Case Study

Enhancing cleanroom design with airflow modeling

STMicroelectronics puts computational fluid dynamics to work to speed completion of a new complex in Singapore

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Airflow modeling has evolved from a “lab curiosity” into a powerful design tool in the field of semiconductor facility and equipment engineering. Models using computational fluid dynamics (CFD) are not only used to “visualize” airflow patterns in cleanrooms but are also working to analyze particle migration paths near wafers transitioning to tool load ports (mini-environments) as well as understanding exhaust plume dispersion and airflow patterns around buildings under different wind conditions.

STMicroelectronics has been using airflow modeling for the past five years for both problem solving in existing cleanrooms and for the design of new facilities. Recent examples include a case study of particle re-deposition on critical parts of equipment located in a gray area, and the complete modeling of a new building complex in Singapore where modeling helped optimize the location of process exhaust stacks and intakes of make-up air units.

In this last case, the result of the model helped STMicroelectronics work with the architectural and engineering team to improve on the original proposed location of make-up air intakes.

CFD considered

CFD involves sophisticated software programs in which numerical calculation methods are used to solve the complex partial differential equations that describe turbulent flow. When a model is properly created, particularly when the elementary cell dimensions and the boundary conditions are correctly defined, the output of the program gives three dimensional mapping of the flow field, temperature and chemical concentration gradients.

The CFD model helps confirm phenomena resulting from “good sense” physics, but which are impossible to measure or simply hard to visualize, even when we are able to use the old dry ice “cleanroom fog” technique in an operating fab. On the other hand, we have found that the ability to graphically visualize a problem enhances decision-making processes for the management and design team.

Two applications of CFD modeling will be examined. The first is how CFD can help reduce the time and cost of raised floor balancing in a conventional bay and chase cleanroom. The second illustrates how CFD can be used to understand and improve airflow characteristics in a “turbulent ballroom” (ISO Class 5) typically designed for a SMIF/mini-environment operation.

Cleanroom floor balancing using CFD

It is possible to aid in the design of a conventional bay and chase cleanroom and accelerate balancing of the raised floor using CFD to predetermine damper positions.

Typically, IDC creates a CFD model of a cleanroom when the cleanroom is a bay and chase design, and has an irregular layout—where bays and chases vary in size throughout the facility.

An example of an irregular layout would be where one area of the clean space has a 65/35 bay to chase area ratio and another area of the clean space has a 30/70 bay to chase area ratio. This is typical in existing facilities where bay and chase sizes are routinely adjusted to accommodate changing processes, and in new facilities to accommodate various tool sets.

The consequence of this layout is air drifting horizontally from the large bays to the smaller bays, resulting in large deviations from vertical unidirectional flow (cross-currents). Deviation from unidirectional flow in a cleanroom is often referred to as "laminarity," or "parallelism," and is defined as the angle in degrees of deviation air streamlines from vertical.

One way to improve laminarity is to adjust the resistance of the perforated floor tiles. This creates more resistance in the smaller bays and forces the air to remain in the larger bays. However, balancing a raised floor manually requires numerous iterations where each 60 x 60-cm floor tile is adjusted during each iteration. A CFD model provides a systematic approach to floor balancing by providing a roadmap for the airflow balancer to follow. This elimination of numerous balancing iterations in the field is where CFD modeling can provide substantial time and cost savings.

A case study using CFD

STMicroelectronics recently refurbished an existing industrial building located in Singapore and installed 4,500 square meters of cleanroom space in record time—fewer than six months from project initiation to the move-in of the first set of process equipment, and including the decommissioning of the existing installations.

Although the performance of the cleanroom was not anticipated for the manufacturing of deep submicron technologies, the goal was to achieve an ISO Class 4 condition complying with the company's standards for temperature and humidity control, noise, and pressurization as well as air flow parallelism and cross-currents.

The specification for unidirectional down flow throughout the clean bays with 100 percent filter coverage calls for a parallelism of ±14 degrees or better from true vertical. The test for this is performed after balancing and completion of airflow velocity and volume uniformity tests.

In addition, when the layout features a bay and chase arrangement with the process bays opened on the central corridor, lateral cross-currents shall not exceed +0.12 m/sec at a bay entrance toward the central corridor and zero from the central corridor toward the clean bays.

The existing multi-story building imposed several constraints, such as limited floor-to-floor clearance and structural columns. A standard bay and chase concept with through-the-floor air return was selected, with low-profile fan filter units used to recirculate the air.

To accommodate the process equipment and the structural columns, the cleanroom has varying sizes of bays ranging from 2.4 m to 3.6 m, and a larger room 14-m wide for photolithography. In order to achieve a ceiling clearance of 2.8 m in the process aisle, the clearance under the raised floor was significantly reduce (40 cm). The level below the cleanroom slab was used as a subfab housing the utility submains, but during the preparation of the tool services fit-up, it appeared that the space under the raised floor would become rapidly crowded introducing additional flow restrictions. Although not the preferred solution, the decision was made to use optional dampers with the perforated tiles of the raised access floor.

These issues created a serious concern regarding the ability of the cleanroom airflow to be balanced. An airflow model of the proposed design was built to quantify the degree to which the cleanroom was out of specification and to determine if a layout change was required. Figures 1 and 2 show results from the model of the cleanroom without floor balancing.

It was found that laminarities were greater than 14 degrees in approximately 50 percent of the cleanroom. In some instances, the deviation from vertical flow was in excess of 60 degrees.

After determining the problem areas, the model was revised in an attempt to reduce laminarities to acceptable values. This included an iterative procedure in which the floor resistance in the model was adjusted successively until laminarities were below 12 degrees in all areas.

In addition, the face velocity of the fan filter units was reduced to 0.35 m/s (68 fpm) to maintain the return velocity under the chase walls of the largest bays (3.6 m wide) below 2 m/s (400 fpm). At the end of the iteration process, the cleanroom floor in the model was made up of a patchwork of differing flow resistance values that easily translated into a map of desired floor damper positions. Figures 3 and 4 show the improvements to the airflow after floor balancing.

Applying the results of the model was straightforward. The balancing contractor used the CFD results, which graphically showed the desired damper positions for all the areas of the cleanroom, to set the floor damper positions correctly.

With the sliding dampers provided by the cleanroom contractor, we found it possible to define four tile configurations: 1.) Fully open (22 percent free area, tile with no dampers); 2.) 2/3 open (~15 percent free area); 3.) 1/3 open (~7 percent free area); 4.) Fully closed. Certification of the cleanroom was then performed, which included deviation from vertical flow measurements, airflow velocity and room pressurization.

CFD modeling has proven just as useful when analyzing a ballroom cleanroom design. In a ballroom, the deviation from vertical flow is dependent on the distance from the chase wall—the wall closest to the return air path.

Without floor balancing, the air in a ballroom will tend to flow toward this wall. The further from the wall the larger the deviation, with the deviation being the worst in the center of the cleanroom. A CFD model can again determine the floor balancing required. Since a ballroom will have the same return air path throughout its life, it is possible to balance the cleanroom floor by varying the free area of the raised floor tiles rather than the floor dampers

Airflow Characteristics in Turbulent Ballrooms

For a majority of semiconductor manufacturers including silicon foundries, most advanced fabs are using the SMIF/mini-environment concept. With the generalization of SMIF fabs, the architectural components and mechanical systems of the cleanroom have undergone significant simplifications leading to an open ballroom design with almost no walls, relaxed temperature specifications, reduced filter coverage and the related reduction in air handler airflow capacity.

The cleanliness class of these “turbulent” cleanrooms does not really fit any of the industry standards, and no longer represents a priority on the list of design criteria. Since designers and owners are not prone to change or de-rate filter specifications, high-performance ULPA filters are typically installed in the ceiling grid, alternating in various patterns with blank panels.

Filter coverages ranging from 16 percent to 33 percent are currently seen, with owners proudly referring to their cleanroom as ISO Class 5. In fact, in this type of cleanroom, we have found the particle density to vary with the location from a perfect “statistical zero” in the shadow of the ULPA filters to ISO Class 6 (237,000 part/m^3 0.2 µ equivalent to former Class-1,000) in vortex zones located under the blank panels.

The SMIF technology has proven to be very effective and forgiving in protecting the wafers against ambient particle contamination, even under harsh conditions like particle bursts during tool hook-up. Raising the question of the right background class level relates to cleanliness class requirements necessary during heavy maintenance of the equipment. More importantly, with the latest generation of 8-inch and 12-inch equipment, the amount of air changes is driven by the amount of heat load dissipated by the process equipment and their peripheral systems located in the air stream.

To aid the design of a new facility compatible for 300 mm manufacturing, we again turned to CFD. The objective was to create an airflow model of the proposed cleanroom design in order to quantify the effects of building geometry, fan placement, and filter layout on cleanroom airflow. The areas of concern were proper pressurization of the supply plenum, degree of turbulence of the airflow across the cleanroom, and effects of equipment heat load on the airflow and temperature distribution. The geometry of the model is shown is Figure 5.

For air recirculation in cleanrooms, STMicroelectronics has been designing fabs with either fan filter units (FFUs) or axial fans. This example illustrates the case for axial fans equipped with integrated sound attenuators to highlight the characteristics of the airflow inside the pressurized plenum. As illustrated in Figure 6, a strong recirculation zone with a clockwise airflow pattern exists in the plenum above the cleanroom ceiling. The uniform clockwise flow results in a small differential pressure inside the supply plenum and uniform irrigation of the filters.

The filter face velocity ranges between 0.48 m/s and 0.56 m/s, and the velocity variance between the filters is ±15% (Figure-7). Despite the partial filter coverage, the overall downflow across the clean space is uniform thanks to the proper depth of the supply plenum chamber and the symmetrical geometry with the return plenum. At 2.4 m above the raised floor, halfway from top of raised floor to ceiling, the air velocity ranges between 0.26 m/s and 0.37 m/s (±17%). At 1 m above the raised floor, the velocity is quite uniform (±12%).

Figure 8 shows the impact of turbulators, a slotted screen diffuser installed below the filters, on the airflow in the cleanroom. The extension of the vortices below the grid between the filters is reduced by 50 percent.

At the halfway point, 2.4 m above the raised floor, the air velocity ranges between 0.29 m/s and 0.33 m/s (±13 percent). At 1 m above the raised floor, the velocity is again quite uniform (less than ±12 percent). If we focus on the working level referred to as the tool load port height (900 mm according to SEMI Standard E15.1-0600 for a 300 mm tool), it is clear that the main contributor to the uniformity factor is the clearance of the cleanroom ceiling (4.8 m). A high ceiling, driven by automated material handling constraints, helps the recombination of the flow streams between the blank panels.

Heat load impact on turbulent cleanroom

The above airflow simulations are related to a cleanroom “as-built” without process equipment. We have used CFD to model the impact of the process equipment on the airflow pattern including the impact of the heat dissipated in the cleanroom ambient area by the equipment.

We have introduced a large box-shaped generic tool with a footprint of 3 m x 5 m. Out of the total power absorbed by the tool, we have assumed a heat transfer of the tool of 4,800 watts (heat not dissipated in the exhausts and the process cooling water). It corresponds to an average heat load of 320 watts/m^2 of cleanroom.

Figure 9 illustrates the vortex developed in the vicinity with the upflow of the combined effects of the air deflected off the tool corner, and convection forces from the tool heat. Both the heat load and the equipment layout are based on simplifications of the likely equipment installation. They are intended to simulate effects that are likely to occur in an actual functioning layout.

When bulky process tools are introduced on the cleanroom floor, the downflow pattern in the turbulent ballroom is modified. Some degree of airflow parallelism is recovered between the equipment, and with a 35 percent free area of the waffle slab, air is circulating below the equipment, under the raised floor. CFD helps understanding the temperature non-uniformity in the cleanroom. Figure 10 shows the result of the model.

Assuming the air is blown through the filter with a uniform temperature of 20ºC and the tool heat load is 320 watts/m^2, the average temperature increase in the cleanroom bay served by one fan measured at the inlet of the fan tower is 0.8ºC—contribution of people and lighting are neglected). This value can be higher if peripheral systems like vacuum pumps, chillers or transformers are located in the return air plenum. In the cleanroom, at the vicinity of the load, the temperature rise can be locally higher (+1.4ºC) introducing spatial variations larger than the desirable specification (±1ºC around the set point).

Conclusion

Clearly the sophistication, accuracy and reliability of airflow modeling have grown appreciably in the last few years. For end users undecided about the appropriateness of this tool for a given cleanroom, a realistic way to value the worth of airflow modeling is to assess the potential losses to productivity and product yield that can result from an improperly balanced cleanroom.

The results of the ballroom model contributed significantly to refine the design of the ISO Class 5 cleanrooms. We found that above 4.2-m ceiling clearance, installation of turbulators or filter diffusers screens are unnecessary if the proper filter coverage is selected.

In a turbulent cleanroom with a ceiling of 4.2 m or higher, a minimum filter coverage of 25 percent is required to achieve enough air changes to dissipate the heat generated by the tools and maintain a background ISO Class 5/6 working level both in the process aisles and on the service side of the equipment.

To maintain the “turbulence,”and therefore the ambient cleanliness class as the ceiling clearance increase, the filter face velocity has to be maintained at 0.5 m/s.

As the equipment installation progresses, the model can also be used to identify the locations where additional filters (or FFUs) need to be installed to minimize hot spots and convection up-flows or improve the background cleanliness at the inlet of the minienvironment of critical process tools.

The microelectronics industry has evolved to a point at which every compromised wafer by the facility design robustness and the cleanroom stability conditions represent a significant financial penalty on the factory floor. As the value and impact of semiconductor facilities has dramatically increased, the value of well-executed airflow modeling has grown accordingly.

How bay and chase layout affects cleanroom airflow

The differences in bay and chase sizes create differing paths of resistance for the air as it travels from the ceiling filter to the chase. In a typical bay and chase design with raised access floors, the largest pressure drop occurs as the air passes under the chase walls.

In the areas of the cleanroom where the bays are small, this pressure drop is small due to the low volume of air passing under the raised floor. Conversely, in areas where the bays are larger, the pressure drop is higher due to larger volumes of air passing under the chase wall. Ultimately, these differences in bay and chase size create a slight pressure differential throughout the cleanroom, causing air to migrate from one bay to the next following the path of least resistance. This is a common cause of deviation from unidirectional flow, resulting in failure of cleanroom laminarity specifications.

Figure 1: Plan view of vector distribution at 1 meter above the raised floor without balancing

Figure 2: Section view AA of vector distribution with without balancing

Figure 3: Plan view of vectors distribution at 1 m above the raised floor with floor balancing

Figure 4: Section view AA of vector distribution with balancing

Figure 5: Fab cross-section used to build the ballroom model

The ceiling clearance is set to 4.8m. The raised floor height is 60 cm above the finished concrete floor and consists of perforated tiles with 20 percent free area. This corresponds to a pressure drop of 6.5 Pa at 0.38m/s. The waffle slab is 90-cm deep with 35 percent free area. This corresponds to a pressure drop of 3.3 Pa at 0.38m/s. Filter coverage is 5 percent in the 3.6-m edge band which forms the tool move-in corridor and 25 percent in the manufacturing space. All filters are 1200 x 600 (mm). Pressure drop for ULPA filters is 100 Pa at 0.45 m/s. Sensible cooling coils pressure drop is not included in the model. The model assumes a steady state condition.

Figure 6: Velocity vectors distribution at fab cross section

Figure 7: Air speed at fab cross section – filters without turbulators

Figure 8 – Air speed at fab cross section – filters with turbulators

Figure 9 – Velocity vector distribution at fab cross section with generic equipment

Figure 10 – Temperature distribution with filter turbulators and process equipment