SIMPLEX CLEANROOMS WHITEPAPER

DESIGN AND BUILD THE PERFECT CLEANROOM

FOCUS
Optimizing Performance
Through Advanced CFD Modeling

This whitepaper examines the fundamentals of cleanroom design and demonstrates how computational fluid dynamics (CFD) can optimize performance and reduce risks in cleanroom construction. It provides practical guidance for achieving optimal cleanroom environments through advanced modeling and validation techniques.

Introduction

Today, cleanrooms are being used more than ever to accomplish tasks that cannot be done in a normal environment or room. Cleanrooms have become an essential part of many industries, including automotive, aerospace, medical/hospital, pharmaceutical, semiconductor/electronics, and biotechnology just to name a few. These rooms are designed with controlled conditions to keep particulate levels low and to prevent product contamination or damage, which is essential to each industry's manufacturing process.

The many technologies and industries using cleanrooms have resulted in high demand for these rooms. For example, the global cleanroom technology market size is estimated at USD 10.04 billion in 2025, and is expected to reach USD 14.15 billion by 2030, at a CAGR of 7.11% during the forecast period (2025–2030), meaning more and more customers and industries are and will invest in cleanrooms in the near future.[1]

With the widespread importance of cleanrooms and their environmental conditions, what can be done during the design phase to reduce construction costs and increase operation and performance? How do cleanrooms work, and why is understanding air pressure in cleanrooms vital for design? What important roles do airflow and air velocity play in achieving a well-designed and overall energy efficient cleanroom? Can CFD airflow modeling enhance cleanroom designs by improving contamination control?

This paper will answer these and many more questions in the following topics:

1. *What is a Cleanroom*
2. *How Do Cleanrooms Work*
3. *Understanding Air Pressure in Cleanrooms*
4. *ISO Standards and Air Changes Per Hour (ACPH)*
5. *CFD for Cleanroom Design Optimization*

Examples of Simplex Cleanroom Solutions

What is a Cleanroom?

A cleanroom is a unique space that's used exclusively for testing and conducting research. It's where a product is manufactured and comes out flawless with minimal contamination corrupting the procedure.

Cleanrooms need to be sterile high-tech environments where companies can conduct research without being concerned with cross-contamination. They help maintain a controlled and consistent environment in which people, processes, and machinery can work to the best of their ability.

Cleanrooms can vary in size and complexity and are used in practically every industry where the chance exists for small particles to adversely affect the manufacturing process because cleanrooms create the best possible working environment for testing product results or even process outcomes.

How do Cleanrooms Work?

One of the main components of any cleanroom is the High Efficiency Particulate Air (HEPA) filter that is used to trap particles from entering the room. All air delivered to a cleanroom must pass through HEPA filters in order to meet various cleanroom classifications. The filter is part of the Fan Filter Unit (FFU) which supplies clean, filtered air to the cleanroom.

A common FFU used in the industry is 2' x 4' and is designed for an airflow of approximately 650 CFM. Air is drawn via the fan, through a pre-filter and then through the HEPA filter which filters the sub-micron particles ensuring clean and processed air supply to the room. FFUs are also a more energy efficient means of supplying clean air versus using

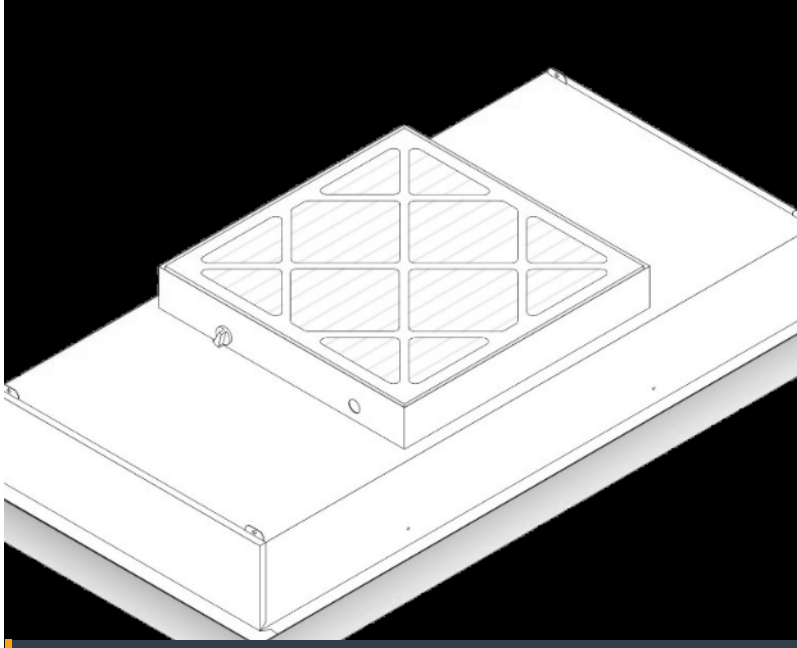


FIGURE 1: Typical FFU with HEPA used by Simplex, SAM® MicroSound 3S NCR – CRI (cleanroomsint.com)

a traditional Air Handling Unit (AHU) and is the preferred approach for supplying air in modern cleanroom designs (**see Figure 1**).

Next, the filtered air is typically directed downward in a constant, straight, unimpeded stream. This unidirectional or laminar airflow ensures that only clean air passes down over the process, thus protecting the critical processing or testing area, freeing the cleanroom environment of particles and contaminants generated from the process.

People working in cleanrooms typically will enter and exit through air showers and/or gowning rooms, and they'll need to wear special clothing designed to trap contaminants. Depending on the room classification and function, gowning may be limited to a zipped coverall, hairnet, gloves, and shoe booties, or as extensive as multiple gowns with a self-contained breathing apparatus. The reason for such stringent procedures in some cases is to prevent particles and contaminants from being released into the cleanroom environment (**see Figure 2**).

FIGURE 2: Wearing personal protection equipment in a cleanroom

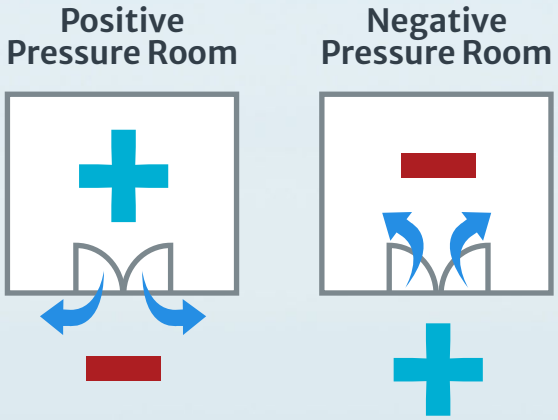


FIGURE 3: Air pressure in cleanrooms

Understanding Air Pressure in Cleanrooms

Pressurizing cleanrooms and varying the level of pressure is an essential characteristic of cleanrooms and helps them reach their desired classifications. Both positive (high) and negative (low) pressure are used in cleanroom design, with the majority of cleanrooms using positive pressure. How does pressure affect the cleanroom environment and why is it an integral part of the design?

As an example, air naturally flows from high to low pressure, with air moving in only one direction as long as that pressure is maintained. This principle can easily be applied to cleanrooms. To prevent the flow of air into a cleanroom, the cleanroom must have positive pressure or higher pressure than the room(s) or surrounding space to limit or prevent particles and contaminants from traveling into the cleanroom. Conversely, if the cleanroom has negative or lower pressure than the room(s) or surrounding space, particles and contaminants will be trapped and prevented from leaving the cleanroom (**see Figure 3**).

Either positive or negative pressure is designed into most cleanrooms for various applications and is achieved by controlling how much or how little air is put into the cleanroom. With positive pressure, any external door that is opened, such as a door to/from the gowning room, will not release contaminants or unfiltered air into the cleanroom since it has higher pressure than the gowning room and outside space. Instead, air is forced out of the cleanroom via vents typically at the bottom of the cleanroom walls, or even via a raised floor in some instances.

Negative pressure does the opposite, the external exhaust from the cleanroom is pulled at a faster rate than air is introduced into the room. The result is negative or low pressure in the cleanroom which effectively stops contaminants from leaving or escaping into other rooms or outside the cleanroom environment.

Some positive pressure cleanroom examples are those that manufacture semiconductor/electronics, aerospace, automotive, just to name a few. Some negative pressure cleanroom examples are medical and pharmaceutical processes. The goal again of

either positive or negative pressure is to protect contaminants from entering the cleanroom (positive or high pressure) or from leaving the cleanroom (negative or low pressure), and both designs are achieved by using the natural movement of air due to pressure.

ISO Standards and Air Changes Per Hour (ACPH)

Cleanroom classifications are important during a cleanroom's design, build, and operational usage. They help determine the degree of cleanliness by the allowed amount of contamination particle count and size, and also need to adhere to air changes per hour (ACPH) in order to achieve specific classification levels.

These classification levels ensure cleanroom cleanliness and are determined by the International Standards Organization (ISO). The classifications are divided into 9 different classes, where Class 1 represents the cleanest cleanroom environment and Class 9 represents the least clean environment, being the equivalent to clean air in a typical office.

The majority of manufactured cleanrooms are within ISO Classes 7–8, with ISO 5 considered to be the cutoff for cleanrooms that need stricter filtration, contamination, and environmental control.

For example, ISO Class 7 cleanrooms are designated under the ISO 14644-1 standard, which specifies air cleanliness in terms of the concentration of airborne particles. These cleanrooms are used in various industries, including some pharmaceutical processes, biotechnology, and electronics manufacturing, where a moderately controlled environment is required. Understanding the specifications of ISO 7 is essential for designing, maintaining, and operating these facilities to ensure they meet the required standards.

Achieving and maintaining ISO 7 standards is all about effective filtration and airflow. HEPA filters are required and must be capable of trapping 99.97% of all particles 0.3 microns or larger. Clean air must come in through FFUs and HEPA filters while moving contaminated air out through vents in the walls or floors. Therefore, the greater the number of FFUs and vents, the greater the air change rate.

FIGURE 4: ISO 14644-1 Cleanroom Standards

Class	Maximum Allowed Particles (per m^3)					Air Change Rate (per hour)	Airflow Velocity (ft/min)	Ceiling Coverage
	≥0.2 µm	≥0.3 µm	≥0.5 µm	≥1 µm	≥5 µm			
ISO1	2.37	1.02	0.35	0.083	0.0029	360–600	60–100	90–100%
ISO 2	23.7	10.2	3.5	0.83	0.029	360–600	60–100	80–100%
ISO 3	237	102	35	8.3	0.29	360–540	60–90	60–100%
ISO 4	2,370	1,020	352	83	2.9	300–540	50–90	50–90%
ISO 5	23,700	10,200	3,520	832	29	240–480	40–80	35–70%
ISO 6	237,000	102,000	35,200	8,320	293	150–240	25–40	25–40%
ISO 7	$2.37x10^6$	1,020,000	352,000	83,200	2,930	60–90	10–15	15–20%
ISO 8	$2.37x10^7$	$1.02x10^7$	3,520,000	832,000	29,300	5–48	1–8	5–15%
ISO 9	$2.37x10^8$	$1.02x10^8$	35,200,000	8,320,000	293,000	0–25	0–5	5–10%

ISO 14644-1 clearly defines the maximum amount and size of particle counts. For example, ISO 7 allows a maximum of 352,000 particles per cubic meter that are 0.5 microns or larger. For particles that are 1 micron and larger, the limit is 83,200 particles per cubic meter. For particles 5 microns and larger, the limit is set at 2,930 particles per cubic meter in order to protect the integrity of the cleanroom and its operation (**see Figure 4**).

ISO 7 cleanrooms should also have between 60 and 90 ACPH. The exact number may vary based on the specific requirements and layout of the cleanroom. The ACPH is expressed as the rate per hour the air in the cleanroom is completely changed or refreshed and is determined by taking total CFM from the FFUs and multiplying that number by 60, then dividing that by the total area (L * W * H) of the cleanroom in ft^3. For example, if total CFM entering the cleanroom is 1,300 CFM and the total area is 1000 ft^3, then the ACPH is (1,300 CFM x 60) / 1000 ft^3, which equals 78 ACPH and is thus classified as an ISO 7 cleanroom.

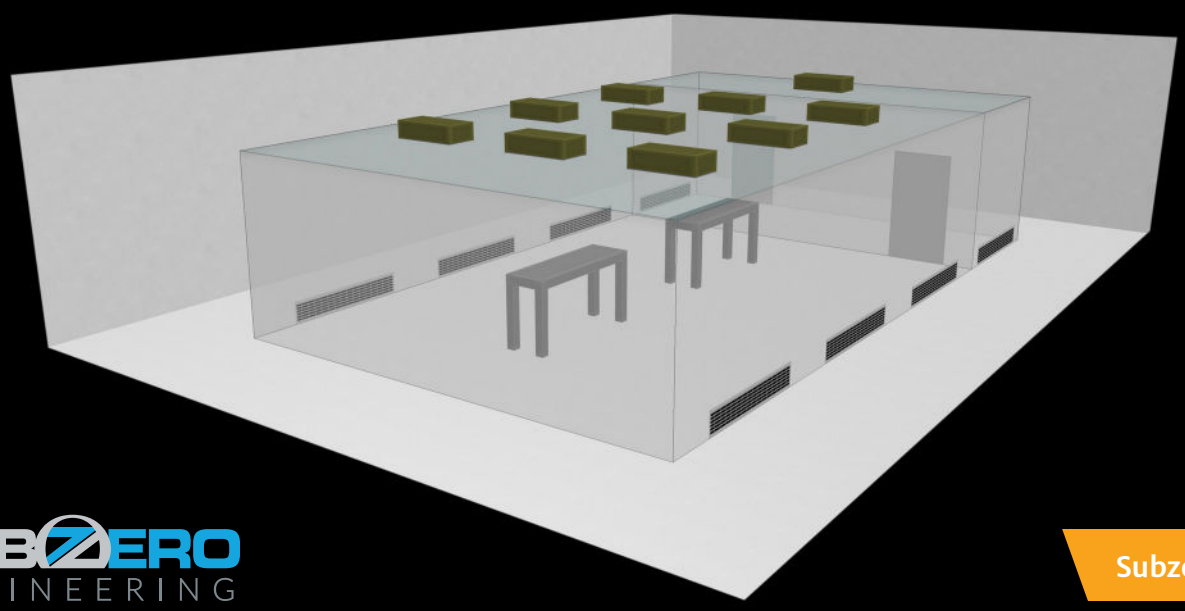
ISO also has 3 different cleanroom classification standards: as-built, at-rest, and operational. After initial construction a cleanroom is "as-built" and changes over time to "at-rest" when equipment is installed. Finally, when people are added and particulate levels rise, the cleanroom is considered "operational".

CFD for Cleanroom Design Optimization

A recent study showed that computational fluid dynamics (CFD) should be used to identify improvement strategies for airflow distribution and to reduce contamination within cleanrooms. This is because it can be used to predict airflow patterns and the cleanroom's ability to remove airborne particles. In addition, CFD is a quick and non-disruptive way to validate design.[2]

So how does CFD for cleanrooms work? Simply put, CFD analysis improves the design, validation, and efficiency by providing predictive results during the design phase of the cleanroom, which is important since it's not always possible to predict what conditions will actually look like in the finished cleanroom. Without CFD there is no certainty that the design will deliver everything that the customer

FIGURE 5a: 3D Layout of Cleanroom and Gowning Area



wants and expects, but CFD helps to change that.

The first step in creating a CFD is to enter data into the model such as room dimensions, location of FFUs, location of doors and vents, etc. The CFD then calculates and simulates the airflow from the FFUs with results that can easily be visualized. The model also predicts any undesirable airflow turbulence, as well as air recirculation due to reduced airflow.[3]

What about the location of the FFUs, vents, and doors in the cleanroom and gowning area? CFD takes the guesswork out of this since it's extremely easy to add and move these and other pertinent objects so as to achieve the best design possible (**see Figure 5a**).

FIGURE 5b: Horizontal Pressure Plane @ 1' Elevation

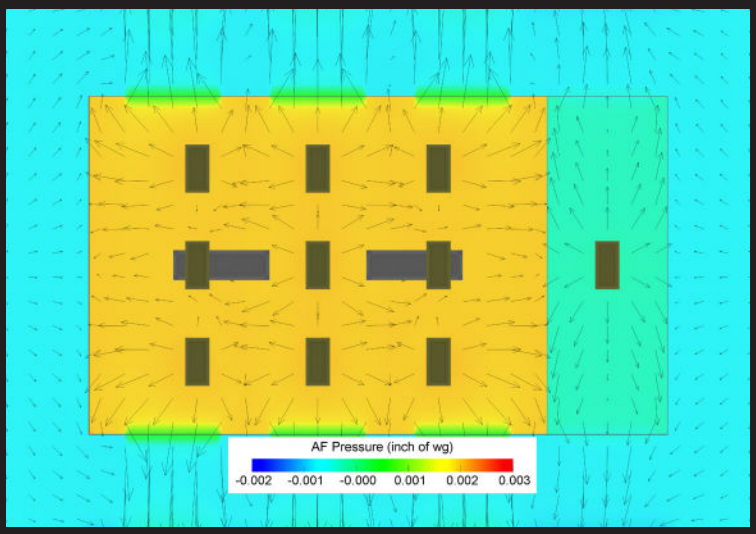


FIGURE 5c: Vertical Pressure Plane

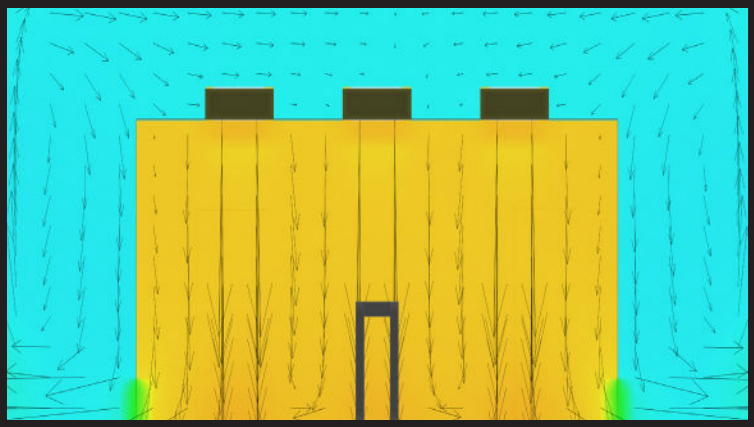
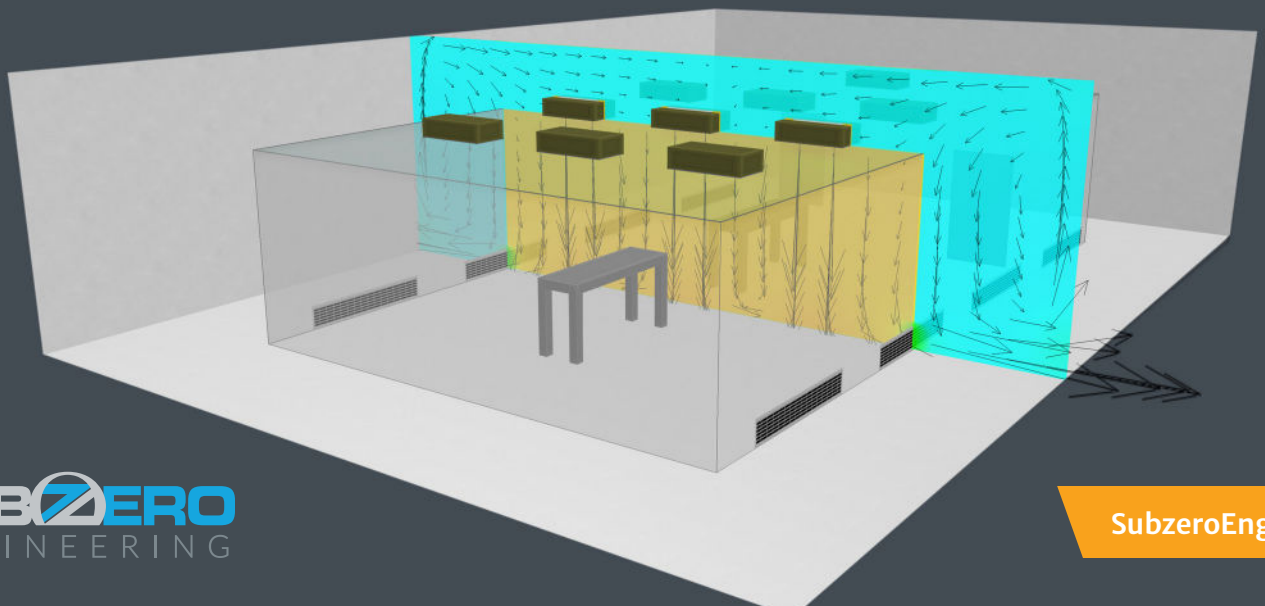


FIGURE 5d: 3D Vertical Pressure Plane



For example, when positive pressure is required in the cleanroom versus the gowning area and surrounding spaces, the quantity and location of FFUs, doors, and vents are essential factors so contamination can't corrupt the manufacturing procedures. CFD easily verifies for both positive and negative pressure designs. If not satisfied with the results, changes can quickly be made to the CFD model to verify that the design will meet cleanroom specifications, including ACPH (**see Figure 5b**).

Finally, since CFD also simulates the flow patterns and flow velocity, it's easy to visualize and correct for undesirable turbulence and air recirculation so that these are kept to a minimum, resulting in cleanroom design optimization (**see Figures 5c & 5d**). Using CFD can lead to the smooth execution of the project while lowering the risk of costly potential design changes, which will boost the ultimate effectiveness of the cleanroom once it's operational.

Conclusion

As can be seen, when it comes to designing and building a cleanroom there is a lot to consider. It's important to choose the right company to design and manufacture the cleanroom of choice so it's robust, module, and expandable. Modular and expandable designs allow for easy scalability and adaptability. Modular designs also accommodate future changes such as expansions, upgrades, and reconfigurations without significant disruptions to existing operations.

When choosing a company to design and manufacturer your next cleanroom, you'll want one with the expertise and experience to deliver the cleanroom project and ensure complete satisfaction. Simplex cleanrooms by Subzero Engineering will do just that, with over 40 years of experience. With Simplex, from the initial design down through the final build, you'll get the perfect cleanroom.

Partner with Subzero Engineering for a tailor-made cleanroom solution that meets your exact specifications.

About the Author

Gordon Johnson is the Senior CFD Engineer at Subzero Engineering and is responsible for planning and managing all CFD related jobs in the U.S. and worldwide. He has over 35 years of experience in the data center and cleanroom industry which includes data center energy efficiency assessments, data center design, CFD modeling for both cleanrooms and data centers, and disaster recovery. He is a certified U.S. Department of Energy Data Center Energy Practitioner (DCEP), a certified Data Centre Design Professional (CDCDP), and holds a Bachelor of Science in Electrical Engineering from New Jersey Institute of Technology. Gordon also brings his knowledge and ability to teach the fundamentals of cleanroom and data center design and energy efficiency via numerous public speaking events annually, white papers, and industry leading researched articles worldwide.

References

1. Mordor Intelligence, Cleanroom Technology Market Size, Growth, Trends & Analysis 2025 - 2030 Segment Forecast
2. CFD airflow stimulations can help enhance cleanroom contamination control, Posted on April 8, 2022 by Hannah Balfour
3. Computational fluid dynamics for cleanroom design optimization, Posted on January 2, 2020 by Amin Razavieh

SUBZERO ENGINEERING