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(54) **PROCESS MONITORING AND CONTROL USING BATTERY-FREE MULTIPOINT WIRELESS PRODUCT CONDITION SENSING**

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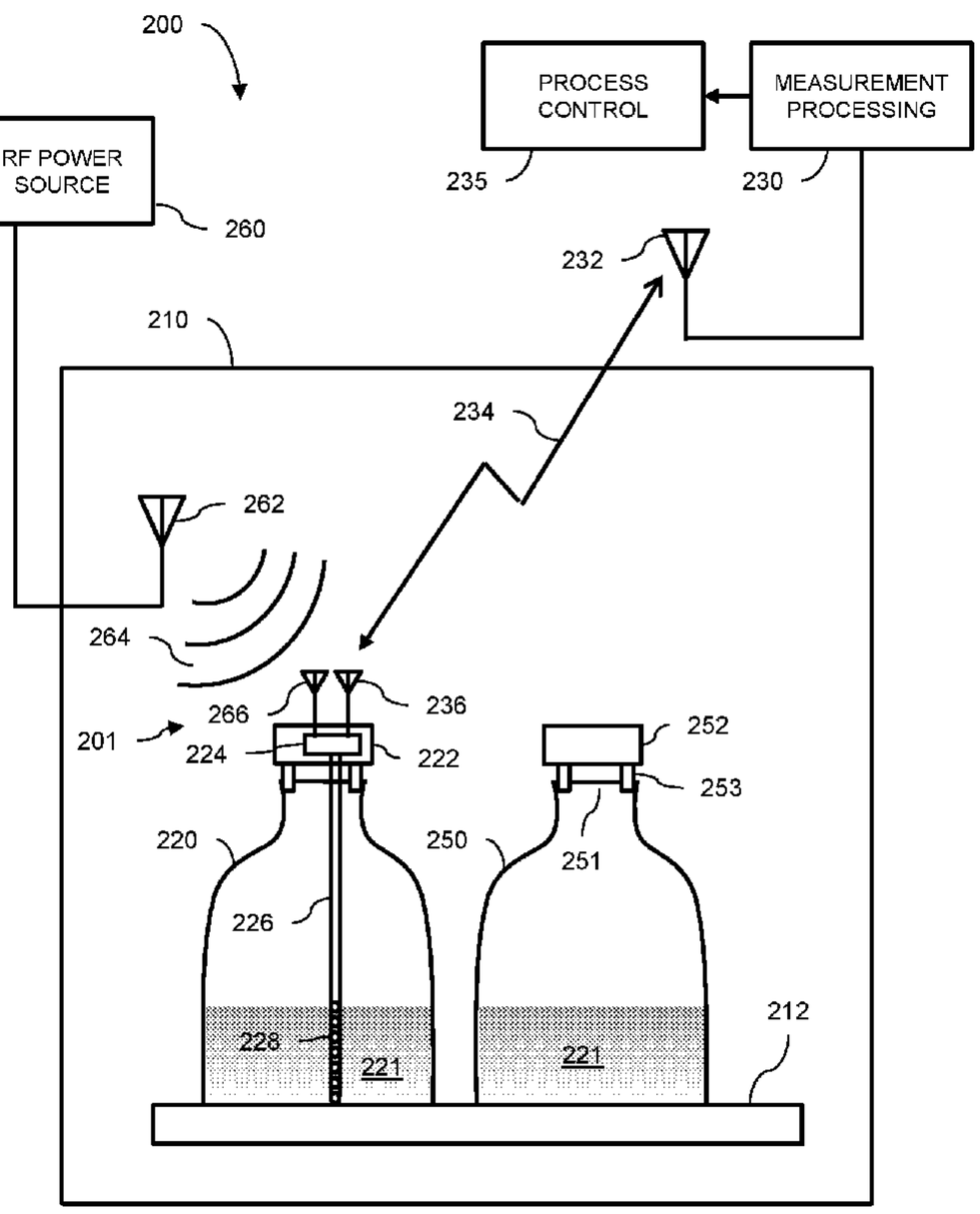
(57) **ABSTRACT**

An arrangement for monitoring an aseptic manufacturing process includes product condition sensors capable of making closely spaced measurements of a product condition such as temperature or humidity. The measurements are made using closely spaced sensors arranged in a linear array on a single probe, which may be used to take measurements at multiple levels within the product. Data from the sensors is transmitted to a data collection point via short range wireless digital communications. The sensors may be used to measure temperature and humidity at a single point. For example, when the sensors are used in pharmaceutical freeze drying, the location of a sublimation front may be calculated for each vial, and the freeze drying process may be controlled using the data.



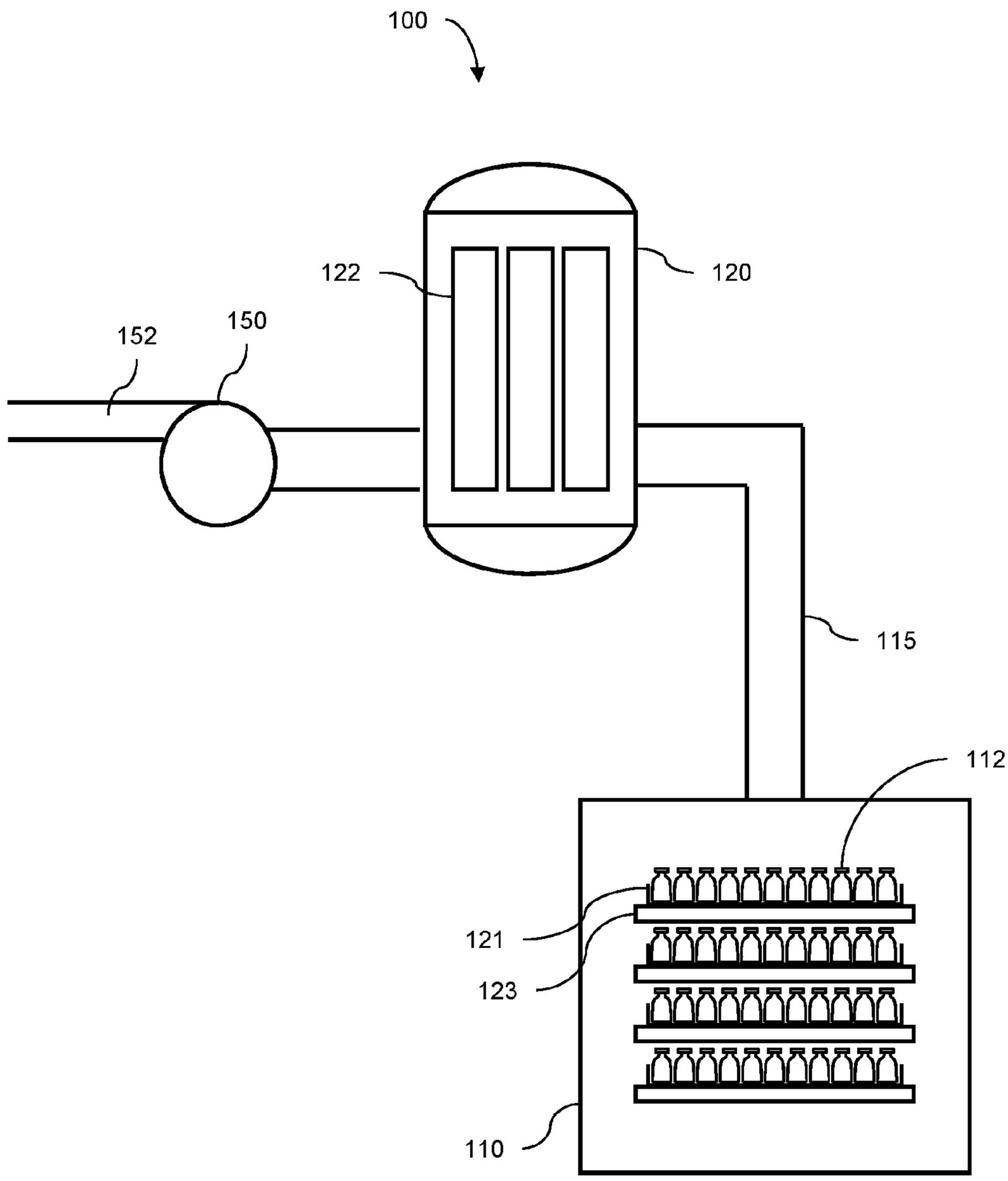


Fig. 1 (prior art)

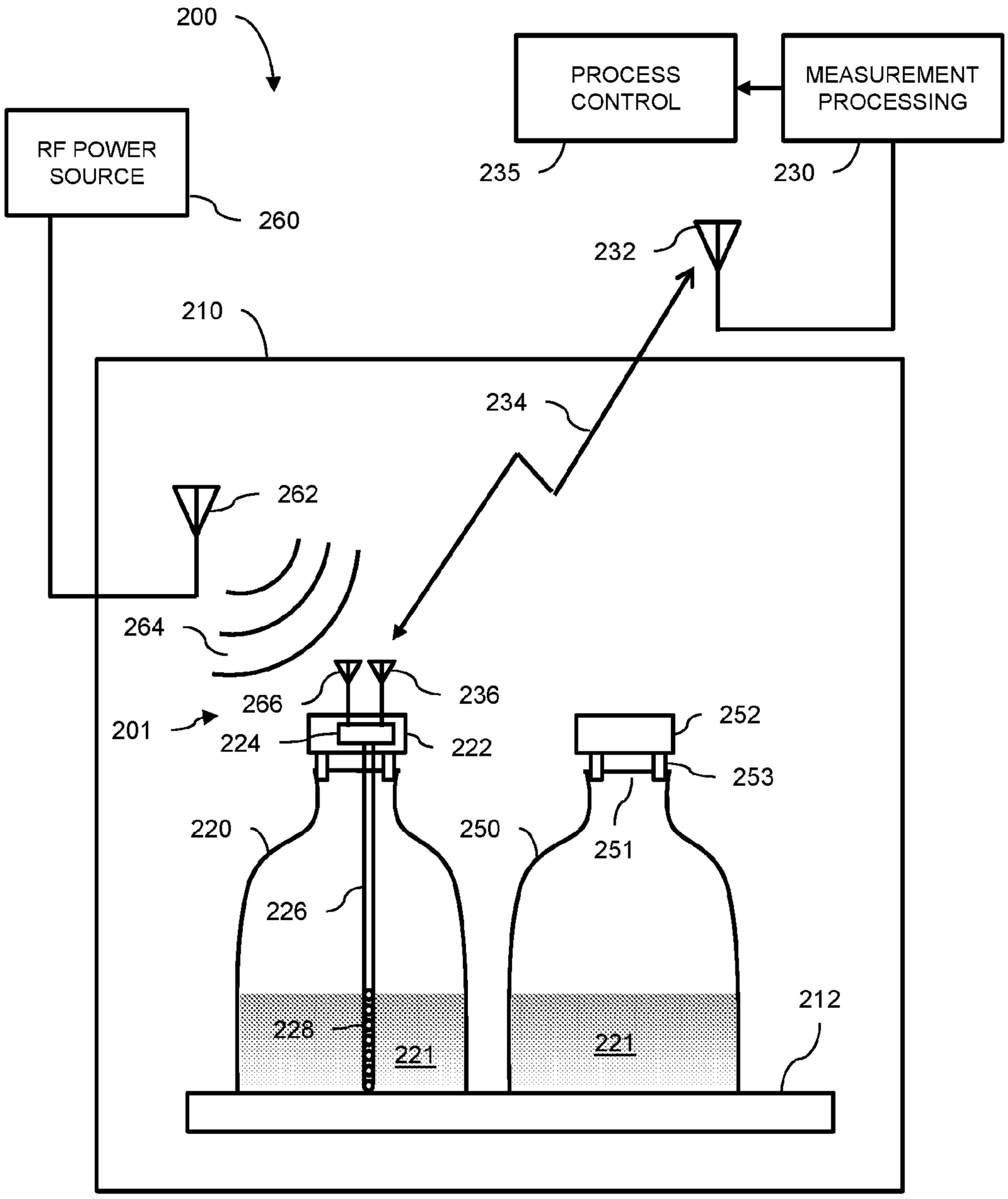

200
RF POWER SOURCE
260
PROCESS CONTROL
MEASUREMENT PROCESSING
235
230
232
210
234
262
264
266
236
201
224
222
252
253
220
250
251
226
228
221
221
212

Fig. 2

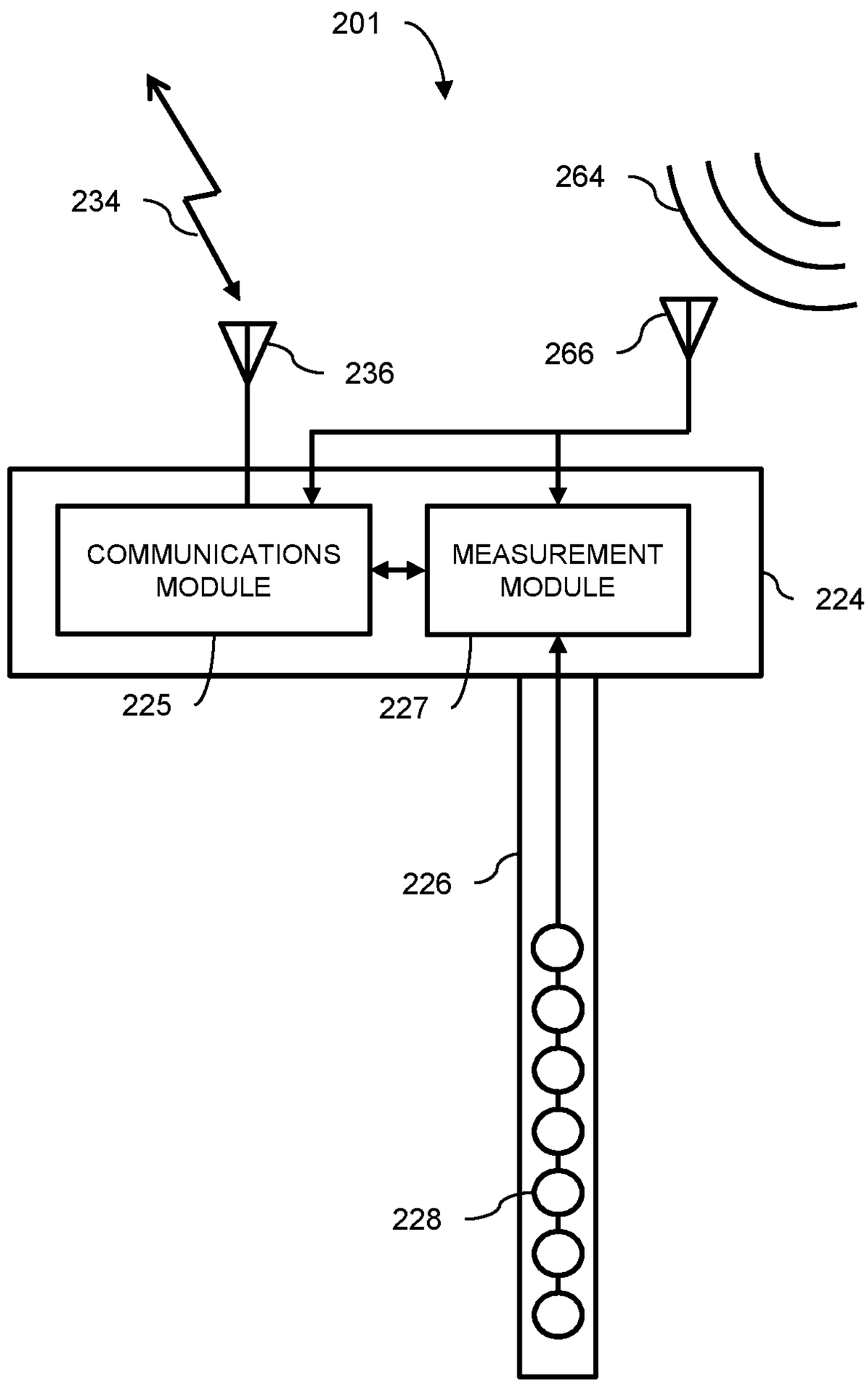

201
234
236
264
266
COMMUNICATIONS MODULE
MEASUREMENT MODULE
224
225
227
226
228

Fig. 3

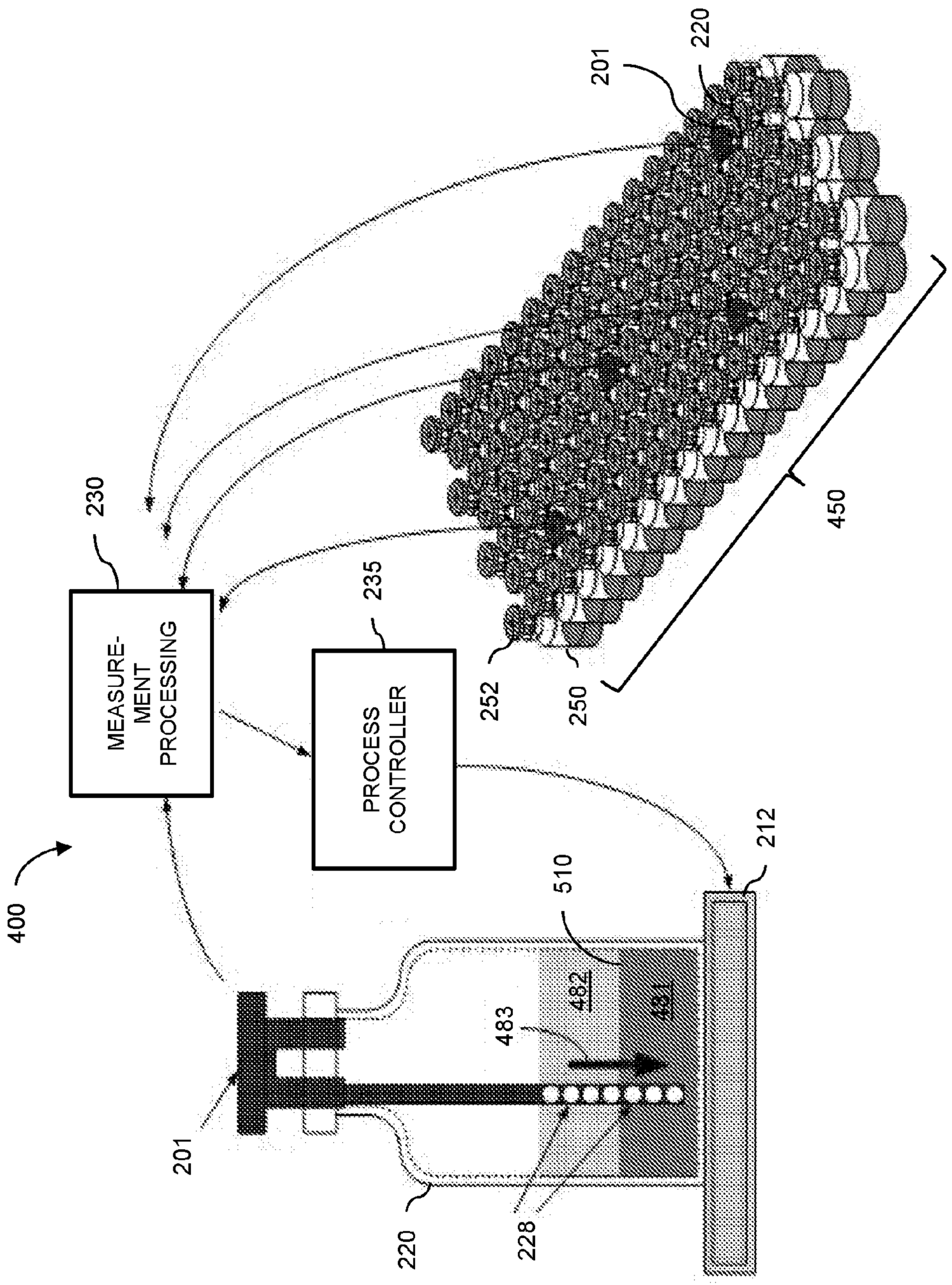

400
MEASURE-MENT PROCESSING
230
PROCESS CONTROLLER
235
201
220
252
250
450
212
510
482
483
491
228

Fig. 4

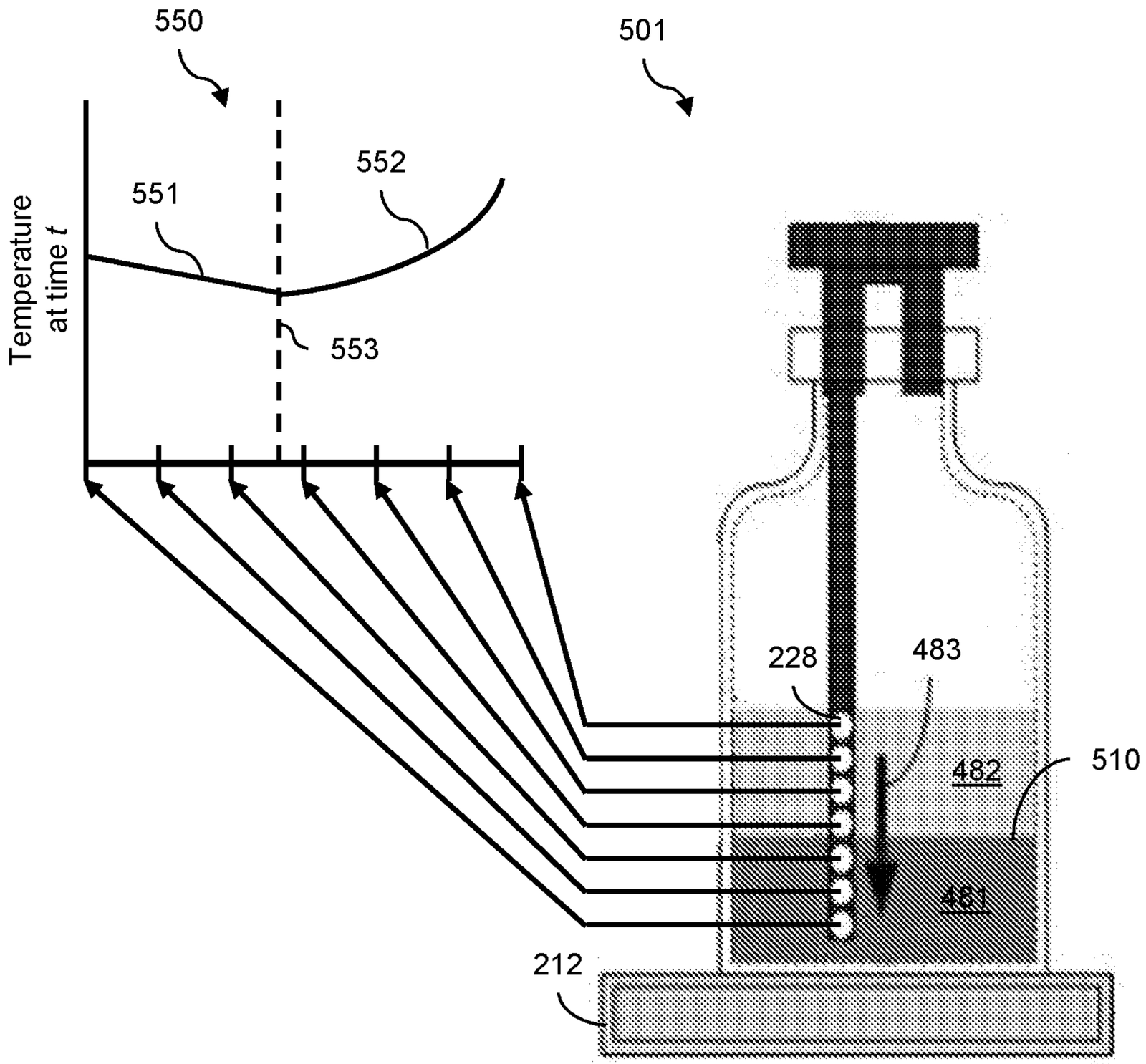

550
501
552
551
Temperature at time t
553
228
483
482
510
461
212

Fig. 5

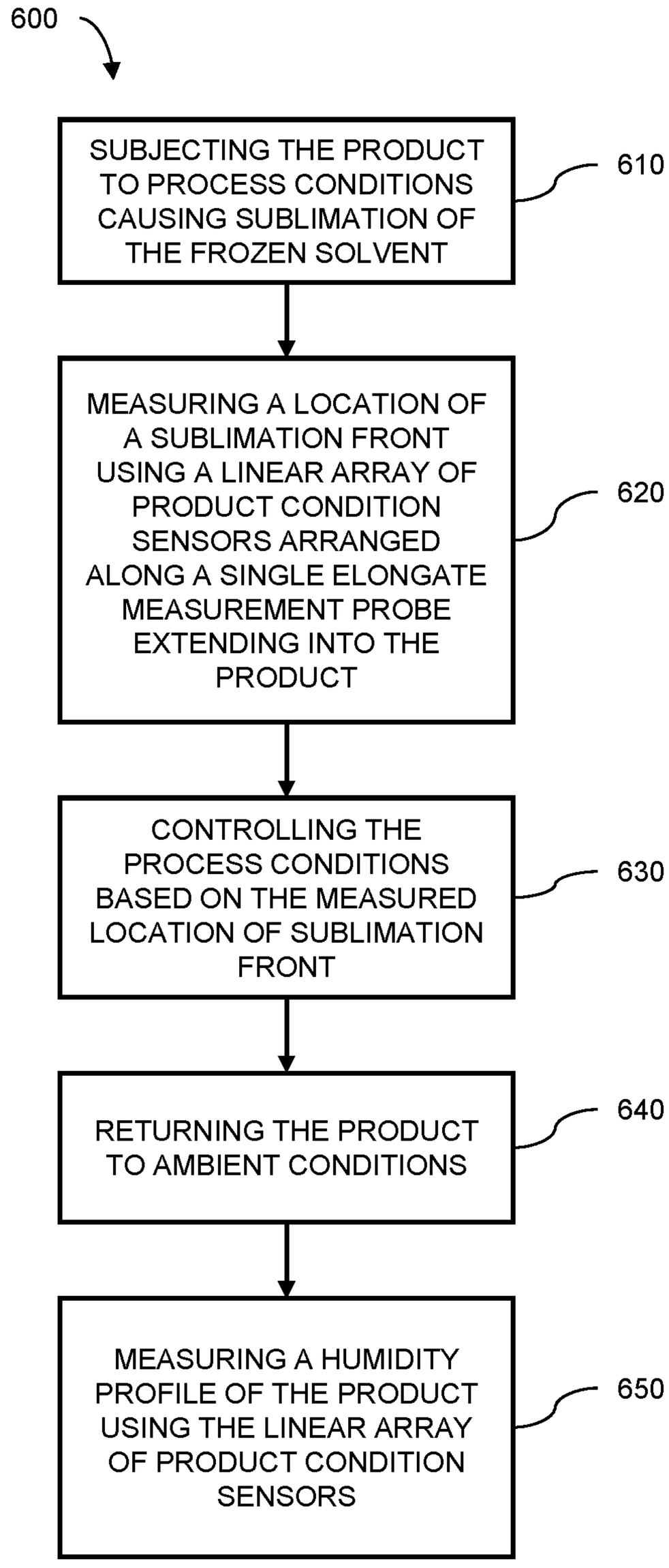

600
SUBJECTING THE PRODUCT TO PROCESS CONDITIONS CAUSING SUBLIMATION OF THE FROZEN SOLVENT
610
MEASURING A LOCATION OF A SUBLIMATION FRONT USING A LINEAR ARRAY OF PRODUCT CONDITION SENSORS ARRANGED ALONG A SINGLE ELONGATE MEASUREMENT PROBE EXTENDING INTO THE PRODUCT
620
CONTROLLING THE PROCESS CONDITIONS BASED ON THE MEASURED LOCATION OF SUBLIMATION FRONT
630
RETURNING THE PRODUCT TO AMBIENT CONDITIONS
640
MEASURING A HUMIDITY PROFILE OF THE PRODUCT USING THE LINEAR ARRAY OF PRODUCT CONDITION SENSORS
650

Fig. 6

PROCESS MONITORING AND CONTROL USING BATTERY-FREE MULTIPOINT WIRELESS PRODUCT CONDITION SENSING

PRIORITY CLAIM

[0001] This application claims the benefit of U.S. Provisional Application No. 62/108,589, filed Jan. 28, 2015, entitled "PROCESS MONITORING AND CONTROL USING BATTERY-FREE MULTIPOINT WIRELESS TEMPERATURE SENSING," and U.S. Provisional Application No. 62/172,829, filed Jun. 9, 2015, entitled "PROCESS MONITORING AND CONTROL USING BATTERY-FREE MULTIPOINT WIRELESS PRODUCT CONDITION SENSING," which are incorporated by reference herein.

FIELD OF THE INVENTION

[0002] The present invention relates to processing and equipment for handling an aseptic product under tightly controlled temperature and humidity conditions. More specifically, the invention relates to the measurement and monitoring of an aseptic process such as a freeze drying process, especially for products such as pharmaceutical products.

BACKGROUND

[0003] Pharmaceutical manufacturing processes are typically carried out in carefully controlled environments. Conditions within those environments must be closely monitored. Those conditions include temperature and humidity, measured both within the product being processed and at selected locations within the controlled environment. As used herein, the term "humidity" refers to absolute humidity, which is the water content of air. Absolute humidity may, for example, be measured as grams of water per cubic meter of air.

[0004] Environmental isolators may be used to maintain carefully controlled aseptic conditions for pharmaceutical processing systems such as container filling systems and packaging systems. The isolators are typically capable of maintaining a "class A" aseptic environment in a surrounding "class C" production room. Such isolators include a dedicated air circuit. Measurements of temperature and humidity at important points within the isolator are necessary to control the air circuit and to monitor for leaks, faults, etc. Temperature and humidity measurements together influence the outcomes of processes taking place in the isolator. Those measurements are made in such isolators using separate sensors.

[0005] Freeze drying is a process that removes a solvent or suspension medium, typically water, from a product. Other solvents, such as alcohol, may also be removed in freeze drying processes.

[0006] In a freeze drying process for removing water, the water in the product is frozen to form ice and, under vacuum, the ice is sublimed and the vapor flows towards a condenser. The water vapor is condensed on the condenser as ice and is later removed from the condenser. Freeze drying is particularly useful in the pharmaceutical and bio-pharmaceutical industries, as the integrity of the product is preserved during the freeze drying process and product stability can be guaranteed over relatively long periods of time. The present disclosure is also applicable to the food industry and other industries with similar requirements. The freeze dried product is ordinarily, but not necessarily, a biological substance.

[0007] Pharmaceutical freeze drying is often an aseptic process that requires sterile and carefully controlled conditions within the freeze drying chamber. It is critical to assure that all components of the freeze drying system coming into contact with the product are sterile.

[0008] Most freeze drying under aseptic conditions is done in a freeze dryer designed for vials, wherein product is contained in vials placed on trays or shelves. In one example of a prior art freeze drying system **100** shown in FIG. **1**, a batch of product is placed in vials **112** arranged on freeze dryer trays **121** within a freeze drying chamber **110**. Freeze dryer shelves **123** are used to support the trays **121** and to transfer heat to and from the trays and the product as required by the process. A heat transfer fluid flowing through conduits within the shelves **123** is used to remove or add heat.

[0009] The product drying chamber is then evacuated using a vacuum pump **150**. Under vacuum, the frozen product in the vials **112** is heated slightly to cause sublimation of the ice within the product. Water vapor resulting from the sublimation of the ice flows through a passageway **115** into a condensing chamber **120** containing condensing coils or other surfaces **122** maintained below the condensation temperature of the water vapor. A coolant is passed through the coils **122** to remove heat, causing the water vapor to condense as ice on the coils.

[0010] Both the freeze drying chamber **110** and the condensing chamber **120** are maintained under vacuum during the process by a vacuum pump **150** connected to the exhaust of the condensing chamber **120**. Non-condensable gases contained in the chambers **110**, **120** are removed by the vacuum pump **150** and exhausted at a higher pressure outlet **152**.

[0011] As the freeze drying process progresses, a sublimation front forms in each vial and moves from the exposed top surface of the product to the bottom of the vial. The sublimation front defines a boundary between freeze dried product above the front, and frozen product containing frozen solvent below the front. In an individual vial, the freeze drying process is complete when the sublimation front reaches the bottom of the vial.

[0012] Accurately monitoring product attributes such as temperature and residual moisture during and after the process is critical to process development and work related to process scale-up, especially in the pharma/bio-pharmaceutical industry. Furthermore, the ability to control product conditions according to critical ranges during production is essential for successfully processing a batch of freeze-dried product. In existing systems, the product temperature is typically monitored by using wired thermocouples that are connected to electrical ports provided in the freeze dryer chamber for that purpose. Product residual moisture is typically measured after the manufacturing process as a destructive test using analytical techniques such as loss on drying or Karl Fischer titration methods.

[0013] Because of the variation in heat transfer among the multiple shelves on which the product vials are placed, the product attributes, including temperature and residual moisture, are position-dependent within the freeze drying chamber. To monitor temperature in an existing system, multiple (typically **8-16**) thermocouples may be used in multiple separate vials in a development cycle to understand that

positional variation. Such a setup, with multiple thermocouple wires across the vials placed in the product chamber, can be cumbersome to handle and can sometimes lead to product loss and/or errors in data collection. To monitor residual moisture, multiple samples are taken at locations throughout the chamber. The testing is time-consuming, and the product in each tested vial is destroyed.

[0014] There is a need for an improved technique for monitoring product conditions both during the development and during production of aseptic, environment-controlled processes such as freeze drying. The technique should eliminate the potential errors and process disruption caused by wired probes, and should be expeditious and non-destructive. The technique should maximize measurement resolution within the volume of the chamber and within the vial. The technique should provide real time data that may be used in controlling a freeze drying process or another process requiring accurate control of conditions.

SUMMARY

[0015] The present disclosure addresses the needs described above by providing an arrangement for monitoring a freeze drying process or another aseptic process, using product condition sensors capable of making closely spaced measurements of a product condition such as temperature or humidity. The measurements are made using closely spaced sensors arranged in a linear array on a single probe, which may be used to take measurements at multiple levels within the product. Data from the sensors is transmitted to a data collection point via short range wireless digital communications. The sensors may be used to measure temperature and humidity at a single point. The location of a sublimation front may be calculated from the measurements.

[0016] Exemplary embodiments of the disclosure feature a product condition measurement unit for measuring a condition profile of a product contained in a product vial being processed in an aseptic pharmaceutical processing chamber. The product condition measurement unit includes a support structure for positioning in an opening of the product vial, and a single elongate probe supported by the support structure and having a plurality of sensors spaced longitudinally along the single elongate probe at incremental distances from the support structure. The product condition measurement unit additionally comprises a processor supported by the support structure and connected for receiving measurements from the plurality of sensors.

[0017] Other embodiments of the present disclosure include a method for freeze drying a product containing a frozen solvent, the product being in a plurality of vials having vial openings and arranged in a freeze drying chamber. The product is subjected to process conditions causing sublimation of the frozen solvent. In a vial of the plurality of vials, while the product is subjected to the process conditions, a location of a sublimation front is measured using a linear array of product condition sensors arranged along a single elongate measurement probe extending into the product, the array having a pitch of less than 2 mm. The process conditions are controlled based on the measured location of sublimation front.

[0018] Additional embodiments of the disclosure include an aseptic pharmaceutical processing system. The system comprises an aseptic enclosure for aseptically isolating an interior of the enclosure from ambient atmosphere, and an environmental control apparatus connected for controlling conditions in the interior of the aseptic enclosure. At least one measurement unit is positioned to measure temperature and humidity in the interior of the aseptic enclosure. The measurement unit is connected for providing measurements to the environmental control apparatus. The measurement unit comprises a sensor and processor for measuring both temperature and humidity at a single location in space.

[0019] The respective features of the exemplary embodiments of the disclosure may be applied jointly or severally in any combination or sub-combination.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] The exemplary embodiments disclosed herein can be understood by considering the following detailed description in conjunction with the accompanying drawings, in which:

[0021] FIG. **1** is a schematic drawing of a current freeze drying system.

[0022] FIG. **2** is a schematic drawing of a freeze drying process monitoring system according to one aspect of the disclosure.

[0023] FIG. **3** is a schematic view of a product condition measurement unit according to one aspect of the disclosure.

[0024] FIG. **4** is a schematic drawing of a freeze drying process monitoring system according to one aspect of the disclosure.

[0025] FIG. **5** is a schematic graph showing a temperature profile within a product vial according to one aspect of the disclosure.

[0026] FIG. **6** is a flow chart showing a method in accordance with one aspect of the disclosure.

DESCRIPTION

[0027] Wireless sensors such as temperature sensors are employed in some current systems as single point monitoring probes in product containment vials. Those sensors may be induction-based sensing systems that are wirelessly excited to determine a resonant frequency that varies with temperature. Other arrangements use thermocouples that communicate with a data acquisition module. Because of the sensing technique and the physical size of those sensors, it is generally feasible to use only a single sensor per sensing probe. Additionally, induction-based sensors operate based on the excitation of a crystal in an electromagnetic field, and induction-based sensors that are placed in proximity tend to interfere with each other, discouraging the use of multiple sensors per vial.

[0028] Wireless capacitive humidity sensors are currently employed as single point monitoring devices typically applied to at- or near-room-temperature applications such as museums, printers and greenhouses.

[0029] A freeze drying system **200** in accordance with embodiments of the present disclosure is shown schematically in FIG. **2**. A product condition measurement unit **201** in accordance with embodiments of the present disclosure is shown schematically in FIG. **3**. Systems in accordance with the disclosure will be described with reference to those figures.

[0030] A freeze drying chamber **210** is connected with equipment (not shown) for evacuating the interior of the chamber **210** and for controlling the temperature of product contained in the chamber, such as by heating a shelf **212**. Product vials **220**, **250** are supported by the shelf **212** and

contain product **221** to be freeze dried. The vial **250** is fitted with a closure **252**. The closure **252** may be in a raised position, as shown, wherein closure legs **253** or other means support the closure in an open condition in the vial opening **251**, allowing solvent vapor to escape during the freeze drying process. After the freeze drying process is completed, the closure is pressed downward to a fully seated position, closing the opening **251**. Standard closures **252** are available in several designs, each with its own geometry and vapor flow characteristics.

[0031] The vial **220** is equipped with a product condition measurement unit **201** (FIGS. **2** and **3**) comprising a support structure **222**, a single elongate probe **226**, a printed circuit board **224** with circuitry as described below, and signal receivers **266**, **236**. A freeze drying system in accordance with embodiments of the disclosure may contain tens of thousands of vials. A selected subset of those vials is fit with product condition measurement units **201**; the remaining vials are closed using standard closures **252**. The subset of vials fit with product condition measurement units **201** is chosen to provide an optimum map of product conditions in the chamber **210**.

[0032] The support structure **222** is designed to match the geometry and vapor flow characteristics of the other closures **252** used in the freeze drying system. In that way, product condition profiles of neighboring vials may be estimated using information from a single instrumented vial.

[0033] A "probe," as that term is used herein, is a single member that is inserted into a product to test conditions at or near the probe. The presently disclosed arrangement utilizes a single elongate probe **226** that supports a plurality of sensors **228** at locations in or near the product **221**. That arrangement provides several advantages. Because the arrangement attempts to estimate conditions in nearby product vials **250** by measuring conditions in the vial **220**, it is critical that the probe itself create a minimum disturbance of characteristics in the vial such as temperature and sublimation rate. By using a single elongate probe **226** to support multiple sensors **228**, disruption of the measured conditions is minimized as compared with the use of multiple probes supporting multiple sensors. Further, because the sensors **228** are supported by the same probe **226**, spacing between the sensors is fixed, thereby increasing the accuracy of a measured profile.

[0034] In one exemplary embodiment of the present disclosure, more than six evenly spaced capacitive sensors monitor product conditions such as temperature and humidity and monitor gradients of those conditions along the product fill in the containment vial **220**. In embodiments, seven sensors may be used. In other embodiments, more than three sensors are used. More or fewer sensors may be used depending on the desired resolution of the measured profile, and on the physical size of the sensors. In embodiments, the sensors **228** may comprise capacitors based on ceramic surface-mount devices. The sensors may require less than 2 mm of space as mounted on a circuit board. Six or more such sensors may therefore be placed in a 12 mm measurement line, permitting the measurement of a profile with relatively high resolution. The sensors may alternatively be integral components of the printed circuit.

[0035] The capacitive sensors **228** may be arranged to make multiple measurements in a linear array having a high spatial resolution. That multi-point sensing capability permits the measurement of a gradient in a small space, such as a small product fill in a vial. The sensors **228**, together with circuitry and signal receivers **266**, **236**, may be mounted on the single printed circuit board **224** that also forms the structural and electrical connection components of the elongate probe **226**.

[0036] A measurement module **227** (FIG. **3**) is included on the printed circuit board **224** and receives measurements from the sensors **228** and converts the measurements to data useable by other components of the freeze drying system. The measurement module **227** may include specialized circuitry for measuring capacitance or another characteristic from the sensors **228**. The measurement module **227** may include a software module of a processor mounted on the printed circuit board for storing values such as calibration values and for converting capacitance measurements into product condition measurements such as temperature measurements and humidity measurements.

[0037] Such temperature measurements may be used in monitoring and controlling a freeze drying process as described below. Additionally, such local humidity measurements of air between particles of the product are reliable indicators of residual moisture in the product, and may therefore be used to measure the efficacy of the freeze drying process.

[0038] A communications module **225** is also included on the printed circuit board **224** and manages the transmission of data from the measurement unit **201** to a measurement processing module **230** located outside the chamber **210**. The communications module **225** performs communications tasks using a sensor sampling protocol such as the ANT™ open access multicast wireless sensor network protocol. Measurements received from the measurement module **227** are wirelessly transmitted by the communications module **225** using a data transmission antenna **266** via a signal **234** utilizing the industrial, scientific and medical (ISM) band (2.4 GHz) of the radio spectrum, and received outside the freeze drying chamber **210** by the measurement processing module **230** via a communications antenna **232**.

[0039] The sensors **228** may be calibrated individually at known product condition calibration points. The resulting calibration coefficients and offsets may be stored on board the measurement unit **201** in the measurement module **227**. Alternatively, calibration information for individual measurement units **201** in the sensor system may be stored with corresponding unit ID codes in a database accessible to the measurement processing module **230** located outside the freeze drying chamber.

[0040] Common temperature/humidity sensing from the same sensing device is possible through simple capacitance-temperature/humidity calibration curves. Thus, by measuring the capacitance, corresponding temperature during a freeze drying process and humidity at the end of the process can be measured using the wireless RF powered devices communicating with data acquisition.

[0041] In accordance with embodiments of the present disclosure, temperature and humidity may be computed from a single capacitance measurement made at a single point in space where a sensor **228** is positioned. The sensors **228** are calibrated to temperature values, and a temperature versus capacitance curve is stored. The sensors **228** are separately calibrated to humidity values at one or more constant temperatures, and those values are stored as humidity versus capacitance curves.

[0042] A capacitance measurement by the sensor **228** is then converted directly into a temperature measurement using the temperature versus capacitance curve. The same capacitance measurement is converted to a humidity reading using the humidity versus capacitance curves.

[0043] The product condition measurement unit **201** utilizes a unique ID code to identify itself to the measurement processing module **230**. Initial loading of the vials **220**, **250** onto the shelves **212** of the freeze drying chamber **210** is done in such a way that the locations of the individual product condition measurement modules **227** are known and tabulated. In an auto loading system using a loading track, positions along the track can be traced to locations on the shelves within the freeze drying chamber **210**. Upon the receipt of a measurement by the measurement processing module **230**, the unique code is then correlated to the location of the identified product condition measurement unit **201** within the chamber **210**, allowing the received product condition measurements to be mapped to that location for analysis and process control.

[0044] Processed measurement data from the measurement processing module **230** is transmitted to other modules for use. For example, the data may be transmitted to a process control module **235** for real-time control of the freeze drying process based on temperature data. Data measured by the same sensors **228** once the process is complete and the chamber is brought back to atmospheric pressure may be used to map humidity as an indicator of residual moisture in the product without the use of destructive testing. The temperature and humidity data may alternatively be transferred to a data analysis module for process development, scaling up and quality analysis.

[0045] The techniques described herein may be performed in part by a discrete processor, an industrial controller or a computer used in conjunction with the described processing equipment. For example, the process control module **235** may reside in a programmable logic controller (PLC) that has operating logic for valves, motors, etc. The measurement processing module **230** may reside in a personal computer (PC) or a PLC or both. Communications with the product condition measurement units **201** may be handled by a USB ANT™ plug-in module that includes an integral communications antenna and firmware for sampling the measurement processing modules and forwarding the received information to the host PC. Such modules may utilize single-chip ANT™ connectivity ICs such as are available from Nordic Semiconductor® of Oslo, Norway. Data acquisition may alternatively be performed by other specialized devices or by using short range communication capabilities of standard devices such as a tablet or a smart phone.

[0046] The measurement units **201**, as well as the PLC and the PC, include central processing units (CPU) and memory. The PLC and the PC also comprise input/output interfaces connected to the CPU via a bus. A PLC is typically connected to the processing equipment via the input/output interfaces to receive data from sensors monitoring various conditions of the equipment such as temperature, position, speed, flow, etc. The PLC is also connected to operate devices that are part of the equipment, such as the vacuum pump **150** (FIG. **1**) and thermal fluid circulation in the shelves **212**.

[0047] The memory may include random access memory (RAM) and read-only memory (ROM). The memory may also include removable media such as a disk drive, tape drive, thumb drive, etc., or a combination thereof. The RAM may function as a data memory that stores data used during execution of programs in the CPU, and is used as a work area. The ROM may function as a program memory for storing a program including the steps executed in the CPU. The program may reside on the ROM, and may be stored on the removable media or on any other tangible, non-transitory computer-readable medium in the PLC or the PC, as computer readable instructions stored thereon for execution by the CPU or other processor to perform the methods disclosed herein.

[0048] The term "computer-readable medium" as employed herein refers to a tangible, non-transitory machine-encoded medium that provides or participates in providing instructions to one or more processors. For example, a computer-readable medium may be one or more optical or magnetic memory disks, flash drives and cards, a read-only memory or a random access memory such as a DRAM, which typically constitutes the main memory. The terms "tangible media" and "non-transitory media" each exclude propagated signals, which are not tangible and are not non-transitory. Cached information is considered to be stored on a computer-readable medium. Common expedients of computer-readable media are well-known in the art and need not be described in more detail here.

[0049] The product condition measurement unit **201** is wirelessly powered via a radio frequency energy harvesting board **266**. A radio frequency powering signal **264** is generated by a radio frequency power signal source **260** and transmitted within the chamber **210** using a powering antenna **262** in the chamber. Multiple powering antennae **262** may be used within the chamber to power a large number of measurement units and to establish line-of-sight communication with all measurement units **201**. The use of wireless radio frequency powering of the measurement units **201** eliminates the need for power wires and batteries, both of which are problematic in a freeze drying process. Because both the communications and the power supplies of the measurement units **201** are wireless, the measurement units may be used in an automatically loaded system wherein locations of the measured vials in the freeze dying chamber are tracked and associated with unique ID codes of the measurement units.

[0050] A process control arrangement **400**, shown in FIG. **4**, demonstrates the use of the product condition measurement units to measure product conditions such as temperatures in a subset of vials and to control the freeze drying process. Of the batch of vials **450** shown in FIG. **4**, only four vials **220** are fitted with product condition measurement units **201**. The remaining vials **250** of the batch **450** are fitted with standard closures **252** such as commercially available stoppers made for that purpose.

[0051] Choosing the locations of the measurement units **201** within the freeze drying chamber may be based on historical measurement data or on qualitative characteristics of the chamber. For example, it may be known that certain locations in the chamber are expected to contain the warmest or coldest vials during a freeze drying cycle, or the most representative vials of the batch **450**, based on data gathered during process development or based on past production data. Vials at those locations are fitted with the measurement units **201**. Measurements taken in the vials **220** fitted with the measurement units **201** are used to control processing conditions for the entire batch **450** of vials.

[0052] Measurement data from the sensors **228** is wirelessly transmitted from the measurement units **201** to the measurement processing module **230**. For each measurement unit **201**, the transmitted data includes a unique ID code that is used by the measurement processing unit **230** to look up a location in the chamber (row, column and shelf) where the measurement was taken.

[0053] The processed data is then transmitted to the process controller **235**. Using the received measurement data from the vials **220**, the process controller **235** can control the freeze drying process in real time to optimize product condition profiles in all the vials in the batch **450**. In the arrangement **400**, the process controller **235** controls the flow of heat transfer fluid to the shelves **212** in the freeze drying chamber, thereby controlling the transfer of heat to the supported vials. For example, the overall flow of heat transfer fluid to the shelves may be controlled based on the temperature within one or more vials **220** in the chamber. Overall shelf temperature in the chamber may be reduced based on the warmest vial in the chamber.

[0054] In another example, the flow of heat transfer fluid to individual shelves or individual regions of shelves is individually controlled. If it is found that sublimation is taking place in vials on a particular shelf at a rate that is behind that of the overall process, the flow rate or temperature of the heat transfer fluid to that particular shelf or region may be adjusted to increase the heat transfer rate from that shelf to the supported vials, and to bring the sublimation rate in those vials back in line with the overall process.

[0055] The tightly arranged capacitive sensors **228** are distributed along the probe **226** (FIG. **3**) to enable the precise measurement of gradients along the product fill in the vials **220**. Each probe contains up to seven or more capacitive sensors, and a large number of measurement units **201** may be deployed (maximum theoretical limit 2^{32}) throughout the load matrix of tens of thousands of vials in the freeze drying chamber.

[0056] As the product dries, a sublimation front **510** propagates through the vial along a drying vector **483** (FIG. **4**). In each vial, the sublimation front **510** separates frozen product **481**, containing frozen water, from dry product **482** wherein the freeze drying process has been completed. As the freeze drying process progresses, the temperature of the front increases due to increasing resistance offered by it to mass transfer of the solvent vapor. Tracking the sublimation front can be a useful process analytical technique to quantify end of drying, or product uniformity characterization, which are critical to process characterization. While the locations of the sublimation fronts are measured only within the vials **220** fitted with measurement units **201**, processing conditions for the entire batch **450** may be controlled based on those measurements.

[0057] Current technology allows measurement of only a single temperature point on a probe, which, in turn, leads to conservative process control because the measurement is not at the ice interface until near the end of the process. In contrast, the presently described technique is capable of providing a high spatial resolution temperature profile along the product fill. That characteristic may be used to advantage in precisely locating the sublimation front during processing.

[0058] In the example process **501** shown in FIG. **5**, a sublimation front **510** is propagating along a drying vector **483**. The sublimation front **510** separates frozen product **481** from dry product **482** during a freeze drying process. A theoretical single scan of product condition measurements, at a given time t, from the sensors **228** is shown in a graph **550**. In the example shown, a temperature profile **551** in the frozen product **481** shows a higher temperature measured by the sensors closer to the shelf **212** and decreasing temperatures toward the line **553** representing the sublimation front **510**. The temperature profile **552** of the dry product **482**, on the other hand, increases with distance from the frozen product below. The temperature profile shown in the graph **550** is merely exemplary, and the exact profile for a given process will vary for different process rates, different product types and different vial geometries.

[0059] It can be seen that an analysis of the temperature profile along the drying vector within a vial will yield a location of the sublimation front. The analysis may comprise, for example, the determination of a maximum, a minimum, a point of inflection, a discontinuity, or another parameter.

[0060] Using current communications technology, the sensors may be sampled at rates up to one sample per microsecond. Multiple samples of a given probe over time may be employed to determine a maximum or a minimum rate of temperature change along the profile, or another time-domain parameter that may be used to locate the sublimation front. The sublimation front in a particular process may therefore be located using a profile-based parameter, a rate-based parameter, or another derived from the temperature measurements. The best parameter to use in a particular process may be determined experimentally.

[0061] A propagation rate of the sublimation front along the drying vector may also be determined and used to control the process.

[0062] Moreover, the same sensing device is capable of measuring humidity as an end-of-process (atmospheric pressure) monitoring tool, using the same capacitive sensors on each probe. For example, once the freeze drying process is complete (and brought back to atmospheric pressure), the humidity in the product is measured by each sensor in the probe, yielding a residual moisture profile of the product in the vial. That is a significant improvement over techniques currently in use for measuring residual moisture. In one such known technique, an overall average residual moisture for all product in a vial is measured after the manufacturing process as a destructive test using analytical techniques such as loss on drying or Karl Fischer titration techniques. Because of the variation in heat transfer across the shelves on which the product is placed, the residual moisture is position dependent. As a result, multiple samples must be taken in a typical development cycle to understand that variation. Such instrumentation and its use is expensive and time consuming. The use of the presently described techniques will help reduce both cost and time associated with such residual moisture tests.

[0063] Embodiments of the present disclosure include a method **600** for freeze drying a product containing a frozen solvent, which is described with reference to FIG. **6**. The product is in a plurality of vials having vial openings and arranged in a freeze drying chamber.

[0064] The product is subjected (operation **610**) to process conditions causing sublimation of the frozen solvent. In addition to vacuum pressure, those conditions typically include low temperature conditions, and the transfer of heat to the vials to provide the energy for sublimation.

[0065] A subset of the plurality of vials may be selected to provide a spatial sampling of measurements in the freeze drying chamber. The subset may be chosen, for example, to include expected warmest and coldest vials in the chamber. During the freeze drying process, as the product is subjected to the process conditions, a location of a sublimation front is measured (operation **620**) using a linear array of product condition sensors arranged along a single elongate measurement probe extending into the product, the array having a pitch of less than 2 mm. The location of the sublimation front may be measured based on a high spatial resolution temperature profile created using the array of product condition sensors.

[0066] The process conditions in the chamber are then controlled (operation **630**) based on the measured location of sublimation front. For example, the plurality of product vials may be arranged on a plurality of shelves having an adjustable heat transfer system for transferring heat to vials supported by the shelves. The temperature and pressure conditions may then be controlled based on the measured locations of the sublimation fronts by adjusting an overall flow of heat transfer fluid to the shelves, or by individually adjusting a transfer of heat from a particular shelf to the supported vials based on a measured location of a sublimation front in a vial located on the particular shelf.

[0067] In one embodiment, the product is then returned to ambient conditions (operation **640**), and, while the product is subjected to the ambient conditions, a humidity profile of the product is measured (operation **650**) using the linear array of product condition sensors. That measurement may be used, for example, to determine residual moisture retained by the product, and thereby evaluate the efficacy of the process.

[0068] The proposed solution can monitor a large number of installed probes simultaneously using a multi-network functionality, and adjust the process conditions, such as heat transfer rate to the vials, based on the warmest probe, or based on a spatial analysis of readings from throughout the chamber, in order to maintain the optimal conditions. The system will also detect for each sensor a rapid temperature shift associated with the passage of the sublimation front, and adjust process control based on output.

[0069] Another identified application of the presently described product condition sensing system is in pharmaceutical applications such as environmental isolators where monitoring temperature and humidity within the barrier system is critical. Isolators provide a fully enclosed environment with dedicated air circuitry, where machines can be segregated, minimizing direct human intervention in the processing area. There is currently no efficient means to measure the temperature and humidity with low spatial resolutions as proposed in the present disclosure. The presently described wireless humidity/temperature sensing device is useful in such applications, which operate at or near atmospheric pressure (atmosphere +/−25 Pa).

[0070] In particular, by utilizing separate calibration values of a single capacitive sensor for temperature and humidity, temperature and humidity may be measured simultaneously at a single point in space. Multiple sensors in an array may be averaged to increase measurement accuracy.

[0071] Although various embodiments that incorporate the teachings of the present invention have been shown and described in detail herein, those skilled in the art can readily devise many other varied embodiments that still incorporate these teachings. The invention is not limited in its application to the exemplary embodiment details of construction and the arrangement of components set forth in the description or illustrated in the drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of "including," "comprising," or "having" and variations thereof herein is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. Unless specified or limited otherwise, the terms "mounted," "connected," "supported," and "coupled" and variations thereof are used broadly and encompass direct and indirect mountings, connections, supports, and couplings. Further, "connected" and "coupled" are not restricted to physical or mechanical connections or couplings.

1. A product condition measurement unit for measuring a condition profile of a product contained in a product vial being processed in an aseptic pharmaceutical processing chamber, comprising:

a support structure for positioning in an opening of the product vial;

a single elongate probe supported by the support structure and having a plurality of sensors spaced longitudinally in a linear array along the single elongate probe at incremental distances from the support structure, the plurality of sensors comprising surface mount sensors mounted on a printed circuit board;

a processor supported by the support structure and connected for receiving measurements from the plurality of sensors.

2. The product condition measurement unit of claim **1**, further comprising:

a radio frequency energy harvesting board connected for powering the processor using a received wireless powering signal.

3. The product condition measurement unit of claim **1**, wherein the condition profile comprises a temperature profile.

4. The product condition measurement unit of claim **1**, wherein the condition profile comprises a humidity profile.

5. The product condition measurement unit of claim **1**, further comprising a measurement processing module configured to convert each one of the measurements to both a temperature measurement and a humidity measurement at a single location in space.

6. The product condition measurement unit of claim **1**, wherein the surface mount sensors comprise ceramic surface mount capacitive sensors.

7. The product condition measurement unit of claim **1**, wherein the processor is mounted on the printed circuit board.

8. The product condition measurement unit of claim **1**, further comprising:

a radio transmitter for transmitting measurement data via a local wireless network.

9. The product condition measurement unit of claim **8**, wherein the processor is configured to transmit a unique ID code of the product condition measurement unit via the local wireless network.

10. The product condition measurement unit of claim **8**, further comprising:

a communications antenna connected to the processor to transmit the measurement data via the local wireless network.

11. The product condition measurement unit of claim **1**, wherein the sensors are spaced less than 2 mm from adjacent sensors along the single elongate probe.

12. The product condition measurement unit of claim **1**, wherein the plurality of sensors comprises more than **6** sensors.

13. A method for freeze drying a product containing a frozen solvent, the product being in a plurality of vials having vial openings and arranged in a freeze drying chamber, the method comprising:

subjecting the product to process conditions causing sublimation of the frozen solvent;

in a vial of the plurality of vials, while the product is subjected to the process conditions, measuring a location of a sublimation front using a linear array of product condition sensors arranged along a single elongate measurement probe extending into the product, the array having a pitch of less than 2 mm, the linear array of product condition sensors comprising surface mount sensors mounted on a printed circuit board; and

controlling the process conditions based on the measured location of sublimation front.

14. The method of the preceding claim, further comprising:

returning the product to ambient conditions; and

in the vial, while the product is subjected to the ambient conditions, measuring a humidity profile of the product using the linear array of product condition sensors.

15. The method of claim **13**, wherein the plurality of product vials is arranged on a plurality of shelves, each individual shelf having an individual adjustable heat transfer system for transferring heat from the shelf to vials supported by the shelf, and wherein controlling the process conditions based on the measured locations of the sublimation fronts further comprises:

regulating an adjustable heat transfer system of a particular shelf on which the vial is located based on the measured location of the sublimation front.

16. The method of claim **13**, further comprising:

powering a product condition measurement unit on the vial using a wireless radio frequency powering signal.

17. The method of claim **13**, further comprising:

transmitting measurement data by a wireless communications transmitter on the vial.

18. The method of claim **13**, wherein the product condition sensors are temperature sensors, the method further comprising:

determining the location of the sublimation front by estimating a product temperature gradient based on temperature measurements of the product.

19. The method of claim **13**, further comprising:

estimating a propagation velocity of the sublimation front based on repeated measurements.

20. An aseptic pharmaceutical processing system, comprising:

an aseptic enclosure for aseptically isolating an interior of the enclosure from ambient atmosphere;

environmental control apparatus connected for controlling conditions in the interior of the aseptic enclosure; and

at least one measurement unit positioned to measure temperature and humidity in the interior of the aseptic enclosure and connected for providing measurements to the environmental control apparatus, the at least one measurement unit comprising a sensor and processor for measuring both temperature and humidity at a single location in space.

21. The aseptic pharmaceutical processing system of the preceding claim, wherein the sensor is a capacitive sensor.

22. The aseptic pharmaceutical processing system of claim **20**, wherein the at least one measurement unit comprises a plurality of sensors arranged on a printed circuit board.

23. The aseptic pharmaceutical processing system of the preceding claim, wherein the plurality of sensors are arranged to measure profiles of temperature and humidity within a product being processed within the aseptic enclosure.

24. The aseptic pharmaceutical processing system of claim **22**, wherein the plurality of sensors are arranged to measure environmental conditions within the aseptic enclosure by averaging measurements from the plurality of sensors.

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