Optimizing Air Circulation in Electrical Enclosures

Impacting airflow through component spacing.

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Introduction

Proper air circulation can make or break an electrical enclosure. Electrical enclosures house critical components that generate heat during operation. Inadequate air circulation can lead to isolated temperature accumulation, running the risk of system malfunctions, reduced component lifespan, and compromised reliability.

To ensure smooth and successful operations, companies can strategically space and position components within electrical enclosures to enhance air circulation and mitigate hot spots. Proper spacing strategies empower companies to optimize air circulation, effectively dissipate heat, and improve overall system performance.

Overview of Electrical Enclosures

Electrical enclosures serve as protective housings for components such as power supplies, circuit boards, drives, motors, and electrical components. To efficiently operate these components, electrical enclosures must maintain optimal operating temperatures. This is because inadequate cooling can form hot spots or pressure pockets. Hot spots are pockets of warm air where cold air cannot circulate, while pressure pockets are sections of air that are circulated repeatedly. As a result of either problem, equipment can become damaged or fail, requiring costly replacements. Another consequence is that equipment can have a shorter lifespan. This is due to the fact that the various components will have to work harder because of the higher operating temperatures. On top of all this, components shutting down can also lead to unforeseen downtime.

Challenges in Electrical Enclosures

Two trends in electrical enclosures can clash to create major challenges. As floor space becomes increasingly limited inside facilities, companies often install smaller electrical enclosures. At the same time, companies try to fit more components into these smaller electrical enclosures.

Due to the smaller design, electrical enclosures often face challenges related to limited space and the complex component arrangements. This means engineers must carefully consider the spatial layout of components to maximize air circulation. Challenges such as tight spaces, irregular shapes, and the need to accommodate various component sizes and shapes within the enclosure can all complicate the process of ensuring components in electrical enclosures remain effective.

Importance of Air Circulation

Effective air circulation is paramount for dissipating the heat generated by each of the electrical components. In order to achieve this, heat that dissipates from components in the enclosure needs to either be cooled or carried outside the enclosure to the ambient environment. This assists in preventing temperature-related issues such as thermal stress, accelerated aging, and potential component failure. Proper air circulation ensures a uniform distribution of temperature within the enclosure, reducing the likelihood of localized hot spots.

Managing Heat Inside Electrical Enclosures

Cooling electrical enclosures maintains the optimal operating temperature and prevents potential damage to electronic components. Various cooling strategies can manage this thermal challenge. Common techniques include incorporating fans that utilize open loop cooling. Other techniques, by contrast, utilize closed loop cooling, such as heat exchangers and air conditioning systems designed specifically for enclosures.

1. Open Loop Cooling inside an Electrical Enclosure

Open loop cooling can consist of two different options: a fan combined with either an exhaust fan or filter, or two exhaust filters.

Using two exhaust filters allows for heat to naturally evacuate out of the enclosure via a type of cooling called natural convection. However, this technique is not typically used because the amount of heat generated in a cabinet often exceeds what companies can accomplish with natural convection.

When companies use a fan paired with an exhaust fan or filter, it results in a type of cooling called forced convection. With forced convection, the fan pushes cooler ambient air into the enclosure to pass over hot components. After it carries heat off the components, the air can naturally release out of a passive exhaust filter or become forced out with an exhaust fan.

Both types of cooling can only work in applications where the ambient temperature is always lower than the temperature required in the electrical enclosure. Both will also only work if installed into a clean and non-hazardous environment. Companies should mount the fan that pushes air into the enclosure on the bottom of the cabinet and should mount the exhaust filter or fan on the top of the cabinet. This positioning supports the natural convection of air: hot air will rise to the top of the cabinet, while the bottom of the cabinet will contain the coldest air.

When pulling air into the enclosure for open loop cooling, companies will have a positive pressure inside of the enclosure. This positive pressure will push the air through the path of least resistance, similar to a passive exhaust filter. It will reduce the chance of contaminant ingress while the enclosure is pressurized.

2. Closed Loop Cooling Inside an Electrical Enclosure

Closed loop cooling requires two systems. One system seals out the ambient air and simultaneously cools and re-circulates clean, cool air throughout the enclosure. This is referred to as the 'evaporator side' of the closed loop cooler. The second system uses ambient air, water, or the refrigerant cycle to remove and discharge the heat. This is referred to as the 'condenser side' of the closed loop cooling. Closed loop cooling is required when electrical enclosures are located in areas with higher ambient temperatures, potential wash down requirements, or the presence of chemicals in the air.

Companies can use an enclosure air conditioning (A/C) unit under two conditions: 1) the ambient air *around* the enclosure will be at a higher temperature than what is needed *inside* the enclosure and 2) the ambient air is contaminated with any type of particulate matter. A/C Units utilize a vapor compression system, also referred to as the refrigerant cycle. In the refrigerant cycle, the refrigerant first enters the compressor as a superheated low-pressure vapor, which is then compressed into a superheated high-pressure vapor. The superheated high-pressure vapor enters the condenser, and the ambient air passing over the condenser coil absorbs the heat from the refrigerant, creating a sub-cooled high-pressure liquid. The sub-cooled liquid then passes through a throttling device (i.e., a metering device or thermal expansion valve).

This sudden reduction in pressure causes the refrigerant to lower its temperature, referred to as adiabatic expansion. The refrigerant's temperature will be lower than the air it is cooling within the enclosure, becoming a saturated low-pressure mixture containing both liquid and gas. The saturated mixture enters the evaporator coil as the warm air passes over the coil. The refrigerant absorbs the heat from the air as it passes over the evaporator, boiling off the remaining liquid, where it becomes a superheated low-pressure vapor. The cold air then passes back into the enclosure. The superheated vapor then enters the compressor to restart the refrigeration cycle again. The refrigeration cycle uses these phase changes to help remove heat from the enclosure and reject the heat into the ambient environment.

Companies can use an enclosure air-to-air heat exchanger instead of A/C units in the following conditions: 1) the ambient air *around* the enclosure will be at a lower temperature than what the enclosure requires and 2) ambient air is contaminated with any type of particulate matter that could potentially pass through a fan, such as oil or grease. Heat exchangers operate on the same principle that fans operate upon: namely, ambient temperature must be lower than the enclosure temperature in order to operate. Air-to-air heat exchangers, however, offer greater energy savings as compared to A/C units as they do not contain any active components (e.g., an A/C unit's compressor) other than fans to circulate air.

In addition to A/C units and air-to-air heat exchangers, companies can use air-to-water heat exchangers if they have chilled water available under the following conditions: 1) the ambient air around the enclosure will be at a higher temperature than what is needed inside the enclosure and 2) if the ambient air is highly contaminated or corrosive (e.g., a wastewater facility or a chemical plant). Air-to-water heat exchangers cycle air in the enclosure over a heat exchanger with chilled water running through it. This process transfers heat from the air, as the heat is absorbed by the chilled water. The cooler air then enters the enclosure while the warmer water either returns to the source, where it is chilled to complete the loop, or returns directly back to the water treatment facility.

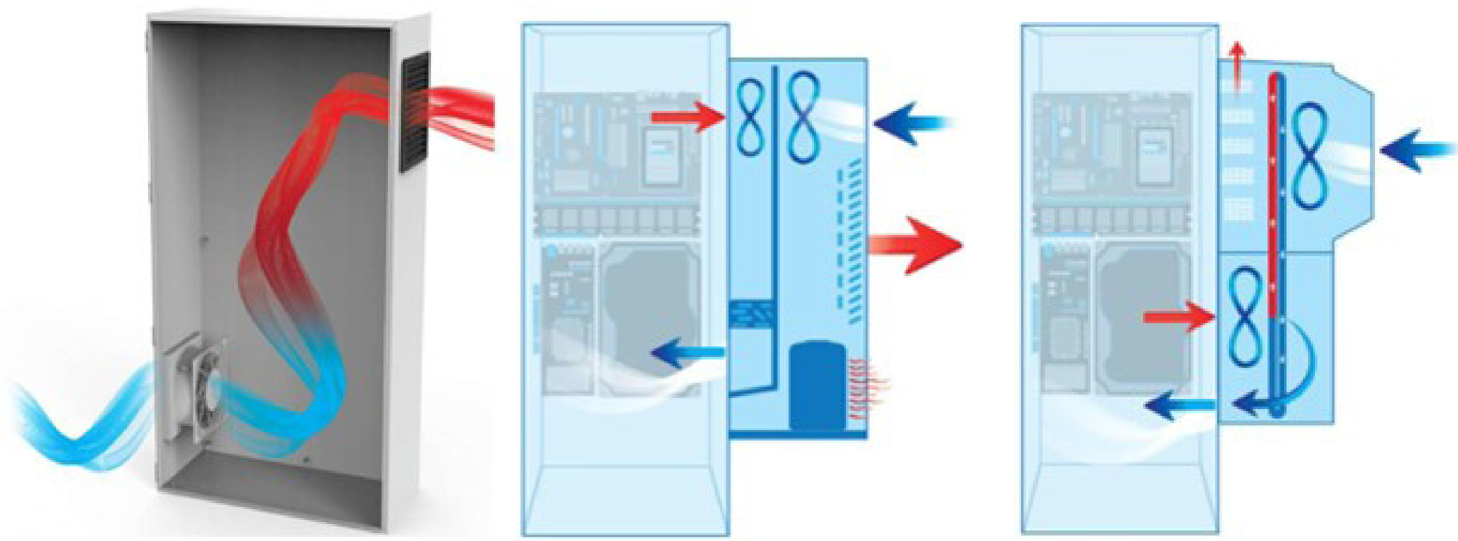


Figure 1: Comparative designs with airflow of a filter fan, A/C unit, and air-to-air heat exchanger

Considerations when Selecting a Cooling Solution for an Enclosure

When selecting a cooling solution for an enclosure, first evaluate the environment where the unit will be installed. One of the factors to consider is the location of the enclosure. If the location is in close proximity to operators, avoid trying to exhaust warmer air on the operator so as not to cause discomfort. To avoid this situation, baffling outside of the enclosure can redirect the warmer air away from the operator. The solution can also be positioned away from the operator.

Another factor to consider is whether the solution is being installed into a temperature controlled facility. This is because the HVAC systems cooling the facility need to account for heat rejected into the ambient environment. Many facilities do not account for this and it causes the facility to overheat because the enclosure's heat becomes rejected into the facility. Working with a mechanical contractor can establish if the heat load inside of the enclosure can be exhausted into the facility. In certain scenarios, an air-to-water heat exchanger can be more beneficial, as it rejects heat into the water where a liquid chiller can handle the additional heat load.

Another factor to consider is airflow inside the enclosure. Since enclosures are becoming more densely packed, companies must maintain proper and consistent airflow to prevent hotspots or potential condensation from overcooling. To preempt and prevent these problems, companies can run air simulations with a tool called CFD Analysis.

1. Computational Fluid Dynamics (CFD) Analysis:

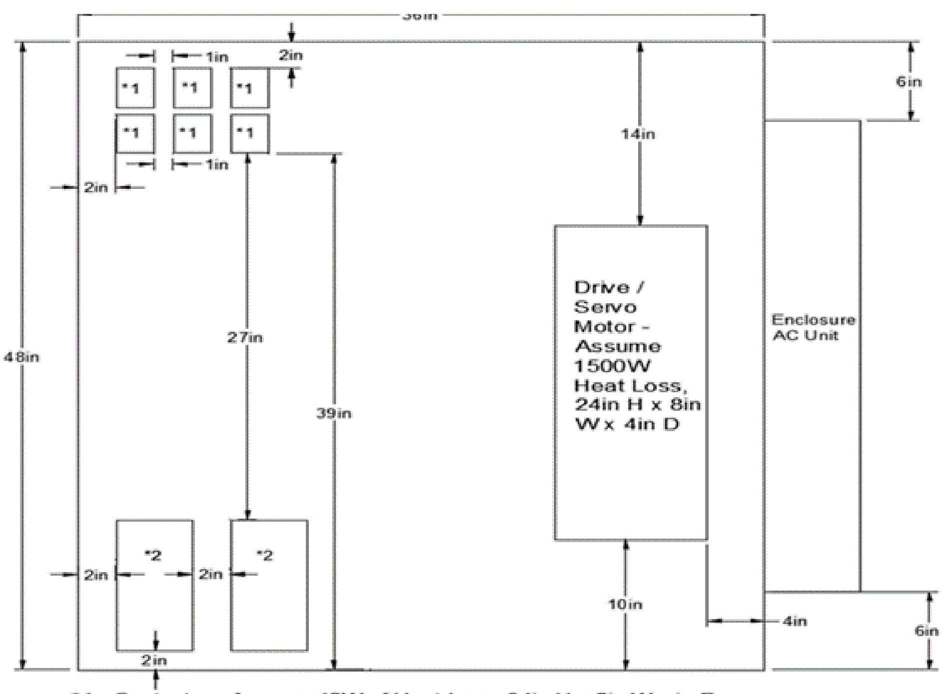
Computational Fluid Dynamics allows you to simulate and optimize airflow patterns within the enclosure. Using this type of analysis, companies can design enclosures while keeping in mind enclosure temperature and air flow. Companies can identify potential hotspots within the enclosure, verify that temperature distribution within the enclosure is manageable for components, check the potential for pressure pockets between components, and even see if specific components are being overcooled. These analyses can help save money, provide increased accuracy of reports, give a better visual understanding of the flows inside of a system, and can empower companies to achieve an overall better design of their system.

CFD Test Scenario

We will consider 3 test scenarios utilizing CFD analysis. We positioned a VFD in front of an A/C's outlet. This will show how the impact on airflow as the drive is the component inside of the enclosure that would be creating the most heat. A big misconception is that designers will mount the most sensitive / highest heat generating components closest to the A/C unit to ensure it is properly cooled, but this will create disturbances in airflow. This was one of the concepts we wanted to create when designing these scenarios.

This test scenario was created to examine the impact of not allowing for proper spacing given to an enclosure A/C unit. All components shown in Figure 2 are mounted centrally inside the enclosure. In each test scenario, the drive in front of the A/C unit will be pushed deeper into the cabinet and away from the cold air outlet's opening on the bottom of the unit. The other components were mounted in a position to show potential hotspots that could generate the further they are away from the cooling apparatus. Drives inside of the enclosures will typically include a fan to bring in air from the bottom of the drive to help reject the heat inside of it or a type of heat sink to transfer heat from the drive into the enclosure's environment. The small drives are assumed to have 100W heat loss each with a small fan inside of them while the smaller contactors are assumed with a 12W heat loss each radiating into the environment.

In the CFD analysis the density of the lines demonstrate the volume of air and the arrows show the direction of the air flow. The colors of the lines are representative of the temperatures of the air travel, blue being the coldest air and red being the hottest air.



*1 - Contactor - Assume 12W of Heat Loss, 34in H x 2in W x in D
*2 - Small Drive - Assume 100W of Heat Loss, 10in H x 4in W x 6in D

Figure 2: Test Scenario Layout

1. 1st Test Scenario – Blockage 4" Away from Air Outlet

The 1st test scenario shown in Figure 3 has the same designed layout as Figure 2 with the VFD placed 4 inches away from the cool air outlet. A majority of the cold air leaving the A/C unit is shown to be blocked by the large drive in front of it and results in it cycling right back into the A/C unit's fan inlet. The cooler air being redirected immediately back into the cooling unit "tricks" the A/C unit into believing setpoint has been reached and will shutoff immediately. Once the heat from the other part of the cabinet comes on, the A/C unit will turn on again.

The short interval between the A/C turning off and on is referred to as short cycling. This means that the A/C unit is not only failing to remove the heat from the cabinet, but puts a strain on the A/C unit's compressor for it to turn on and off in consecutive use and could lead to potential icing inside of the A/C unit's air outlet. A pressure pocket forms in the top right hand corner of the enclosure due to the drive's exhaust being sucked directly into the A/C unit's fan inlet and blocks the airflow path for the hot air to return to be cooled by the A/C unit. The contactors in the top left hand corner of the enclosure are getting warm air delivered to it which could make it diffcult for the components to reject heat.

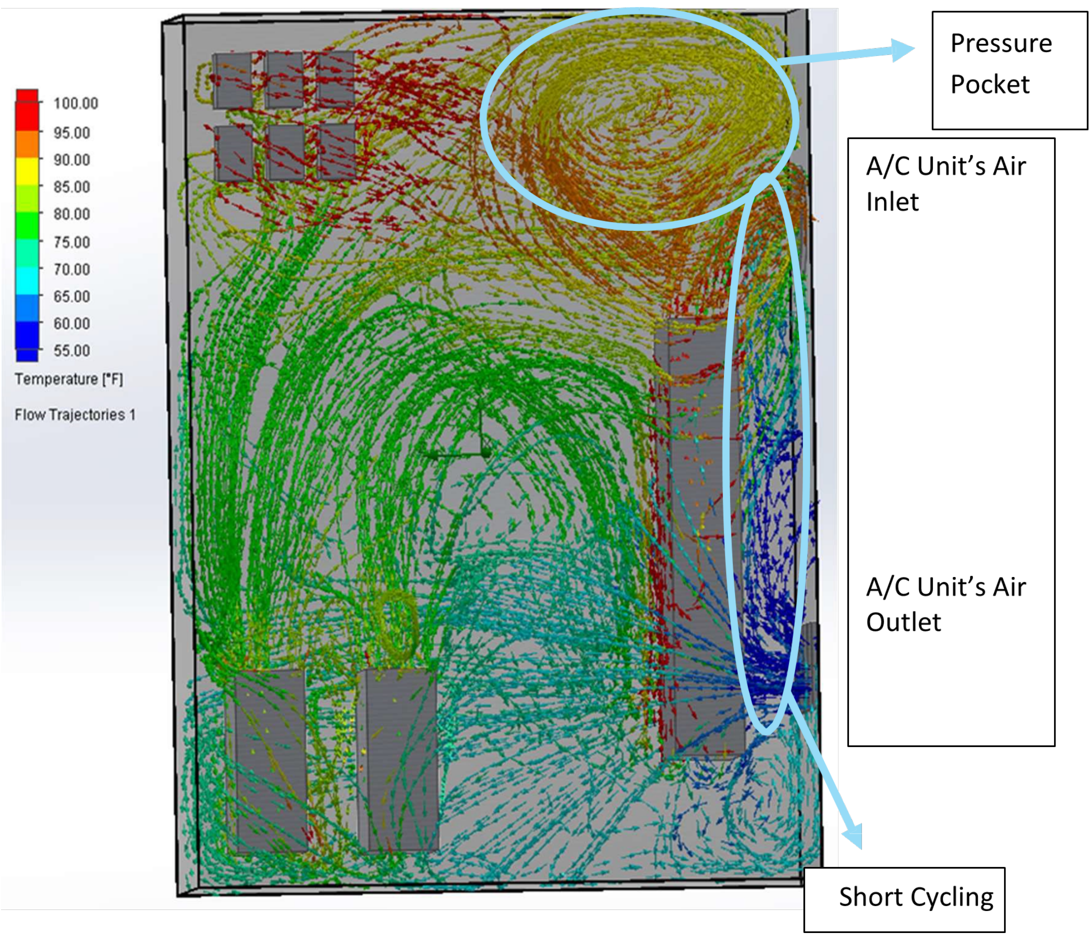


Figure 3: CFD Analysis Scenario #1

2. 2nd Test Scenario – Blockage 8" Away from Air Outlet

The 2nd test scenario shown in Figure 4 has the same designed layout as Figure 2, but moves the VFD 8 inches away from the AC outlet. While the unit still risks short cycling of cold air being pushed back into the evaporator fan inlet, more airflow is able to get across and reach the other side of the enclosure. A smaller pressure pocket forms in the lower right hand corner where air is being sucked directly into the large drive's fan which leads to improper airflow inside of the cabinet. Since the fan on the large drive is blocking airflow to the A/C unit's air inlet, a large pressure pocket of hot air forms due to the airflow path being blocked, creating a wall of air that does not allow the hot air to escape. This could cause the contactors to overheat due to it not getting cold air. The two smaller drives in the corner of the enclosure risk overheating due to the positioning, with the left one being poised to overheat as the right drive is taking in the cold air before it can reach the left one.

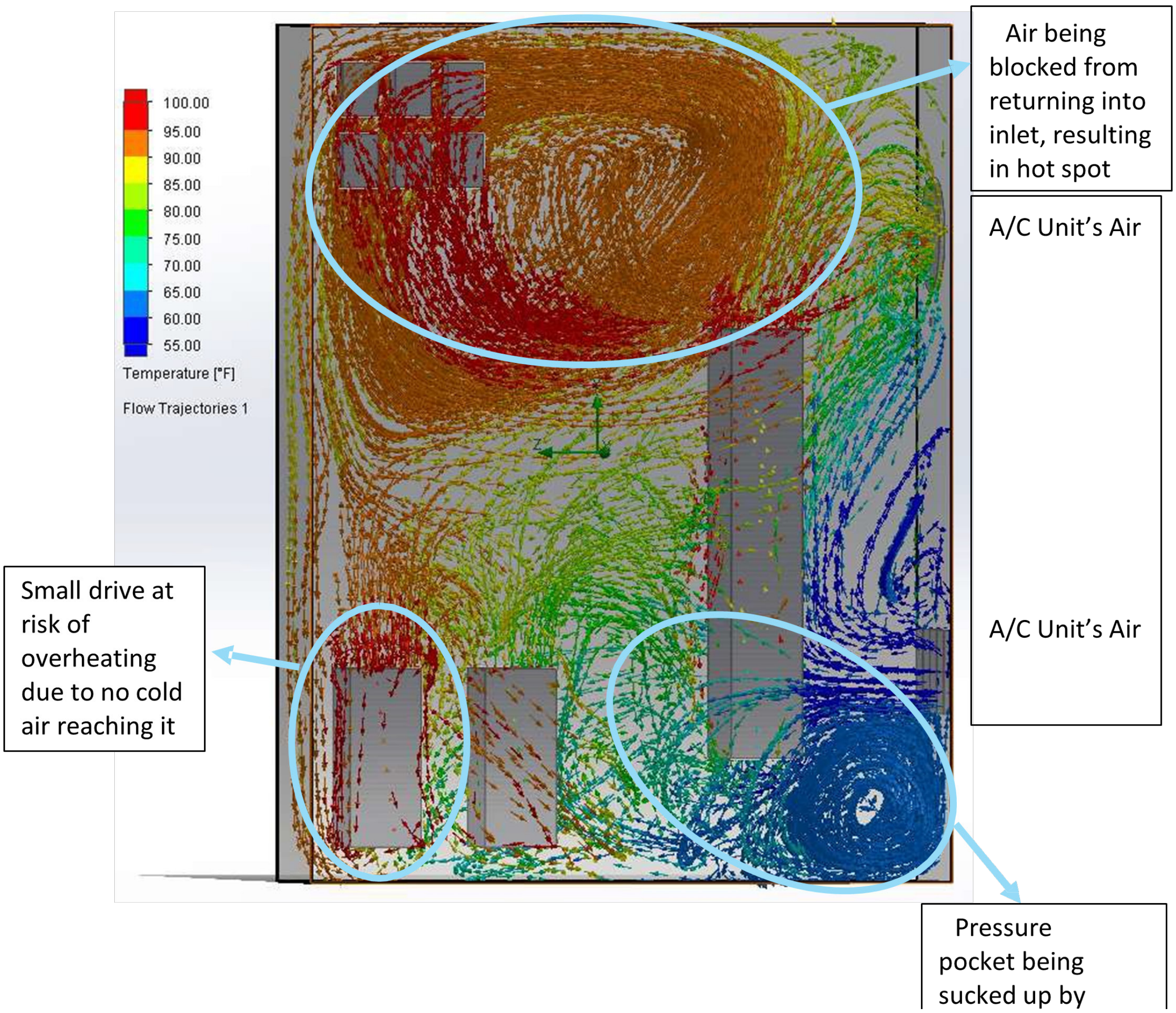


Figure 4: CFD Analysis Scenario #2

3. 3rd Test Scenario – Blockage 12" Away from Air Outlet

The 3nd test scenario shown in Figure 5 has the same designed layout as Figure 2, but pushes the blockage to 12" of total distance between the A/C unit's air outlet and drive. Figure 5's unit has the lowest chances of short cycling as compared to the other Figures' units. Additional airflow is able to get across and reach the other side of the enclosure due to the pressure pocket in the lower right corner dispersing under the drive and to the rest of the enclosure. The large pressure pocket of hot air that formed in Figure 4 is completely dispersed in Figure 5, being shown where the airflow path is able to travel at the top and around the drive while still being able to cool the large drive. The airflow from the two smaller drives can push cooler airflow near the contactors and is able to carry the heat from them and bring it to the A/C unit.

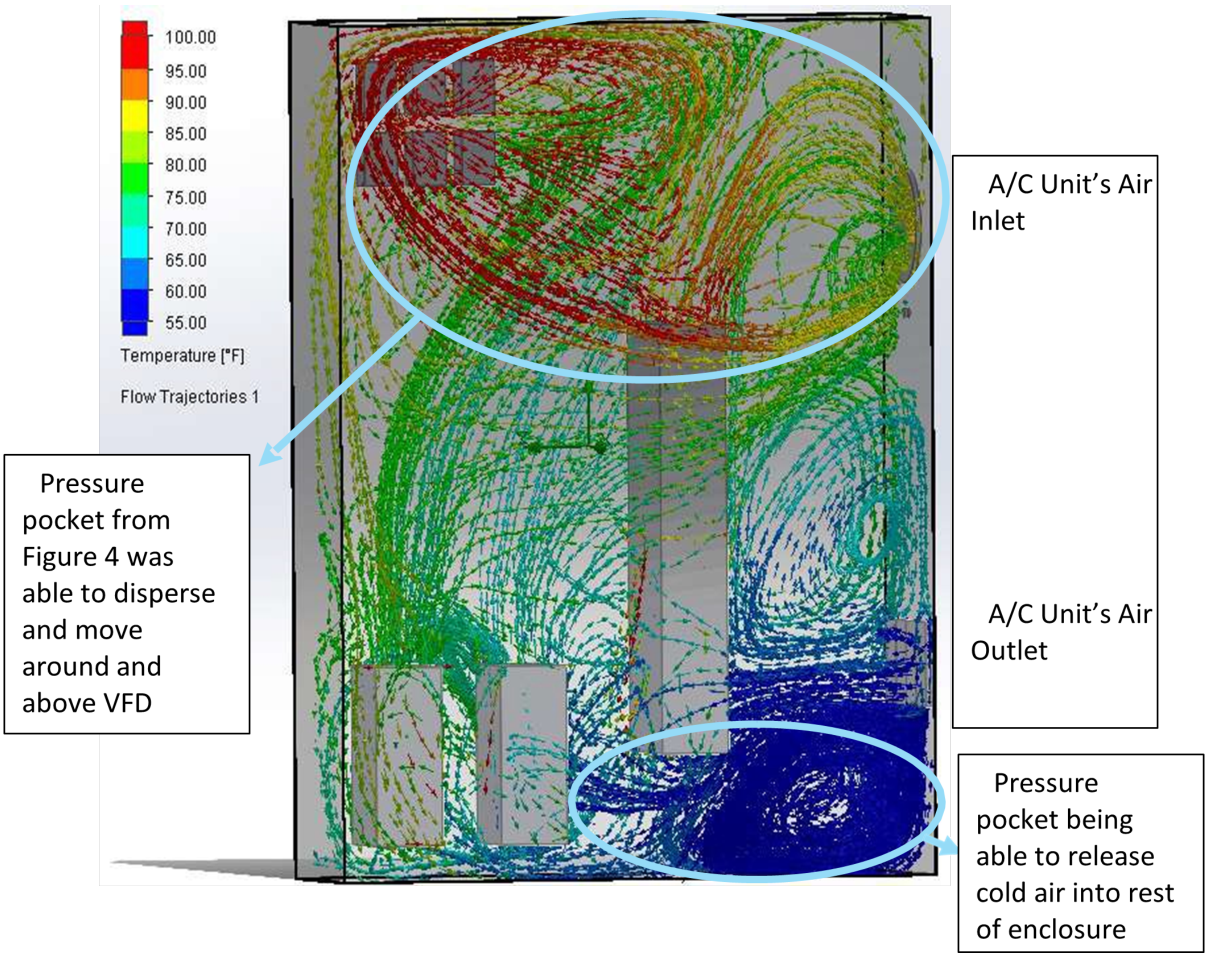


Figure 5: CFD Analysis Scenario #3

CFD Simulation Summary

After reviewing the results of all 3 scenarios, the most ideal scenario is Scenario #3, Figure 5. This scenario presents the least possible risk of short cycling of cold air being redirected into the A/C unit and all components having air flowing around them as well as air flowing into them. Scenario #1, Figure 3, had the highest chance of short cycling overall which would cause the unit to shut off early and not cool the enclosure to the desired temperature. Scenario #2, Figure 4, had a large pressure pocket of hot air that would prevent the air from circulating correctly and would end up causing most of the contactors to overheat.

Every enclosure design is unique. While these scenarios are simulated conclusions are able to be drawn from this simulation. These conclusions could be used as best practices when designing the layout of your enclosure.

As the blockage was pushed further out, there was better airflow in the enclosure, but it became apparent that the large drive's exhaust air was blocking airflow in the cabinet.

This is why it is recommended to typically mount components with their own larger fans farther away from the A/C unit to help cycle airflow throughout the enclosure.

A common misconception is that since the large drive is the most sensitive component, it would need to be mounted as close as possible to the A/C unit to receive the coldest air.

This is incorrect because it would end up restricting airflow for the other components inside of the enclosure. It should be mounted farther away from the A/C unit, preferably where the smaller drives are located in the lower left hand corner of Figure 2, this would allow for airflow to travel towards it and would support a full circular motion of airflow throughout the enclosure.

Design Considerations

When designing electrical enclosures for optimal air circulation, engineers should consider the following:

1. Ventilation and Cooling Systems

Integrating ventilation and cooling systems, such as fans or heat sinks, can complement the effects of component spacing. These systems can further enhance heat dissipation within the enclosure. Using enclosure fans inside electrical enclosures are a great way to help move air within the enclosure. In scenarios where the possibility of repositioning components is limited, enclosure fans can be installed to help ensure air is reaching all points of the enclosure.

2. Enclosure's Material and Color

In outdoor applications or hotter environments, you would have heat transferring into your enclosure from the hotter ambient air through the metal enclosure or having a solar load from the sun hitting your enclosure. If you were to use a darker color, you would be absorbing more heat from the sun while if you were to use a light color, you would reflect the heat from the sun and have less likelihood of solar loading. Every material used to construct enclosures has a heat transfer coeffcient and can affect the amount of heat transfer from the environment into the enclosure and vice versa. If you are worried about heat transfer into your enclosure, you can use insulation on the inside of your enclosure to help prevent the ambient environment's heat transfer from affecting your enclosure or use a type of sun roof to keep the sun from directly hitting your enclosure to prevent solar loading.

Material	**Heat Transfer Coeffcient (W/m^2K)**
Aluminum	12
Mild Steel	5.5
Stainless Steel	3.7
Plastic	3.5
Fiberglass	3.5

Figure 6 – Heat Transfer Coefficient of Common Enclosure Materials

3. Mounting Style of Enclosure

The amount of surface area on your enclosure can affect the amount of heat transfer you can achieve either if the ambient environment is cooler than your enclosure or the amount of heat transfer to the enclosure if the ambient environment is hotter than your enclosure. Surface area is often overlooked as a factor that can lead to large amounts of unplanned heat inside the cabinet due to heat transfer from the ambient environment. For example, if it is mounted up against a wall, you no longer have to factor the heat transfer of the back of the enclosure into your heat transfer.

Conclusion

Strategic positioning of components within electrical enclosures is a critical factor in ensuring optimal air circulation and minimizing hot spots. By avoiding densely packed configurations, you allow air to move more freely, carrying away heat generated by components. This promotes a uniform temperature distribution and minimizes the risk of hot spots. Additionally, optimized airflow enhances the overall cooling effciency of the system, ensuring that each component operates within its recommended temperature range.

By promoting even heat dissipation, you can mitigate the risk of hot spots and enhance overall system stability. It is best to allow for cold air to flow from the bottom of the enclosure up to the top, this helps support natural convection inside of the enclosure, proven in the test scenarios that as cold air gets warmer. Heat will rise and want to stay at the top of the enclosure. Maintaining proper spacing between components is crucial for proper thermal management and reduces the risk of hot spots. This strategic component positioning not only contributes to improved thermal management but also extends the lifespan of hardware by reducing the likelihood of overheating-related issues.

By addressing these design considerations, you can enhance the overall reliability and performance of electrical systems. As technology advances and component densities increase, the importance of effective component spacing becomes even more pronounced in mitigating thermal challenges within electrical enclosures.

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