Cleanroom Ventilation Analysis

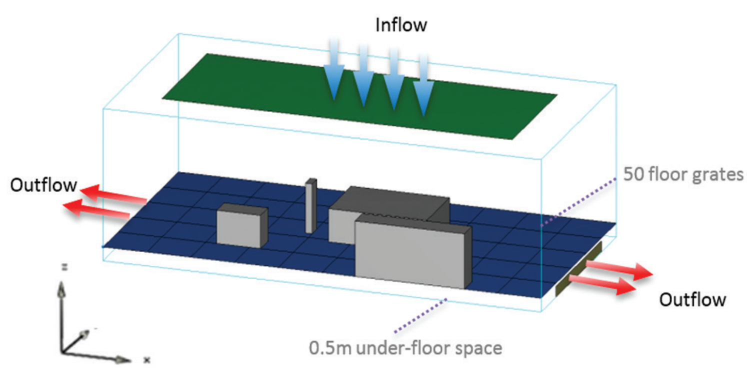
scSTREAM Computational Fluid Dynamics (CFD) Software and Novel Optimization Method Used to Efficiently Optimize Cleanroom Air Ventilation

Cleanrooms are used in a variety of manufacturing processes including electronics, biotechnology, medical devises, micromechanics, optics, and semiconductors. A cleanroom is defined by ISO standard 14644 as a "room in which the concentration of airborne particles is controlled, and which is constructed and used in a manner to minimize the introduction, generation, and retention of particles inside the room and in which other relevant parameters, e.g. temperature, humidity, and pressure, are controlled as necessary" [1]. A raised floor system is one of the flooring methods used in cleanrooms. It consists of solid, perforated or grating panels with various finishing materials and open areas. The contaminated air flows through the floor panels and is exhausted through outlets placed in the sub-floor area. Choosing the proper opening areas for the panels and the panel layout are very important. They directly influence the air flow by creating a different pressure loss and air velocity across the floor panels. Work equipment within the room will impact the local air flow as well. Neglecting the impact of cleanroom geometry could create undesirable flow recirculation such that airborne particles are brought back into the work area. The purpose of this study is to introduce a computer simulation and optimization methodology, using Cradle scSTREAM Computational Fluid Dynamics (CFD) software that can be used to optimize cleanroom ventilation system designs with the minimum amount of design iterations.

Design Objective: Uniform downdraft air flow near the work piece

A cleanroom requires different levels of control depending on air cleanliness classes that are defined by industry standards: ISO 14644, FED STD 209E, BS 5295 or GMP EU. A good cleanroom design must consider several parameters. These include air changes per hour (ACH), pressure, temperature, humidity, and flow direction. This study focuses on obtaining the desirable flow direction (downdraft) by optimizing the opening ratio of the floor gratings.

Computational Domain: 16(m)*8(m) *5.5(m)
Inlet flow rate : 22.951(m^3/s)
Two outlet flow rates: 11.4755(m^3/s) each
Wall boundary condition: no-slip
Fifty floor Grates: 1.6(m)*1.6(m) each



For this example, the computational model consists of a single cleanroom. Some work pieces are placed within the cleanroom that disturb the air flow, but no workers are in the room, and the entrance is not modeled. The inlet and two outlets use fixed flow rates. The raised floor cleanroom uses floor grates, and the entire floor has 50 floor grates.

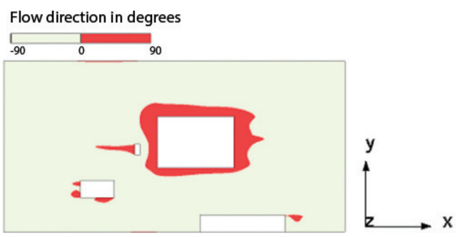
The objective for this design is to achieve uniform downward air flow from 0 to 0.2m above the floor grate.

Effect of Floor Grate Opening Ratio

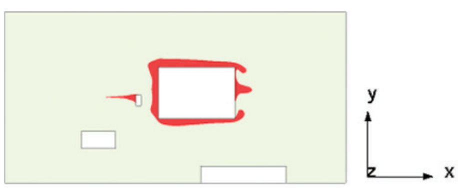
The floor grate opening ratio (OpR) is defined as

$$\text{OpR} = \frac{\text{(Open Area with Floor Grate)}}{\text{(Open Area without Floor Grate)}}$$

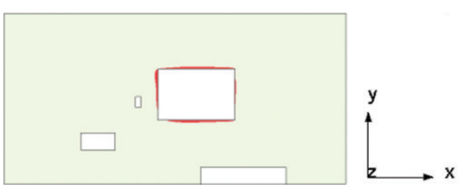
Simulations are run for floor grate OpR = 30%, 20%, 15%, 10%, 5% and 1%. Significant updraft at 0.2m is observed around the work piece for OpR = 30%. The amount of updraft decreases as OpR decreases due to the increased backpressure. However, the updraft is not totally removed until OpR is reduced to 1%.



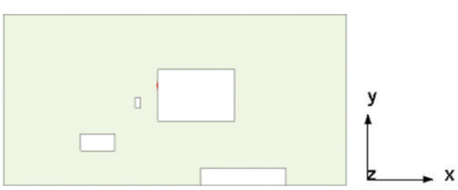
Top view: *Updraft (marked in red). OpR 30%*



Top view: *Updraft (marked in red). OpR 20%*



Top view: *Updraft (marked in red). OpR 10%*



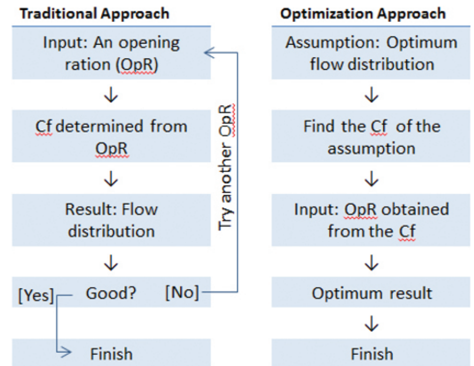
Top view: *Updraft (marked in red). OpR 1%*
Description: *Effects of OpR on Updraft.*

While a 1% OpR eliminates the updraft, the resultant pressure differential is 380 Pa (1.5 in H_2O). Excessive energy consumption would be incurred to maintain this pressure which would result in very high operating costs.

The next step is to consider how to locally control the airflow while still maintaining a reasonable pressure differential. This is achieved by locally varying the OpR based on the pressure loss, i.e. the floor grates around the work piece would have a different pressure loss compared to the floor grates around outlets. However, this increases the complexity of the analysis immensely because additional variables are introduced: how much should the OpRs be varied, and how should the OpRs be distributed? This can be an overwhelming optimization problem with a near infinite number of simulations needed to determine the optimum OpRs and floor pattern that result in the minimum amount of updraft near the work piece and a reasonable overall pressure differential.

A Deductive Optimization Approach

The traditional approach for obtaining the best solution, where many simulations are run with varying inputs and the results assessed for best performance, can be considered an inductive approach. In contrast, a deductive methodology defines the intended result and traces backward to determine the inputs needed to produce this result. This methodology is achieved by a User-defined Function (UDF). Additional calculations needed to define more mathematical relationships are performed using the UDF. These processes are diagrammed in the following figure.



The UDF calculates the pressure loss coefficient through the floor grate (Cf) that will produce the optimum flow distribution. Pressure loss is expressed using the following equation.

Pressure loss $\Delta p = (Cf * \rho * V^2)/2$
Cf: pressure loss coefficient
ρ: fluid density
V: velocity

For the initial calculation, the inlet flow rate is fixed at 22.95 m^2/s with the resultant air velocity across the floor grate at 0.2 m/s assuming all the air is equally distributed across the floor. The UDF first fixes the air velocity across the entire floor grate at 0.2 m/s which is considered the optimal value. The Cf values are solved accordingly.

The total floor area: 16(m)*8(m)=128 (m^2)
The objects' footprint: 24.765 (m^2)
The unobstructed floor area: 103.235 (m^2)---(1)
Inlet flow rate : -22.951 (m^3/s)-------------------(2)
**Assumption: the flow will be evenly distributed over the floor area.
Flow velocity on the floor level (2)/(1): -0.2 (m/s)

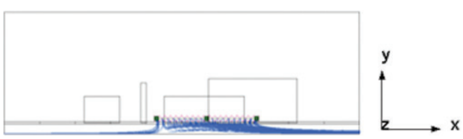
In the scSTREAM CFD model, 17,523 elements are used along the 50 floor grates. Because a Cf is obtained for each element by default, there would be 17,523 Cf values which is more resolution than can be accommodated in the real world. To solve this issue, an additional UDF is used, which calculates the average Cf values of the floor grates. As a result, each of the 50 different floor grates has a Cf and a resultant OpR.

The optimized OpR distribution and resultant streamlines and flow distribution using the deductive approach is shown in the following figures. The total pressure differential for the optimized solution is 4 Pa (0.016 in H_2O).

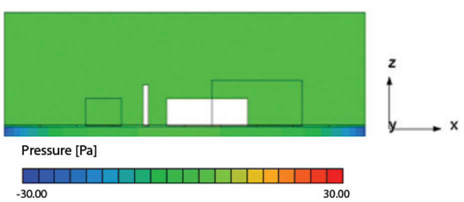
7%	9%	12%	19%	41%	32%	17%	11%	8%	7%
5%	7%	11%	18%	32%	30%	19%	11%	7%	5%
5%	7%	11%	17%	36%	-	29%	11%	7%	4%
5%	8%	13%	18%	29%	25%	16%	11%	8%	5%
7%	9%	12%	17%	31%	25%	20%	15%	9%	7%

Top view: *OpRs to be applied to grates. Each cell represents a floor grate.*

Top view: *Updraft (marked in red) after optimization.*



Top view: *Streamlines near the object after the optimization.*

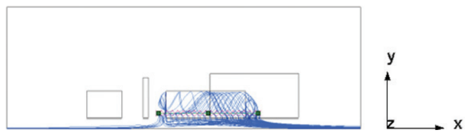


Section view: y-direction: *Pressure after optimization.*

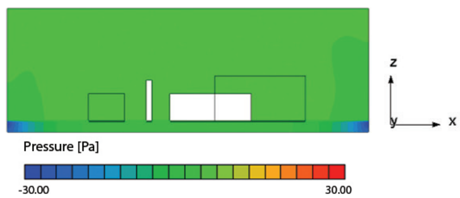
Comparison between uniform floor grate and optimized floor grate for the same total indoor pressure differential

A uniform 10% OpR also produced a 4 Pa total pressure differential just as the optimized case outlined above. However, the streamlines (see figure) shows significant unwanted turbulence near the work pieces compared to the optimized case where the downdraft near the work piece is uniform at the floor grate.

With a uniform floor grate, maintaining a pressure differential of 4 Pa is usually not recommended because of the turbulence induced near the work piece. ISO recommends maintaining a positive pressure differential of 5-20 Pa (0.02-0.08 in H_2O) [2]. However, for the optimized floor grate distribution shown here, a 4 Pa pressure differential could be maintained with little concern about unwanted updraft.

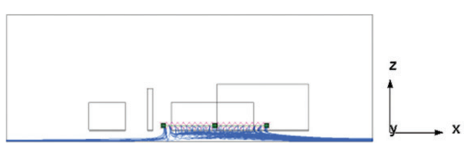


Section view: *Streamlines near the object. OpR: 10%*

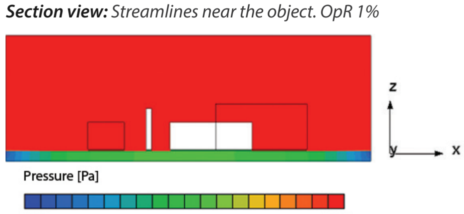


Section view: y-direction: *Pressure, OpR 10%*
Description: *These streamlines images show how the flow near the object has been developed at the 0.2m level.*

Using a very low OpR (e.g. 1%) would also not be desirable due to the significantly increased indoor pressure of 380 Pa (1.5 in H_2O). While this great pressure differential would be reduced if total air flow is reduced, minimum air flow rates are usually required to maintain satisfactory air quality.



Section view: *Streamlines near the object. OpR 1%*



Section view: y-direction: *Pressure.*
Description: *The flow movement improved much. However, the pressure differential significantly increased (380Pa).*

The Flexibility of the UDF Optimization Approach

In this study, the floor grate OpRs were optimized to produce a uniform downdraft near the work piece for a reasonable total pressure differential. This optimization approach can be used in different ways depending on the circumstances or design constraints. If identical grates must be used and the indoor pressure must be maintained at 20 Pa (0.08 in H_2O), the UDF can be used to solve for the optimized OpR. A similar process can be applied to determine the best flow rate for a specific OpR to achieve a certain level of ACH (air changes per hour).

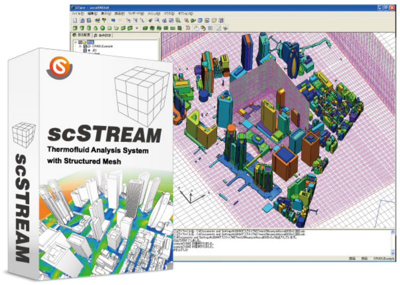
Conclusions

Use of advanced optimization and CFD methodologies can improve process and performance efficiency, design flexibility, and accuracy.

1. **Process efficiency:** Design options are much easier and less expensive to evaluate using computer simulation compared to hardware tests. Novel optimization approaches can identify the best solutions quickly.
2. **Performance efficiency:** Cleanroom facilities have the potential to operate with lower total pressure differentials (lower costs) due to better control of the air flow near the floor grates.
3. **Design Flexibility:** Novel design concepts can be evaluated using CFD. Improved insight gained by visualizing the flow can lead to improved understanding and better solutions.
4. **Accuracy:** Confidence that the final design will produce the expected results increases when using computer simulation as par to the design process.

Bibliography

[1] International Organization for Standardization, "ISO 14644-1:1999, Cleanrooms and associated controlled--Part1:Classification of air cleanliness," Genève, 1999.
[2] International Organization for Standardization, "ISO 14644-4:2001, Cleanrooms and associated controlled-Part 4:Design, construction and start-up," Geneva, 2001.
[3] "FEDERAL STANDARD 209E: Airborne Particulate Cleanliness Classes in Cleanrooms and Clean Zones," Institute of Environmental Sciences, Mount Prospect, IL, 1992.
[4] J. W. Useller, Clean Room Technology, Cleveland, OH: National Aeronautics and Space Administration, 1969.



scSTREAM

scSTREAM uses a structured mesh to model general purpose thermal/fluid applications where tiny details and curved surfaces are not critical for an accurate simulation. scSTREAM can both create the mesh and calculate the solution quickly and efficiently using the finite volume method. A one million element model only consumes 350MB of RAM. In addition to highly capable models for simulating complex physics, scSTREAM also includes a set of Visual Basic interfaces and table/function inputs that make it customizable.

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