Guide to air change effectiveness

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ABSTRACT

Green Star rating under the Green Building Council of Australia is increasingly considered and demanded by the building developers. One of the Green Star rating categories is air change effectiveness (ACE). Two points are awarded if ventilation systems are designed to achieve ACE of at least 95 % of the net lettable area (NLA) when measured in accordance with ASHRAE 129-1997. During the design stage this can only be demonstrated through computational fluid dynamics (CFD) modelling of the air conditioning system other than the nominated DTS criteria. This study summaries the factors affecting ACE and provides design guidelines to assist in achieving compliance with the GBCA ACE requirements. The effect of return air plenum on ACE is discussed.

Keywords: Air change effectiveness (ACE), Green Building Council of Australia (GBCA), computational fluid Dynamics (CFD), effect of return air plenum

INTRODUCTION

Air change effectiveness (ACE) is a description of an air distribution system's ability to deliver ventilation air to a building, zone or space. One common definition of ACE is the ratio of a nominal time constant to a mean age of air. The nominal time constant is calculated as a ratio of the domain volume (m^3) to the supply air volume to that domain (m^3/s).

ACE can sometimes be confused with ventilation effectiveness. Ventilation effectiveness is a description of an air distribution system's ability to remove internally generated pollutants from a zone.

ACE simply indicates how well the air is distributed within the breathing height. ACE = 1 indicates that the air distribution system delivers air equivalent to that of a system with perfectly mixed air in the space. An ACE value less than 1 indicates that the air distribution within the zone is less than perfect mixing. A short-circuiting flow pattern between the air-supply diffusers and return grilles increases the room-air age and causes ACE to be less than unity. Preferentially supplying the air to the breathing zone will cause the ACE to be greater than unity.

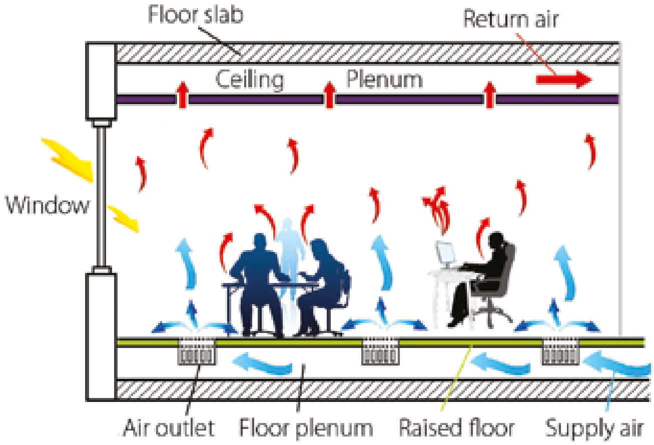


Figure 1: Displacement flow within a space

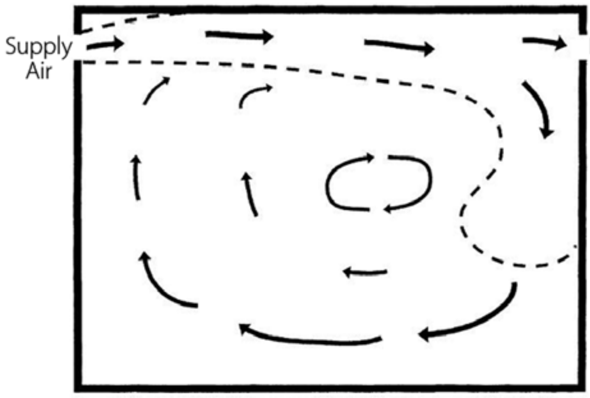


Figure 2: Entrainment flow within a room (ASHRAE)

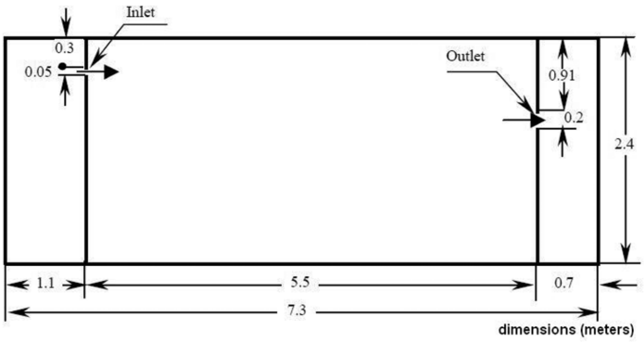


Figure 3: Section of the room lay-out for the flow pattern study [2].

Providing more fresh air than required by AS 1668.2 does not guarantee GBCA [1], Green Star ACE compliance. In order to achieve better ACE and comply with GBCA requirements, air distribution systems need to deliver the supply air to the breathing zone. Air movement within the space directly affects the occupant comfort, indoor air quality and ACE. Displacement flow and entrainment flow are the two distinct flow patterns commonly used to characterise air movements in buildings.

Displacement flow is characterised with the movement of air within a space like a piston motion. (Figure 1). In an

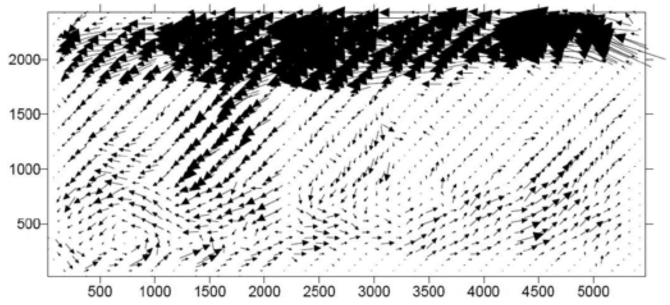


Figure 4: Flow pattern of the room shown in Figure 3 when air change rate is 19.5 ACH [2].

ideal displacement flow, the room air does not mix. A typical entrainment flow is shown in Figure 2. Ceiling-based air supply and return air grilles generally exhibit an entrainment flow. Displacement flow has a higher potential to achieve a better ACE value than the entrainment flow.

Air distribution systems that show entrainment flow pattern might cause short circuiting. Lingying Zhao et al [2] conducted an experimental study to determine the flow pattern in a room. Figures 3 and 4 show the experimental room lay-out and one of the flow patterns (velocity vector map).

Lingying Zhao et al concluded that "The different ventilation modes [different inlet velocity, KG] do create quite different airflow patterns. Some parts of the patterns have conflicts with previous measurements, and some parts agree very well with flow principles revealed by previous researchers. Airflow velocities in the occupant zones vary a lot for the tested four ventilation modes."

William J. Fisk et al [3] measured the ACE in 26 laboratory experiments. Ceiling-mounted induction-type supply-air diffusers and return grilles were used with a VAV ventilation system. They stated that "In 15 tests with heated supply air supplied at relatively low volumetric flow rates, 100% outside air, and three typical supply diffusers (including a very basic unit), the ACE ranged from 0.69 to 0.89. In four previous laboratory tests with heating and 100% outside air, the ACE ranged from approximately 0.7 to 0.9 (Fisk and Faulkner 1992). Two prior ACE measurements by Offermann (1988) with heating and 33% outside air yielded values of 0.66 and 0.73."

Poorly designed, installed, or operated systems – in particular, ceiling based systems in heating mode – can exhibit short-circuiting. The studies cited show the need for properly designed, installed and operated air-distribution systems.

Accurate prediction of air-flow patterns within rooms and through buildings becomes more and more important for the HVAC system designs. For maximum energy efficiency, high thermal comfort, and optimum indoor air quality and ACE, the details of the flow pattern must be known during the design phase of a building.

CFD simulation is the only way to determine the flow pattern and demonstrate the GBCA's Green Star compliance during the design phase.

VARIABLES THAT CAN AFFECT THE FLOW PATTERNS

The bases for air movement, both inside and outside of buildings, are temperature and pressure differences. ACE is dependent on the air-flow pattern. In a building environment, flow pattern and ACE are dependent on a large number of variables. Some of the variables are listed below:

- Room geometry;
- Location of supply-air terminals within the room;
- Flow rates and flow characteristics of supply-air terminals;
- Temperature of supply air;
- Location of return-air terminals or other pathways within the room;
- Internal heat gains and their distribution within the room;
- Physical obstructions to air movement, including walls, columns, and workstation surfaces;
- Boundary surface temperatures and heat fluxes;
- Stack effect; and
- Wind pressure/infiltration air.

Small changes in these parameters can have a pronounced effect on the assessment outcome, as they can result in significant variations to the room air flow patterns around the measurement plane or the room as a whole. Figures 5a and 5b demonstrate the effect of changing supply-air flow direction of a single air-supply terminal. Figure 5a shows the original design. Air is directed towards the facade, and about 4% of NLA fails to comply with GBCA ACE requirements. Figure 5b shows that all the floor area complies after only one diffuser flow direction is reversed (i.e. flow direction is from perimeter zone to centre zone).

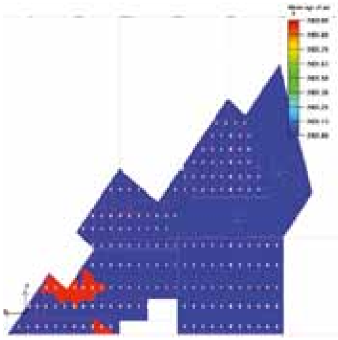


Figure 5a: Original design

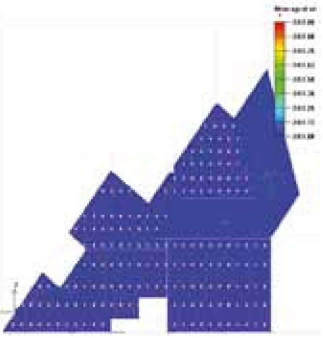


Figure 5b: One diffuser flow direction was reversed.

Anticipating the impact of any change is not always possible. Field measurement is the only objective method to determine the effect of change on the flow pattern and ACE in built environments. During the design stage, a CFD simulation can be successfully used to identify and establish the flow pattern for a building.

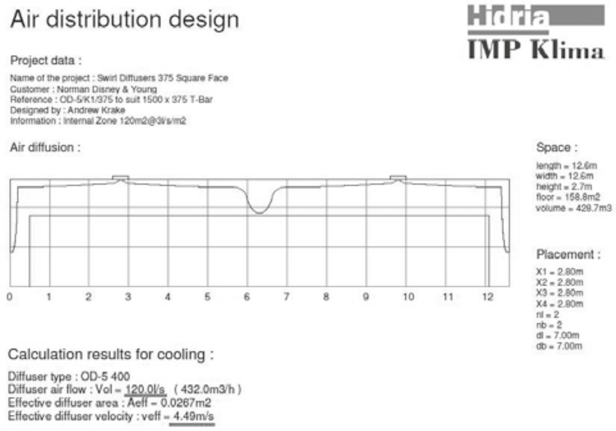
CFD SIMULATION

When a CFD simulation is used to determine the flow pattern, new parameters in addition to the ones listed above can affect the results.

First and most important of the new parameters is the CFD software package chosen for the job. Not every CFD software package is suitable for GBCA Green Star ACE simulation. A CFD package should be capable of modelling from momentum source scale to at least building scale, if it is used for the ACE simulation.

Meshing size and quality is another parameter that has an impact on the results. The primary role of a mesh is to enable an accurate simulation to be performed on a computer. As such, it is appropriate to consider mesh quality in terms of error analyses, which is not examined in this study. A description of mesh-quality metrics can be found in Knupp [7] and Kwok and Chen [8]. A comprehensive background could be found in Perez [9]

Supply-air terminal flow characteristics need to be known for a successful simulation. Figure 6 shows typical information provided by the supply-air terminal manufacturer.



Air distribution design

Hidria
IMP Klima

Project data :

Name of the project : Swirl Diffusers 375 Square Face
Customer : Norman Disney & Young
Reference : OD-5/K1/375 to suit 1500 x 375 T-Bar
Designed by : Andrew Krake
Information : Internal Zone 120m2@3l/s/m2

Air diffusion :

Space :
length = 12.6m
width = 12.6m
height = 2.7m
floor = 158.8m2
volume = 428.7m3

Placement :
X1 = 2.80m
X2 = 2.80m
X3 = 2.80m
X4 = 2.80m
nl = 2
nb = 2
dl = 7.00m
db = 7.00m

Calculation results for cooling :

Diffuser type : OD-5 400
Diffuser air flow : Vol = 120.0l/s (432.0m3/h)
Effective diffuser area : Aeff = 0.0267m2
Effective diffuser velocity : veff = 4.49m/s

Figure 6: Supply-air terminal flow characteristics needed for the CFD model calibration.

This type of information is the least amount of information required for a CFD supply air terminal calibration. Calibration of the supply air terminals is imperative for a realistic CFD simulation. Figure 7 shows the velocity contours after the CFD calibration process of the described supply-air terminal.

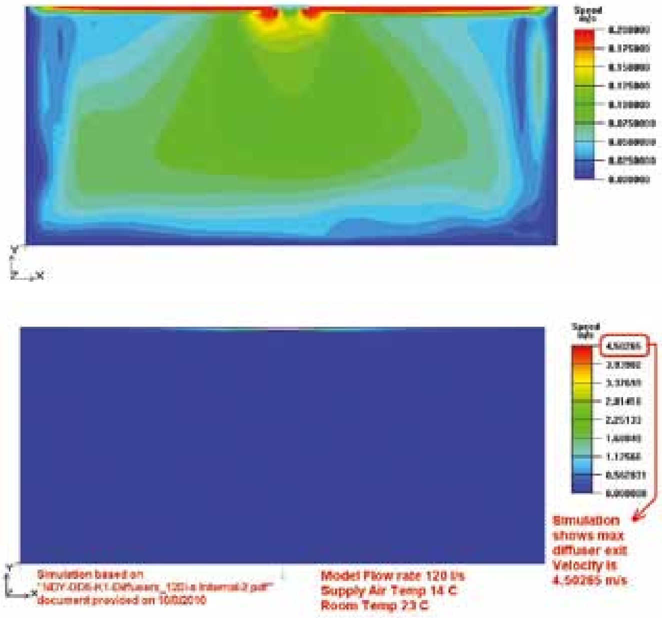


Figure 7: Calibrated supply-air terminals velocity contours. (Only scales are different)

DESIGN ISSUES INFLUENCING AIR CHANGE EFFECTIVENESS OUTCOMES

As mentioned, there are many parameters affecting ACE, and any small variation of these parameters can potentially alter the flow pattern, resulting in significant change to the assessment results. (Figure 5). In a typical ACE simulation, the CFD model would have up to six to seven million, if not more, meshing nodes; the results of one meshing node calculation would be the input of adjoining nodes.

Due to this large number of interactions, anticipating the impact of any change to boundary conditions is not always possible. Therefore the discussion presented here should be considered as guidance only. Since all the designs are unique to each project, a CFD analysis is the only objective method to determine if a design can achieve a GBCA ACE compliance other than the nominated DTS criteria.

WHICH VENTILATION SYSTEM ACHIEVES BETTER ACE?

Selection of the ventilation/AC system can have a profound effect on ACE results. Brief information about the ACE performance potential of ventilation and air conditioning systems is below. Simulations presented in this study have been carried out with the ANSYS Airpak software package using the mechanical design specifications and drawings for that project in cooling mode.

CAV+ chilled beam

Chilled beam systems (active and passive) offer some energy-saving advantages, and could be an attractive solution when ESD is considered. There are many shapes and sizes of both types of chilled beams, from rectilinear slots to 600mm squares and rectangles. There are also varieties of both passive and active chilled beams that incorporate other elements – for example, lights, sprinklers, speakers, space-occupancy sensors and smoke detectors – in a multi-service beam configuration. These can be surface-mounted, suspended or recessed in a lay-in ceiling.

All of the chilled-beam arrangements have a common feature: they all create additional vertical air movements within the space they are installed. A typical air-flow pattern created by an active chilled bean is shown in Figure 8.

This additional vertical air movements will provide better air mixtures within the space compared to a VAV system. CAV+ chilled beam systems usually achieve compliance

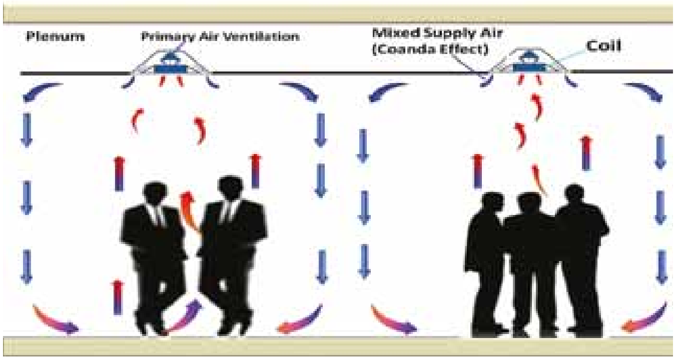


Figure 8: Typical air movements caused by a chilled bean system.

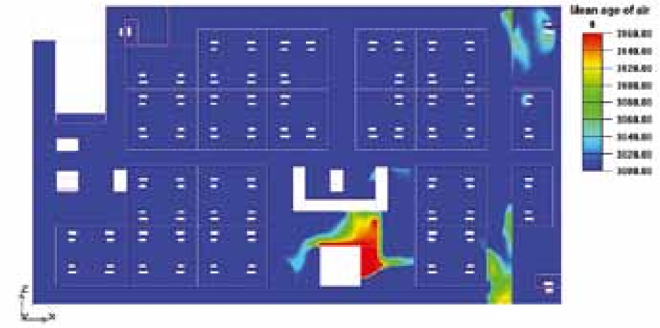
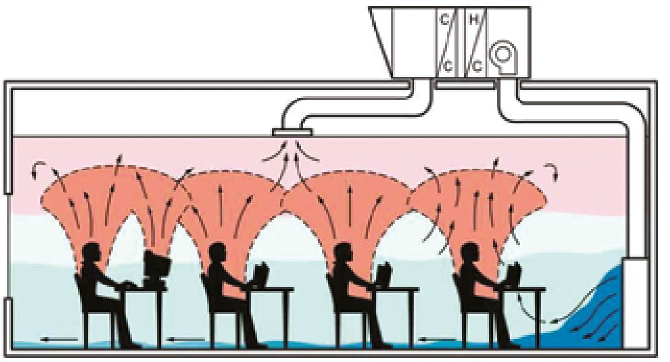


Figure 9: Compliance area of passive chilled beam system (NDY Melbourne office first floor)

with the GBCA ACE requirements. The NDY Melbourne headquarters has a passive chilled beam system. Figure 9 shows the mean age of air contours for the office first floor. The blue area indicates compliance. Images given in Figure 5 also have passive chilled beams.

Displacement ventilation (UFAD)

The principle of displacement ventilation is that cooled air is supplied with low momentum in the lower part of a room. The cold air displaces the contaminated air from the occupied zone upwards in a room. Buoyancy forces (temperature differences) control the air movement in the room, as the free convection around heat sources (occupants, equipments and lightning) creates vertical air movements. In the same way, a cold window or a cold wall will result in a downward convective flow.



source: http://www.energydesignresources.com

Figure 10: Typical air movements caused by displacement ventilation system.

A very important characteristic of displacement ventilation is the formation of stratified layers of air. This characteristic provides a substantial advantage in order to achieve GBCA ACE compliance. It is expected that many of the underfloor distribution systems would achieve compliance with GBCA ACE requirements by CFD simulation.

Variable air volume (VAV) systems

In variable air volume (VAV) systems, changes in the room heat-load are met by controlling the volume of air supply to the room without changing the supply temperature until the minimum permissible air supply is reached. On the other hand, seasonal control of the supply-air temperature takes place as a function of the outdoor temperature. A VAV system can operate over a wide range of air-flow rates, and this will have a flow-on effect on the flow pattern within a room. GBCA ACE assessment requires that all the simulation be performed at the lowest turn-down ratios.

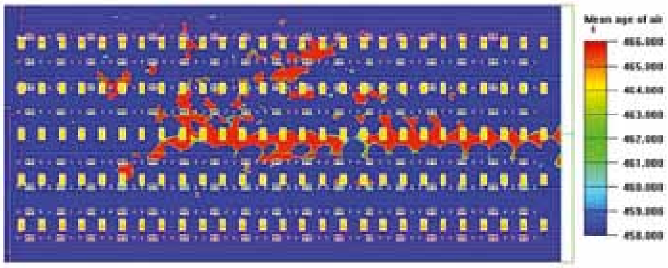


Figure 11: Mean age of air contours for the ANZ project CFD model 4. (Compliance achieved)

A typical office VAV system would have supply and return-air terminals located on the ceiling, and there is a wide variety of air terminals that could be considered. Figure 12 to 16 shows flow characteristics of some supply-air terminals.

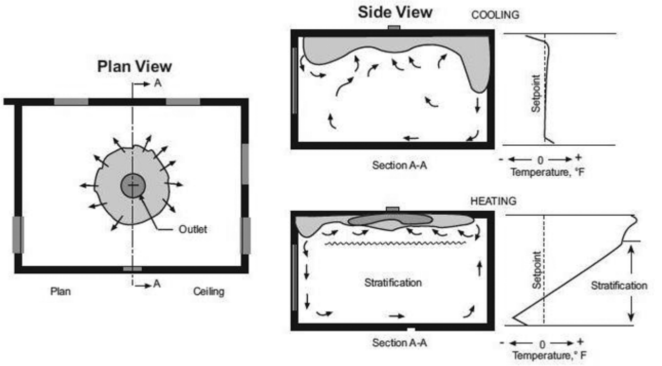


Figure 12: Swirl diffuser flow pattern [4].

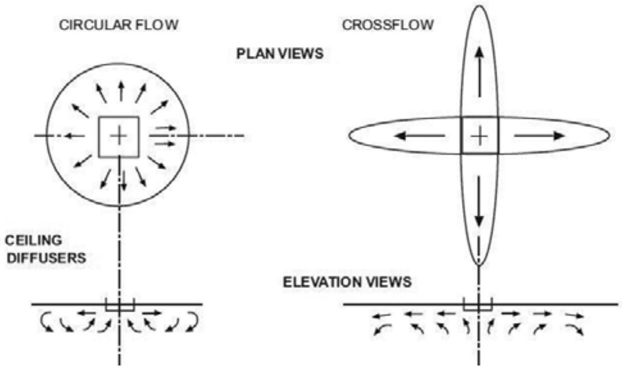


Figure 13: Circular, horizontal and cross-flow pattern [4].

ACE assessment results are dependent on the selection and location of supply and return-air terminals. Due to the high induction air motion and strong mixing characteristics, swirl diffusers are an attractive option for many designers and architects. Swirl diffusers produce relatively poor ACE results when used with perforated ceilings or light troffers/return plenum slot diffusers. Figure 17 and 18 show open-plan office ACE simulation results. The building has a VAV system with swirl diffuser and light troffers RA arrangements, and also some perforated ceiling at the building's break-up area.

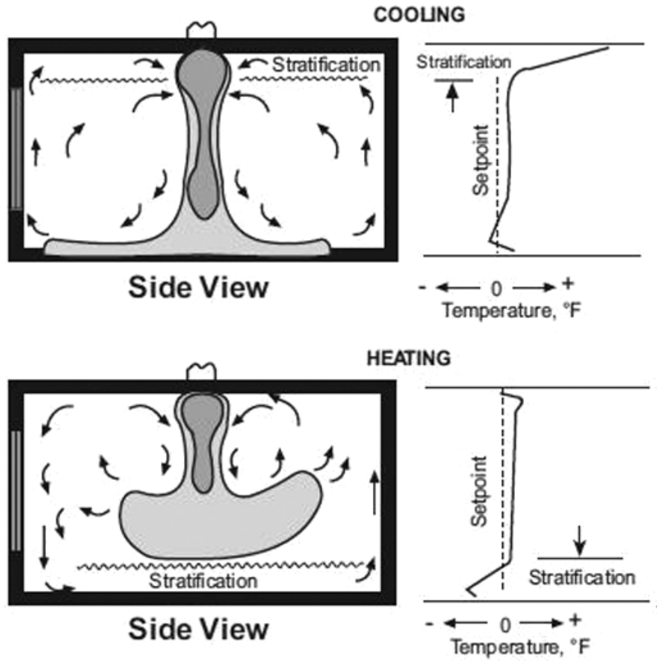


Figure 14: Downward projection characteristics from ceiling diffusers [4].

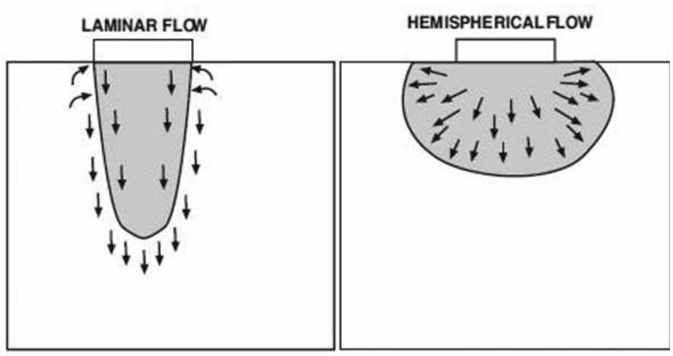


Figure 15: Downward laminar flow diffusion pattern and hemispherical flow diffusion pattern [4].

Figure 16: An image from a round adjustable diffuser smoke test.

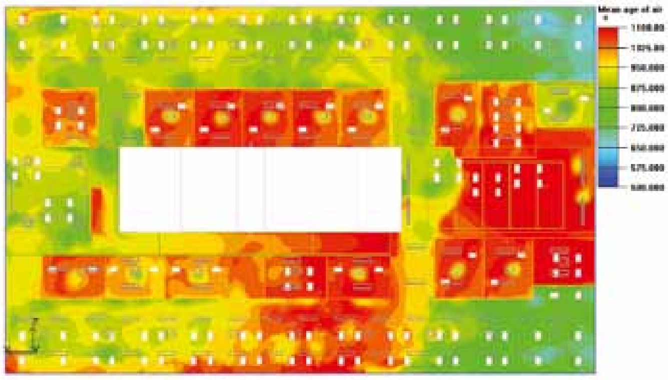


Figure 17: Mean age of air contours of an open-plan office.

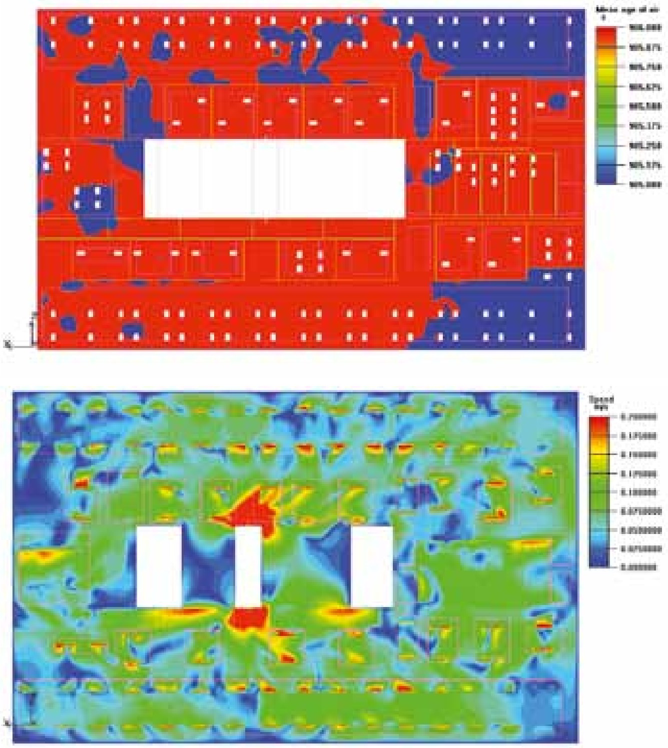


Figure 18: Open-plan complied area indicated with blue; velocity contours at plenum level.

Figure 19 shows the ACE assessment results of another open-plan office. This building also has a VAV system. Supply air, again, delivered to the zone via swirl diffusers, and light troffers and plenum used as the return air path. Most of the office area failed to achieve 0.95 ACE.

As figures 17–19 indicate, swirl diffuser air supply and perforated ceiling or light troffers/plenum slot return-air arrangements is likely to fail to comply with GBCA ACE requirements when the ACE is calculated in accordance with the ASHRAE F27-2005 methodology. Use of return-air grilles achieves a better ACE then perforated ceiling or light troffers return-air arrangement, but in many cases it would still fail to comply with Green Star requirements.

The design, shown in Figure 19, is modified. When the light troffers were replaced with regulated return-air grilles and some of the supply-air flow rates are finetuned (~1.5% increased) then compliance is achieved. Figure 20 shows the final ACE simulation results based on ASHRAE F27-2005 methodology.

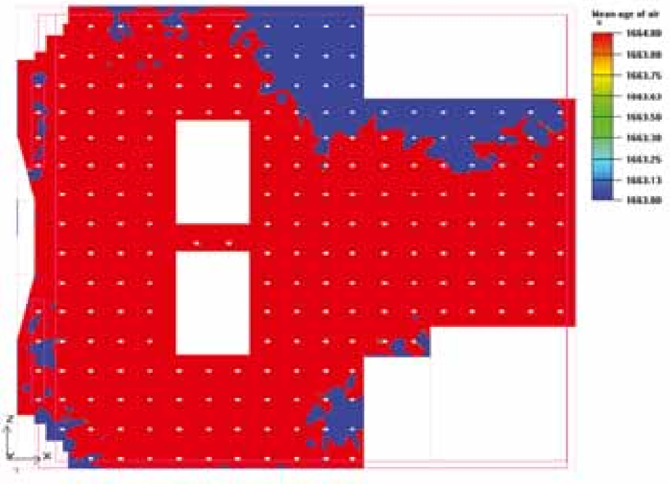


Figure 19: Open-plan office ACE assessment. Blue indicates ACE≥0.95. (Original design)

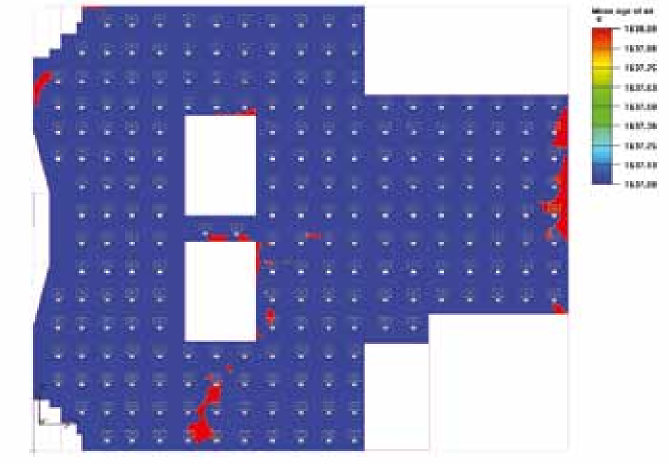


Figure 20: Modified design achieves GBCA ACE compliance. (East Bld Lev 4).

Use of balancing damper with strategically located return air grilles further improves the ACE and compliance with green star is achievable.

In many cases, this compliance comes at a significant modelling effort which requires trial and error with the adjustment of flow rates and location of diffusers/grilles.

EFFECT OF RETURN-AIR PLENUM

Does the return-air plenum affect the ACE or should the return-air plenum be included in the ACE calculations? The answer depends on the interpretation of the terminology. ASHRAE [5] states that “One common definition of air change effectiveness is the ratio of a time constant to an age of air”, and below equations are given:

$$\varepsilon_I = \frac{\tau}{Q_{age}} \tag{1}$$

and local air change effectiveness , $\varepsilon_{I,L,}$

$$\varepsilon_{I,N} = \frac{\tau_N}{Q_{age}} \tag{2}$$

where τ is time constant and Q_{age} is age of air. In AHRAE[5], the time constant was defined as follows “*The space time constant is the inverse of the space air exchange rate*”. Definition of air exchange rate is given by below equation (ASHRAE, F27-2005, Eq.2)

$$I = \frac{V}{Q} \tag{3}$$

Where

Q = volumetric flow rate of air into space, m³/s

V = interior volume of space, m³

So the time constant can be written as follows

$$\tau = \frac{V}{Q} \tag{4}$$

Based on these definitions, return-air plenum volume should not be taken in to account when the ACE is calculated.

GBCA [6] ACE compliance criteria refers to ASHRAE Standard 129. This standard describes a method for measuring ACE of mechanically ventilated spaces and buildings. The standard gives the below equation for the time constant.

$$\tau_N = \frac{\Sigma m\,(Q_{ex,m}A_{ex,m})}{\Sigma m\, Q_{ex,m}} \tag{4}$$

Where

τ_N	is the nominal time constant
m	is an identification number unique for each exhaust airstream
τ_N	is the rate of airflow in exhaust airstream m
$A_{ex,m}$	is the age air in exhaust airstream m

The symbol Σm indicates a summation for all m exhaust airstreams.

Since the standard is about measuring the ACE, and some of the flow-rate and age-of-air measurements need to be taken at the exhaust location, it’s important to consider the time taken air leaving a room to reaching the exhaust point.

In the standard, indoor air volume is defined as, “*indoor air volume: the entire air volume of space or building in which the ventilation air is distributed including ductwork and plenums. The volume of indoor furnishings, equipment, and occupants must be subtracted from the gross indoor volume that is based on interior dimensions of the space or building.*”

This definition provides a base to take in the plenum’s volume in ACE calculations. Using the volume of the plenum in ACE calculations will increase the time constant and improve the ACE results.

If a typical office is assumed to have 2700mm floor-to-false-ceiling height and 900 mm plenum height, then the time constant would increase by 20% when the plenum volume is taken in to calculations of the volume (10% allowance made for ductwork, etc). This is a significant increase and may change the “GBCA ACE” assessment outcomes.

ACE calculations were repeated for the same building featured in Figures 17 and 18 but this time the volume of the return-air plenum was taken into consideration in the time constant calculations. Figure 21 shows the compliance area when plenum volume is included in the calculations.

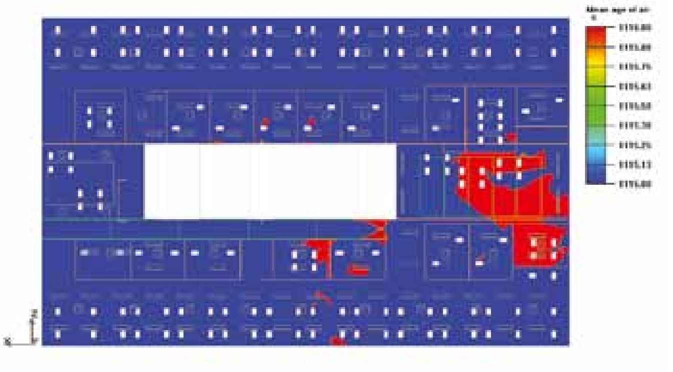


Figure 21: Compliance area for the same simulation shown in Figure 18. (Time constant includes plenum volume)

As some experimental studies [2, 3] highlight, ACE values of 0.95 appear difficult to achieve when calculated in accordance with ASHRAE F27-2005 methodology. However, if the return-air plenum volume is considered then there is a potential risk of that even a poorly design ventilations might comply with the GBCA. This ambiguity needs to be clarified in order to achieve more objective comparisons and assessments.

SUMMARY AND CONCLUSION

CFD simulation is sensitive to a large number of input variables, minor changes to which can significantly affect the airflow pattern, the mean age of air and consequently ACE. VAV systems have the highest risk factor when compared to the other ventilation systems. In many cases it is possible, though requiring significant trial and error with the adjustment of flow rates, to achieve a Green Star-compliant solution or very close to (in accordance with ASHRAE F27-2005 methodology).

The following are some general design considerations that are generally expected to improve the ACE outcome for a project.

- Increasing the supply of fresh air may not necessarily improve the ACE.
- Ventilation systems that can preferentially deliver the air to the breathing zone will achieve better ACE. Personal ventilation systems, task-air ventilation, displacement ventilation and under-floor ventilation will generally provides best ACE results.
- Chilled beam systems create additional vertical air circulation, which improves ACE and in most cases complies with GBCA ACE requirements.
- The use of return-air light slots significantly impairs the achievement of a good ACE outcome when the supply-air terminals are also located at ceiling level.
- The use of discrete return-air grilles provides a better solution compared to perforated ceiling/air-handling luminaries, and this can be further improved by regulating the return-air flow through each with a balancing damper.
- The location of return-air grilles has more impact on ACE than the number of return-air grilles.
- It is believed that the GBCA assessment would be performed in accordance with ASHRAE F27-2005 methodology. ▮

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