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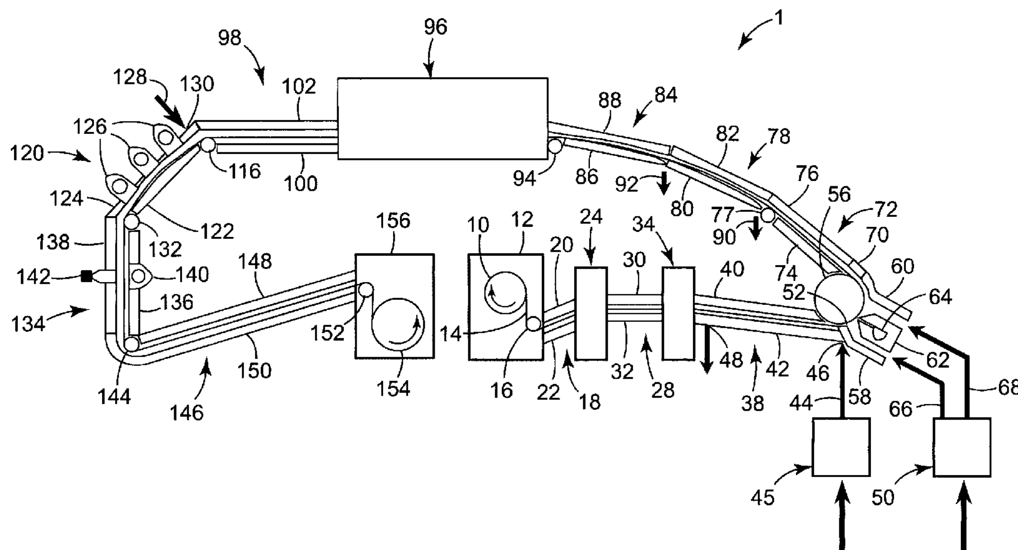
[Continued on next page]

(54) Title: COATING PROCESS AND APPARATUS



(57) Abstract: A web coating process and apparatus employing a coating applicator, dryer or curing station and web-handling equipment for conveying the web (14) past the coating applicator and through the dryer. The web (14) is enclosed from at least the coating applicator to the dryer or curing station in a close-coupled enclosure (72) or series of close-coupled enclosures supplied with one or more streams of conditioned gas flowing at a rate sufficient to reduce materially the particle count or change materially a physical property of interest in a close-coupled enclosure.

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COATING PROCESS AND APPARATUS

Field of the Invention

[0001] This invention relates to coating processes and equipment for treating moving substrates of indefinite length.

Background

[0002] Moving substrates of indefinite length (*viz.*, moving webs) can be coated in controlled environments when ordinary ambient air conditions might disrupt the coating process or pose a safety hazard. Typical controlled environments include clean rooms and the use of inert, low oxygen or saturated atmospheres. Clean rooms and special atmospheres require costly auxiliary equipment and large volumes of filtered air or specialty gases. For example, a typical clean room operation may require many thousands of liters per minute of filtered air.

[0003] Conventional practices for the removal and recovery of components during drying of coated webs generally utilize drying units or ovens. Collection hoods or ports are utilized in both closed and open drying systems to collect the solvent vapors emitted from the web or coating. Conventional open vapor collection systems generally utilize air handling systems that are incapable of selectively drawing primarily the desired gas phase components without drawing significant flow from the ambient atmosphere. Closed vapor collection systems typically introduce an inert gas circulation system to assist in purging the enclosed volume. In either system, the introduction of ambient air or inert gas dilutes the concentration of the gas phase components. Thus the subsequent separation of vapors from the diluted vapor stream can be difficult and inefficient.

[0004] Additionally, the thermodynamics associated with the conventional vapor collection systems often permit undesirable condensation of the vapor at or near the web or coating. The condensate can then fall onto the web or coating and adversely affect either the appearance or functional aspects of the finished product. In industrial settings, the ambient conditions surrounding the process and processing equipment may include extraneous matter. In large volume drying units, the extraneous matter may be drawn into the collection system by the large volumetric flows of conventional drying systems.

Summary of the Invention

[0005] The disclosed invention includes a process and apparatus for coating a moving substrate of indefinite length in a controlled environment using low volumes of filtered air or

specialty gases. The disclosed process and apparatus utilize a close-coupled enclosure that envelopes the moving substrate from at least a coating applicator to a dryer or curing station, the close-coupled enclosure being supplied with one or more streams of conditioned gas flowing at a rate sufficient to reduce materially the close-coupled enclosure particle count. The invention thus provides in one aspect a process for coating a moving substrate of indefinite length comprising conveying the substrate past a coating applicator and to a dryer or curing station in a close-coupled enclosure or series of interconnected close-coupled enclosures while supplying the enclosure or series of enclosures with one or more streams of conditioned gas flowing at a rate sufficient to reduce materially the particle count(s) in a close-coupled enclosure.

[0006] The invention provides in another aspect an apparatus for coating a moving substrate of indefinite length comprising a coating applicator, dryer or curing station and substrate-handling equipment for conveying the substrate past the coating applicator and through the dryer or curing station, the substrate being enveloped from at least the coating applicator to the dryer or curing station in a close-coupled enclosure or series of close-coupled enclosures supplied with one or more streams of conditioned gas flowing at a rate sufficient to reduce materially the particle count(s) in a close-coupled enclosure.

[0007] The invention provides in yet another aspect a process for coating a moving substrate of indefinite length comprising conveying the substrate past a coating applicator and to a dryer or curing station in a close-coupled enclosure or series of interconnected close-coupled enclosures while supplying the enclosure or series of enclosures with one or more streams of conditioned gas flowing at a rate sufficient to cause a material change in a physical property of interest for the atmosphere in a close-coupled enclosure.

[0008] The invention provides in yet another aspect an apparatus for coating a moving substrate of indefinite length comprising a coating applicator, dryer or curing station and substrate-handling equipment for conveying the substrate past the coating applicator and through the dryer or curing station, the substrate being enveloped from at least the coating applicator to the dryer or curing station in a close-coupled enclosure or series of close-coupled enclosures supplied with one or more streams of conditioned gas flowing at a rate sufficient to cause a material change in a physical property of interest for the atmosphere in a close-coupled enclosure.

Brief Description of the Drawing

[0009] The above, as well as other advantages of the disclosed invention will become readily apparent to those skilled in the art from the following detailed description when considered in light of the accompanying drawing in which:

[0010] **Fig. 1** is a schematic side sectional view of a disclosed controlled environment coating apparatus.

[0011] **Fig. 2** is a schematic cross sectional view of a gap dryer.

[0012] **Fig. 3** is a schematic side sectional view of a disclosed close-coupled enclosure.

[0013] **Fig. 4** is a perspective view of a disclosed distribution manifold.

[0014] **Fig. 5** is a partial schematic, partial cross sectional view of the distribution manifold of **Fig. 4** and associated conditioned gas supply and gas withdrawal components.

[0015] **Fig. 6** is a schematic cross sectional view of a transport roll and distribution manifold.

[0016] **Fig. 7** is a schematic side sectional view of another disclosed close-coupled enclosure.

[0017] **Fig. 8** is a schematic cross sectional view of the close-coupled enclosure of **Fig. 7**.

[0018] **Fig. 9** is a schematic side sectional view of another disclosed close-coupled enclosure.

[0019] **Fig. 10** is a schematic plan view of the overlying control surface in **Fig. 9**.

[0020] **Fig. 11** is a graph showing particle count versus pressure in a disclosed close-coupled enclosure.

[0021] **Fig. 12** is a graph showing oxygen level versus pressure in a disclosed close-coupled enclosure.

[0022] **Fig. 13** is a graph showing particle count versus pressure in a disclosed close-coupled enclosure.

[0023] **Fig. 14** is a graph showing pressures at various positions within a disclosed close-coupled enclosure.

[0024] **Fig. 15** is a graph showing pressures at various positions inside and outside a conventional oven.

[0025] **Fig. 16** is a graph showing pressure versus web slot height for a disclosed close-coupled enclosure.

[0026] **Fig. 17** is a graph showing particle count versus web slot height for a disclosed close-coupled enclosure.

[0027] **Fig. 18** is a graph showing particle count versus web speed at various pressures for a disclosed close-coupled enclosure.

[0028] Like reference symbols in the various figures indicate like elements. The elements in the drawing are not to scale.

Detailed Description

[0029] When used with respect to a moving substrate or an apparatus for coating such substrates, the words “downstream” and “upstream” refer respectively to the direction of substrate motion and its opposite direction.

[0030] When used with respect to an apparatus for coating a moving substrate or a component or station in such an apparatus, the words “leading” and “trailing” refer respectively to regions at which the substrate enters or exits the recited apparatus, component or station.

[0031] When used with respect to a moving substrate or an apparatus for coating such substrates, the word “width” refers to the length perpendicular to the direction of substrate motion and in the plane of the substrate.

[0032] When used with respect to an apparatus for coating a moving substrate or a component or station in such an apparatus, the phrase “coating applicator” refers to a device that applies a continuous or discontinuous layer of a coating composition to the substrate.

[0033] When used with respect to an apparatus for coating a moving substrate or a component or station in such an apparatus, the word “dryer” refers to a device that employs heat or other energy to remove one or more volatile liquids from a coating composition.

[0034] When used with respect to an enclosed apparatus for coating a moving substrate or an enclosed component or station in such an apparatus, the phrase “appreciable drying” refers to drying sufficient to render a coating detectably less sensitive to contamination from airborne particulates.

[0035] When used with respect to a moving substrate or an apparatus for coating such substrates, the word “solidification” refers to hardening, curing, crosslinking or other alteration in the coating sufficient to cause a noticeable phase change in at least a portion of the coating.

[0036] When used with respect to an apparatus for coating a moving substrate or a component or station in such an apparatus, the phrase “curing station” refers to a device that employs heat, light, microwaves, electron beam or other energy source to accomplish solidification of a coating composition.

[0037] When used with respect to an enclosed apparatus for coating a moving substrate or an enclosed component or station in such an apparatus, the phrase “appreciable curing” refers to

curing sufficient to render a coating detectably less sensitive to contamination from airborne particulates.

[0038] When used with respect to an apparatus for coating a moving substrate or a component or station in such an apparatus, the phrase "web-handling equipment" refers to a device or devices that transport the substrate through the apparatus.

[0039] When used with respect to an enclosed apparatus for coating a moving substrate or an enclosed component or station in such an apparatus, the phrase "control surface" refers to a surface that is generally parallel to a major face of the substrate and located sufficiently close to the substrate so that an atmosphere that may affect coating quality is present between the control surface and the substrate. A control surface may include for example an enclosure housing, a separate plate, the walls of a slit, or other surface having an appreciable area generally parallel to a major face of the substrate.

[0040] When used with respect to an enclosed apparatus for coating one or both sides of a moving substrate or an enclosed component or station in such an apparatus, the word "headspace" refers to the distance from the substrate to a nearby control surface measured on the coated side perpendicular to the substrate.

[0041] When used with respect to an enclosed apparatus for coating one side of a moving substrate or an enclosed component or station in such an apparatus, the word "footspace" refers to the distance from the substrate to a nearby control surface measured on the uncoated side perpendicular to the substrate.

[0042] When used with respect to an enclosed apparatus for coating a moving substrate or an enclosed component or station in such an apparatus, the phrase "close-coupled enclosure" refers to an enclosure whose average headspace plus average footspace throughout the enclosure is no greater than about 30 cm and that at its upstream or downstream end is sealed with respect to the substrate or connected to a cabinet, enclosed component, enclosed station or other enclosure.

[0043] When used with respect to an enclosed apparatus for coating one side of a moving substrate or an enclosed component or station in such an apparatus, the word "overlying" refers to an apparatus, component or station on the coated or to be coated side of the substrate.

[0044] When used with respect to an enclosed apparatus for coating one side of a moving substrate or an enclosed component or station in such an apparatus, the word "underlying" refers to an apparatus, component or station on the uncoated side of the substrate.

[0045] When used with respect to an enclosed apparatus for coating a moving substrate or an enclosed component or station in such an apparatus, the phrase "conditioned gas" refers to gas that is different from the ambient air surrounding the apparatus in at least one property of interest.

[0046] When used with respect to an enclosed apparatus for coating a moving substrate or an enclosed component or station in such an apparatus, the phrase "particle count" refers to the number of 0.5 µm or larger particles in a volume of 28.3 liters.

[0047] When used with respect to a physical property of interest (e.g., the particle count) for the atmosphere in an enclosed apparatus for coating a moving substrate or an enclosed component or station in such an apparatus, the word "material" refers to at least a 50% reduction or increase in the property of interest compared to the ambient air surrounding the apparatus, component or station.

[0048] When used with respect to an enclosed apparatus for coating a moving substrate or an enclosed component or station in such an apparatus, the phrase "negative pressure" refers to pressure below that of the ambient air surrounding the apparatus, component or station, and the phrase "positive pressure" refers to a pressure above that of the ambient air surrounding the apparatus, component or station.

[0049] When used with respect to an apparatus for coating a moving substrate or a component or station in such an apparatus, the phrase "pressure gradient" refers to a pressure differential between an interior portion of the apparatus, component or station and that of the ambient air surrounding the apparatus, component or station.

[0050] A webline **1** employing a nearly end-to-end implementation of the disclosed close-coupled enclosure is shown in **Fig. 1**. Unwind reel **10** and takeup reel **154** are located inside cabinets **12** and **156**. Cabinets **12** and **156** typically do not benefit from employing a close-coupled enclosure, and instead desirably have a sufficiently roomy and uncluttered interior to house large uncoated or coated web rolls and permit easy roll changeover and transport. Cabinets **12** and **156** may be unventilated, ventilated with ambient air, or supplied with a suitable conditioned gas stream as desired. Uncoated web **14** passes from unwind reel **10** over transport roll **16** and into a first close-coupled enclosure **18** whose operation is explained in more detail below. Close-coupled enclosure **18** includes underlying control surface **20** and overlying control surface **22** which each lie in close proximity to the major surfaces of web **14**. Web **14** next passes into web cleaning apparatus **24**. Apparatus **24** may employ any of a variety of methods that will be familiar to those skilled in the art (e.g., plasma treatment or tacky rolls)

to remove unwanted debris, surface oils or other contaminants from at least one surface of web **14**. Apparatus **24** may be unventilated or supplied with a suitable conditioned gas stream as desired. In the latter instance the conditioned gas may flow upstream or downstream into neighboring enclosures. Web **14** next passes from cleaning apparatus **24** through a second close-coupled enclosure **28** whose underlying control surface **30** and overlying control surface **32** lie in close proximity to the major surfaces of web **14**, and into priming apparatus **34**. Apparatus **34** may employ any of a variety of methods that will be familiar to those skilled in the art (e.g., corona treatment) to make at least one surface of web **14** receptive to a subsequently-applied coating. Apparatus **34** may be unventilated or supplied with a suitable conditioned gas stream as desired. In the latter instance the conditioned gas may flow upstream or downstream into neighboring enclosures.

[0051] The cleaned and corona-treated web **14** next passes from corona treater **34** through a third close-coupled enclosure **38** whose underlying control surface **40** and overlying control surface **42** lie in close proximity to the major surfaces of web **14**. Close-coupled enclosure **38** may be supplied with a conditioned gas stream **44** that flows into close-coupled enclosure **38** through downstream inlet **46** and exits through upstream outlet **48**. Conditioned gas stream **44** differs from the ambient air in at least one property of interest, e.g., a different chemical composition due to the absence or presence of one or more gases (including humidity), a different (e.g., lower) particle count, or a different temperature. For example, humidifier/dehumidifier **45** may be used to alter the moisture content of conditioned gas stream **44** and to add or remove moisture to or from web **14**.

[0052] Web **14** next moves past seal **52** and into a fourth close-coupled enclosure **54**. Close-coupled enclosure **54** is bounded in part by seal **52**, backing roll **56** and lower and upper clamshell housings **58, 60**, thereby forming a die enclosure system. Further details regarding die enclosure systems may be found in U.S. Patent No. 6,117,237 (Yapel et al.), the disclosure of which is incorporated herein by reference. Coating die **62** applies one or more layers of coating material **64** to one major side of web **14**. The other major side of web **14** contacts backing roll **56**. Backing roll **56** may be heated using an appropriate temperature control system (not shown in **Fig. 1**), to provide, for example, improved applied coating quality or improved solidification control. Close-coupled enclosure **54** is supplied with conditioned gas streams **66, 68**. Use of a vacuum (not shown in **Fig. 1**) upstream from coating die **62** in addition to conditioned gas stream **66** may help stabilize the applied coating. An inspection or measurement station **70** located downstream from coating die **62** (e.g., at or near the trailing edge of upper housing **60**),

may be in the form of a transparent viewing window and illumination device for the operator to monitor coating quality, or may be any of a number of other devices or instruments that will be familiar to those skilled in the art.

[0053] Following coating deposition the coating will undergo wetting, spreading and eventual solidification. Solidification may be brought about, for example, by measures including chilling, heating, reaction, or drying. Appropriate control of these processes and the avoidance of coating contamination or disturbance can be facilitated through the use of one or more additional close-coupled enclosures. For example, web **14** may pass from backing roll **56** to transport roll **77** through a fifth close-coupled enclosure **72** whose underlying control surface **74** and overlying control surface **76** lie in close proximity to the major surfaces of web **14** in a "flat" gap arrangement. Close-coupled enclosure **72** may be supplied with a separate conditioned gas stream (not shown in **Fig. 1**) that flows into close-coupled enclosure **72** through an inlet (not shown in **Fig. 1**). A separate conditioned gas stream may not be needed in close-coupled enclosure **72**. For example, close-coupled enclosure **72** may simply receive a portion of the conditioned gas stream **68** that moves between web **14** and housing **60** in the direction of motion of web **14**. Close-coupled enclosure **72** may be, for example, a leveling zone that allows a non-uniformly applied coating to spread and self-level. The operating conditions in such a leveling zone typically will be set to minimize the drying rate by minimizing mass transfer from the coating surface to the surrounding close-coupled enclosure (e.g., by controlling the conditioned gas velocity, humidity or temperature). This acts to keep the coating viscosity low and provides assistance in leveling non-uniformities in the coated film. In some processes it may be desirable to carry out solidification as fast as possible before flow-induced uniformities can form. In such processes the close-coupled enclosure zone operating conditions downstream from the coater may be set for high drying rates. Close-coupled enclosure **72** may also be configured to add an additional component or layer to the coating, or to provide a dry environment that may discourage "blushing" in the coating.

[0054] Further controlled drying or solvent recovery may be accomplished using sixth and seventh close-coupled enclosures **78, 84** whose respective underlying control surfaces **80, 86** and overlying control surfaces **82, 88** lie in close proximity to the major surfaces of web **14**. Close-coupled enclosures **78, 84** may be gap drying systems such as those described in U.S. Patent Nos. 4,980,697, 5,581,905, 5,694,701, 5,813,133, 6,047,151 and 6,134,808. When close-coupled enclosures **78, 84** are gap drying systems, then condensed solvent streams **90, 92** can be collected at the lower ends of close-coupled enclosures **78, 84**.

[0055] **Fig. 2** shows a schematic cross-sectional view of gap dryer **200**. Dryer **200** has a hot plate **202** and cold plate **204** separated by a small gap **G**. Web **206** bearing coating **208** may be dried by passing it over hot plate **202** which supplies energy to evaporate solvents from coating **208**. Cold plate **204** provides a driving force for condensation and solvent vapor transport across gap **G**. Cold plate **204** is provided with a structured (e.g., grooved) surface **210** that prevents the condensed solvent liquid from dripping back onto the coated surface. Instead, the condensed solvent streams **212** are "pumped" off cold plate **204** and into collection troughs **214**, which may be connected to a solvent recovery system (not shown in **Fig. 2**). Thus both drying and solvent recovery may occur simultaneously as web **206** is transported through gap **G**. Transport of a web through such a gap drying system may be facilitated by employing radiused plate web floatation as described in U.S. Patent No. 6,511,708 (Kolb et al.). Web floatation over radiused plates can provide a controllable and scratch-free system for supporting and heating a moving substrate while minimizing (e.g., to 4 mm or less) the footspace.

[0056] Referring again to **Fig. 1**, web **14** exits close-coupled enclosure **84** and passes from transport roll **94** to transport roll **116** through conventional drying oven **96** where heat transfer to web **14** and solidification of its coating may be accomplished by, for example, one or more of convection, conduction or radiation. If desired, multiple temperature zones and controls may be employed in oven **96** to enable timely temperature adjustment of web **14** and its coating. Web **14** next passes through a transition zone in the form of an eighth close-coupled enclosure **98**. Close-coupled enclosure **98** has an underlying control surface **100** and overlying control surface **102** which lie in close proximity to the major surfaces of web **14** in a flat gap arrangement. Web **14** exits close-coupled enclosure **98** and passes over transport roll **116**.

[0057] Some coated substrates require drying, curing or a combination of both drying and curing. Curing may be performed using a variety of mechanisms and curing stations that will be familiar to those skilled in the art (e.g., by using UV radiation to cure a 100% solids or solvent-borne (e.g., waterborne) coating composition). Curing may be accomplished in a ninth close-coupled enclosure **120** whose underlying control surface **122** and overlying control surface **124** lie in close proximity to the major surfaces of web **14**. UV lamps **126** are integrated into overlying control surface **124**. If required, close-coupled enclosure **120** may be supplied with an inert gas stream **128** through inlet **130**. If required, temperature control during curing can accomplished through appropriate selection or control of the heat transfer properties of components in close-coupled enclosure **120** such as underlying control surface **122**. Curing could also be carried out prior to drying in oven **96** or at other locations within the disclosed web

handling process, or, depending on the nature of the coating composition, dispensed with entirely. Drying could likewise, depending on the nature of the coating composition, be dispensed with entirely.

[0058] Web **14** next passes over transport rolls **132, 144** through a tenth close-coupled enclosure **134** whose underlying control surface **136** and overlying control surface **138** lie in close proximity to the major surfaces of web **14**. A light source **140** and camera or measuring instrument **142** (or other measuring or inspection devices that will be familiar to those skilled in the art) are respectively integrated into underlying control surface **136** and overlying control surface **138**.

[0059] Web **14** may be passed over transport rolls **144, 152** through an eleventh close-coupled enclosure **146** whose underlying control surface **148** and overlying control surface **150** lie in close proximity to the major surfaces of web **14**. Close-coupled enclosure **146** may serve as an equilibration zone to adjust web **14** and its solidified coating to one or more desired conditions (e.g., temperature, humidity or web tension) prior to roll formation at takeup reel **154**.

[0060] The disclosed process and apparatus do not need to employ all the close-coupled enclosures shown in **Fig. 1**, and may employ different close-coupled enclosures or processes than those shown or more close-coupled enclosures or processes than those shown. Two or more of the disclosed close-coupled enclosures may be interconnected in series in a web process thereby creating multiple successive zones or applications. Each individual close-coupled enclosure may be operated at different pressures, temperatures and headspace or footspace gaps to address process and material variants. Individual close-coupled enclosures may have none, one or more than one conditioned gas inputs or gas withdrawal devices. A positive pressure could be maintained or established in some close-coupled enclosures and a negative pressure in other close-coupled enclosures. Use of interconnected close-coupled enclosures is recommended from at least the point of coating application (e.g., from the trailing edge of the coating bead when a coating die is employed) up to at least a station at which appreciable drying or appreciable curing occurs. Such interconnection can provide continuous protection that may discourage contamination of the unsolidified coating and facilitate control of the particle count in the atmosphere immediately surrounding the coated substrate while using only small volumes of conditioned gases. Additional control of coating conditions can be achieved by employing a close-coupled enclosure from at least the point of coating application through at least a station at which appreciable drying or appreciable curing occurs. Further control of coating conditions can be achieved by employing a close-coupled enclosure from at least the point of coating

application up to at least the last drying or curing station in the process. Additional control can also be achieved by employing a close-coupled enclosure from a pre-coating station (e.g., a cleaning or priming station) up to the point of coating application. In one exemplary embodiment the coated substrate is not exposed to ambient air from at least the time the coating is applied until after the coating has solidified. The disclosed apparatus may also include one or more sections that do not represent a close-coupled enclosure, but desirably the number, total volume and gas flow patterns of such sections is such that undesirable contamination of the substrate does not arise.

[0061] If desired, conditioned gas streams could be injected (or gas could be withdrawn) at more or fewer locations along webline **1** than are shown in **Fig. 1**. In one exemplary embodiment, a conditioned gas stream could be injected at the first of several interconnected close-coupled enclosures, and the conditioned gas could be carried along with the moving substrate to the downstream close-coupled enclosures or pushed to an upstream enclosure or process. In another exemplary embodiment, conditioned gas streams could be injected wherever needed to maintain or establish a slight positive pressure in each of several interconnected close-coupled enclosures. In yet another exemplary embodiment, conditioned gas streams could be injected where needed to maintain or establish a slight positive pressure in some of several interconnected close-coupled enclosures, and a slight negative or zero pressure could be maintained or established in other interconnected close-coupled enclosures. In yet another exemplary embodiment, conditioned gas streams could be injected at each of several interconnected close-coupled enclosures.

[0062] A cleanroom could optionally surround webline **1**. However, this could be of a much lower classification and much smaller volume than that which might typically be used today. For example, the cleanroom could be a portable model using flexible hanging panel materials. A similar cleanroom could be used in addition to or in place of cabinets **12** and **156** in **Fig. 1**.

[0063] Those skilled in the art will appreciate that the disclosed apparatus could readily be adapted to coat both major surfaces of a moving substrate. Those skilled in the art will also appreciate that a variety of coating devices may be used, including roll coaters, slide coaters, bath coaters, spray coaters, fluid bearing coaters and the like. Also, a variety of web support systems that will be familiar to those skilled in the art may be employed in the disclosed process and apparatus, including porous air tubes, air bars, and air foils.

[0064] In addition to or in place of the cleaning and priming operations shown in **Fig. 1**, a variety of other dry converting operations may be employed in the disclosed apparatus and

process, such as the dry converting operations described in copending U.S. Patent Application Serial No. (Attorney docket number 55752US019), filed even date herewith and entitled "DRY CONVERTING PROCESS AND APPARATUS".

[0065] In one embodiment of the disclosed process, a moving substrate of indefinite length has at least one major surface with an adjacent gas phase. The substrate is treated with an apparatus having a control surface in close proximity to a surface of the substrate to define a control gap between the substrate and the control surface. The control gap may be referred to as the "headspace" for a control gap between a coated (or to be coated) side of a substrate and a control surface, and as the "footspace" for a control gap between an uncoated side of a substrate and a control surface.

[0066] A first chamber may be positioned near a control surface, with the first chamber having a gas introduction device. A second chamber may be positioned near a control surface, the second chamber having a gas withdrawal device. The control surface and the chambers together define a region wherein the adjacent gas phases possess an amount of mass. At least a portion of the mass from the adjacent gas phases is transported through the gas withdrawal device by inducing a flow through the region. The mass flow can be segmented into the following components:

M1 means total net time-average mass flow per unit of substrate width into or out of the region resulting from pressure gradients,

M1' means the total net time-average mass flow of a gas per unit width into the region through the first chamber from the gas introduction device,

M2 means the time-average mass flow of conditioned gas per unit width from or into the at least one major surface of the substrate or coating into or from the region,

M3 means total net time-average mass flow per unit width into the region resulting from motion of the material, and

M4 means time-average rate of mass transport through the gas withdrawal device per unit width, where

"time-average mass flow" is represented by the equation $MI = \frac{1}{t}\int_0^t mi\,dt$, wherein MI is the time-average mass flow in kg/second, t is time in seconds, and mi is the instantaneous mass flow in kg/second.

The mass flow in the gas phase is represented by the equation:

$$\mathbf{M1 + M1' + M2 + M3 = M4} \qquad \text{(Equation A).}$$

[0067] **M1**, **M1'**, **M2**, **M3** and **M4** are further illustrated in **Fig. 3**. **Fig. 3** is a schematic side sectional view of a close-coupled enclosure **300**. A substrate **312** has at least one major surface **314** with an adjacent gas phase (not shown in **Fig. 3**). The substrate **312** is in motion in the direction of arrow "**V**" under a control surface **315**, thus defining a control gap "G_C". A first chamber **317** having a gas introduction device **318** is positioned near the control surface **315**. The exact form of the gas introduction device **318** may vary, and expedients such as a gas knife, a gas curtain, or a gas manifold can be used. While the illustrated embodiment depicts first chamber **317** in the form of a plenum, it is not necessary that the gas introduction device **318** be positioned at a remove from the level of control surface **315**. A second chamber **319** is also positioned near the control surface **315**, and has a gas withdrawal device **320**. Once again, while the illustrated embodiment depicts the second chamber **319** in the form of a plenum, it is not necessary that the gas withdrawal device **320** be positioned at the level of control surface **315**. In an exemplary embodiment, the first chamber **317** and the second chamber **319** will be at opposing ends of the control surface **315** as depicted in **Fig. 3**. The first chamber **317** defines a first gap **G1** between the first chamber **317** and the substrate **312**. The second chamber **319** defines a second gap **G2** between the second chamber **319** and the substrate **312**. In some embodiments, the first gap **G1**, the second gap **G2**, and the control gap G_C are all of equal height, however in other embodiments, at least one of the first gap **G1** or the second gap **G2** has a height different than the control gap G_C. Best results appear to be achieved when the first gap, second gap and control gap are all 10 cm or less. In some exemplary embodiments the first gap, the second gap, and the control gap are all 5 cm or less, 3 cm or less, or even smaller values, e.g., 2 cm or less, 1.5 cm or less, or 0.75 cm or less. The airflow required to attain a desired low particle count may vary in part with the square of the combined headspace and footspace, and accordingly the disclosed gaps desirably have relatively small values. Similarly, best results appear to be achieved when the total of the average headspace and average footspace is 10 cm or less, 5 cm or less, 3 cm or less, or even smaller values, e.g., 2 cm or less, 1.5 cm or less, or 0.75 cm or less.

[0068] In addition to gaps G_C, **G1** and **G2**, the dilution of the vapor component may also be minimized by using mechanical features, such as extensions **323** and **325** in **Fig. 3**. The extensions **323** and **325**, having gaps **G3** and **G4**, may be added to one of both of the upstream or downstream ends of the apparatus. Those skilled in the art will recognize that the extensions may be affixed to various members of the apparatus or provided with alternate shapes depending on the specific embodiment selected for a particular purpose. Dilution will generally be reduced

as the substrate area "covered" by the extensions increases. The adjacent gas phase between the control surface **315**, first chamber **317**, second chamber **319** and the surface **314** of the substrate **312** define a region possessing an amount of mass. The extensions **323** and **325** may further define the region under the control surface having an adjacent gas phase possessing an amount of mass. The mass in the region is generally in a gas phase. However, those skilled in the art will recognize that the region may also contain mass that is in either the liquid or solid phase, or combinations of all three phases.

[0069] **Fig. 3** depicts the various flow streams encountered in close-coupled enclosure **300** when practicing the disclosed process. **M1** is the total net time-average mass flow per unit width into or out of the region resulting from pressure gradients. **M1** is a signed number, negative when it represents a small outflow from the region as the drawing depicts, and positive when it represents a small inflow into the region, opposing the depicted arrows. Positive values of **M1** essentially represent a dilution stream and possible source of contaminants that desirably are reduced and more desirably are made negative for the overall portion of the apparatus constituting interconnected close-coupled enclosures. **M1'** is the total net time-average mass flow of conditioned gas per unit width into the region from gas introduction device **318**. If brought to a sufficient level, **M1'** reduces the particle count in the close-coupled enclosure. **M1'** can provide a sufficient improvement in the cleanliness of major surface **314** that the dilution **M1'** engenders can be tolerated. Excessively high **M1'** flows desirably are avoided in order to limit disturbance of coating **314**. **M2** is the time-average mass flow per unit width from or into at least one major surface of the substrate or coating into the region and through the chamber. **M2** essentially represents evolution of solvent or other material into close-coupled enclosure **300**. **M3** is the total net time-average mass flow per unit width into the region and through the chamber resulting from motion of the substrate. **M3** essentially represents gas swept along with the substrate in its motion. **M4** is the time-average rate of mass transported per unit width through the gas withdrawal device **320**. **M4** represents the sum of **M1** + **M1'** + **M2** + **M3**.

[0070] Mass flow through a close-coupled enclosure may be assisted by employing a suitable seal with respect to the moving substrate (*viz.*, a "moving substrate seal") at an upstream or downstream inlet or outlet of a close-coupled enclosure or connected chain of close-coupled enclosures. The seal may function as a sweep to prevent gas from entering or exiting the close-coupled enclosures. A coating head can provide a built-in liquid seal where the coating bead contacts the substrate. The seal could also include for example a forced gas, mechanical or retractable mechanical seal such as those shown in U.S. Patent No. 6,553,689, or a pair of

opposed nip rolls. A retractable mechanical sealing mechanism can allow passage of overly thick coatings, splices and other upset conditions. It may be desirable briefly to increase one or more nearby conditioned gas flow rates (or to decrease or switch one or more nearby gas withdrawal rates) to maintain the desired atmosphere near the seal. A pair of opposed nip rolls may be located for example, upstream from the coating device or downstream from the point at which the coating has sufficiently solidified to withstand (or benefit from) nip roll compression.

[0071] By using a control surface in close proximity to the substrate surface, a supply of conditioned gas and a positive or small negative pressure gradient, a material particle count reduction may be obtained within a close-coupled enclosure. The pressure gradient, **Δp**, is defined as the difference between the pressure at the chamber's lower periphery, **pc**, and the pressure outside the chamber, **po**, wherein **Δp=pc-po**. Through appropriate use of conditioned gas and adjustment of the pressure gradient, particle count reductions of, for example, 50% or more, 75% or more, 90% or more or even 99% or more may be achieved. An exemplary pressure gradient is at least about -0.5 Pa or higher (*viz.*, a more positive value). Another exemplary pressure gradient is a positive pressure gradient. As a general guide, greater pressures can be tolerated at higher moving substrate speeds. Greater pressures can also be tolerated when moving substrate seals are employed at the upstream and downstream ends of a series of interconnected close-coupled enclosure. Those skilled in the art will appreciate that the close-coupled enclosure pressure(s) may be adjusted based on these and other factors to provide a desirably low particle count within appropriate portions of the disclosed apparatus while avoiding undue disturbance in the unsolidified coating.

[0072] The disclosed process and apparatus may also substantially reduce the dilution gas flow, **M1**, transported through the chamber. The disclosed process and apparatus may, for example, limit **M1** to an absolute value not greater than 0.25 kg/second/meter. **M1** may be, for example, less than zero (in other words, representative of net outflow from the close-coupled enclosure) and greater than -0.25 kg/second/meter. In another exemplary embodiment, **M1** may be less than zero and greater than -0.1 kg/second/meter. As is shown in the examples below, small negative enclosure pressures (which may correspond to slight positive **M1** flows) can be tolerated. However, large negative enclosure pressures (which may correspond to large positive **M1** flows) may cause adverse effects including dilution of mass in the adjacent gas phase, introduction of particles and other airborne contaminants, and introduction of uncontrolled ingredients, temperatures or humidity.

[0073] In one exemplary embodiment we control a process by appropriately controlling **M1'** and **M4**. A deliberate influx of a conditioned gas stream (e.g., a clean, inert gas having a controlled humidity) can materially promote a clean, controlled atmosphere in the close-coupled enclosure without unduly increasing dilution. By carefully controlling the volume and conditions under which **M1'** is introduced and **M4** is withdrawn (and for example by maintaining a slight positive pressure in the close-coupled enclosure), flow **M1** can be significantly curtailed and the close-coupled enclosure particle count can be significantly reduced. Additionally, the **M1'** stream may contain reactive or other components or optionally at least some components recycled from **M4**.

[0074] The close proximity of control surfaces in the close-coupled enclosure to the substrate major surfaces, and the relatively small pressure gradient, enable the transport of the mass in the adjacent gas phase through the close-coupled enclosure with minimal dilution. Thus lower flow rates at higher concentrations may be transported and collected. The disclosed process is also suitable for transporting and collecting relatively small amounts of mass located in the adjacent gas phase.

[0075] The headspace or footspace may be substantially uniform from the upstream end to the downstream end and across the width of the close-coupled enclosure. The headspace or footspace may also be varied or non-uniform for specific applications. The close-coupled enclosure may have a width wider than the substrate and desirably will have closed sides that further reduce time-average mass flow per unit width from pressure gradients (**M1**). The close-coupled enclosure can also be designed to conform to different geometry material surfaces. For example, the close-coupled enclosure can have a radiused periphery to conform to the surface of a cylinder.

[0076] The close-coupled enclosure may also include one or more mechanisms to control the phase of the mass transported through the close-coupled enclosure thereby controlling phase change of the components in the mass. For example, conventional temperature control devices may be incorporated into the close-coupled enclosure to prevent condensate from forming on the internal portions of the close-coupled enclosure. This may help discourage blushing in the solidified coating. Non-limiting examples of suitable temperature control devices include heating coils, electrical heaters, external heat sources and heat transfer fluids.

[0077] Optionally, depending upon the composition of the gas phase composition, the withdrawn gas stream (**M4**) may be vented or filtered and vented after exiting the close-coupled enclosure. The disclosed process may be used for the continuous collection of a gas phase

composition. The gas phase composition may flow from one or more of the close-coupled enclosures to a subsequent processing location, e.g., without dilution. The subsequent processing may include such optional steps as, for example, separation or destruction of one or more components in the gas phase. The collected vapor stream may also contain a liquid phase mixture or particulate matter which can be filtered prior to the separation process. Separation processing may also occur internally within the close-coupled enclosure in a controlled manner. Suitable separation processes will be familiar to those skilled in the art and include concentration of the vapor composition in the gaseous stream; direct condensation of the dilute vapor composition in the gaseous stream; direct condensation of the concentrated vapor composition in the gaseous stream; direct two stage condensation; adsorption of the dilute vapor composition in the gaseous stream using activated carbon or synthetic adsorption media; adsorption of the concentrated vapor composition in the gaseous stream using activated carbon or synthetic adsorption media; absorption of the dilute vapor phase component in the gaseous stream using media with high absorbing properties; and absorption of the concentrated vapor phase component in the gaseous stream using media with high absorbing properties. The high concentration and low volumetric flows of the vapor composition enhance the overall efficiency of conventional separation practices. For example, at least a portion of the vapor component may be captured at concentrations high enough to permit subsequent separation of the vapor component at a temperature of 0° C or higher. This temperature prevents the formation of frost during the separation process, and may provide both equipment and process advantages. Suitable destruction processes will also be familiar to those skilled in the art and include conventional devices such as thermal oxidizers.

[0078] Depending on the specific gas phase composition, the close-coupled enclosure may optionally include flame-arresting capabilities. A flame arresting device placed internally within the close-coupled enclosure allows gases to pass through but extinguishes flames in order to prevent a large scale fire or explosion. A flame is a volume of gas in which a self-sustaining exothermic (energy producing) chemical reaction occurs. Flame arresting devices are generally needed when the operating environment includes oxygen, high temperatures and a flammable gas mixed with the oxygen in suitable proportions to create a combustible mixture. A flame-arresting device works by removing one of the noted elements. In one exemplary embodiment, the gas phase components pass through a narrow gap bordered by heat absorbing materials. The size of both the gap and the material are dependent upon the specific vapor composition. For example, the chamber may be filled with expanded metallic heat-absorbing material, such as, for

example, aluminum, contained at the bottom by a fine mesh metallic screen with mesh openings sized according to the National Fire Protection Association Standards. Optional separation devices and conveying equipment that may be utilized in the disclosed process and apparatus may also possess flame arresting capabilities. Those skilled in the art will be familiar with suitable flame arresting devices and techniques for use with such devices and equipment.

[0079] Representative articles that can be made using the disclosed process and apparatus include, for example, coatings containing polymers, pigments, ceramics or pastes. The substrate may be, for example, a polymer, woven or non-woven material, fibers, powder, paper, a food product, pharmaceutical product or combinations thereof. The coating may include at least one evaporative component or may be a 100% solids coating composition. If present, the evaporative component may be any liquid or solid composition that is capable of vaporizing and separating from the coated substrate. Non-limiting examples would include organic compounds and inorganic compounds or combinations thereof, such as water or ethanol. Sufficient energy is supplied to the article to vaporize at least one evaporative component or to cure the coating, or both. The supplied energy may involve radiation, conduction, convection or combinations thereof. Conductive heating, for example could include passing the substrate or coating in close proximity to a flat heated plate, curved heated plate or partially wrapping the substrate around a heated cylinder. Examples of convective heating may include directing hot air by nozzle, jet or plenum at the article. Electromagnetic radiation such as radio frequency, microwave, or infrared, may be directed at the substrate or coating and absorbed causing internal heating. Energy may be supplied to any or all surfaces of the substrate or coating. Additionally, the substrate or coating may be supplied with sufficient internal energy, for example a pre-heated substrate or an exothermic chemical reaction occurring in the substrate or coating. The various energy sources may be used individually or in combination. Those skilled in the art will recognize that the recited energy may be supplied from a variety of sources, including electricity, the combustion of fuels, and other thermal sources. The energy may be supplied directly to the application point, or indirectly through heated liquids such as water or oil, heated gases such as air or inert gas or heated vapors such as steam or conventional heat transfer fluids.

[0080] The total mass flow (**M4**) through the close-coupled enclosure may be selected to match or exceed the generation rate of gas phase components from the substrate or coating (**M2**). This may assist in preventing either the dilution or loss of vapor components.

[0081] It is desirable to avoid airflow patterns that might disturb the unsolidified coating and cause "mottle" or other defects. **Fig. 4** is a perspective view of a disclosed distribution manifold

400 that can assist in providing an even flow of supplied conditioned gas (**M1'**). Manifold **400** has a housing **402**, and mounting flanges **404** flanking slit **406**. Further details regarding manifold **400** are shown in **Fig. 5**, which is a schematic partial cross sectional view of manifold **400** and an associated gas conditioning system. Gas source **502** supplies a suitable gas (e.g., nitrogen or an inert gas) to gas conditioning system **508** via line **504** and valve **506**. System **508** is optionally supplied with additional reactive species via lines **510**, **512** and **514** and valves **511**, **513** and **515**. System **508** supplies the desired conditioned gas stream to manifold **400** via line **520**, valve **516** and flow sensor **518**. Vacuum line **522** may be used to withdraw gas from manifold **400** via flow sensor **524**, valve **526** and vacuum pump **528**. The presence of both a supply line and a vacuum line enables manifold **400** to be used as a conditioned gas introduction or gas withdrawal device. Gases entering manifold **400** pass through head space **520**, around diverter plate **532**, and through distribution media **534** (made, e.g., using white SCOTCHBRITE™ nonwoven fabric, commercially available from 3M Co.), and then pass through a first perforated plate **536**, HEPA filter media **538** and a second perforated plate **540** before entering slit **406**. Gasket **542** helps maintain a seal between flanges **404** and perforated plate **540**. Manifold **400** can help supply a substantially uniform flow of supplied conditioned gas across the width of a close-coupled enclosure. The pressure drop laterally in the head space **520** is negligible in comparison to the pressure drop through the remaining components of manifold **400**. Those skilled in the art will appreciate that the dimensions or shape of head space **520** and the pore size of distribution media **534** may be adjusted as needed to vary the flow rate across the length of distribution manifold **400** and along the width of a close-coupled enclosure. The flow rate along the length of distribution manifold **400** can also be adjusted by using an array of bolts or other suitable devices arranged to bear against diverter plate **532** and compress distribution media **534**, thereby adjustably varying the pressure drop along the length of distribution manifold **400**.

[0082] **Fig. 6** shows a close-coupled enclosure in the form of a transition zone **600** coupled at its upstream end to a gap dryer **602** having underlying control surface **604** and overlying control surface **606**. The downstream end of transition zone **600** is coupled to process **608** operating at a pressure **pB**. Gaskets **610** provide a seal at each end of transition zone **600** and permit removal of the overlying or underlying control surfaces for, e.g., cleaning or web threadup. Transition zone **600** has a fixed overlying control surface **611** and a positionable overlying control surface **612** (shown in phantom in its raised position **613**) that may be manually or automatically actuated to provide headspace values of **h2a**, **h2b** and values in

between. Upper distribution manifold **614** may be used to supply conditioned gas stream **M1'**$_{U}$. The underlying side of transition zone **600** has transport roll **616** inside housing **618**, and underlying control surface **620**. Lower distribution manifold **622** may be used to supply conditioned gas stream **M1'**$_{L}$. Transition zone **600** may be helpful in avoiding mottle or other defects by discouraging large gas flows between adjacent connected processes involving a material difference in respective operating pressures. For example, there may a two-fold or greater, five-fold or greater or even ten-fold or greater pressure difference between a disclosed close-coupled enclosure at an upstream or downstream end of a transition zone and a conventional oven at the other end of the transition zone.

[0083] **Fig. 7** and **Fig. 8** respectively show a schematic sectional view and a cross sectional view of a close-coupled enclosure **700** having overlying control surface **702**, underlying control surface **704** and sides **706** and **708**. Close-coupled enclosure **700** has length $\mathbf{l_e}$ and width $\mathbf{w_e}$. Web **14** has width **w**, and is transported through close-coupled enclosure **700** at velocity **V**. Gaskets **709** provide a seal at the sides of overlying control surface **702** and permit its height adjustment or removal (e.g., for cleaning or web threadup). Overlying control surface **702** and underlying control surface **704** are spaced apart a distance $\mathbf{h_{e1}}$. Underlying control surface **704** is spaced apart from substrate **14** a distance $\mathbf{h_{e2}}$. These distances may vary in the upstream or downstream directions. Upstream transition zone **710** has underlying and overlying web slot pieces **711** and **712**. These web slot pieces are spaced apart a distance $\mathbf{h_{1a}}$, and have length $\mathbf{l_1}$. Underlying web slot piece **711** is spaced apart from web **14** a distance $\mathbf{h_{1b}}$. An upstream process (not shown in **Fig. 7** or **Fig. 8**) is in direct gaseous communication with transition zone **710** and has pressure $\mathbf{P_A}$. Downstream transition zone **714** has underlying and overlying web slot pieces **716** and **718**. These web slot pieces are spaced apart a distance $\mathbf{h_{2a}}$, and have length $\mathbf{l_2}$. Underlying web slot piece **716** is spaced apart from web **14** a distance $\mathbf{h_{2b}}$. A downstream process (not shown in **Fig. 7** or **Fig. 8**) is in direct gaseous communication with transition zone **714** and has pressure $\mathbf{P_B}$. When an upstream or downstream process is required to operate at a large pressure differential from an enclosure such as close-coupled enclosure **700**, the transition zones between the upstream or downstream process and the close-coupled enclosure may utilize additional dilution (or exhaust) streams to decrease the pressure differential between the process and the close-coupled enclosure. For example, convection ovens often operate at large negative pressures (-25 Pa is not uncommon), inducing large gas flows.

[0084] Upper and lower manifolds **720** and **722** respectively may provide gas flows into or out of the upstream end of close-coupled enclosure **700** (e.g., conditioned gas streams $\mathbf{M1'_U}$ and $\mathbf{M1'_L}$). Upper and lower manifolds **724** and **726** respectively may provide gas flows into or out of the upstream end of close-coupled enclosure **700** (e.g., withdrawn gas streams $\mathbf{M4_U}$ and $\mathbf{M4_L}$). The pressures inside the enclosure can be characterized by $\mathbf{P_1}$, $\mathbf{P_2}$, $\mathbf{P_{13}}$, $\mathbf{P_{23}}$, $\mathbf{P_3}$ and $\mathbf{P_4}$. The ambient air pressure outside close-coupled enclosure **700** is given by $\mathbf{P_{atm}}$.

[0085] The disclosed process and apparatus typically will utilize a web handling system to transport a moving substrate of indefinite length through the apparatus. Those skilled in the art will be familiar with suitable material handling systems and devices.

[0086] In operation, exemplary embodiments of the disclosed apparatus can significantly reduce the particle count in the atmosphere surrounding a moving coated web. Exemplary embodiments of the disclosed apparatus may also capture at least a portion of a vapor component from an unsolidified or solidified coating (if present) without substantial dilution and without condensation of the vapor component in a drying system. The supplied conditioned gas may significantly reduce the introduction of particulates into portions of the apparatus surrounding the coating and thus may reduce or prevent product quality problems in the finished product. The relatively low air flow may significantly reduce disturbances to the coating and thus may further reduce or prevent product quality problems. The collection of a vapor component at high concentrations may permit efficient recovery of the vapor component. The absence of or reduction in condensation in a drying system may further reduce or prevent product quality issues caused by condensate falling onto the coating.

Example 1

[0087] A single close-coupled enclosure was constructed to illustrate the effect of certain variables. **Fig. 9** shows a schematic side sectional view of a close-coupled enclosure **900**. Close-coupled enclosure **900** has overlying control surface **902**, underlying control surface **904** and side **906** equipped with sample ports A, B and C for measuring pressure, particle count and oxygen levels within close-coupled enclosure **900**. Overlying control surface **902** and underlying control surface **904** are spaced apart a distance $\mathbf{h_{e1}}$. Underlying control surface **904** is spaced apart from substrate **14** a distance $\mathbf{h_{e2}}$. Upstream transition zone **908** has underlying and overlying web slot pieces **910** and **912**. These web slot pieces are spaced apart a distance $\mathbf{h_{1a}}$, and have length $\mathbf{l_1}$. Underlying web slot piece **910** is spaced apart from web **14** a distance

$\mathbf{h_{1b}}$. Downstream transition zone **914** has underlying and overlying web slot pieces **916** and **918**. These web slot pieces are spaced apart a distance $\mathbf{h_{2a}}$, and have length $\mathbf{l_2}$. Underlying web slot piece **916** is spaced apart from web **14** a distance $\mathbf{h_{2b}}$. Upper and lower distribution manifolds **920** and **922** respectively supply conditioned gas streams $\mathbf{M1'_U}$ and $\mathbf{M1'_L}$ at the upstream end of close-coupled enclosure **900**. Web **14** is transported through close-coupled enclosure **900** at velocity **V**.

[0088] Downstream process **924** has movable underlying control surface **926,** overlying control surface **928** equipped with ambient gas inlet **930** and vacuum outlet **932**, and underlying and overlying web slot pieces **926** and **928**. These web slot pieces are spaced apart a distance $\mathbf{h_{B1}}$. Underlying web slot piece **926** is spaced apart from web **14** a distance $\mathbf{h_{B2}}$. These web slot pieces have length $\mathbf{l_3}$. Through appropriate regulation of the flows through inlet **930** and outlet **932**, process **924** can simulate a variety of devices, e.g., a conventional oven.

[0089] For purposes of this example close-coupled enclosure **900** was used with an uncoated web and was not connected at either its upstream or downstream ends to another close-coupled enclosure. Thus the surrounding room, with a defined ambient pressure of zero, lies upstream from transition zone **908** and downstream from process **924**. The room air temperature was about 20° C.

[0090] **Fig. 10** shows a plan view of overlying control surface **902**. Surface **902** has length $\mathbf{l_e}$ and width $\mathbf{w_e}$, and contains 5 rows of 3 numbered holes each having a 9.78 mm diameter and a 0.75 cm^2 area, with the lowest numbered holes located at the upstream end of control surface **902**. The holes can be used as sample ports for measuring pressure, particle count and oxygen levels at different locations within the enclosure and may also be left open or taped closed to vary the open draft area of close-coupled enclosure **900**.

[0091] Particle counts were measured using a MET ONE™ Model 200L-1-115-1 Laser Particle Counter (commercially available from Met One Instruments, Inc.), to determine the number of 0.5 μm or larger particles in a volume of 28.3 liters, at a 28.3 liters/min flow rate. Pressures were measured using a Model MP40D micromanometer (commercially available from Air-Neotronics Ltd.). Oxygen levels were measured using a IST-AIM™ Model 4601 Gas Detector (commercially available from Imaging and Sensing Technology Corporation). Gas velocities were evaluated using a Series 490 Mini Anemometer (commercially available from Kurz Instruments, Inc.).

[0092] Upper and lower distribution manifolds **920** and **922** were connected to a nitrogen supply and the flow rates adjusted using DWYER™ Model RMB-56-SSV flow meters (commercially available from Dwyer Instruments, Inc.). Vacuum outlet **932** was connected to a NORTEC™ Model 7 compressed air driven vacuum pump (commercially available from Nortec Industries, Inc.). The flow rate was adjusted using a pressure regulator and a DWYER Model RMB-106 flow meter (commercially available from Dwyer Instruments, Inc.).

[0093] Close-coupled enclosure **900** was adjusted so that $\mathbf{l_e}$ = 156.2 cm, $\mathbf{w_e}$ = 38.1 cm, $\mathbf{h_{e1}}$ = 4.45 cm, $\mathbf{h_{e2}}$ = 0.95 cm, $\mathbf{h_{1a}}$ = 0.46 cm, $\mathbf{h_{1b}}$ = 0.23 cm, $\mathbf{l_1}$ = 7.62 cm, $\mathbf{h_{2a}}$ = 1.27 cm, $\mathbf{h_{2b}}$ = 0.13 cm, $\mathbf{l_2}$ = 3.8 cm, $\mathbf{h_{B1}}$ = 0.46 cm, $\mathbf{h_{B2}}$ = 0.23 cm, $\mathbf{l_3}$ = 2.54 cm and **V** = 0. The enclosure pressure was adjusted by varying the flow rates $\mathbf{M1'_U}$ and $\mathbf{M1'_L}$ and the rate of gas withdrawal at outlet **932**, using sample port B (see **Fig. 9**) to monitor pressure. Hole 11 (see **Fig. 10**) was used to monitor particle count and sample port C (see **Fig. 9**) was used to monitor the oxygen level. Inlet **930**, the remaining holes in control surface **902** and sample port A were taped closed, thereby providing a minimal open draft area in close-coupled enclosure **900**. The results are shown in **Fig. 11** (which uses a logarithmic particle count scale) and **Fig. 12** (which uses a linear oxygen concentration scale), and demonstrate that for a stationary web, material particle count reductions were obtained, at, e.g., pressures greater than or equal to about -0.5 Pa. At positive enclosure pressures, the particle counts were at or below the instrument detection threshold. The curves for particle count and oxygen level were very similar to one another.

Example 2

[0094] Example 1 was repeated using an 18 m/minute web velocity **V**. The particle count results are shown in **Fig. 13** (which uses a logarithmic particle count scale). **Fig. 13** demonstrates that for a moving web, material particle count reductions were obtained, at, e.g., pressures greater than -0.5 Pa.

Example 3

[0095] Using the method of Example 1, a – 0.5 Pa enclosure pressure was obtained in close-coupled enclosure **900** by adjusting the flow rates $\mathbf{M1'_U}$ and $\mathbf{M1'_L}$ to 24 liters/min and by adjusting the rate of gas withdrawal at outlet **932** to 94 liters/min. In a separate run, a +0.5 Pa enclosure pressure was obtained by adjusting the flow rates $\mathbf{M1'_U}$ and $\mathbf{M1'_L}$ to 122 liters/min and by adjusting the rate of gas withdrawal at outlet **932** to 94 liters/min. The respective particle

counts were 107,889 at -0.5 Pa, and only 1 at +0.5 Pa. For each run the enclosure pressure above the substrate was measured at several points along the length of close-coupled enclosure **900** using holes 2, 5, 8, 11 and 14 (see **Fig. 10**). As shown in **Fig. 14**, the enclosure pressure above the substrate was very steady for each run and did not measurably vary along the length of close-coupled enclosure **900**. Similar measurements were made below the web using ports A, B and C. No variation in pressure was observed in those measurements either.

[0096] In a comparison run, pressure measurements were made at varying points inside and outside a TEC™ air flotation oven (manufactured by Thermal Equipment Corp.) equipped with a HEPA filter air supply set to maintain a – 0.5 Pa enclosure pressure. The upper and lower flotation air bar pressures were set to 250 Pa. The make-up air flowed at 51,000 liters/min (equivalent to about 7.5 air changes/minute for a 6800 liter oven capacity, not taking into account equipment inside the oven). The ambient room air particle count was 48,467. The particle count measured approximately 80 centimeters inside the oven was 35,481. The particle counts at several other positions were measured as shown in **Fig. 15**. **Fig. 15** demonstrates that the enclosure pressure varied considerably at the various measuring points, and exhibited further variation due to the action of the oven pressure regulator.

Example 4

[0097] Using the general method of Example 1, the $\mathbf{M1'_U}$ and $\mathbf{M1'_L}$ flow rates were set at 122 liters/min and the rate of gas withdrawal at outlet **932** was set at 94 liters/min. The web slot height $\mathbf{h_{1a}}$ was adjusted to values of 0, 0.46, 0.91, 1.27, 2.54 and 3.81 cm. The ambient air particle count was 111,175. **Fig. 16** and **Fig. 17** (which both use linear vertical axis scales) respectively show the pressure and particle count inside the enclosure at various web slot heights. In all instances, a material particle count reduction (compared to the ambient air particle count) was obtained.

Example 5

[0098] Using the general method of Example 1 and a 23 cm wide polyester film substrate moving at 0, 6 or 18 m/min, the $\mathbf{M1'_U}$ and $\mathbf{M1'_L}$ flow rates and the rate of gas withdrawal at outlet **932** were adjusted to obtain varying enclosures pressures. The ambient air particle count was 111,175. The enclosure particle count was measured as a function of web speed and enclosure pressure. The results are shown in **Fig. 18** (which uses a logarithmic particle count scale). **Fig. 18** demonstrates that material particle count reductions were obtained for all

measured substrate speeds at, e.g., pressures greater than
-0.5 Pa.

[0100] From the above disclosure of the general principles of the disclosed invention and the preceding detailed description, those skilled in this art will readily comprehend the various modifications to which the disclosed invention is susceptible. Therefore, the scope of the invention should be limited only by the following claims and equivalents thereof.

We claim:

1. A process for coating a moving substrate of indefinite length comprising conveying the substrate past a coating applicator and to a dryer or curing station in a close-coupled enclosure or series of interconnected close-coupled enclosures while supplying the enclosure or series of enclosures with one or more streams of conditioned gas flowing at a rate sufficient to reduce materially the particle count in a close-coupled enclosure.

2. A process according to claim 1 comprising conveying the substrate from the coating applicator through the dryer or curing station in a close-coupled enclosure or series of close-coupled enclosures.

3. A process according to claim 1 comprising conveying the substrate from the coating applicator through the dryer and curing station in a close-coupled enclosure or series of close-coupled enclosures.

4. A process according to claim 1 comprising conveying the substrate in a close-coupled enclosure or series of close-coupled enclosures from a pre-coating station to the coating applicator.

5. A process according to claim 1 comprising conveying the substrate in a close-coupled enclosure or series of close-coupled enclosures from a pre-coating station through the dryer or curing station.

6. A process according to claim 1 comprising conveying the substrate in a close-coupled enclosure or series of close-coupled enclosures from a cabinet containing an unwind reel to a cabinet containing a takeup reel.

7. A process according to claim 1 comprising coating the substrate and protecting it from particulate contamination until the coating can solidify.

8. A process according to claim 1 comprising coating the substrate and not exposing it to ambient air from at least the time the coating is applied until the coating solidifies.

9. A process according to claim 1 wherein at least two close-coupled enclosures have different pressures, temperatures, average headspaces or average footspaces.

10. A process according to claim 1 comprising maintaining or establishing a positive pressure in at least one close-coupled enclosure and maintaining or establishing a negative pressure in at least one other close-coupled enclosure.

11. A process according to claim 1 comprising supplying a conditioned gas stream to at least the first in a series of interconnected close-coupled enclosures whereby the conditioned gas is carried along with the moving substrate to a downstream close-coupled enclosure or pushed to an upstream enclosure or process.

12. A process according to claim 1 comprising supplying conditioned gas streams to a plurality of close-coupled enclosures and withdrawing gas from a plurality of close-coupled enclosures.

13. A process according to claim 1 comprising supplying conditioned gas streams to each in a series of interconnected close-coupled enclosures.

14. A process according to claim 1 comprising sealing the moving substrate at the upstream and downstream ends of a series of interconnected close-coupled enclosure.

15. A process according to claim 1 comprising maintaining a pressure gradient of at least about -0.5 Pa or higher in a close-coupled enclosure.

16. A process according to claim 1 comprising maintaining a positive pressure gradient in a close-coupled enclosure.

17. A process according to claim 1 comprising connecting first and second enclosures having a material difference in their respective operating pressures via a close-coupled enclosure comprising a transition zone.

18. A process according to claim 17 wherein the first enclosure comprises a close-coupled enclosure, the second enclosure comprises an oven and there is a ten-fold or greater pressure difference between atmospheres in the first and second enclosures.

19. A process according to claim 1 wherein the total of the average headspace and average footspace in a close-coupled enclosure is 10 cm or less.

20. A process according to claim 1 wherein the total of the average headspace and average footspace in a close-coupled enclosure is 5 cm or less.

21. A process according to claim 1 wherein the total of the average headspace and average footspace in any close-coupled enclosure is 3 cm or less.

22. A process according to claim 1 wherein a first chamber having a gas introduction device is positioned near a control surface, a second chamber having a gas withdrawal device is positioned near the control surface, the control surface and first and second chambers together define a region wherein adjacent gas phases possess an amount of mass, at least a portion of the mass from the adjacent gas phases is transported through the gas withdrawal device by inducing a flow through the region, and the mass flow can be segmented into the following components:

M1 means total net time-average mass flow per unit of substrate width into or out of the region resulting from pressure gradients,

M1' means the total net time-average mass flow of a gas per unit width into the region through the first chamber from the gas introduction device,

M2 means the time-average mass flow of conditioned gas per unit width from or into the at least one major surface of the substrate or coating into or from the region,

M3 means total net time-average mass flow per unit width into the region resulting from motion of the material, and

M4 means time-average rate of mass transport through the gas withdrawal device per unit width.

23. A process according to claim 22 wherein **M1** has a value less than zero and greater than -0.25 kg/second/meter.

24. A process according to claim 22 wherein **M1** has a value less than zero and greater than -0.10 kg/second/meter.

25. A process according to claim 1 comprising flowing a stream of conditioned gas at a rate sufficient to reduce a close-coupled enclosure particle count by 75% or more.

26. A process according to claim 1 comprising flowing streams of conditioned gas at a rate sufficient to reduce the close-coupled enclosure particle counts by 90% or more.

27. An apparatus for coating a moving substrate of indefinite length comprising a coating applicator, dryer or curing station and substrate-handling equipment for conveying the substrate past the coating applicator and through the dryer or curing station, the substrate being enveloped from at least the coating applicator to the dryer or curing station in a close-coupled enclosure or series of close-coupled enclosures supplied with one or more streams of conditioned gas flowing at a rate sufficient to reduce materially the particle count in a close-coupled enclosure.

28. An apparatus according to claim 27 wherein the substrate is enveloped from the coating applicator through the dryer or curing station in a close-coupled enclosure or series of close-coupled enclosures.

29. An apparatus according to claim 27 wherein the substrate is enveloped from the coating applicator through the dryer and curing station in a close-coupled enclosure or series of close-coupled enclosures.

30. An apparatus according to claim 27 wherein the substrate is enveloped in a close-coupled enclosure or series of close-coupled enclosures from a pre-coating station to the coating applicator.

31. An apparatus according to claim 27 wherein the substrate is enveloped in a close-coupled enclosure or series of close-coupled enclosures from a pre-coating station through the dryer or curing station.

32. An apparatus according to claim 27 wherein the substrate is enveloped in a close-coupled enclosure or series of close-coupled enclosures from a cabinet containing an unwind reel to a cabinet containing a takeup reel.

33. An apparatus according to claim 27 wherein an unsolidified coating on the substrate is protected from particulate contamination until the coating can solidify.

34. An apparatus according to claim 27 wherein the substrate is coated and not exposed to ambient air from at least the time the coating is applied until the coating solidifies.

35. An apparatus according to claim 27 wherein at least two close-coupled enclosures have different average headspaces or average footspaces.

36. An apparatus according to claim 27 wherein a conditioned gas stream is supplied to at least the first in a series of interconnected close-coupled enclosures and the conditioned gas is carried along with the moving substrate to a downstream close-coupled enclosure or pushed to an upstream enclosure or process.

37. An apparatus according to claim 27 wherein conditioned gas streams are supplied to a plurality of close-coupled enclosures and gas streams are withdrawn from a plurality of close-coupled enclosures.

38. An apparatus according to claim 27 wherein conditioned gas streams are supplied to each in a series of interconnected close-coupled enclosures.

39. An apparatus according to claim 27 having seals with respect to the moving substrate at the upstream and downstream ends of a series of interconnected close-coupled enclosure.

40. An apparatus according to claim 27 wherein a close-coupled enclosure has a pressure gradient of at least about -0.5 Pa or higher.

41. An apparatus according to claim 27 wherein a close-coupled enclosure has a positive pressure gradient.

42. An apparatus according to claim 27 comprising first and second enclosures having a material difference in their respective operating pressures connected by a close-coupled enclosure comprising a transition zone between the first and second enclosures.

43. An apparatus according to claim 42 wherein the first enclosure comprises a close-coupled enclosure, the second enclosure comprises an oven and there is a ten-fold or greater pressure difference between atmospheres in the first and second enclosures.

44. An apparatus according to claim 27 wherein the total of the average headspace and average footspace in a close-coupled enclosure is 10 cm or less.

45. An apparatus according to claim 27 wherein the total of the average headspace and average footspace in a close-coupled enclosure is 5 cm or less.

46. An apparatus according to claim 27 wherein the total of the average headspace and average footspace in any close-coupled enclosure is 3 cm or less.

47. An apparatus according to claim 27 wherein a first chamber having a gas introduction device is positioned near a control surface, a second chamber having a gas withdrawal device is positioned near the control surface, the control surface and first and second chambers together define a region wherein adjacent gas phases possess an amount of mass, at least a portion of the mass from the adjacent gas phases can be transported through the gas withdrawal device by inducing a flow through the region, and the mass flow can be segmented into the following components:

M1 means total net time-average mass flow per unit of substrate width into or out of the region resulting from pressure gradients,

M1' means the total net time-average mass flow of a gas per unit width into the region through the first chamber from the gas introduction device,

M2 means the time-average mass flow of conditioned gas per unit width from or into the at least one major surface of the substrate or coating into or from the region,

M3 means total net time-average mass flow per unit width into the region resulting from motion of the material, and

M4 means time-average rate of mass transport through the gas withdrawal device per unit width.

48. An apparatus according to claim 47 wherein **M1** has a value less than zero and greater than -0.25 kg/second/meter.

49. An apparatus according to claim 47 wherein **M1** has a value less than zero and greater than -0.10 kg/second/meter.

50. An apparatus according to claim 27 wherein a stream of conditioned gas flows at a rate sufficient to reduce a close-coupled enclosure particle count by 75% or more.

51. An apparatus according to claim 27 wherein the streams of conditioned gas flow at a rate sufficient to reduce the close-coupled enclosure particle counts by 90% or more.

52. A process for coating a moving substrate of indefinite length comprising conveying the substrate past a coating applicator and to a dryer or curing station in a close-coupled enclosure or series of interconnected close-coupled enclosures while supplying the enclosure or series of enclosures with one or more streams of conditioned gas flowing at a rate sufficient to cause a

material change in a physical property of interest for the atmosphere in a close-coupled enclosure.

53. An apparatus for coating a moving substrate of indefinite length comprising a coating applicator, dryer or curing station and substrate-handling equipment for conveying the substrate past the coating applicator and through the dryer or curing station, the substrate being enveloped from at least the coating applicator to the dryer or curing station in a close-coupled enclosure or series of close-coupled enclosures supplied with one or more streams of conditioned gas flowing at a rate sufficient to cause a material change in a physical property of interest for the atmosphere in a close-coupled enclosure.

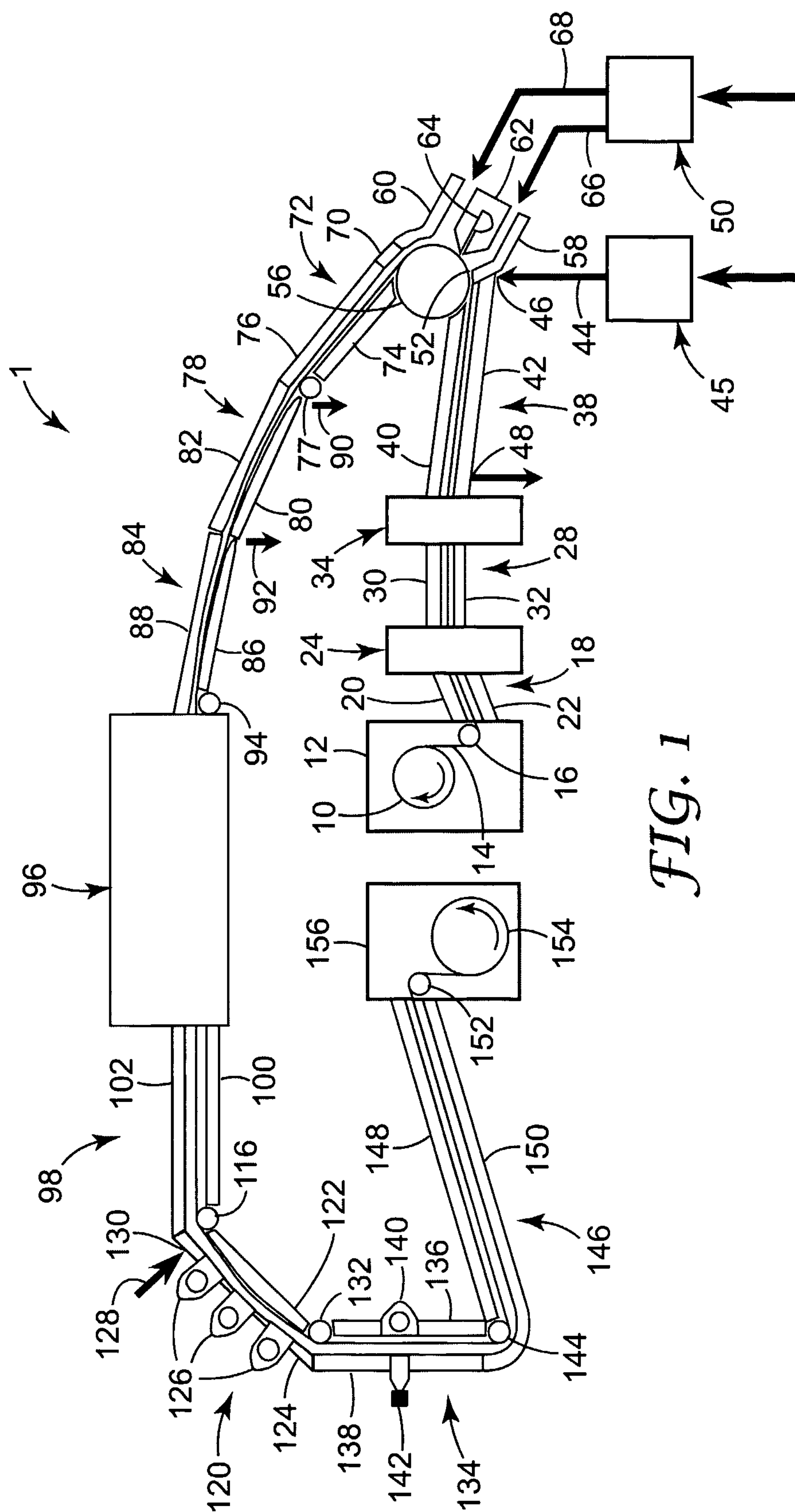

FIG. 1

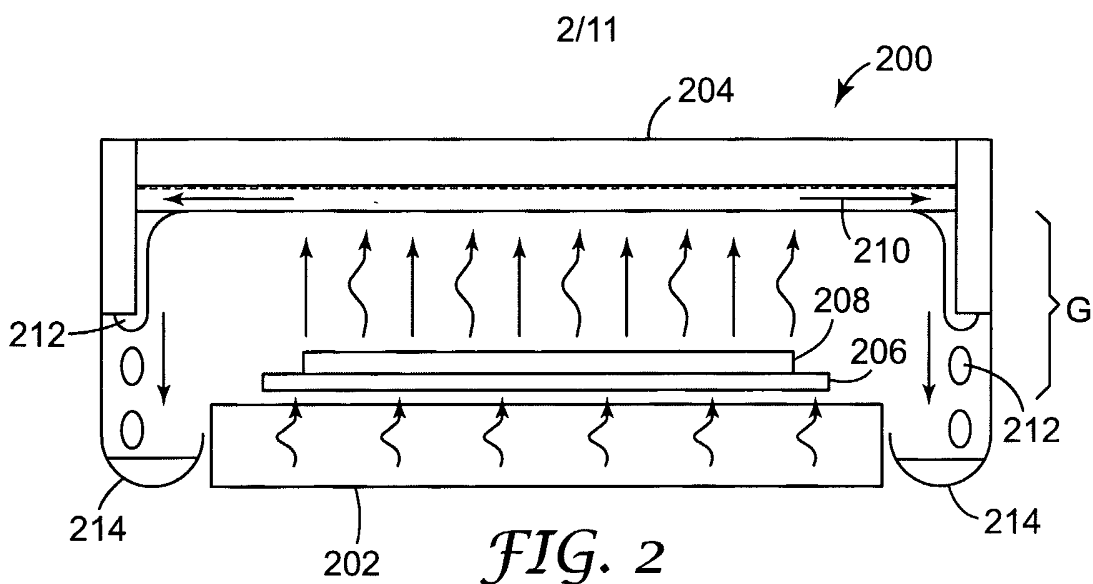

FIG. 2

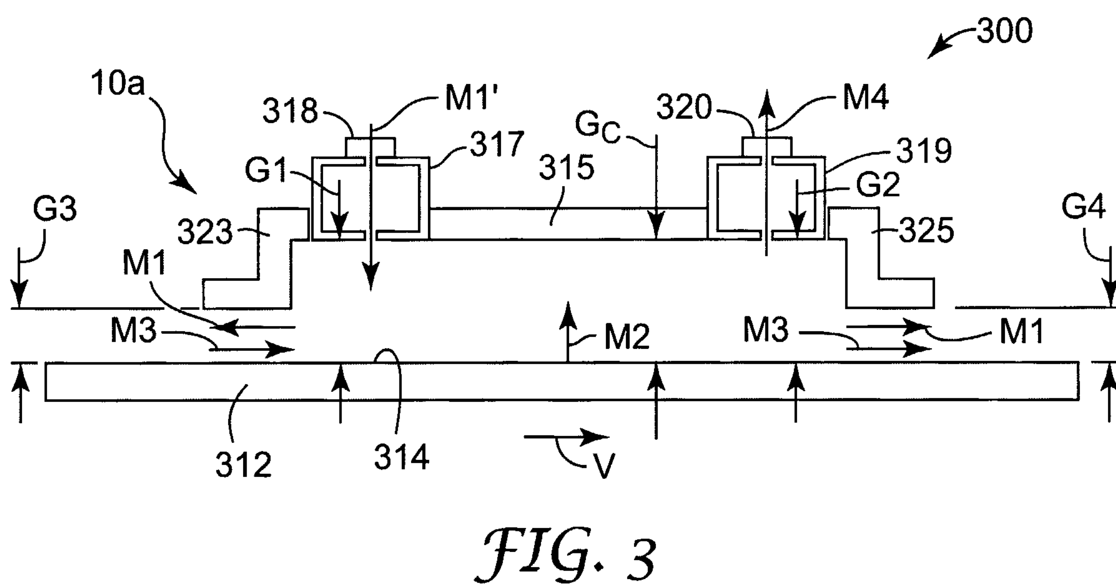

FIG. 3

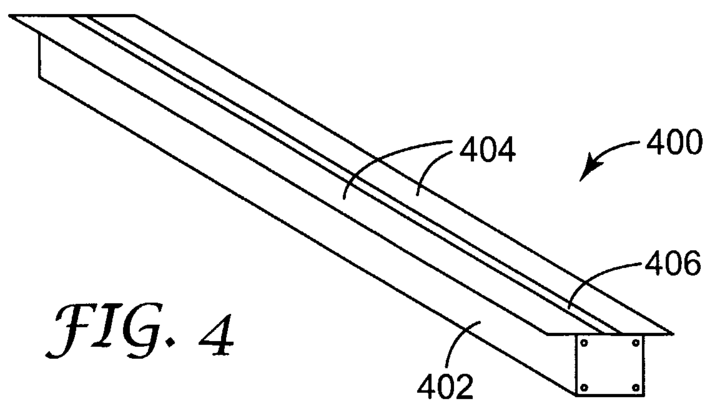

FIG. 4

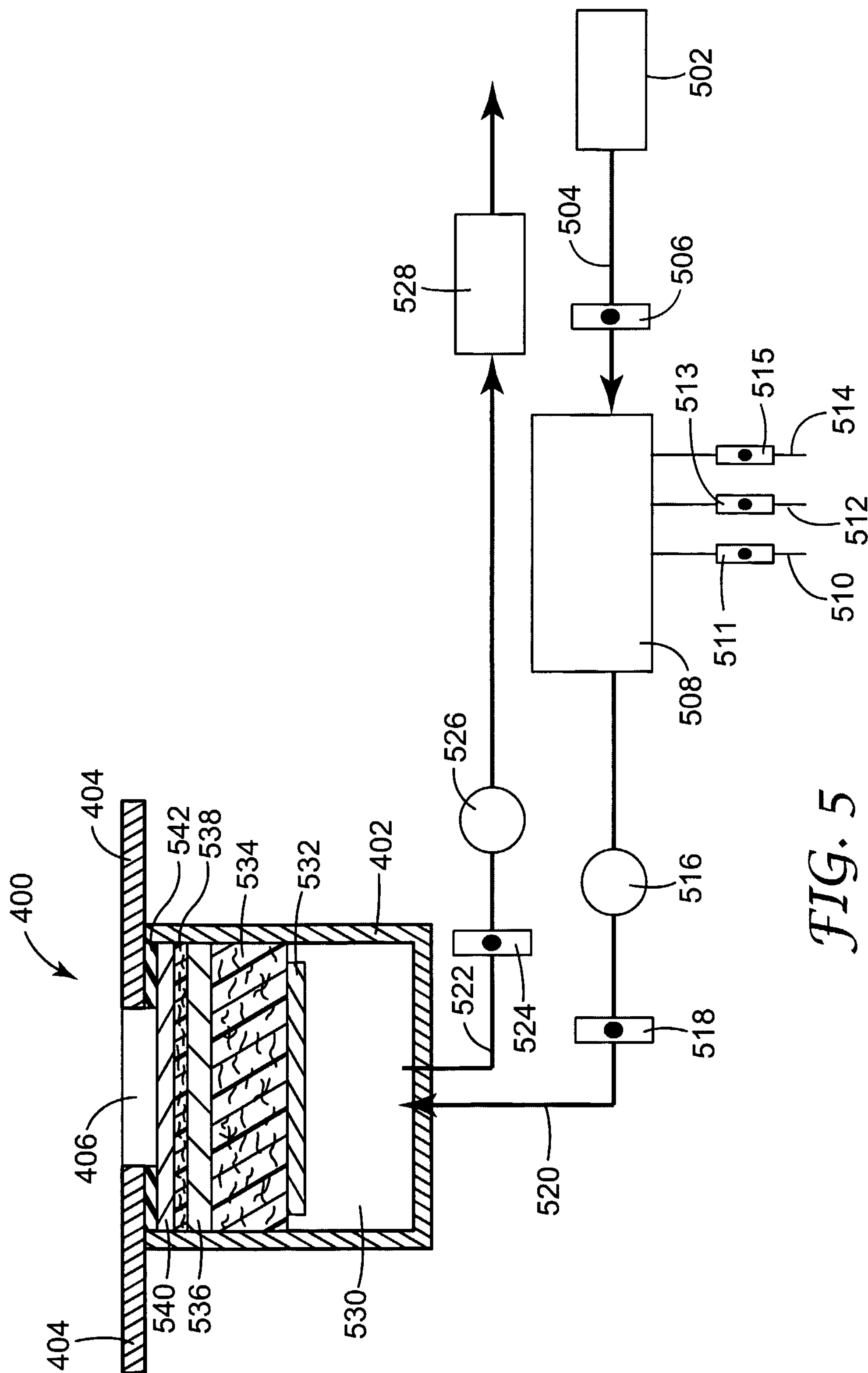

FIG. 5

FIG. 6

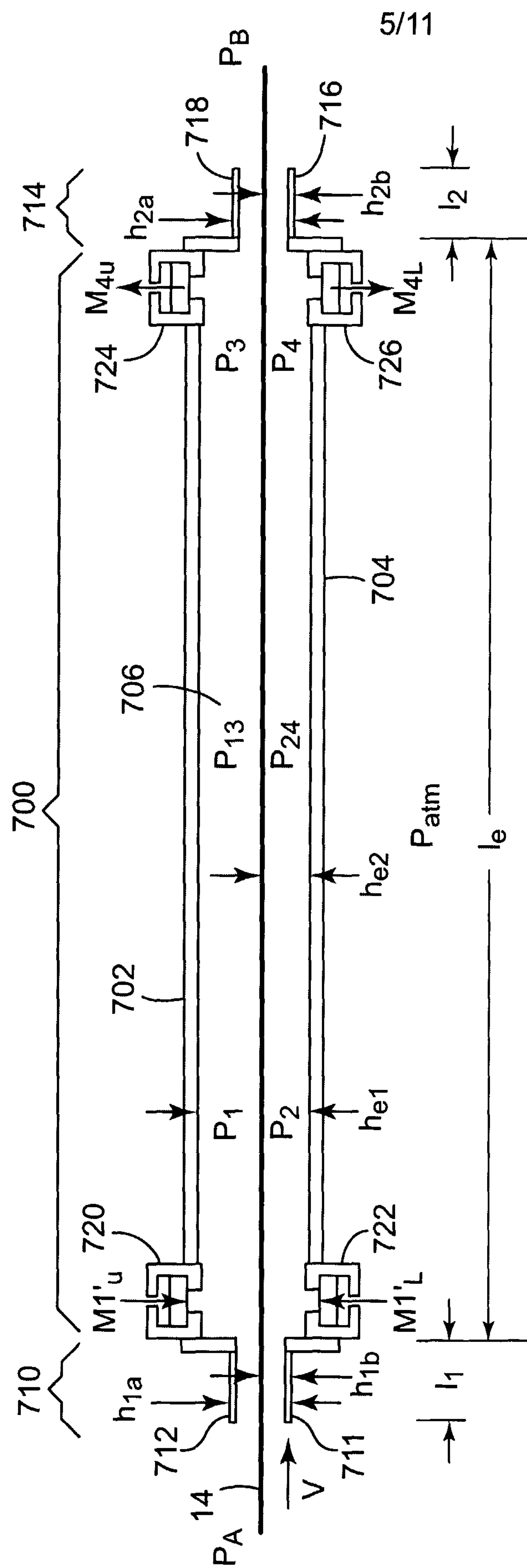

FIG. 7

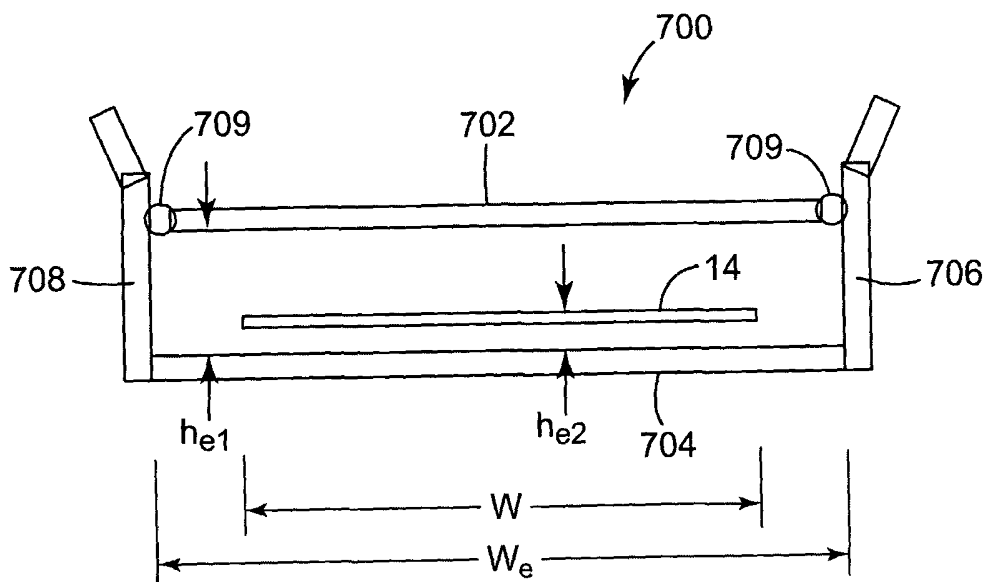

FIG. 8

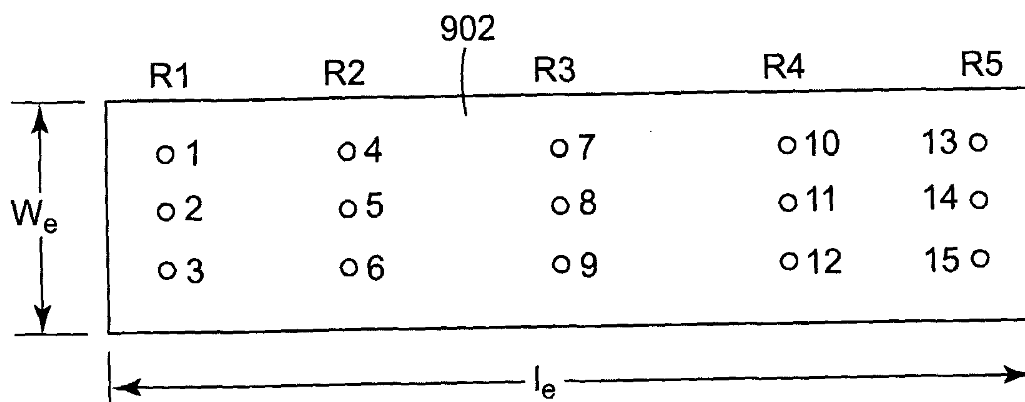

FIG. 10

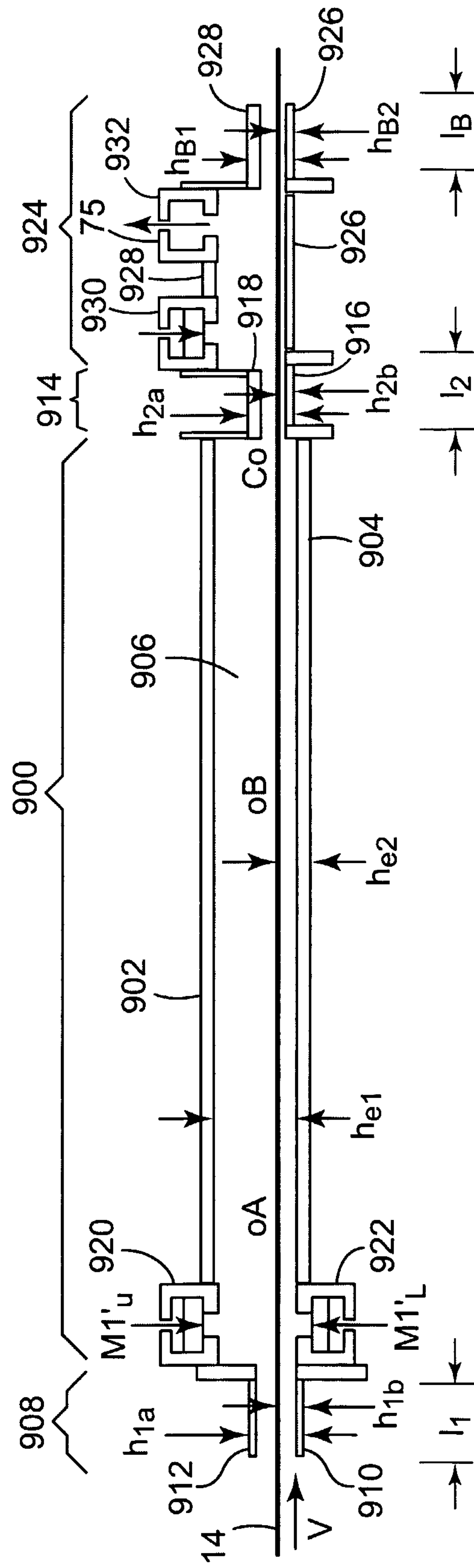

FIG. 9

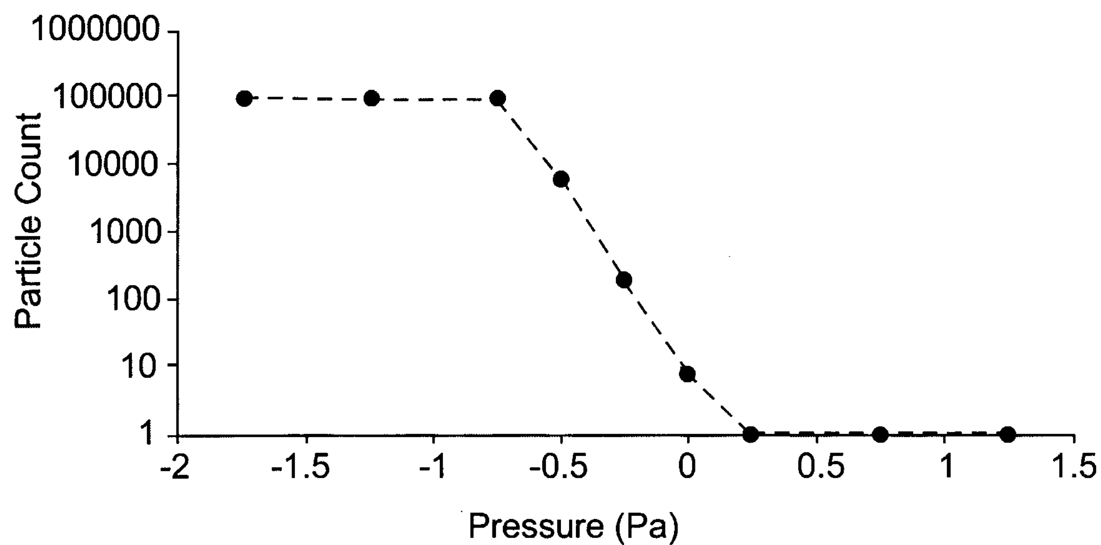

FIG. 11

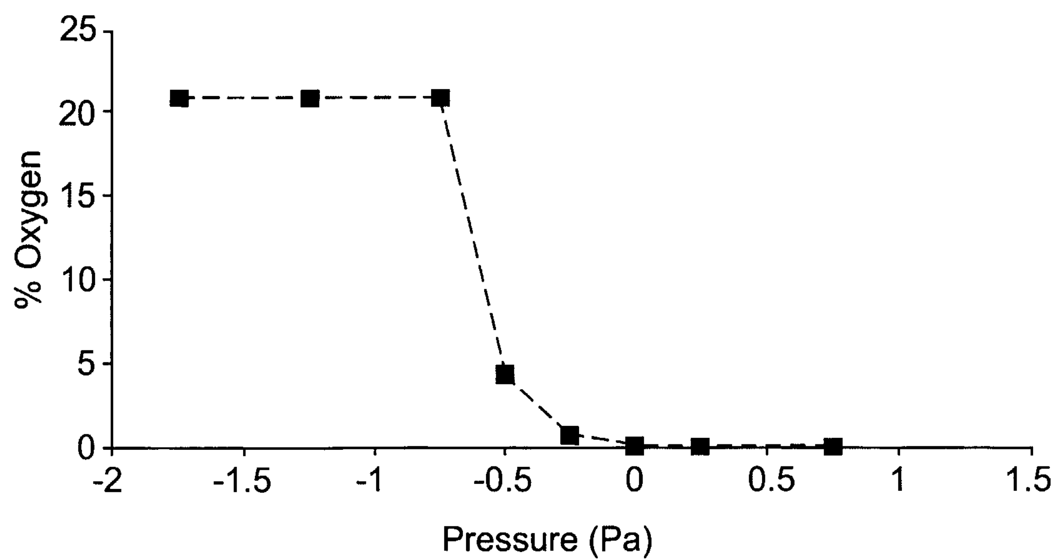

FIG. 12

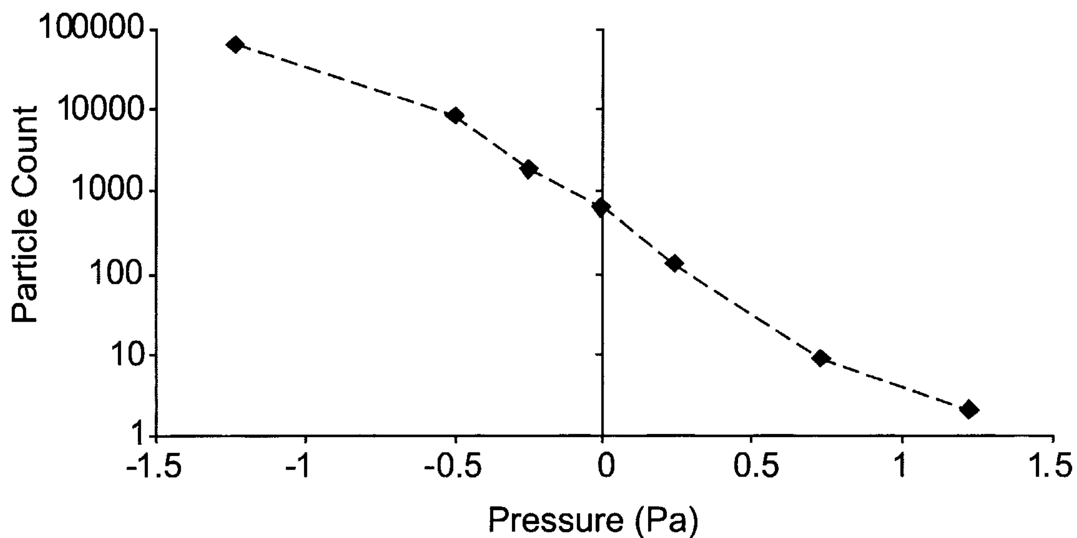

FIG. 13

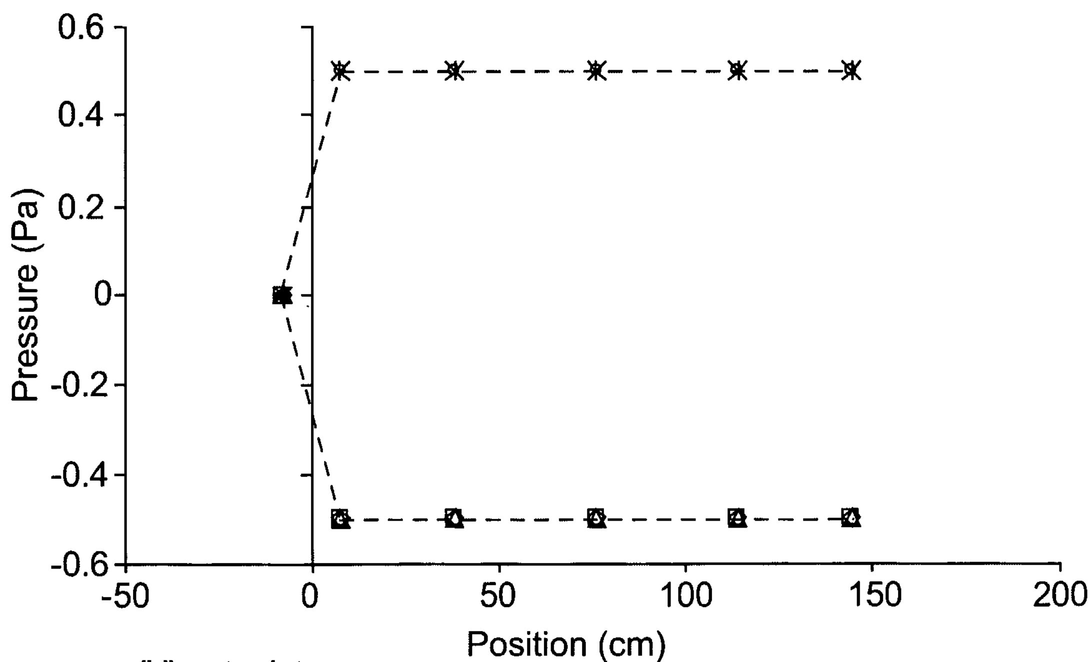

FIG. 14

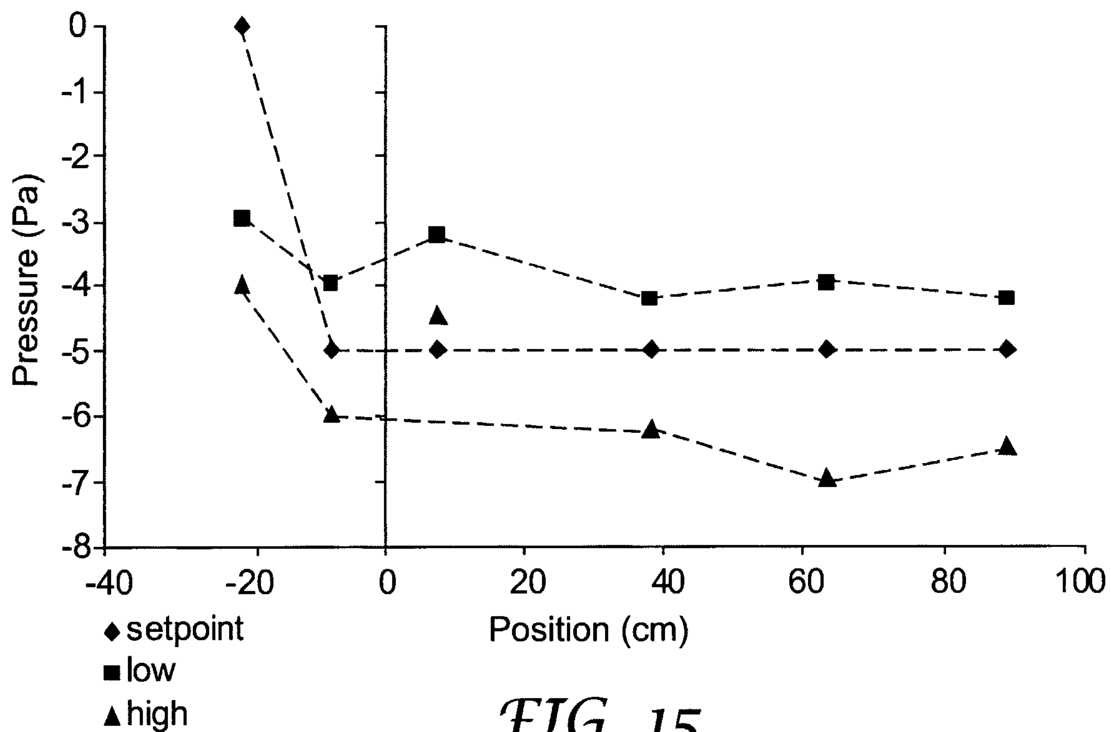

FIG. 15

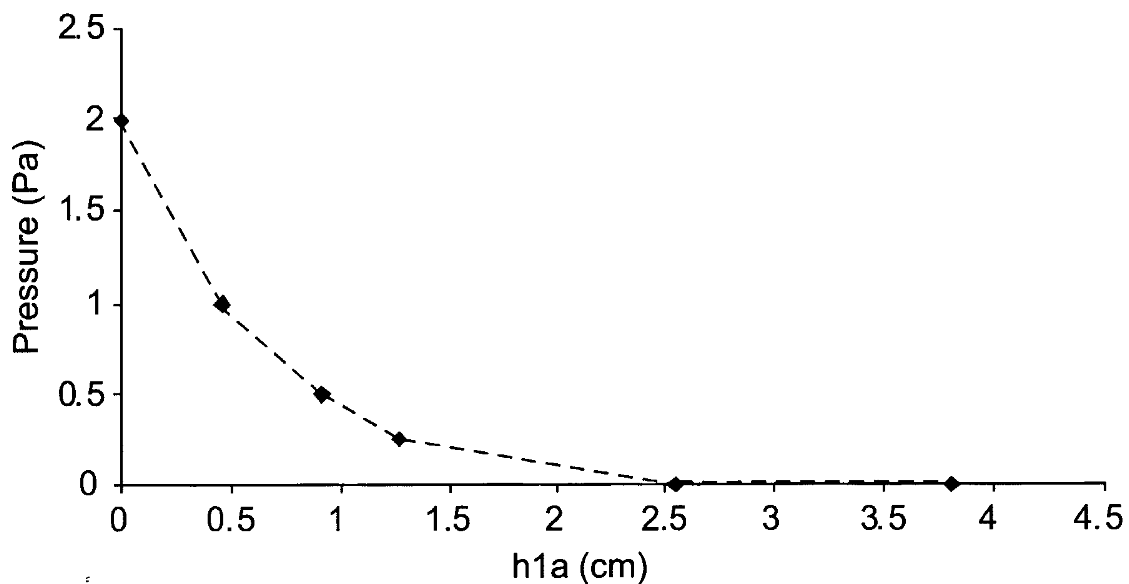

FIG. 16

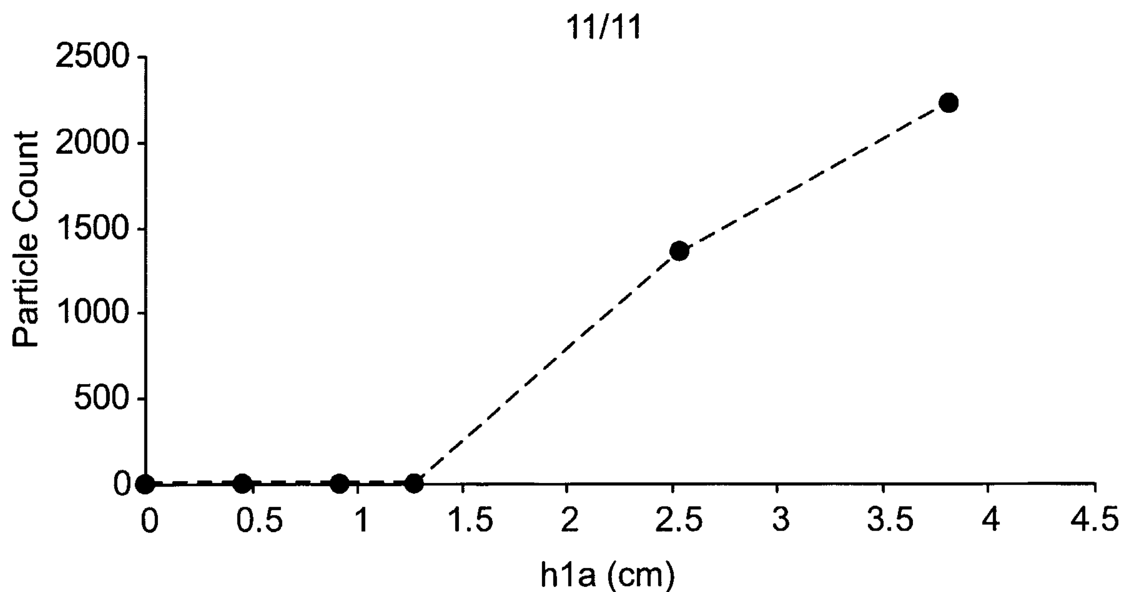

FIG. 17

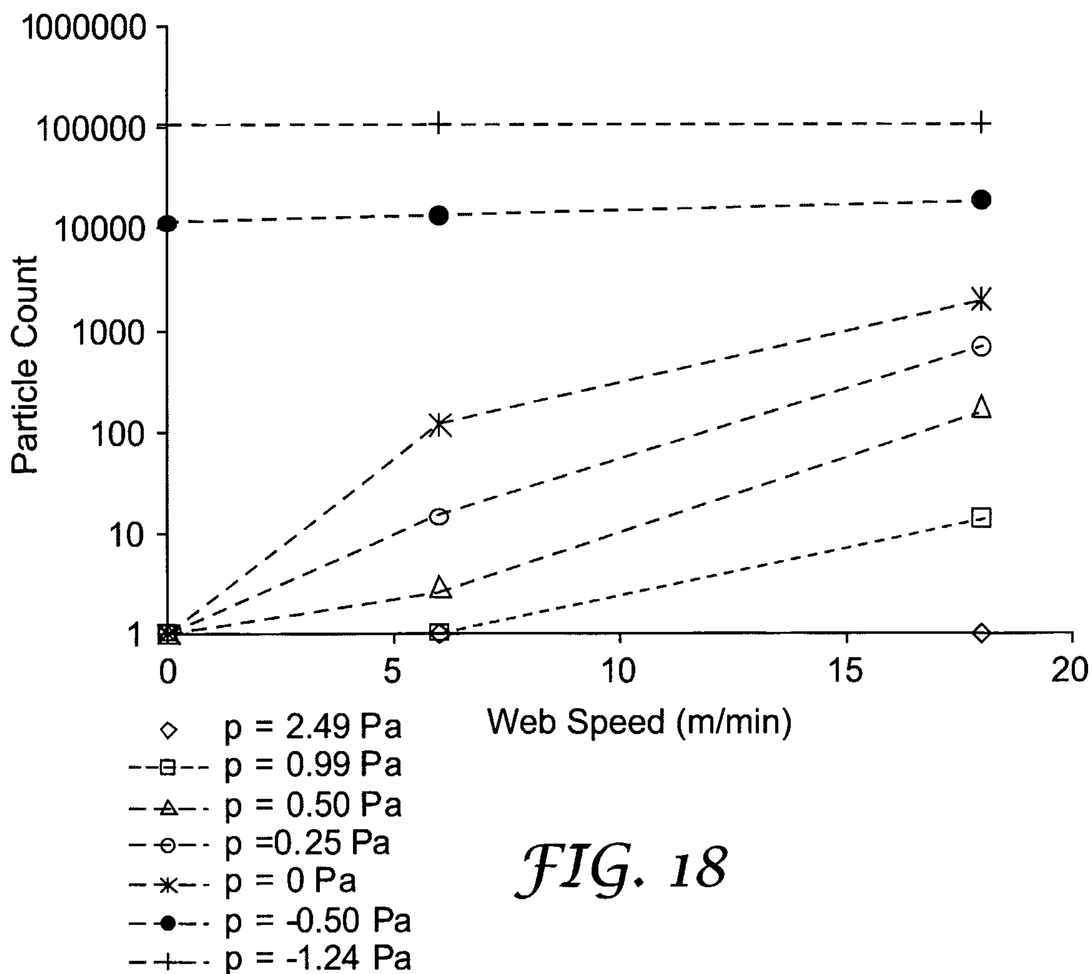

FIG. 18

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US2005/003787

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 B05C3/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 B05C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2 815 307 A (BECK ROBERT HAUN) 3 December 1957 (1957-12-03) the whole document -----	1-9, 11-21, 27-47, 52,53
X	US 4 051 278 A (DEMOCH ET AL) 27 September 1977 (1977-09-27) the whole document -----	1-9, 11-21, 27-47, 52,53
X	US 6 562 412 B1 (FONTAINE PASCAL) 13 May 2003 (2003-05-13) the whole document -----	1-9, 11-21, 27-47, 52,53

Further documents are listed in the continuation of box C.

Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 April 2005	03/05/2005

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Eberwein, M

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US2005/003787

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