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(54) LOW-POWER LOW-NOISE DATA STORAGE ARRAY COOLING

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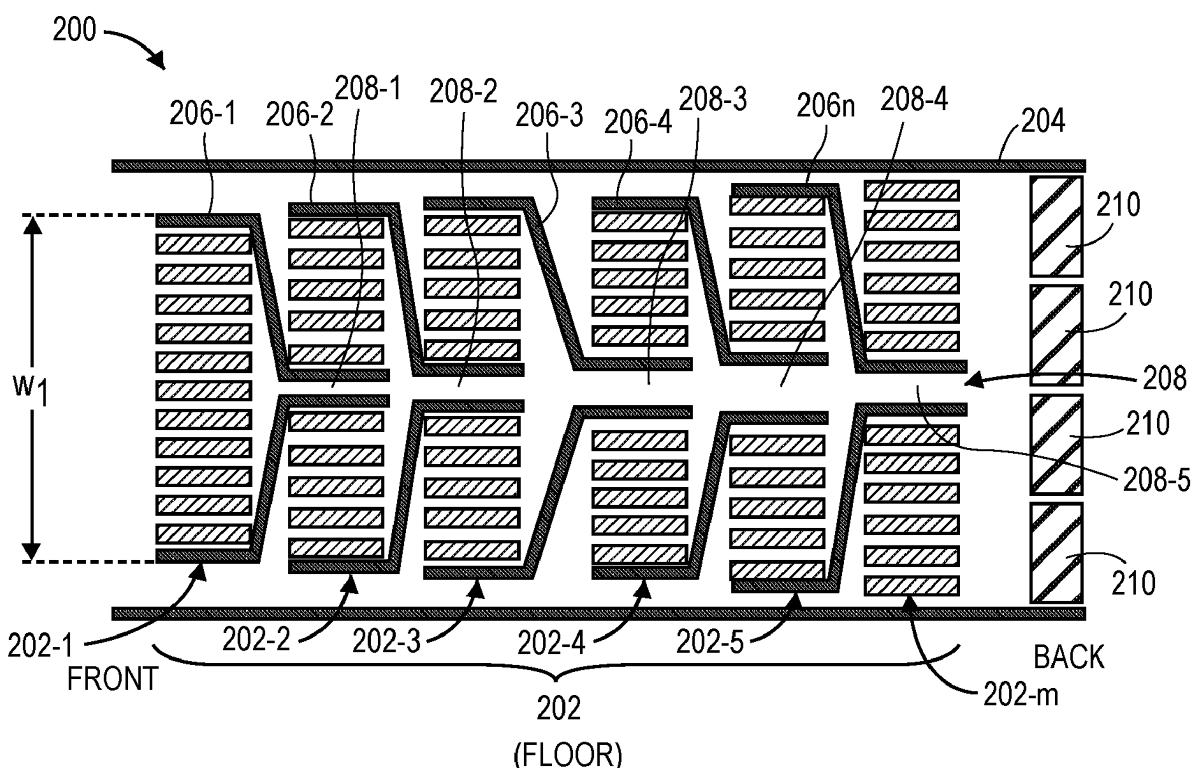
(57) **ABSTRACT**

A data storage system having data storage devices (DSDs) housed in rows in an enclosure further includes a series of funnel structures within which a respective row of DSDs is positioned, where the funnel structures are configured successively wider from front to back to direct airflow through the respective row to a successively wider central exhaust channel. The system may further include an upper wall structure with a deflector portion configured to direct airflow from above down to a back section of the DSDs, side channels extending beyond the deflector portion toward the back to direct airflow down to successive rows of DSDs beyond the deflector portion, and a central channel extending from the deflector portion toward the front and over a cutout portion of a ceiling structure and configured to receive exhaust airflow from a front section of the DSDs via the cutout portion.



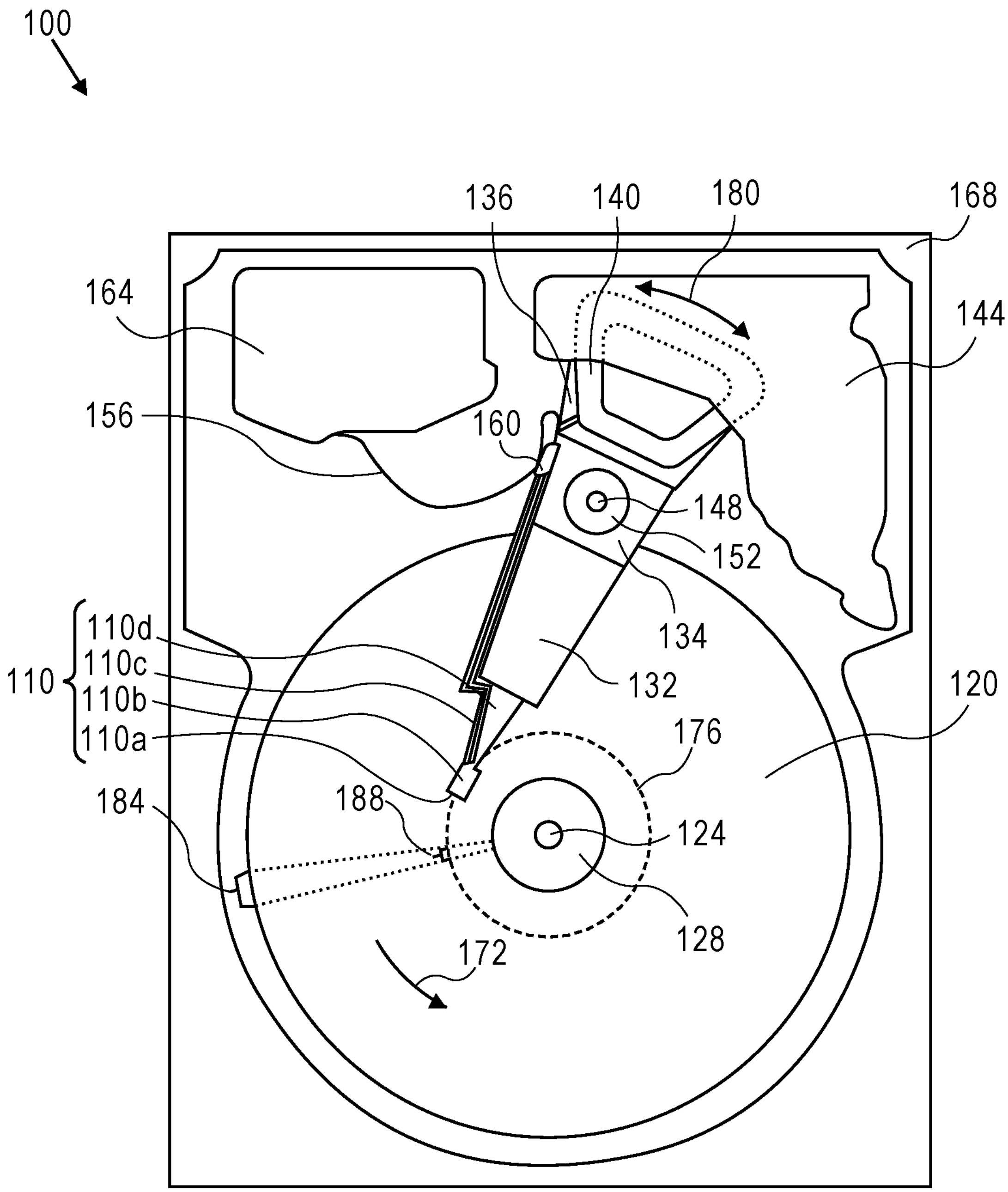

100
136
140
180
168
164
144
156
160
148
152
134
110d
110c
110
110b
110a
132
120
176
184
188
124
128
172

FIG. 1A

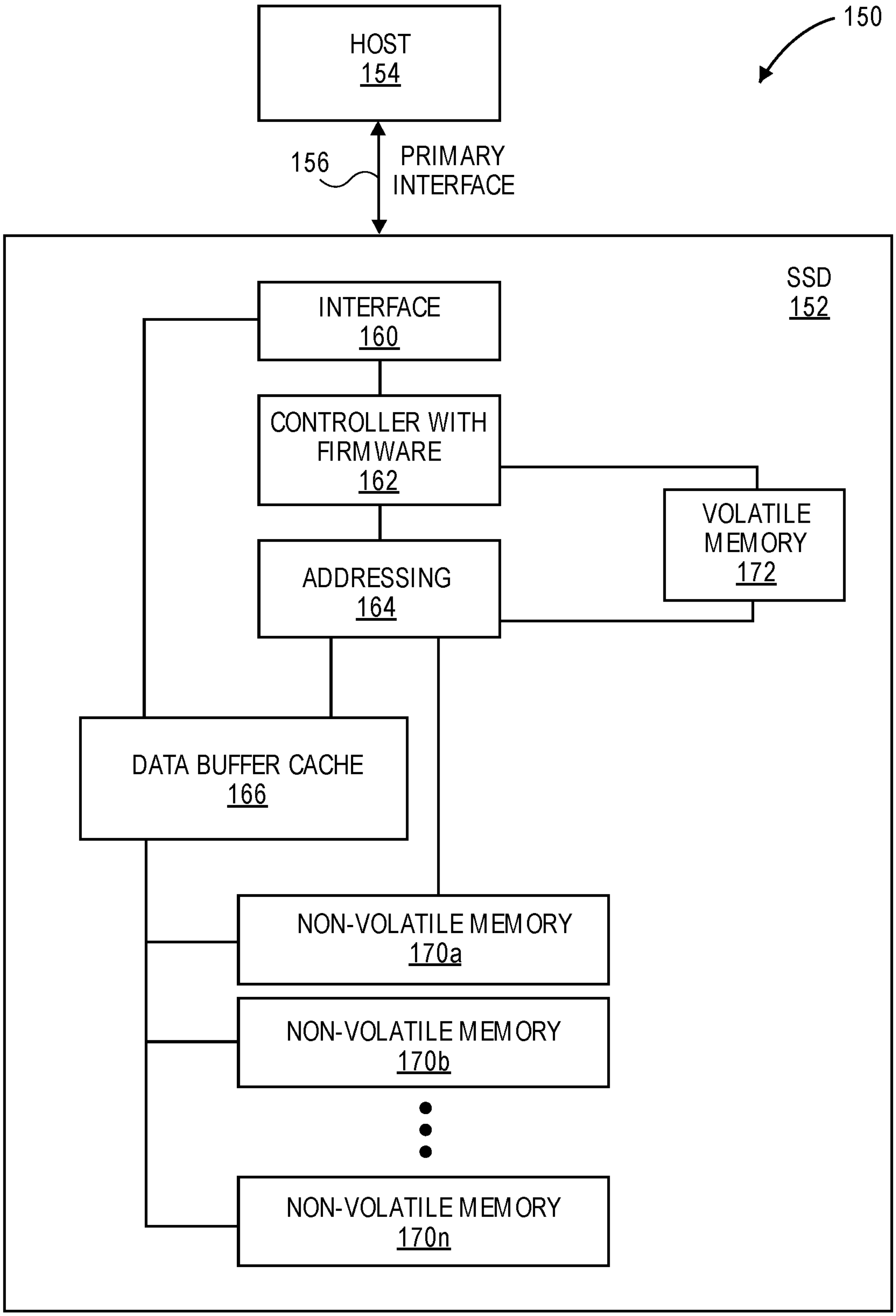

150
HOST
154
156
PRIMARY
INTERFACE
SSD
152
INTERFACE
160
CONTROLLER WITH
FIRMWARE
162
VOLATILE
MEMORY
172
ADDRESSING
164
DATA BUFFER CACHE
166
NON-VOLATILE MEMORY
170a
NON-VOLATILE MEMORY
170b
NON-VOLATILE MEMORY
170n

FIG. 1B

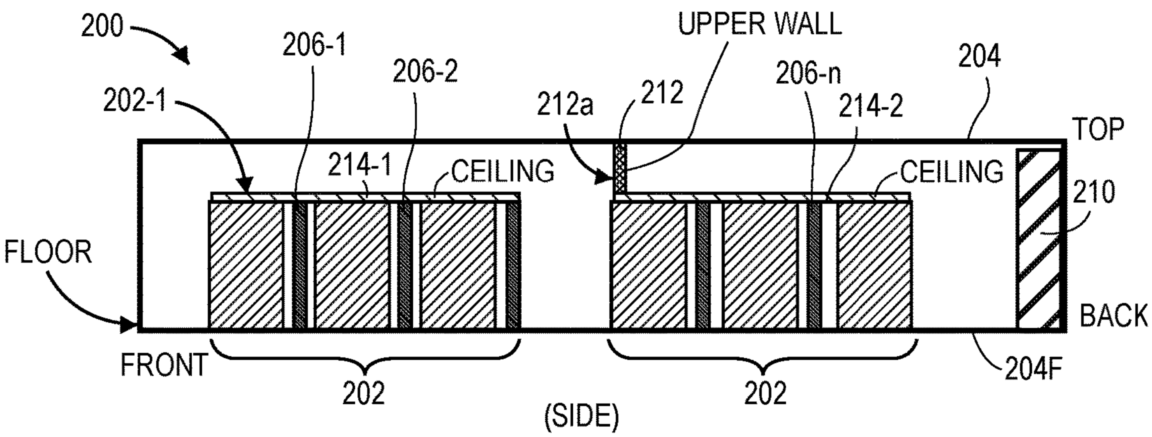

200
206-1
206-2
UPPER WALL
204
202-1
212a
212
206-n
214-2
TOP
214-1
CEILING
CEILING
210
FLOOR
BACK
FRONT
204F
202
202
(SIDE)

FIG. 2A

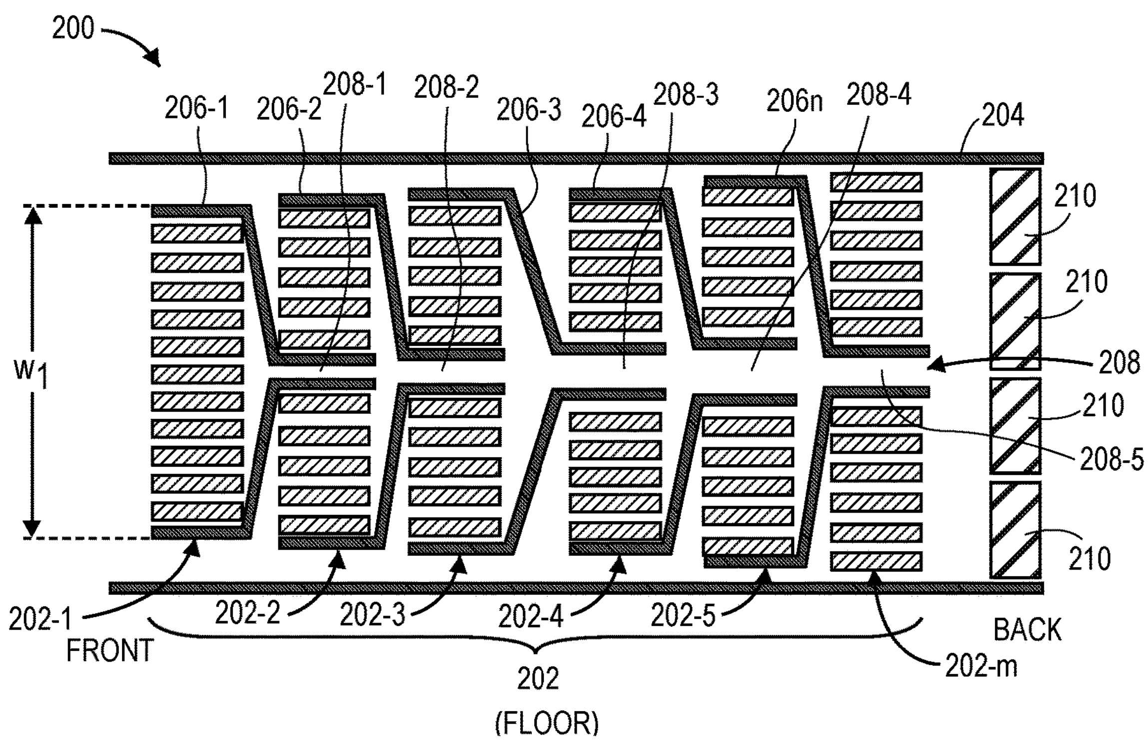
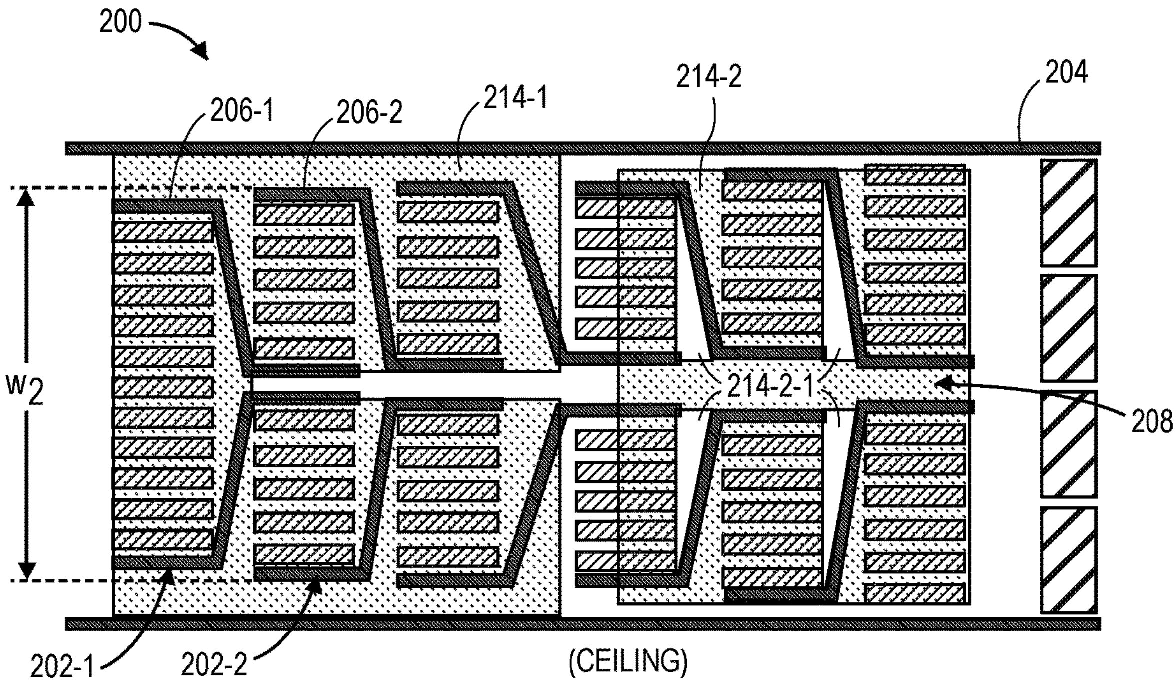
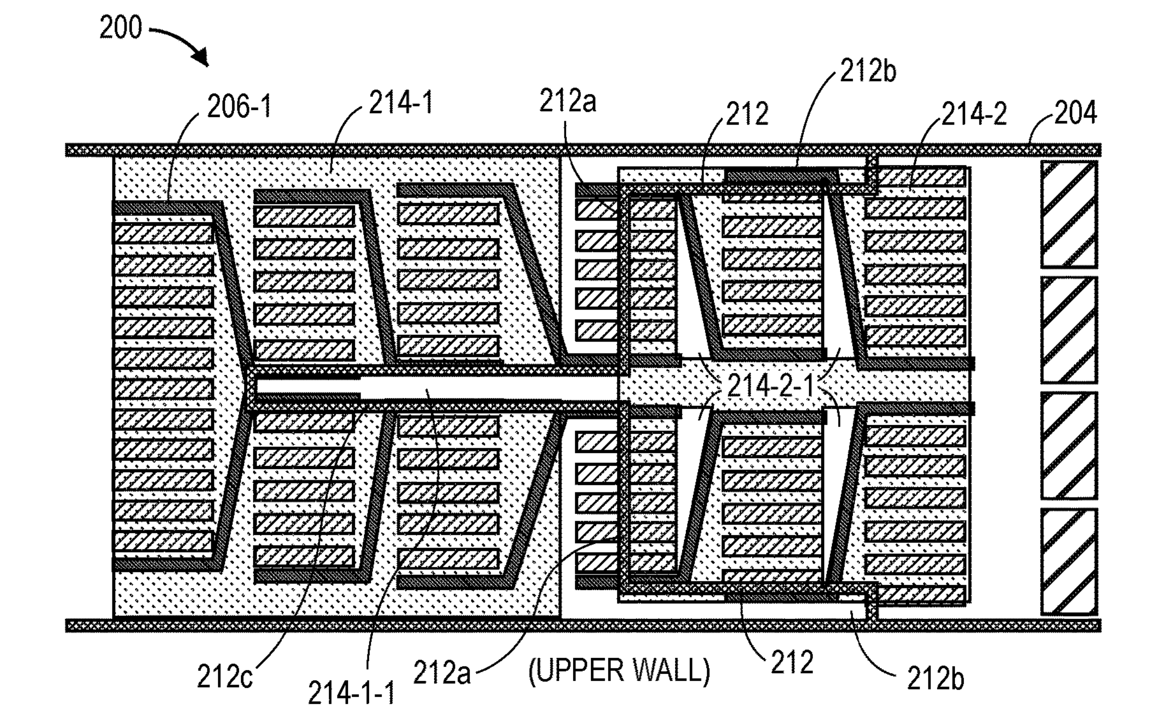

200
206-1
206-2
208-1
208-2
206-3
206-4
208-3
206n
208-4
204
210
210
w1
208
210
208-5
210
202-1
202-2
202-3
202-4
202-5
BACK
FRONT
202-m
202
(FLOOR)

FIG. 2B



200
206-1
206-2
214-1
214-2
204
$w_2$
214-2-1
208
202-1
202-2
(CEILING)


**FIG. 2C**



200
206-1
214-1
212a
212
212b
214-2
204
214-2-1
212c
214-1-1
212a
(UPPER WALL)
212
212b


**FIG. 2D**

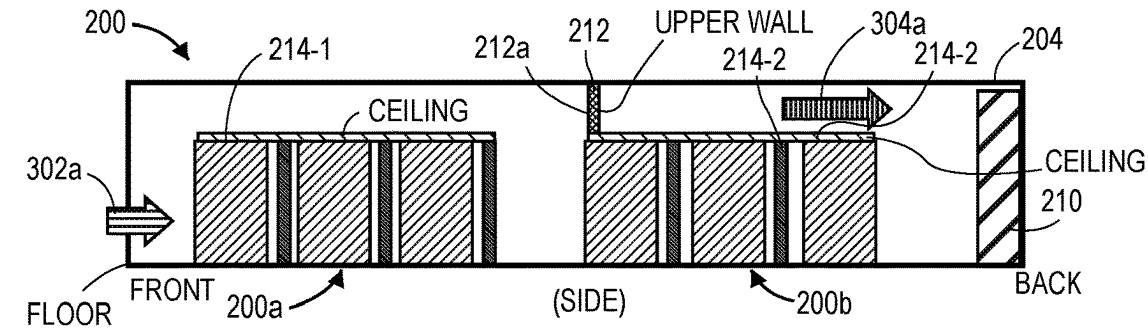



FIG. 3A

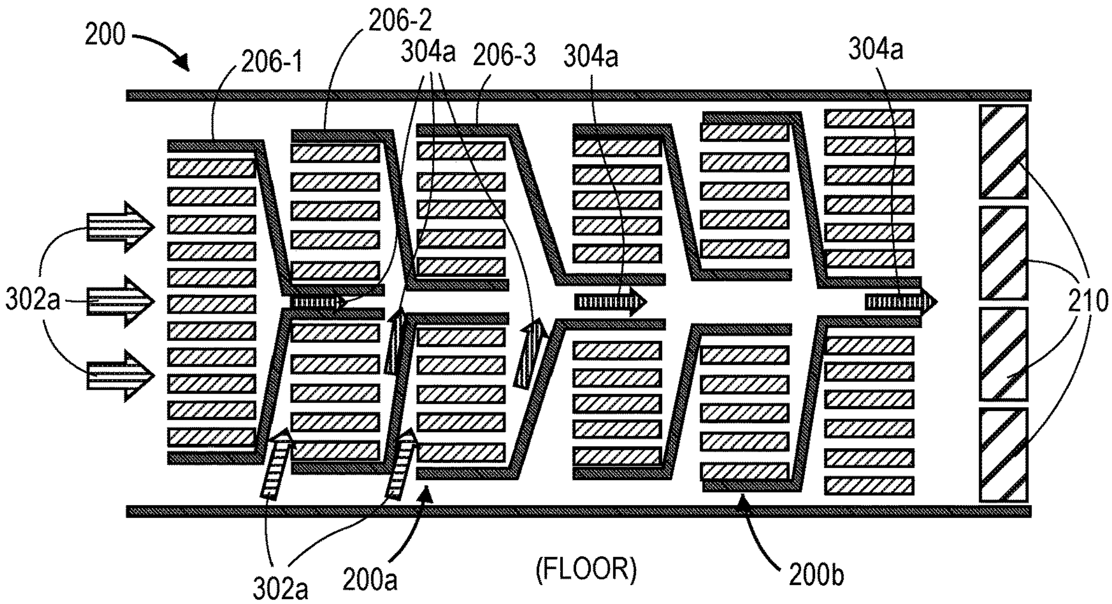



FIG. 3B

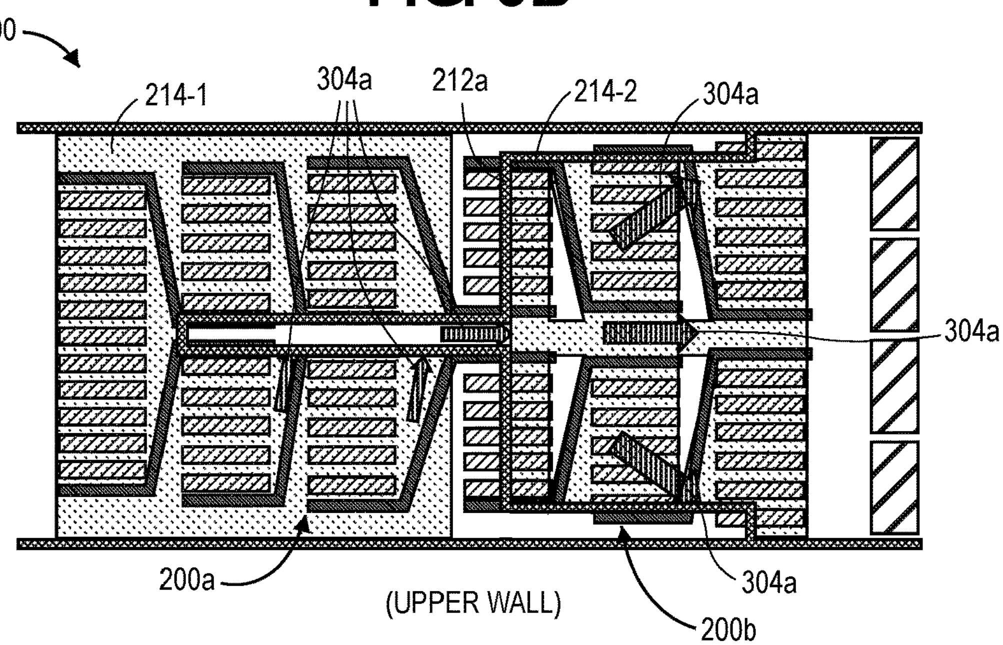



FIG. 3C

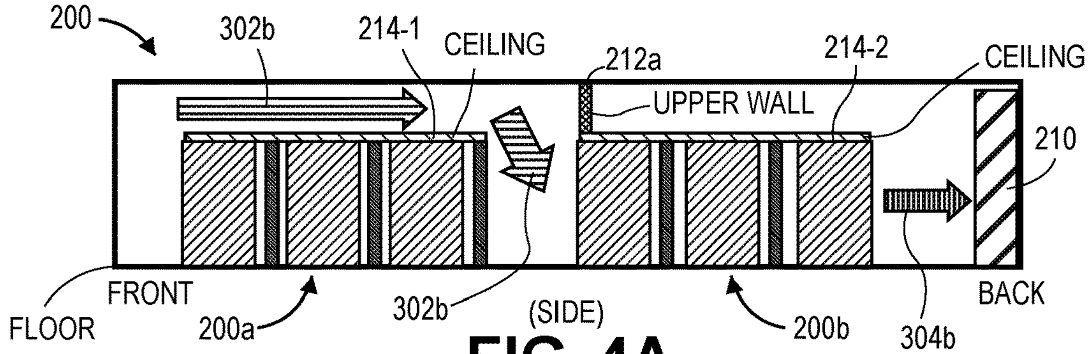



FIG. 4A

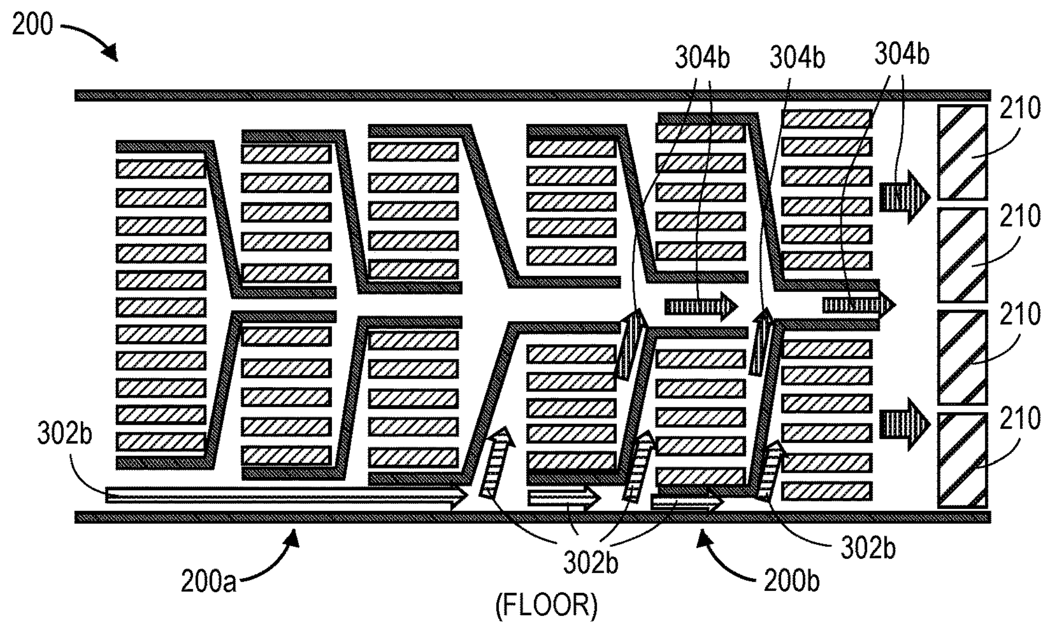



FIG. 4B

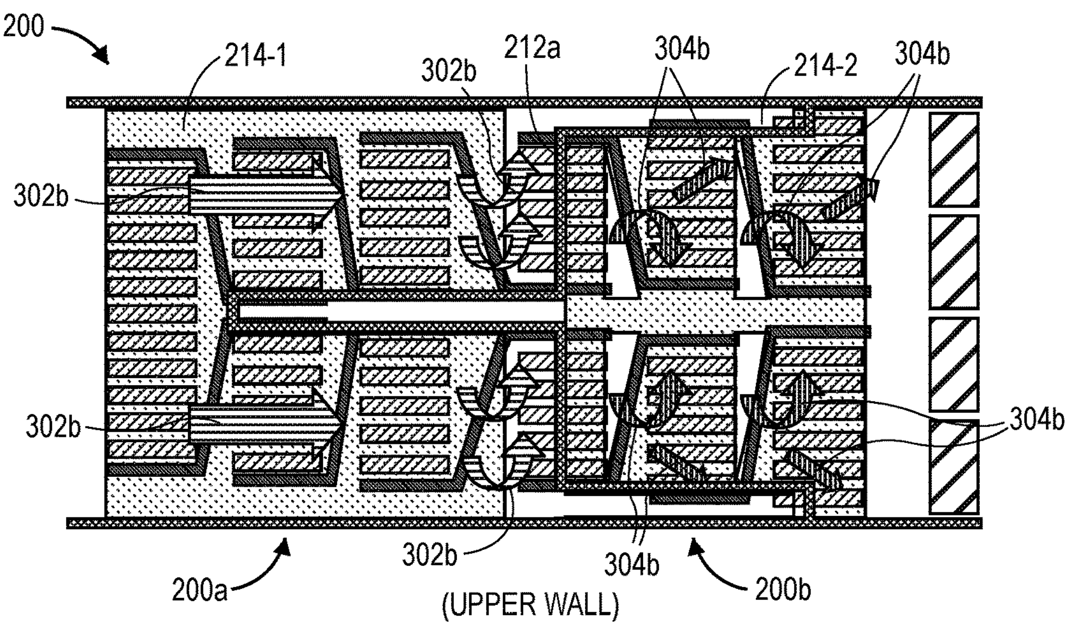



FIG. 4C

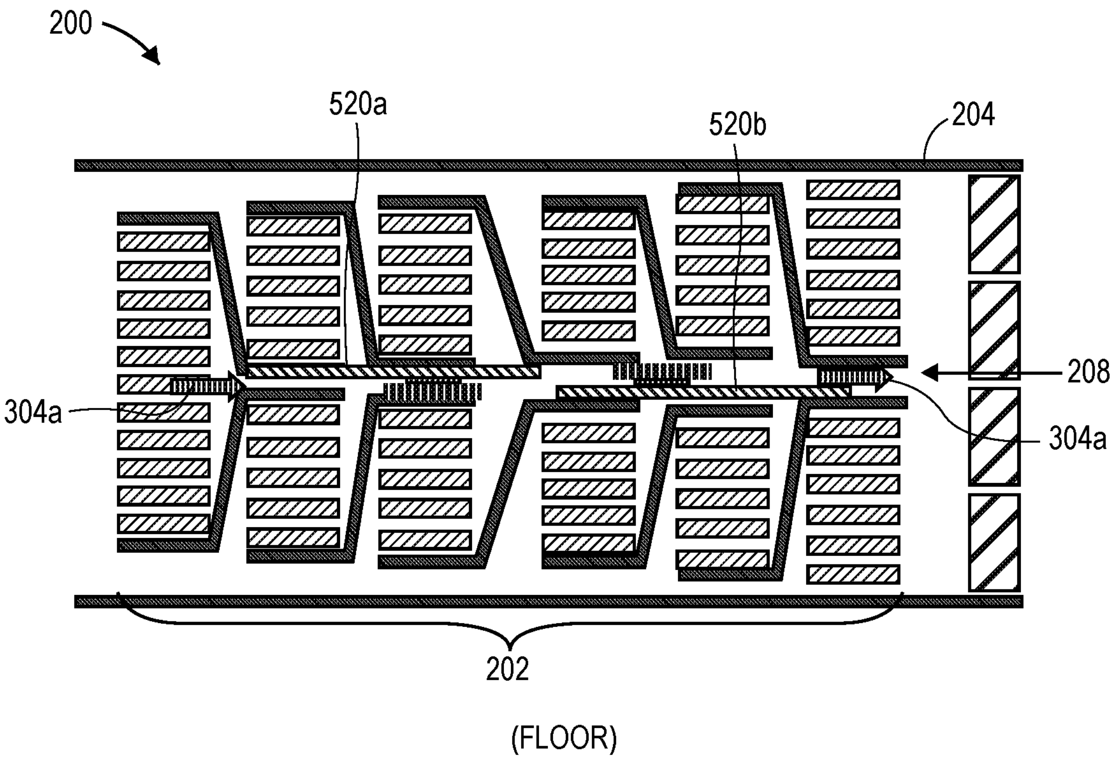



FIG. 5

# LOW-POWER LOW-NOISE DATA STORAGE ARRAY COOLING

## FIELD OF EMBODIMENTS

**[0001]** Embodiments of the invention may relate generally to arrays of storage devices, and particularly to guiding cooling air within a storage device array.

## BACKGROUND

**[0002]** As networked computing systems grow in numbers and capability, there is a need for more data storage system capacity. Cloud computing and large-scale data processing further increase the need for digital data storage systems that are capable of transferring and holding significant amounts of data. One approach to providing sufficient data storage in data centers is the use of arrays of data storage devices typically configured and provisioned as one or more data storage systems. Many data storage devices can be housed in an electronics enclosure, which is typically a modular unit that can hold and operate independent data storage devices in an array, computer processors, routers and other electronic equipment. For example, one such approach to vast data storage is referred to as a JBOD ("Just a Bunch of Disks", or "Just a Bunch of Drives"), which is typically a collection of hard disk drives (HDDs) that may be exposed as independent devices or combined to operate as one logical volume. A similar approach in the context of solid-state storage is referred to as a JBOF ("Just a Bunch of Flash"), which is typically a collection of solid-state drives (SSDs). Data centers may include many such rack-mountable data storage systems mounted within respective shelves of a larger enclosure, often referred to as a "rack", and which are used to store massive amounts of data. Temperature management within such a rack-mountable enclosure is of critical importance for proper and reliable operational capabilities of a data center and data storage system, generally, and of the constituent data storage devices, particularly.

**[0003]** Any approaches that may be described in this section are approaches that could be pursued, but not necessarily approaches that have been previously conceived or pursued. Therefore, unless otherwise indicated, it should not be assumed that any of the approaches described in this section qualify as prior art merely by virtue of their inclusion in this section.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0004]** Embodiments are illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings and in which like reference numerals refer to similar elements and in which:

**[0005]** FIG. **1**A is a plan view illustrating a hard disk drive (HDD), according to an embodiment;

**[0006]** FIG. **1**B is a block diagram illustrating a solid-state drive (SSD), according to an embodiment;

**[0007]** FIG. **2**A is a block diagram side view illustrating a data storage system, according to an embodiment;

**[0008]** FIG. **2**B is a first block diagram top view illustrating the data storage system of FIG. **2**A, according to an embodiment;

**[0009]** FIG. **2**C is a second block diagram top view illustrating the data storage system of FIG. **2**A, according to an embodiment;

**[0010]** FIG. **2**D is a third block diagram top view illustrating the data storage system of FIG. **2**A, according to an embodiment;

**[0011]** FIG. **3**A is a block diagram side view illustrating front section airflow for the data storage system of FIG. **2**A, according to an embodiment;

**[0012]** FIG. **3**B is a first block diagram top view illustrating front section airflow for the data storage system of FIG. **2**A, according to an embodiment;

**[0013]** FIG. **3**C is a second block diagram top view illustrating front section airflow for the data storage system of FIG. **2**A, according to an embodiment;

**[0014]** FIG. **4**A is a block diagram side view illustrating back section airflow for the data storage system of FIG. **2**A, according to an embodiment;

**[0015]** FIG. **4**B is a first block diagram top view illustrating back section airflow for the data storage system of FIG. **2**A, according to an embodiment;

**[0016]** FIG. **4**C is a second block diagram top view illustrating back section airflow for the data storage system of FIG. **2**A, according to an embodiment; and

**[0017]** FIG. **5** is a block diagram top view illustrating I/O module airflow for the data storage system of FIG. **2**A, according to an embodiment.

## DETAILED DESCRIPTION

**[0018]** Generally, approaches to data storage array cooling air guiding features are described. In the following description, for the purposes of explanation, numerous specific details are set forth to provide a thorough understanding of the embodiments of the invention described herein. It will be apparent, however, that the embodiments of the invention described herein may be practiced without these specific details. In other instances, well-known structures and devices may be shown in block diagram form to avoid unnecessarily obscuring the embodiments of the invention described herein.

## INTRODUCTION

### Terminology

**[0019]** References herein to "an embodiment", "one embodiment", and the like, are intended to mean that the particular feature, structure, or characteristic being described is included in at least one embodiment of the invention. However, instances of such phrases do not necessarily all refer to the same embodiment,

**[0020]** The term "substantially" will be understood to describe a feature that is largely or nearly structured, configured, dimensioned, etc., but with which manufacturing tolerances and the like may in practice result in a situation in which the structure, configuration, dimension, etc. is not always or necessarily precisely as stated. For example, describing a structure as "substantially vertical" would assign that term its plain meaning, such that the sidewall is vertical for all practical purposes but may not be precisely at 90 degrees throughout.

**[0021]** While terms such as "optimal", "optimize", "minimal", "minimize", "maximal", "maximize", and the like may not have certain values associated therewith, if such terms are used herein the intent is that one of ordinary skill in the art would understand such terms to include affecting a value, parameter, metric, and the like in a beneficial direction consistent with the totality of this disclosure. For example, describing a value of something as "minimal" does not require that the value actually be equal to some theoretical minimum (e.g., zero), but should be understood in a practical sense in that a corresponding goal would be to move the value in a beneficial direction toward a theoretical minimum.

## CONTEXT

**[0022]** Recall that many data storage devices can be housed in a shared enclosure, such as with a JBOD for a non-limiting example, and that data centers may include many such rack-mountable data storage systems mounted within a rack. Temperature management within such a rack-mountable enclosure is of critical importance for proper and reliable operational capabilities. Data centers consume huge amounts of power and operators are interested in ways to reduce power consumption, such as to save operating cost and to reduce environmental impact. Note that a significant portion of the power consumed by a data center is for equipment cooling purposes, e.g., for every watt of equipment power usage about a watt is used to cool the equipment. Generally, data center owners and operators seem to prefer high-density packing of data storage devices within a data storage system. However, high-density systems typically require higher cooling fan power, and powerful fans generate significant acoustic noise and corresponding vibration, which can degrade hard disk drive performance and may even prevent such system use except in dedicated locations such as closed rooms. Thus, the cooling needs of a data storage system remain a challenge, especially in view of the trend toward high-density storage systems in which many devices are packed closely together.

Cooling Airflow Guiding Structures within Data Storage System Enclosure

**[0023]** FIG. **2**A is a block diagram side view illustrating a data storage system, FIG. **2**B is a first block diagram top view illustrating the data storage system of FIG. **2**A, FIG. **2**C is a second block diagram top view illustrating the data storage system of FIG. **2**A, and FIG. **2**D is a third block diagram top view illustrating the data storage system of FIG. **2**A, all according to embodiments. In particular, FIG. **2**A is a simplified cross-sectional side view diagram along the width of the data storage system and illustrates a floor, an upper wall, and a ceiling over each of a plurality of sets or groupings of data storage devices. FIG. **2**B is a simplified diagram illustrating the data storage system of FIG. **2**A at the "floor" level, FIG. **2**C is a simplified diagram illustrating the data storage system of FIG. **2**A at the "ceiling" level, and FIG. **2**D is a simplified diagram illustrating the data storage system of FIG. **2**A at the "upper wall" level.

**[0024]** Data storage system **202** ("DSS 200") comprises a plurality of data storage devices **202**, such as hard disk drives (HDDs) and/or solid-state drives (SSDs), housed in a plurality of rows in an enclosure **204**. According to an embodiment, within the enclosure **204**, DSS **200** further comprises one or more cooling airflow guiding structural features, including a first funnel structure **206-1** extending from a floor **204*f*** of the enclosure **204**, and within which at least part of a first row **202-1** of the data storage devices **202** is positioned, where the first funnel structure **206-1** has a first width w**1** and is configured to direct airflow past the first row **202-1** to a first central exhaust channel **208-1**. DSS **200** further comprises a second funnel structure **206-2** extending from the floor **204*f*** of the enclosure **204**, and within which at least part of a second row **202-2** of the data storage devices **202** is positioned, where the second funnel structure **206-2** has a second width w**2** that is greater (i.e., wider) than the first width w**1** and is configured to direct airflow past the second row **202-2** to a second central exhaust channel **208-2** substantially colinear with the first exhaust channel **208-1**. According to an embodiment, the second exhaust channel **208-2** is wider than the first exhaust channel **208-1**, thus enabling increasingly more exhaust (e.g., warm) airflow from front to back as the rows are traversed. According to an embodiment, DSS **200** further comprises one or more cooling fans **210**, depicted here at the back of the enclosure **204** for purposes of example. According to an embodiment, the cooling fans **210** are constituent to one or more power supply unit (PSU). That is, with four appropriately sized PSU cooling fans (for a non-limiting example, around 3.5 Watt each), the desired airflow and redundancy for DSS **200** is considered achievable without the need for additional cooling fans.

**[0025]** Stated otherwise, DSS **200** comprises a series of funnel structures **206-1**, **206-2**, **206-3**, **206-4** through **206-*n***, where n represents an arbitrary number of funnel structures that may vary from implementation to implementation, extending upward from the floor **204*f*** of the enclosure **204** and within which a respective row **202-1**, **202-2** through **202-*m*** of data storage devices **202** is positioned, where m represents an arbitrary number of rows that may vary from implementation to implementation. The funnel structures **206-1** through **206-*n*** are configured successively wider from a front toward a back of the enclosure **204** to direct airflow past each respective row **202-1**, **202-2** through **202-*m*** to a successively wider central exhaust channel **208**. The successively wider funnel structures enable airflow intake to respective successive rows of devices, and in view of decreasing air pressure in the direction from front to back as the rows are traversed. Note that the cooling airflow system may be effectively run in reverse, where the airflow inlet would be the central channel **208** (i.e., back-to-front the channel would be a convergent channel) and the airflow outlet would be the two side channels outboard of the series of funnel structures **206-1** through **206-*n*** (back-to-front these side channels would be divergent).

**[0026]** With reference to FIG. **2**D, according to an embodiment DSS **200** further comprises an upper wall structure **212** positioned above the data storage devices **202** and extending to an enclosure top. The upper wall structure **212** is configured at least in part to effectively or functionally separate a first set of rows (e.g., three rows **202-1** through **202-3** depicted here for purposes of example; see, e.g., FIG. **2**B) of data storage devices **202**, including the aforementioned first row **202-1** and second row **202-2**, from a second set of rows (e.g., three rows **202-4** through **202-*m*** depicted here for purposes of example; see, e.g., FIG. **2**B) of data storage devices **202**. According to an embodiment, the upper wall structure comprises a deflector portion **212*a*** positioned over a first row of data storage devices of the second set of rows **202-4** through **202-*m***, which is configured to direct or guide the airflow from above the devices down to the second set of rows **202-4** through **202-*m***.

**[0027]** With reference to FIG. **2**D, according to an embodiment the upper wall structure **212** of DSS **200** further comprises at least one side channel **212*b*** (e.g., two side channels **212*b*** depicted here for purposes of example) extending beyond the deflector portion **212**_a_ in a direction toward the back of the enclosure **204**. The side channel **212**_b_ is configured to direct airflow from above down to one or more successive rows of data storage devices, beyond the first row, of the second set of rows (e.g., rows **202-5** through **202**-_m_; see, e.g., FIG. **2**B).

**[0028]** According to an embodiment, DSS **200** further comprises a first ceiling structure **214-1** (FIGS. **2**C-**2**D) over the first set of rows **202-1** through **202-3**, and a second ceiling structure **214-2** (FIGS. **2**C-**2**D) over the second set of rows **202-4** through **202**-_m_. Such ceiling structures facilitate maintaining some degree of separation or isolation of relatively cooler cooling airflow, e.g., from the storage device "bays" under each respective ceiling, from relatively warmer exhaust airflow, e.g., from above the storage device "bays" over each respective ceiling to which at least some of the exhaust air is directed or enabled to flow.

**[0029]** According to an embodiment, the upper wall structure **212** further comprises a central channel **212**_c_ (FIG. **2**D) extending in a direction toward the front of the enclosure **204** and over a cutout portion **214-1-1** (FIG. **2**D) of the first ceiling structure **214-1**. The central channel **212**_c_ of the upper wall structure **212** is configured to receive exhaust airflow from first set of rows **202-1** through **202-3** to above the first set of rows via the cutout portion **214-1-1** of the first ceiling **214-1**. Furthermore and according to an embodiment, the second ceiling structure **214-2** also comprises at least one cutout portion **214-2-1** configured to enable exhaust airflow from the second set of rows **202-4** through **202**-_m_ to above the second set of rows beyond the deflector portion **212**_a_ of the upper wall structure **212** in a direction toward the back of the enclosure **204**. According to a related embodiment, the at least one cutout portion **214-2-1** of the second ceiling structure **214-2** comprises a cutout portion **214-2-1** corresponding to each of multiple rows of the second set of rows **202-4** through **202**-_m_, as depicted as triangular portions in FIGS. **2**C-**2**D. Each cutout portion **214-2-1** is positioned beyond a respective row in a direction toward the back of the enclosure **204**, as depicted in FIGS. **2**C-**2**D, and configured to enable exhaust airflow from the respective row.

**[0030]** Note that the entire array of drives and the motherboard they are mounted on may be elevated, such that the gap between drives **202**_a_-**202**_m_ and enclosure **204** (here, the bottom rather than the top) exists at the basement and not the ceiling. All else would effectively be the same, except that inlet fresh air plenum(s) and exhaust plenum(s) would be positioned below the drives **202**_a_-**202**_m_ rather than above them. Such a configuration may enable the utilization of more air gaps that are inherently existent below the motherboard, but would likely rely on cutouts to the motherboard which is considered undesirable.

## Cooling Airflow Diagrams for Front Section of Devices

**[0031]** FIG. **3**A is a block diagram side view illustrating front section airflow for the data storage system of FIG. **2**A, FIG. **3**B is a first block diagram top view illustrating front section airflow for the data storage system of FIG. **2**A, and FIG. **3**C is a second block diagram top view illustrating front section airflow for the data storage system of FIG. **2**A, all according to embodiments. In particular, FIG. **3**A is a simplified cross-sectional side view diagram along the width of the data storage system **200** similar to FIG. **2**A, and illustrates a floor, an upper wall, and a ceiling over each of the sets or groupings of data storage devices, e.g., a front (or "first") section and a back (or "second") section. FIG. **3**B is a simplified diagram illustrating the data storage system of FIG. **2**A at the "floor" level similar to FIG. **2**B, and FIG. **3**C is a simplified diagram illustrating the data storage system of FIG. **2**A at the "upper wall" level similar to FIG. **2**D. FIGS. **3**A-**3**C are set forth to aid in understanding the general effect of the aforementioned structures on the internal airflow. In each, block arrows having a horizontal cross-hatching are used to represent relatively cool (e.g., blue) cooling airflow and block arrows having a vertical cross-hatching are used to represent relatively warm (e.g., red) exhaust airflow.

**[0032]** FIG. **3**A depicts relatively cool airflow **302**_a_ coming into enclosure **204** of DSS **200** and flowing through a front section **200**_a_ of DSS **200**, such as equipment cooling airflow generated by one or more fan **210**. Here, fan **210** is shown at the back of enclosure **204** with the cool airflow **302**_a_ entering at the front of enclosure **204**, for purposes of example. However, such positioning may vary or may be reversed. FIG. **3**A further depicts relatively warm airflow **304**_a_ flowing from the front section **200**_a_ into and along the central channel **212**_c_ (FIG. **2**D) of upper wall **212** (FIGS. **2**A, **2**D) via cutout portion **214-1-1** (FIG. **2**D) of ceiling **214-1**, and over a back section **200**_b_ of DSS **200**, i.e., over ceiling **214-2** and behind or beyond deflector portion **212**_a_ of upper wall **212**.

**[0033]** FIG. **3**B depicts, generally at the floor level, the relatively cool airflow **302**_a_ coming into enclosure **204** of DSS **200**, and particularly into each funnel structure **206-1**, **206-2**, **206-3** (FIG. **2**B) (including into the side inlet/intake portions of funnel structure **206-2**, **206-3**), and flowing through the front section **200**_a_ of rows **202-1**, **202-2**, **202-3** of data storage devices **202** (see, e.g., FIG. **2**B) of DSS **200**. FIG. **3**B further depicts relatively warm airflow **304**_a_ flowing to each respective central exhaust channel **208-1**, **208-2**, **208-3** (FIG. **2**B), collectively central exhaust channel **208** (FIGS. **2**B-**2**C), and out the back via multiple fans **210**.

**[0034]** FIG. **3**C depicts, generally at the upper wall level, the relatively warm airflow **304**_a_ flowing upward from the front section **200**_a_ and into the central channel **212**_c_ (FIG. **2**D) of upper wall **212** (FIGS. **2**A, **2**D) via cutout portion **214-1-1** (FIG. **2**D) of ceiling **214-1**. FIG. **3**C further depicts the relatively warm airflow **304**_a_ continuing to flow over the back section **200**_b_ from the front section **200**_a_, over ceiling **214-2** beyond deflector portion **212**_a_ of upper wall **212**.

## Cooling Airflow Diagram for Input/Output Module

**[0035]** FIG. **5** is a block diagram top view illustrating I/O module airflow for the data storage system of FIG. **2**A, according to an embodiment. According to an embodiment, DSS **200** further comprises at least one I/O (Input/Output) module **520**_a_, **520**_b_ positioned within the central exhaust channel **208**, which generally enable connectivity and communication with the data storage devices **202**. Each I/O module **520**_a_, **520**_b_ is positioned centrally within the enclosure **204** to minimize latency with the data storage devices **202**, which is relative to the distance between I/O module **520** and the data storage devices **202** with which they are in communication. Furthermore, the I/O modules **520**_a_, **520**_b_ are staggered relative to each side of the central exhaust channel **208** to minimize the impact on the warm airflow **304**_a_ through the central exhaust channel **208**.

Cooling Airflow Diagrams for Back Section of Devices

**[0036]** FIG. **4**A is a block diagram side view illustrating second section airflow for the data storage system of FIG. **2**A, FIG. **4**B is a first block diagram top view illustrating second section airflow for the data storage system of FIG. **2**A, and FIG. **4**C is a second block diagram top view illustrating second section airflow for the data storage system of FIG. **2**A, all according to embodiments. In particular, FIG. **4**A is a simplified cross-sectional side view diagram along the width of the data storage system **200** similar to FIG. **2**A, and illustrates a floor, an upper wall, and a ceiling over each of the sets or groupings of data storage devices, e.g., a front (or "first") section and a back (or "second") section. FIG. **4**B is a simplified diagram illustrating the data storage system of FIG. **2**A at the "floor" level similar to FIGS. **2**B, **3**B; and FIG. **4**C is a simplified diagram illustrating the data storage system of FIG. **2**A at the "upper wall" level similar to FIGS. **2**D, **3**C. FIGS. **4**A-**4**C are set forth to aid in understanding the general effect of the aforementioned structures on the internal airflow. In each, block arrows having a horizontal cross-hatching are used to represent relatively cool (e.g., blue) cooling airflow and block arrows having a vertical cross-hatching are used to represent relatively warm (e.g., red) exhaust airflow.

**[0037]** FIG. **4**A depicts relatively cool airflow **302***b* flowing over the ceiling **214-1** of front section **200***a* of DSS **200**, such as equipment cooling airflow generated by one or more fan **210**, and then flowing downward to the back section **200***b* under the guidance or deflection of the deflector portion **212***a* of upper wall **212**. FIG. **4**A further depicts relatively warm airflow **304***b* flowing from the back section **200***b* and out the back via fan **210**.

**[0038]** FIG. **4**B depicts, generally at the floor level, the relatively cool airflow **302***b* coming into enclosure **204** of DSS **200** and flowing past funnel structures **206-1**, **206-2**, **206-3** (FIG. **2**B) along the increasingly narrow side channels of the front section **200***a* and into the side inlet/intake portions of funnel structure **206-4** through **206-***n* (FIG. **2**B) of the back section **200***b*, and flowing through the back section **200***b* of rows **202-4**, **202-5**, **202-***m* of data storage devices **202** (see, e.g., FIG. **2**B) of DSS **200**. FIG. **4**B further depicts the relatively warm airflow **304***b* flowing to each respective central exhaust channel **208-4**, **208-5** (FIG. **2**B) of each funnel structure **206-4** through **206-***n* (FIG. **2**B) of the back section **200***b*, collectively central exhaust channel **208** (FIGS. **2**B-**2**C), and out the back via multiple fans **210**.

**[0039]** FIG. **4**C depicts, generally at the upper wall level, the relatively cool airflow **302***b* flowing over the front section **200***a* and downward to the back section **200***b* under the guidance or deflection of the deflector portion **212***a* of upper wall **212**. FIG. **4**C further depicts the relatively warm airflow **304***b* flowing upward via one or more cutout **214-2-1** of ceiling **214-2** of back section **200***b* and over the ceiling **214-2** of back section **200***b* beyond deflector portion **212***a* of upper wall **212**.

**[0040]** In view of the foregoing cooling air structural guiding features, a data storage array such as data storage system **200** is provisioned with a low power, low operating cost, low acoustic noise cooling regime. Embodiments provide for relatively "fresh" cooling air coming to each drive separately, thereby enabling for significantly low airflow rates and low pressure losses. Furthermore, embodiments enable "used" exhaust air to exit the drive array as rapidly as practical to avoid contaminating cool air.

Hard Disk Drive Configuration

**[0041]** As discussed, embodiments may be used in the context of a data storage system in which multiple data storage devices (DSDs) including hard disk drives (HDDs) are employed. Thus, in accordance with an embodiment, a plan view illustrating an HDD **100** is shown in FIG. **1**A to illustrate exemplary operating components.

**[0042]** FIG. **1**A illustrates the functional arrangement of components of the HDD **100** including a slider **110***b* that includes a magnetic read-write head **110***a*. Collectively, slider **110***b* and head **110***a* may be referred to as a head slider. The HDD **100** includes at least one head gimbal assembly (HGA) **110** including the head slider, a lead suspension **110***c* attached to the head slider typically via a flexure, and a load beam **110***d* attached to the lead suspension **110***c*. The HDD **100** also includes at least one recording medium **120** rotatably mounted on a spindle **124** and a drive motor (not visible) attached to the spindle **124** for rotating the medium **120**. The read-write head **110***a*, which may also be referred to as a transducer, includes a write element and a read element for respectively writing and reading information stored on the medium **120** of the HDD **100**. The medium **120** or a plurality of disk media may be affixed to the spindle **124** with a disk clamp **128**.

**[0043]** The HDD **100** further includes an arm **132** attached to the HGA **110**, a carriage **134**, a voice coil motor (VCM) that includes an armature **136** including a voice coil **140** attached to the carriage **134** and a stator **144** including a voice-coil magnet (not visible). The armature **136** of the VCM is attached to the carriage **134** and is configured to move the arm **132** and the HGA **110** to access portions of the medium **120**, all collectively mounted on a pivot shaft **148** with an interposed pivot bearing assembly **152**. In the case of an HDD having multiple disks, the carriage **134** may be referred to as an "E-block," or comb, because the carriage is arranged to carry a ganged array of arms that gives it the appearance of a comb.

**[0044]** An assembly comprising a head gimbal assembly (e.g., HGA **110**) including a flexure to which the head slider is coupled, an actuator arm (e.g., arm **132**) and/or load beam to which the flexure is coupled, and an actuator (e.g., the VCM) to which the actuator arm is coupled, may be collectively referred to as a head-stack assembly (HSA). An HSA may, however, include more or fewer components than those described. For example, an HSA may refer to an assembly that further includes electrical interconnection components. Generally, an HSA is the assembly configured to move the head slider to access portions of the medium **120** for read and write operations.

**[0045]** With further reference to FIG. **1**, electrical signals (e.g., current to the voice coil **140** of the VCM) comprising a write signal to and a read signal from the head **110***a*, are transmitted by a flexible cable assembly (FCA) **156** (or "flex cable"). Interconnection between the flex cable **156** and the head **110***a* may include an arm-electronics (AE) module **160**, which may have an on-board pre-amplifier for the read signal, as well as other read-channel and write-channel electronic components. The AE module **160** may be attached to the carriage **134** as shown. The flex cable **156** may be coupled to an electrical-connector block **164**, which provides electrical communication, in some configurations, through an electrical feed-through provided by an HDD housing **168**. The HDD housing **168** (or "enclosure base" or "baseplate" or simply "base"), in conjunction with an HDD cover, provides a semi-sealed (or hermetically sealed, in some configurations) protective enclosure for the information storage components of the HDD **100**.

**[0046]** Other electronic components, including a disk controller and servo electronics including a digital-signal processor (DSP), provide electrical signals to the drive motor, the voice coil **140** of the VCM and the head **110***a* of the HGA **110**. The electrical signal provided to the drive motor enables the drive motor to spin providing a torque to the spindle **124** which is in turn transmitted to the medium **120** that is affixed to the spindle **124**. As a result, the medium **120** spins in a direction **172**. The spinning medium **120** creates a cushion of air that acts as an air-bearing on which the air-bearing surface (ABS) of the slider **110***b* rides so that the slider **110***b* flies above the surface of the medium **120** without making contact with a thin magnetic-recording layer in which information is recorded. Similarly in an HDD in which a lighter-than-air gas is utilized, such as helium for a non-limiting example, the spinning medium **120** creates a cushion of gas that acts as a gas or fluid bearing on which the slider **110***b* rides.

**[0047]** The electrical signal provided to the voice coil **140** of the VCM enables the head **110***a* of the HGA **110** to access a track **176** on which information is recorded. Thus, the armature **136** of the VCM swings through an arc **180**, which enables the head **110***a* of the HGA **110** to access various tracks on the medium **120**. Information is stored on the medium **120** in a plurality of radially nested tracks arranged in sectors on the medium **120**, such as sector **184**. Correspondingly, each track is composed of a plurality of sectored track portions (or "track sector") such as sectored track portion **188**. Each sectored track portion **188** may include recorded information, and a header containing error correction code information and a servo-burst-signal pattern, such as an ABCD-servo-burst-signal pattern, which is information that identifies the track **176**. In accessing the track **176**, the read element of the head **110***a* of the HGA **110** reads the servo-burst-signal pattern, which provides a position-error-signal (PES) to the servo electronics, which controls the electrical signal provided to the voice coil **140** of the VCM, thereby enabling the head **110***a* to follow the track **176**. Upon finding the track **176** and identifying a particular sectored track portion **188**, the head **110***a* either reads information from the track **176** or writes information to the track **176** depending on instructions received by the disk controller from an external agent, for example, a microprocessor of a computer system.

**[0048]** An HDD's electronic architecture comprises numerous electronic components for performing their respective functions for operation of an HDD, such as a hard disk controller ("HDC"), an interface controller, an arm electronics module, a data channel, a motor driver, a servo processor, buffer memory, etc. Two or more of such components may be combined on a single integrated circuit board referred to as a "system on a chip" ("SOC"). Several, if not all, of such electronic components are typically arranged on a printed circuit board that is coupled to the bottom side of an HDD, such as to HDD housing **168**.

**[0049]** References herein to a hard disk drive, such as HDD **100** illustrated and described in reference to FIG. **1**, may encompass an information storage device that is at times referred to as a "hybrid drive". A hybrid drive refers generally to a storage device having functionality of both a traditional HDD (see, e.g., HDD **100**) combined with solid-state storage device (SSD) using non-volatile memory, such as flash or other solid-state (e.g., integrated circuits) memory, which is electrically erasable and programmable. As operation, management and control of the different types of storage media typically differ, the solid-state portion of a hybrid drive may include its own corresponding controller functionality, which may be integrated into a single controller along with the HDD functionality. A hybrid drive may be architected and configured to operate and to utilize the solid-state portion in a number of ways, such as, for non-limiting examples, by using the solid-state memory as cache memory, for storing frequently-accessed data, for storing I/O intensive data, and the like. Further, a hybrid drive may be architected and configured essentially as two storage devices in a single enclosure, i.e., a traditional HDD and an SSD, with either one or multiple interfaces for host connection.

Solid State Drive Configuration

**[0050]** As discussed, embodiments may be used in the context of a data storage system in which multiple data storage devices (DSDs) including solid-state drives (SSDs) are employed. Thus, FIG. **1**B is a block diagram illustrating an example operating context with which embodiments of the invention may be implemented. FIG. **1**B illustrates a generic SSD architecture **150**, with an SSD **152** communicatively coupled with a host **154** through a primary communication interface **156**. Embodiments are not limited to a configuration as depicted in FIG. **1**B, rather, embodiments may be implemented with SSD configurations other than that illustrated in FIG. **1**B. For example, embodiments may be implemented to operate in other environments that rely on non-volatile memory storage components for writing and reading of data.

**[0051]** Host **154** broadly represents any type of computing hardware, software, or firmware (or any combination of the foregoing) that makes, among others, data I/O requests or calls to one or more memory device. For example, host **154** may be an operating system executing on a computer, a tablet, a mobile phone, or generally any type of computing device that contains or interacts with memory, such as host **350** (FIG. **3**). The primary interface **156** coupling host **154** to SSD **152** may be, for example, a storage system's internal bus or a communication cable or a wireless communication link, or the like.

**[0052]** The example SSD **152** illustrated in FIG. **1**B includes an interface **160**, a controller **162** (e.g., a controller having firmware logic therein), an addressing **164** function block, data buffer cache **166**, and one or more non-volatile memory components **170***a*, **170***b*-**170***n*.

**[0053]** Interface **160** is a point of interaction between components, namely SSD **152** and host **154** in this context, and is applicable at the level of both hardware and software. This enables a component to communicate with other components via an input/output (I/O) system and an associated protocol. A hardware interface is typically described by the mechanical, electrical and logical signals at the interface and the protocol for sequencing them. Some non-limiting examples of common and standard interfaces include SCSI (Small Computer System Interface), SAS (Serial Attached SCSI), and SATA (Serial ATA).

**[0054]** An SSD **152** includes a controller **162**, which incorporates the electronics that bridge the non-volatile memory components (e.g., NAND (NOT-AND) flash) to the host, such as non-volatile memory **170***a*, **170***b*, **170***n* to host

**154**. The controller is typically an embedded processor that executes firmware-level code and is an important factor in SSD performance.

**[0055]** Controller **162** interfaces with non-volatile memory **170***a*, **170***b*, **170***n* via an addressing **164** function block. The addressing **164** function operates, for example, to manage mappings between logical block addresses (LBAs) from the host **154** to a corresponding physical block address on the SSD **152**, namely, on the non-volatile memory **170***a*, **170***b*, **170***n* of SSD **152**. Because the non-volatile memory page and the host sectors are different sizes, an SSD has to build and maintain a data structure that enables it to translate between the host writing data to or reading data from a sector, and the physical non-volatile memory page on which that data is actually placed. This table structure or "mapping" may be built and maintained for a session in the SSD's volatile memory **172**, such as DRAM (dynamic random-access memory) or some other local volatile memory component accessible to controller **162** and addressing **164**. Alternatively, the table structure may be maintained more persistently across sessions in the SSD's non-volatile memory such as non-volatile memory **170***a*, **170***b*-**170***n*.

**[0056]** Addressing **164** interacts with data buffer cache **166**, in addition to non-volatile memory **170***a*, **170***b*-**170***n*. Data buffer cache **166** of an SSD **152** typically uses DRAM as a cache, similar to the cache in hard disk drives. Data buffer cache **166** serves as a buffer or staging area for the transmission of data to and from the non-volatile memory components, as well as serves as a cache for speeding up future requests for the cached data. Data buffer cache **166** is typically implemented with volatile memory so the data stored therein is not permanently stored in the cache, i.e., the data is not persistent.

**[0057]** Finally, SSD **152** includes one or more non-volatile memory **170***a*, **170***b*-**170***n* components. For a non-limiting example, the non-volatile memory components **170***a*, **170***b*-**170***n* may be implemented as flash memory (e.g., NAND or NOR flash), or other types of solid-state memory available now or in the future. The non-volatile memory **170***a*, **170***b*-**170***n* components are the actual memory electronic components on which data is persistently stored. The non-volatile memory **170***a*, **170***b*-**170***n* components of SSD **152** can be considered the analogue to the hard disks in hard-disk drive (HDD) storage devices.

**[0058]** Furthermore, references herein to a data storage device may encompass a multi-medium storage device (or "multi-medium device", which may at times be referred to as a "multi-tier device" or "hybrid drive"). A multi-medium storage device refers generally to a storage device having functionality of both a traditional HDD (see, e.g., HDD **100**) combined with an SSD (see, e.g., SSD **150**) using non-volatile memory, such as flash or other solid-state (e.g., integrated circuits) memory, which is electrically erasable and programmable. As operation, management and control of the different types of storage media typically differ, the solid-state portion of a hybrid drive may include its own corresponding controller functionality, which may be integrated into a single controller along with the HDD functionality. A multi-medium storage device may be architected and configured to operate and to utilize the solid-state portion in a number of ways, such as, for non-limiting examples, by using the solid-state memory as cache memory, for storing frequently-accessed data, for storing I/O intensive data, for storing metadata corresponding to payload data (e.g., for assisting with decoding the payload data), and the like. Further, a multi-medium storage device may be architected and configured essentially as two storage devices in a single enclosure, i.e., a traditional HDD and an SSD, with either one or multiple interfaces for host connection.

Extensions and Alternatives

**[0059]** In the foregoing description, embodiments of the invention have been described with reference to numerous specific details that may vary from implementation to implementation. Therefore, various modifications and changes may be made thereto without departing from the broader spirit and scope of the embodiments. Thus, the sole and exclusive indicator of what is the invention, and is intended by the applicants to be the invention, is the set of claims that issue from this application, in the specific form in which such claims issue, including any subsequent correction. Any definitions expressly set forth herein for terms contained in such claims shall govern the meaning of such terms as used in the claims. Hence, no limitation, element, property, feature, advantage or attribute that is not expressly recited in a claim should limit the scope of such claim in any way. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense.

**[0060]** In addition, in this description certain process steps may be set forth in a particular order, and alphabetic and alphanumeric labels may be used to identify certain steps. Unless specifically stated in the description, embodiments are not necessarily limited to any particular order of carrying out such steps. In particular, the labels are used merely for convenient identification of steps, and are not intended to specify or require a particular order of carrying out such steps.

What is claimed is:

**1**. A data storage system comprising:

a plurality of data storage devices;

an enclosure in which the data storage devices are housed in a plurality of rows;

a first funnel structure extending from a floor of the enclosure and within which at least part of a first row of data storage devices is positioned, the first funnel structure having a first width and configured to direct airflow past the first row of data storage devices to a first central exhaust channel; and

a second funnel structure extending from the floor of the enclosure and within which at least part of a second row of data storage devices is positioned, the second funnel structure having a second width greater than the first width and configured to direct airflow past the second row of data storage devices to a second central exhaust channel substantially colinear with the first exhaust channel.

**2**. The data storage system of claim **1**, wherein the second exhaust channel is wider than the first exhaust channel.

**3**. The data storage system of claim **1**, further comprising:

an upper wall structure positioned above the data storage devices and extending to an enclosure top, the upper wall structure separating a first set of rows of data storage devices, including the first and second rows, from a second set of rows of data storage devices, the upper wall structure comprising:

a deflector portion positioned over a first row of data storage devices of the second set of rows and configured to direct airflow from above down to the second set of rows of data storage devices.

**4**. The data storage system of claim **3**, further comprising:

a third funnel structure extending from the floor of the enclosure and within which at least part of a first row of data storage devices of the second set of rows is positioned, the third funnel structure having a third width and configured to direct airflow past the first row of the second set of rows to a third central exhaust channel substantially colinear with the first and second central exhaust channels.

**5**. The data storage system of claim **3**, the upper wall structure further comprising:

at least one side channel extending beyond the deflector portion in a direction toward a back of the enclosure, the side channel configured to direct airflow from above down to one or more successive rows of data storage devices, beyond the first row, of the second set of rows.

**6**. The data storage system of claim **5**, further comprising:

a third funnel structure extending from the floor of the enclosure and within which at least part of a first row of data storage devices of the second set of rows is positioned, the third funnel structure having a third width and configured to direct airflow past the first row of the second set of rows to a third central exhaust channel; and

a fourth funnel structure extending from the floor of the enclosure and within which at least part of a second row of data storage devices of the second set of rows is positioned, the fourth funnel structure having a fourth width greater than the third width and configured to direct airflow past the second row of the second set of rows to a fourth central exhaust channel substantially colinear with the first, second, and third central exhaust channels.

**7**. The data storage system of claim **6**, wherein:

the third exhaust channel is wider than the second exhaust channel; and

the fourth exhaust channel is wider than the third exhaust channel.

**8**. The data storage system of claim **3**, further comprising:

a first ceiling structure over the first set of rows; and

a second ceiling structure over the second set of rows.

**9**. The data storage system of claim **8**, the upper wall structure further comprising:

a central channel extending in a direction toward a front of the enclosure and over a cutout portion of the first ceiling structure, the central channel configured to receive exhaust airflow from first set of rows via the cutout portion.

**10**. The data storage system of claim **8**, the second ceiling structure comprising:

at least one cutout portion configured to enable exhaust airflow from the second set of rows to above the second set of rows beyond the deflector portion of the upper wall structure in a direction toward a back of the enclosure.

**11**. The data storage system of claim **10**, the at least one cutout portion of the second ceiling structure comprising:

a cutout portion corresponding to each of multiple rows of the second set of rows, each cutout portion positioned beyond a respective row in a direction toward the back of the enclosure and configured to enable exhaust airflow from the respective row.

**12**. The data storage system of claim **1**, further comprising:

at least one input/output (I/O) module positioned in the first and/or second central exhaust channel.

**13**. The data storage system of claim **1**, wherein the plurality of data storage devices comprises hard disk drives.

**14**. The data storage system of claim **1**, wherein the plurality of data storage devices comprises solid-state drives.

**15**. A data storage system comprising:

a plurality of data storage devices housed in rows in an enclosure;

a series of funnel structures extending upward from a floor of the enclosure and within which a respective row of data storage devices is positioned, wherein the funnel structures are configured successively wider from a front toward a back of the enclosure to direct airflow past the respective row of data storage devices to a successively wider central exhaust channel; and

an upper wall structure comprising a deflector portion configured to direct airflow down to one or more rows of the data storage devices.

**16**. The data storage system of claim **15**, wherein the upper wall structure further comprises:

side channels extending beyond the deflector portion in a direction toward the back of the enclosure, wherein each side channel is configured to direct airflow down to one or more successive rows of data storage devices beyond the deflector portion.

**17**. The data storage system of claim **15**, further comprising:

at least one ceiling structure over one or more rows of the data storage devices.

**18**. The data storage system of claim **17**, wherein the upper wall structure further comprises:

a central channel extending in a direction from the deflector portion toward the front of the enclosure and over a cutout portion of a ceiling structure, wherein the central channel is configured to receive exhaust airflow from one or more rows of the data storage devices via the cutout portion.

**19**. The data storage system of claim **17**, wherein at least one ceiling structure comprises:

at least one cutout portion beyond the deflector portion and configured to enable exhaust airflow from a row of the data storage devices to above the row in a direction toward the back of the enclosure.

**20**. A rack-mountable data storage system comprising:

a plurality of data storage devices housed in rows in a rack-mountable enclosure, the data storage devices comprising:

a plurality of disk media rotatably mounted on a spindle,

means for reading from and writing to the disk media, and

means for moving the means for reading and writing to access portions of the disk media;

a series of funnel structures extending upward from a floor of the enclosure and within which a respective row of data storage devices is positioned, wherein the funnel structures are configured successively wider from a front toward a back of the enclosure to direct airflow past the respective row of data storage devices to a successively wider central exhaust channel;

an upper wall structure comprising:

a deflector portion configured to direct airflow from above down to one or more rows of the data storage devices,

side channels extending beyond the deflector portion in a direction toward the back of the enclosure, wherein each side channel is configured to direct airflow down to one or more successive rows of data storage devices beyond the deflector portion, and

a central channel extending in a direction from the deflector portion toward the front of the enclosure and over a cutout portion of a first ceiling structure over one or more rows of the data storage devices, wherein the central channel is configured to receive exhaust airflow from the one or more rows via the cutout portion;

a second ceiling structure comprising at least one cutout portion configured to enable exhaust airflow from a row of the data storage devices behind the deflector portion of the upper wall structure and to above the row in a direction toward the back of the enclosure; and

a plurality of cooling fans for drawing airflow through the enclosure.

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