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Sealed Enclosure Cooling with Internal Delta-T Sized Air-to-Air Exchanger

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Abstract

This disclosure describes a sealed air-to-air heat exchanger system designed for cooling electrical enclosures while preventing the ingress of dust and other airborne contaminants. The system is sized to maintain a specified internal temperature gradient relative to the ambient environment, avoiding issues associated with filtered fan systems where filter maintenance is neglected. It details the heat exchange mechanism, control strategies for condensation, and identifies specific failure modes that standard temperature monitoring may not detect, ensuring reliable operation for critical infrastructure.

1. Technical Field

[0001] The technical field is the thermal management and environmental protection of electrical enclosures, particularly those housing sensitive electronic equipment within industrial or outdoor environments. The objective is to dissipate heat generated by internal components while preventing the ingress of particulate matter, moisture, and corrosive gases, thereby enhancing equipment reliability and operational lifespan.

2. Technical Context

[0002] Electrical enclosures in many industrial settings are exposed to ambient conditions that include airborne dust, fibers, and moisture. Traditional cooling methods often involve filtered fan systems that draw ambient air directly into the enclosure. While effective for heat dissipation, these systems rely on regular maintenance to replace or clean air filters. Neglected filter maintenance leads to filter clogging, which reduces airflow and cooling capacity, potentially causing equipment overheating. Furthermore, compromised filters or unsealed openings can allow contaminants to enter the enclosure, leading to short circuits, corrosion, and premature component failure. This arrangement addresses the challenge of maintaining an optimal internal temperature within a sealed enclosure, eliminating the need for routine filter changes or the risk of direct contamination from the external environment.

3. System Overview

[0003] The system comprises a sealed enclosure (10) containing heat-generating electrical components, an internal air circulation fan (12), an air-to-air heat exchanger (14), an external air circulation fan (16), and a control unit (18). As shown conceptually in FIG. 1, the heat exchanger (14) is mounted to an opening in the enclosure (10) such that the internal air circuit is completely sealed from the external air circuit. The internal fan (12) circulates air within the enclosure (10) and through one side of the heat exchanger (14). The external fan

(16) draws ambient air across the other side of the heat exchanger (14) and expels it. Heat generated by components inside the enclosure (10) is transferred from the internal air, through the heat exchanger (14) core, to the external ambient air without any mixing of the two air streams. A condensate pan (30) and drain valve (20) are integrated into the heat exchanger (14) to manage moisture. The control unit (18) monitors temperatures and regulates fan (12, 16) operation to maintain the enclosure's internal temperature within specified limits.

4. Components

[0004] The primary components of this system include:

[0005]

- **Enclosure (10):** A rigid, sealed housing for electrical equipment. It is typically constructed from painted steel, stainless steel, or aluminum, designed to an ingress protection (IP) rating of IP54 or higher to prevent environmental contamination. The enclosure (10) features mounting provisions for the heat exchanger (14) and internal components.
- **Internal Air Circulation Fan (12):** This fan circulates the air contained within the enclosure (10) and directs it through the internal passages of the heat exchanger (14). It is typically an axial or centrifugal fan, selected for its ability to move a specified volume of air against the pressure drop of the internal circuit. A design flow rate of 100 to 500 cubic meters per hour might be typical, depending on the enclosure volume and heat load.
- **Air-to-Air Heat Exchanger (14):** The core component responsible for heat transfer. As depicted in FIG. 2, it consists of a series of parallel plates or channels that create two independent air paths. The internal air passes through one set of channels, and the external air passes through the other set, separated by the plate material. The plates are commonly made of aluminum or stainless steel, with fin spacing designed for optimal heat transfer and minimal pressure drop. The total heat transfer surface area is sized based on the maximum internal heat dissipation, the desired internal temperature, and the maximum ambient temperature.
- **External Air Circulation Fan (16):** This fan draws ambient air into the external side of the heat exchanger (14) and exhausts it. Similar to the internal fan (12), it is chosen for its airflow capacity and ability to overcome external circuit pressure drop. It often has a higher flow rate than the internal fan (12) to leverage the larger thermal mass of the ambient environment.
- **Control Unit (18):** An electronic controller that monitors the internal enclosure temperature via a temperature sensor (32) and potentially the external ambient temperature. It actuates the internal fan (12) and external fan (16) based on programmed setpoints. The control unit (18) may also manage the condensate drain valve (20) and provide alarm signals.
- **Condensate Pan (30) and Drain Valve (20):** Integrated at the base of the heat exchanger (14), the condensate pan (30) collects moisture that condenses from the internal air stream if its dew point is reached. A drain valve (20), often a solenoid-actuated valve, is opened periodically by the control unit (18) to discharge collected condensate to the exterior. A siphon break or trap is typically incorporated to prevent air ingress while allowing liquid drainage.
- **Temperature Sensor (32):** Typically a thermistor or RTD, placed within the enclosure (10) to measure the internal air temperature, providing feedback to the control unit (18).

Additional sensors might monitor external ambient temperature or heat exchanger core temperature.

5. Operation

[0006] The system's operation focuses on maintaining a desired internal temperature difference relative to the external ambient.

[0007] **Start-up:** Upon system power-up, the control unit (18) initializes and reads the internal enclosure temperature from the temperature sensor (32). If the internal temperature exceeds a pre-defined activation setpoint, the internal fan (12) and external fan (16) are activated simultaneously. This ensures immediate heat removal from the enclosure (10).

[0008] **Steady Running:** During normal operation, heat generated by the electrical components inside the enclosure (10) raises the internal air temperature. The internal fan (12) continuously circulates this warmed air through the internal passages of the heat exchanger (14). Simultaneously, the external fan (16) draws cooler ambient air across the external passages of the heat exchanger (14). Heat transfers from the warmer internal air through the heat exchanger (14) plates to the cooler external air. The control unit (18) monitors the internal temperature and modulates the speed of the fans (12, 16) or cycles them on/off to maintain the internal temperature within a specified range, typically 5 K to 10 K above the ambient temperature. This delta-T approach ensures that the system provides cooling only when necessary and minimizes energy consumption when the ambient temperature is sufficiently low.

[0009] **Condensation Management:** If the internal air's dew point is reached within the heat exchanger (14) due to cooling, moisture will condense on the colder surfaces of the internal air passages. This condensate drips into the condensate pan (30). The control unit (18) can trigger the drain valve (20) to open periodically, or based on a liquid level sensor in the pan (30), to discharge the collected water. The drain valve (20) is typically kept closed to maintain the enclosure's (10) sealed integrity.

[0010] **Fault or Interruption:** In the event of a fan (12, 16) failure or a blockage in the heat exchanger (14) airflow paths, the internal temperature will begin to rise. The control unit (18) will detect this rise via the temperature sensor (32). If the internal temperature exceeds a critical alarm setpoint, typically 15 K to 25 K above the desired operating range, the control unit (18) will activate an alarm signal. This signal can be local (e.g., an indicator light) or remote (e.g., a signal to a building management system). In some configurations, if a fan (12, 16) fails, the remaining fan may operate at maximum speed, or the system might shut down critical internal equipment to prevent damage.

[0011] One specific failure that a simple temperature alarm will not immediately catch is a gradual degradation of the heat exchanger (14) efficiency. This could be due to internal fouling of the external air passages by airborne particulates (e.g., spiderwebs, leaves, fine dust accumulating over many years), or a long-term reduction in the performance of one of the fans (12, 16) without complete failure. The system would still operate, but the internal temperature would slowly creep up to the alarm threshold over an extended period. The control unit (18) might continuously command maximum fan speed, indicating an issue without the temperature reaching the critical setpoint for an immediate alarm. A system designed to monitor the difference between the internal temperature and the ambient temperature (delta-T) and compare it against a design delta-T would be able to detect this gradual degradation earlier. If the actual delta-T increases significantly above the design delta-T under full load conditions, even if the absolute internal temperature is still below the critical alarm, it indicates a loss of cooling capacity.

6. Example Embodiments

[0012] **Embodiment 1** This embodiment features a standard plate-fin heat exchanger (14) designed for vertical mounting on the side of an enclosure (10). The internal fan (12) is an axial flow type, directly mounted to the internal inlet of the heat exchanger (14), pulling air from the top of the enclosure (10) and discharging it downwards after cooling. The external fan (16) is a high-static pressure centrifugal fan, configured to draw air from a bottom vent, push it through the external passages of the heat exchanger (14), and exhaust it through a top vent. The control unit (18) utilizes a single internal temperature sensor (32) to activate both fans (12, 16) in unison, operating them in an on/off cycle to maintain a internal temperature range of 28 °C to 32 °C when the ambient temperature is up to 40 °C. The maximum heat load is 500 W. Condensate is managed by a gravity drain through a simple P-trap.

[0013] **Embodiment 2** This configuration employs a counter-flow heat exchanger (14) core with enhanced heat transfer fins. Both the internal fan (12) and external fan (16) are variable-speed EC (electronically commutated) axial fans. The control unit (18) uses two temperature sensors (32), one measuring internal air temperature and another measuring external ambient temperature. The fan (12, 16) speeds are continuously modulated to maintain a target internal-to-ambient temperature differential of 7 K. If the measured differential exceeds 10 K for a sustained period under maximum fan speed, a "reduced cooling capacity" warning is triggered. The condensate pan (30) includes a level sensor, and the drain valve (20) is opened only when a specific volume of condensate is detected, ensuring minimal cycling. This embodiment is sized for an enclosure (10) with a heat load of approximately 1.2 kW.

[0014] **Embodiment 3** This embodiment is designed for high heat load applications and features multiple heat exchanger (14) units mounted on a single large enclosure (10). Each heat exchanger (14) has its own independent internal fan (12) and external fan (16) pair. The internal air path for each unit is fed from different zones within the enclosure (10) to manage localized hot spots. The control unit (18) is a distributed system, with local controllers for each heat exchanger (14) unit, reporting to a central master controller. The master controller coordinates fan (12, 16) operation across all units to maintain an average internal temperature and ensures redundancy; if one unit fails, the others increase their output to compensate, if possible, before an alarm is issued. The condensate from all units drains into a common collection tank with a pumped discharge system. This system is suitable for enclosures with heat dissipation requirements up to 5 kW.

7. Alternative Configurations

[0015] Instead of a simple plate-fin design, the air-to-air heat exchanger (14) could utilize a heat pipe array or a thermosiphon arrangement, where a working fluid within sealed pipes transfers heat. This can offer advantages in certain orientations or where passive heat transfer is desired at low temperature differences. The external fan (16) could be omitted in environments with strong natural convection, with the heat exchanger (14) designed with larger, widely spaced fins to promote natural airflow. The control unit (18) might incorporate humidity sensors to more proactively manage condensation by adjusting fan speeds or activating internal heaters if the internal dew point approaches the heat exchanger (14) surface temperature. For very high thermal loads, a liquid-to-air heat exchanger could be used on the internal side, circulating a coolant through a sealed internal loop, which then transfers heat to the external air via the air-to-air exchanger.

8. Parameter Variations

Parameter	Realistic Range	Effect of Moving Within Range
Internal Heat Dissipation	100 W to 5000 W	Higher dissipation requires a larger heat exchanger surface area (14) and higher airflow rates from fans (12, 16) for a given delta-T.
Desired Internal Delta-T	5 K to 15 K	Smaller delta-T (cooler internal) requires a larger, more efficient heat exchanger (14) or higher fan (12, 16) speeds, increasing power consumption.
Maximum Ambient Temperature	30 °C to 55 °C	Higher ambient temperatures necessitate greater heat exchanger (14) effectiveness to maintain the desired internal temperature.
External Airflow Rate	100 to 1000 m^3/hr	Increased external airflow generally improves heat transfer effectiveness, but also increases fan (16) power consumption and noise.
Internal Airflow Rate	50 to 500 m^3/hr	Higher internal airflow improves internal heat distribution and heat transfer to the exchanger (14), but increases fan (12) power.
Heat Exchanger Material	Aluminum, Stainless Steel	Aluminum offers higher thermal conductivity for the same thickness; stainless steel provides better corrosion resistance in harsh environments.
Plate/Fin Spacing	1 mm to 5 mm	Tighter spacing increases surface area, improving heat transfer, but also increases pressure drop and risk of fouling.
Control Unit Activation Setpoint	25 °C to 40 °C	Determines when cooling fans (12, 16) engage. Lower setpoints result in more frequent fan operation and tighter temperature control.
Control Unit Alarm Setpoint	40 °C to 60 °C	Defines the critical temperature at which an alarm is triggered, ensuring equipment protection.

9. Additional Implementations

[0017] The described system can be adapted for applications beyond standard electrical enclosures. For instance, it can be integrated into battery storage cabinets to manage thermal runaway risks and optimize battery life by maintaining a stable internal temperature. It can also be applied to control cabinets in telecommunications infrastructure, where consistent temperature is critical for network equipment reliability and where dust ingress from outdoor environments is a constant concern. Furthermore, the principles of delta-T sizing and sealed heat exchange can be extended to small modular data centers or edge computing enclosures, providing a passive or semi-passive cooling solution in remote or difficult-to-maintain locations. The condensate management system could be enhanced with a small heating element in the pan (30) to evaporate collected moisture in low-humidity environments, eliminating the need for a drain line. The external fan (16) could be equipped with a fine mesh screen that is easily cleanable from the outside, primarily for larger debris, without compromising the sealed nature of the heat exchanger (14).

10. Figures

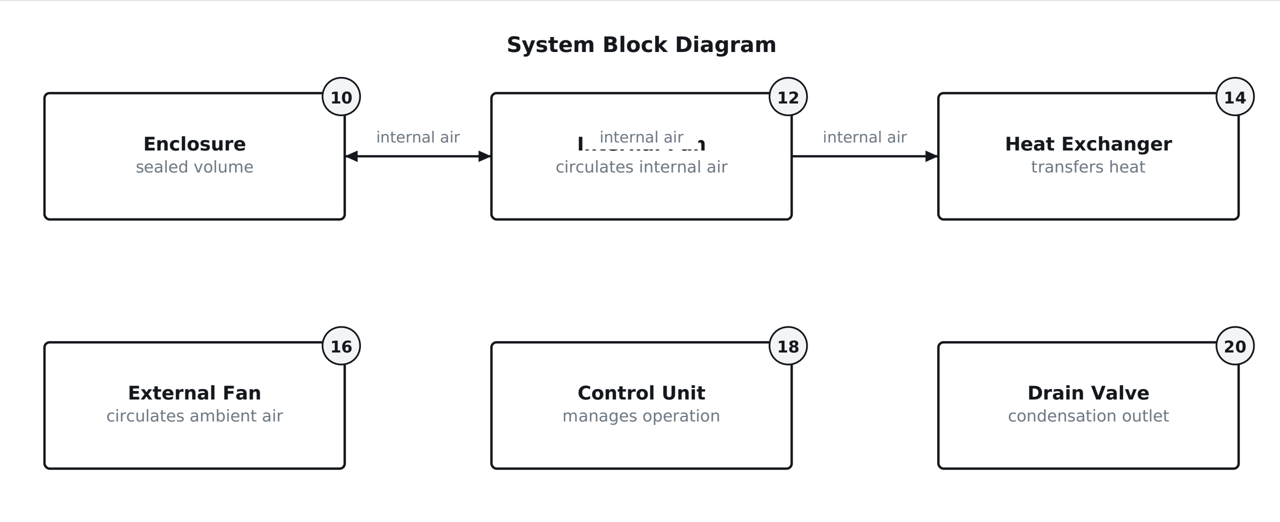

FIG. 1 A block diagram illustrating the sealed enclosure cooling system with internal and external air circuits. PNG

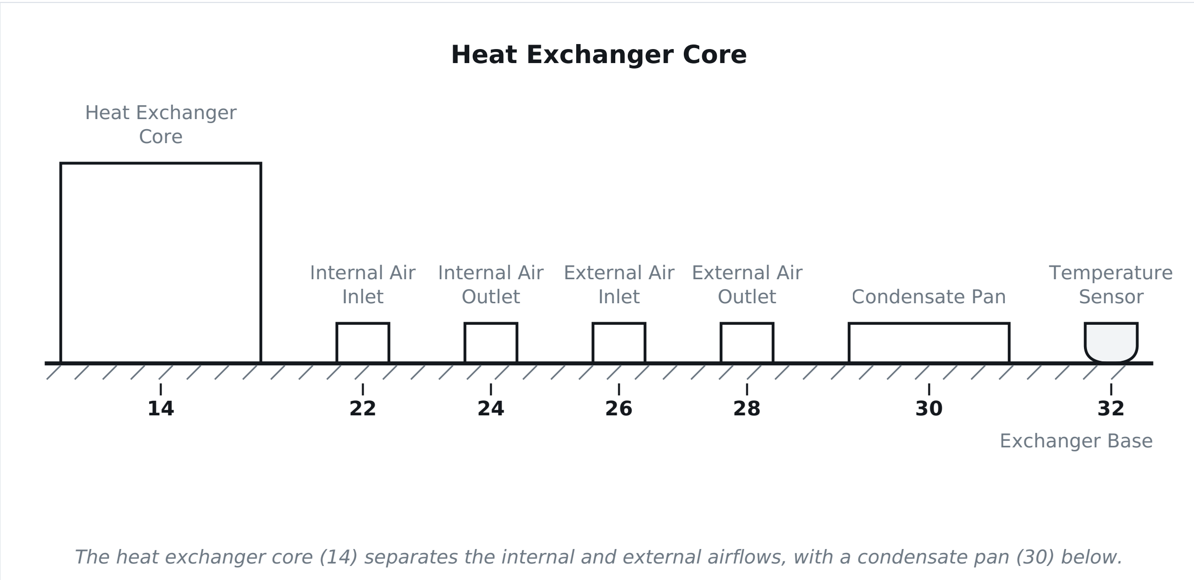

FIG. 2 An elevation view of the air-to-air heat exchanger core and associated components. PNG

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