CONSTRUCTION

# An Evaluation of Air Distribution Effectiveness for the NAD Klima Ceiling High Induction Diffusers

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National Research Council Canada
Conseil national de recherches Canada

# An Evaluation of Air Distribution Effectiveness for NAD Klima Ceiling High Induction Diffusers

## Swirl Diffusers DAL 359 and DAL 358


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# Executive Summary

This report details the experiments that were undertaken as part of the project A1-008251 on the air distribution effectiveness of overhead systems using high induction diffusers compared to a system using conventional square diffusers.

NAD Klima manufactures a new model of swirl diffuser DAL359 and DAL 358 equipped with off-centre drums (rollers). This technology is able at the same time, to diffuse air with high flow rate and with a low acoustic power, to produce any form of flow of air even after assembly, to vary the outlet velocity of the air and especially allows a better mixture between the primary air and the air of the room realized by a high induction immediately at exit of the slits.

Experiments were undertaken at the NRC Construction Indoor Environment Research Facility (IERF). The study investigated the ventilation effectiveness of overhead distributions systems using two types of high induction diffusers as indicated by the air distribution effectiveness. The assessment of the ventilation effectiveness required the use of tracer gas techniques.

This investigation evaluated the performance of two overhead systems using two swirl high induction diffusers; DAL 358 Swirl diffusers which is a high induction swirl airflow diffuser with square front plate and eccentric ABS cylinders and profiles controlling air stream, and DAL 359 which is a highly inductive swirl diffuser with a square front plate and fitted air control blades of ABS. The performance of the swirl diffusers was also compared to the air distribution performance of conventional square diffusers.

The study measured several aspects of the performance of overhead systems with the focus on the air change effectiveness. The measured air change effectiveness for the baseline (conventional square ceiling diffusers) was an average value of 0.77 (nominalized to 0.8), value reported in ASHRAE 62.1-2016 for overhead system in heating mode with ceiling supply of warm air (8°C or more above space temperature) and ceiling return. The measured ACE for overhead system using high induction diffusers DAL 359 was an average value of 1.03 (nominalized to 1.0), showing no need to increase of 25% the required rate of outdoor air supply. The measured ACE for overhead system with high induction diffusers DAL 358 was higher with an average value of 1.1 (nominalized to 1.1), showing not only that the increase of rate of outdoor air supply by 25% is not required but could be reduced by 9%. This means that when using DAL 358 diffusers, the rate of outdoor air supply could be reduced by 27%. Results obtained in this study provide evidence of improved air distribution effectiveness of overhead ventilation systems using swirl high induction diffusers.

The predicted thermal comfort, in terms of vertical air temperature difference and limit to air speed obtained for overhead systems using high induction diffusers under test conditions (in heating mode) were not different from those obtained for an overhead system using conventional square diffusers and were within the limit set by ASHRA 55-2013.

# An Evaluation of Air Distribution Effectiveness for the NAD Klima Ceiling High Induction Diffusers

## 1. Introduction

Overhead air distribution is a common method of supplying heated or cooled air throughout a building. With such system, conditioned air, normally a mixture of recirculated and outdoor air is supplied to the occupied spaces via supply diffusers inserted at desired locations in the ceiling. Air is removed from the space via return grilles inserted in the ceiling at desired locations.

ASHRAE Fundamental Handbook defines ventilation effectiveness as an air distribution system's ability to remove internally generated pollutants from a building, zone or space. It also defines air change effectiveness as an air distribution system's ability to deliver ventilation air to a building, zone, or space. ASHRAE Standard 62.1-2016 uses zone air distribution effectiveness, $E_z$, which is a measure of how effectively the air distribution system uses its supply air to maintain acceptable air quality in breathing zone.

Table 6.2.2.1 of ASHRAE Standard 62.1-2016 defines the minimum amount of outdoor air required ($V_{bz}$), to be delivered to the space (or zone) for controlling contaminant concentration. Table 6.2.2.2 of the standard defines values of zone air distribution effectiveness for different air distribution configurations. The outdoor airflow required for the space is determined as $V_{bz}$ divided by $E_z$. Thus, the zone air distribution effectiveness plays an important role in determining the required minimum amount of outside air for a space to achieve acceptable indoor air quality.

Overhead air distribution systems in heating mode with ceiling supply of warm air 8°C (15°F) or more above space temperature and ceiling return, are assigned $E_z = 0.8$. In this configuration the amount of outdoor air delivered to the space shall be increased by 25% to achieve acceptable air quality. $E_z$ is calculated using the ASHRAE Standard 129-2002.

NAD Klima claims that its high induction diffusers would achieve higher ventilation effectiveness than a value assigned by ASHRAE 62.1-2016 in heating mode. A downward airflow pattern created by its swirl high induction diffusers would lead to an improvement in the ventilation efficiency.

A primary objective of this study was to determine whether overhead ventilation systems with high inductions ceiling supply diffusers, in practice, result in a ventilation effectiveness above the value 0.8 assigned by ASHRAE 62.1-2016.

This report presents ventilation effectiveness performance of overhead ventilation systems using ceiling swirl high induction diffusers in term of air distribution effectiveness, for a full-scale test room simulating an office space of six cubicles with overhead systems during heating season and under specific experimental conditions of ceiling supply of warm air at 8°C or more above space temperature.

### *1.1 Nad Klima High Induction Diffusers*

DAL 358 – The DAL 358 is a high induction swirl airflow diffuser with a square front plate. It has eccentric ABS cylinders and profiles controlling air stream. Eccentric cylinders integrated into the front plate permit a variety of airstream configurations, even after installation. Turning the cylinders individually can produce a multitude of airstream patterns. In this manner, obstacles to efficient air flow can be avoided (lamp bases, ceiling drops, etc.). When installing in high ceilings

(>5 m), a portion of the cylinders in the centre of the slot must be directed to produce a vertical blast.

DAL 359 – Diffuser type DAL 359 is a highly induction swirl diffuser with a square front plate and fitted air control blades of ABS. The blades, designed as wing-shaped profiles, produce a favorable deflection of the vertically streaming air into the horizontal direction of the face plate. Rotating around the bearing centre achieves a defined and reproducible reduction by 50% of the discharge free area. A greater penetration depth and flat, horizontal air distribution is achieved with the same discharge volume flow.

## 2. Experimental Setup

The measurements were performed at the NRC Construction Indoor Environment Research Facility (IERF) located in the Ottawa campus of the National Research Council Canada. The facility has a dedicated HVAC system with the conditioned air entering the simulated office space through air supply diffusers installed in the suspended ceiling. The supply diffusers are swirl high induction diffusers that cause the exiting air swirl about a vertical axis. Air exits the space through return grilles also in the suspended ceiling. Indoor temperature is maintained by operating the HVAC system in VAV mode. A series of experiments were performed to obtain data for overhead ventilation systems using, DAL 359, DAL 358 swirl diffusers and conventional square diffusers, to study and compare their air distribution effectiveness in heating mode.

Measurement poles were placed in workstations number 1 and 3 (interior area), 4 and 6 (exterior area) and in the vicinity of exterior wall (large window) with sensors held vertically by pole 0.6 m from desk (measurement normal to the desk). Each pole supports anemometers, RTDs (for air and globe temperature measurement), RH&T sensors, and tracer gas sampling tubes. The measurement was conducted under steady state conditions and distribution of air velocity, air temperature, and tracer gas concentrations were used to investigate the performance of air distribution achieved by high induction diffusers.

### *2.1 Indoor Environment Research facility (IERF)*

This state-of-the-art research facility was designed to allow full-scale testing and physical modeling of office space lighting, thermal comfort, indoor air quality, airflow, contaminant-flow patterns, ventilation, acoustical characteristics, and occupants' reactions to these parameters. A plan of the facility is shown in Figure 1 and Figure 2, and the dimensions in Table 1.

Figure 1: IERF office environment, with a window on the exterior wall.

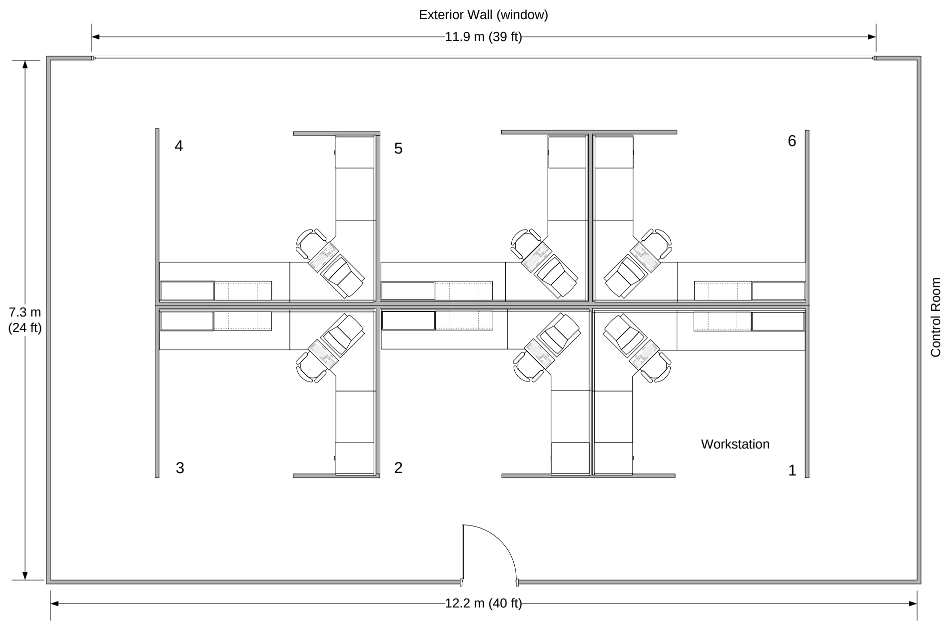


Figure 2: Plan view of the IERF test area.

The IERF test facility has a floor area of 89.2 $m^2$, volume of 245 $m^3$, window area (including framing) of 20.8 $m^2$ and opaque external wall area of 12.6 $m^2$. The east, south and north walls are fixed internal walls. The west wall is a curtain wall system with fixed and operable windows and insulated opaque spandrel panels. Table 2 details the construction details of the IERF envelope. The test area can be subdivided into five enclosed spaces to represent 4 private offices and a connecting corridor. The HVAC and lighting systems are zoned to allow local environment and luminaires control in these five spaces.

Table 1: Dimensions of the IERF test area.

| **Space** | **Dimensions [m]** | |
|---|---|---|
| Room | Length | 7.32 |
| | Width | 12.19 |
| | Height | 2.74 |
| Floor Plenum | Height | 0.61 |
| Ceiling Plenum | Height | 1.64 |
| Curtain wall (centrally positioned in west wall) | Distance to south wall | 0.15 |
| | Distance from floor | 0.85 |
| | Width | 11.88 |
| | Height | 1.75 |
| Cubicles | Length | 2.20 |
| | Width | 2.75 |
| | Height | 1.70 |
| Cubicle partitions | Distance to west wall | 1.45 |
| | Distance to east wall | 1.45 |
| | Distance to north wall | 1.87 |
| | Distance to south wall | 1.87 |
| Suspended lights | Distance from floor | 2.18 |

Table 2: Construction properties of the IERF envelope

| Surface | Description | U value [W/m²K] |
|---|---|---|
| Curtain wall glazing (SHGC=0.27, Visible T=0.63) | Double glazed low-e argon filled 1" units (6/13/6 mm glass/gap/glass) | 1.36 |
| Spandrel panel | Glazed & insulated units (R20) | 0.25 |
| Plenum slab | Concrete slab | - |
| Raised floor | Carpet tile on metal/plastic units | - |
| Partition walls | 6" stud, insulated cavity with ½" drywall on both sides | - |
| Suspended ceiling | Acoustical tiles | - |
| Roof | Insulated concrete slab | 0.30 |

The facility has a dedicated air handling unit (AHU). The system is zoned (into the five zones) and has supply and return ducts in both the floor and ceiling plenums allowing air delivery/return from either high or low level. Each zone is equipped with re-heat. The system can be operated in variable air volume (VAV) or constant air volume (CAV) mode.

The AHU, Figure 3, has an air pre-filter, a supply air fan, a chilled water cooling coil, a steam heating coil, a steam humidifier, and a high efficiency air filter (HEPA). The AHU also has an internal by-pass to allow the supply air to by-pass all the components except the air filters. The system capacities are detailed in Table 3. This design facilitates testing of a wide range of ventilation and air distribution system. An Energy Management and Control System (EMCS) is used to control and monitor the operation of the HVAC system.

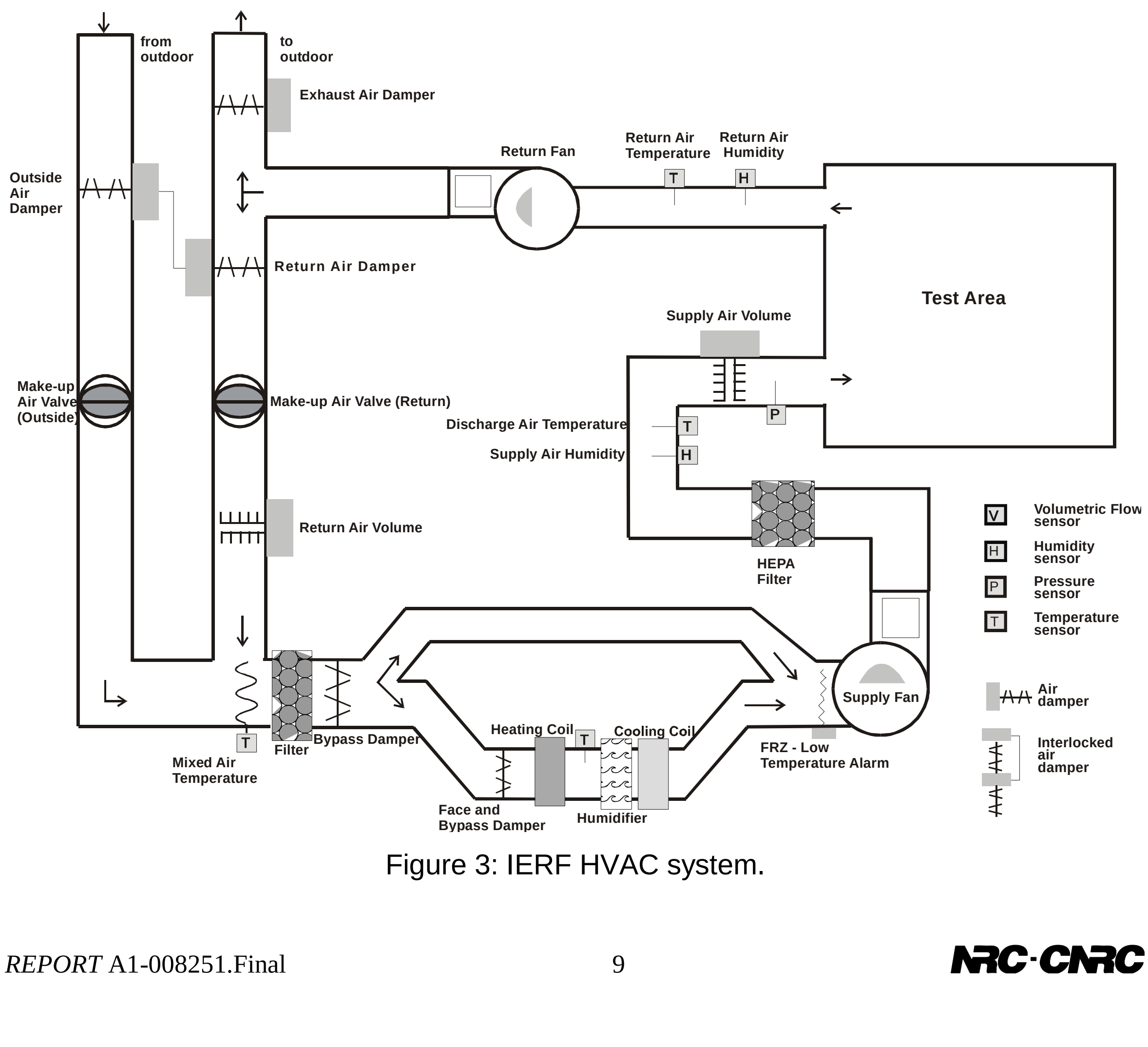


Figure 3: IERF HVAC system.

Table 3: Design HVAC capacity.

| Parameters | Range |
|---|---|
| Air Flow Rate [L/s] | 0 – 1130 (0 – 15 ach) |
| Temperature [°C] | 8 – 30 |
| Humidity [%] | 20 – 80 |
| Outdoor Air [%] | 0 – 100 |

## 2.2 Tracer Gas System

The schematic diagram of a multi-position tracer gas sampling system is presented in Figure 4.

Tracer measurement system has the following components shown in Figure 5:

- An injection system allowing the injection of controlled quantities of tracer gases $SF_6$ into the IERF return air plenum and supply air plenum as well,
- A sampling system (plastic tubing, multi-position valve (PMV), digital valve sequence programmer (DVSP) and pumps), taking samples of air in the centre of the room, supply register and return grille to bring them to the analyzer Gas Chromatograph (GC),
- An analyzer, Varian Gas Chromatograph 3400 (GC), measuring the concentration of trace(s) in the sampled air, and
- A control system, controlling all the measurement functions.

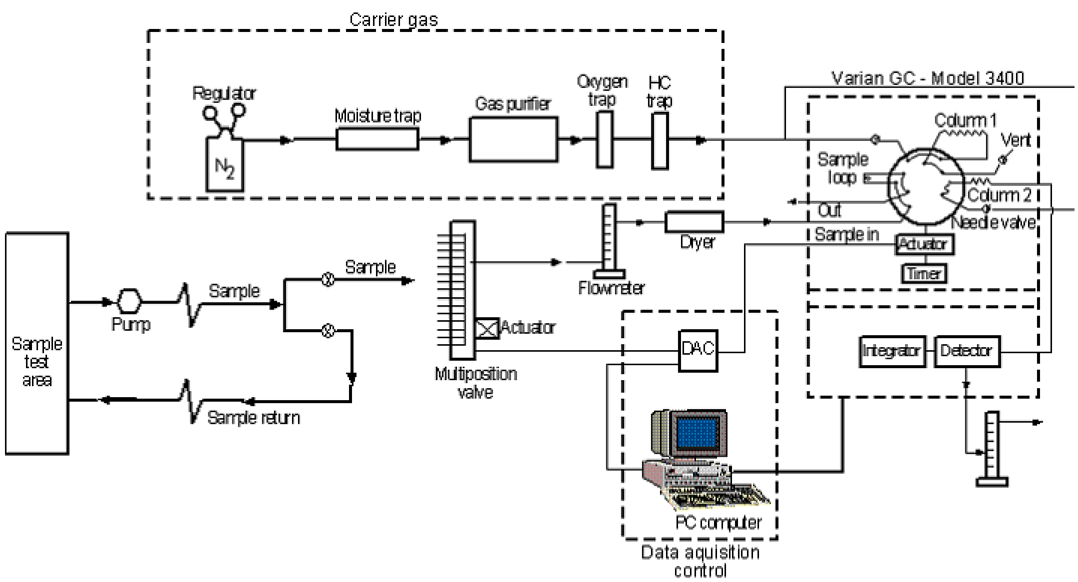


Figure 4: Schematic diagram of a multi-position tracer gas sampling system.

One source of $SF_6$ is introduced at constant rate into the air supply plenum via dosing system using a mass flow controller. The dosing was done at rate of 16 mL/min.

Prior to the tracer gas injection, the computer that operates the multi-position sampling valve (MSV) and the GC is switched ON and the Agilent VEE program is started. The automatic concentration measurements by GC will continue for 3-4 hours following the constant injection of $SF_6$, following the background concentrations and mixing period. Gas samples are withdrawn through sampling line at regular time intervals from the test room (IERF) at four cubicles (2 heights), supply diffusers and returns and injected into the gas Chromatograph for concentration analysis.

Figure 5: Automated tracer gas system.

### 2.3 Data Acquisition Systems

The facility has a computerized data acquisition system for recording measured data. The flow rate, temperature and relative humidity are measured continuously in each duct using orifice plates, thermocouples and relative humidity sensors, which have been installed in all supply and return ducts. Additional instrumentation has been installed to record the air temperatures, air velocities and relative humidity in the test area when human subjects are not part of the experimental procedure, using three instrumented poles. The Data Acquisition Cart (Figure 6) was used to record the sensor values. On the left of the Figure, we can see the Laptop and the Agilent 34980A Data Acquisition Unit. On the right we see the back of the cart where we observe from top to bottom: DAU, network switch, and power bar. All the 25-pair cables from the 3 collection boxes are connected to the DAU.

Figure 6: Portable Data Acquisition

### 2.4 Tested Diffusers

Configurations of mixing ventilation with overhead induction diffusers were physically tested in the IERF. The experiment tested a DAL 359, DAL 358 and conventional square ceiling diffusers under heating mode. The DAL 358 DN500 and DAL 358 DN600 are shown in Figure 7 and Figure 8. Diffuser DAL 359 DN500 and DAL 359 DN600 are respectively shown in Figure 9 and

Figure 10. Both diffusers were supplied with plenum box from the manufacturer. The plenum made from galvanized steel 24 gages and should include a perforated plate. Plenum supported at each corner and the input at side or above the plenum.

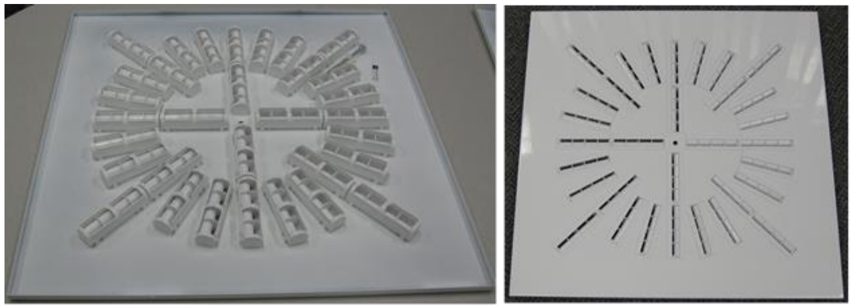

Figure 7: Diffuser DAL 358 DN500

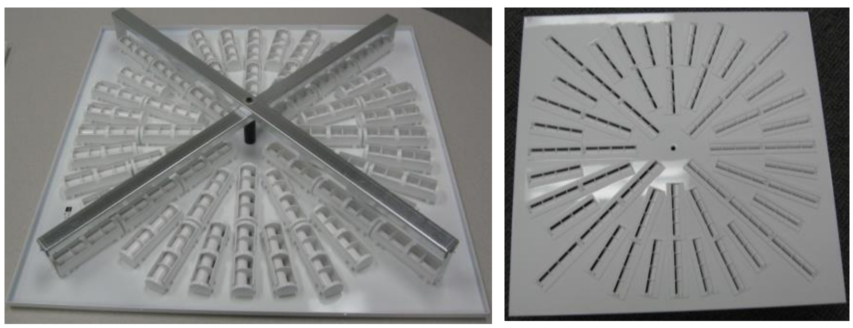

Figure 8: Diffuser DAL 358 DN600

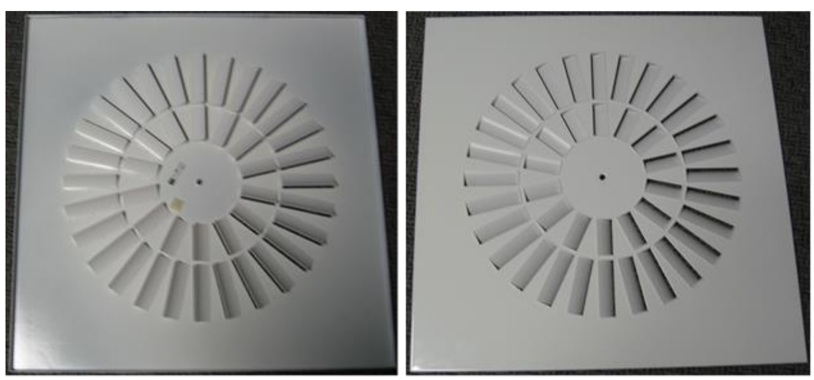

Figure 9: Diffuser DAL 359 DN500

Figure 10: Diffuser DAL 359 DN600

The DAL 358 and DAL 359 swirl high induction diffusers were compared to the conventional 6” square diffusers shown in Figure 11.

Figure 11: Conventional 6” square diffuser

## 3. Measurement Techniques

Measurement poles were placed in selected workstations. The instruments were held vertically by a pole 0.6 m from the desk (measurement normal to the desk). Each pole supports anemometers, RTDs, RH sensors, anemometers and tracer gas sampling tubes. Measurement poles have been placed in workstations number 1, 3, 4 and 6 and close to exterior wall/window (cubicle 4 and 6 locations) as shown in Figure 12.

Figure 12: Measurement poles installed in a workstation (left) and at the exterior wall (window)

### 3.1 Measurement Locations

The list of measured variables, which are used for the assessment of the performance of the air distribution systems and indoor thermal conditions are listed below:

1. Indoor air dry bulb temperature and relative humidity from the ECMS.
2. Dry bulb air temperature at each diffuser.
3. Dry bulb air temperature at each return grille.
4. Dry bulb air temperature and air velocity at 4 heights (0.1, 1.1, 1.7 and 2.7 m) above floor level in instrumented workstations (1, 3, 4 and 6).
5. Dry bulb temperature and air velocity at 2 heights (1.1 and 1.7 m) above floor level at the exterior wall (window) aligned with workstation 4 and 6.
6. Globe temperature and relative humidity at 1.1 m above floor level in workstations 1, 3, 4 and 6.
7. $SF_6$ concentrations at 2 breathing heights (1.1 and 1.7 m) above the floor level in workstations 1, 3, 4 and 6, and at diffusers and returns.
8. Flow, temperature and humidity readings from the HVAC system.

The measurement locations/heights for this project as specified by the client are shown in Figure 13. Measurements were taken in the workstation below the ceiling supply diffusers in the perimeter (workstations 4 and 6), core zone (workstations 1 and 3) and in the vicinity of the exterior wall (window) at two locations beside workstations 4 and 6.

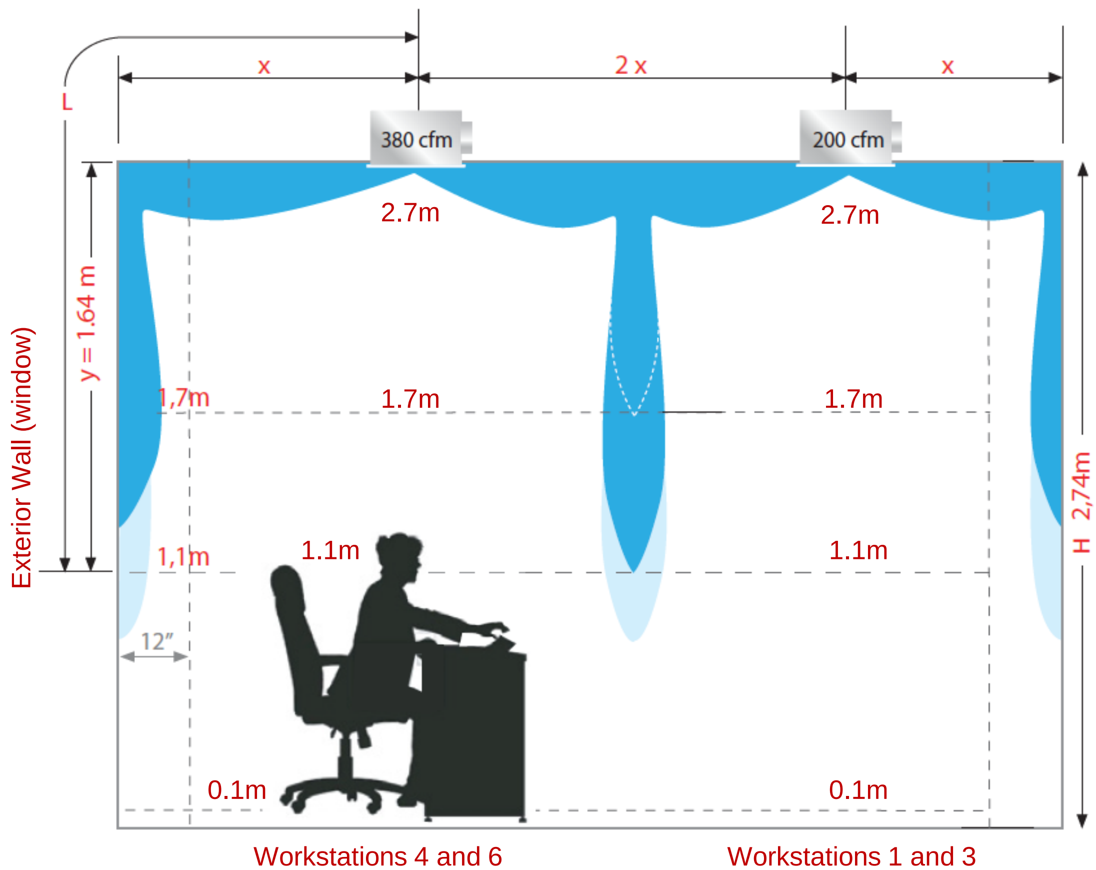


Figure 13: Measurement heights in the vicinity of exterior wall (window), exterior workstation 4 & 6 and interior workstations 1 & 3

## 3.2 Instrumentation

The measurements of air velocity, air temperature, relative humidity and $SF_6$ concentration were conducted in cubicles 1, 3, 4 and 6. Instruments were supported by poles with sensors attached to a sensor holder (cluster) as shown in Figure 14 and sensor holder was located on the pole at different heights above the floor.

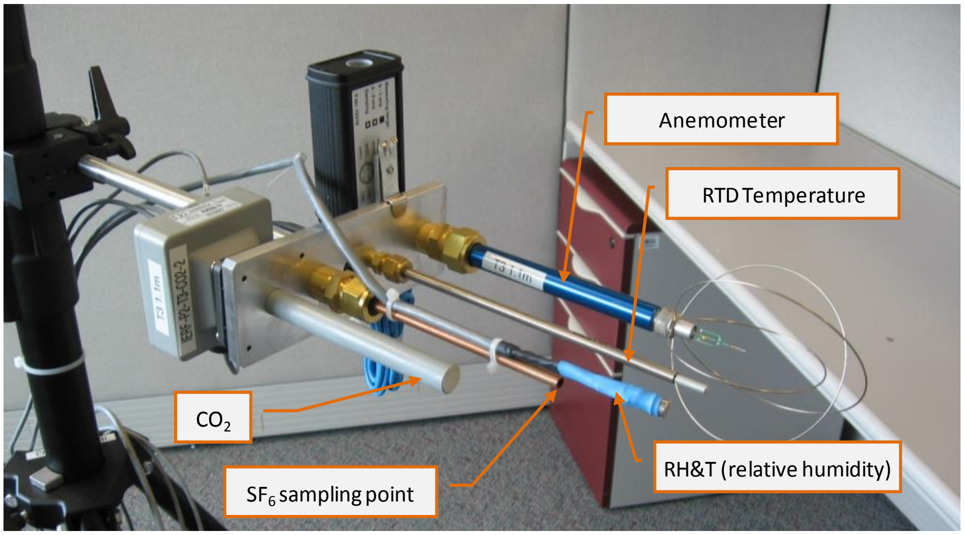


Figure 14: Sensor holder with sensors attached. A PVC pipe was attached to the back end of the copper pipe for $SF_6$ sampling.

This investigation measured the distributions of air velocity using omni-directional hot-sphere anemometers (Model Thermo Air 6/64) in the four workstations (cubicle 1, 3, 4 and 6) and in the vicinity of exterior wall (large window). Table 4 provides detailed information about the sensor probes.

Table 4: Specifications of the anemometers

| | |
|---|---|
| Type | Hot-spherical anemometer |
| Velocity range | 0.01 ~ 1.0 m/s |
| Response time | 0.2 s |
| Temperature range | 0 - 40°C |
| Accuracy | ±0.5% of full scale and ±1.5% of reading |

In order to measure boundary conditions such as supply and return air temperature, and vertical air temperature profiles in the same four workstations, RTDs (model 500M) were used. The specifications of the RTDs used in this experiment are shown in Table 5.

Table 5: Specifications of the temperature sensors

| | |
|---|---|
| Type | RTD |
| Temperature range | -50 ~ +250°C |
| Accuracy | 100 Ohms ±12% |
| Calibration range | -10 ~ +40°C |
| Calibration accuracy | ±0.1°C |

In order to measure relative humidity levels at height 1.1 m above the floor level, in the four workstations, RH&T sensors were used. The specifications of the RH&T sensor used in this experiment are shown in Table 6.

Table 6: Specification of the RH&T sensor.

| | |
|---|---|
| Type | RH&T |
| RH range | 10 ~ 90% |
| RH Accuracy | 3% |
| Temperature range | -10 ~ +40°C |
| Temperature Accuracy | 0.2°C |

A Gas Chromatograph (GC-ECD) was used with an automated sampling system to measure the tracer gas concentration in the IERF. The Gas Chromatograph (GC) separates the tracer gas from the other components of the sample and analyses its concentration. The experiment used a tracer gas $SF_6$ to simulate a gaseous contaminant generated in the chamber because the background of $SF_6$ in the atmosphere is almost zero. The specifications of the tracer gas analyzer are listed in Table 7.

Table 7: Specification of the analyzer system

| | |
|---|---|
| Type | 3400 GC |
| Measurement range | Minimum 1 ppb |
| Response time | About 40s |
| Repeatability | 1% of measured value |
| Operating temperature | 5°C to 40°C |

# 4. Method

The performance of overhead ventilation systems was assessed using criteria:

- Air change effectiveness/air distribution effectiveness
- Predicted thermal comfort – vertical air temperature difference (VATD)
- Predicted thermal comfort – air speed limit

## 4.1 Air Change Effectiveness

The performance of overhead ventilation systems using high induction diffusers was assessed using the criteria of air change effectiveness. Chapter 27 of the ASHRAE Handbook of Fundamental (ASHRAE 2013) defined ventilation effectiveness as an air distribution system's ability to remove internal generated pollutants from a building, zone or space. The chapter also defined air change effectiveness as an air distribution system's ability to deliver ventilation air to a building, zone, or space. ASHRAE Standard 62.1-2016 used zone air distribution effectiveness, $E_z$, which is a measure of how effectively the air distribution system uses its supply air to maintain acceptable air quality in breathing zone. The standard did not give a mathematical description of $E_z$ but it did provide a list of $E_z$ values for different air distributions.

HVAC design engineers do not have control of actual pollutant sources within buildings, so the ventilation effectiveness may change dramatically if the pollutant source moves from one location to another. Therefore, in this study, the air distribution effectiveness is assumed to be the same as the ventilation effectiveness or air change effectiveness since it aligns well with the philosophy of the ASHRAE standard, and the contaminant source is assumed to be uniformly distributed in the entire indoor space. The air change effectiveness has been used to determine ventilation performance using a tracer gas (decay) procedures and calculations as described in the ANSI/ASHRAE Standard 129-1997 (RA 2002).

We measured tracer gas concentrations as function of time at four workstations per test in the simulated office space, in each exhaust airstream, and in each stream of incoming air (at supply diffusers). At measurement workstations, we monitored tracer gas concentrations at two heights above the floor level, representing the breathing level of seated and standing adults, and at the two return air grilles. A typical tracer gas concentrations as function of time is presented in Figure 15.

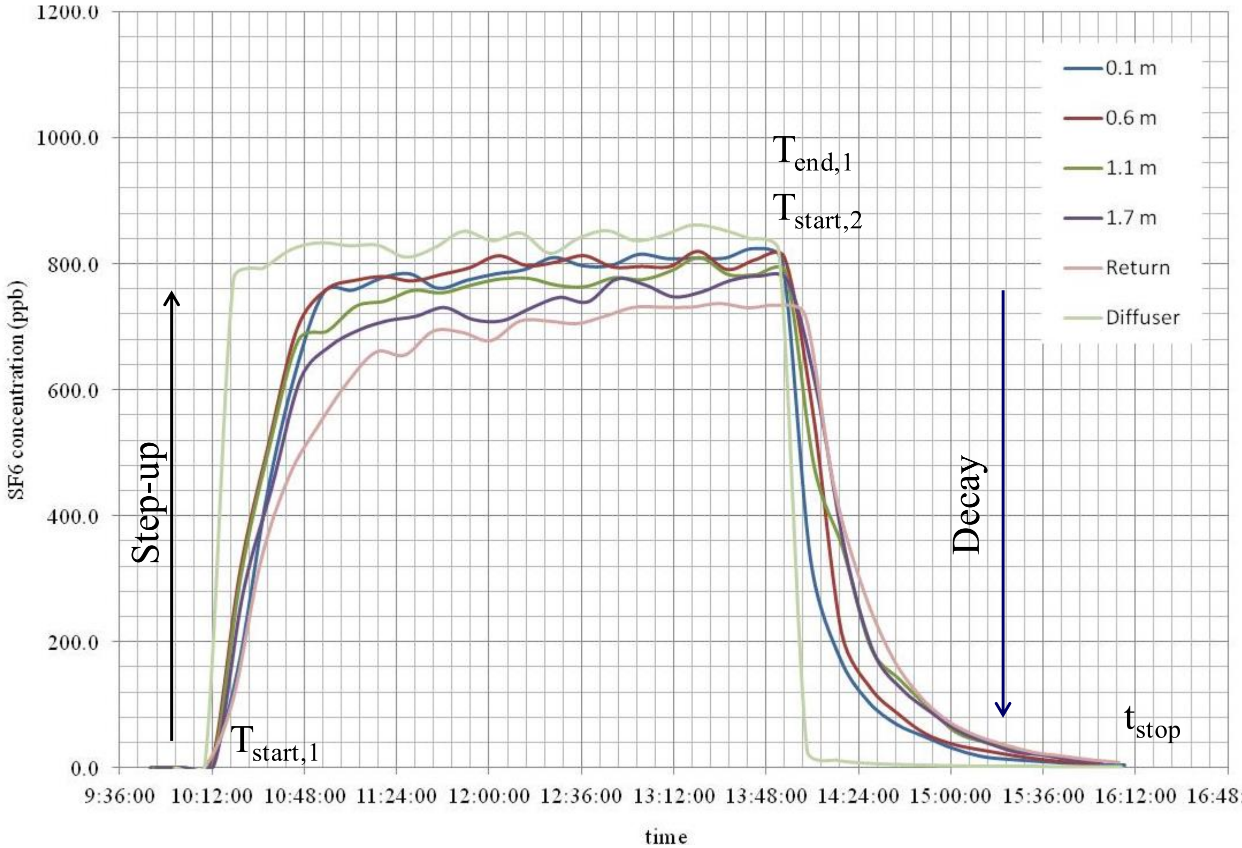


Figure 15: Tracer gas concentration variation - step-up and decay

The age of air at location *i* from a tracer gas test step-up measurement is calculated from Equation 1:

$$A_i = (t_{end} - t_{start})\left\{1 - \left(\frac{C_{i,avg}}{C_i(t_{end})}\right)\right\} \qquad (1)$$

The age of air at location *i* from tracer gas decay is calculated from Equation 2:

$$A_i = \left(t_{stop} - t_{start}\right)\frac{C_{i,avg}}{C_i(t_{start})} \qquad (2)$$

Finally, the air change effectiveness at location *i* is:

$$ACE_i = \frac{\tau}{A_i} \qquad (3)$$

With the nominal time constant τ calculated using Equation 4:

$$\tau = \frac{\sum_m (Q_m A_m)}{\sum_m (Q_m)} \qquad (4)$$

The nominal time constant is the average age of air in airstreams exhausted from the building and equals the age of air that would occur throughout the space if the indoor air were perfectly mixed. Because we were most interested in the ACE in the workstations where people would be spending most time, we also calculated local values of ACE, substituting the age of air at a return air grille for τ and replacing $A_i$ with the age of air nearby the seated or standing breathing-level measurement location. $ACE_i$ is calculated using Equation 3, which is a measure of how effectively the ventilation system supplies air to a given location.

### 4.2 Predicted Thermal Comfort – Vertical Air temperature Difference

According to ASHRAE Standard 55-2013 the temperature difference between the head level (1.7 m above the floor for a standing person, 1.1 m for a seated person) and the ankle level (0.1 m above the floor) should be less than 3°C for acceptable conditions.

### 4.3 Predicted Thermal Comfort – Air Speed Limit

The new ASHRAE 55-2013 has removed the draft ratio and allows elevated air speed to be used to increase the maximum operative temperature for acceptability under certain conditions. Limits are imposed depending on environmental and personal factors and whether the occupants have local control of air speed.

The ASHRAE Standard 55-2013 edition revises requirements and calculation methods when increased air movement is used to maintain comfort in warm conditions. Standard Effective Temperature (SET) is reintroduced into the Standard as the calculation basis for determining the cooling effect of air movement. In general, the calculation method has been modified with the removal of turbulence intensity and draft risk calculations, and the personal control limitations have been relaxed. Without local control, where occupants do not have control over the local air speed in their space, limits apply, as follow:

- For operative temperatures below 22.5°C, the limit shall be 0.15 m/s in order to avoid local discomfort due to draft.
- For operative temperatures above 25.5°C, the upper limit to air speed shall be 0.8 m/s for light, primarily sedentary office activities, such as in offices.
- For operative temperatures between 22.5°C and 25.5°C, the allowable speed shall follow the equal-SET curve for 0.6 clo and 1.1 met and it is acceptable to approximate the curve by the following equation:

$$V = 50.49 - 4.4047\,t_o + 0.096425(t_o)^2 \qquad (5)$$

## 5. Results

Measurements were performed in March and April 2016. The HVAC was operating in VAV mode with main supply air temperatures set at 32°C and the room temperature set at 24°C. For the main supply air temperature requirement for this project, we did not have a choice than using the facility HVAC system in VAV mode. The only way to maintain the indoor temperature at acceptable level set by the thermostat is to vary the supply air flow arte to meet the rising heat gains within the simulated space.

### 5.1 Case Setup

The IERF was set up to simulate six cases, which represented an office space with six cubicles:

Case 1 – Air was supplied to the space through two exterior diffusers, DAL 359 DN600, installed close to the exterior wall (large window), over workstations 4 and 6.

Case 2 – Air was supplied to the space through two interior diffusers, DAL 359 DN500, installed over cubicles 1 and 3.

Case 3 – Air was supplied to the space through a combination of case 1 and 2, through two exterior diffusers (DAL 359 DN600) and two interior diffusers (DAL 359 DN500).

Case 4 – Air was supplied to the space through a combination of two exterior diffusers (DAL358 DN600) and two interior diffusers (DAL358 DN500) installed in the same ceiling locations as in Case 3.

Case 5 – This case was a baseline where the air was supplied to the space through four square conventional diffusers installed in the same ceiling locations as Case 3 and Case 4.

Case 6 – Air was supplied to the space through two exterior diffusers (DAL358 DN600), installed at the same ceiling locations as in Case 1.

Simulated cases with experimental airflow conditions through each diffuser and total airflow to the space are presented in Table 8.

Table 8: Simulated Cases

| Case | Diffuser type | Location | Number | Flow rate to diffuser [L/s (cfm)] | Total Flow rate [L/s (cfm)] |
|---|---|---|---|---|---|
| 1 | DAL 359 DN600 | Workstations 4 & 6 | 2 | 181 (380) | 362 (760) |
| 2 | DAL 359 DN500 | Workstation 1 & 2 | 2 | 95 (200) | 190 (400) |
| 3 | DAL 359 DN600 | Workstations 4 & 6 | 2 | 181 (380) | 362 (760) |
| | DAL 359 DN500 | Workstations 1 & 2 | 2 | 95 (200) | 190 (400) |
| 4 | DAL 358 DN600 | Workstations 4 & 6 | 2 | 181 (380) | 362 (760) |
| | DAL 358 DN500 | Workstations 1 & 2 | 2 | 95 (200) | 190 (400) |
| 5 | Square diffusers | Workstations 4 & 6 | 2 | 181 (380) | 362 (760) |
| | | Workstations 1 & 2 | 2 | 95 (200) | 190 (400) |
| 6 | DAL 358 DN600 | Workstations 4 & 6 | 2 | 181 (380) | 362 (760) |

The space layouts and location of supply diffusers and return grilles used in the experiment are shown in Figure 16 for Case 1 (office space with two ceiling high induction diffusers), Figure 17 for Case 2 (office with two interior ceiling high induction diffusers) and Figure 18 for case 3 (office space with a combination of interior and exterior ceiling high induction diffusers).

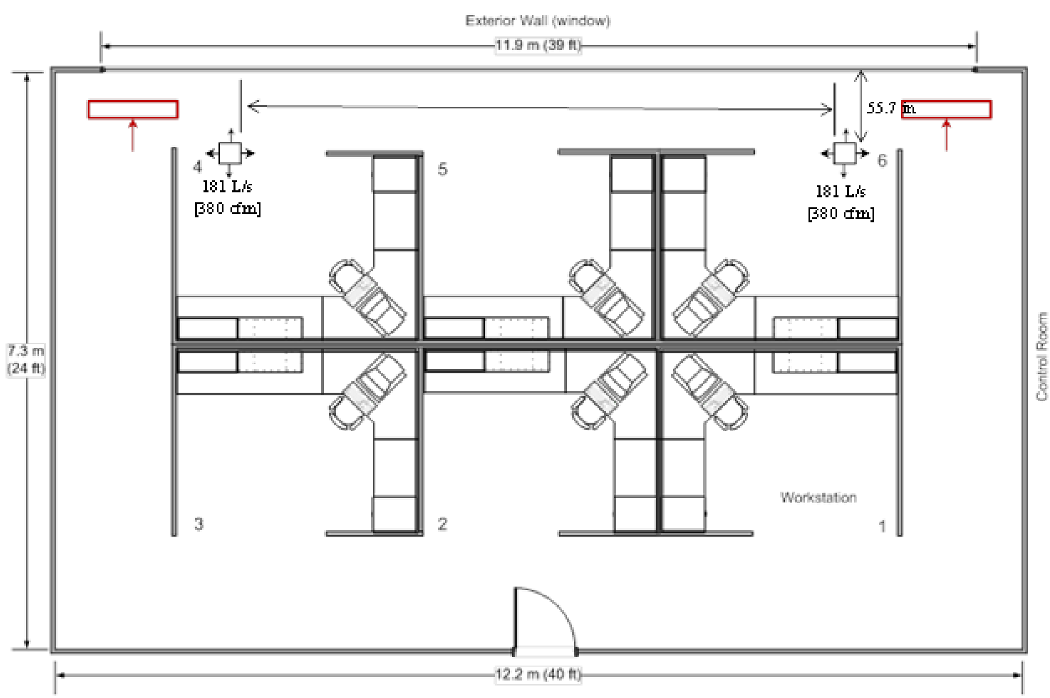


Figure 16: Cases 1 and 6 – exterior diffusers (DAL 359 DN600 or DAL 358 DN600)

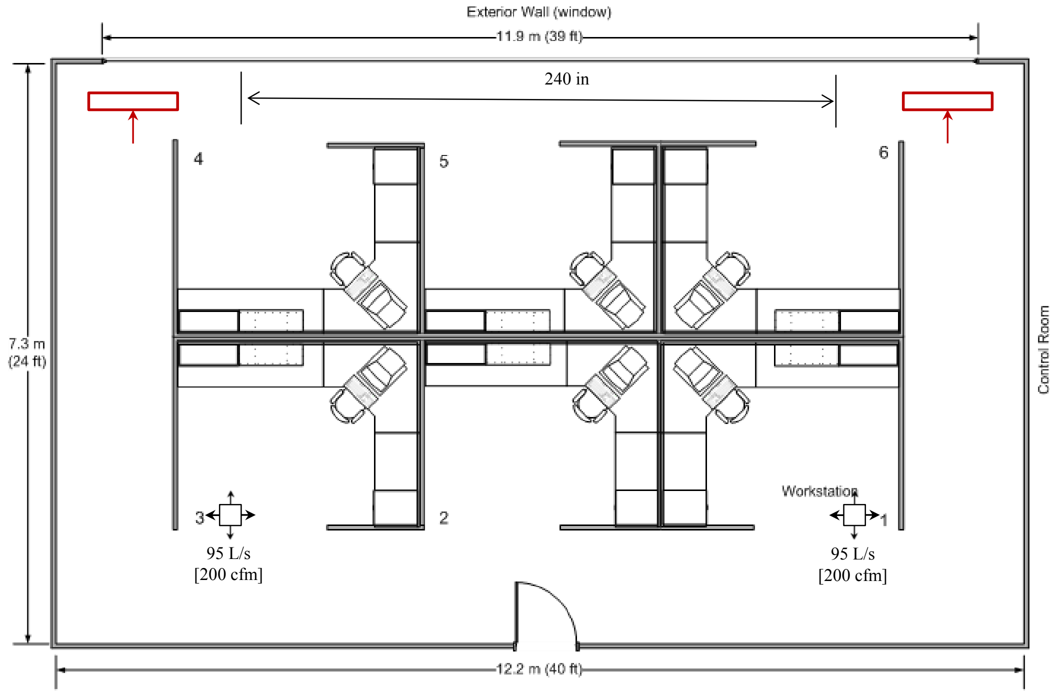


Figure 17: Case 2 – interior diffusers DAL 359 DN500

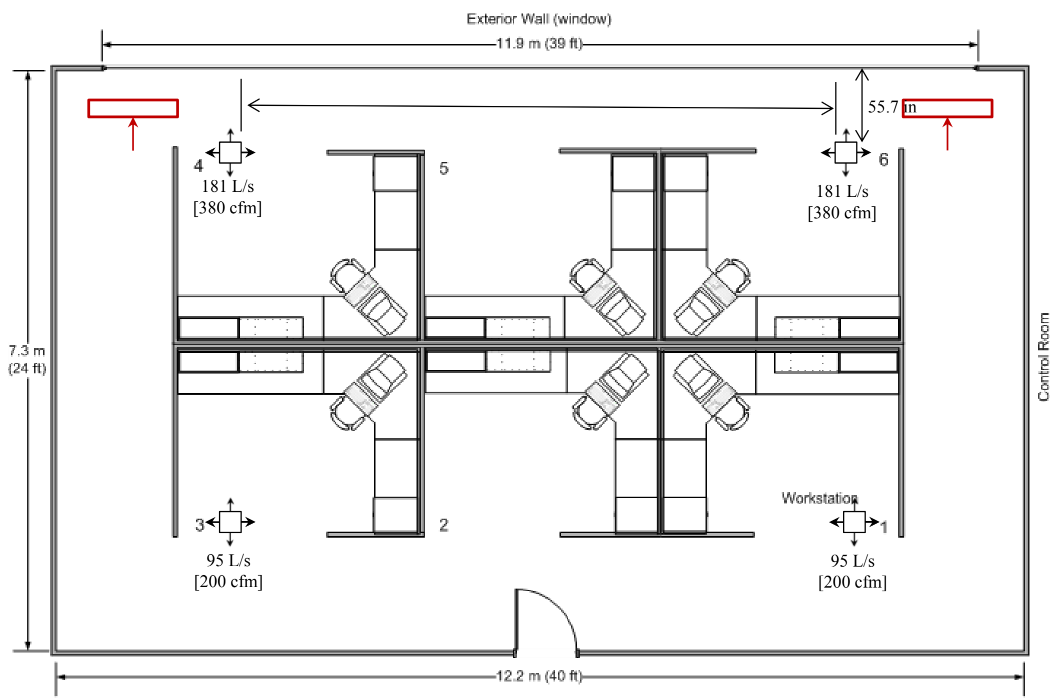


Figure 18: Case 3 (DAL 359), Case 4 (DAL 358) and Case 5 (Square Diffusers)

## 5.2 Supply Air Temperature

A test condition in term of supply warm air temperature to determine the air distribution effectiveness of an overhead ventilation system (supply and return from ceiling) is set by

ASHRAE 62.1-2013. The temperature of the supply warm air has to be 8°C or more above the space temperature.

Figure 19 and Figure 20 provide two typical examples of the daily measured distributions of supply warm air temperature, space temperature and the difference between the two. Other daily results are presented in Appendix A.

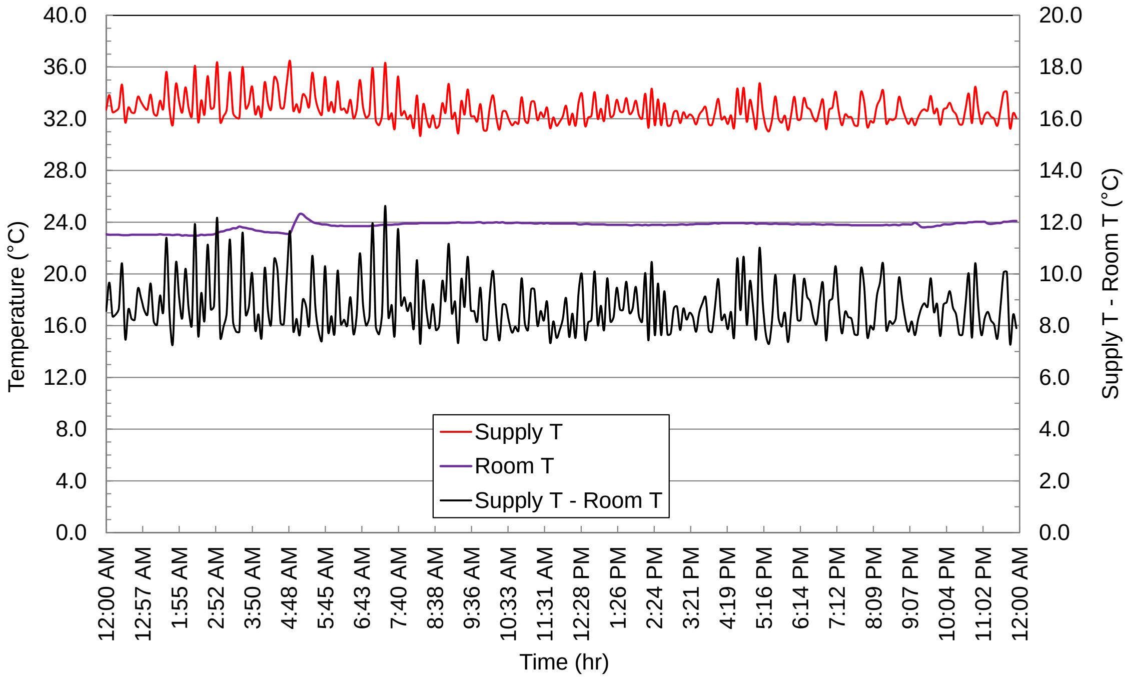


Figure 19: Supply and space temperature distribution - 24/03/2016

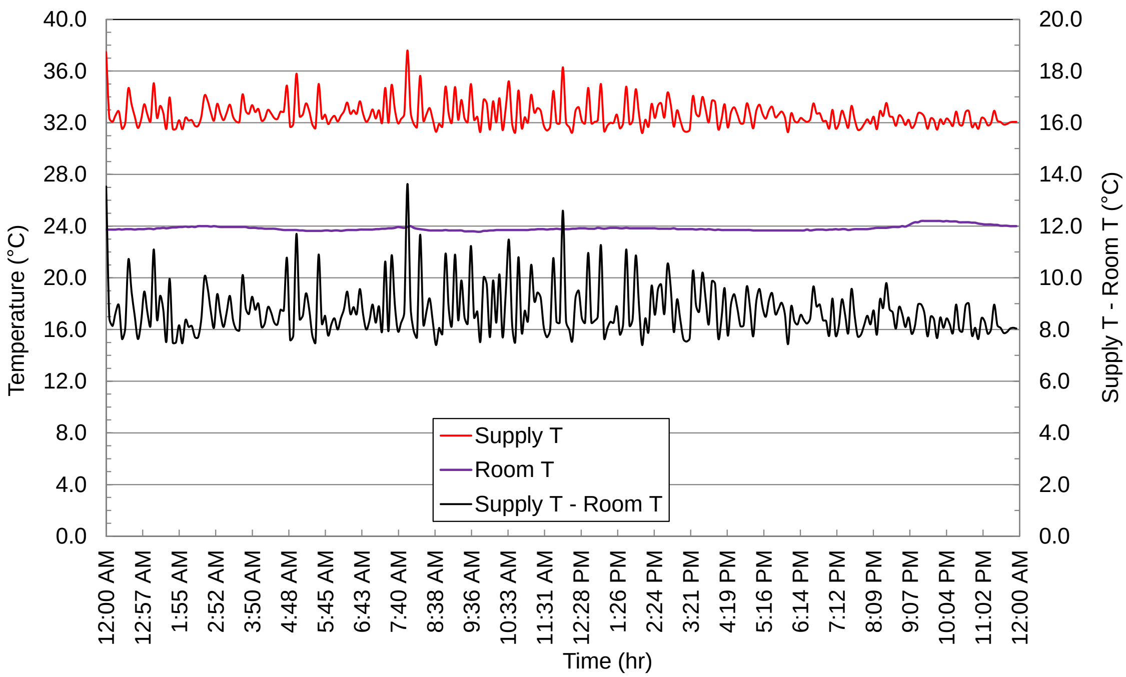


Figure 20: Supply and space temperature distribution – 29/03/2016

The average value of the difference between the supply warm air temperature and space temperature was maintained higher that 8°C as show in Table 9 and Table 10. The statically data is presented in terms of minimum, maximum, average measured and standard deviation values of supply warm air temperature to the space, space temperature and the temperature difference between the supply and space.

Table 9: Summary data of supply, room temperatures and the difference

| Date | Stat | Supply T [°C] | Room T [°C] | Difference [°C] |
|---|---|---|---|---|
| 03/03/2016 | Min | 30.2 | 22.6 | 7.4 |
| | Max | 35.1 | 24.8 | 11.7 |
| | Mean | 32.4 | 23.4 | **9.0** |
| | STDV | 1.1 | 0.6 | 1.1 |
| 04/03/2016 | Min | 31.6 | 23.6 | 7.4 |
| | Max | 37.3 | 26.6 | 12.5 |
| | Mean | 32.8 | 24.4 | **8.4** |
| | STDV | 0.9 | 0.4 | 0.8 |
| 10/03/2016 | Min | 30.9 | 23.8 | 7.2 |
| | Max | 39.1 | 24.2 | 15.2 |
| | Mean | 33.1 | 24.0 | **9.2** |
| | STDV | 1.5 | 0.1 | 1.5 |
| 11/03/2016 | Min | 30.7 | 23.0 | 7.3 |
| | Max | 36.1 | 24.3 | 12.2 |
| | Mean | 32.3 | 23.6 | **8.7** |
| | STDV | 0.8 | 0.3 | 0.8 |
| 23/03/2016 | Min | 30.5 | 23.0 | 7.3 |
| | Max | 38.3 | 24.6 | 15.3 |
| | Mean | 32.7 | 23.7 | **9.0** |
| | STDV | 1.3 | 0.3 | 1.3 |
| 24/03/2016 | Min | 30.7 | 23.3 | 7.3 |
| | Max | 36.4 | 24.9 | 12.6 |
| | Mean | 32.7 | 24.0 | **8.7** |
| | STDV | 1.1 | 0.3 | 1.0 |
| 25/03/2016 | Min | 31.1 | 23.2 | 7.3 |
| | Max | 38.3 | 24.8 | 14.6 |
| | Mean | 32.7 | 23.9 | **8.9** |
| | STDV | 1.3 | 0.3 | 1.2 |
| 26/03/2016 | Min | 31.1 | 23.6 | 7.3 |
| | Max | 36.4 | 24.4 | 12.2 |
| | Mean | 32.4 | 23.8 | **8.6** |
| | STDV | 0.9 | 0.2 | 0.8 |
| 29/03/2016 | Min | 31.2 | 23.7 | 7.4 |
| | Max | 37.6 | 24.1 | 13.6 |
| | Mean | 32.6 | 23.9 | **8.7** |
| | STDV | 1.0 | 0.1 | 1.0 |
| 02/04/2016 | Min | 31.1 | 23.7 | 7.4 |
| | Max | 38.8 | 25.9 | 14.8 |
| | Mean | 33.2 | 24.5 | **8.8** |
| | STDV | 1.2 | 0.6 | 1.2 |

The average value of the difference between the supply warm air temperature and the space temperature ranged from 8.4 to 9.2°C above the lower limit set by ASHRAE 62.1-2013.

Table 10: Summary data of supply, room temperature and the difference

| Date | Stat | Supply T [°C] | Room T [°C] | Difference [°C] |
|---|---|---|---|---|
| 03/04/2016 | Min | 31.2 | 23.4 | 7.5 |
| | Max | 36.4 | 25.9 | 12.2 |
| | Mean | 32.7 | 24.2 | **8.6** |
| | STDV | 1.0 | 0.7 | 0.8 |
| 04/04/2016 | Min | 31.0 | 23.1 | 7.4 |
| | Max | 37.7 | 24.5 | 14.1 |
| | Mean | 32.6 | 23.9 | **8.7** |
| | STDV | 1.2 | 0.3 | 1.1 |
| 05/04/2016 | Min | 30.9 | 23.2 | 7.5 |
| | Max | 38.3 | 25.6 | 14.6 |
| | Mean | 33.0 | 24.1 | **8.9** |
| | STDV | 1.4 | 0.6 | 1.3 |
| 08/04/2016 | Min | 31.1 | 23.6 | 7.4 |
| | Max | 38.8 | 25.0 | 14.9 |
| | Mean | 32.9 | 24.1 | **8.8** |
| | STDV | 1.2 | 0.4 | 1.2 |
| 09/04/2016 | Min | 30.9 | 23.3 | 7.6 |
| | Max | 39.7 | 24.6 | 15.2 |
| | Mean | 32.5 | 23.9 | **8.5** |
| | STDV | 1.1 | 0.3 | 1.0 |
| 10/04/2016 | Min | 30.7 | 23.0 | 7.5 |
| | Max | 38.2 | 26.0 | 14.8 |
| | Mean | 33.0 | 24.2 | **8.8** |
| | STDV | 1.6 | 0.8 | 1.3 |

### 5.3 Supply Airflow

The IERF HVAC system was set under a VAV mode for cases 3, 4 and 5, where the supply warm air temperature was set at 32°C and room temperature was set at 24°C. Under such conditions, the air flow rate must vary to meet the rising and falling heat gains or losses within the space served.

Figure 21 provides the daily measured airflow distribution of the supplied air to the space during Case 3, overhead system using high induction diffusers DAL 359. Figure 22 presents the daily measured airflow distribution of the supplied air to the space during Case 5, overhead system using conventional square diffusers. Figure 23 provides the daily airflow distribution during Case 4, overhead system using high induction diffusers DAL 358. All cases presented a variation of airflow supplied to the space depending on the outdoor conditions (call for heating).

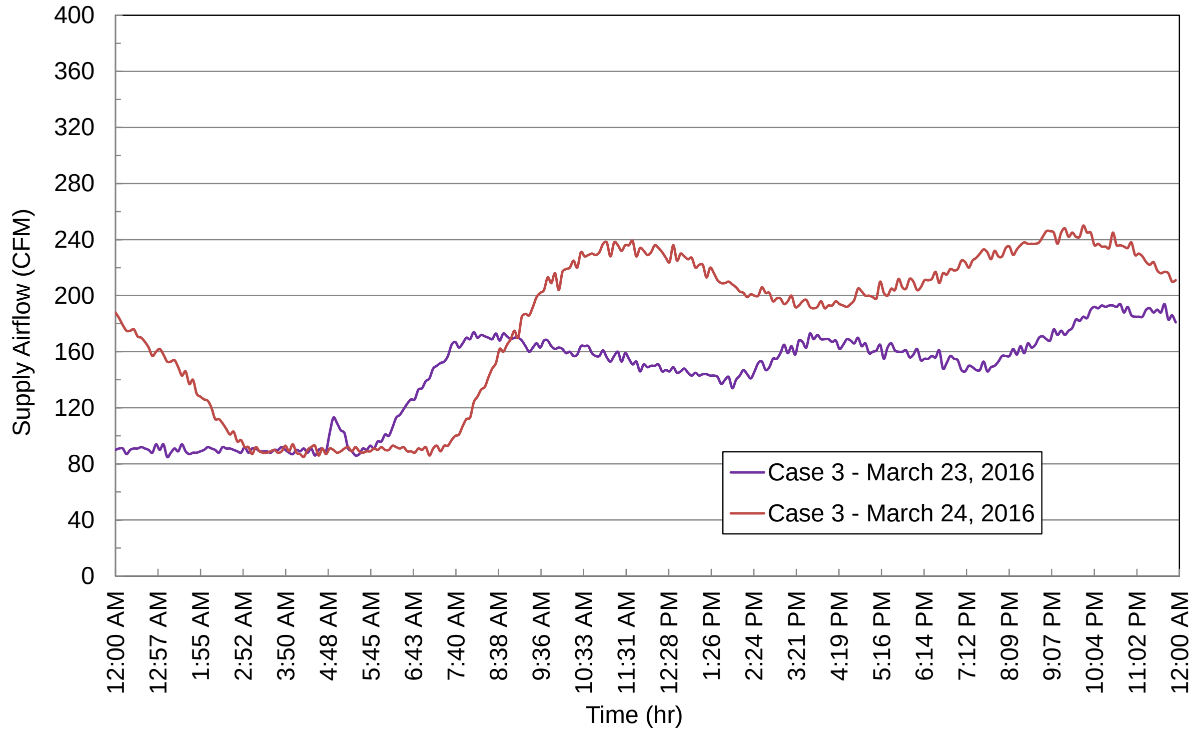


Figure 21: Daily airflow distribution for Case 3

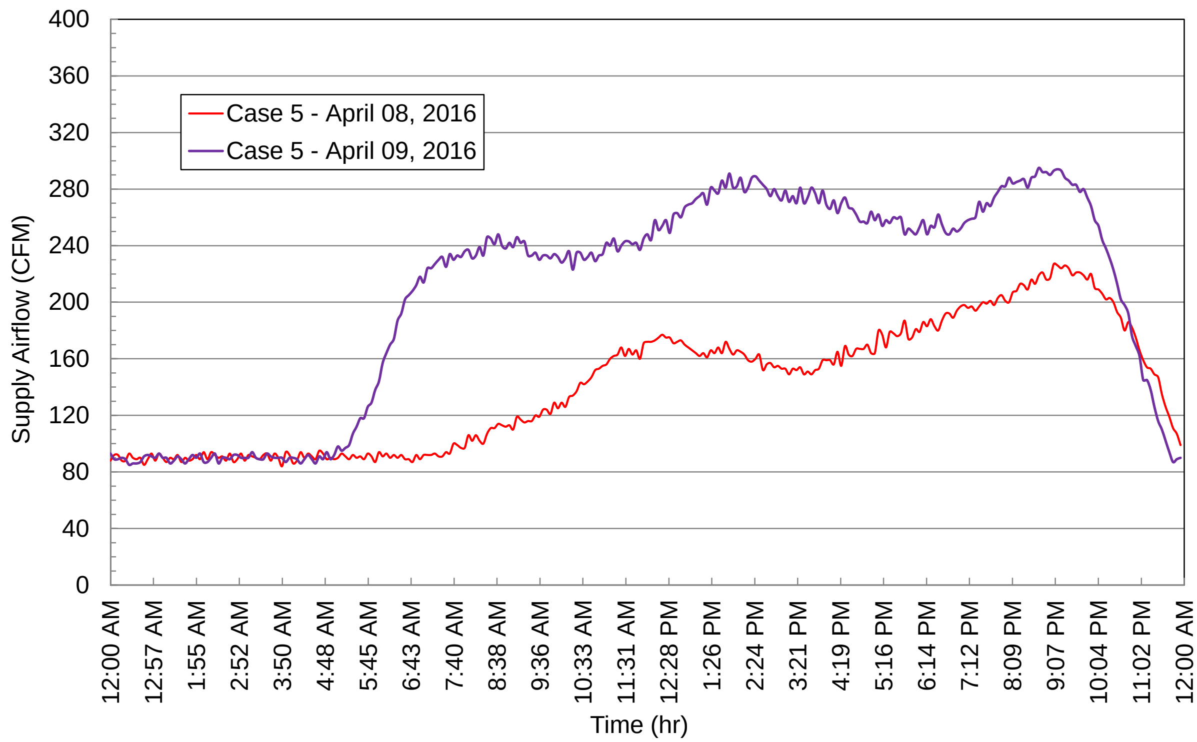


Figure 22: Daily airflow distribution for Case 5

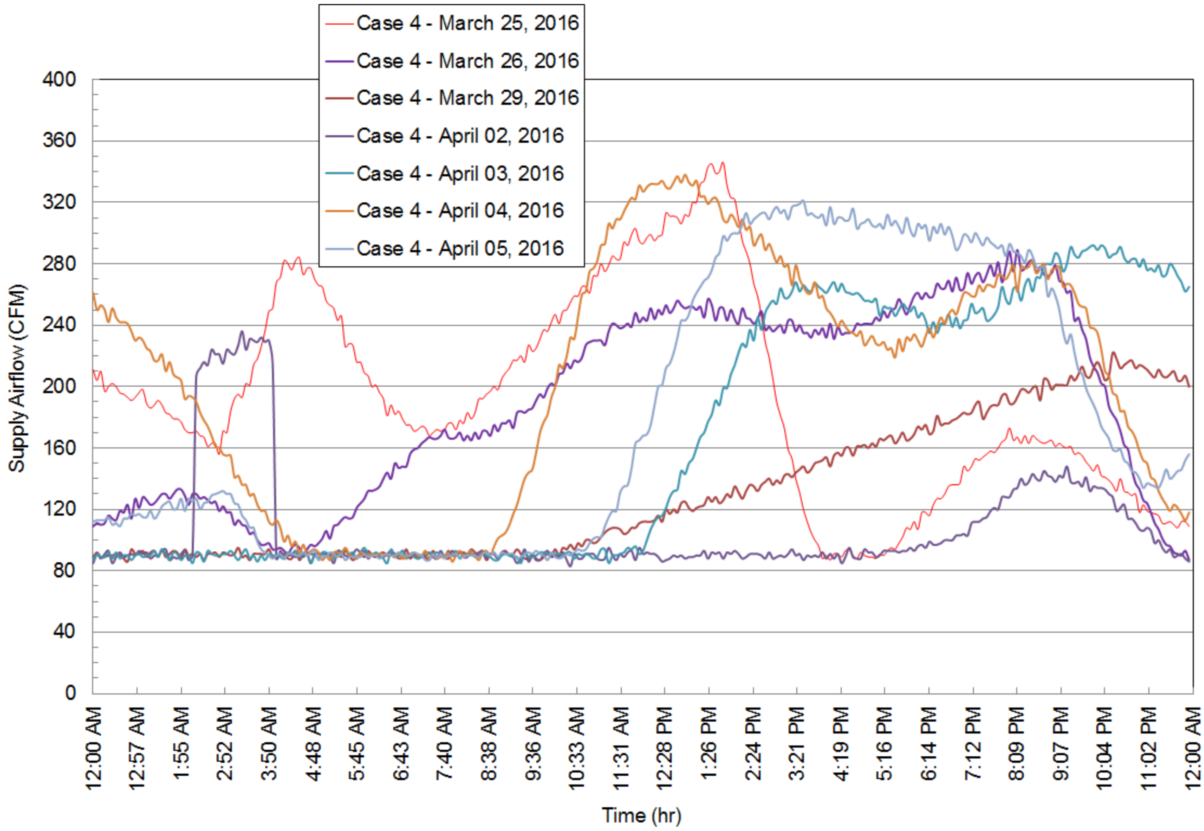


Figure 23: Daily airflow distribution for Case 4

## 5.4 Air Change Effectiveness (ACE)

The tracer gas tests conducted to evaluate the air distribution effectiveness for the investigated cases are listed in Table 11.

Figure 24 provides a typical example of tracer gas test results showing the tracer gas concentration variation (set-up and decay phases) with time. In this figure, the reported concentrations are for the breathing heights of a standing and seated persons, and for the two ceiling return grilles.

The measured values of ACE for Case 1 (DAL 359 exterior diffusers DN600) based on the average exhaust airstream age of air (based on concentrations measured at the two return grilles) and the ages of air at two breathing levels are presented in Figure 25 for seated position and in Figure 26 for standing position. The ACE values ranged from 0.92 to 1.1 and averaged 1.01.

The measured values of ACE for Case 2 (DAL 359 interior diffusers DN500) based on the average exhaust airstream age of air (based on concentrations measured at the two return grilles) and the ages of air at two breathing heights are presented in Figure 27 doe seated position and in Figure 28 for standing position. The ACE values ranged from 0.88 to 1.12 and averaged 0.96.

The measured values of ACE for Case 3 (DAL 359 interior and exterior diffusers) based on the average exhaust airstream age of air (based on concentrations measured at the two return grilles) and the ages of air at two breathing heights are presented in Figure 29 for seated person and in Figure 30 for standing person. The ACE values ranged from 0.91 to 1.16 and averaged 1.03.

Table 11: Tracer gas test schedule

| Case | Test | Date | Start time | End time | Outdoor Temperature (average) |
|---|---|---|---|---|---|
| 1 | 1 | 03/03/2016 | 07:30 | 15:00 | -20.1°C to -10.7°C (-15.0°C) |
| | 2 | 03/03/2016 | 19:00 | 07:00 (March 4) | -22.0°C to -13.0°C (-18.1°C) |
| | 3 | 04/03/2016 | 07:00 | 15:00 | -21.7°C to -2.3°C (-11.2°C) |
| 2 | 4 | 02/03/2016 | 09:00 | 16:00 | -12.7°C to -7.4°C (-9.8°C) |
| | 5 | 10/03/2016 | 17:00 | 07:00 (March 11) | -1.6°C to 3.4°C (0.7°C) |
| | 6 | 11/03/2016 | 08:00 | 15:00 | -1.2°C to 6.4°C (2.5°C) |
| 3 | 7 | 21/03/2016 | 08:00 | 16:30 | -9.1°C to 4.1°C (-0.6°C) |
| | 8 | 21/03/2016 | 18:00 | 08:00 (March 22) | -6.4°C to 1.1°C (-3.4°C) |
| | 9 | 23/03/2016 | 08:30 | 17:00 | -1.6°C to 3.1° (0.8°C) |
| | 10 | 23/03/2016 | 17:30 | 06:30 (March 24) | -2.9°C to 2.1°C (-1.1°C) |
| | 11 | 24/03/2016 | 07:00 | 14:00 | -7.3°C to -4.1°C (-6.5°C) |
| 4 | 12 | 24/03/2016 | 15:00 | 01:30 (March 25) | -6.1°C to -2.6°C (-4.6°C) |
| | 13 | 25/03/2016 | 19:00 | 08:00 (March 26) | -7.7°C to -0.4°C (-4.4°C) |
| | 14 | 26/03/2016 | 18:30 | 08:15 (March 27) | -3.1°C to 4.4°C (-0.7°C) |
| | 15 | 29/03/2016 | 17:00 | 08:30 (March 30) | -1.6°C to 6.1°C (1.5°C) |
| | 16 | 02/04/2016 | 18:00 | 07:30 (April 3) | -10.3°C to 4.8°C (-3.8°C) |
| | 17 | 03/04/2016 | 16:00 | 06:30 (April 4) | -9.4°C to -6.0°C (-8.1°C) |
| | 18 | 04/04/2016 | 06:30 | 15:30 | -9.3°C to -1.5°C (-6.4°C) |
| | 19 | 05/04/2016 | 17:00 | 08:00 (April 6) | -5.3°C to -0.6°C (-3.1°C) |
| 5 | 20 | 08/04/2016 | 07:30 | 15:00 | -4.5°C to -1.5°C (-3.4°C) |
| | 21 | 08/04/2016 | 15:00 | 05:00 (April 09) | -7.9°C to -3.4°C (-5.0°C) |
| | 22 | 09/04/2016 | 05:30 | 14:30 | -9.5°C to -2.3°C (-6.7°) |
| 6 | 23 | 09/04/2016 | 16:00 | 06:00 (April 10) | -9.8°C to -0.6°C (-4.9°C) |
| | 24 | 10/04/2016 | 06:30 | 15:30 | -10.1°C to 2.3°C (-3.6°C) |
| | 25 | 10/04/2016 | 17:00 | 08:00 (April 11) | -2.4°C to 2.8°C (-0.9°C) |

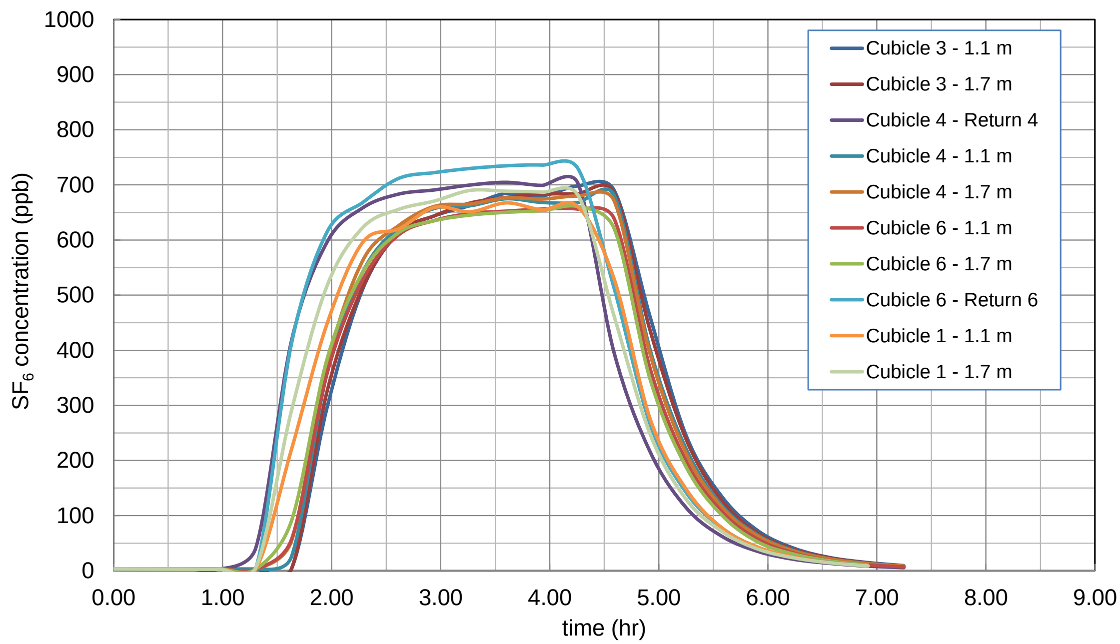


Figure 24: Example of tracer gas test results

The measured values of ACE for Case 4 (DAL 358 interior and exterior diffusers) based on the average exhaust airstream age of air (based on concentrations measured at the two return grilles) and the ages of air at two breathing heights are presented in Figure 31 for seated position and in Figure 32 for standing position. The ACE values ranged from 0.92 to 1.18 and averaged 1.1.

The measured values of ACE for Case 5 (Conventional square diffusers) based on the average exhaust airstream age of air (based on concentrations measured at the two return grilles) and the ages of air at two breathing heights are presented in Figure 33 for seated position and in Figure 34 for standing position. The ACE values ranged from 0.68 to 0.87 and averaged 0.77.

The measured values of ACE for Case 6 (DAL 358 exterior diffusers DN600) based on the average exhaust airstream age of air (based on concentrations measured at the two return grilles) and the ages of air at two breathing heights are presented in Figure 35 for seated person and in Figure 36 for standing position. The ACE values ranged from 0.97 to 1.16 and averaged 1.06.

The summary of the measured ACE for all cases is presented in Table 12. The statically data is presented in terms of minimum, maximum and average measured values of ACE for all tested overhead systems. The mean values are at least equal to unity for the overhead systems with high induction diffusers, Thus, the ACE in this simulated office space was indistinguishable (even higher for DAL 358) from ACE that would occur in a building with perfectly mixed indoor air.

Table 12: Summary of measured ACE in the simulated office space

| **Case** | **1** | **2** | **3** | **4** | **5** | **6** |
|---|---|---|---|---|---|---|
| Diffuser | DAL 359 | DAL 359 | DAL 359 | DAL 358 | Square Conv. | DAL 358 |
| Number (type) | 2 (DN600) | 2 (DN500) | 2 (DN500)<br>2 (DN 600) | 2 (DN500)<br>2 (DN600) | 4 | 2 (DN600) |
| Workstation | 4 & 6 | 1 & 3 | 1 & 3 / 4 & 6 | 1 & 3 / 4 & 6 | 1 & 3 / 4 & 6 | 4 & 6 |
| Minimum | 0.92 | 0.88 | 0.91 | 0.92 | 0.68 | 0.97 |
| Maximum | 1.11 | 1.12 | 1.16 | 1.18 | 0.87 | 1.16 |
| Mean | 1.01 | 0.96 | 1.03 | 1.10 | 0.77 | 1.06 |
| STDV | 0.05 | 0.06 | 0.07 | 0.05 | 0.04 | 0.06 |

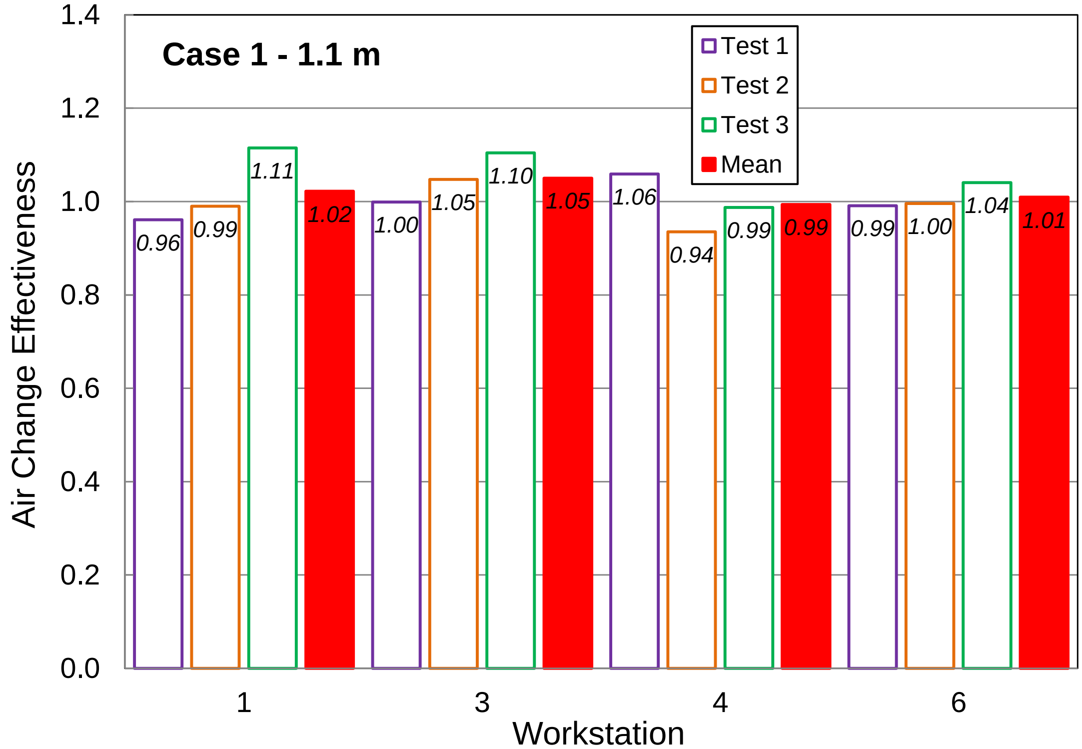


Figure 25: Measured values ACE for case 1 at seated breathing height of 1.1 m.

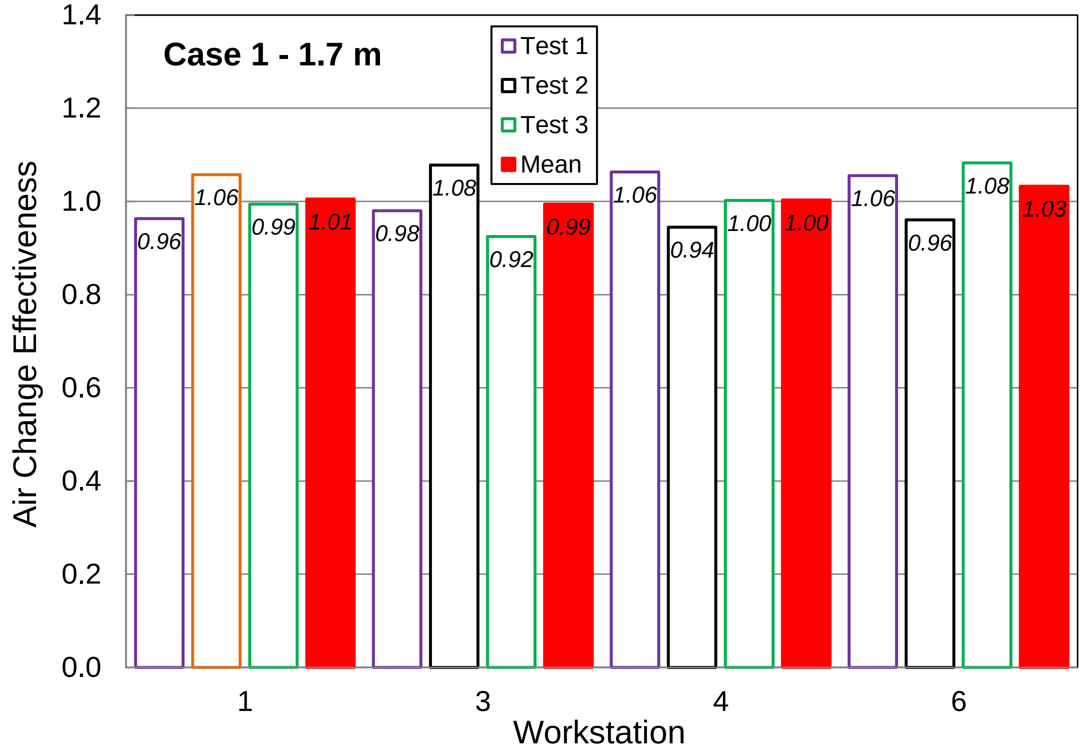


Figure 26: Measured values ACE for case 1 at standing breathing height of 1.7 m.

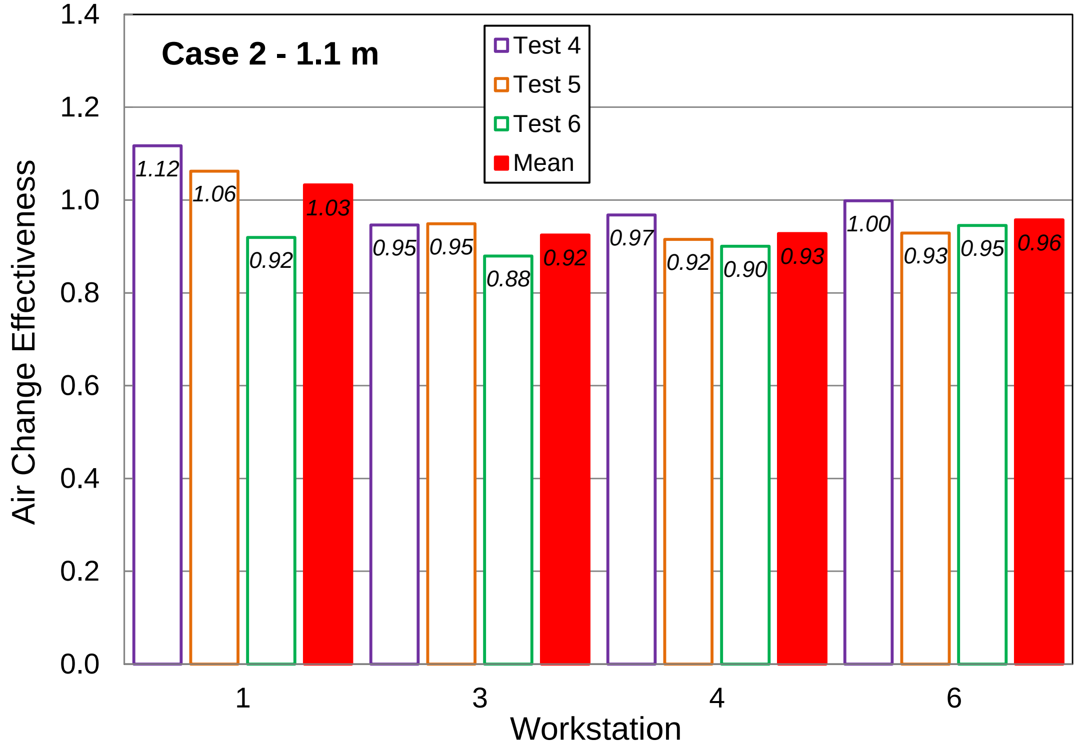


Figure 27: Measured values ACE for case 2 at seated breathing height of 1.1 m.

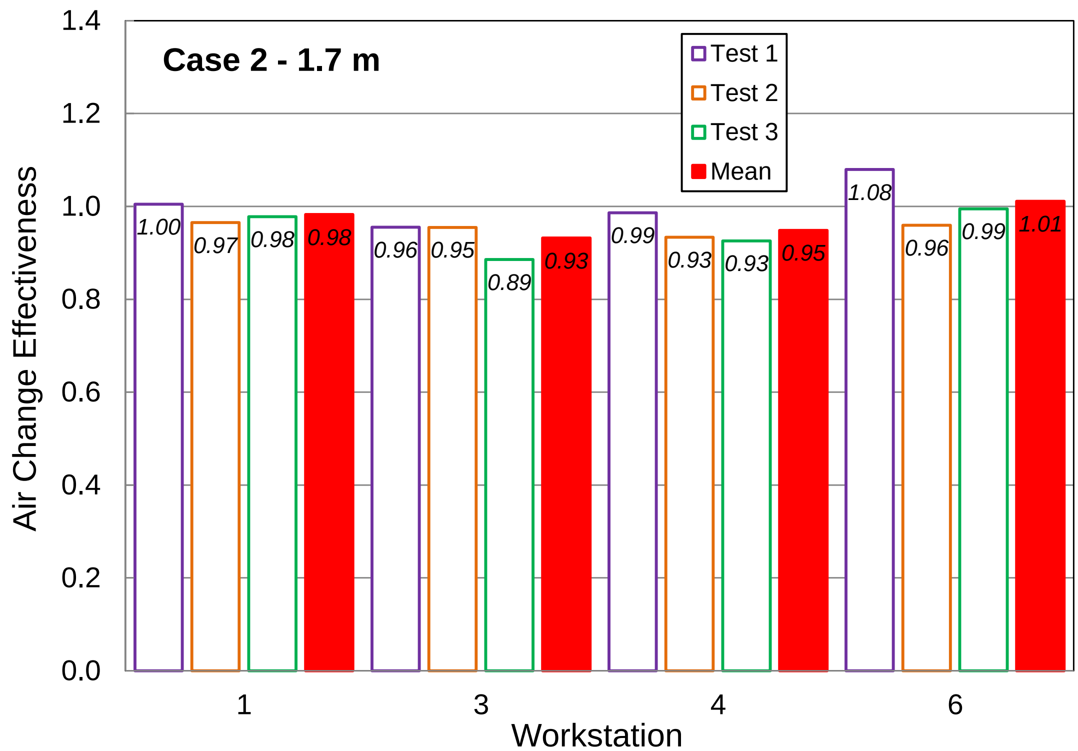


Figure 28: Measured values ACE for case 2 at standing breathing height of 1.7 m.

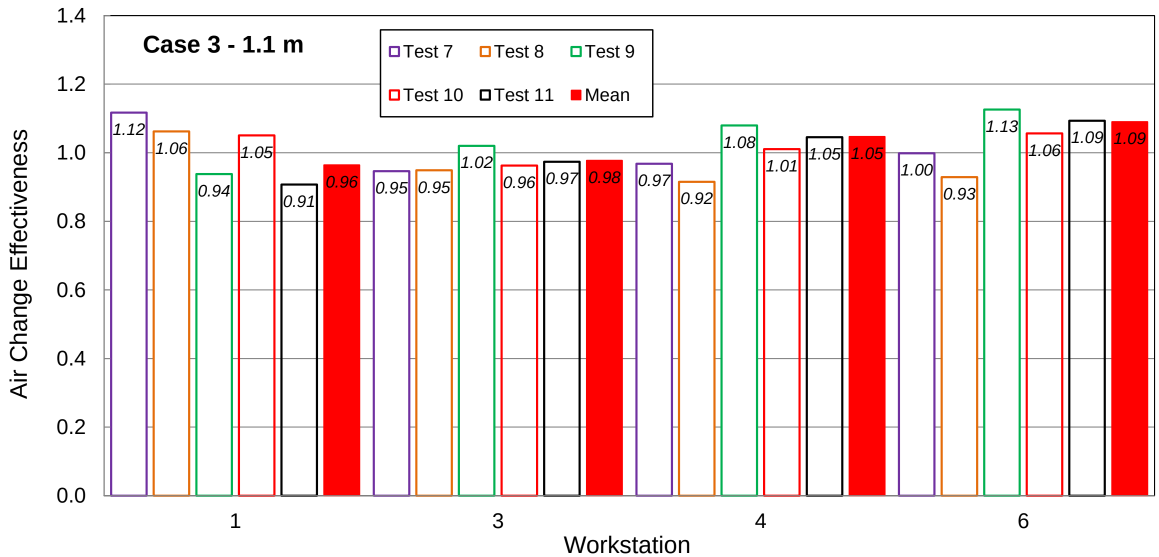


Figure 29: Measured values ACE for case 3 at seated breathing height of 1.1 m.

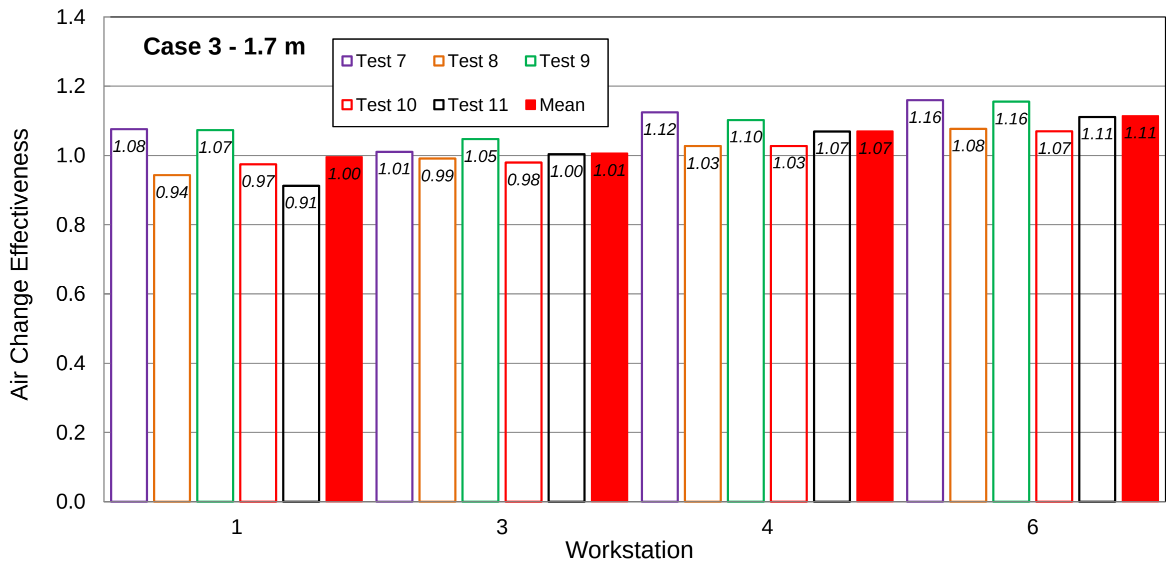


Figure 30: Measured values ACE for case 3 at standing breathing height of 1.7 m.

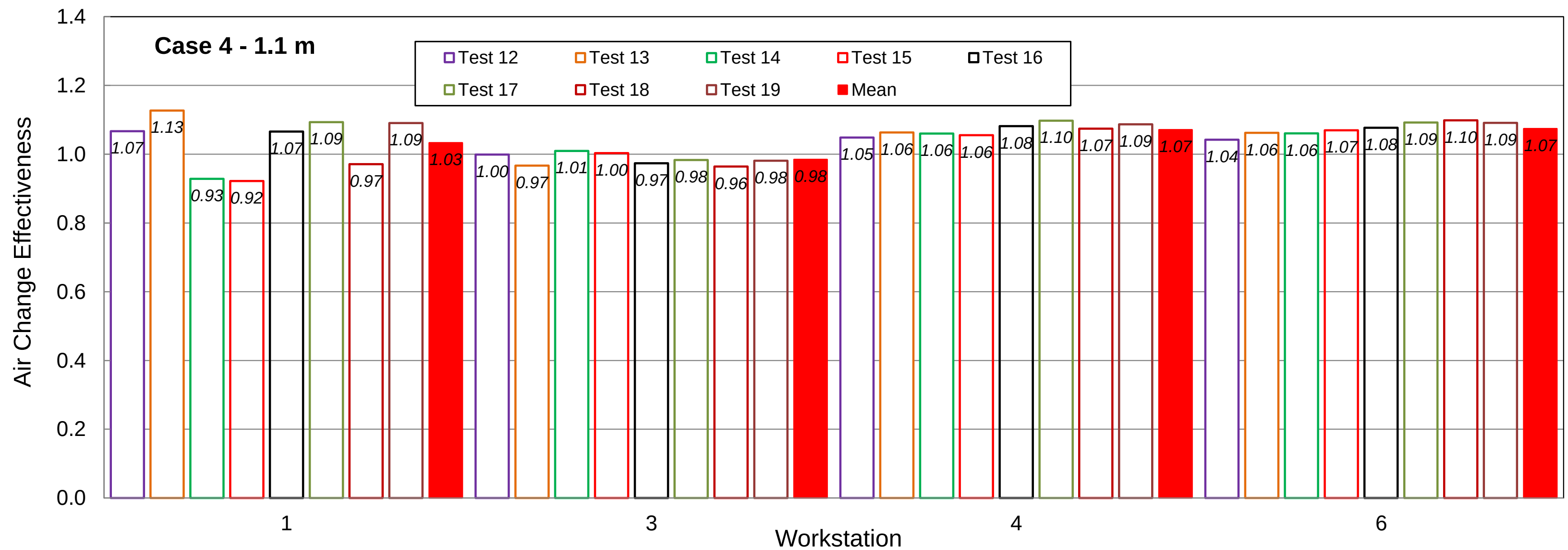


Figure 31: Measured values ACE for case 4 at seated breathing height of 1.1 m.

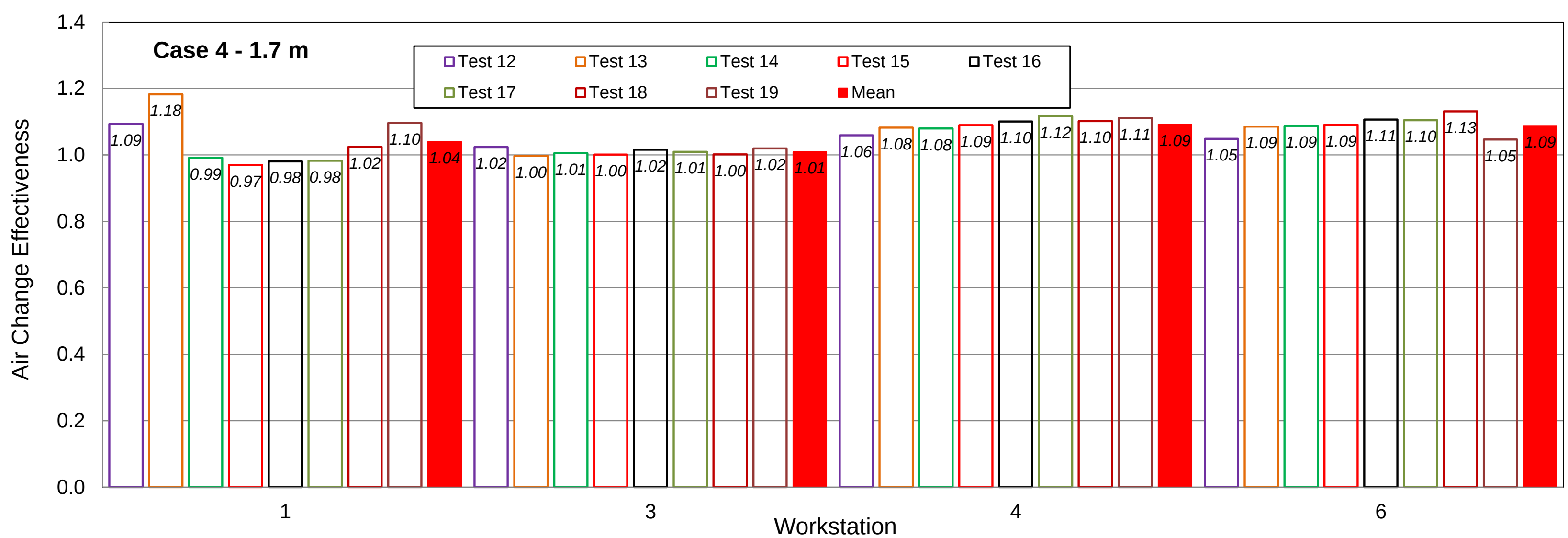


Figure 32: Measured values ACE for case 4 at standing breathing height of 1.7 m.

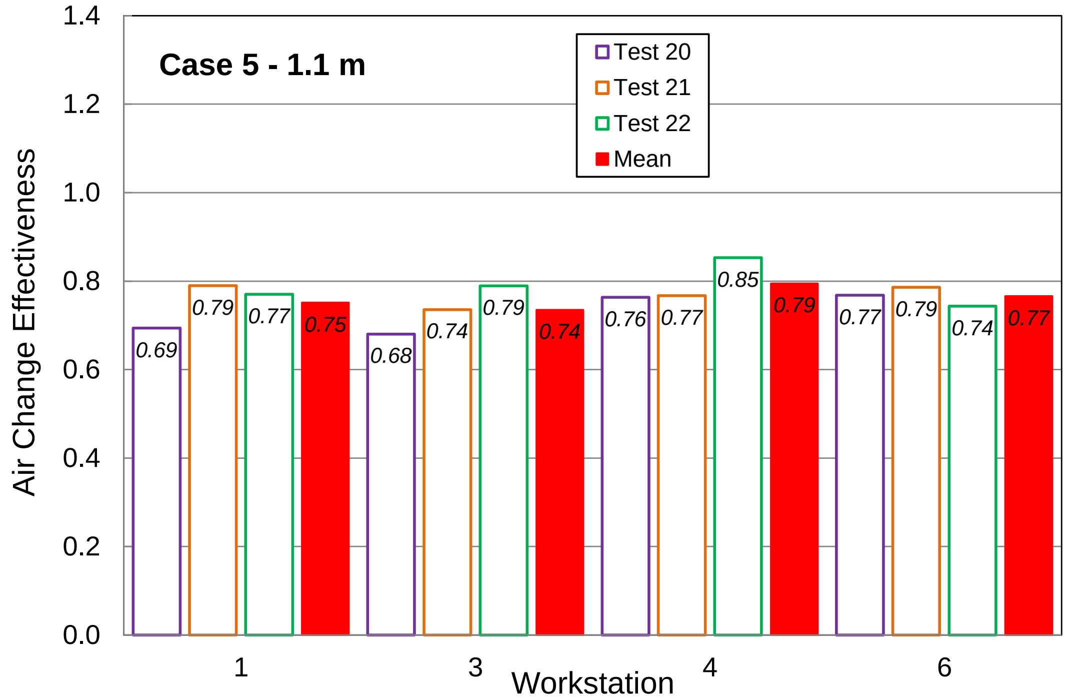


Figure 33: Measured values ACE for case 5 at seated breathing height of 1.1 m.

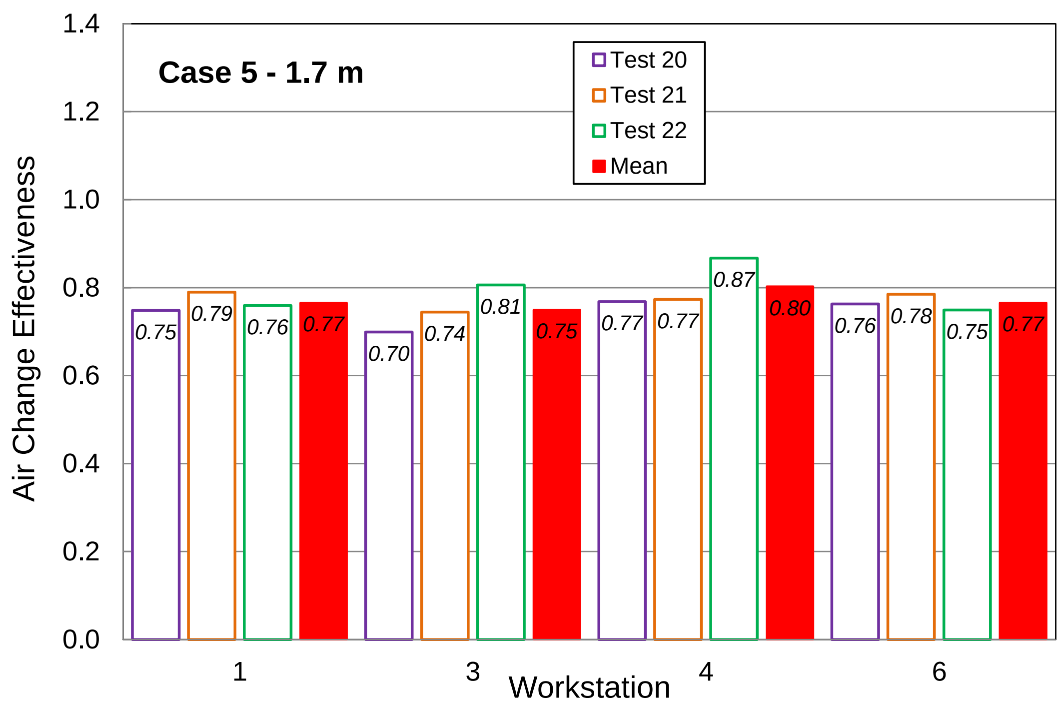


Figure 34: Measured values ACE for case 5 at standing breathing height of 1.7 m.

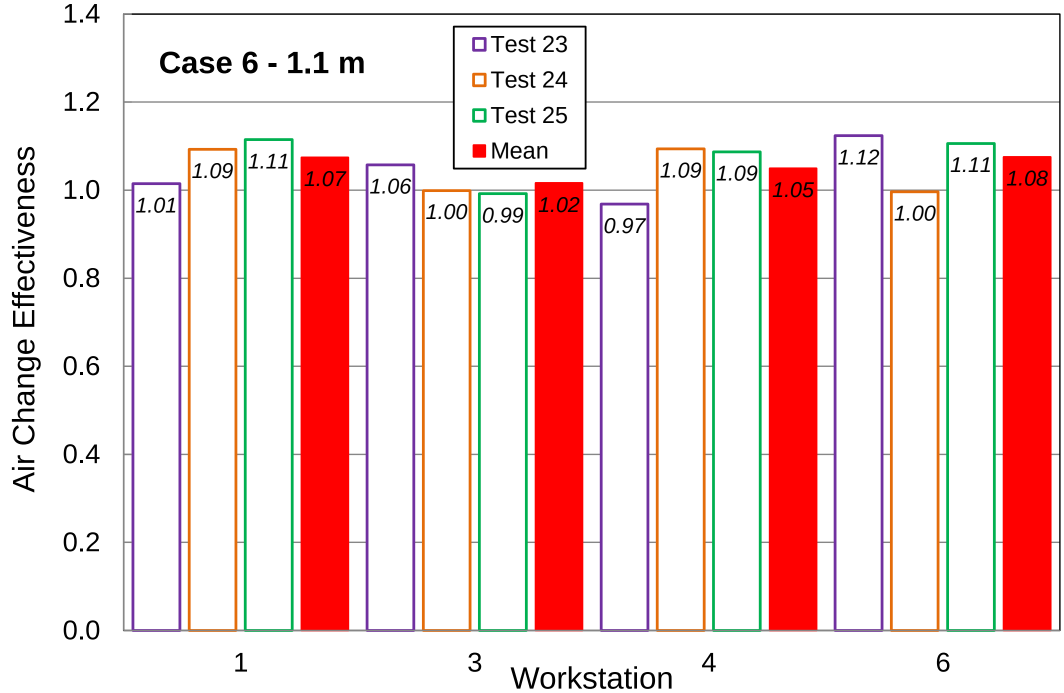


Figure 35: Measured values ACE for case 6 at seated breathing height of 1.1 m.

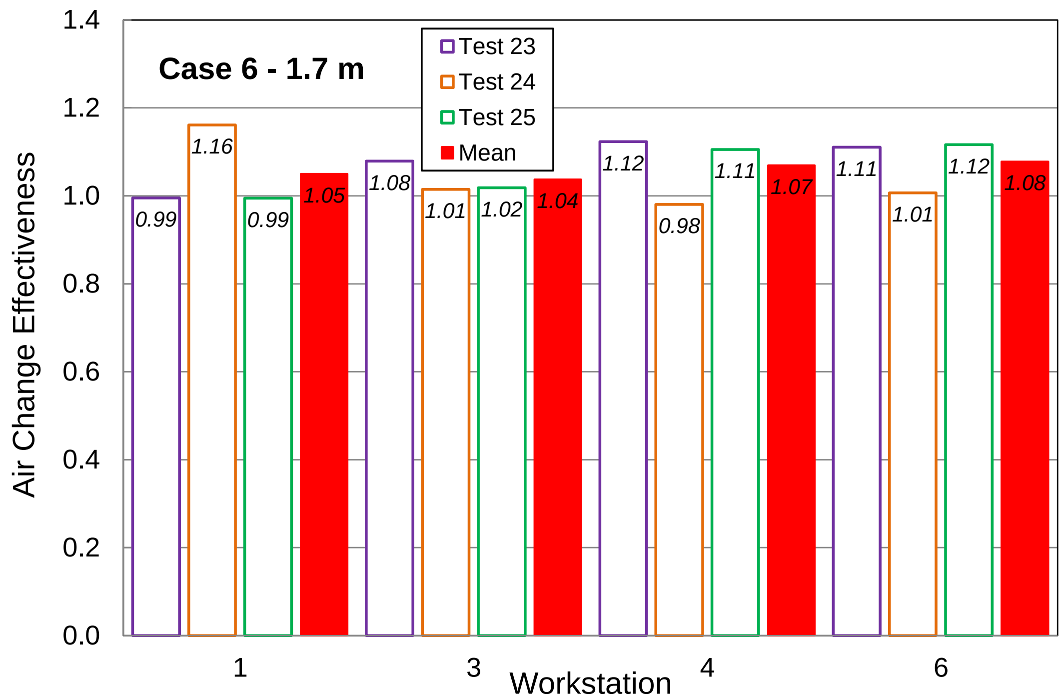


Figure 36: Measured values ACE for case 6 at standing breathing height of 1.7 m.

## 5.5 Thermal Stratification

To quantify the extent of thermal stratification in the simulated office space, air temperatures were measured and logged at four heights above the floor and at two heights close to exterior wall (window). The measurements heights were 0.1, 1.1, 1.7 and 2.7 m above the floor in cubicle 1, 3, 4 and 6 and at 1.1 and 1.7 m close to the exterior wall (window) in the vicinity of cubicles 4 and 6.

Figure 37 provides a typical example of the vertical air temperature distribution at three heights, head level of a standing person (1.7 m), head level of a sitting person (1.1 m), at 0.1 m ankle level and at the supply diffuser 1 (2.75 m at ceiling) in workstations 3, 4 and 6 for case 3 (configuration with 4 DAL 359 high induction diffusers). Similar vertical air temperature distributions with height are presented in Figure 38 for Case 4 (configuration with 4 DAL 358 high induction diffusers) and in Figure 39 for Case 5 (configuration with 4 square diffusers). The air temperature increased approximately 3°C between heights of 0.1 and 2.75 m.

## 5.6 Vertical Air Temperature Difference (VATD)

Thermal stratification results in warmer air temperature at head level in comparison to that at ankle level. ASHRAE Standard 55-2013 specifies a maximum allowable vertical air temperature difference of 3°C between heights of 1.7 m and 0.1 m.

The vertical air temperature differences measured at two heights, head level of a standing person (1.7 m) and head level of a sitting person (1.1 m) in workstation 3, workstation 4 and 6 with respect to the temperature at ankle level are presented respectively in Table 13, Table 14, Table 15, Table 16, Table 17, Table 18 and Table 19. The statically data is presented in terms of minimum, maximum and average measured values of VATD for two breathing heights (1.1 m for seated position and 1.7 m for standing position). The mean values are presented in red and maximum measured values are in bold.

Table 13: VATD for Case 1.

| Date (Test #) | | 03/03/2016 (1) | | | 03/03/2016 (2) | | | 04/03/2016 (3) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cubicle | | 3 | 4 | 6 | 3 | 4 | 6 | 3 | 4 | 6 |
| 1.1 m | Minimum | 1.60 | 1.67 | 1.39 | 1.34 | 1.09 | 1.17 | 1.16 | 1.11 | 1.03 |
| | Maximum | 2.23 | 2.05 | 2.07 | 1.99 | 1.51 | 1.61 | 2.20 | 2.13 | **2.25** |
| | Mean | 1.99 | 1.83 | 1.81 | 1.85 | 1.33 | 1.47 | 1.85 | 1.80 | 1.75 |
| | STDV | 0.18 | 0.10 | 0.19 | 0.13 | 0.07 | 0.08 | 0.29 | 0.21 | 0.33 |
| 1.7 m | Minimum | 1.54 | 1.96 | 1.51 | 1.36 | 1.27 | 1.32 | 1.18 | 1.16 | 1.09 |
| | Maximum | 2.03 | 2.71 | **3.02** | 1.80 | 1.81 | 2.42 | 1.98 | 2.65 | 2.94 |
| | Mean | 1.86 | 2.16 | 2.40 | 1.72 | 1.63 | 2.19 | 1.73 | 2.05 | 2.22 |
| | STDV | 0.14 | 0.22 | 0.45 | 0.07 | 0.09 | 0.19 | 0.22 | 0.31 | 0.55 |

Table 14: VATD for Case 2.

| Date (Test #) | | 02/03/2016 (4) | | | 10/03/2016 (5) | | | 11/03/2016 (6) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cubicle | | 3 | 4 | 6 | 3 | 4 | 6 | 3 | 4 | 6 |
| 1.1 m | Minimum | 1.50 | 1.64 | 1.19 | 0.79 | 0.80 | 0.83 | 0.96 | 1.02 | 0.94 |
| | Maximum | 1.98 | **2.00** | 1.91 | 1.11 | 1.18 | 1.00 | 1.82 | 1.51 | 1.17 |
| | Mean | 1.82 | 1.80 | 1.41 | 0.89 | 1.09 | 0.93 | 1.48 | 1.36 | 1.07 |
| | STDV | 0.11 | 0.05 | 0.16 | 0.06 | 0.07 | 0.04 | 0.20 | 0.14 | 0.06 |
| 1.7 m | Minimum | 1.50 | 1.83 | 1.30 | 1.00 | 1.09 | 0.99 | 0.96 | 1.13 | 1.05 |
| | Maximum | 1.91 | **2.89** | 2.55 | 1.22 | 1.41 | 1.35 | 1.60 | 1.66 | 1.39 |
| | Mean | 1.68 | 2.06 | 1.64 | 1.09 | 1.33 | 1.21 | 1.37 | 1.51 | 1.25 |
| | STDV | 0.10 | 0.21 | 0.38 | 0.04 | 0.07 | 0.07 | 0.14 | 0.15 | 0.10 |

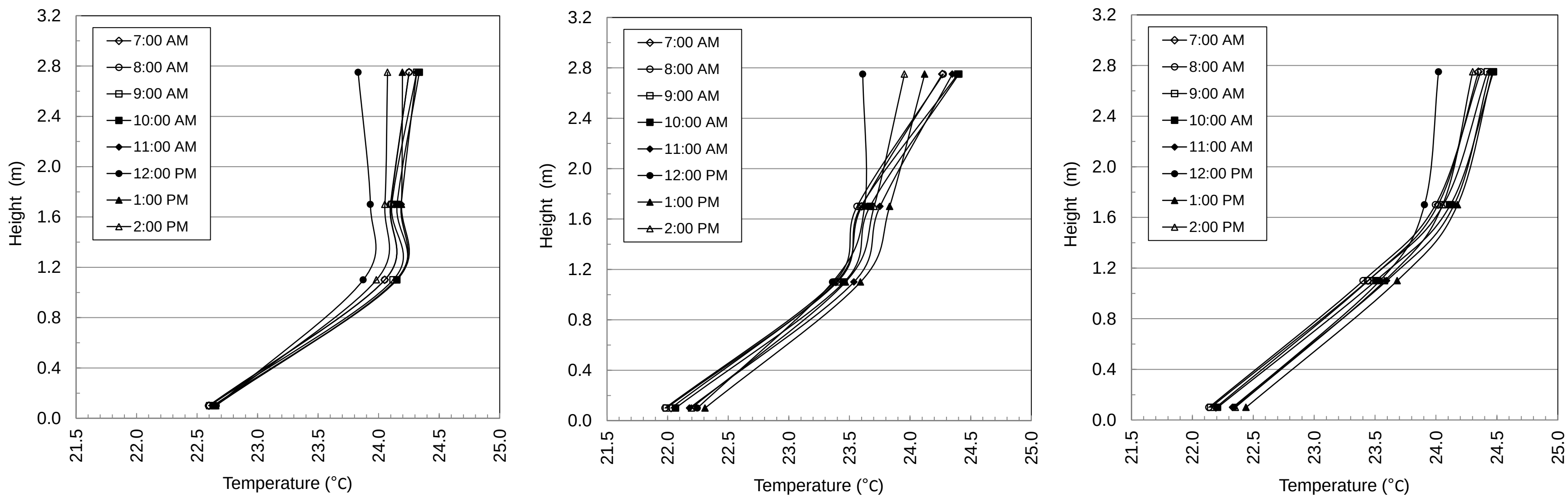


Figure 37: Examples of vertical temperature profiles in workstations 3 (left), 4 (centre), 6 (right) for Case 3

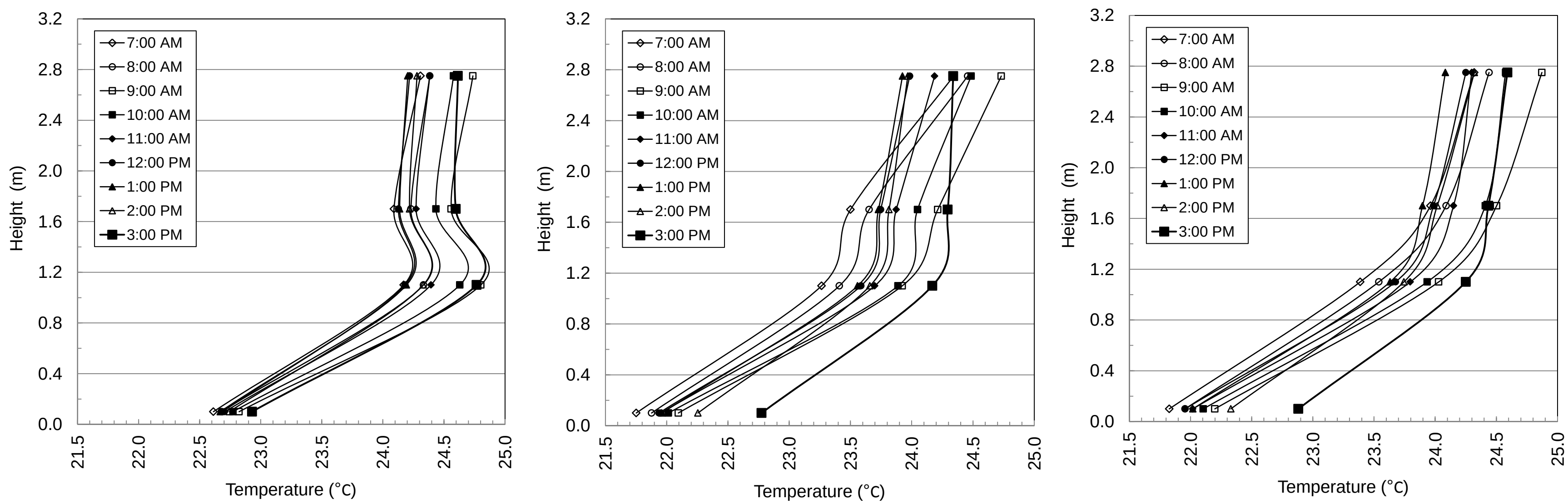


Figure 38: Examples of vertical temperature profiles in workstations 3 (left), 4 (centre), 6 (right) for Case 4

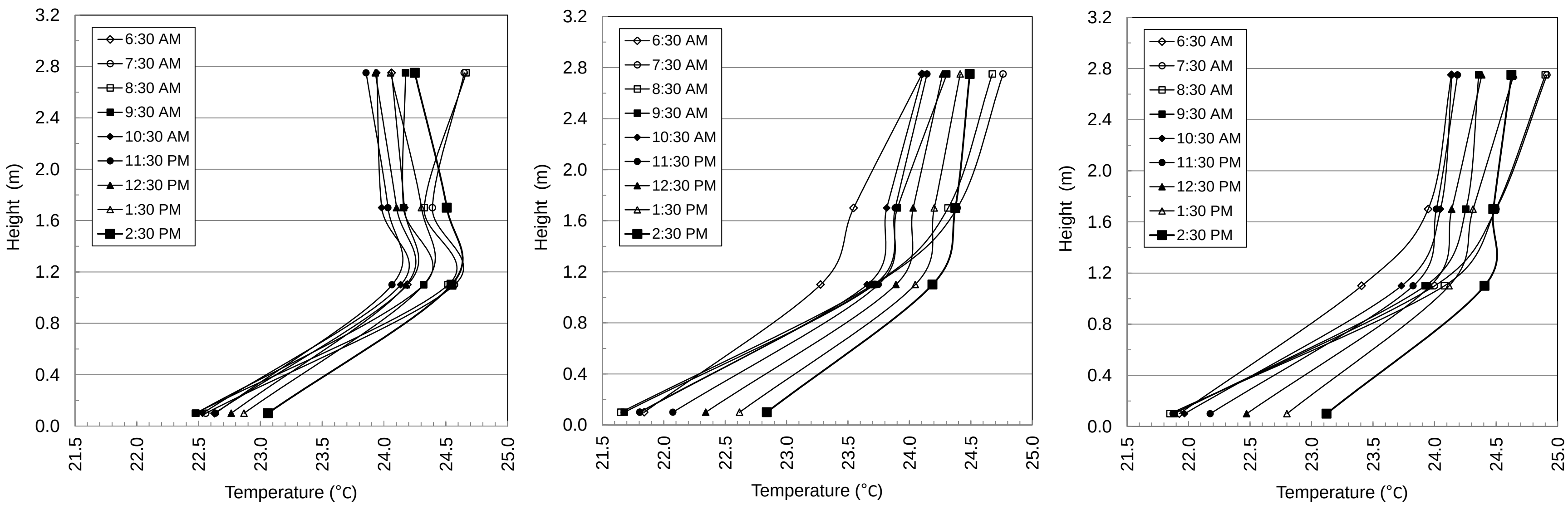


Figure 39: Examples of vertical temperature profiles in workstations 3 (left), 4 (centre), 6 (right) for Case 5

Table 15: VATD for Case 3.

| Date (Test #) | | 21/03/2016 (7) | | | 21/03/2016 (8) | | | 23/03/2016 (9) | | | 23/03/2016 (10) | | | 24/03/2016 (11) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cubicle | | 3 | 4 | 6 | 3 | 4 | 6 | 3 | 4 | 6 | 3 | 4 | 6 | 3 | 4 | 6 |
| 1.1 m | Minimum | 1.33 | 1.18 | 1.11 | 1.33 | 0.87 | 1.02 | 1.29 | 0.98 | 1.13 | 1.06 | 1.02 | 1.05 | 1.19 | 1.11 | 1.17 |
| | Maximum | **2.28** | 2.00 | 2.04 | 1.87 | 1.38 | 1.33 | 1.81 | 1.61 | 1.59 | 1.64 | 1.75 | 1.94 | 1.58 | 1.43 | 1.31 |
| | Mean | 1.89 | 1.65 | 1.61 | 1.61 | 1.21 | 1.23 | 1.58 | 1.34 | 1.38 | 1.44 | 1.31 | 1.26 | 1.45 | 1.33 | 1.26 |
| | STDV | 0.27 | 0.24 | 0.28 | 0.14 | 0.13 | 0.08 | 0.12 | 0.15 | 0.13 | 0.10 | 0.12 | 0.20 | 0.07 | 0.07 | 0.03 |
| 1.7 m | Minimum | 1.31 | 1.34 | 1.24 | 1.35 | 1.06 | 1.13 | 1.23 | 1.22 | 1.24 | 1.20 | 1.24 | 1.35 | 1.26 | 1.37 | 1.55 |
| | Maximum | 2.28 | 2.64 | **3.05** | 1.78 | 1.60 | 1.93 | 1.73 | 1.76 | 1.96 | 1.65 | 2.00 | 2.19 | 1.54 | 1.62 | 1.94 |
| | Mean | 1.78 | 1.92 | 2.09 | 1.60 | 1.42 | 1.64 | 1.52 | 1.48 | 1.60 | 1.50 | 1.53 | 1.74 | 1.49 | 1.55 | 1.80 |
| | STDV | 0.24 | 0.38 | 0.57 | 0.11 | 0.15 | 0.23 | 0.09 | 0.14 | 0.22 | 0.08 | 0.12 | 0.14 | 0.05 | 0.05 | 0.09 |

Table 16: VATD for Case 4

| Date (Test #) | | 24/03/2016 (12) | | | 25/03/2016 (13) | | | 26/03/2016 (14) | | | 29/03/2016 (15) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cubicle | | 3 | 4 | 6 | 3 | 4 | 6 | 3 | 4 | 6 | 3 | 4 | 6 |
| 1.1 m | Minimum | 0.57 | 0.33 | 0.36 | 1.23 | 1.23 | 1.28 | 0.74 | 0.74 | 1.09 | 0.69 | 0.70 | 0.94 |
| | Maximum | 1.82 | 1.71 | 1.61 | 1.66 | 1.63 | 1.62 | **1.94** | 1.44 | 1.93 | 1.64 | 1.42 | 1.39 |
| | Mean | 1.37 | 1.28 | 1.35 | 1.44 | 1.40 | 1.43 | 1.25 | 1.15 | 1.30 | 1.31 | 1.17 | 1.25 |
| | STDV | 0.21 | 0.19 | 0.16 | 0.10 | 0.08 | 0.08 | 0.23 | 0.20 | 0.17 | 0.24 | 0.18 | 0.12 |
| 1.7 m | Minimum | 0.69 | 0.61 | 0.40 | 1.43 | 1.47 | 1.72 | 0.94 | 0.95 | 1.22 | 0.96 | 0.92 | 1.10 |
| | Maximum | 1.98 | 1.98 | **2.22** | 1.78 | 1.78 | 2.13 | 1.83 | 1.63 | 1.99 | 1.60 | 1.61 | 1.90 |
| | Mean | 1.44 | 1.52 | 1.82 | 1.52 | 1.64 | 1.95 | 1.32 | 1.36 | 1.63 | 1.34 | 1.39 | 1.59 |
| | STDV | 0.17 | 0.18 | 0.22 | 0.06 | 0.07 | 0.11 | 0.17 | 0.22 | 0.23 | 0.15 | 0.20 | 0.25 |

Table 17: VATD for Case 4

| Date (Test #) | | 02/04/2016 (16) | | | 03/04/2016 (17) | | | 04/04/2016 (18) | | | 05/04/2016 (19) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cubicle | | 3 | 4 | 6 | 3 | 4 | 6 | 3 | 4 | 6 | 3 | 4 | 6 |
| 1.1 m | Minimum | 0.90 | 0.90 | 1.10 | 0.96 | 0.91 | 0.51 | 1.35 | 1.36 | 1.32 | 0.80 | 0.80 | 1.01 |
| | Maximum | 1.82 | 1.57 | 1.64 | 1.78 | 2.03 | **2.43** | 1.98 | 1.89 | 1.88 | 1.93 | 1.54 | 1.53 |
| | Mean | 1.31 | 1.28 | 1.37 | 1.39 | 1.42 | 1.53 | 1.64 | 1.62 | 1.62 | 1.42 | 1.28 | 1.31 |
| | STDV | 0.24 | 0.19 | 0.14 | 0.25 | 0.19 | 0.24 | 0.17 | 0.15 | 0.16 | 0.28 | 0.21 | 0.14 |
| 1.7 m | Minimum | 1.01 | 1.05 | 1.20 | 1.07 | 0.84 | 0.72 | 1.37 | 1.50 | 1.52 | 0.99 | 1.01 | 1.11 |
| | Maximum | 1.71 | 1.78 | 2.25 | 1.61 | 2.33 | 2.26 | 1.74 | 2.16 | **2.35** | 1.81 | 1.73 | 2.06 |
| | Mean | 1.34 | 1.47 | 1.78 | 1.39 | 1.61 | 1.90 | 1.54 | 1.82 | 2.00 | 1.44 | 1.48 | 1.64 |
| | STDV | 0.18 | 0.21 | 0.32 | 0.16 | 0.25 | 0.34 | 0.10 | 0.16 | 0.24 | 0.19 | 0.22 | 0.30 |

Table 18: VATD for Case 5.

| Date (Test #) | | 08/04/2016 (20) | | | 08/04/2016 (21) | | | 09/04/2016 (22) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cubicle | | 3 | 4 | 6 | 3 | 4 | 6 | 3 | 4 | 6 |
| 1.1 m | Minimum | 1.04 | 0.43 | 0.72 | 0.67 | 0.31 | 0.45 | 1.17 | 1.19 | 0.99 |
| | Maximum | 1.53 | 1.13 | 1.17 | 1.57 | 1.29 | 1.11 | **1.99** | 1.94 | 1.83 |
| | Mean | 1.28 | 0.92 | 1.06 | 1.34 | 0.97 | 0.93 | 1.51 | 1.52 | 1.41 |
| | STDV | 0.12 | 0.16 | 0.09 | 0.19 | 0.30 | 0.17 | 0.19 | 0.24 | 0.27 |
| 1.7 m | Minimum | 1.17 | 0.79 | 0.99 | 0.76 | 0.54 | 0.81 | 1.27 | 1.47 | 1.24 |
| | Maximum | 1.52 | 1.39 | 1.43 | 1.54 | 1.56 | 1.44 | 1.84 | **2.12** | 2.11 |
| | Mean | 1.37 | 1.21 | 1.29 | 1.38 | 1.26 | 1.22 | 1.51 | 1.74 | 1.65 |
| | STDV | 0.09 | 0.15 | 0.10 | 0.17 | 0.30 | 0.17 | 0.14 | 0.19 | 0.25 |

Table 19: VATD for Case 6.

| Date (Test #) | | 09/04/2016 (23) | | | 10/04/2016 (24) | | | 10/04/2016 (25) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cubicle | | 3 | 4 | 6 | 3 | 4 | 6 | 3 | 4 | 6 |
| 1.1 m | Minimum | 0.79 | 0.71 | 0.85 | 1.29 | 1.32 | 1.22 | 0.83 | 0.88 | 0.98 |
| | Maximum | 1.83 | 1.64 | 1.48 | 2.09 | 2.09 | 2.24 | **2.36** | 1.59 | 1.55 |
| | Mean | 1.45 | 1.24 | 1.26 | 1.64 | 1.71 | 1.70 | 1.44 | 1.21 | 1.26 |
| | STDV | 0.26 | 0.20 | 0.14 | 0.26 | 0.24 | 0.33 | 0.31 | 0.19 | 0.12 |
| 1.7 m | Minimum | 0.95 | 0.92 | 0.97 | 1.28 | 1.45 | 1.35 | 1.01 | 1.04 | 1.10 |
| | Maximum | 1.76 | 1.71 | 2.03 | 1.88 | **2.73** | 2.69 | 2.17 | 1.82 | 1.83 |
| | Mean | 1.45 | 1.44 | 1.56 | 1.54 | 1.97 | 1.99 | 1.44 | 1.42 | 1.55 |
| | STDV | 0.21 | 0.21 | 0.30 | 0.20 | 0.39 | 0.46 | 0.24 | 0.21 | 0.23 |

A very few tests have shown that the maximum value of VATD at 1.7 m above the floor has exceeded the limit of 3°C set by ASHRAE 55-2013. In general the thermal comfort index VATD was within the maximum allowable vertical air temperature difference between heights of 1.1 m (seated position) and 1.7 m (standing position) and 0.1 m.

### 5.7 Air Speed

For operative temperature between 22.5°C and 25.5°C, the allowable air speed small follow the equal-SET (Standard Effective Temperature) curve for 0.6 clo and 1.1 met and the approximated curve is presented in Figure 40:

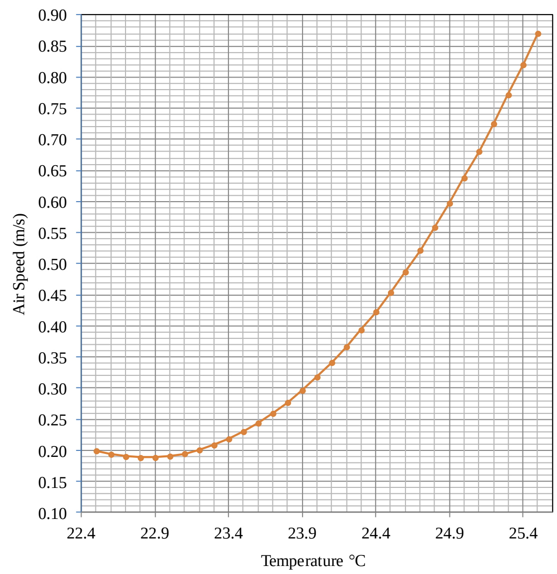


Figure 40: Equal-SET curve for 0.6 clo and 1.1 met (ASHRAE 55-2010).

Examples of the plot of the measured air velocity versus operative temperature on a same plot as the equal-curve SET provided bu ASHRAE 55-2013 are shown in Figure 41 for Case 1 (configuration with exterior diffusers DAL 359 DN600 only), in Figure 42 for Case 2 (configuration with interior diffusers DAL 359 DN500 only), in Figure 43 for Case 3 (combination of DAL 359, interior diffusers DN500 and exterior diffusers DN600), in Figure 44 for Case 3 (configuration combining DAL 358, interior diffusers DN500 and exterior diffusers DN500), in Figure 45 for Case 5 (configuration with four conventional square diffusers) and in Figure 46 for Case 6 (exterior DAL 358 diffusers DN600).

The results are presented for four workstations; 1 (top left), 3 (top right), 4 (Bottom left) and 6 (bottom right). For operative temperature below 22.5°C, all corresponding measured air velocities were lower than 0.15 m/s. For measured operative temperatures between 22.5°C and 25.5°C, few values exceeded the limit to air speed set by the equal-SET curve in workstations 1 and 3.

In general the thermal comfort index Limit to air speed was within the maximum allowable value, equal-SET curve at three heights 0.1 m (feet level of a person), 1.1 m (head of seated person) and 1.7 m (head level of a standing person).

The air speeds measured at three heights, head level of a standing person (1.7 m), head level of a sitting person (1.1 m) and feet level of both seated and standing person in workstation 1 and 3, workstation 4 and 6 are presented respectively in Table 20, Table 21, Table 22, Table 23, Table 24, Table 25, Table 26 and Table 27. The statically data is presented in terms of minimum, maximum and average measured values of air speed with mean values presented in red and maximum measured values in bold.

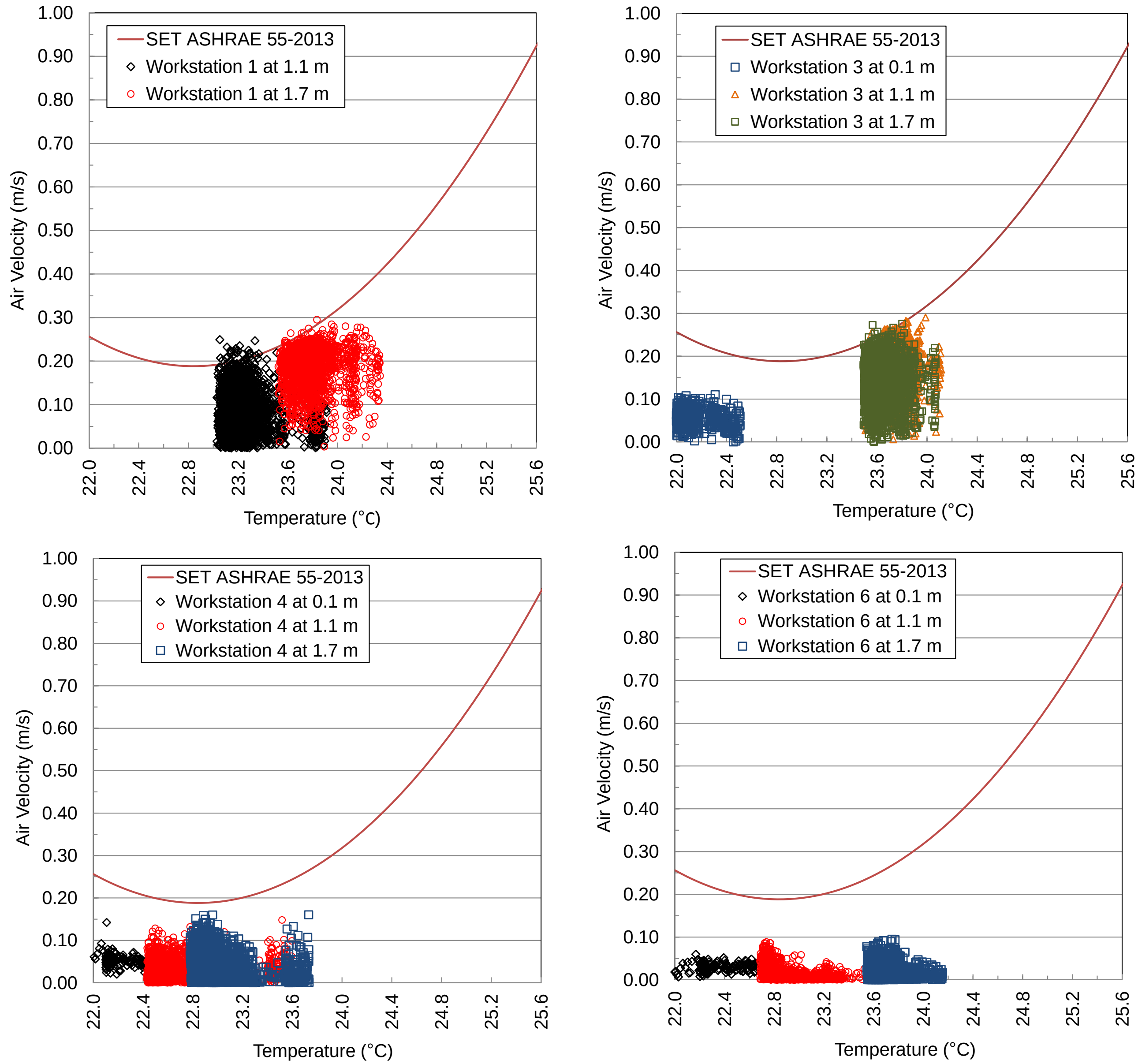


Figure 41: Limit to air speed for Case 1, Test 2

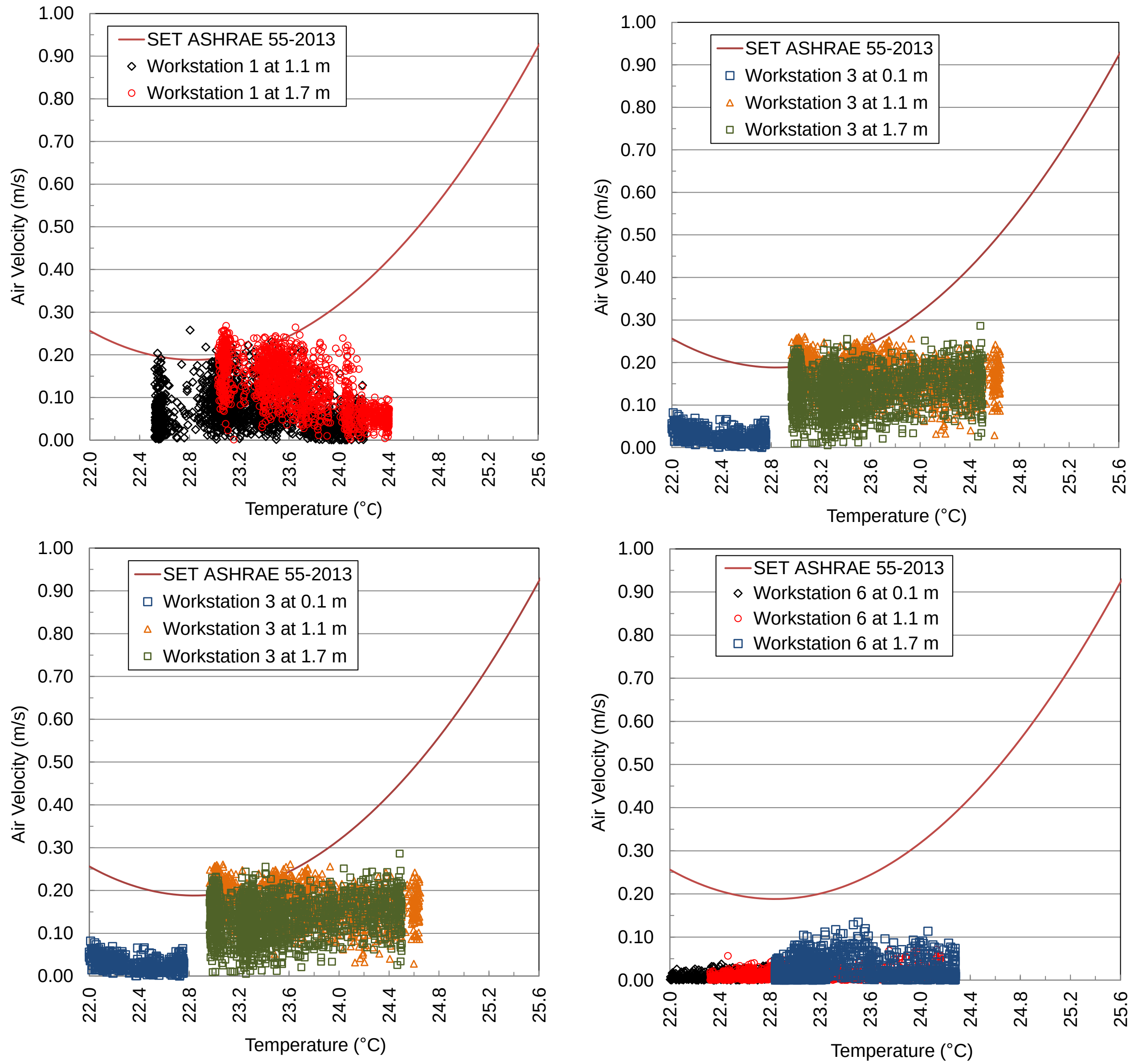


Figure 42: Limit to air speed for Case 2, Test 4

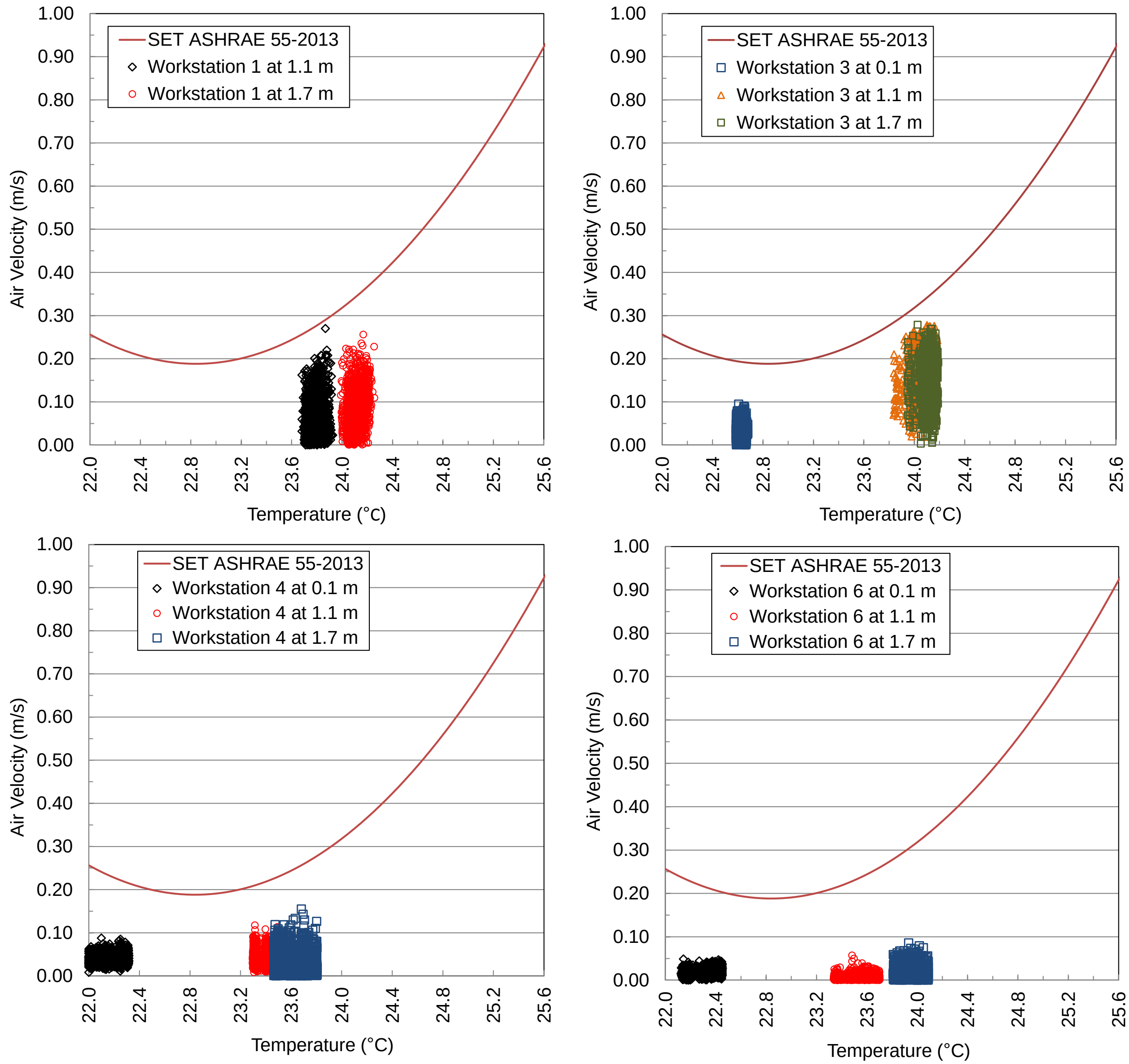


Figure 43: Limit to air speed for Case 3, Test 11

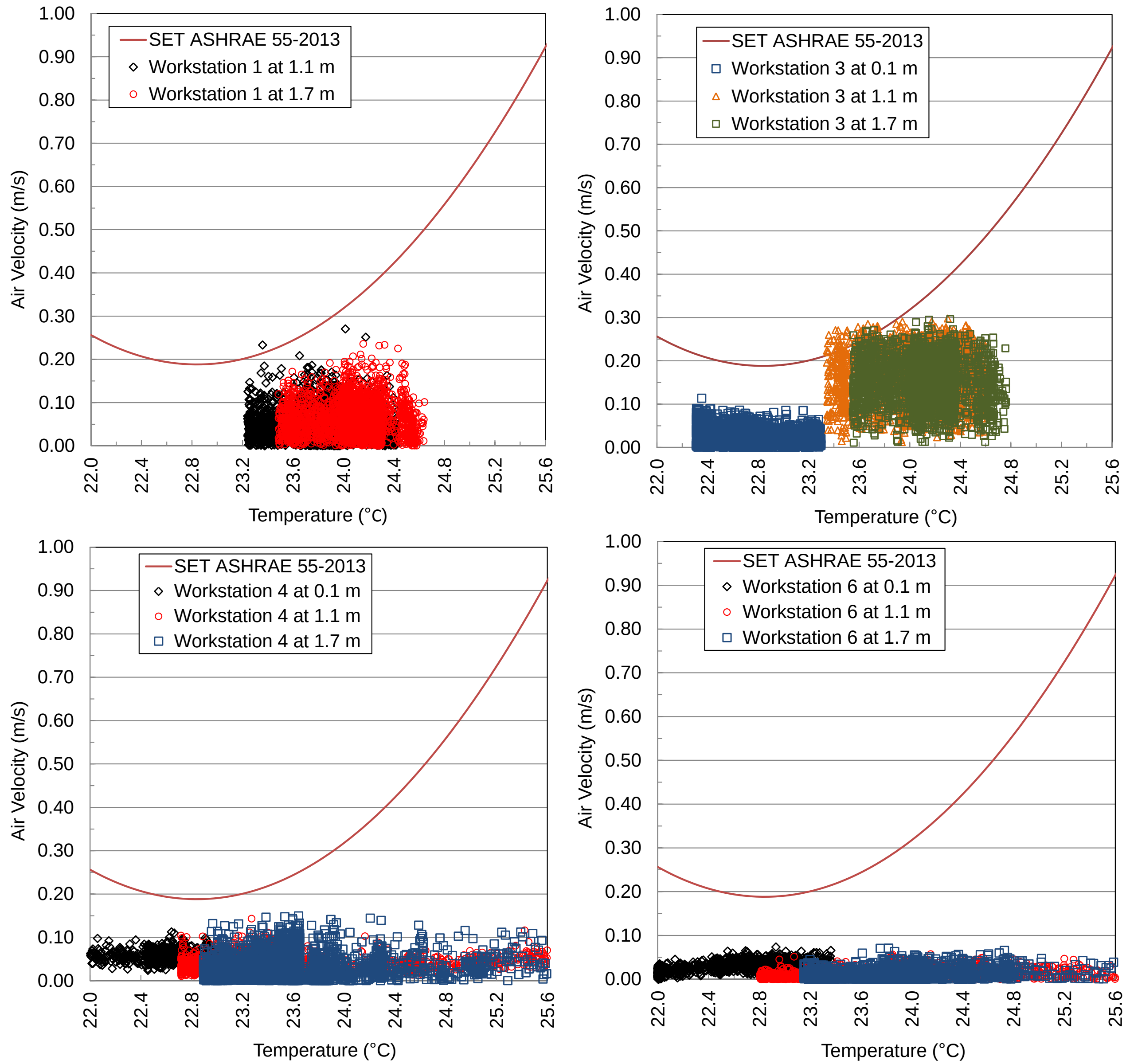


Figure 44: Limit to air speed for Case 4, Test 17

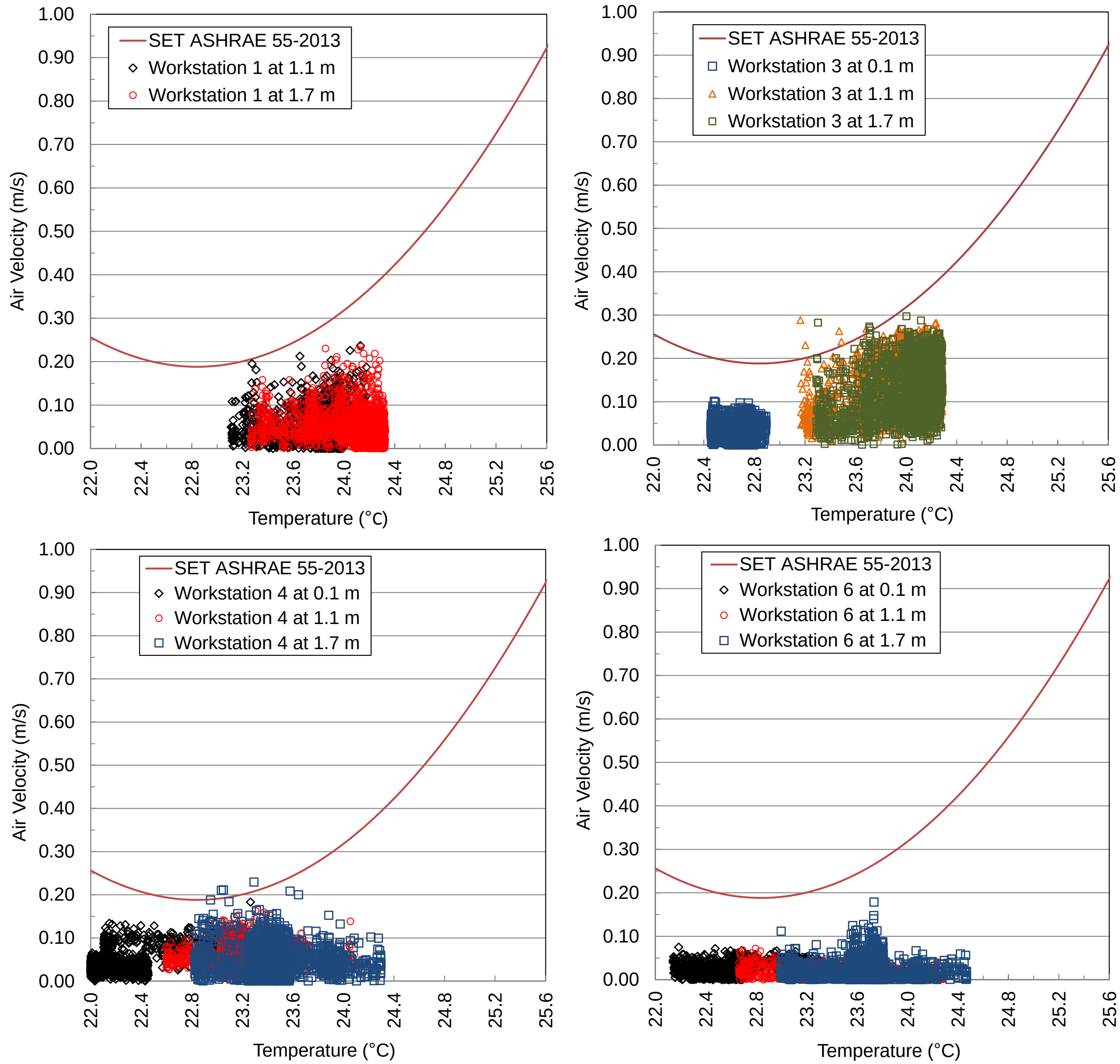


Figure 45: Limit to air speed for Case 5, Test 21

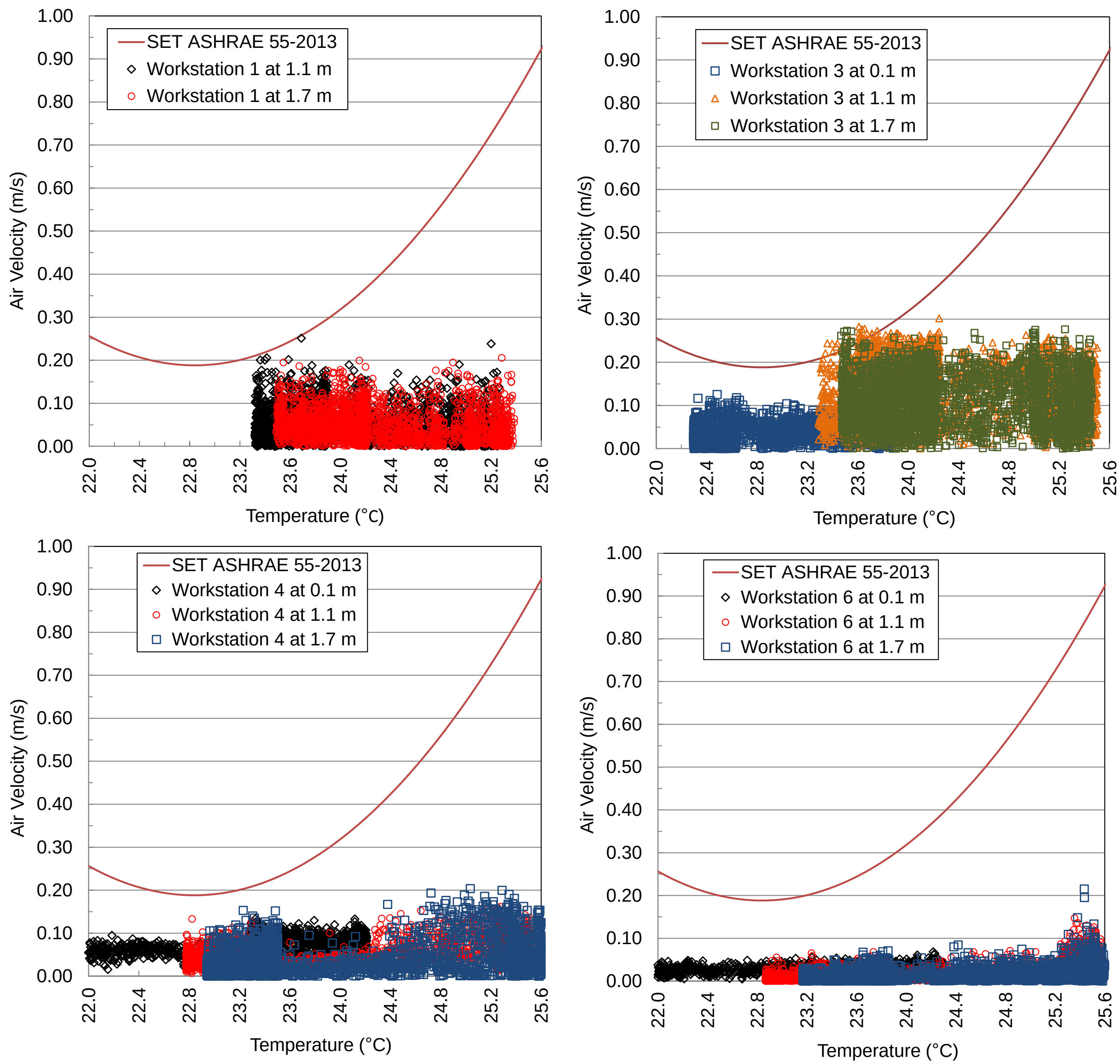


Figure 46: Limit to air speed for Case 6, Test 23

Table 20: Measured air Velocity for Case 1.

| Date (Test #) | | 1 | | | | 2 | | | | 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cubicle | | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 |
| 0.1 m | Minimum | - | 0.00 | 0.00 | 0.00 | - | 0.00 | 0.00 | 0.00 | - | 0.00 | 0.01 | 0.00 |
| | Maximum | - | 0.08 | 0.12 | 0.06 | - | 0.13 | 0.14 | 0.06 | - | 0.14 | **0.17** | 0.11 |
| | Mean | - | 0.03 | 0.04 | 0.02 | - | 0.04 | 0.04 | 0.02 | - | 0.05 | 0.06 | 0.02 |
| | STDV | - | 0.02 | 0.02 | 0.01 | - | 0.02 | 0.02 | 0.01 | - | 0.02 | 0.02 | 0.01 |
| 1.1 m | Minimum | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Maximum | 0.25 | 0.26 | 0.15 | 0.06 | 0.25 | **0.29** | 0.15 | 0.09 | 0.26 | 0.27 | 0.20 | 0.24 |
| | Mean | 0.11 | 0.14 | 0.06 | 0.01 | 0.08 | 0.19 | 0.03 | 0.01 | 0.09 | 0.15 | 0.05 | 0.01 |
| | STDV | 0.05 | 0.04 | 0.03 | 0.01 | 0.05 | 0.04 | 0.02 | 0.02 | 0.05 | 0.05 | 0.03 | 0.01 |
| 1.7 m | Minimum | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Maximum | 0.28 | 0.26 | 0.19 | 0.11 | **0.29** | 0.28 | 0.16 | 0.09 | 0.27 | 0.28 | 0.25 | 0.20 |
| | Mean | 0.15 | 0.09 | 0.08 | 0.02 | 0.19 | 0.14 | 0.05 | 0.02 | 0.15 | 0.10 | 0.06 | 0.02 |
| | STDV | 0.05 | 0.05 | 0.04 | 0.02 | 0.04 | 0.05 | 0.03 | 0.02 | 0.06 | 0.05 | 0.00 | 0.02 |

Table 21: Measured air velocity for Case 2.

| Date (Test #) | | 4 | | | | 5 | | | | 6 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cubicle | | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 |
| 0.1 m | Minimum | - | 0.00 | 0.00 | 0.00 | - | 0.00 | 0.00 | 0.00 | - | 0.00 | 0.01 | 0.00 |
| | Maximum | - | 0.09 | 0.10 | 0.04 | - | 0.13 | **0.19** | 0.05 | - | 0.12 | 0.12 | 0.07 |
| | Mean | - | 0.03 | 0.04 | 0.01 | - | 0.05 | 0.03 | 0.01 | - | 0.05 | 0.04 | 0.02 |
| | STDV | - | 0.02 | 0.01 | 0.01 | - | 0.02 | 0.01 | 0.01 | - | 0.02 | 0.01 | 0.01 |
| 1.1 m | Minimum | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| | Maximum | 0.26 | 0.26 | 0.16 | 0.07 | 0.28 | 0.28 | 0.14 | 0.06 | 0.25 | **0.29** | 0.15 | 0.09 |
| | Mean | 0.07 | 0.17 | 0.05 | 0.01 | 0.07 | 0.10 | 0.03 | 0.01 | 0.10 | 0.17 | 0.05 | 0.02 |
| | STDV | 0.05 | 0.04 | 0.03 | 0.01 | 0.04 | 0.05 | 0.01 | 0.01 | 0.06 | 0.06 | 0.02 | 0.02 |
| 1.7 m | Minimum | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Maximum | 0.27 | **0.29** | 0.19 | 0.13 | 0.27 | 0.27 | 0.16 | 0.13 | 0.28 | 0.27 | 0.18 | 0.14 |
| | Mean | 0.12 | 0.13 | 0.06 | 0.02 | 0.06 | 0.10 | 0.03 | 0.02 | 0.13 | 0.14 | 0.05 | 0.04 |
| | STDV | 0.06 | 0.05 | 0.04 | 0.02 | 0.04 | 0.05 | 0.02 | 0.02 | 0.06 | 0.06 | 0.04 | 0.03 |

Table 22: Measured air velocity for Case 3.

| Date (Test #) | | 7 | | | | 8 | | | | 9 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cubicle | | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 |
| 0.1 m | Minimum | - | 0.00 | 0.00 | 0.00 | - | 0.00 | 0.01 | 0.00 | - | 0.00 | 0.01 | 0.00 |
| | Maximum | - | 0.12 | **0.14** | 0.05 | - | 0.11 | 0.08 | 0.05 | - | 0.11 | 0.13 | 0.05 |
| | Mean | - | 0.04 | 0.05 | 0.02 | - | 0.05 | 0.04 | 0.02 | - | 0.05 | 0.05 | 0.02 |
| | STDV | - | 0.02 | 0.02 | 0.01 | - | 0.02 | 0.01 | 0.01 | - | 0.02 | 0.02 | 0.01 |
| 1.1 m | Minimum | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| | Maximum | 0.25 | 0.26 | 0.17 | 0.08 | 0.24 | 0.28 | 0.14 | 0.04 | 0.24 | **0.29** | 0.15 | 0.09 |
| | Mean | 0.07 | 0.14 | 0.07 | 0.01 | 0.06 | 0.16 | 0.04 | 0.01 | 0.05 | 0.16 | 0.05 | 0.01 |
| | STDV | 0.05 | 0.05 | 0.03 | 0.01 | 0.04 | 0.05 | 0.02 | 0.01 | 0.04 | 0.05 | 0.02 | 0.01 |
| 1.7 m | Minimum | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Maximum | 0.25 | 0.27 | 0.22 | 0.13 | 0.26 | 0.27 | 0.16 | 0.08 | 0.25 | **0.28** | 0.18 | 0.11 |
| | Mean | 0.10 | 0.11 | 0.05 | 0.02 | 0.09 | 0.14 | 0.03 | 0.01 | 0.07 | 0.14 | 0.04 | 0.02 |
| | STDV | 0.05 | 0.05 | 0.04 | 0.02 | 0.05 | 0.05 | 0.03 | 0.01 | 0.05 | 0.06 | 0.03 | 0.02 |

Table 23: Measured air velocity for Case 3.

| Date (Test #) | | 10 | | | | 11 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Cubicle | | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 |
| 0.1 m | Minimum | - | 0.00 | 0.00 | 0.00 | - | 0.00 | 0.01 | 0.00 |
| | Maximum | - | **0.19** | 0.14 | 0.08 | - | 0.09 | 0.09 | 0.05 |
| | Mean | - | 0.04 | 0.04 | 0.02 | - | 0.03 | 0.04 | 0.02 |
| | STDV | - | 0.02 | 0.02 | 0.01 | - | 0.02 | 0.01 | 0.01 |
| 1.1 m | Minimum | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.02 | 0.01 | 0.00 |
| | Maximum | 0.27 | **0.30** | 0.19 | 0.09 | 0.27 | 0.28 | 0.12 | 0.06 |
| | Mean | 0.06 | 0.16 | 0.05 | 0.01 | 0.06 | 0.17 | 0.04 | 0.01 |
| | STDV | 0.04 | 0.06 | 0.02 | 0.01 | 0.04 | 0.05 | 0.02 | 0.01 |
| 1.7 m | Minimum | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Maximum | **0.30** | 0.28 | 0.19 | 0.10 | 0.26 | 0.28 | 0.16 | 0.09 |
| | Mean | 0.08 | 0.14 | 0.04 | 0.02 | 0.08 | 0.15 | 0.03 | 0.02 |
| | STDV | 0.05 | 0.05 | 0.03 | 0.01 | 0.04 | 0.05 | 0.03 | 0.01 |

Table 24: Measured air velocity for Case 4.

| Date (Test #) | | 12 | | | | 13 | | | | 14 | | | | 15 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cubicle | | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 |
| 0.1 m | Minimum | - | 0.00 | 0.00 | 0.00 | - | 0.00 | 0.01 | 0.00 | - | 0.00 | 0.00 | 0.00 | - | 0.00 | 0.00 | 0.00 |
| | Maximum | - | 0.12 | 0.13 | **0.18** | - | 0.10 | 0.10 | 0.06 | - | 0.14 | 0.15 | **0.18** | - | 0.12 | 0.13 | 0.08 |
| | Mean | - | 0.02 | 0.05 | 0.02 | - | 0.03 | 0.04 | 0.02 | - | 0.04 | 0.05 | 0.02 | - | 0.03 | 0.05 | 0.02 |
| | STDV | - | 0.02 | 0.02 | 0.01 | - | 0.02 | 0.01 | 0.01 | - | 0.02 | 0.02 | 0.01 | - | 0.02 | 0.02 | 0.01 |
| 1.1 m | Minimum | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| | Maximum | **0.33** | 0.28 | 0.15 | 0.15 | 0.24 | 0.30 | 0.15 | 0.08 | 0.28 | 0.29 | 0.21 | 0.19 | 0.27 | 0.29 | 0.15 | 0.14 |
| | Mean | 0.06 | 0.15 | 0.04 | 0.01 | 0.04 | 0.14 | 0.04 | 0.00 | 0.04 | 0.13 | 0.04 | 0.01 | 0.05 | 0.15 | 0.04 | 0.01 |
| | STDV | 0.05 | 0.07 | 0.02 | 0.01 | 0.03 | 0.08 | 0.02 | 0.00 | 0.04 | 0.07 | 0.02 | 0.01 | 0.04 | 0.07 | 0.02 | 0.02 |
| 1.7 m | Minimum | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Maximum | **0.34** | 0.30 | 0.22 | 0.19 | 0.23 | 0.27 | 0.15 | 0.08 | 0.30 | 0.29 | 0.17 | 0.19 | 0.24 | 0.30 | 0.17 | 0.14 |
| | Mean | 0.07 | 0.12 | 0.04 | 0.01 | 0.04 | 0.11 | 0.03 | 0.01 | 0.06 | 0.11 | 0.03 | 0.01 | 0.06 | 0.13 | 0.03 | 0.01 |
| | STDV | 0.04 | 0.06 | 0.03 | 0.01 | 0.03 | 0.07 | 0.03 | 0.01 | 0.04 | 0.06 | 0.03 | 0.02 | 0.04 | 0.06 | 0.03 | 0.02 |

Table 25: Measured air velocity for Case 4.

| Date (Test #) | | 16 | | | | 17 | | | | 18 | | | | 19 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cubicle | | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 |
| 0.1 m | Minimum | - | 0.00 | 0.01 | 0.00 | - | 0.00 | 0.01 | 0.00 | - | 0.00 | 0.01 | 0.00 | - | 0.00 | 0.00 | 0.00 |
| | Maximum | - | 0.10 | 0.13 | 0.08 | - | 0.11 | 0.12 | 0.07 | - | 0.09 | 0.12 | 0.05 | - | 0.13 | **0.14** | 0.05 |
| | Mean | - | 0.04 | 0.06 | 0.02 | - | 0.03 | 0.05 | 0.02 | - | 0.03 | 0.05 | 0.02 | - | 0.03 | 0.05 | 0.02 |
| | STDV | - | 0.02 | 0.02 | 0.01 | - | 0.02 | 0.01 | 0.01 | - | 0.02 | 0.01 | 0.01 | - | 0.02 | 0.02 | 0.01 |
| 1.1 m | Minimum | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| | Maximum | 0.24 | 0.29 | 0.17 | 0.10 | 0.27 | **0.30** | 0.14 | 0.06 | 0.26 | 0.28 | 0.17 | 0.07 | 0.20 | 0.29 | 0.14 | 0.11 |
| | Mean | 0.05 | 0.16 | 0.04 | 0.01 | 0.04 | 0.18 | 0.04 | 0.01 | 0.05 | 0.18 | 0.05 | 0.01 | 0.04 | 0.15 | 0.04 | 0.01 |
| | STDV | 0.04 | 0.06 | 0.02 | 0.01 | 0.03 | 0.05 | 0.02 | 0.01 | 0.04 | 0.04 | 0.02 | 0.01 | 0.03 | 0.06 | 0.02 | 0.01 |
| 1.7 m | Minimum | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Maximum | 0.23 | 0.29 | 0.17 | 0.13 | 0.24 | **0.30** | 0.15 | 0.08 | 0.21 | 0.27 | 0.18 | 0.08 | 0.23 | **0.30** | 0.20 | 0.11 |
| | Mean | 0.06 | 0.14 | 0.03 | 0.01 | 0.06 | 0.16 | 0.03 | 0.01 | 0.06 | 0.15 | 0.04 | 0.01 | 0.05 | 0.13 | 0.03 | 0.01 |
| | STDV | 0.04 | 0.06 | 0.03 | 0.01 | 0.04 | 0.05 | 0.03 | 0.01 | 0.04 | 0.05 | 0.03 | 0.01 | 0.04 | 0.06 | 0.03 | 0.01 |

Table 26: Measured air velocity for Case 5.

| Date (Test #) | | 20 | | | | 21 | | | | 22 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cubicle | | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 |
| 0.1 m | Minimum | - | 0.00 | 0.00 | 0.00 | - | 0.00 | 0.00 | 0.00 | - | 0.00 | 0.00 | 0.00 |
| | Maximum | - | 0.09 | **0.18** | 0.05 | - | 0.10 | **0.18** | 0.07 | - | 0.09 | 0.11 | 0.06 |
| | Mean | - | 0.03 | 0.04 | 0.02 | - | 0.02 | 0.04 | 0.02 | - | 0.02 | 0.04 | 0.02 |
| | STDV | - | 0.02 | 0.02 | 0.01 | - | 0.02 | 0.02 | 0.01 | - | 0.02 | 0.02 | 0.01 |
| 1.1 m | Minimum | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| | Maximum | 0.23 | 0.27 | 0.14 | 0.05 | 0.24 | **0.29** | 0.16 | 0.07 | 0.23 | 0.28 | 0.15 | 0.11 |
| | Mean | 0.03 | 0.11 | 0.05 | 0.01 | 0.04 | 0.16 | 0.05 | 0.01 | 0.05 | 0.14 | 0.05 | 0.01 |
| | STDV | 0.03 | 0.06 | 0.02 | 0.01 | 0.03 | 0.05 | 0.02 | 0.01 | 0.04 | 0.06 | 0.02 | 0.01 |
| 1.7 m | Minimum | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Maximum | 0.25 | 0.27 | 0.15 | 0.10 | 0.23 | **0.30** | 0.23 | 0.18 | 0.25 | 0.28 | 0.19 | 0.18 |
| | Mean | 0.04 | 0.10 | 0.03 | 0.02 | 0.04 | 0.14 | 0.04 | 0.02 | 0.05 | 0.13 | 0.04 | 0.02 |
| | STDV | 0.03 | 0.06 | 0.02 | 0.01 | 0.03 | 0.05 | 0.03 | 0.02 | 0.04 | 0.06 | 0.03 | 0.02 |

Table 27: Measured air velocity for Case 6.

| Date (Test #) | | 23 | | | | 24 | | | | 25 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cubicle | | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 | 1 | 3 | 4 | 6 |
| 0.1 m | Minimum | - | 0.00 | 0.00 | 0.00 | - | 0.00 | 0.01 | 0.00 | - | 0.00 | 0.00 | 0.00 |
| | Maximum | - | **0.13** | **0.13** | 0.07 | - | 0.11 | 0.12 | 0.07 | - | 0.12 | **0.13** | 0.07 |
| | Mean | - | 0.04 | 0.06 | 0.02 | - | 0.03 | 0.06 | 0.03 | - | 0.04 | 0.05 | 0.02 |
| | STDV | - | 0.02 | 0.02 | 0.01 | - | 0.02 | 0.02 | 0.02 | - | 0.02 | 0.02 | 0.01 |
| 1.1 m | Minimum | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Maximum | 0.25 | **0.30** | 0.16 | 0.15 | 0.23 | 0.28 | 0.15 | 0.09 | 0.25 | 0.29 | 0.16 | 0.13 |
| | Mean | 0.05 | 0.14 | 0.05 | 0.02 | 0.06 | 0.15 | 0.05 | 0.01 | 0.04 | 0.14 | 0.04 | 0.02 |
| | STDV | 0.04 | 0.06 | 0.03 | 0.02 | 0.04 | 0.05 | 0.02 | 0.01 | 0.03 | 0.06 | 0.02 | 0.02 |
| 1.7 m | Minimum | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Maximum | 0.21 | 0.28 | 0.20 | 0.22 | 0.24 | **0.29** | 0.18 | 0.10 | 0.28 | **0.29** | 0.19 | 0.20 |
| | Mean | 0.05 | 0.11 | 0.04 | 0.02 | 0.08 | 0.11 | 0.04 | 0.01 | 0.05 | 0.11 | 0.03 | 0.02 |
| | STDV | 0.04 | 0.06 | 0.04 | 0.02 | 0.05 | 0.06 | 0.03 | 0.01 | 0.03 | 0.06 | 0.03 | 0.02 |

# 6 Discussion

Indoor air quality and thermal comfort are two of the leading factors in determining the success of a building's HVAC system performance. The design solution in the vast majority of commercial buildings has been to use an overhead air distribution system with 6" square diffusers that attempts to maintain close to uniform temperatures and ventilation air quality throughout the conditioned space.

This study investigated the performance of overhead ventilation systems using swirl high induction diffusers in heating season, and the comparison of these overhead systems with an overhead system using conventional square diffusers in terms of ACE and predicted thermal comfort (VATD and limit to air speed). The heating was achieved by an HVAC system functioning in a VAV mode, with supply air temperature 8°C above the room air temperature.

The ventilation performance of overhead (mixing) air distribution systems has been addressed by ASHRAE Standard 62.1-2016 through the air distribution effectiveness. Table 6.2.2.1 of ASHRAE Standard 62.1-2016 defines the minimum amount of outdoor air required ($V_{bz}$), to be delivered to the space (or zone) for controlling contaminant concentration. Table 6.2.2.2 of the standard defines zone air distribution effectiveness, $E_z$, for different air distribution configurations. The outdoor airflow required at the zone, through the supply diffusers, is determined as $V_{bz}$ divided by $E_z$. Thus, the zone air distribution effectiveness plays an important role in determining the required minimum amount of outside air for a space to achieve acceptable indoor air quality.

Overhead air distribution systems with ceiling supply of warm air 8°C above space temperature and ceiling return are assigned $E_z$ = 0.8 and when the systems are used with ceiling supply of warm air and floor return in heating mode, the $E_z$ increases to 1.0. It appears that these single $E_z$ values are not affected by type of diffusers (low, high induction, etc.). It is necessary in practice to develop a database containing $E_z$ values for various diffusers type.

The study included two overhead systems using swirl high induction diffusers and one overhead system using conventional diffusers as baseline to assess the ventilation performance of mixing systems. The supply air temperature was set at 32°C and room set point temperature was set at 24°C.

The ventilation effectiveness of mixing systems was assessed using ACE calculated based on the age air obtained from tracer gas measurements. The ACE was calculated for four workstations and two breathing heights. The overhead cases investigated in this study included (1) office space with six cubicles and 2 exterior (DN600) ceiling diffusers DAL 359; (2) same office space with two interior (DN500) ceiling diffusers DAL 359 and (3) same space with a combination of two exterior (DN600) and interior (DN500) swirl diffusers DAL 359; (4) same space with a combination of two exterior (DN600) and interior (DN500) swirl diffusers DAL 358, (5) same space with four conventional 6" square ceiling diffusers, (6) same space with two exterior (DN600) ceiling diffusers DAL 358..

This study identified significant improvement in ACE with swirl high induction diffusers, in comparison to conventional square diffusers and value assigned by ASHRAE Standard 62.1-2016. The results showed that the ACE achieved by the conventional square ceiling diffusers under the condition of air supplied to the space at 8°C above the room temperature set point was very close to 0.8. This value is same as the value assigned by ASHRAE standard 62.1-2016. This indicates that to achieve effective ventilation rate at the breathing zone would require increasing the minimum required rate of outdoor air supply by 25%.

Same space using swirl high induction diffusers DAL 359 and under same thermal conditions provided ACE with an average values very close to 1.0. The practical interpretation is that an ACE equal to 1.0 will achieve a perfect mixing throughout the indoor space without increasing by 25% the minimum required rate of outdoor air supply, leading to reduced energy consumption.

Same space, using swirl high induction diffusers DAL 358 and under same thermal conditions, provided higher ACE than 1.0, with average value of 1.1. This gives the potential to reduce the minimum required rate of outdoor air supply by (multiplied by 1/ACE) 9%. This means that with DAL 358 the rate of outdoor air supply could be reduced by 27%, resulting in significant energy saving.

This study has shown that one value of ACE could not be assigned to all types of overhead systems using different type of diffusers. This will avoid penalizing innovative advanced technologies. Swirl high induction downward ventilation airflow pattern obtained for overhead application in heating season provides air change effectiveness equal or higher than 1.0.

Even that the focus of this study was to performance of overhead ventilation systems using swirl high induction diffusers in term of air change effectiveness, we have looked at the predicted thermal comfort in terms of VATD and limit to air speed.

Thermal comfort is an important factor in determining the success of a building's air distribution system performance. Thermal stratification that results in the difference of air temperature between the head level being warmer and the ankle level may cause thermal discomfort. ASHRAE 55-2013 set the allowable vertical air temperature difference between head and ankles to 3K. Our study has shown that for all tested cases done with swirl high induction diffusers have shown similar results as the case with conventional square diffusers. The temperature differences between 0.1 m and 1.1 m (seated person) and between 0.1 m and 1.7 m (standing person) above the floor were lower than the limit of 3K.

Air velocity is one of the main factors affecting human thermal comfort, and a maximum limit on air speed has always been incorporated into thermal comfort standards. There are different opinions as to what air velocities create draught sensation for a person. Usually, 0.15 m/s or 0.20 m/s is utilized as an upper limit. We know that the sensitivity to draft increases when temperature decreases and the risk is higher for fluctuating velocities than for constant air velocities.

ASHRAE 55-2013 applies limits to air speed based on operative temperatures. For operative temperatures above 25.5°C, the upper limit to air speed is 0.8 m/s (allowing more air movement for warmer conditions) for light, primarily sedentary office activities. For operative temperatures between 22.5°C and 25.5°C, the allowable speed is recommended to follow the curve of an equal Standard Effective Temperature (SET) model curve. For operative temperatures below 22.5°C, the limit is 0.15 m/s (lower to 0.2 m/s set in previous ASHRAE 55-2005) in order to avoid local discomfort due to draft. Experiments conducted in this study for overhead system with swirl high induction diffusers has shown very few locations where the local air speeds exceeded the limit set by the equal Standard Effective Temperature (SET) model for operative temperature between 22.5°C and 25.5°C. In general the predicted thermal discomfort caused by air speed was not a significant issue for the overhead systems using the high induction diffusers in heating season.

# 7 Conclusions

Experimental investigations of overhead systems using high induction diffusers regarding the air change effectiveness (air distribution effectiveness) were performed in a real-sized experimental office space room.

In this study the space was conditioned by the ventilation system in a VAV mode. The ventilation effectiveness for the mixing ventilation systems was assessed using ACE as the IAQ index. The occupant comfort was assessed using the predicted thermal comfort indices: VATD and limit to air speed.

The Research Project A1-008521 "An evaluation the air distribution effectiveness of high induction diffusers" has drawn the following conclusions:

- The project identified improvement in ACE for overhead system with swirl high induction diffusers in heating mode, in comparison to values assigned by ASHRAE Standard 62.1-2016 (Table 6.2.2.2).
- In heating mode and with supply of warm air 8°C above room set point temperature, the simulated space with overhead system using swirl high induction diffusers DAL 359 achieved average air change effectiveness equal to 1.0.
- Same space simulated with an overhead system using swirl high induction diffusers DAL 358 provided higher air change effectiveness with average value of 1.1, identifying an opportunity to save energy by reducing the rate of outdoor air supply by 27%.
- Same space simulated with an overhead system using conventional square diffusers provided air change effectiveness close to 0.8, same value assigned by ASHRAE 62.1-2016 for overhead systems with ceiling supply of warm air and ceiling return.
- The predicted thermal comfort, in terms of vertical air temperature difference and limit to air speed obtained for overhead ventilation using swirl high induction diffusers under the test conditions were satisfactory.

The results of this investigation provide an evidence of energy and improved ventilation-related benefits of overhead systems using swirl high induction diffusers. This benefits need to be confirmed in other studies during cooling season.

## 8 Acknowledgments

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## 9 References

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ASHRAE Standard 62.1-2016, Ventilation for Acceptable Indoor Quality, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE Standard 55-2013 Thermal environmental conditions for human occupancy, American Society of Heating Refrigerating and Air Conditioning Engineers, Atlanta, GA.

ASHRAE Standard 113-2005 Method of testing for room air diffusion, American Society of Heating Refrigerating and Air Conditioning Engineers, Atlanta, GA, 6 p.

ASHRAE Standard 129 (1997-RA 2002) Measuring air change effectiveness, American Society of Heating Refrigerating and Air Conditioning Engineers, Atlanta, GA, 15 p.

# Appendix A – Air Temperature Distribution

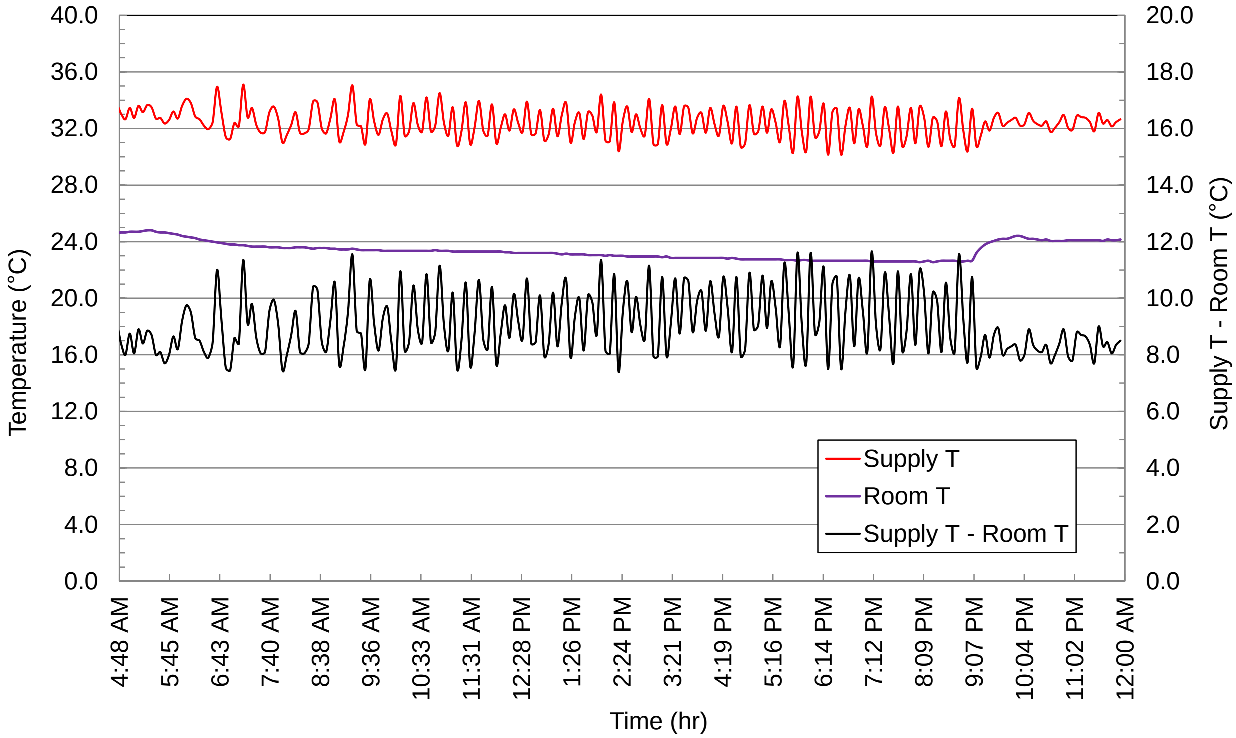


Figure 47: 03/03/2016

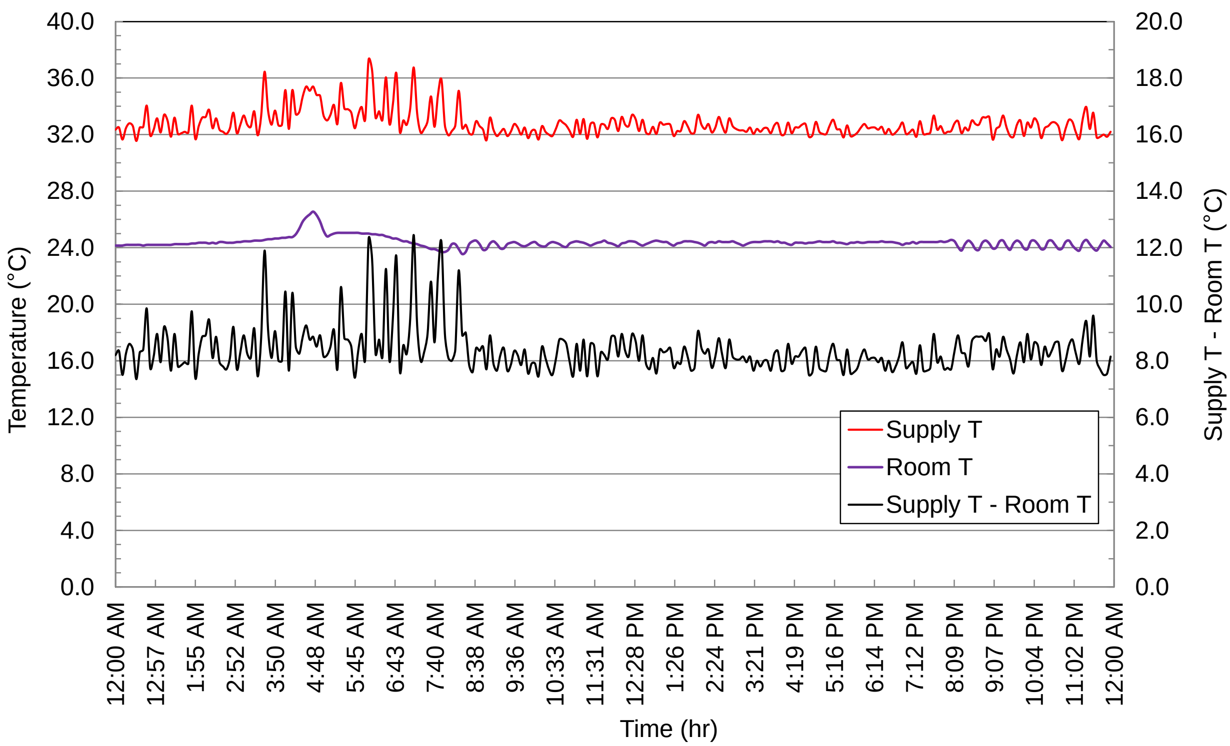


Figure 48: 04/03/2016

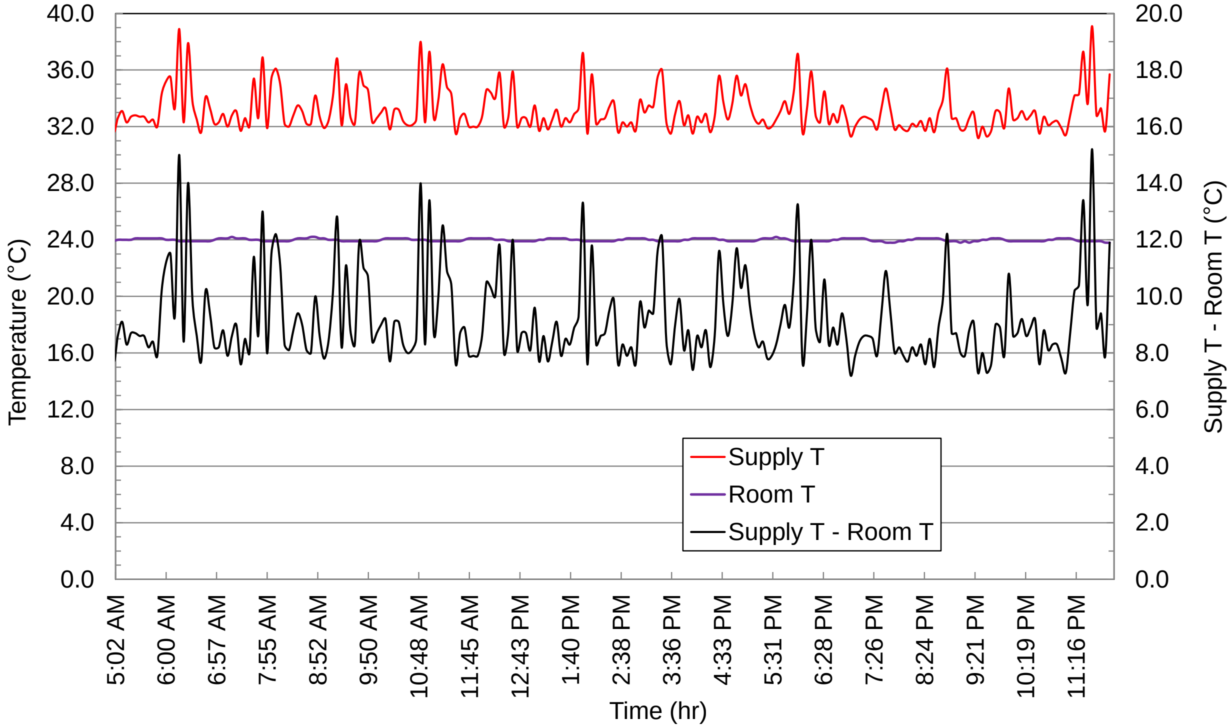


Figure 49: 10/03/2016

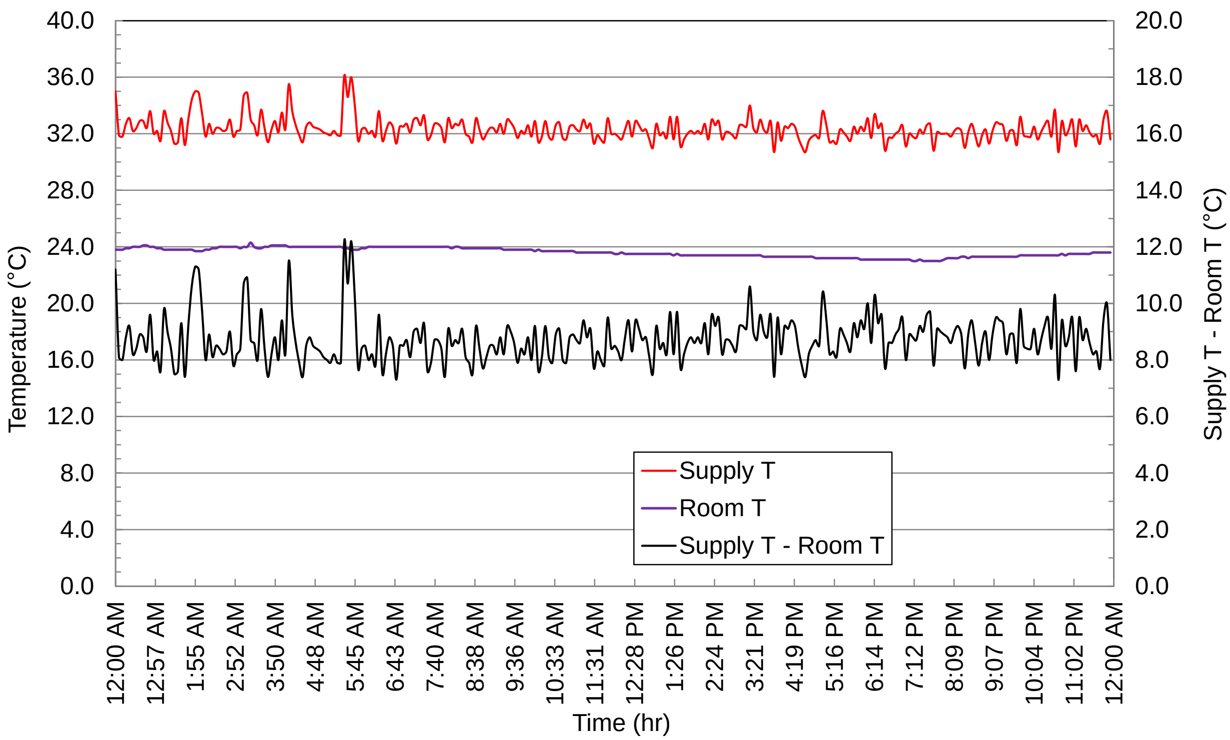


Figure 50: 11/03/2016

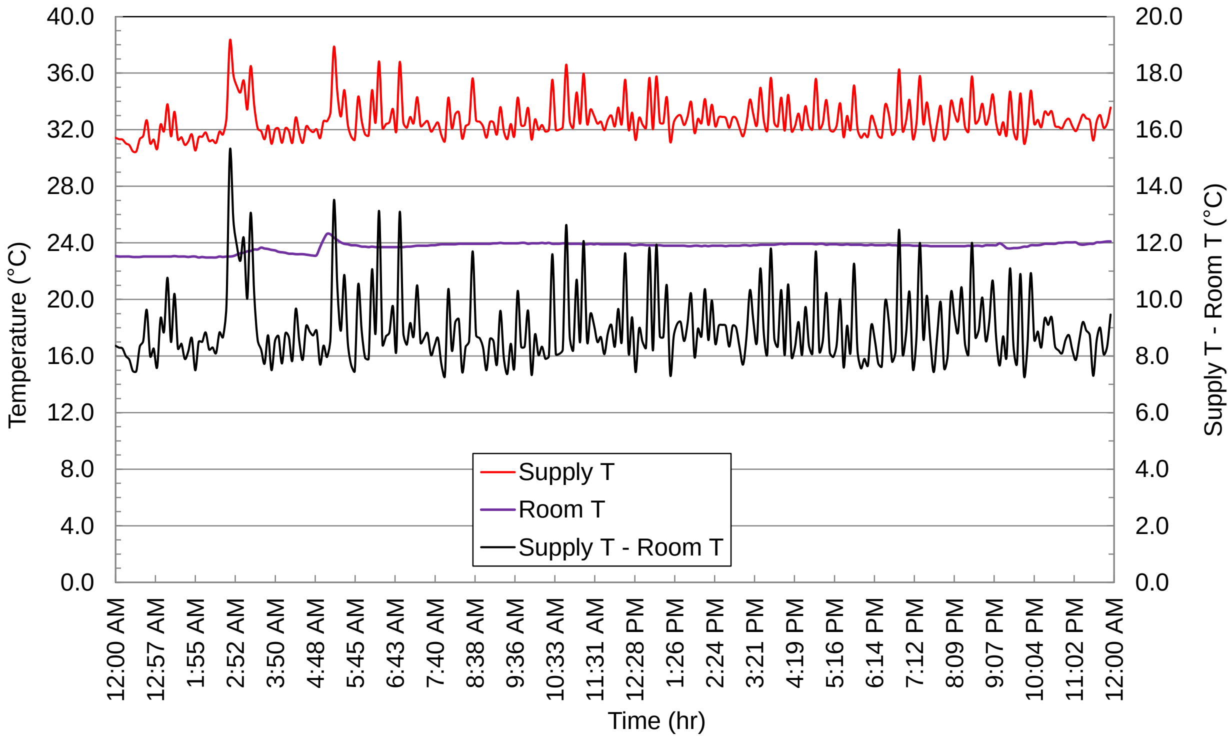


Figure 51: 23/03/2016

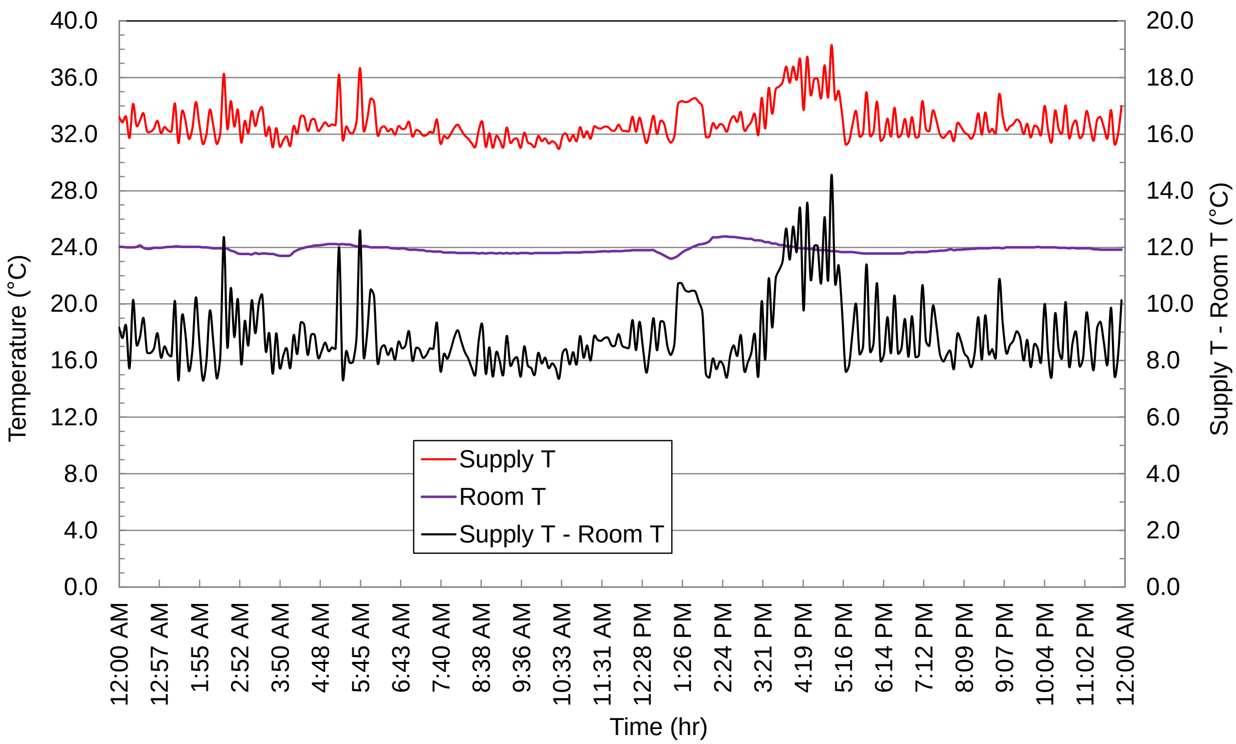


Figure 52: 25/03/2016

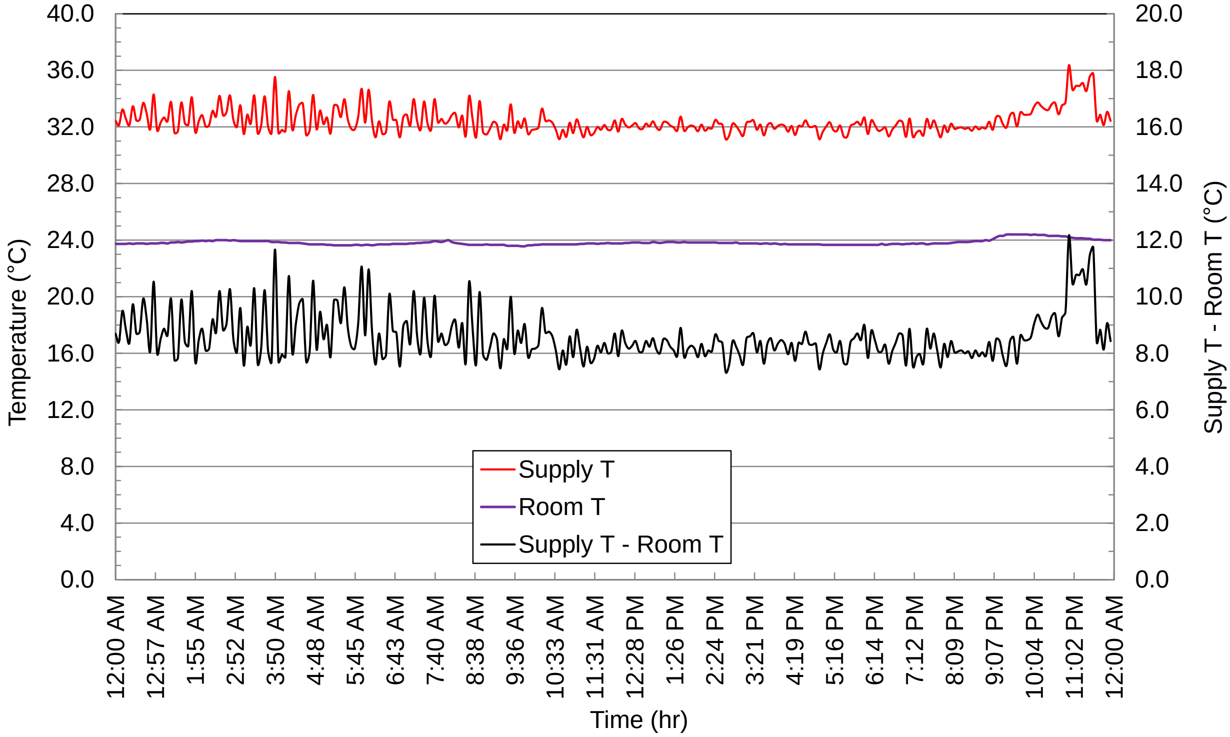


Figure 53: 26/03/2016

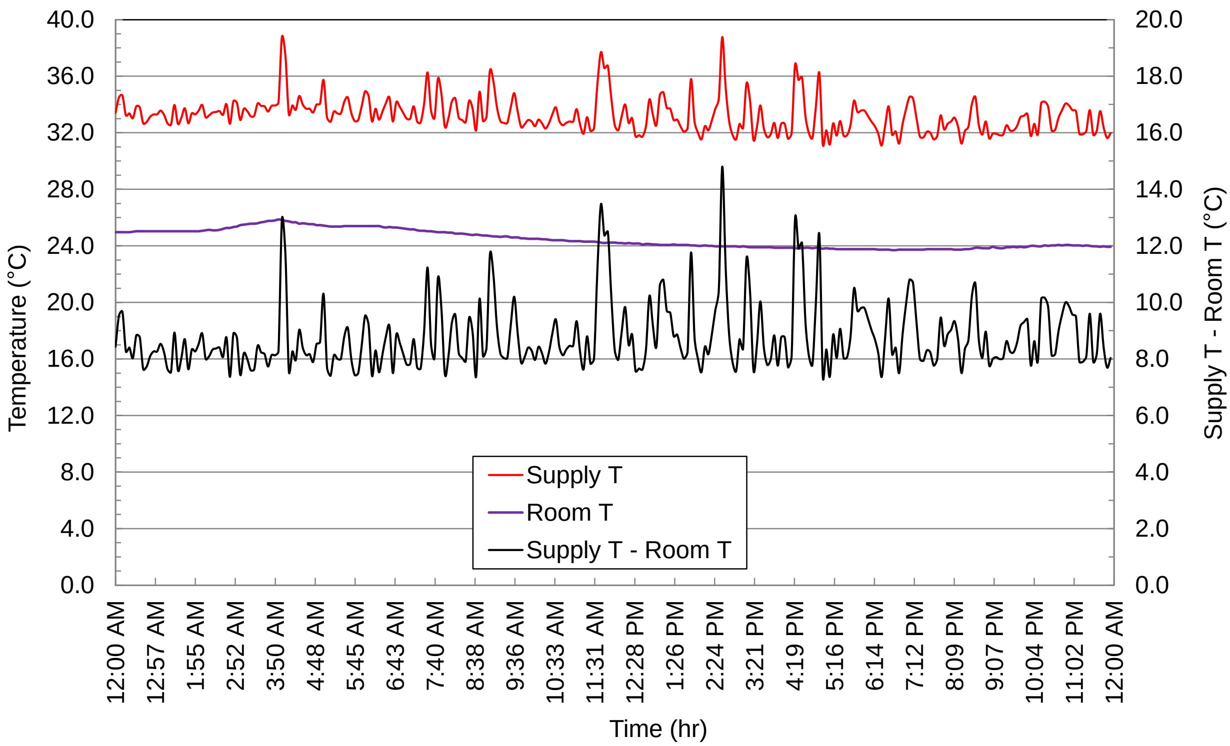


Figure 54: 02/04/2016

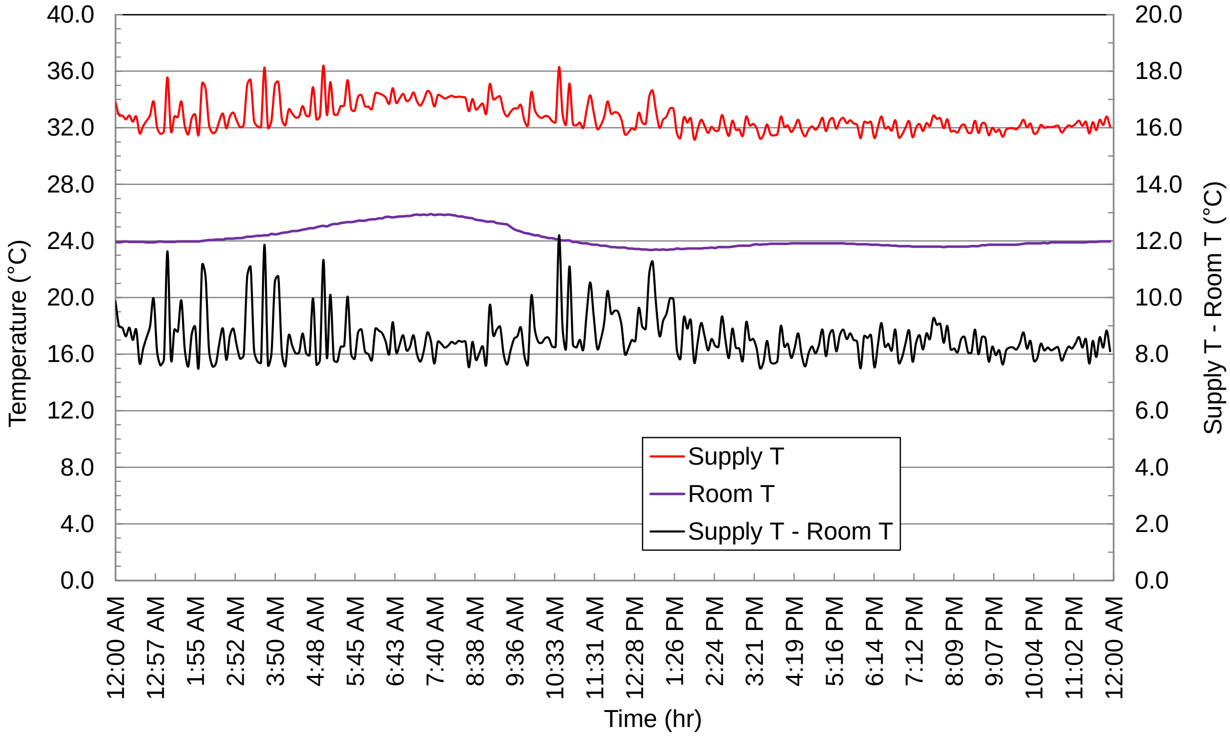


Figure 55: 03/04/2016

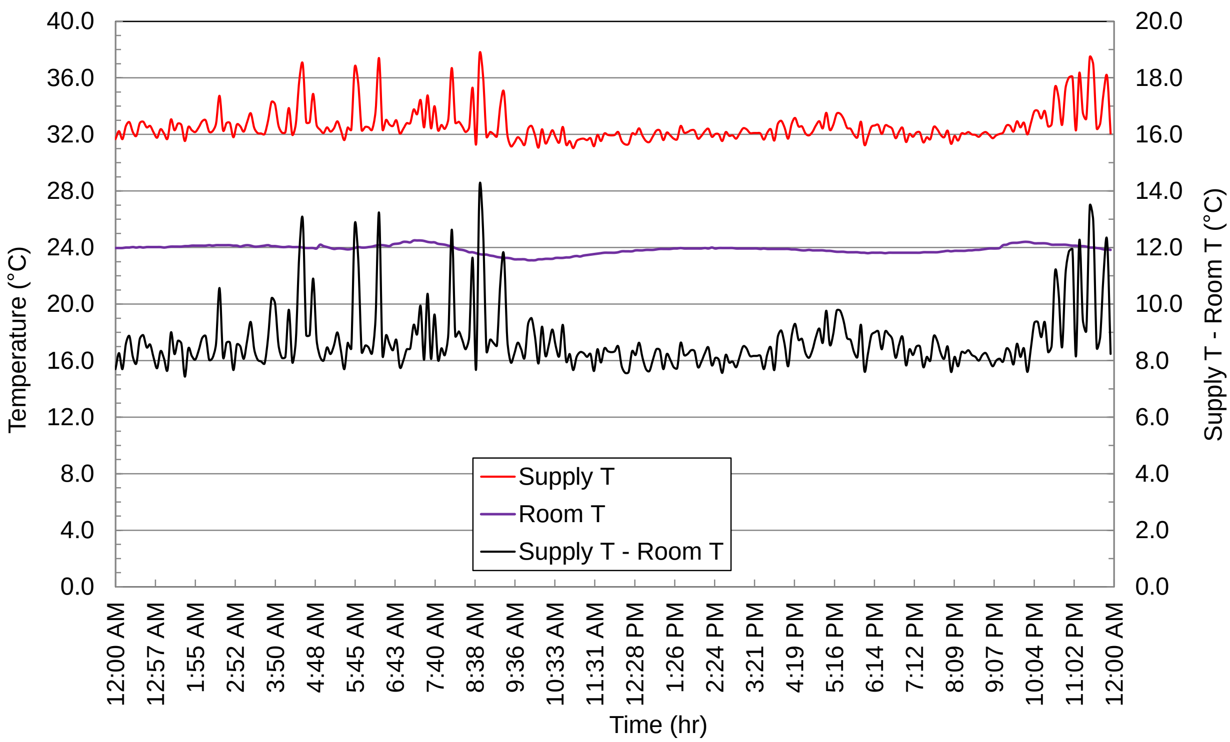


Figure 56: 04/04/2016

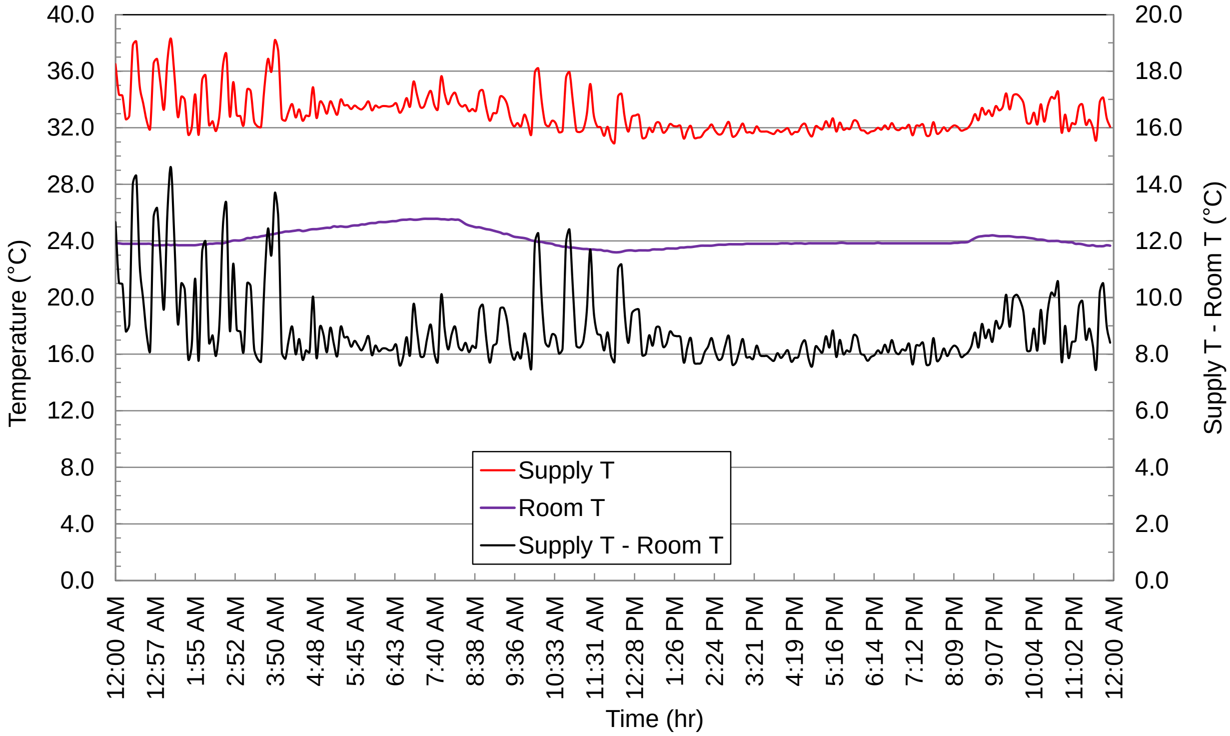


Figure 57: 05/04/2016

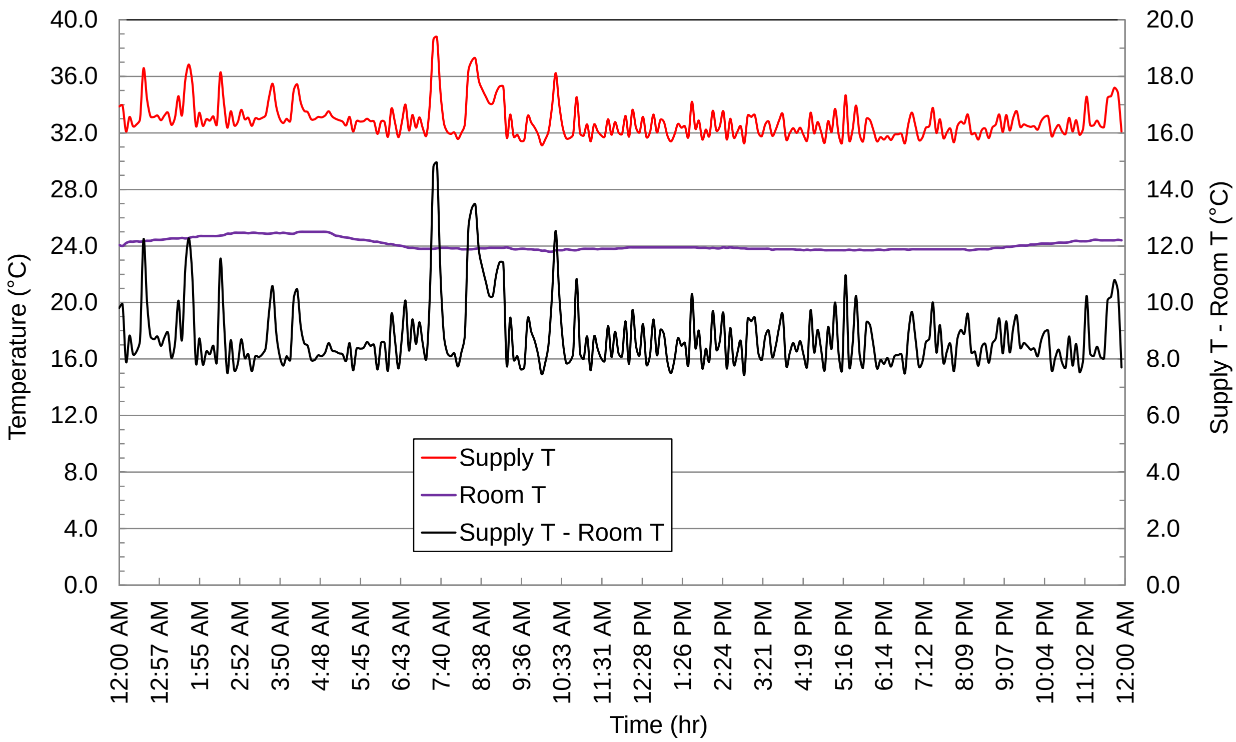


Figure 58: 08/04/2016

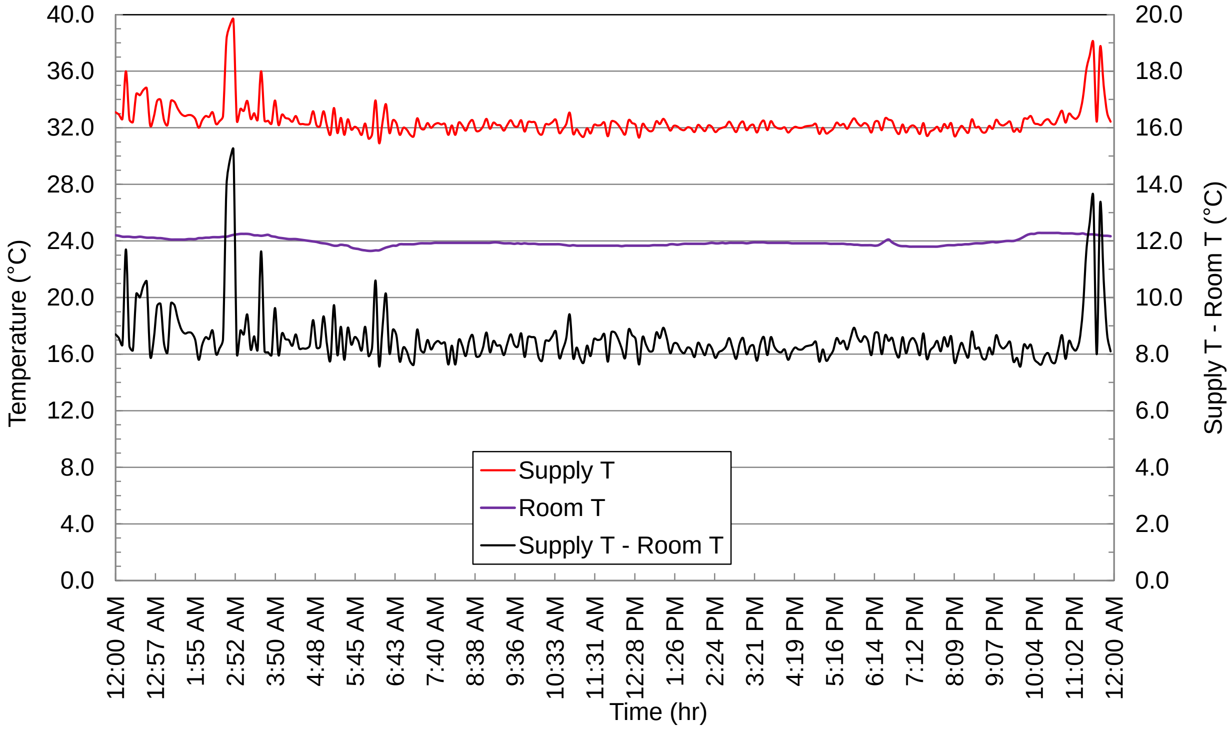


Figure 59: 09/04/2016

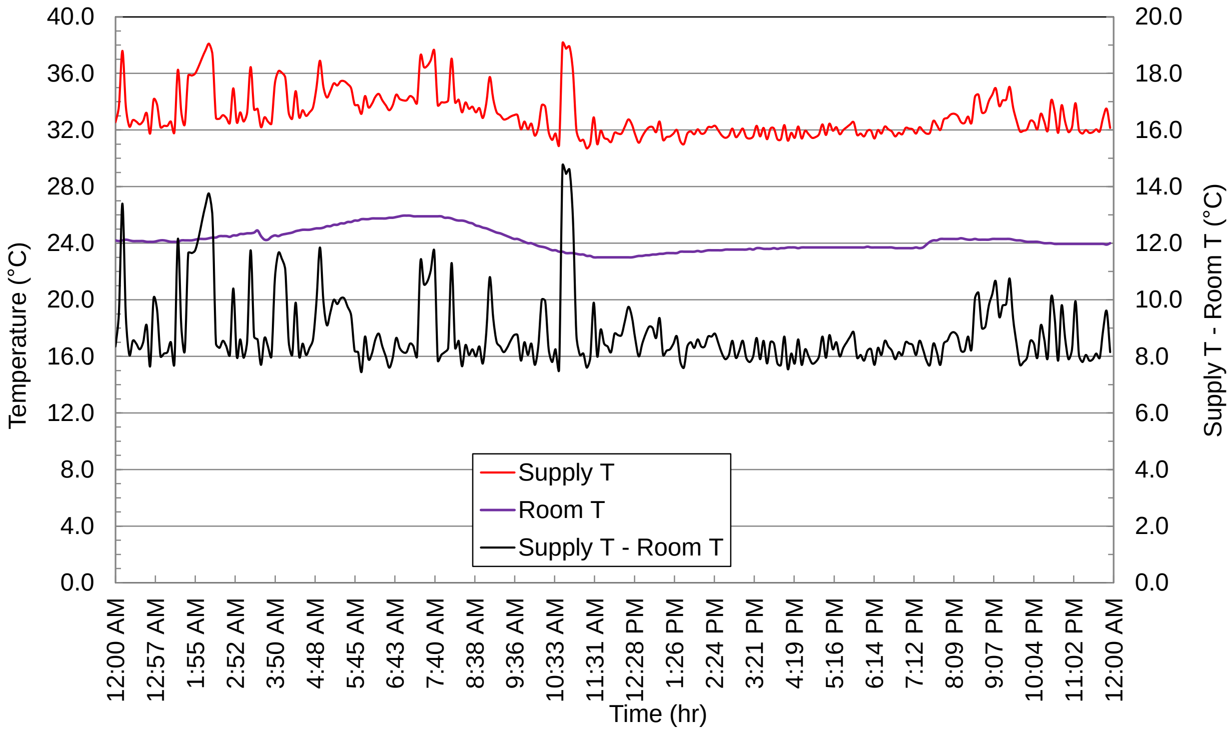


Figure 60: 10/04/2016