COMPUTATIONAL FLUID DYNAMICS (CFD) APPLIED TO CLEANROOM AND ISOLATOR APPLICATIONS

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INTRODUCTION

The performance of a cleanroom is determined by extremely complex physical laws. Ultimately it will be controlled by a combination of interactions between obstructions, the layout of equipment, heat and / or contamination sources and the proposed ventilation system. This means that for many designs, the traditional techniques using empirical relationships and methodologies based on past experience are inadequate. Empirically based techniques have now been used for many years in calculating the required air flow rate to achieve a certain standard of cleanliness class or to compensate heat loads within the space. Over the years, however, the figures thus calculated have had margin upon margin added to them with the result being that many systems are over-designed with capital and operating costs far in excess of what they would have been for a more optimised design. Furthermore, the only confidence a designer has that the system will operate as intended is based more often than not, on “gut feeling” and experience.

This paper outlines how airflow modelling or CFD can be used to predict exactly how a cleanroom will perform given a certain set of conditions. To a large extent, these techniques, dispense with historical calculations and allow each new design to be treated as just that without having to rely entirely on experiences from the past or mock-ups of the space being designed. This paper gives some background to airflow modelling and describes some case studies of where it has been applied in cleanroom and isolator design.

WHAT IS AIRFLOW MODELLING?

Airflow modelling solves the set of Navier Stokes equations by superimposing a grid of many tens or even hundreds of thousands of cells which describe the physical geometry heat and contamination sources and air itself. Figures 1and 2 below, shows a typical research laboratory and the corresponding space discretisation, subdividing the laboratory into tens or hundreds of thousands of cells.

The simultaneous equations thus formed are solved iteratively for each one of these cells, to produce a solution which satisfies the conservation laws for mass momentum and energy. As a result we can then trace the flow in any part of the room simultaneously colouring the air according to another parameter such as temperature.

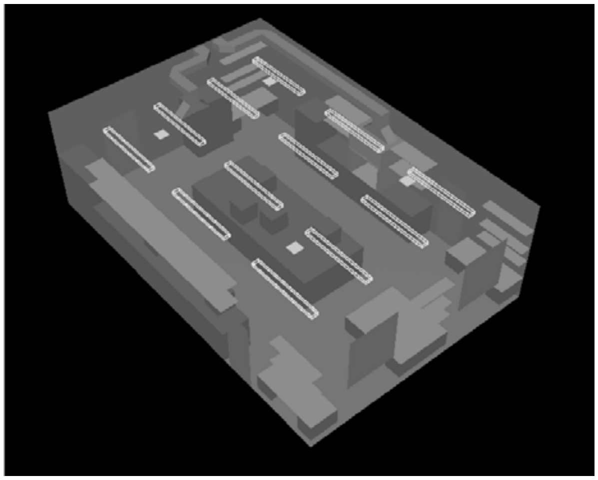

Figure 1. Geometric model of a laboratory

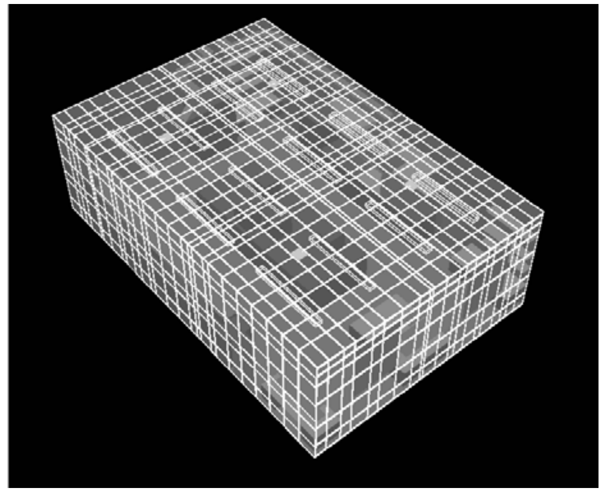

Figure 2. Superimposed grid of cells for calculation

In the case of the above laboratory imagine a smoke tube is positioned inside the supply air diffuser and behind the make up air grille, figure 3. As the air moves, the smoke changes colour according to its air speed. The intention of the Total Air Diffuser used in this design is to generate low velocities from the supply air diffuser which sweep the laboratory air to the hood exhaust. Low velocities from the supply air are shown in figure 3 by the blue air. As air speeds increase the colour changes from blue through green and yellow to red. The red condition represents a velocity of 0.5m/s (the mean sash opening velocity for the design) or more. Indeed, the cool supply air from the diffuser does not impact on the open sash of the laboratory hood, but falls to the floor. The warm air from the make-up air grille however floats across in front of the hood destroying containment. Figure 4. Shows the disturbed flow in front of the laboratory hood by placing the smoke source on the faces of an imaginary box extending approximately 1 ft outside the sash opening into the laboratory. Instead of the potentially contaminated air being entrained into the hood it is swept around the laboratory by the cross-flow from the make-up air grille.

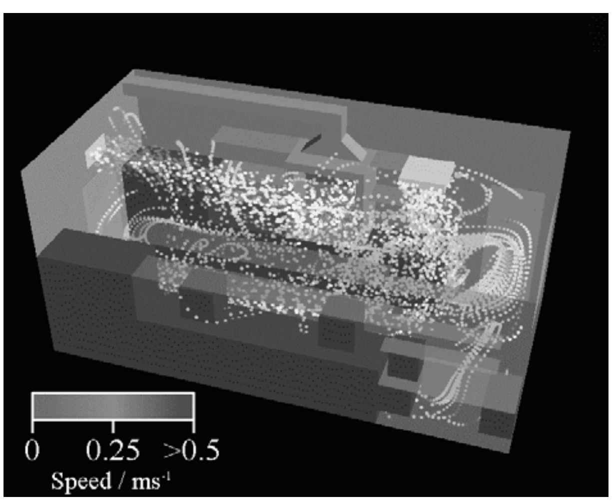

Figure 3. Flow from Total Air Diffuser and

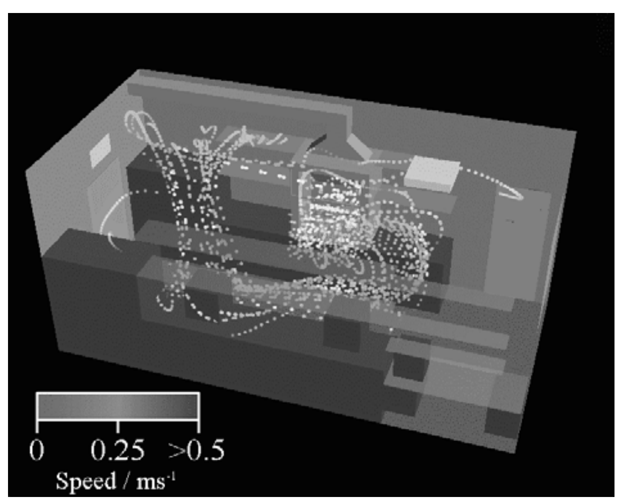

Figure 4. Disturbed flow in front of hood

The sensitivity to small changes in design can be seen clearly when we move the supply air diffuser to the other side of the hood. The two incoming air streams now combine, Figure 5 with the result that the air from outside the hood is almost entirely re-entrained into the laboratory hood, Figure 6.

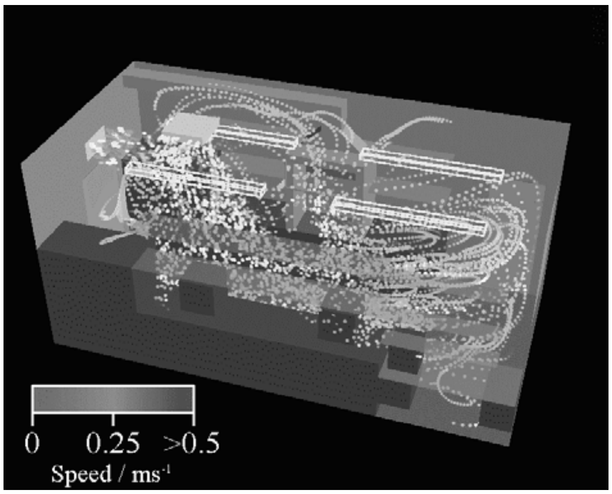

Figure 5. Flow with Total Air Diffuser

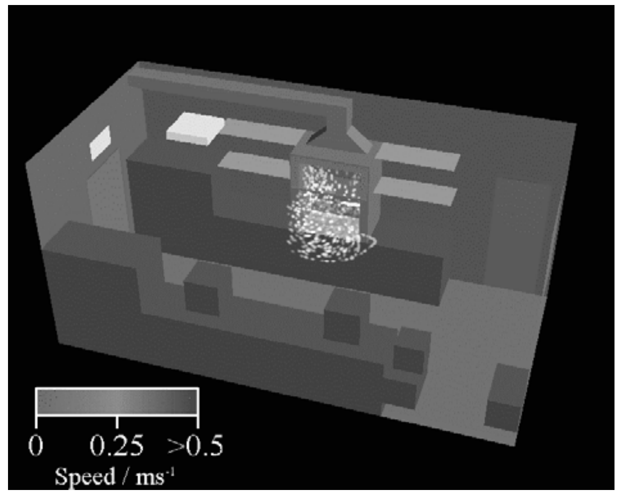

Figure 6. Flow re-entrained in front of hood

Of course it is not just the configuration of the room that affects the airflow but also the overall construction of the building. Specifically the supply air plenum and the return air void and chases have a dramatic impact.

WHY USE AIRFLOW MODELLING?

Many people nowadays, have seen airflow modelling in one form or another but what are the advantages of using such techniques? In order to answer this question, let us look at the alternatives, all the while remembering that each new building is, in effect, a prototype.

Traditional methods of designing HVAC systems normally rely on an engineers experience and "Rule of Thumb" techniques as well as some empirical relationships. The limitation to this is that each building is unique in terms of it geometry, use, heat gains, personnel, location etc. and therefore favourable experiences on one project cannot necessarily be applied to another. There is also the tendency to add margins into the design to compensate these shortcomings. Further down the line designing on the experience of one project, margins can be added on to margins with the result being a system over designed for the purpose it was originally intended for.

In certain circumstances it may be appropriate to consider building a physical mock-up of the room or a section of it in order to have some confidence that the designed system will operate as intended. These types of exercises, however, are expensive, time consuming, and have certain limitations in that by the stage in the design where a mock-up is considered it is normally too late or very expensive to make significant changes to the design. A mock-up also takes up floor space and therefore must have a limited life. A computer model of the airflow can be referred back to months or even years later.

Airflow Modelling, on the other hand, can tackle all of these shortcomings and provide information that is difficult to interpret or measure during a physical test. In short, the advantages are:

- Scientific calculation of airflow patterns, temperature and contaminant spread as opposed to relying on an individuals experiences and "rule of thumb" design guides.
- Less expensive and time consuming than physical mock-ups.
- Knowledge of the airflow in a room can be decided at the conceptual stage and will ultimately save time correcting conceptual mistakes as they propagate further down the design process.
- Demonstration to clients or management how a particular design will work.
- Potential capital and running cost savings for a more optimised design.

CASE STUDY EXAMPLES

Traditionally, the most reliable method of ensuring a clean environment is by introducing a uni-directional airflow into the space. In this way, clean filtered air flows down over the product or process with little possibility of recirculation regions in which contamination may become caught. This type of flow control is extremely important in manufacturing in the pharmaceutical industry. The unintentional flow regimes shown in the examples so far can be a great risk to the products which must not be contaminated by other substances even in the smallest quantities.

The vial filling room (courtesy of Chiron Corporation), figure 7, addresses the effect of HEPA filter layout and exhaust grille layout on minimizing upward flow in the room. The flow visualisations are coloured according to **vertical velocity**. This is a measure of air flow uniformity (laminarity) and thus better ventilation design. To provide the aseptic environment the key process areas are ventilated by HEPA filters from above. Above the fill equipment and in the laminar flow hood, the air is drawn from the room through high level returns. The air is then filtered and re-supplied to the room through the HEPA filters. The remainder of the HEPA filters are supplied from the main plant, with the return air exhausted from the room at low level. Other processes (eg the autoclave and oven - located on the long wall nearest the viewer) are not however completely surrounded by HEPA filters and so are more vulnerable to non-uniformity of airflow.

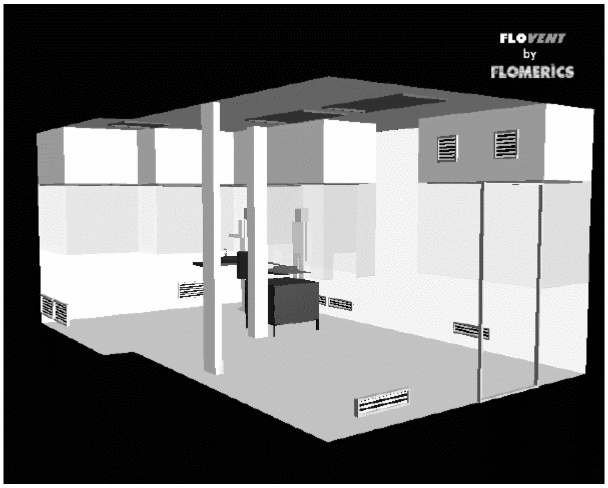

Figure 7. Geometric model of vial filling room

The design team at Chiron are upgrading the fill machine and are considering the possibility of using the opportunity to enhance the aseptic performance of the room. The chosen method was to use airflow modelling to understand the current performance, introduce the new equipment, assessing its impact on the ventilation performance, and to refine the design to minimise and contain any areas of upward flow. The consensus of opinion is that such a design outcome would lessen the risk to the air flow's laminarity around the vials.

The case study documented here deals with the latter part the optimisation. The current configuration with the new fill machine can be seen to perform well within the main 'laminar' flow areas, however there are some features of the flow which are considered less than optimal. Figure 8. Show the air from the main laminar flow panels. In this view, air from the laminar flow hood can be seem to hit the floor turn back upwards into the LAF itself and also flow across the room before flowing upwards in front of the autoclave and oven.

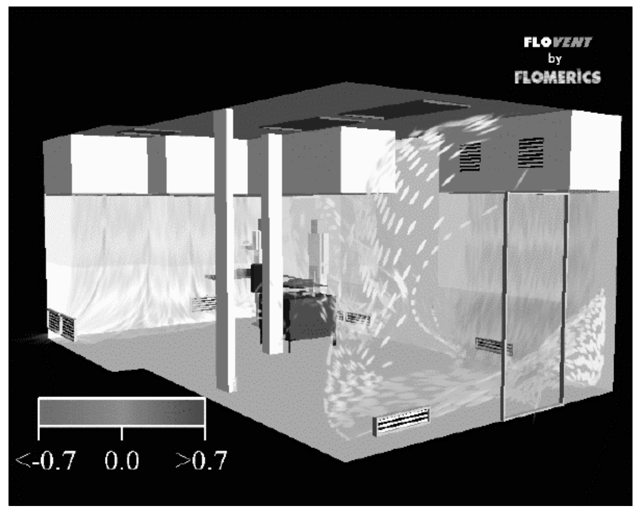

Figure 8. Flow in the Original Configuration

Less visible in this view is the upward flow behind The pillar adjacent to the fill machine or the upward flow to the high level returns above the fill machine. Both are a potential source for turbulent diffusion against the downward flow.

The process of re-design is an iterative one inspecting the features of the flow and using engineering judgement to modify the configuration to resolve the perceived problems. In this case, the high level returns are removed and the HEPA filter layout in the open part of the room is redesigned. Removing the high level returns as expected has reduced the amount of upward flow while placing the HEPA filters closer to the autoclave and oven protects them. Selective placement adjacent to the fill line has also reduced the risk of non-laminarity.

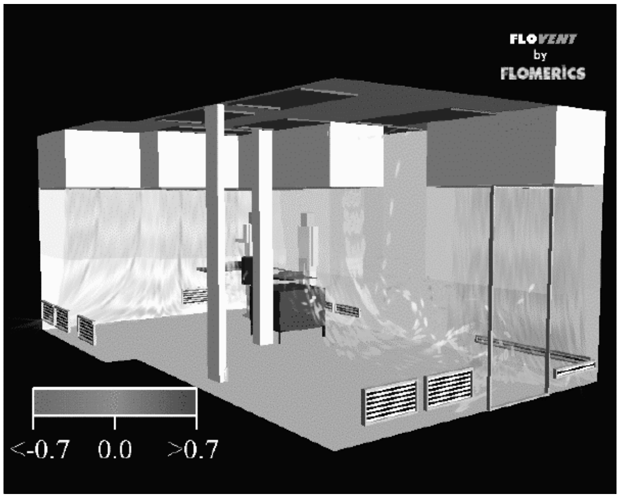

Figure9. Local exhaust under the LAF

Also, one solution to the reducing upward flow in the LAF is to provide local exhaust around the corner of the room below the LAF, figure 9. This reduces the quantity of air moving off across the floor towards the fill line thus reducing the upward flow there.

In Conclusion

Using airflow modelling techniques, facilities engineers in companies such as Chiron, Zeneca, Smithkline Beecham, Merck and Rhone Polenc Rorer have identified significantly improved configurations for the clean rooms of many types without interfering with the normal manufacturing processes. The opportunities this technique provides allow facilities operators and designers to use the technique further, not only to improve the cleanliness of the environment but to have confidence that this will be achieved and in the shortest possible time scale. This can be undertaken to establish whether new designs, or changes to the design and layout of the equipment, protective curtains and so on, will enable more efficient use of the facility.