical orientation of the glass tubes **102** allows a downward protruding portion of each glass tube **102** to be cycled progressively through the processing stations **106** of the main circuit **116**. Each holder **130** may be individually rotatable relative to the main turret **108** about holder axis D, which may be generally parallel to the central axis A of the main turret **108**. Each of the holders **130** may be operatively coupled to a motor (not shown), continuous drive belt, or other drive mechanism for rotation of each of the holders **130** relative to the main turret **108**. Rotation of the holders **130** allows for rotation of the glass tube **102** relative to stationary burners, forming tools, cooling nozzles, or other features of the processing stations **106**.

(41) Referring to FIGS. 1 and 2, the converter **100** may have a plurality of secondary processing stations **112**, which are also spaced apart and arranged in a secondary circuit **118** (FIG. 2), and a secondary turret **114** (FIG. 1) for indexing an article **103** (FIG. 1), which has been separated from the glass tube **102**, through the plurality of secondary processing stations **112**. The secondary turret **114** may be rotatable about a second axis B relative to the base **104**. The second axis B may be generally parallel to central axis A of the main turret **108**. The secondary turret **114** also includes a plurality of holders **130** to hold the glass articles **103** and position the glass articles **103** to engage with each of the secondary processing stations **112** in succession. The secondary turret **114** may receive the articles **103** from a separating station **206** (FIG. 2) of the main turret **108**, index the articles **103** through the plurality of secondary processing stations **112** through rotation of the secondary turret **114**, and discharge the finished articles from the converter **100**.

(42) The glass tube loading turret **110** is positioned above the main turret **108**. In embodiments, the glass tube loading turret **110** may be offset from the central axis A of the main turret **108**. The glass tube loading turret **110** may be rotatable about an axis C, which may be generally parallel to the central axis A of the main turret **108**. The glass tube loading turret **110** may be independently supported in a stationary position relative to the main turret **108**, and rotation of the glass tube loading turret **110** may be independent of the rotation of the main turret **108**. Referring to FIGS. 1 and 2, in some embodiments, the glass tube loading turret **110** may include a plurality of loading channels **132** arranged in a circular circuit **134** and configured to hold glass tubes **102**. The glass tube loading turret **110** may be positioned to orient one of the loading channels **132** into vertical alignment (i.e., aligned in a direction parallel to the central axis A of the main turret **108** and/or parallel to the Z axis of FIG. 1) with a processing station **106** of the main circuit **116** of the converter **100** and the corresponding holders **130** on the main turret **108** that are indexed through the processing station **106** of the main circuit **116**. In one or more embodiments, the processing station **106** aligned with the glass tube loading turret **110** may be a tube loading station **214** (FIG. 2). When the converter **100** has converted all or a portion of the glass tube **102** at a specific holder position **136** into one or more articles, the glass tube loading turret **110** may deliver a new length of glass tube **102** through the top of the main turret **108** to the holder **130** at the holder position **136**, when the holder position **136** indexes into alignment with the tube loading station **214** of the main circuit **116**. In alternative embodiments, the converter **100** may include an arm (not shown) electromechanically movable between the main turret **108** and the glass tube loading turret **110**. When the converter **100** has converted all or a portion of the glass tube **102** at a specific holder position **136**, the arm may grab a new length of glass tube **102** from the glass tube loading turret **110** or other glass tube staging device and deliver the new length of glass tube **102** to the main turret **108** at the specific holder position **136**. Other methods of delivery new lengths of glass tube **102** to the main turret **108** are contemplated.

(43) Referring to FIG. 2, as previously described, the plurality of processing stations **106** of the converter **100** may include one or more heating stations **202**, forming stations **204**, separating stations **206**, polishing stations **208**, cooling stations **210**, piercing stations **212**, tube loading stations **214**, discharge stations **216**, measuring stations **218**, tube length drop stations **220**, or other stations and/or combinations of these stations. FIG. 2 schematically depicts the arrangement of the processing stations **106** for a converter **100** having a main circuit **116** of sixteen processing stations **106** and a secondary circuit **118** of eight secondary processing stations **112**. As described, the processing stations **106** of the main circuit **116** are evenly spaced apart and evenly distributed about a circular circuit and the secondary processing stations **112** of the secondary circuit **118** are also evenly spaced apart and evenly distributed about a circular circuit. FIG. 2 also schematically depicts the glass tube loading turret **110** having a plurality of loading channels **132**. In FIG. 2, the glass tube loading turret **110** is shown in a position spaced apart from the main circuit **116** for purposes of illustration. Although the glass tube loading turret **110** is depicted as having twenty-four loading channels **132**, it is understood that the glass tube loading turret may have more or less than twenty-four loading channels **132**.

(44) The main circuit **116** of the converter schematically depicted in FIG. 2 may include one or more heating stations **202**, a separating station **206**, a flame pierce station **212**, one or more forming stations **204**, one or more cooling stations **210**, a measuring station **218**, a tube length drop station **220**, and a tube loading station **214**. With respect to the direction of indexing **222** of the main turret **108**, the heating stations **202** may be positioned before the separating stations **206** and each of the forming stations **204** to preheat target regions of the glass tube **102** to a target temperature at which the target region of the glass tube **102** becomes plastically deformable and may effectively be shaped or cut without cracking or shattering the glass. At the separating station **206**, the formed glass article **103** (FIG. 1) may be separated from the glass tube **102** (FIG. 1). The separating station **206** may also be the processing station **106** at which the partially formed glass article **103**, once

separated, is transferred to the secondary turret **114** (FIG. 1) to be indexed through the secondary circuit **118** of secondary processing stations **112**. The piercing station **212** may be positioned on the main circuit **116** downstream of the separating station **206** in the direction of indexing **222** of the main turret **108**. At the piercing station **212**, an end of the glass tube **102** previously closed by the separating station **206** is pierced, thereby forming an opening in the glass tube **102**.

(45) The forming stations **204** of the main turret **108** may be positioned downstream of the piercing station **212** in the direction of indexing **222**. At the forming stations **204**, the glass tube **102** is iteratively shaped into the desired shape of the finished glass article. As noted above, one or more heating stations **202** may be positioned before each of the forming stations **204** to preheat target regions of the glass tube **102** to a temperature at which the glass tube may be formed. The forming stations **204** of the main turret **108** shape one end of the glass articles **103**, and the forming stations **204** of the secondary turret **114** shape the other end of the glass articles **103**. In one or more embodiments, the converter **100** may be used to produce vials from the glass tubes **102**, and the forming stations **204** of the converter **100** may include one or more shoulder forming stations, one or more flange forming stations, and one or more flange finishing stations, with one or more heating stations **202** positioned before and between each of the forming stations **204**. The main circuit **116** may further include a measuring station **218**, at which a dimensioning system **1310** (FIG. 13) may be used to measure one or more dimensions of the glass tube **102**, such as the diameter and thickness for example, and one or more dimensions of the features formed by the forming stations **204**. Feature dimensions may include flange thickness, flange length, neck length, neck thickness, overall article length, other feature dimension, or combinations thereof. The measuring station **218** may be positioned directly after the last forming station **204** so that the dimensions are measured while the glass tube **102** is still at elevated temperature. Alternatively, the measuring station **218** may be positioned after one or more cooling stations **210** to measure the dimensions of the glass tube **102** and/or glass article at a lower temperature.

(46) Still referring to FIG. 2, one or more cooling stations **210** may be positioned after the forming stations **204** in the direction of indexing **222** of the main turret **108**. A tube length drop station **220** may be positioned after the forming stations **204**, between the forming stations **204** and the separating station **206**, to drop the partially formed glass tube **102** down, thereby positioning the glass tube **102** for cutting to a target length at the separating station **206**. The main circuit **116** may also include a tube loading station **214** for loading a new length of glass tube **102** feedstock from the glass tube loading turret **110** to the main turret **108** (FIG. 1). In one or more embodiments, the tube loading station **214** may be incorporated into a cooling station **210**. The tube loading station **214** may be positioned between the last forming station **204** and the separating station **206**.

(47) The forming stations **204** of the main turret **108** form features at a first end of the glass article **103**. For example, the forming stations **204** may form the shoulder **142** and flange **144** at the top (first end) of a glass article **103** that is a vial or cartridge. Once the glass article **103** is separated from the glass tube **102** at the separating station **206**, the glass article **103** is transferred to the secondary processing stations **112** of the secondary turret **114**. The secondary processing stations **112** may include one or more forming stations **204** for forming a second end of the glass article **103**, which is opposite the first end of the glass article **103**. For example, the forming stations **204** of the secondary processing stations **112** may form one or more features at a bottom (second end) of the glass article **103** that is a vial.

(48) The secondary processing stations of the secondary circuit may include one or more heating stations **202**, forming stations **204**, polishing stations **208**, cooling stations **210**, discharge stations **216**, or other stations or combinations of secondary processing stations **112**. In one or more embodiments, the secondary processing stations **112** of the secondary circuit **118** may be used to form one or more features of the glass article **103**, such as a vial, ampoule, cartridge, or syringe, for example, at an end of the glass article **103** opposite the end formed by the main turret **108**. For example, in some embodiments, the glass article **103** is a vial and the forming stations **204** of the

secondary circuit **118** may form the bottom of the vial. Other features are also contemplated such as those features characteristic of ampoules, cartridges, syringes, and the like. The secondary circuit **118** may include one or more polishing stations **208** to finish the surface of the glass article. The secondary circuit **118** may further include a plurality of cooling stations **210** and the discharge station **216**, at which station the finished glass article may be discharged from the converter **100**. (49) The previous description of the processing stations **106** of the main circuit **116** and the secondary processing stations **112** of the secondary circuit **118** may represent a typical converter **100** for producing vials from the glass tube **102**. However, it is understood that more or fewer processing stations **106** and secondary processing stations **112** may be utilized to make vials having different shapes or other glass articles, such as cartridges, syringes, ampoules, or other glass articles. Additionally, it is understood that the processing stations **106** and secondary processing stations **112** may be arranged in any of a number of different orders and/or configurations in order to produce differently shaped glass articles.

(50) Referring now to FIG. 3A, a heating station **202** of the converter **100** is schematically depicted. Each of the heating stations **202** may include one or more heating elements **301**. Examples of heating elements **301** may include, but are not limited to fuel burners, lasers such as CO.sub.2 lasers for example, induction heaters, other heating devices, or combinations of these. In some embodiments, a laser may be used to heat the glass tube **102**. As illustrated in FIG. 3A, in embodiments, the heating element **301** may include one or more burners **302**, which are used to heat targeted regions of the glass tube **102** prior to a forming operation performed at the forming station **204** (FIG. 2) or separating operation performed at the separating station **206** (FIG. 2). Although FIG. 3A depicts a single burner **302**, it is understood that more than one burner **302** may be employed in a single heating station **202**. Each burner **302** may be fluidly coupled to a fuel supply **304**, an oxygen supply **306**, and, optionally, an air supply **308**. Examples of fuels for the burner may include, but are not limited to hydrogen, hydrocarbon fuel gases such as methane, propane, and butane for example, other fuels, or combinations of these. Each burner **302** may include a fuel control valve **310** to control the mass flow rate of fuel gas to the burner **302**. Each burner **302** may also include an oxygen control valve **312** to control the mass flow rate of oxygen to the burner **302**. Each burner **302** may further include an air control valve **314** for optionally controlling a mass flow rate of air to the burner **302**. The burner **302** combusts the fuel gas in the presence of oxygen and/or air to produce a flame that heats at least the target region of the glass tube **102**.

(51) The heat of the flame generated by the burner **302** may be increased or decreased by changing the mass flow rates of fuel gas, oxygen, and air to the burner **302** and by changing the ratio of fuel gas to oxygen and/or the ratio of fuel gas to air fed to the burner **302**. One or more of the fuel control valve **310**, oxygen control valve **312**, or air control valve **314** may be adjusted to adjust the ratio of fuel to oxygen and/or air. The burners **302** may be continuously burning and the glass tubes **102** may be indexed into and out of contact with the flame produced by the burners **302** by rotation of the main turret **108** and/or the secondary turret **114** to index the glass tube **102** into and out of the heating station **202**. While positioned at the heating station **202**, each glass tube **102** may be rotated by the holder **130** about the holder axis D relative to the burner **302** so that the glass tube **102** may be evenly heated around the circumference of the glass tube **102** in the specific regions to be formed in downstream forming stations **204** (FIG. 2).

(52) Referring now to FIG. 3B, a separation station **206** of the converter **100** is schematically depicted. The separating station **206** is positioned after one or more heating stations **202** in the direction of indexing **222** of the main turret **108**. The heating stations **202** positioned before the separating station **206** heat the glass tube **102** to make the glass plastically deformable. The separating station **206** may include a separating tool **320**. While the glass tube **102**, which has been made plastically deformable by the previous heating stations **202**, is rotated by the holder **130** about the holder axis D, the separating tool **320** may be engaged with the outer surface **140** of the

glass tube **102** to cut the glass tube **102** to a target length, thereby separating an article **103** (FIG. 1) from the glass tube **102**. Alternatively, in some embodiments, the separating station **206** may include a burner, such as a hydrogen/oxygen burner for example, and/or a laser, such as a CO<sub>2</sub> laser for example, for cutting the glass tube **102** to the target length and separating the article **103** from the glass tube **102**. In other embodiments, the separating station **206** may include separating tools **320** and at least one of a hydrogen/oxygen burner or a laser. Once separated from the glass tube **102**, the article **103** may be transferred to the secondary turret **114** (FIG. 1) or discharged from the converter **100**.

(53) Referring now to FIGS. 3C and 3D, examples of forming stations **204** of the converter **100** are schematically depicted. Each forming station **204** may include one or more forming tools **324** rotationally coupled to the forming station **204**. The forming tools **324** may be rotatable relative to the base **104** (FIG. 1) about tooling axis E, which are generally parallel to the central axis A (FIG. 1) of the main turret **108** (FIG. 1). When indexed into the forming station **204**, the glass tube **102**, which has been heated in a prior heating station **202**, is rotated by the holder **130**. The rotatable forming tools **324** are engaged with the outer surface **140** of the glass tube **102**. The forming tools **324** may be actuated into engagement with the outer surface **140** of the glass tube **102** by one or more actuators **326**. The forming tools **324** are maintained in contact with the glass tube **102** at a tool pressure maintained by the actuators **326** for a contact time. Contact of the forming tools **324** with the outer surface **140** of the heated glass tube **102** forms the glass tube **102** into the desired shape. Upon expiration of the contact time, the actuators **326** withdraw the forming tools **324** from engagement with the glass tube **102**. In one or more embodiments, the contact time may be different than a dwell time of the converter **100**.

(54) FIG. 3C schematically illustrates an embodiment of a forming station **204** for forming the shoulder **142** of a glass vial formed from the glass tube **102**. FIG. 3D schematically depicts an exemplary embodiment of a forming station **204'** for forming the flange **144** of a glass vial formed from the glass tube **102**. The forming station **204'** for forming the flange **144** comprises three forming tools **324a**, **324b**, and **324c**. Two of the forming tools **324a** and **324b** contact the outer surface **140** of the glass tube **102** to form the outer contour of the flange **144**. The third forming tool **324c** contacts inner surface of the glass tube **102** radially inward of the flange **144** to form the inner diameter of the glass tube **102** at the flange **144**. The third forming tool **324c** also contacts the axial end of the glass tube **102** to form the axial surface of the flange **144**. In embodiments, the third forming tool **324c** may be stationary and the glass tube **102** rotated about the third forming tool **324c** by the holder **130**. In embodiments, a thin layer of lubricant, such as oil for example, may be disposed between the glass tube **102** and the third forming tool **324c** to separate the glass tube **102** from making contact with the third forming tool **324c**. Although described relative to forming the structures of a vial, the forming stations **204** may be configured to form other structures, such as the shoulder, neck, or tapered tip of an ampoule for example, or any other structure associated with articles other than glass vials.

(55) FIG. 3E schematically depicts a cooling station **210** having one or more cooling nozzles **340** positioned to direct a cooling fluid **342**, such as chilled air or an inert gas for example, towards the glass tube **102**. One or more of the cooling nozzles **340** may be positioned to direct the cooling fluid **342** to specific regions of the glass tube **102**. One or more cooling fluid control valves **344** may be fluidly coupled to the cooling nozzles **340** to control the mass flow rate of cooling fluid **342** to the cooling nozzles **340**, which enable control of the rate of cooling of the glass tube **102** as well as the temperature of the glass tube **102** and temperature gradients in the glass tube **102**.

(56) FIGS. 3A-3E include schematic illustrations of several different examples of processing stations **106** that may be utilized in the converter **100**. However, it should be understood that other processing stations **106** having different structures, combinations of structures, or functions, may be utilized to achieve the desired conversion of the glass tube **102** into one or more glass articles.

(57) Referring again to FIG. 2, in operation, the main turret **108** indexes the glass tubes **102**, which



are secured in the holders **130**, into a processing station **106**. A specific operation, such as heating, forming, piercing, separating, cooling, dropping, feeding, etc., is performed on the glass tubes **102** at each of the processing stations **106**. A dwell time is the time that the glass tube **102** spends in a particular processing station **106** before being indexed by the main turret **108** to the next subsequent processing station **106**. The converter **100** may be tuned so that all of the processing stations **106** complete their operations within the dwell time. At the end of the dwell time, the main turret **108** indexes the glass tubes **102** to the next processing stations **106**. The index time refers to the time that it takes for the main turret **108** to index the glass tubes **102** from one processing station **106** to the next processing station **106** and is measured in units of time. The total time per part per station, as used in this disclosure, is the sum of the dwell time and the index time. The part rate (production rate) is the number of parts produced per unit of time and is the inverse of the total time per part per station. In embodiments, the index time of the main turret **108** may be up to 25% of the total time per part per station.

(58) Examples of converters **100** for converting glass tube **102** into glass vials include the Vial Forming Machine Model RP16 with Automatic Tube Feeder manufactured by AMBEG Dr. J. Dichter GmbH, which includes sixteen processing stations **106** in the main circuit **116** and eight secondary processing stations **112**. Other examples include the Vial Forming Machine Model RP32 manufactured by AMBEG Dr. J. Dichter GmbH, which has thirty-two processing stations **106** in the main circuit **116** and two secondary circuits **118** with eight secondary processing stations **112** in each secondary circuit **118**, and the Zeta 098 Vial Forming Machine manufactured by Euromatic S.R.L., which has 36 processing stations **106**. Another example may include the Zeta 103 Cartridge Forming Machine manufactured by Euromatic S.R.L., which is a converter for converting glass tube **102** into cartridges. The cartridge converter has similar characteristics to the previously described vial converters **100** but is utilized to produce glass articles having a cartridge form factor rather than a vial.

(59) Although described in the context of a converter **100** for producing glass vials from glass tube **102**, it should be understood that the converter **100** may be configured to produce one or more other articles, such as cartridges, syringes, ampoules, or other glass articles, by changing the forming tools **324** and/or the order or configuration of processing stations **106** in the main circuit **116** or secondary processing stations **112** in one or more secondary circuits **118**.

(60) A typical converter **100** for producing articles from glass tube **102** may operate at production rates of from 30 parts per minute to 50 parts per minute. At these production rates, thermal gradients within the glass tube **102** are extremely high and dynamic. It is typical for a short length of glass tube **102** to be heated from 200° C. to 1500° C. within a time period from 2 seconds to 4 seconds. Specifically, the heated length of glass tube **102** may experience temperature gradients along a length of the tube of up to 100° C./minute, or up to 200° C./minute. Referring to FIG. 4, for the glass tube **102**, the length L is measured in the +Z/-Z direction of the reference axis provided in FIG. 4. These large temperature gradients along the length L of the glass tube **102** help facilitate precise dimensional control of the thermal separation within a converter **100** and precise control of, for example, the thickness of the bottom of the glass article as well as control over the contours of the glass article.

(61) Rapid heating of the glass tube **102** in one or more processing stations **106** may also induce maximum temperature gradients through the thickness T of the heated glass tube **102**. These temperature gradients may be, for example and without limitation, from 200° C./min to 300° C./min. Similar or higher temperature gradients may be induced during forming processes in forming stations **204** for forming the shoulder **142** and flange **144** of a vial. These high thermal gradients induced along the length L and through the thickness T of the glass tube **102** during conversion are important for understanding the dynamics of the conversion process but are only modestly understood within the capabilities of current commercially available converters **100**.

(62) Referring now to FIGS. 5-6, embodiments of the converter **100** described herein may utilize a

thermal imaging system **120** to provide and/or enhance automated control of the converter **100** and the conversion process. The thermal imaging system **120** may be employed to measure one or more surface temperatures of the glass tube **102** during the conversion process. The thermal imaging system **120** includes the thermal imager **122** and the mounting apparatus **126** for mounting the thermal imager **122** to the main turret **108**. In embodiments, the thermal imaging system **120** may also include one or more mirrors **124** coupled to the thermal imager **122** by the mounting apparatus **126**. The mirror **124** may enable the thermal imager **122** to be oriented generally vertically to reduce the spatial footprint of the converter **100**. The thermal imaging system **120** is mounted to the main turret **108** so that the thermal imaging system **120** rotates with the main turret **108** and travels with the glass tube **102** through each of the processing stations **106** (FIG. **1**) of the converter **100**. By traveling with the glass tube **102** through each of the successive processing stations **106**, the thermal imaging system **120** may be used to develop temperature profiles of the glass tube **102** throughout the entire converting process from glass tube to finished glass article. The temperature profiles may be used to identify, study, and control temperature gradients from one processing station **106** to the next.

(63) In embodiments, the thermal imager **122** may be a 2-dimensional infrared thermal imaging camera capable of capturing light having wavelengths in the infrared spectrum. In particular, in some embodiments, the thermal imager **122** may be capable of receiving long wave infrared light having wavelengths from 4 microns to 14 microns, from 4 microns to 10 microns, from 4 microns to 8 micron, from 4 microns to 7 microns, from 5 microns to 14 microns, from 5 microns to 10 microns, from 5 microns to 8 microns, from 5 microns to 7 microns, from 7 microns to 14 microns, from 7 microns to 10 microns, or from 7 microns to 8 microns. Infrared light includes a broad spectrum of wavelengths from 700 nanometers (nm) to 1 millimeter. However, longer wavelengths of infrared light are generally indicative of the infrared light emitted by the outer surface **140** of the glass tube **102**, which is the surface that is directly heated. Shorter wavelengths of infrared light of from 700 nm to about 4 microns may be at least partially transmitted through glass composition of the glass tube **102**. Thus, shorter wavelength infrared light received by the thermal imager **122** may have been emitted by internal portions of the glass tube **102** or by external structures positioned behind the glass tube **102** relative to the position of the thermal imager **122**. The shorter wavelengths of infrared light less than about 4 microns are not therefore indicative of a surface of the glass tube **102**. At long wavelengths of infrared light, such as infrared light having wavelengths greater than about 14 microns, at least a portion of the infrared light having long wavelengths emitted from a surface of the glass tube **102** may be reflected away from the thermal imaging system. Glass compositions of the glass tubes **102** converted by the converter **100** exhibit low transmission and low reflectivity of infrared light having wavelengths of from 4 microns to 14 microns and, thus, exhibit greater emissivity of infrared light in this wavelength range. For example, the glass tubes **102** exhibit 0% transmission and only 3% reflectivity of infrared light having wavelength of about 5 microns. Thus, the emissivity of infrared light having wavelengths of about 5 microns from the glass tube **102** is about 97%. In another example, the reflectivity of infrared light having wavelengths of about 7.5 microns from the glass tube **102** is about 10% and the emissivity is 90%. Capturing infrared light having wavelengths in a range of from about 4 microns to about 14 microns, such as from 4 microns to 7.5 microns, or about 5 microns, may reduce errors in the surface temperature measurements by avoiding integration of the temperature gradient through the thickness of the glass tube **102**. Transmission of infrared light through the glass tube **102** and reflectivity of the infrared light from the glass tube **102** introduce errors in the thermal image data captured by the thermal imager **122**. Thermal imagers **122** capable of capturing infrared light having wavelengths of from 4 micron to 14 micron may exhibit enhanced temperature accuracy of the thermal images obtained with the thermal imager **122**. In one or more embodiments, the thermal imager **122** may have an object temperature range of from 100° C. to 2000° C., or from 300° C. to 2000° C.

(64) The thermal imager **122** may have an image capture rate of at least 30 Hertz (Hz). In some embodiments, the thermal imager **122** may have an image capture rate of from 30 Hertz (Hz) to 60 Hz, or from 30 Hz to 50 Hz. Additionally, the thermal imager **122** may be compliant with one or more interface protocols, such as GigE Vision for example, to enable the imager to communicate with and transfer data high-speed imaging data over an Ethernet connection to one or more image analysis systems having image analysis software, such as LabVIEW™ distributed by National Instruments, for example. The thermal imager **122** may have an internal temperature sensor (not shown) integrated with a self-calibration system to allow the thermal imager **122** to measure the temperature of the infrared sensor suite and adjust image data to compensate for changes in temperature of the thermal imager **122**.

(65) As previously noted, the thermal imager **122** is mounted to the main turret **108** of the converter **100** using the mounting apparatus **126**. Referring to FIG. 6, the mounting apparatus **126** may attach to an outer portion **128** of the main turret **108** so that the mounting apparatus **126** and the thermal imager **122** rotate with the main turret **108**. In embodiments, the main turret **108** of the converter **100** may be enclosed in a housing, such as steel mesh housing **127**. In these embodiments, the steel mesh housing **127** is the outer portion **128** of the main turret **108**. The mounting apparatus **126** may be mounted to the steel mesh housing **127** with a rail support system **129** (FIG. 5). In some embodiments, the mounting apparatus **126** may allow for temporary removal of the thermal imager **122** and/or the mirror **124** from the main turret **108** of the converter **100**.

(66) The mounting apparatus **126** positions the thermal imager **122** and the mirror **124** at a fixed angular position **138** on the main turret **108** so that the thermal imager **122** and mirror **124** follow a single holder **130** and glass tube **102** through an entire cycle of the converter **100**. The mounting apparatus **126** may include an imager support **502** and a mirror support **504**. The thermal imager **122** may be removably coupled to the imager support **502**. The imager support **502** may be adjustable in one or more directions to orient the thermal imager **122** with respect to the holder **130** and/or glass tube **102**. For example, the imager support **502** may include vertical adjustment (i.e., up or down parallel with the central axis A of the main turret **108**), radial adjustment relative to the main turret **108** (i.e., to move the thermal imager **122** closer to or farther from the outer portion **128** of the main turret **108**), angular adjustment (i.e., to adjust the angular position of thermal imager **122** relative to one of the holders **130**), rotational adjustment (i.e., rotationally adjusting the camera to change an angle formed between the optical centerline OC of the camera and the X-Y plane of the axes in FIG. 6), or other adjustment.

(67) In some embodiments, the imager support **502** may be configured to position the thermal imager **122** to directly capture an image of the glass tube **102** as it is being processed. In this configuration, the optical centerline OC of the thermal imager **122** may be aligned in the X-Y plane of the coordinate axes of FIGS. 5 and 6. However, in a typical converter **100**, space around the processing stations **106** of the main circuit **116** and/or the secondary processing stations **112** of the secondary circuit **118** is limited and positioning the thermal imager **122** so that the optical centerline OC of the thermal imager **122** is in the X-Y plane and is radially aligned with a glass tube **102** causes the thermal imager **122** to extend radially outward from the main turret **108**. This may cause the thermal imager **122** and/or the mounting apparatus **126** to contact parts of the converter **100** or interfere with the operation of the converter **100** when the thermal imager **122** rotates with rotation of the main turret **108**. Additionally, in this configuration, the thermal imager **122** would extend radially outward from the rotating main turret **108**, which may create a hazardous condition during operation.

(68) To avoid these spatial issues, in some embodiments, the imager support **502** may be adjustable to orient the thermal imager **122** so that the optical centerline OC of the thermal imager **122** forms a non-zero angle relative to the X-Y plane of the coordinate axes of FIGS. 5 and 6. In one or more embodiments, the thermal imager **122** may be positioned so that the optical centerline OC of the thermal imager **122** is parallel to the central axis A of the main turret **108** (i.e., generally

perpendicular to the X-Y plane of the coordinate axes of FIGS. 5 and 6). Alternatively, the thermal imager **122** may be positioned so that the optical centerline OC forms a non-zero angle of less than 90° relative to the axial plane of the main turret **108**. Mounting the thermal imager **122** at a non-zero angle relative to the axial plane of the main turret **108** may help to avoid interfering with operation of the converter **100** and/or creating a hazardous condition.

(69) The mirror support **504** may be coupled to the imager support **502** and may position the mirror **124** to reflect infrared light from the glass tube **102** towards the lens **506** of the thermal imager **122**. In embodiments, the mirror support **504** may position the mirror **124** in alignment with the optical centerline OC of the thermal imager **122**. In one or more embodiments, the mirror support **504** may allow for one or more of vertical (i.e., along the +Z/-Z axis of the coordinate axes of FIGS. 5 and 6), radial, angular, rotational, or other directional adjustment of the mirror **124** relative to the thermal imager **122**.

(70) Referring to FIG. 5, the mirror **124** may be coupled to the mounting apparatus **126** and positioned within a field of view of the thermal imager **122** so that the mirror **124** reflects infrared light towards the lens **506** of the thermal imager **122**. In one or more embodiments, the mirror **124** may be positioned so that the optical centerline OC of the thermal imager **122** intersects the reflective surface **508** of the mirror. Alternatively, the mirror **124** may be positioned within the field of view of the thermal imager **122** so that the reflective surface **508** reflects infrared light to the lens **506**, but the optical centerline OC of the thermal imager **122** does not intersect the reflective surface **508** of the mirror **124**. The mirror **124** may be angled relative to the optical centerline OC of the thermal imager **122** to reflect infrared light emitted from the outer surface **140** of the glass tube **102** at a specific holder position **136** to the thermal imager **122**. Referring to FIG. 7, generally, the mirror **124** is angled so that the reflective surface **508** of the mirror **124** forms a non-zero angle  $\alpha$  with the optical centerline OC of the thermal imager **122** that is less than 90°. In other words, the reflective surface **508** of the mirror **124** may be angled so that the reflective surface **508** is not perpendicular to the optical centerline OC of the thermal imager **122**. In one or more embodiments, the mirror **124** may be positioned to reflect infrared light from the holder position **136** that is located directly radially inward from the thermal imager **122** relative to the central axis A of the main turret **108** to the thermal imager **122**. Alternatively, in other embodiments, the mirror **124** may be positioned to reflect infrared light from a holder position **136** that is one or more positions clockwise or counterclockwise from the position of the thermal imager **122** (i.e., one or more positions forward/upstream of or backward/downstream of position where the thermal imager **122** is attached to the main turret **108**). While specific orientations of the mirror **124** and the thermal imager **122** have been described herein, it should be understood that the mirror **124** and the thermal imager **122** could be positioned and oriented in any of a number of configurations depending on the configuration of the particular converter **100**.

(71) In embodiments, the reflective surface **508** of the mirror **124** may be highly reflective of infrared light. In one or more embodiments, the reflective surface **508** of the mirror **124** may have an average reflectance of greater than or equal to 96%, greater than or equal to 97% or greater, greater than or equal to 98%, or greater than or equal to 99% of infrared light having wavelengths from 4 microns ( $\mu\text{m}$ ) to 14  $\mu\text{m}$ . In one or more embodiments, the reflective surface **508** of the mirror **124** may have an average reflectance of greater than or equal to 96% for light having wavelengths from 4  $\mu\text{m}$  to 14  $\mu\text{m}$ . Referring to FIG. 17, the mirror **124** may include a mirror base **510** and a reflective coating **512** applied to the mirror base **510** to create the reflective surface **508**. The mirror base **510** may be thermally stable to avoid distorting the image. In embodiments, the mirror base **510** may be quartz, such as fused quartz for example. In some embodiments, the reflective coating **512** may be a gold coating, for example.

(72) Referring to FIG. 7A, as previously described, in some embodiments, the thermal imager **122** may be positioned to directly receive infrared light emitted from the outer surface **140** of the glass tube **102** at a specific holder position **135** of the main turret **108**. In particular, the thermal imager

**122** may be positioned such that infrared light emitted from the outer surface **140** of the glass tube **102** travels along pathway **710** directly to the lens **506** of the thermal imager **122** without being reflected by a mirror, such as mirror **124**. The thermal imager **122** receives the infrared light emitted by the outer surface **140** of the glass tube **102** and captures a thermal image representative of the wavelengths and intensities of the infrared light received by the thermal imager **122**. The thermal imager **122** travels with the main turret **108** so that the thermal imaging system **120** captures thermal image data of the outer surface **140** of the glass tube **102** at the specific holder position **136** as the glass tube **102** is indexed through each of the successive processing stations **106** (FIG. 1). Capturing thermal image data from infrared light emitted by the outer surface **140** of the glass tube **102** may enable profiling of the temperature of the outer surface **140** of the glass tube **102** as a function of time throughout the converting process.

(73) Referring to FIG. 7B, in embodiments, the thermal imager **122** may be positioned to directly receive infrared light emitted by the outer surface **140** of the glass tube **102**. Additionally, one or more stationary mirrors **700** may be coupled to the base **104** of the converter **100** at a processing station **106** to reflect infrared light emitted by an inner surface **146** of the glass tube **102** to the thermal imager **122**. In some embodiments, each of the stationary mirrors **700** may be positioned vertically lower than the processing station **106** (i.e., in the  $-Z$  direction of the coordinate axes of FIG. 7B relative to the processing station **106**). Positioning the stationary mirror **700** vertically lower than the processing station **106** enables the stationary mirror **700** to reflect infrared light emitted by the inner surface **146** (FIG. 4) of the glass tube **102** towards the lens **506** of the thermal imager **122** when the thermal imager **122** is indexed into position at the processing station **106**. Reflecting infrared light emitted from the inner surface **146** of the glass tube **102** toward the thermal imager **122** may enable the thermal imaging system **120** to profile or determine temperatures of the inner surface **146** of the glass tube **102**. The infrared light emitted from the inner surface **146** of the glass tube **102** may travel along pathway **712**, which extends in a generally downward direction (i.e., in the  $-Z$  direction of the coordinate axes of FIG. 7B) from the inner surface **146** of the glass tube **102** and reflects off of the stationary mirror **700** towards the lens **506** of the thermal imager **122**. Since the thermal imager **122** is coupled to the main turret **108** and rotates with the main turret **108**, the thermal imager **122** only passes into position to receive the infrared light emitted by the inner surface **146** of the glass tube **102** and reflected from a specific stationary mirror **700** once per cycle of the main turret **108** through the main circuit **116** of processing stations **106**. In embodiments, stationary mirrors **700** may be positioned at a plurality of the processing stations **106** so that the thermal imager **122** may capture thermal image data from the inner surface **146** of the glass tube **102** at a plurality of the processing stations **106** during each cycle of the main turret **108**.

(74) Referring to FIG. 7C, as previously described, the thermal imager **122** may be positioned so that the lens **506** of the thermal imager **122** is not oriented to receive infrared light directly from the outer surface **140** of the glass tube **102**. The thermal imager **122** is shown in FIG. 7C as being generally vertically oriented (i.e., in the  $\pm Z$  direction of the coordinate axes of FIG. 7C). In embodiments, the thermal imager **122** may be oriented such that the optical centerline OC of the thermal imager **122** is generally parallel to the centerline CL of the glass tube **102**. As previously described, the mounting apparatus **126** may enable the thermal imager **122** to be rotated, tilted or angled relative to the centerline CL of the glass tube **102**. The mirror **124** is coupled to the mounting apparatus **126** so that the mirror **124** travels with the thermal imager **122** as the main turret **108** indexes through the processing stations **106**. The mirror **124** may be positioned to reflect infrared light from the outer surface **140** of a glass tube **102** towards the lens **506** of the thermal imager **122**. In this configuration, the mirror **124** and the thermal imager **122** both travel with the main turret **108** so that the thermal imaging system **120** captures thermal image data of the outer surface **140** of the glass tube **102** at the specific holder position **136** as the glass tube **102** is rotated to and between each of the successive processing stations **106** (FIG. 1). In particular, the mirror **124**

may be positioned to reflect infrared light emitted radially outward by the outer surface **140** of the glass tube **102** to the thermal imager **122**, which receives the infrared light reflected from the mirror **124** and captures a thermal image representative of the wavelengths and intensities of the infrared light received by the thermal imager **122**. The infrared light travels along pathway **714** outward from the outer surface **140** of the glass tube **102** and reflects off of the mirror **124** towards the lens **506** of the thermal imager **122**.

(75) Referring now to 7D, the mirror **124** may be positioned to reflect infrared light emitted by the outer surface **140** of the glass tube **102** and infrared light emitted by the inner surface **146** of the glass tube **102** towards the lens **506** of the thermal imager **122**. The infrared light emitted from the outer surface **140** of the glass tube **102** travels along pathway **714** outward from the outer surface **140** of the glass tube **102** and reflects off of the mirror **124** towards the lens **506** of the thermal imager **122**. The infrared light emitted from the inner surface **146** travels along pathway **716** from the inner surface **146** of the glass tube **102** to the mirror **124** and is reflected by the mirror **124** towards the lens **506** of the thermal imager **122**. Since the mirror **124** travels with thermal imager **122** as it is indexed through the plurality of processing stations **106**, the mirror **124** may enable the thermal imager **122** to capture thermal image data from the outer surface **140** and the inner surface **146** of the glass tube **102** at each of the processing stations **106**. In embodiments, the thermal imager **122** may capture thermal image data from the outer surface **140** and the inner surface **146** of the glass tube **102** simultaneously, such as in a single thermal image for example.

(76) Referring to FIG. 7E, in embodiments, the thermal imaging system **120** may include a supplemental mirror **125** that may be coupled to the mounting apparatus **126** so that the supplemental mirror **125** travels with the thermal imager **122** and the mirror **124**. In these embodiments, infrared light emitted from the outer surface **140** of the glass tube **102** travels along pathway **714** from the outer surface **140** of the glass tube **102** to the mirror **124** and is reflected by mirror **124** towards the lens **506** of the thermal imager **122**. The infrared light emitted from the inner surface **146** of the glass tube **102** travels along pathway **718** from the inner surface **146** of the glass tube **102** to the supplemental mirror **125** and is reflected by the supplemental mirror **125** towards the lens **506** of the thermal imager **122**. In some embodiments, the supplemental mirror **125** may be positioned vertically lower (i.e., in the  $-Z$  direction of the coordinate axes of FIG. 7E) than the mirror **124**. Since the mirror **124** and the supplemental mirror **125** both travel with thermal imager **122** as it is indexed through the plurality of processing stations **106**, the mirror **124** and supplemental mirror **125** may enable the thermal imager **122** to capture thermal image data from the outer surface **140** and the inner surface **146** of the glass tube **102** at each of the processing stations **106**. In embodiments, the thermal imager **122** may capture thermal image data from the outer surface **140** and the inner surface **146** of the glass tube **102** simultaneously.

(77) Referring to FIG. 7F, in embodiments, one or more stationary mirrors **700** may be coupled to the base **104** of the converter **100** at a processing station **106**. In embodiments, each of the stationary mirrors **700** may be positioned vertically below a processing station **106**. The stationary mirrors **700** may be angled to reflect infrared light emitted by the inner surface **146** of the glass tube **102** to the thermal imager **122**, when the thermal imager **122** indexes into position in the processing station **106**. The infrared light emitted from the inner surface **146** of the glass tube **102** may travel generally downward (i.e., generally in the  $-Z$  direction of the coordinate axes of FIG. 7F) along pathway **720** to the stationary mirror **700** and is reflected by the stationary mirror **700** towards the lens **506** of the thermal imager. Since the thermal imager **122** is coupled to the main turret **108** and rotates with the main turret **108** as it indexes each holder **130** through the plurality of processing stations **106**, the thermal imager **122** passes into position to receive the reflected infrared light from the stationary mirror **700** once per cycle of the main turret **108** through the main circuit **116** of processing stations **106**. The infrared light reflected to the thermal imager **122** by the stationary mirror **700** may only be captured by the thermal imager **122** once per cycle of the main turret **108**. Positioning the stationary mirror **700** below the processing station **106** allows the

stationary mirror **700** to reflect infrared light emitted by one or more inner surfaces **146** (FIG. 4) of the glass tube **102**, which may enable the thermal imaging system **120** to profile or determine the temperatures of one or more inner surfaces **146** of the glass tube **102**.

(78) Referring to FIG. 7G, in embodiments, the stationary mirror **700** may be oriented to reflect the infrared light from the inner surface **146** of the glass tube **102** towards the mirror **124** coupled to the mounting apparatus **126**. In these embodiments, the infrared light from the inner surface **146** of the glass tube **102** travels along pathway **722** from the inner surface **146** of the glass tube **102** to the stationary mirror **700**, reflects off of the stationary mirror **700** towards the mirror **124**, and then reflects off of the mirror **124** towards the lens **506** of the thermal imager **122**. Simultaneously, infrared light emitted from the outer surface **140** of the glass tube **102** travels along pathway **714** from the outer surface **140** of the glass tube **102** towards the mirror **124** and is reflected from the mirror **124** towards the lens **506** of the thermal imager **122**. Other stationary mirrors **700** may be coupled to the base **104** below other processing stations **106**, and other supplemental mirrors **124** may be coupled to the main turret **108** or mounting apparatus **126** to achieve different configurations or different view angles of the glass tube **102** during one or more stages of the converting process.

(79) In some embodiments, the thermal imaging system **120** may include a plurality of thermal imagers **122**. The plurality of thermal imagers **122** may be coupled to the main turret **108**, the secondary turret **114**, or both for rotation with the main turret **108** or the secondary turret **114**. In some embodiments, each of the plurality of thermal imagers **122** may be positioned to capture thermal image data from a separate holder position **136**. In embodiments, the thermal imaging system **120** may include one or more than one thermal imager **122** coupled to the base **104** of the converter **100** or other stationary structure (e.g., the floor, wall, or other structure adjacent to the converter **100**) in a stationary position to capture thermal image data from a specific processing station **106** and/or secondary processing station **112** as glass tubes **102** are indexed through the specific processing station **106** and/or secondary processing station **112**.

(80) Referring now to FIG. 8A, coupling the thermal imaging system **120** to the main turret **108** so that the thermal imaging system **120** travels in a continuous circuit centered about the central axis A of the main turret **108** presents unique challenges for delivering power and cooling fluid to the thermal imaging system **120** and receiving data from the thermal imaging system **120**. Therefore, in embodiments, the thermal imaging system **120** may include one or more rotating electrical and/or gas unions, which may allow for the powering, data exchange, and cooling of the thermal imaging system. In one or more embodiments, the thermal imaging system may include a slip ring **802** (i.e., sometimes referred to as a rotary electrical joint), which may provide a rotating connection to allow for power transmission and data transfer to and from the thermal imaging system **120**. The slip ring **802** may operatively couple the thermal imager **122** to the processor **900** (FIG. 9). The slip ring **802** may be a double annular structure having an inner ring **804** and an outer ring **806**. The inner ring **804** or the outer ring **806** is stationary and the other one of the inner ring **804** or outer ring **806** rotates relative to the stationary ring. The slip ring **802** may have an axis of rotation parallel to and aligned with the central axis A of the main turret **108**. Aligning the axis of the slip ring **802** with the central axis A of the main turret **108** may prevent electrical cables **808** and data cables **810** extending from the slip ring **802** to the thermal imaging system **120** from wrapping upon rotation of the main turret **108**.

(81) The slip ring **802** may include multiple circuits (not shown) formed between the inner ring **804** and the outer ring **806**. Power (e.g., 24 volt power, for example) and data may be electronically transferred radially between an inner radial surface of the outer ring **806** and the outer radial surface of the inner ring **804**, while the inner ring **804** and outer ring **806** are rotated relative to one another. The outer ring **806** may be electrically coupled to a power source and/or may also be communicatively coupled to a processor **900** (FIG. 9). The inner ring **804** may be electrically coupled to the thermal imager **122** to deliver power to the thermal imager **122** and may be

communicatively coupled to the thermal imager **122** to send and receive data from the thermal imager **122**. Electrical power may be transferred from the slip ring **802** to the thermal imager **122** by one or more electrical cables **808**. Additionally, data may be transferred between the slip ring **802** and the thermal imager **122** through one or more data cables **810**, such as an Ethernet cable, for example. The slip ring **802** may communicatively couple the thermal imager **122** to the processor **900** (FIG. **9**), which may be located remotely (i.e., spaced apart) from the thermal imager **122** in a stationary location, to facilitate transfer of data to and from the thermal imager **122**. The processor **900** (FIG. **9**) may be temperature sensitive, and the ability to remotely locate the processor **900** and effectively transfer the data to the processor **900** may avoid incorporating special heat resistant structures or cooling systems to further protect the processor **900**.

(82) In one or more embodiments, the rotating portion of the slip ring **802** (e.g., shown as the inner ring **804** in FIG. **8A**) may be supported by a support **812**, such as electrical conduit or a bracket for example, which is coupled to the main turret **108** for rotation with the main turret **108**. The stationary part of the slip ring **802** (e.g., shown as the outer ring **806** in FIG. **8A**) may be coupled to a stationary support **814** attached to a fixed non-rotating surface (not shown) separate from the main turret **108**. The stationary support **814** may be an electrical conduit, bracket or other support structure, for example. Additionally, in one or more embodiments, the inner ring **804** of the slip ring **802** may have a central bore **816**, which provides access therethrough for one or more fluid conduits **818**. The central bore **816** may be centered on the axis of rotation of the slip ring **802**, which is aligned with the central axis A of the main turret **108**. The fluid conduit **818** may pass through the central bore **816** of the inner ring **804** to deliver cooling fluids or other fluids to the thermal imaging system **120** or other parts of the main turret **108**. In some embodiments, the slip ring **802** is freely rotatable relative to the fluid conduit **818** (i.e., the slip ring **802** is not coupled to the fluid conduit **818**).

(83) Referring to FIG. **8B**, in alternative embodiments, the thermal imaging system **120** may include a power source **840**, such as a battery for example, removeably coupled to the main turret **108** for rotation therewith. The power source **840** may be electrically coupleable to the thermal imager **122** to provide power to the thermal imager **122**. The power source **840** may be removable from the main turret **108** so that the power source **840** may be replaced and/or recharged. In one or more embodiments, the thermal imager **122** may be communicatively coupled to the processor **900** through one or more wireless communication devices **842** using one or more wireless communication protocols. The wireless communication device **842** may be coupled to the main turret **108** for rotation therewith. The wireless communication device **842** may be communicatively coupled to the thermal imager **122**. In embodiments, the thermal image data may be transferred between the thermal imager **122** and the processor **900** using the one or more wireless communication devices and/or protocols.

(84) Referring back to FIG. **8A**, in embodiments, the thermal imaging system **120** may also include a cooling system **820** for cooling the thermal imager **122**. The cooling system **820** may include a cooling fluid source **822**, a fluid rotating union **824** in fluid communication with the cooling fluid source **822**, and the fluid conduit **818**, which is in fluid communication with the fluid rotating union **824**. The cooling fluid may be a compressed gas, such as filtered air, nitrogen, or other gas or combinations of gases, for example. In embodiments, the cooling fluid may be clean dry air (i.e., air having moisture, particulates, dirt, oils, or other contaminants removed therefrom) to avoid introducing contaminants to the thermal imaging system **120**, which could adversely affect performance of the thermal imaging system **120**. Alternatively, the cooling fluid may be nitrogen. In embodiments, the cooling system **820** may include at least one of a regulator, moisture remover, particulate filter, coalescing filter, or combinations of these. The cooling fluid source **822** may include a compressed gas storage tank, gas compressor, or other compressed gas system or combinations of cooling fluid sources.

(85) The fluid rotating union **824** includes a stationary portion **826** fluidly coupled to the cooling



fluid source **822** and a rotating portion **828** that is rotatably coupled to the stationary portion **826** and rotatable relative to the stationary portion **826**. The fluid rotating union **824** includes a union axis that is parallel to and aligned with the central axis A of the main turret **108** so that the rotating portion **828** of the fluid rotating union **824** may rotate in concert with rotation of the main turret **108**. The rotating portion **828** of the fluid rotating union **824** may be fluidly coupled to the fluid conduit **818**, which extends from the fluid rotating union **824** to the thermal imager **122** to deliver the cooling fluid to the thermal imager **122**.

(86) The cooling system **820** may further include one or more cooling fluid conduits **830** in fluid communication with the fluid conduit **818** and positioned to deliver the cooling fluid to parts of the thermal imaging system **120**. In one or more embodiments, one or more of the cooling fluid conduits **830** may be positioned to deliver cooling fluid to the thermal imager **122**. In embodiments, the thermal imager **122** may be maintained at a temperature of less than about 50° C. to maintain accurate operation of the infrared sensor suite within the thermal imager **122**. A combustion gas hood (not shown) integrated with the converter **100** may operate to pull combustions gases and excess heat generated by the heating elements **301** (FIG. 3A) towards the central axis A of the main turret **108** and out of the converter **100**. Thus, the thermal imager **122** is not generally exposed to the majority of the heat from the heating elements **301** (FIG. 3A). However, the thermal imager **122** may be exposed to some heat from the converting process and may generate additional heat internally through operation of the sensor suite and electronics of the thermal imager **122**. The cooling fluid directed towards the thermal imager **122** may operate to maintain the temperature of the thermal imager **122** at or below 50° C. In some embodiments, the cooling system **820** is independent of the cooling stations **210** (FIG. 3E) of the converter **100**. However, in one or more embodiments the cooling stations **210** (FIG. 3E) and the cooling system **820** may share a common cooling fluid source **822**.

(87) In some embodiments, the thermal imaging system **120** may include a cleaning system **832** for purging the lens **506** of the thermal imager **122**, the reflective surface **508** of the mirror **124**, or both. During operation of the converter **100** and the thermal imaging system **120**, oils and combustion products may deposit on the lens **506** of the thermal imager **122** and the reflective surface **508** of the mirror **124**, such as through condensation of oil on the mirror **124** or lens **506**, which may reduce the reflectance of the mirror **124** and interfere with passage of the infrared light through the lens **506** of the thermal imager **122**, thus, introducing errors and inaccuracies into the image data collected by the thermal imager **122**. In embodiments, the cleaning system **832** may include one or more nozzles **834** positioned to deliver a fluid to the lens **506** of the thermal imager **122** to purge the lens **506** of oils, dirt, and other contaminants. The nozzles **834** may be fluidly coupled to a fluid delivery conduit **836** that delivers the fluid from a fluid source (not shown) to the nozzles **834**. In embodiments, one or more of the nozzles **834** may be positioned to deliver the fluid to the reflective surface **508** of the mirror **124** to purge the reflective surface **508** of oils, dirt, and other contaminants. A fluid free of particulates, dirt, oils, or other contaminants may be used to purge the lens **506** of the thermal imager **122**, the reflective surface **508** of the mirror **124**, or both to avoid further contamination of the lens **506** and the mirror **124**. For example, the fluid may be nitrogen, clean air, other gas or combinations thereof. In some embodiments, the cleaning system **832** may be fluidly coupled to the cooling system **820** such that the cooling fluid is delivered to the nozzles **834** and used as the fluid for cleaning the lens **506** of the thermal imager **122**, mirror **124**, or both.

(88) The thermal imaging systems **120** described herein may be adapted for use with the secondary turret **114** of the converter **100**. Referring to FIGS. 18A and 18B, the secondary turret **114** may include a thermal imaging system **120** coupled to the secondary turret **114** for rotation therewith. In some embodiments, the thermal imaging system **120** may be coupled to the shaft **1806** of the secondary turret **114** such that the thermal imaging system **120** is positioned in the center of the secondary turret **114**. As previously discussed, the thermal imaging system **120** includes the

thermal imager **122** and the mounting apparatus **126**. The thermal imaging system **120** coupled to the secondary turret **114** may capture thermal image data from the inner surface **146** and/or outer surface **140** of the glass tube **102** as the glass tube **102** is indexed through the secondary processing stations **112** of the secondary circuit **118** by the secondary turret **114**. Referring to FIG. **18A**, in some embodiments, the thermal imager **122** may be positioned in the center of the secondary turret **114** and oriented vertically (i.e., in the  $\pm Z$  direction of the coordinate axes of FIG. **18A**) so that the optical centerline OC of the thermal imager **122** is generally parallel to the center axis B of the secondary turret **114**. In this configuration, the mirror **124** may be positioned and oriented to reflect the infrared light from the outer surface **140** and/or the inner surface **146** of the glass tube **102**. Referring to FIG. **18B**, in other embodiments, the thermal imager **122** may be oriented generally horizontally (i.e., in the X-Y plane of the coordinate axis of FIG. **18B**) such that the thermal imager **122** directly receives the infrared light from the outer surface **140** of the glass tube **102**. In these embodiments, the thermal imager **122** may face generally radially outward from the center line B of the secondary turret **114**. In this orientation, the infrared light emitted by the outer surface **140** of the glass tube **102** may travel radially inward from the glass tube **102** directly to the thermal imager **122**. Other configurations of the thermal imaging system **120**, including embodiments utilizing supplemental mirrors **125** (FIG. **7E**), stationary mirrors **700** (FIG. **7B**), or combinations of mirrors **124**, **125**, **700** as described herein for reflecting infrared light from the inner surfaces **146** or outer surfaces **140** of the glass tube **102** to the thermal imager **122**, may be adapted to the secondary turret **114**.

(89) Referring back to FIG. **9**, the thermal imaging system **120** may include the processor **900**, one or more memory modules **902** communicatively coupled to the processor **900**, and machine readable instructions stored in the one or more memory modules **902**. The processor **900** may be communicatively coupled to the thermal imager **122** through a communication pathway **904**, which may include data cables **810** (FIG. **8**) and/or one or more wireless communication devices **842** (FIG. **8B**) utilizing standard wireless communication protocols. Suitable wireless communication protocols may include the 802.11 families of protocols, the Bluetooth® protocol, the ZigBee IEEE 802 Standard protocol, or the like. Communicatively coupling the processor **900** to the thermal imager **122** using data cables **810** passed through the slip ring **802** or other rotating electrical coupler is illustrated in FIG. **8A**. The data cables **810** may be electric wires, fiber optic data cables, or other data cables. Communicatively coupling the processor **900** to the thermal imager **122** using the wireless communication device **842** is illustrated in FIG. **8B**.

(90) The processor **900** may enable automated analysis of the image data collected by the thermal imager **122**. By executing the machine readable instructions stored in the memory modules **902**, the processor **900** may cause the thermal imaging system **120** to receive the image data captured by the thermal imager **122**, process the image data, and determine at least one characteristic of the glass tube **102**. Characteristics of the glass tube **102** determined from the thermal image data may include one or more surface temperatures, temperature gradients, dimensions of the glass tube **102** (i.e., dimensions of the physical boundaries of the glass tube), viscosity of the glass tube **102** at various positions, temperature profile of the glass tube as a function of time, centerline of the glass tube, other characteristic, or combinations thereof. The machine readable instructions, when executed by the processor **900**, may also cause the thermal imaging system **120** to store the thermal image data and/or the characteristics of the glass tube **102** determined therefrom, or display the data and/or characteristics of the glass tube **102** on one or more displays **906**. In one or more embodiments, the machine readable instructions stored in the memory modules **902** may comprise one or more image analysis software packages. An example of an image analysis software package may include LabVIEW® distributed by National Instruments, for example. Other commercial image analysis software, off-the shelf or otherwise modified, may also be used with the thermal imaging system **120**.

(91) The machine readable instructions, when executed by the processor **900**, may cause the

thermal imaging system **120** to perform at least the following: capture thermal image information of the glass tube **102** using the thermal imager **122**, transmit the thermal image information from the thermal imager **122** to the processor **900**, receive the thermal image information from the thermal imager **122** at the processor **900**, process the thermal image information, and determine one or more characteristics of the glass tube **102** from the thermal image information. In some embodiments, the machine readable instructions, when executed by the processor **900**, may cause the thermal imaging system **120** to further determine one or more physical boundaries of the glass tube **102** from the thermal image data. In some embodiments, the machine readable instructions, when executed by the processor **900**, may cause the thermal imaging system **120** to perform one or more of identifying the centerline of the glass tube **102** from the thermal image information, drawing a centerline on the thermal images captured by the thermal imager **122**, converting the infrared wavelength data to temperature data, compiling the temperature data to determine one or more temperature profiles and/or temperature gradients of the glass tube **102**, and/or determining a temperature profile (e.g., graphical plot or data table) of the glass tube **102** as a function of time. In some embodiments, the machine readable instructions, when executed by the processor **900**, may cause the thermal imaging system **120** to calculate a viscosity of the glass at a specific position of the glass tube **102** from the temperature of the glass tube **102** and a viscosity as a function of temperature model for the glass tube **102**. In some embodiments, the thermal imaging system **120** may calculate a viscosity gradient through the thickness of the glass tube **102**.

(92) In some embodiments, the machine readable instructions, when executed by the processor **900**, may cause the thermal imaging system **120** to calculate at least one metric from the processed thermal image information. The at least one metric may be retrieved by a control algorithm that may calculate at least one process control variable, such as a controlled variable for example, or process control parameter, such as a gain constant or other process control parameter for example, from the at least one metric.

(93) Indirect capture of thermal images by reflecting the infrared light to the thermal imager **122** using a mirror **124** introduces errors from the mirror when compared to a direct image taken without using a mirror **124**. In processing the thermal image information, the machine readable instructions, when executed by the processor **900**, may cause the thermal imaging system **120** to apply one or more correction factors to the thermal image information to correct for errors introduced by the mirror **124**. When one or more stationary mirrors **700** (FIG. 7) are used with the thermal imaging system **120**, the machine readable instructions, when executed by the processor **900**, may cause the thermal imaging system **120** to apply a plurality of correction factors to the thermal image information.

(94) In one or more embodiments, the machine readable instructions stored in the one or more memory modules **902** may cause the thermal imaging system **120** to perform at least the following when executed by the processor **900**: determine a first characteristic or temperature of the glass tube **102** at a first processing station **106**, determine a second characteristic or temperature of the glass tube **102** at a second processing station **106** positioned downstream of the first processing station **106**, calculate a difference between the first characteristic or temperature and the second characteristic or temperature, and transmit an output representative of the difference between the first characteristic or temperature and the second characteristic or temperature. In some embodiments, the first characteristic and the second characteristic are temperatures evaluated at a specific physical point or region of the outer surface **140** (FIG. 4) or inner surface **146** (FIG. 4) of the glass tube **102** or glass article **103** (e.g., temperature of the outer surface **140** at the shoulder **142** depicted in FIG. 4). Alternatively, in other embodiments, the first characteristic and the second characteristic may be an average temperature of the glass tube **102**. For example, in some embodiments, the first characteristic and the second characteristic may refer to the average centerline temperature of the glass tube **102**. Additionally, the first and second characteristic may be an average temperature taken over a region of the glass tube **102** or glass article **103**. The first

characteristic and the second characteristic may be an internal surface temperature or an external surface temperature of the glass tube **102** or glass article **103**.

(95) In one or more embodiments, the machine readable instructions, when executed by the processor **900**, may cause the thermal imaging system **120** to store the thermal image data in one or more of the memory modules **902**. In one or more embodiments, the machine readable instructions may cause the thermal imaging system **120** to store and maintain a database of thermal image data and/or characteristics of the glass tube determined from the thermal image data, which may be used to develop baseline targets and/or metrics for converter **100** operating parameters to facilitate machine startup and/or to use as set points for one or more process control methods for controlling the converter **100**. In some embodiments, the machine readable instructions, when executed by the processor **900**, may cause the thermal imaging system **120** to store data from specific glass articles in the one or more memory modules **902** and index the data from specific glass articles according to a part identification such that the thermal history of the specific part may be accessible for further analysis and study.

(96) Regular errors caused by the mirror **124** may be introduced into the image data captured by the thermal imager **122**. In one or more embodiments, the machine readable instructions, when executed by the processor **900**, may cause the thermal imaging system **120** to apply one or more data filters to the thermal image data. In one or more embodiments, the machine readable instructions, when executed by the processor **900**, may cause the thermal imaging system **120** to receive thermal image data from the thermal imager **122** at a target sampling rate. The target sampling rate may be modified to influence the overall capture rate of the thermal imaging system **120**.

(97) Still referring to FIG. **9**, the thermal imaging system **120** may further include a display **906** communicatively coupled to the processor **900**. The memory modules **902** may include machine readable instructions that, when executed by the processor **900**, cause the thermal imaging system **120** to display one or more outputs (e.g., thermal images, graphical plots, and/or data tables comprising glass tube temperature data from the thermal images) on the display **906**. The outputs may be one or more graphical outputs, such as a graph of a surface temperature of the glass tube **102** at a particular position as a function of time as illustrated in FIG. **10** or thermal images of the glass tube **102** as depicted in FIGS. **11A-11D**. The output to the display **906** may also include one or more data tables providing numeric representations of the temperature data generated by the thermal imaging system **120** rather than graphical representations.

(98) Referring to FIGS. **7** and **9**, in operation, the thermal imager **122** is positioned to capture thermal image data from a glass tube **102** removably secured in a holder **130** of the main turret **108**. As the glass tube **102** is indexed through the plurality of processing stations **106**, the glass tube **102** is heated and cooled. When heated to an elevated temperature, one or more outer surfaces **140** or inner surfaces **146** (FIG. **4**) of the glass tube **102** emits infrared radiation outward from the glass tube **102** in the radial direction, axial direction or other direction. This infrared light may be reflected by the reflective surface **508** (FIG. **6**) of the mirror **124** towards the lens **506** (FIG. **6**) of the thermal imager **122**. Alternatively, the thermal imager **122** may be positioned to directly capture the infrared light emitted from the glass tube **102** without the mirror **124**. The thermal imager **122** captures the infrared light using a plurality of sensors and outputs thermal image data comprising wavelength and intensity of the infrared light received by the thermal imager **122**. As shown in FIG. **9**, the thermal image data output by the thermal imager **122** is transferred from the thermal imager **122** to the processor **900** by way of the communication pathway **904**, which may be wired or wireless. The processor **900** receives the thermal image data, processes the thermal image data, and outputs one or more attributes (e.g., temperatures) of the glass tube **102** determined from processing the thermal image data.

(99) In one or more embodiments, the thermal imaging system **120** may be configured to capture thermal image data of the glass tube **102** at specific stages or processing stations **106** of the

converting processes, such as the start or end of the dwell time at a heating station **202** (FIG. 2), a start or an end of the dwell time of a forming operation at a forming station **204** (FIG. 2), or other stage in the converting process. Thermal image data may be captured at the beginning of the dwell time, middle of the dwell time, end of the dwell time, or while the glass tube **102** is being indexed between one processing station **106** and a subsequent processing station **106** by the main turret **108**. (100) Alternatively, in other embodiments, the thermal imaging system **120** may be configured to capture thermal image data of the glass tube **102** at set time intervals throughout the converting process. As described previously, the thermal imager **122** may have an image capture rate in a range of from 30 Hz to 60 Hz. An overall capture rate of the thermal imaging system **120** may be defined as the rate at which the thermal imaging system **120** produces an output data set and may include the capture rate of the thermal imager **122** as well as the time periods necessary to transfer the thermal image data to the processor **900**, process the thermal image data, and output the thermal image data to a memory module **902**, display **906**, process controller, or other device. The minimum overall capture rate of the thermal imaging system **120** is the fastest rate at which the thermal imaging system **120** is capable of capturing, transferring, processing, and outputting thermal image data. The minimum overall capture rate of the thermal imaging system **120** may be generally greater than or equal to about 10 Hz. In other embodiments, the minimum overall capture rate of the thermal imaging system **120** may be at least 20 Hz. For example, the minimum overall capture rate of the thermal imaging system **120** may be from 10 Hz to 50 Hz, from 10 Hz to 40 Hz, from 10 Hz to 30 Hz, from 10 Hz to 20 Hz, from 20 Hz to 50 Hz, from 20 Hz to 40 Hz, from 20 Hz to 30 Hz, from 30 Hz to 50 Hz, or from 30 Hz to 40 Hz. A minimum overall capture rate of the thermal imaging system **120** of at least 10 Hz may facilitate capturing the very high temperature gradients that are created during certain stages of the converting process. In one or more embodiments, one or more data filters may be employed to increase the overall capture rate of the thermal imaging system **120**. In one or more embodiments, the sampling rate may be adjusted to change the overall capture rate of the thermal imaging system **120**.

(101) Referring to FIGS. **11A-11D**, thermal images captured by the imager are provided. Regions of greater temperature on the glass tube **102** are indicated as being lighter in color, and regions of lesser temperature are indicated as being darker in color. FIG. **11A** shows a preheating step in which the glass tube **102** is heated prior to separating the glass tube **102**. In FIG. **11B**, the glass tube **102** is being cut and separated from the glass tube stock. As indicated by the very light colored region between the two sections of glass tube **102**, the glass tube in the region of the cut **1102** is at very high temperature at the separating station **206**. In embodiments, the temperature of the glass tube **102** in the region of the cut **1102** may reach temperatures of 1500° C. or greater. The contrast in color indicates a high temperature gradient from the region of the cut **1102** toward the opposite end **1104** of the glass tube **102**. FIGS. **11C** and **11D** show thermal images captured during forming operations, in the shoulder **142** and flange **144** of a glass tube **102** being shaped into a vial. Again, the changing contrast in color between the lighter color of the forming regions (e.g., the shoulder **142** and flange **144**) and the darker color moving towards the opposite end **1104** of the glass tube **102** indicates a high temperature gradient along the length **L** of the glass tube **102**.

(102) Temperature data may be extracted from a series of images similar to those of FIGS. **11A-11D** to generate a temperature history of the glass tube **102** throughout the converting process in the converter **100**. The wavelength of infrared light captured in the thermal image is correlated to the temperature of the glass tube **102** that emits the specific wavelength of infrared light captured. In FIG. **10**, an example of a temperature history of a surface of a glass tube **102** processed through a converter **100**, as captured by the thermal imaging system **120**, is illustrated. FIG. **10** shows a first temperature **1002** of the glass tube **102** determined at a first portion of the surface of the glass tube **102**. Additionally, the thermal imaging system **120** may also be used to extract temperature information for different regions of the article, for example the flange **144** (FIG. **3A**) and the neck **145** (FIG. **3A**) regions of the partially formed glass tube **102**, during formation of the flange **144**

and neck **145**. In FIG. **10**, a second temperature **1004** was determined at a second portion of the surface of the glass tube **102**, and a third temperature **1006** was determined at a third portion of the surface of the glass tube **102**. In some embodiments, the second temperature **1004** and the third temperature **1006** may be determined at portions of the glass tube **102** corresponding to the flange **144** and the neck **145**, respectively.

(103) Operational experience on tube part converters **100** shows that the converting process is very interactive, meaning that small changes in temperature at one processing station **106** of the converter **100** may equally impact the glass temperature and forming processes across the entire converter **100**. The thermal imaging system **120** allows for monitoring of the temperature of a single glass tube **102** through all of the processing stations **106** and operations performed in each processing station **106** so that the impact of temperature changes in one processing station **106** on downstream forming operations can be observed and studied. Because the thermal imaging system **120** travels with the main turret **108** as it indexes between processing stations **106**, the thermal imaging system **120** is also capable of capturing thermal images of the glass tube **102** between processing stations **106** to study the impact of cooling of the glass tube **102** between processing stations **106**.

(104) Referring again to FIGS. 7A-7G, as previously described, the thermal imaging system **120** may be configured to obtain thermal image data of an outer surface **140** of the glass tube **102**. Additionally, the thermal imaging system **120** may be configured to obtain thermal image data, and thus surface temperature data, of one or more inner surfaces **146** (FIG. 4) of the glass tube **102**. The ability to measure the surface temperature of an inner surface **146** may be helpful in characterizing a part converting process where temperature gradients through the thickness **T** (FIG. 4) of the glass tube **102** of several hundred degrees Celsius (i.e., 200° C. to 300° C. or greater) have been measured. Additionally, in one or more embodiments, measurements of the temperature of an inner surface **146** of the glass tube **102** may facilitate identification of a temperature range that results in quality defects. For example, during a flange forming operation conducted at a forming station **204** of a converter **100** for making vials, small cracks in the inner surface **146** at the flange **144** (FIG. 3D) may develop at certain internal surface temperatures. Measuring the internal surface temperature of the glass tube **102** may be used to identify these internal surface temperatures that result in cracks so that changes can be made to the converting process to prevent the cracks.

(105) Multiple mirror pathways may be configured to obtain thermal image data for an inner surface **146** (FIG. 4) of the glass tube **102**. As previously described, a plurality of stationary mirrors **700** may be utilized to configure the thermal imaging system **120** to obtain thermal images of an end view of the glass tube **102**. An end view of the open end of the glass tube **102** may enable the thermal imaging system **120** to determine one or more interior temperatures of the glass tube **102**, such as the temperature of an inner surface **146** of the glass tube **140**. To capture the end view of the open end of the glass tube **102**, one or more stationary stand-alone thermal image devices (not shown) may be mounted directly underneath one or more of the processing stations **106** of the converter **100**. The optical centerline of the stationary thermal imaging devices may be aligned with the centerline **CL** of the glass tube **102** to capture the end view of the glass tube **102**.

Mounting a plurality of individual thermal image devices under a plurality of processing stations **106** may be expensive and cost prohibitive. In another configuration, a stationary imaging device (not shown) may be mounted at a position radially outward from a processing station **106** and a stationary mirror **700** may be mounted underneath the processing station **106** to reflect the end view image of the glass tube **102** to the lens (not shown) of the thermal imaging device. In this configuration, a plurality of thermal imaging devices would be necessary to capture thermal data for an inner surface **146** of the glass tube **102** at different processing stations **106**.

(106) Alternatively, in one or more embodiments, the thermal imaging system **120** coupled to the main turret **108**, which was previously described herein, may be used in conjunction with one or more stationary mirrors **700**, each of which may be positioned underneath one of the plurality of

processing stations **106**. As shown in FIG. 7, the mirror **124** may be positioned to reflect infrared light emitted radially outward from the outer surface **140** of the glass tube **102** towards the lens **506** of the thermal imager **122** and the stationary mirrors **700** may be positioned to reflect infrared light, which is emitted axially downward (i.e., in a direction parallel to the centerline CL of the glass tube **102** and oriented towards the base **104**), from the inner surfaces **146** of the glass tube **102** towards the lens **506** of the thermal imager **122**. When the thermal imager **122** is indexed with the main turret **108** into alignment (e.g., angular alignment) with the stationary mirror **700**, both the mirror **124** and the stationary mirror **700** may reflect infrared light to the lens **506** of the thermal imager **122**, enabling the thermal imager **122** to simultaneously capture thermal images of the outer surfaces **140** and inner surfaces **146** of the glass tube **102**. FIG. 12 depicts a thermal image taken with the thermal imaging system **120** having mirror **124** and stationary mirror **700**. The thermal image of FIG. 9 shows a single thermal image that simultaneously captures thermal data of the outer surface **140** and thermal data of the inner surface **146**. The single thermal image may enable the thermal imaging system **120** to determine one or more external surface temperatures and one or more internal temperatures from a single thermal image dataset. Although described using a combination of the mirror **124** and a stationary mirror **700**, capturing infrared light emitted from the inner surfaces **146** of the glass tube **102** may be accomplished by positioning the mirror **124** to reflect infrared light from both the outside surface **140** and inside surface **146** of the glass tube **102** towards the thermal imager **122** or by coupling a supplemental mirror **125** to the mounting apparatus **126** to reflect the infrared light from the inner surface **146** of the glass tube towards the thermal imager **122**, as previously described in this disclosure.

(107) Although the thermal imaging system **120** has been described relative to a vertically oriented converter **100**, in which the central axis A of the main turret **108** is generally perpendicular to the ground, it should be understood that the thermal imaging system **120** may also be adapted for use with a horizontally oriented converter or angled converter. The thermal imaging system **120** is also described herein relative to a converter **100** having a main turret **108** that is generally circular to index the glass tube **102** around a generally circular main circuit **116** of processing stations **106**, however, it should be understood that the thermal imaging system **120** may be used with a converter **100** having any non-circular continuous loop or track that indexes the glass tube **102** through a plurality of processing stations **106**. The processing stations **106** may be laid out in any convenient pattern. As previously noted, it is also understood that the thermal imaging system **120** may be used with a vial converter **100** as well as converters for producing other articles, such as cartridges, ampoules, syringes, or other glass articles, from glass tubes **102**.

(108) The thermal imaging systems **120** described in this disclosure may aid in developing process measurements, mathematical models, and experiments to build foundational understanding and glass-centered characterization of the converter **100** and the converting process practiced therewith. Developing a better understanding of the converting process through use of the thermal imaging system **120** reduces dependency on art and experience to guide setup of the converter **100**, tooling, process configuration, and the ability to successfully translate between conversion platforms. The thermal imaging system **120** also allows for quantitative mapping of process windows and process limitations. The thermal imaging system **120** enables automatic analysis of the thermal image and locating the centerline CL of the glass tube **102** and/or the article made therefrom. Additionally, the thermal imaging system **120** allows for easier adaptation of the converter **100** and converting processes to incorporate alternative glass formulations.

(109) The thermal imaging system **120** also provides process temperature measurements that may be incorporated into a control system for controlling the converter **100**. At a specific processing station **106**, measurements of surface temperatures of glass tubes **102** indexed through the processing station **106** indicate significant short term and long term variability of the surface temperature of the glass tube **102**. Short term variability in surface temperatures of the glass tube **102**, which is variability from one individual piece to the next individual piece, may be attributed to

manufacturing tolerances in the tube drawing process, which result in variation in tube dimensions, such as tube diameter W (FIG. 4) and wall thickness T (FIG. 4), along the length L of glass tube 102 stock. Mass variability from tube to tube may be from  $\pm 2.5$  percent (%) to  $\pm 5\%$ . The heating elements 301 (FIG. 3A) of a glass tube converter 100 are positioned to heat a specific area of the glass tube 102. Therefore, changes in the mass of glass in that specific area, which may arise from these manufacturing variations from glass tube 102 to glass tube 102, directly results in corresponding variations in surface temperatures of the glass tube 102. Other factors, such as uncertainty and variations in machine timing, may also contribute to short term variations in surface temperature, but manufacturing variances in the glass tube 102 stock make the most significant contribution to these short term variances. Conventional converting machines have no systems to compensate for these short term variations in surface temperature of the glass tubes 102. (110) Long term variances (i.e., from cycle-to-cycle measured in minutes and/or hours) in surface temperature of the glass tube 102 may be caused by a number of factors, which induce variations into the thermal state of the converting process. Conditions that may give rise to long term variances in glass surface temperature may include machine heat-up as the converter 100 increases in temperature from ambient conditions to steady state operational conditions. The heat up process may take from 2 hours to 12 hours. Long term variability in surface temperature may also arise from fuel heating value changes (variations in the composition of the fuel gas received from the natural gas supplier), burner 302 deterioration, changes in manifold pressures (i.e., fuel gas, air, oxygen), ambient conditions, exhaust hood flow rate variability, other factors, and/or combinations of factors. Conventional converting machine systems must be manually adjusted to account for these long term variations in surface temperature.

(111) Referring to FIG. 13, a control system 1300 for a glass tube converter 100 is disclosed that may provide a system and method for compensating for both short term and long term variations in surface temperature to provide more consistent and efficient operation of the converter 100. The control system 1300 comprises the converter 100, the thermal imaging system 120, and a controller 1302.

(112) The converter 100 may have any of the features of the converter 100 previously described herein. As previously described, the one or more heating stations 202 may include heating elements 301 that may be manipulated to change the amount of heating of the glass tube 102 and thus change the temperature of the glass tube 102. For example, in embodiments, the heating element 301 may be a burner 302 having a fuel control valve 310, oxygen control valve 312, and optionally a combustion air control valve 314, all of which may be manipulated to change the heat of the flame produced by the burner 302 and thus change the temperature of the glass tube 102 as it is indexed through the heating station 202. Alternatively, in other embodiments, the heating element 301 may be a laser, such as a carbon dioxide laser, for example. A power input to the laser, an exposure time of the glass tube 102 to the laser, or both may be manipulated to change the degree of heating of the glass tube 102 and thus change the temperature of the glass tube 102. Referring to FIG. 3E, as previously described, the converter 100 may also have one or more cooling stations 210, which may include one or more cooling fluid control valves 344 for controlling a mass flow rate of cooling fluid 342, which may also influence the temperature of the glass tube 102 indexed through the cooling station 210.

(113) The thermal imaging system 120 may be used to measure and determine one or more process variables for use by the control system 1300. The thermal imaging system 120 may have any of the features described herein relative to the thermal imaging system 120 coupled to the main turret 108 for rotation with the main turret 108. As previously described, the thermal imaging system 120 comprises at least one thermal imager 122, a processor 900 communicatively coupled to the thermal imager 122, and one or more memory modules 902 having machine readable instructions thereon for receiving and processing the thermal image data captured by the thermal imager 122. The thermal imaging system 120 may also include at least one mirror 124 positioned to reflect



infrared light from the glass tube **102** to the thermal imager **122**. In some embodiments, a single processor may serve as both the controller **1300** of the control system **1300** and processor **900** of the thermal imaging system **120**. The thermal imaging system **120** may also have one or more stationary mirrors **700** (FIG. 7) positioned vertically below one or more processing stations **106** to reflect infrared light emitted by an inner surface **146** (FIG. 4) of the glass tube **102** to the thermal imager **122** when the thermal imager **122** indexes into position to receive the light reflected from the stationary mirror **700**. In one or more embodiments, a plurality of thermal imagers **122** may be coupled to the main turret **108** to measure process variables for a plurality of processing stations **108** or secondary processing stations **112** simultaneously.

(114) The thermal imaging system **120** may output one or more process variables, which may be used by the control system **1300** to control the converter **100** and converting process. Alternatively, the thermal imaging system **120** may save the one or more process variables to the memory modules **902** for retrieval by the controller **1302**. In one or more embodiments, the process variables determined by the thermal imaging system **120** may include one or more temperatures of an outer surface **140** of the glass tube **102** at one or more points on the outer surface **140** of the glass tube **102** and at one or more stages of the converting process. In embodiments, the process variables determined by the thermal imaging system **120** may include one or more temperatures of an inner surface **146** (FIG. 4) of the glass tube **102** at one or more points on the inner surface **146** of the glass tube **102** and at one or more stages of the converting process. In embodiments, the process variable may be a peak centerline glass temperature (i.e., maximum temperature of the glass tube **102** along the centerline CL of the glass tube **102**). In other embodiments, the process variable may also be one or more dimensions of the glass tube **102** at one or more regions of the glass tube **102**, a viscosity of the glass tube **102** at one or more regions of the glass tube **102**, a temperature profile of the glass tube **102** as a function of time, other characteristic of the glass tube **102**, or combinations of these.

(115) The control system **130** may receive other process variables of the converter **100**. For example, the control system **130** may receive information on dimensions or other physical attributes of the glass tube **102**, such as outer diameter, inner diameter, and/or thickness. Dimensions of the glass tube **102** or other process variables may be received by the control system **130** from external sources or from other measurement systems integrated with the converter **100** and/or the control system **1300**. Referring to FIG. 13, in some embodiments, the control system **1300** may include a dimensioning system **1310** for measuring the diameter W and thickness T of the glass tube **102** and determining a glass mass per unit length of the glass tube **102** from the diameter W, thickness T, and density of the glass. Any one of the diameter W, thickness T, or glass mass per unit length of the glass tube **102** may be used as process variables by the control system **1300**.

(116) The dimensioning system **1310** may include at least one of a visual imaging system, a laser reflectometer, laser gauge, other measuring device, or combinations of these. Alternatively, the dimensioning system **1310** may include an optical micrometer, such as micrometer comprising a collimated beam of light emitted from a light source on one side of the glass tube **102** and an optical receiver, such as a camera or optical sensor for example, positioned on an opposite side of the glass tube. As illustrated in FIG. 13, in some embodiments, the dimensioning system **1310** may include a visual imaging system **1312** having a visual imaging device configured to capture a visual image of the glass tube **102**. In some embodiments, the visual imaging device of the visual imaging system **1312** may be stationary and focused on a single processing station **106**. In embodiments, the visual imaging system **1312** may be coupled to the base **104** of the converter **100**. In embodiments, the visual imaging system **1312** may be positioned to capture a visual image of the glass tube **102** at a processing station **106** directly following the last forming station **204** (FIG. 2) in the main circuit **116** (FIG. 2). Alternatively, in other embodiments, the visual imaging system **1312** may be positioned at a processing station **106** located before the first forming station **204** of the converter

**100.** In still other embodiments, the visual imaging system **1312** may be positioned to capture a visual image of the glass tube **102** before it is loaded into the holder **130**. The visual image obtained from the visual imaging system **1312** may be used to obtain the outer diameter  $W$  of the glass tube **102**.

(117) In some embodiments, the dimensioning system **1310** may further include a laser reflectometer **1314** fixed at a stationary position relative to the base **104** of the converter **100**. The laser reflectometer **1314** may be oriented to measure the thickness  $T$  of the glass tube **102** (i.e., the wall thickness) at a single processing station **106**. In one or more embodiments, the laser reflectometer **1314** may be positioned at the same processing station **106** as the visual imaging system **1312**. Alternatively, the laser reflectometer **1314** may be positioned at a processing station **106** different than the processing station **106** to which the visual imaging system **1312** is directed. In some embodiments, the visual imaging system **1312** may be positioned and oriented to capture a visual image of the glass tube **102**, such as an end view of the glass tube **102**, from which the outside diameter  $W$  and the inside diameter of the glass tube can be determined. The visual imaging system **1312** may then use the outside diameter and inside diameter of the glass tube **102** to determine the thickness  $T$  and mass per unit length of the glass tube **102**. Although the dimensioning system **1310** is described herein as having a visual imaging system **1312**, laser reflectometer **1314**, or both, it is contemplated that other dimension measuring devices may be incorporated into the dimensioning system **1310** to determine the dimensions and mass per unit length of the glass tube **102**.

(118) In alternative embodiments, one or more parts of the dimensioning system **1310**, such as the visual imaging system **1312**, laser reflectometer, or other dimensioning device, may be positioned upstream of the processing stations **106** of the converter **100** to measure the dimensions of the glass tube stock prior to feeding the glass tube stock to the converter **100**. For example, dimensioning system **1310** may be positioned at the tube loading apparatus, such as the glass tube loading turret **110** (FIG. 1) or glass tube loading arm (not shown) for example, to measure the dimensions of the glass tube **102** before loading the glass tube **102** into the converter **100**.

(119) The dimensioning system **1310** may further comprise a dimensioning processor **1316** having one or more dimensioning memory modules **1318** having machine readable instructions thereon that, when executed by the dimensioning processor **1316**, cause the dimensioning system **1310** to receive measurement data from at least one dimensioning device, process the measurement data, and determine a diameter  $W$  and a thickness  $T$  of the glass tube from the measurement data. For example, in some embodiments, the machine readable instructions, when executed by the dimensioning processor **1316**, may cause the dimensioning system **1310** to receive visual image data from the visual imaging system **1312**, receive thickness information from the laser reflectometer **1314**, process the visual image data, determine a diameter  $W$  of the glass tube **102**, process the thickness information from the laser reflectometer **1314**, and determine a thickness  $T$  of the glass tube **102**. Alternatively, in other embodiments, the machine readable instructions, when executed by the dimensioning processor **1316**, may cause the dimensioning system **1310** to receive visual image data from the visual imaging system **1312**, determine an outer diameter  $W$  of the glass tube **102**, determine a thickness, and determine a mass per unit length of the glass tube **102** from the thickness  $T$  and the outer diameter  $W$ . The machine readable instructions may comprise commercially available visual image processing software such as those image processing programs previously described. The machine readable instructions, when executed by the dimensioning processor **1316**, may cause the dimensioning system **1310** to store and/or output the thickness  $T$  and diameter  $W$  of the glass tube **102**. In embodiments, the machine readable instructions, when executed by the dimensioning processor **1316**, may cause the dimensioning system **1310** to determine a mass of glass per unit length of glass tube **102** (i.e., mass per unit length of the glass tube **102**) from the measured diameter  $W$  and thickness  $T$  of the glass tube **102**. The dimensioning system **1310** may store the mass per unit length of the glass tube in the one or more dimensioning

memory modules **1318** or may output the mass per unit length of the glass tube **102**.

(120) In embodiments, the control system **1300** may determine the temperature gradient through the thickness  $T$  of the glass tube **102** from the thickness  $T$  determined by the dimensioning system **1310** and surface temperatures, such as the temperatures of the outer surface **140** and inner surface **146** of the glass tube **102** for example, determined by the thermal imaging system **120**. The temperature gradient may be used as the process variable in one or more control methods. In some embodiments, the control system **130** may determine a viscosity gradient of the glass through the thickness  $T$  of the glass tube **102** from the temperature information from the thermal imager **122** and the thickness  $T$  of the glass tube **102** determined by the dimensioning system **1310**. The viscosity gradient may be used as the process variable in some embodiments. The process variables may also include the index time of the turret.

(121) Still referring to FIG. **13**, the controller **1302** for the control system **1300** may include a control processor **1304** and one or more control memory modules **1306** having machine readable instructions stored thereon, which, when executed by control processor **1304**, cause the control system **1300** to implement one or more control methods for controlling the converter **100**, which control methods will be further described herein. The controller **1302** may have a plurality of inputs communicatively coupled to one or more of the thermal imaging system **120**, the dimensioning system **1310**, or other sensors. The controller **1302** may have a plurality of outputs communicatively coupled to one or more control devices, which may include one or more of the fuel control valves **310**, oxygen control valves **312**, air control valves **314**, cooling fluid control valves **344** (FIG. 3E), forming tool actuators **326** (FIG. 3D), or other control devices associated with one or more heating stations **202**, forming stations **204**, cooling stations **210**, or other processing station **106**. In embodiments, the controller **1302** may be a proportional-integrated-derivative (PID) controller.

(122) The machine readable instructions stored in the one or more control memory modules **1306**, when executed by the control processor **1304**, may cause the control system **1300** to receive a process variable, such as a temperature, viscosity, dimension, temperature gradient, viscosity gradient, other characteristic, or combinations of characteristics of the glass tube **102** for example, from the thermal imaging system **120**, compare the process variable against a set point stored in memory, determine a controlled variable based on the comparison of the process variable to the set point, and transmit a control signal representative of the controlled variable to the one or more control devices. In embodiments, the controller **1302** may receive one or more process variables, such as the diameter  $W$ , thickness  $T$ , and/or glass mass per unit length for the glass tube **102**, from the dimensioning system **1310**. In one or more embodiments, the machine readable instructions, when executed by the control processor **1304**, may cause the controller **1302** to retrieve the process variable from the thermal imaging system **120**, dimensioning system **1310**, or other sensor or sensor system.

(123) The set points for the process variables may be determined from a database of historic process variable measurements collected during operation of the converter **100**. In embodiments, the database may include process variable measurements and operating conditions representing acceptable production conditions. In embodiments, the database may include a data set of process variable measurements and operating conditions corresponding to representative cycles collected to characterize typical variability of the converter **100**. The process variable measurements in the database may be used to develop set points for the one or more process variables. The variability of the process variable measurements may be determined from the database to define control parameters, such as one or more gain constants for example, to maximize thermal consistency, and avoid over-control of the converter **100**. In embodiments, the set point may be calculated as a rolling average of the process variable taken over a specific period of time, such as time periods of at least 3 minutes, at least 30 minutes, at least 60 minutes, at least 3 hours, at least 10 hours, or even at least 3 days, for example.

(124) Referring now to FIG. 14, one embodiment of a temperature feedback control method **1400** is schematically depicted. A process variable **1402** of the converter **100** is measured and transmitted to the controller **1302**. The control processor **1304** of the controller **1302** compares the process variable **1402** to a set point **1404** and calculates an error **1406**, which may be the difference between the set point **1404** and the process variable **1402**. The control processor **1304** may then calculate one or more controlled variables **1408** and transmit one or more control signals representative of the controlled variables **1408** back to the converter **100**, in particular to a control device **1410** of the converter **100**. In embodiments, the process variable **1402** may be one or more temperatures of the glass tube **102** measured by the thermal imaging system **120**. In some embodiments, the temperature of the glass tube **102** may be used by the controller **1302** to control one or more control devices **1410** associated with a heating station **202** (FIG. 3A) to control heating of the glass tube **102** at the heating station **202**. The control processor **1304** may calculate the controlled variable **1408** using one or more proportional, integral, or derivative calculation methodologies. Calculation of the controlled variable **1408** may include applying a gain constant **1409** to the controlled variable **1408** to adjust for the sensitivity of the converting process to changes in the controlled variable **1408**. Specifically, in some embodiments, the controlled variable **1408** may be determined by multiplying the error **1406** by the gain constant **1409**. Alternatively, the control processor **1304** may incorporate modeling, such heat transfer modeling for example, system level control methods, or other control strategies to determine the controlled variable **1408**.

(125) The temperature measured by the thermal imaging system **120** may be a single temperature of the glass tube **102** taken at a specific location on the glass tube **102** at a specific stage of the converting process, such as an end-of-cycle temperature, an end of dwell temperature (i.e., the temperature of the glass tube **102** at the end of an operation in a processing station **106** just before the main turret **108** indexes the glass tube **102** to the next processing station **106**), a beginning of dwell temperature (i.e., the temperature of the glass tube **102** at a processing station **106** at the start of the dwell time), or any other temperature of the glass tube **102** at any location on the glass tube **102** and at any stage of the converting process. In some embodiments, the temperature measured by the thermal imaging system **120** may be an end-of-cycle maximum centerline temperature and/or a maximum centerline temperature at any processing station **106**. The process variable **1402** may include a temperature of the outer surface **140** (FIG. 4) of the glass tube **102** or a temperature of the inner surface **146** (FIG. 4) of the glass tube **102**. In some embodiments, the process variable **1402** may include one or more average temperatures, such as an average centerline temperature of the glass tube **102**, for example.

(126) In some embodiments, the process variable **1402** may be a difference between any two temperatures of the glass tube **102** measured with the thermal imaging system **120**. For example, in some embodiments, the process variable **1402** may be a difference between a centerline temperature of the glass tube **102** at the beginning of the dwell time at a processing station **106** (FIG. 1), such as a heating station **202** or forming station **204**, and a centerline temperature of the glass tube **102** at the end of the dwell time of the same processing station **106**. In some embodiments, the process variable **1402** may be a difference between the end-of-cycle temperature of the glass tube **102** (i.e., the temperature of the glass tube **102** measured at the end of the last processing station of the converting process) and the start-of-cycle temperature of the glass tube **102** (i.e., the temperature of the glass tube **102** measured at the first processing station of the converting process). The process variable **1402** may be a difference between temperatures of the glass tube **102** at the same holder position **136** (FIG. 2) at different stages of the converting process. Alternatively, the process variable **1402** may include a difference between a temperature at one position on the glass tube **102** and a temperature at a second position on the glass tube **102** at the same stage of the converting process. For example, the process variable **1402** may include a difference between a temperature of the outer surface **140** (FIG. 4) of the glass tube **102** and a temperature of the inner surface **146** (FIG. 4) of the glass tube **102** at the same processing station

**106.** The process variable **1402** may be representative of a temperature gradient between two positions on the glass tube **102**, such as the temperature gradient through the thickness *T* of the glass tube **102**. The process variable **1402** may also be a physical dimension of the glass tube **102** determined from the thermal image data. The process variable may also be a viscosity of the glass tube **102** or a viscosity gradient through the thickness *T* of the glass tube **102**. The process variable **1402** may be any other process variable or characteristic of the glass tube **102** described herein. (127) The process variable **1402** (e.g., a temperature of the glass tube) may be compared to the set point **1404**, which may be stored in the one or more control memory modules **1306** of the controller **1302**. The set point **1404** may be periodically updated in the control memory modules **1306** based on changes observed from continued accumulation of process variable **1402** measurements and operating conditions in the database of operating conditions previously described.

(128) In some embodiments, the controlled variables **1408** may include one or more variables that influence the heating of the glass tube **102** by the heating element **301** (FIG. 3A) in one or more heating stations **202** (FIG. 3A). For example, in embodiments, the controlled variables **1408** may include the position of one or more of the fuel control valve **310** (FIG. 3A), oxygen control valve **312** (FIG. 3A), and air control valve **314** (FIG. 3A) for one or more burners **302** (FIG. 3A) of one or more heating stations **202** of the converter **100**. Communicatively coupling the fuel control valves **310**, oxygen control valves **312**, and/or the optional air control valves **314** of one or more heating stations **202** to the outputs of the controller **1302** enables the controller **1302** to control the heating station **202** by manipulating the mass flow of fuel gas to one or more of the burners **302** (FIG. 3) with proportional changes to the flow of oxygen and/or air.

(129) In some embodiments, the ratio of the mass flow rate of oxygen and/or air to the mass flow rate of the fuel gas may be fixed and constant so that adjusting the mass flow rate of the fuel gas changes the corresponding mass flow rates of the oxygen and/or air. In these embodiments, the controller **1302** may be configured to manipulate the fuel control valve **310**, oxygen control valve **312**, and/or the air control valve **314** to maintain a constant stoichiometric ratio of the fuel gas delivered to the burner. For example, in embodiments in which both air and pure oxygen are provided to a burner, a ratio of the flow of air to the flow of pure oxygen must also be maintained in order to maintain stoichiometry. In the case where burner combustion is supplied by multiple streams—such as is the case for air and oxygen—both air and pure oxygen mass flowrates are held in a constant ratio to maintain a constant oxidant concentration at the burner **302**, which refers to the total oxygen concentration of the combined air and oxygen streams. Thus, in embodiments in which a burner **302** is supplied with fuel gas, pure oxygen gas, and air, the stoichiometry for oxidation of the fuel gas is maintained by maintaining the ratio of the fuel gas flowrate to the pure oxygen flowrate and by maintaining the ratio of the air flowrate to the pure oxygen flowrate. In operation, a controller **1302** may send a control signal to the fuel control valve **310** to change the mass flow rate of fuel gas to the burner **302**. To maintain stoichiometry, the controller **1302** will also make corresponding changes to the pure oxygen flowrate and air flowrate to maintain a constant ratio of the air flowrate to the pure oxygen flowrate and a constant ratio of the fuel gas flowrate to the pure oxygen flowrate. Maintaining a constant stoichiometric ratio of the fuel gas delivered to the burner **302** will hold the heating levels of the burner **302** in proportion to the fuel flow increase, which may increase the predictability of the temperature control response to changes in controlled variables **1408**.

(130) Alternatively, in other embodiments, the mass flow rate of fuel gas and the mass flow rate of oxygen and/or air may be adjusted independent of each other such that the ratio of oxygen and/or air to fuel gas may be adjusted in response to a control signal from the controller **1302**. For example, adjusting the ratio of fuel gas to oxidant introduced to the burner **302** at a heating station **202** may be used to adjust the amount of heating conducted at a heating station **202** and, thus, influence the temperature of the glass tube **102**. In some embodiments, the fuel control valve **310**

may be controlled to control heating in the heating station **202**, and the oxygen control valve **312** and/or the air control valve **314** may be controlled to maintain a constant stoichiometric ratio of fuel gas to oxygen at the burner **302** of the heating station **202**. Additionally, in heating stations **202** having multiple burners **302**, the proportion of fuel gas mass flow between each of the burners **302** may be fixed such that a change in fuel gas mass flow rate of one burner **302** results in a proportional change to the fuel gas mass flow of the other burners **302**. In embodiments, each of the burners **302** may be independently controlled by the controller **1302**. In alternative embodiments, the heating station **202** may include one or more laser heating elements and the controlled variable **1408** may be a power output to the laser or an exposure time of the glass tube **102** to the laser light.

(131) The gain constant **1409** may be determined by performing a series of bump tests on individual processing stations **106** (FIG. **1**). Generally, a bump test refers to the process of making a small step change in one or more controlled variables **1408** and measuring the process variable **1402** to determine the response of the process variable **1402** to the small step change in the controlled variable **1408**. For example, mass flow rates of fuel gas and/or oxygen may be changed in very small increments and the thermal response of the converter **100** to the changes in the mass flow rates of fuel and/or oxygen may be measured using the thermal imaging system **120**. For glass converters **100**, the heating stations **202** (FIG. **2**) are very highly coupled, so bump tests may be conducted individually for each of the heating stations **202** with the changes to the mass flow rates of fuel and oxygen kept very small.

(132) The feedback control method **1400** depicted in FIG. **14** may operate to maintain a consistent surface temperature of the glass tube **102** as averaged over a period of 2 to 3 complete rotations of the main turret **108** (FIG. **1**). Configuring the control system **1300** to maintain a consistent surface temperature through the feedback control method **1400** of FIG. **14** may reduce or eliminate the effects of the long term sources of surface temperature variability previously described.

(133) However, the feedback control method **1400** may not effectively reduce or eliminate short term variations, such as those caused by variations in the glass mass per unit length of the glass tube **102**, as previously described. For example, for a converter **100** having N number of processing stations **106** and a thermal imaging system **120** with a single thermal imager **122**, the thermal imager **122** may measure the process variable **1402** (i.e., a temperature) of a single glass tube **102** as it is indexed through the N processing stations **106**. Adjustments to the controlled variables **1408** based on the temperature of the single glass tube **102** are then maintained through the next (N-1) glass tubes **102** until the thermal imager **122** cycles back through to measure the process variables **1402** again. Thus, operating conditions are held constant for the (N-1) glass tubes **102** between cycles of the thermal imager **122**. For larger converters **100** having more than 18 processing stations **106**, such as 36 or more stations, controlling the converter **100** in response to one measurement of the process variables **1402** for one glass tube **102** out of every N glass tubes **102** may not account for short term variability in the process. Additionally, the dimensions and/or mass of the (N-1) glass tubes **102** may vary, which may introduce more variability into the process between cycles of the thermal imager **122**. In some embodiments, the thermal imaging system **120** may include a plurality of thermal imagers **122** distributed around the holder positions. The incorporation of multiple thermal imagers **122** may increase the frequency of measurement of the process variables **1402** and may improve control of the converter **100**.

(134) Alternatively, to account for the short term variations, such as the variations in the glass mass per unit length of the glass tube **102**, a cascade control method **1500**, such as the method schematically depicted in FIG. **15**, may be implemented with the control system **1300** (FIG. **13**). In the cascade control method **1500**, a second process variable **1516** may be measured or provided from an external source for at least the (N-1) glass tubes **102** between cycles of the thermal imager **122**. The cascade control method **1500** provides the ability to compensate for short term variations, such as variations in glass tube mass and/or dimensions, on a tube-by-tube basis. Thus, the cascade

control method **1500** may enable the control system **1300** to compensate for temperature changes at holder positions at which the temperature is not being measured by the visual imaging system **120**. The cascade control method **1500** may provide improved and/or enhanced process control of the converter **100** compared to the feedback control method **1400**, which may rely on measurement of the process variables by the thermal imaging system **120** once per cycle of the thermal imager **122** through the processing stations **106**.

(135) Referring to FIG. **15**, in a first feedback loop **1502**, a first process variable **1506** of the converting process is measured and transmitted to the controller **1302**. The controller **1302** compares the first process variable **1506** to a first set point **1508** associated with the first process variable **1506** and calculates a first error **1510**, which may be the difference between the first set point **1508** and the first process variable **1506**. The controller **1302** may then calculate an intermediate controlled variable (not shown) and adjust the intermediate controlled variable by applying a first gain constant **1514**. In a second feedback loop **1504**, a second process variable **1516** of the converter **100** is measured and transmitted to the controller **1302**. The controller **1302** compares the second process variable **1516** to a second set point **1518** associated with the second process variable **1516** and calculates a bias (i.e., a second error, not shown). The controller **1302** may then adjust the controlled variable **1512**, which was determined by the controller **1302** in the first feedback loop **1502**, using the bias and a second gain constant **1522** to generate the controlled variable **1512**. The controller **1302** may then transmit one or more control signals representative of the controlled variable **1512** to one or more control devices **1410** of the converter **100**.

(136) In embodiments, the first process variable **1506** may be one or more temperatures of the glass tube **102** measured by the thermal imaging system **120**, and the second process variable **1516** may be a physical dimension of the glass tube **102**, such as the diameter, thickness, or glass mass per unit length of the glass tube **102** for example, measured by the dimensioning system **1310**. The temperature of the glass tube **102** and physical dimension of the glass tube **102** may be used by the controller **1302** in the cascade control method **1500** to control the heating at one or more of the heating stations **202** (FIG. **3A**). The first feedback loop **1502** having the first process variable **1506** that is a temperature of the glass tube **102** may allow the control system **1300** to control the converter **100** on a cycle-to-cycle basis to reduce or eliminate the effects of the long term sources of surface temperature variability as previously described. The second feedback loop **1504** having the second process variable **1516** that is a physical dimension of the glass tube **102** may allow the control system **1300** to control the converter **100** on a glass-tube-to-glass-tube basis to reduce or eliminate the effects of short term sources of surface temperature variability, such as variability in the dimensions of the glass tube **102**, as previously described herein.

(137) In one or more embodiments, the first feedback loop **1502** of the cascade control method **1500** may be the same as the feedback loop depicted in FIG. **14** and previously described in relation thereto. Similarly, the first process variable **1506**, first set point **1508**, first gain constant **1514**, and controlled variable **1512** may be similar to the process variable **1402**, set point **1404**, gain constant **1409**, and controlled variable **1408** described previously in relation to FIG. **14**.

(138) Referring back to FIG. **15**, the second process variable **1516**, which may be a physical attribute of the glass tube **102**, may be measured and/or calculated by the dimensioning system **1310** (FIG. **13**). The second process variable **1516** (e.g., diameter, thickness, or glass mass per length of the glass tube) may be compared to the second set point **1518**, which may be stored in the one or more control memory modules **1306** of the controller **1302**. In embodiments, the second set point **1518** may be a nominal tube mass per unit length. The second set point **1518** may be periodically updated in the control memory modules **1306** based on changes observed from continued accumulation of process variable measurements and operating conditions in the database. A bias (not shown) may be calculated for each glass tube **102** processed, and the controlled variable **1512** may be adjusted on a tube-by-tube basis. The bias may be calculated using a mathematical model relating the mass per unit length of the glass tube **102** and the temperature profile of the

glass tube **102**. The mathematical model may include heat transfer models or may be empirically determined from historic thermal data stored by the thermal imaging system **120**.

(139) As previously described, the controlled variable **1512** may include the position of one or more of the fuel control valve **310** (FIG. 3A), oxygen control valve **312** (FIG. 3A), and/or air control valve **314** (FIG. 3A) for one or more heating stations **202** of the converter **100**.

(140) Referring again to FIG. 13, as described herein, the thermal imaging system **120** follows a single glass tube **102** through the converter **100**, so that at the fixed position **138** on the main turret **108** corresponding to the thermal imaging system **120**, the control system **1300** operates in full cascade mode (i.e., according to the cascade control method **1500** depicted in FIG. 15). However, for glass tubes **102** at holder positions **136** not corresponding to the fixed position **138** of the thermal imaging system **120**, the control system **1300** may operate as a single loop feedback control method in which the heating stations **202** are controlled based on the second process variable **1516** (FIG. 15), which may be a physical attribute of the glass tube **102** (e.g., diameter, thickness, or glass mass per unit length of the glass tube **102**). Heating flows are continually modified based on the physical attribute of the glass tube for the holder positions **136** between the fixed positions **138** of the thermal imaging system **120**. As previously described, in one or more embodiments, more than one thermal imaging system **120** may be coupled to the main turret **108** of the converter **100** to provide measurements of the first process variable **1506** at two fixed positions **138** on the main turret **108**, which enables measurement of the first process variable **1506** at a frequency greater than one time per cycle.

(141) Referring to FIG. 16, an embodiment of a single loop feedback control method **1600** is depicted that is based on glass-tube-to-glass-tube control of one or more heating elements **301** (FIG. 3A) of the heating stations **202** (FIG. 3A) in response to changes in the glass mass per unit length of the glass tube **102** as measured by the dimensioning system **1310**. In the embodiment of FIG. 16, the process variable **1602** may be a physical attribute of the glass tube **102**, such as the diameter, thickness, or glass mass per unit length of the glass tube **102**. The process variable **1602** may be compared against a set point **1604**, which may be a nominal diameter, nominal thickness, or nominal glass mass per unit length of the glass tube **102**. The error **1606**, which may be the difference between the process variable **1602** and the set point **1604**, and a gain constant **1609** may be used to determine the controlled variable **1608**, which may be a position of one or more of the fuel control valve **310**, oxygen control valve **312**, and/or air control valve **314**, which combine to control the mass flow rate of fuel, oxygen, and/or air to the burner **302** (FIG. 3) of one or more heating stations **202**. The single loop feedback control method **1600** of FIG. 16 may represent operation of the control system **1300** (FIG. 13) with respect to the glass tubes **102** in holder positions **136** that are not the fixed position **138**, which is the holder **130** at which the thermal imaging system **120** is positioned. At the fixed position **138**, the control system **1300** operates in full cascade mode as previously described and illustrated in FIG. 15.

(142) In some embodiments, for any of the control methods depicted in FIGS. 14-16, the controlled variable **1408**, **1512**, **1608** may be a position of the cooling fluid control valve **344**, which controls the mass flow of cooling fluid **342** (FIG. 3E) to one or more cooling stations **210** (FIG. 3E). In these embodiments, the cooling fluid control valve **344** (FIG. 3E) for a cooling station **210** may be communicatively coupled to the control system **1300**. Additionally, in embodiments, the controlled variables **1408**, **1512**, **1608** may also include an index time of the main turret **108** of the converter **100**.

(143) In embodiments, a feedback control method **1400** (FIG. 14) or cascade control method **1500** (FIG. 15) may be used to control the contact time of the forming tools **324** (FIGS. 3C-3D) with the glass tube **102** in a forming station **204** (FIGS. 3C-3D). The contact time may be controlled as the controlled variable **1408**, **1512** in response to a process variable **1402**, **1506**, such as a temperature of the glass tube **102** measured using the thermal imaging system **120** or a physical attribute of the glass tube **102**, such as the diameter, thickness, or glass mass per unit length of the glass tube **102**,



which may be measured by the dimensioning system **1310** (FIG. 13). The contact time of the forming tools **324** with the glass tube **102** may be increased or decreased in response to the process variable **1402**, **1506**.

(144) In one or more embodiments, the controlled variable **1408** may be the contact time. When the measured surface temperature reaches the target surface temperature, the controller **1302** may set the contact time to the time period starting from when the forming tools **324** first engaged the glass tube **102** and ending at the time at which the measured surface temperature reached the target surface temperature. As the main turret **108** indexes glass tubes **102** through the forming station **204**, the controller **1302** maintains the controlled variable **1408** equal to the contact time determined by the controller **1302** until the thermal imaging system **120** cycles back around into position at the forming station **204** to measure the process variable **1402** again. In these embodiments, the contact time may change from cycle to cycle and may be effective to reduce or eliminate the effects of long term sources of surface temperature variability on the contact time.

(145) In one or more embodiments, the cascade control method **1500** depicted in FIG. 15 and described previously in this disclosure may be adapted to control the contact time of the forming tools **324** with the glass tube **102** based on the surface temperature of the glass tube **102** as well as a physical attribute of the glass tube **102**. In these embodiments, the first process variable **1506** may be the surface temperature of the glass tube **102** as measured by the thermal imaging system **120**. The second process variable **1516** may be the glass mass per unit length of the glass tube **102** as determined by the dimensioning system **1310**. The controlled variable **1512** may be the contact time. The contact time (controlled variable **1512**) is initially established for a cycle based on comparing the measured surface temperature (first process variable **1506**) provided by the thermal imaging system **120** to the target surface temperature (first set point **1508**) stored in the control memory modules **1306**. The contact time may then be further adjusted on a glass-tube-to-glass-tube basis based on comparison of the glass mass per unit area (second process variable **1516**) as measured by the dimensioning system **1310** and compared to the target glass mass per unit area (second set point **1518**). Implementing the cascade control method **1500** may further enable the control system **1300** to reduce and/or eliminate the effects of short term sources of variability in glass tube temperature, such as variability in glass tube **102** dimensions.

(146) Based on the foregoing, it should now be understood that the embodiments described herein relate to thermal imaging systems **120** and control systems **1300** for use with converters **100** for producing a plurality of glass articles from glass tube **102**. The thermal imaging system **120** and control systems **1300** described herein may be implemented to replace or minimize the dependency of existing converters on operator experience and art in fine-tuning thermal conditions on a glass tube converter **100**. The thermal imaging system **120** and converter control systems **1300** may minimize the requirement of experience and shorten the learning curve for new part makers in reaching high quality and stable production. The thermal imaging system **120** and control systems **1300** may also enable faster process tuning for production of new products or incorporation of different glass compositions. The control system **1300** may also enable manufacturers to maximize yield and throughput of the converter **100**.

(147) The present disclosure may be embodied in hardware and/or in software (including firmware, resident software, micro-code, etc.). The thermal imaging system **120** and/or control system **1300** may include at least one processor and the computer-readable medium (i.e., memory module) as previously described in this specification. A computer-usable or the computer-readable medium or memory module may be any medium that can contain, store, communicate, propagate, or transport the program for use by or in connection with the instruction execution system, apparatus, or device.

(148) The computer-usable or computer-readable medium or memory module may be, for example but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, device, or propagation medium. More specific examples (a non-exhaustive list) of the computer-readable medium would include the following: an electrical connection having one

or more wires, a portable computer diskette, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), an optical fiber, and a portable compact disc read-only memory (CD-ROM). Note that the computer-usable or computer-readable medium could even be paper or another suitable medium upon which the program is printed, as the program can be electronically captured, via, for instance, optical scanning of the paper or other medium, then compiled, interpreted, or otherwise processed in a suitable manner, if necessary, and then stored in a computer memory.

(149) Computer program code for carrying out operations of the present disclosure may be written in a high-level programming language, such as C or C++, for development convenience. In addition, computer program code for carrying out operations of the present disclosure may also be written in other programming languages, such as, but not limited to, interpreted languages. Some modules or routines may be written in assembly language or even micro-code to enhance performance and/or memory usage. However, software embodiments of the present disclosure do not depend on implementation with a particular programming language. It will be further appreciated that the functionality of any or all of the program modules may also be implemented using discrete hardware components, one or more application specific integrated circuits (ASICs), or a programmed digital signal processor or microcontroller.

(150) While various embodiments of thermal imaging systems **120** and techniques for using the thermal imaging systems **120** for studying, starting-up, optimizing, and controlling glass tube converters **100** have been described herein, it should be understood it is contemplated that each of these embodiments and techniques may be used separately or in conjunction with one or more embodiments and techniques.

(151) It will be apparent to those skilled in the art that various modifications and variations can be made to the embodiments described herein without departing from the spirit and scope of the claimed subject matter. Thus it is intended that the specification cover the modifications and variations of the various embodiments described herein provided such modification and variations come within the scope of the appended claims and their equivalents.

## Claims

1. A method for producing glass articles with an opening at an end portion from a glass tube having an inner surface and an outer surface, the method comprising: determining dimensional data for the glass tube, one or more features of the glass articles, or combinations thereof, wherein the determining the dimensional data comprises measuring the dimensional data with a dimensioning system; shaping an end portion of the glass tube using at least one forming station, the at least one forming station comprising an outer surface forming tool and an inner surface forming tool; controlling a position of the outer surface forming tool operatively associated with the end portion of the glass tube based on the dimensional data; and controlling a position of the inner surface forming tool operatively associated with the end portion of the glass tube based on the dimensional data, wherein the dimensioning system is positioned upstream or downstream of the at least one forming station.
2. The method of claim 1, further comprising controlling the position of the inner surface forming tool based on the dimensional data independent of controlling the position of the outer surface forming tool.
3. The method of claim 1, wherein the outer surface forming tool comprises a plurality of outer surface forming tools and wherein the controlling the position of the outer surface forming tool comprises independently controlling a position of each of the plurality of outer surface forming tools based on the dimensional data.
4. The method of claim 1, wherein the controlling the position of the inner surface forming tool based on the dimensional data comprises controlling an axial position of the inner surface forming

tool.

5. The method of claim 1, further comprising adjusting a position of a heating element operatively associated with the end portion of the glass tube based on the dimensional data.
6. The method of claim 1, wherein the dimensional data for the glass tube is selected from a group consisting of a tube diameter, tube wall thickness, a glass mass per unit length of the glass tube, and any combinations thereof.
7. The method of claim 1, wherein the glass articles are glass vials and the method further comprises forming a glass vial opening for each of the glass vials from the glass tube, the glass vial opening having one or more of a flange, a neck, a shoulder, or any combination thereof, wherein controlling the position of the outer surface forming tool based on the dimensional data comprises forming a flange thickness, a flange length, a neck length, a neck thickness, or combinations thereof.
8. The method of claim 1, wherein the dimensioning system comprises a non-contact measurement system.
9. The method of claim 8, wherein the non-contact measurement system comprises at least one of a thermal imaging system, a visual imaging system, a laser reflectometer, a laser gauge, an optical micrometer, or any combinations thereof.
10. The method of claim 1, further comprising processing the dimensional data by a control module to output a control variable, wherein the controlling the position of the outer surface forming tool or the controlling the position of the inner surface forming tool comprises inputting the control variable into an actuator that adjusts the position of the outer surface forming tool or the position of the inner surface forming tool based on the control variable.
11. The method of claim 10, wherein the processing the dimensional data for the glass tube, the one or more features of the glass articles, or combinations thereof comprises comparing the dimensional data with a set point stored in a memory module of the control module.
12. The method of claim 1, wherein the controlling the position of the inner surface forming tool comprises introducing the inner surface forming tool into an opening of the end portion of the glass tube in an axial direction relative to a center axis of the glass tube.
13. The method of claim 12, wherein the controlling the position of the outer surface forming tool comprises moving the outer surface forming tool into contact with the outer surface at the end portion of the glass tube to form a radial surface of a flange for the glass article, wherein the outer surface forming tool comprises a plurality of rotatably-movable forming tools.
14. The method of claim 12, wherein the controlling the position of the inner surface forming tool further comprises contacting an axial end of the glass tube to form an axial surface of a flange for the glass article.
15. The method of claim 1, further comprising: holding a plurality of glass tubes in a plurality of holders that are distributed circumferentially around a rotary table, wherein the plurality of glass tubes are held by a portion of the glass tubes other than the end portion; defining a plurality of processing stations around the rotary table, the plurality of processing stations including the at least one forming station; and rotating the rotary table so that each of the plurality of holders presents the end portion of the glass tube held therein to a respective one of the plurality of processing stations, wherein the controlling the position of the outer surface forming tool, the controlling the position of the inner surface forming tool, or both have a contact time that is shorter than a dwell time for the rotating the rotary table.
16. The method of claim 1, wherein the shaping the end portion of the glass tube comprises: heating the end portion of the glass tube; introducing the inner surface forming tool along a first direction into an opening in the end portion of the glass tube while the glass tube is rotating; and pressing the outer surface forming tool along a second direction on an outer surface of the end portion of the glass tube while the glass tube is rotating with the inner surface forming tool disposed in the opening.

17. The method of claim 16, further comprising: withdrawing the inner surface forming tool along a direction opposite the first direction from the opening; and withdrawing the outer surface forming tool along a direction opposite the second direction from the outer surface of the end portion.
18. The method of claim 17, wherein the withdrawing the inner surface forming tool from the opening occurs before or after the withdrawing the outer surface forming tool from the outer surface of the end portion.
19. The method of claim 16, wherein the first direction and the second direction are perpendicular to one another.
20. The method of claim 19, further comprising moving the inner surface forming tool along the second direction.
21. The method of claim 16, wherein the dimensioning system comprises at least one of a visual imaging device, a laser reflectometer, a laser gauge, an optical micrometer, or any combinations thereof.
22. The method of claim 21, further comprising: processing the dimensional data; and determining a physical attribute of the glass tube from the dimensional data.
23. The method of claim 22, wherein the physical attribute is one or more of a diameter, thickness, glass mass per unit length, or any combination thereof of the end portion of the glass tube.
24. The method of claim 23, wherein the glass container is a pharmaceutical glass vial and the shaping the end portion of the glass tube comprises forming a flange having one or more of a flange thickness, a flange length, a neck length, a neck thickness, or any combinations thereof.
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