HEALTH CARE RESEARCH COLLABORATIVE

Healthcare Ventilation Research Collaborative: Displacement Ventilation Research

Phase II Summary Report

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Health Care Without Harm has initiated a research collaborative coordinated by faculty of the University of Illinois at Chicago School of Public Health, with support from the Pioneer Portfolio of the Robert Wood Johnson Foundation, aimed at stimulating collaborative research around health and safety improvements in health care. The Research Collaborative is designed to increase the evidence base concerning the impacts of sustainable design, construction, organization, operations, materials and chemicals in the health care sector on patient, worker and environmental safety.

This paper is the sixth in a series of papers in which the Collaborative provides research and analysis of factors influencing patient, worker and environmental safety and sustainability in the healthcare sector. The editors of this series are Peter Orris, MD, MPH and Susan Kaplan, JD.

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ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support and contributions of the following individuals and organizations:

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1. EXECUTIVE SUMMARY

Low sidewall displacement ventilation (DV) in hospital patient rooms appeared promising in healthcare applications as an HVAC application to reduce operating cost and first cost while providing improved environmental comfort, ventilation effectiveness, and infection control. Testing in 2006 and 2007 in vendor laboratories and in the field supported the hypothesis that low sidewall ventilation at two thirds the air flow of traditional mixing overhead ventilation (OHV) had equal or better performance in all areas. As with any change, practical questions arose from hospital design, operations and code enforcement agencies regarding DV. The questions precipitated a more formal research effort in 2008 to more rigorously test the findings from 2006 and 2007, and to create and validate a Computational Fluid Dynamics (CFD) design tool to respond to the questions that had been raised.

A formal research process was undertaken, including independent, highly qualified, empirical and numerical researchers and an independent advisory committee. Dr. Yan Chen of Purdue University was selected for empirical testing, and Dr. Weiran Xu and Dr. Andy Manning of Mentor Graphics (formerly Flomerics) were selected for numerical CFD modeling. The purpose of the research was to compare the performance of DV – at two thirds air flow – to a code-compliant OHV configuration, considering environmental comfort, ventilation effectiveness, and particle dispersion control (a surrogate for air borne pathogens). The empirical testing was used to validate the numerical model, so that the numerical model could then be used to evaluate performance under a variety of dynamic conditions that would be difficult to simulate in an empirical model.

In order to be acknowledged by regulating and standards bodies as an acceptable method of ventilation, the already accepted minimum overhead air flow rate of six air changes per hour (ACH) was used as the yardstick against which to measure the performance of DV.

This research effort focused on low-risk, single patient hospital rooms. The room configuration was modeled according to Kaiser Permanente's standard single-bed patient room with a bathroom on the exterior wall. The research concluded that DV at 4 ACH performed equally or better than OHV at 6 ACH for thermal comfort, ventilation effectiveness and contaminant concentration, and that the performance of DV is dependent on several integrated elements of the air delivery and room exhaust air system design. The study identified the following design issues that need to be carefully considered:

1. The cooling capacity of a DV system is limited by the minimum allowable supply air temperature required to maintain thermal comfort.
2. Room thermal gains and losses must be controlled if the performance of the DV system is to be maintained, i.e.:
   a. Facades should be designed to minimize the thermal gains and losses to prevent warm and cold surfaces, especially with respect to glazing. The warm surfaces could affect the DV air flow.
   b. Manual or automatic solar shading devices should be installed to minimize/ eliminate direct solar gains. The field tests showed that floor surfaces warmed up by direct solar gains can act as a thermal hot spot, creating localized thermal chimneys, and causing most of the displacement supply air to short circuit the breathing level.
   c. Lighting and medical equipment loads should be minimized.

3. DV should not be used for space heating, i.e.:
    a. Providing supply air from the low sidewall displacement diffuser at a higher temperature than the room's temperature will result in decreased performance of the DV system.
    b. When using a supplemental heating method such as radiant or convective baseboard heating, the performance of the DV can be maintained, if not improved.
4. The placement of the supply air diffuser is not critical, but should be coordinated with the room design. The diffuser should be located at low level in a location that will not be blocked with solid furniture such as a storage cabinet.
5. The toilet transfer grille should be located at high level. The empirical experiments showed that the DV effect/ pluming/ high level removal of air borne particles can be seriously affected if the supply air is allowed to short circuit at low level, directly into the toilet room.

2. BACKGROUND

2.1 History

2.1.1 Context

Healthcare facilities are one of the most difficult types of buildings to "green". Given their purpose in service of vulnerable populations, they are regulated more heavily than any other building type. They must function first and foremost in a capacity that ensures quality of patient care and occupant (caregivers, visitors, and patients) safety, and as such, infection control cannot be compromised by the need or the means to reduce energy.

Conversely, healthcare facilities offer a unique opportunity for incorporating sustainable strategies that simultaneously improve the healing environment and reduce the environmental impact. Healthcare facilities rank as the second highest building type for energy-density, so the corresponding potential to reduce energy use is significant. Alternate ventilation methods such as displacement ventilation (DV) have proven in other types of facilities (such as schools, office buildings, and areas of assembly) to improve indoor environmental quality and thermal comfort with reduced energy consumption compared to traditional mixing overhead ventilation (OHV) systems.

The thermal and ventilation effectiveness performance of DV has been well documented. The issue that differentiates healthcare ventilation from other building types is airborne infection control. While there are studies that have considered airborne particle movement with DV, none (to the best of the authors' knowledge) has done a side by side comparison of DV to OHV considering environmental comfort, ventilation effectiveness, and particle control all together.

2.1.2 Phase I and the Healthcare Ventilation Research Collaborative

The Healthcare Ventilation Research Collaborative (HVRC) was formed in 2006 by two healthcare engineering design companies (Stantec and Mazzetti Nash Lipsey Burch) to consolidate the efforts of several organizations toward the common goal of promoting improved patient and staff safety and sustainable design in healthcare facilities through the implementation of innovative engineering concepts that have been thoroughly and scientifically documented. The HVRC represents a group of industry professionals including healthcare providers, infection control experts, architects, engineers, equipment manufacturers, and affiliated professionals. The current roster of the HVRC is listed in the Acknowledgements.

In Phase I, research was conducted to assess both natural ventilation and DV in exam rooms, patient rooms and emergency waiting rooms. Research methods included laboratory mockups (at the E.H. Price laboratory in Winnipeg, Canada), field testing, and computational fluid dynamics (CFD) analysis. Testing focused on environmental comfort per ASHRAE Standard 55, ventilation effectiveness per ASHRAE Standard 62, and particle dispersion per a test designed by Andrew Streifel, MPH, Hospital Environment Specialist at the University of Minnesota.

Phase I results indicated that DV at 4 ACH in a patient room provides better particle dispersal, ventilation effectiveness, and environmental comfort than OHV at 6 ACH. However, more stringent test procedures were needed to demonstrate conclusive results.

Dr. Farhad Memarzadeh, of the National Institutes of Health, recommended a detailed follow-up effort be performed, under the guidance of an independent advisory committee, with a double blind comparison between an empirical and numerical test. A key purpose of the empirical testing would be to validate a numerical model and facilitate its use for evaluating multiple room and system design configurations in a more practical and feasible manner than continued physical testing. Contained herein are the results of this follow up Phase II research.

2.2 System Comparison: Displacement Ventilation vs. Overhead Ventilation

Conventional OHV systems generally supply air in a manner such that the air in the entire room is fully mixed. In cooling mode, the cool supply air, typically around 55°F at design conditions, exits the outlet at high velocity and induces room air to mix and equalize temperature. Because the entire room is essentially fully mixed, temperature variations are small while the contaminant concentration is fairly uniform throughout the room.

DV systems, on the other hand, introduce air at low velocities and at low level to specifically avoid induction and mixing. Such systems utilize natural buoyancy and convective forces (created by heat sources such as people, lighting, equipment, etc.) to move contaminants and heat from the occupied zone to the return or exhaust grilles above.

Cool air (cooler than the room air) is supplied at low velocity into the lower zone and pools across the floor because it is more 'dense' or less buoyant than the room air. Convection from heat sources then draws the air vertically into the upper zone where high level return openings extract the air. In most cases, these convection heat sources are also the contamination sources (people, equipment, etc.), thereby bringing the contaminants directly to the upper portion of the room, away from the occupants. In doing so, the air quality in the occupied zone is generally considered superior to that achieved with mixing room air distribution, and the thermal loads in the occupied zone are less than the entire room volume. ASHRAE's System Performance Evaluation and Design Guidelines for Displacement Ventilation[3] describes how thermal loads can be discounted when using DV.

Since the conditioned air is supplied directly into the occupied space, the supply air temperatures must be higher than mixing systems to avoid overly cool temperatures at the floor. By introducing the air at higher supply air temperatures and lower outlet velocities than OHV systems, a high level of thermal comfort can be achieved with DV.

The energy benefits for DV come from the fact that air is supplied at a higher temperature than with OHV systems, and much of the thermal cooling load in the space does not come into the occupied zone but is drawn through natural buoyancy and convection directly to the upper unoccupied zone without mixing. This results in higher return air temperatures and lower air flow rates, which contribute to a reduced mechanical cooling and ventilation plant size and energy consumption.

Because it relies on more passive forces for its effectiveness, DV can be a less robust system than OHV. As such, an integrated design approach is generally recommended to optimize its performance. The key parameters affecting DV performance are investigated in this study.

2.3 Code Considerations

In the United States, healthcare facility design requirements, including their HVAC systems, are governed on a state-by-state basis. Most states utilize the Guidelines for Design and Construction of Health Care Facilities published by the Facilities Guidelines Institute (FGI) as the basis of their regulations. Ventilation requirements for hospitals and outpatient facilities are covered in Table 2.1-2 of the Guidelines (2006 Edition), prescribing space-pressure relationships, minimum air exchange rates (for both total and OSA), exhaust requirements, and temperature and humidity controls.

Extensive footnotes to Table 2.1-2 provide clarifications and exceptions to these requirements. For example, the Table requires minimums of 6 air changes total and 2 outside air (OSA) changes for patient rooms, and minimums of 12 air changes total and 2 OSA changes for emergency waiting rooms, but Footnote 10 allows the minimum total air changes in a patient room to drop to 4 if using supplemental heating and/or cooling. So, technically, the Guidelines allow DV as low as 4 ACH in a patient room with supplemental heating and/or cooling. However, while most state regulations include a version of Table 2.1-2, the extent to which the footnotes are adopted varies widely.

The Health Guidelines Revision Committee (HGRC), in conjunction with the Facility Guidelines Institute, updates the Guidelines every three years.

ASHRAE had also recently developed *Standard 170: Ventilation of Healthcare Facilities*, which defines ventilation system requirements for healthcare facilities. Rather than have parallel guidelines for ventilation requirements for healthcare facilities, the HGRC elected to adopt Standard 170 to replace Table 2.1-2 in the *Guidelines* for the 2010 Edition.

3 Chen, Qingyan and Leon Glicksman. System Performance Evaluation and Design Guidelines for Displacement Ventilation. ASHRAE: 2003.

3. HYPOTHESIS

The HVRC initiated this research to determine if low sidewall DV can maintain or improve airborne pathogen removal from patient rooms at equal or lower air change rates than those currently required using conventional OHV, while maintaining or improving patient and staff comfort, and reducing energy use and environmental degradation. If the hypothesis is proven, the results will prompt revisions to codes and standards for healthcare design and construction.

4. APPROACH

The HVRC initiated the formation of an Advisory Committee in 2007 to serve as an independent party to guide the research and evaluate the results. The Advisory Committee roster is included as Appendix 7.2.

The research consisted of two independent blind components: empirical analysis and numerical analysis. Researchers for each component were selected with the guidance of the Advisory Committee based on their general experience, qualifications, and capability to meet the requirements of a detailed test protocol.

The empirical research analyzed environmental comfort and particle dispersion for a single-bed hospital patient room (with a bathroom), comparing an OHV system at 6 ACH (current accepted minimum) to low sidewall DV at 4 ACH.

In addition, the empirical OHV and DV tests were compared to a numerical computational fluid dynamic (CFD) simulation for the purposes of validation. The blind, independent test results were submitted to the HVRC for a statistical correlation evaluation.

Following validation, the numerical model was used to test a number of key parameters, including outdoor conditions, supply air temperatures, grille and diffuser layouts, and supplemental heating and cooling.

Additional empirical and numerical testing was performed to evaluate the effects of coughing and movement.

4.1 Empirical Analysis

Dr. Qingyan (Yan) Chen of Purdue University conducted the empirical analysis. An environmental chamber was created to simulate a one-person patient room, in which the patient could breathe or cough out contaminants. The complete results of the empirical study are included in Appendix 7.3. An overview of the research follows below.

4.1.1 Objective

The objectives of the empirical analysis were to:

- Develop a testing configuration to compare the performance of a conventional OHV system with a low sidewall DV system at lower airflow rates;
- Collect measurements to be used for establishing boundary conditions for the numerical model; and
- Provide high quality output results to facilitate validation of the numerical model.

A secondary objective was to determine at an early stage of the experimental process whether a tracer gas (SF_6) could be used to simulate contaminants breathed or coughed out by a patient, since tracer gases are much simpler to model than actual particles.

4.1.2 Experimental Setup

The empirical validation tests were done at room envelope conditions as close to adiabatic as practically possible, with boundary conditions carefully measured and supplied to the numerical analysis team so that the same surface temperatures, room loads, and air flow rates could be used for both models. Comparison measurements included temperature, velocity, and tracer gas (SF6) concentrations.

The patient room set up was based on a Kaiser Template Hospital single-bed patient room. Figures 1 through 4 show the initial configuration and measurement locations.

Figure 1:
Initial configuration
of the patient room

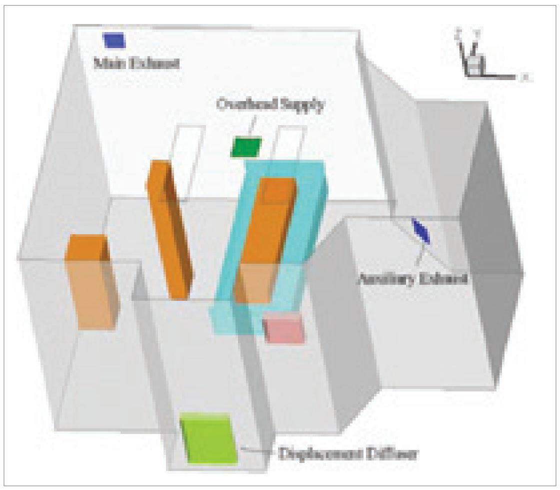


Figure 3:
Photo of patient, bed,
and caretaker

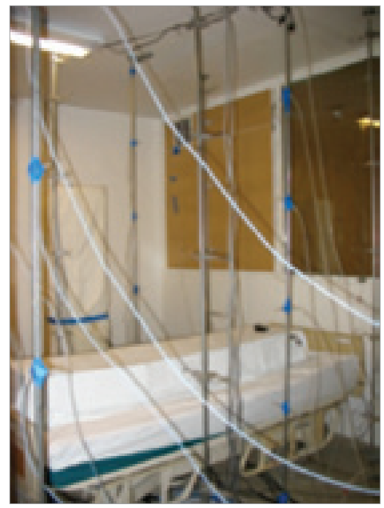


Figure 2:
Dimensions of the patient room

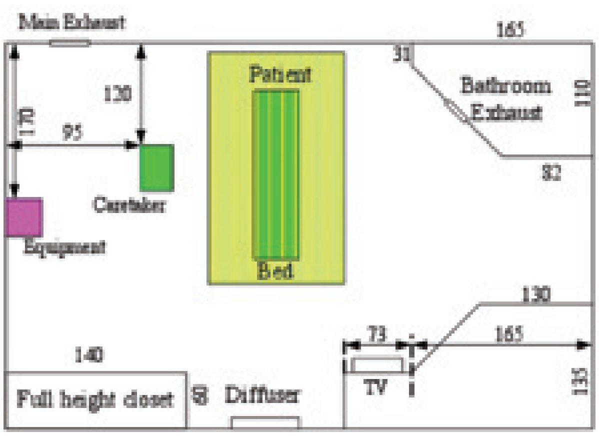
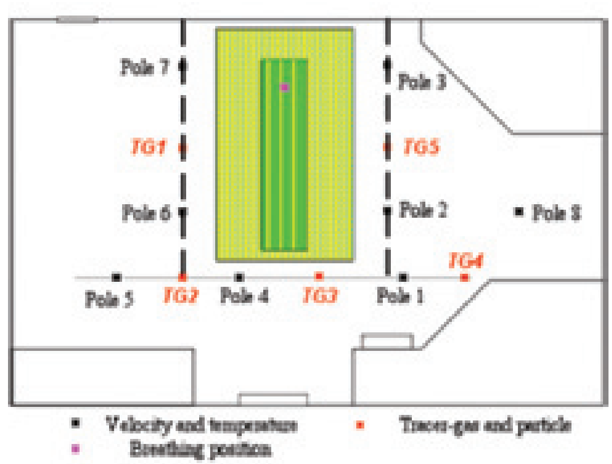


Figure 4:
Measurement locations: Poles 1-8 for air velocity and temperature and TGs 1-5 for tracer gas or particles



The patient room included the following elements:

a. Patient (thermal manikin) lying on bed – breathing zone at 1.1m above floor is the contaminant source; patient assumed to be contaminant source

b. Caretaker (thermal manikin) standing at bedside – breathing zone at 1.7m above floor; one of the critical points for measuring contaminant concentration

c. For the OHV configuration: overhead ceiling diffuser centered above bed

d. For the DV configuration: low sidewall supply diffuser against wall opposite foot of bed

e. For both DV and OHV: main room exhaust high on headwall – near interior wall

f. For both DV and OHV: transfer grille to bathroom – initially low in toilet door, then moved to high wall above bathroom door

g. Interior loads: Equipment on interior wall, TV on wall opposite bed, lights on ceiling

h. Temperature and velocity measurements: eight pole locations at seven elevations each, for a total of 56 points

i. Tracer gas/Particle concentration measurements: five pole locations, four around bed and one near exterior window, representing locations of people in room, at seven elevations, for a total of 30 points

The empirical testing consisted of eight cases designed to test OHV vs. DV systems. The cases are summarized in Table 1 below.

4.1.3 Testing and Validation

Multiple test cases were run in the lab. Cases looked at an OHV system at 6 ACH, and low sidewall DV at both 4 and 6 ACH. Tests were performed for both tracer gas (SF6) and 1 micron and 3 micron particles to evaluate the acceptability of using of tracer gas as a surrogate for particles. Initial testing demonstrated poor performance of the DV system when the transfer grille between the patient room and the toilet was located at low level. Further tests were run with a high transfer grille which showed a significant improvement of the DV system. Subsequent tests were performed with the high transfer grille location. Two (2) base cases were established (cases 1 and 2 in Table 1) to be used for validation of the numerical model. Even with significant efforts to create adiabatic room envelope conditions, heat transfer cannot be totally eliminated in the physical world. As such, it was critical to measure airflow characteristics and the rate of heat transfer on all surfaces of the room to establish boundary conditions for the numerical testing team. Each case was run three times to verify the repeatability of the data.

Table 1: Empirical Cases for Validation

Cases	ROOM CONDITIONS			Contaminant source
	Ventilation	Bathroom exhaust grille	Flow rate (ACH)	
1	Overhead Supply	Low level	6	SF_6
2	Sidewall Displacement	Low level	4	SF_6
3	Overhead Supply	High level	6	SF_6
4	Sidewall Displacement	High level	4	SF_6
5	Sidewall Displacement	Low level	6	SF_6
6	Sidewall Displacement	High level	6	SF_6
7	Sidewall Displacement	High level	4	1 µm particles
8	Sidewall Displacement	High level	4	3 µm particles

Empirical testing produced two primary outputs: measured test output data for temperature, velocity, and tracer gas concentration, as well as boundary conditions for defining the numerical base case analysis. Boundary conditions included the following:

a. Room dimensions

b. Grille locations

c. Airflows

d. Data measuring point dimensions

e. Interior loads and locations, including thermal manikins

f. Wall heat transfer data

g. Supply diffuser velocity profiles

The empirical test output data were kept blind to the numerical modelers.

4.2 Initial Numerical Modeling and Validation

Dr. Andy Manning and his associate, Dr. Weiran Xu, with Mentor Graphics (previously Flomerix), conducted the numerical modeling research. Complete results of the numerical research are included in Appendix 7.4. An overview of the research follows below.

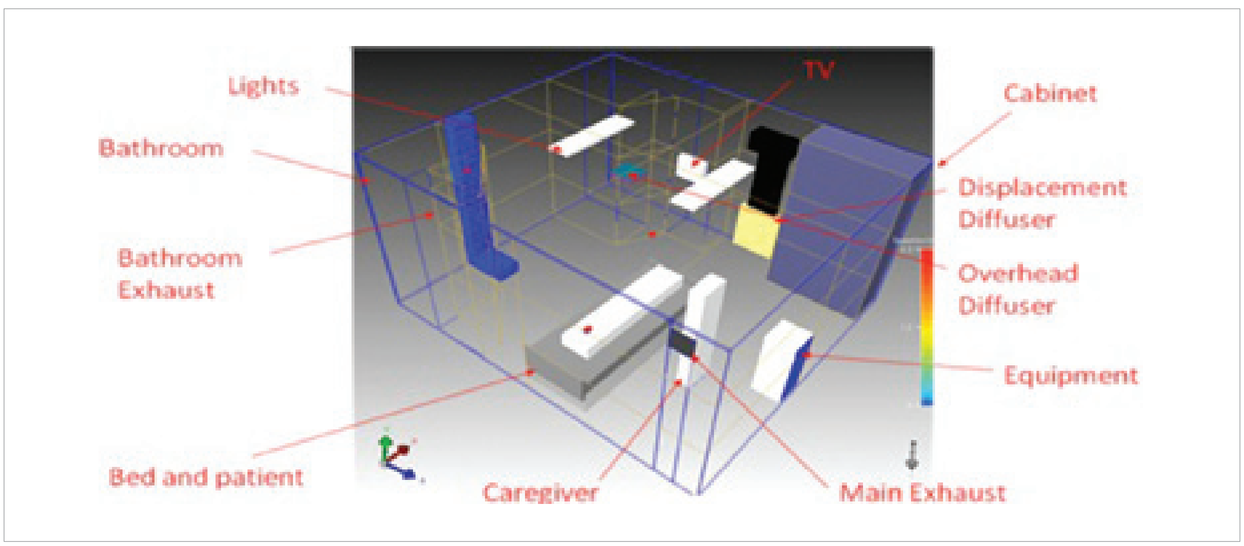
4.2.1 Objectives

The objective of the initial numerical analysis was to validate the numerical model from the empirical results. Once validated, the numerical model could be used to evaluate a range of variables applied to DV and OHV.

4.2.2 Modeling Setup

The numerical model was set up to match the empirical model, based on boundary data provided. Figure 5 shows the model set up.

Figure 5: Initial numerical model setup



C O L O R   F I G U R E S

Figure 6:
Summer Base Case Normalized
Contaminant Concentration:
Whole Room

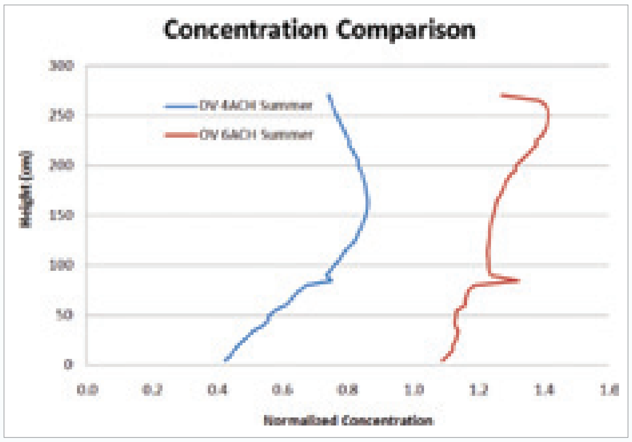


Figure 7:
Summer Base Case Normalized
Contaminant Concentration:
At Caregiver Height

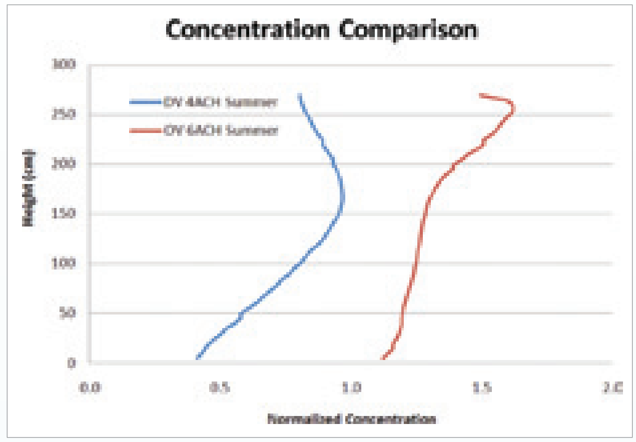


Figure 8:
Summer Base Case: 3ppm Iso-Surface
for DV at 4 ACH

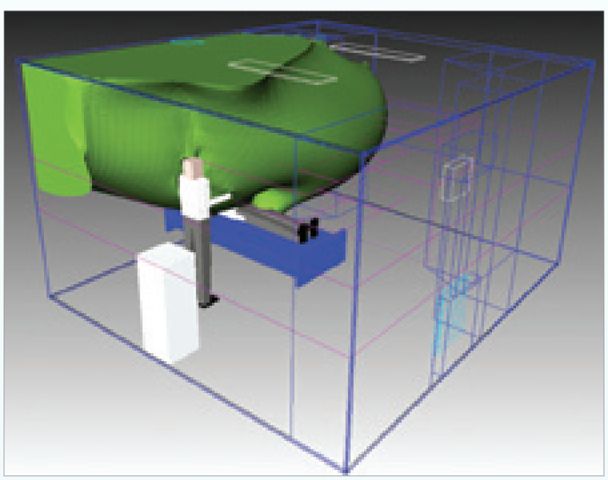


Figure 9:
Summer Base Case: 3ppm Iso-Surface
for OHV at 6 ACH

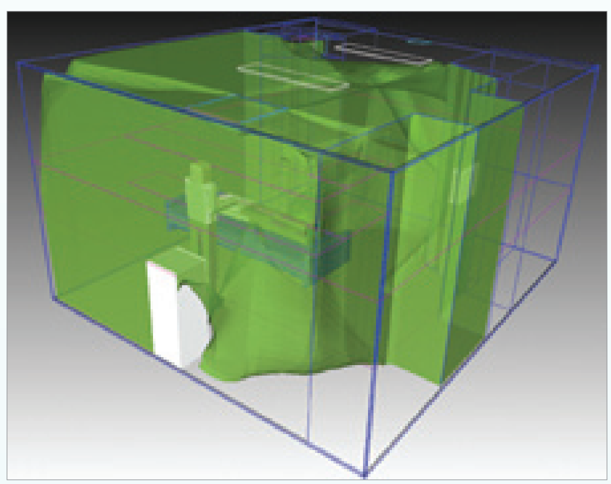


Figure 10:
Temperature profile for DV at 4 ACH

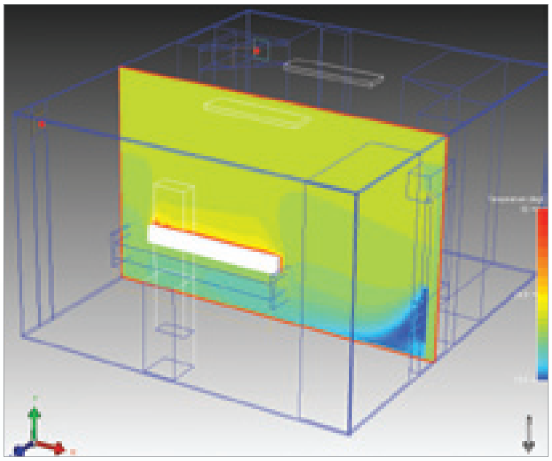


Figure 11:
Velocity profile for DV at 4 ACH

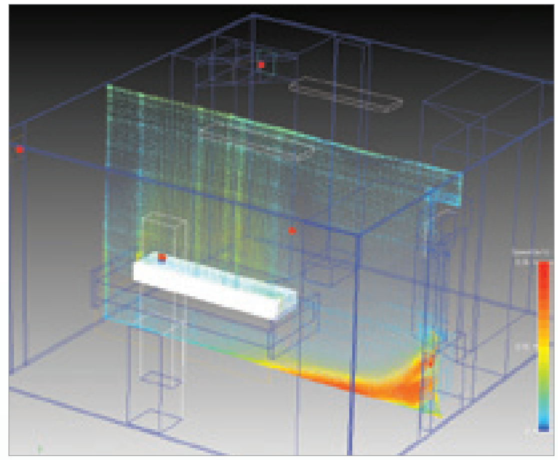


Figure 12:
Temperature profile for OHV at 6 ACH

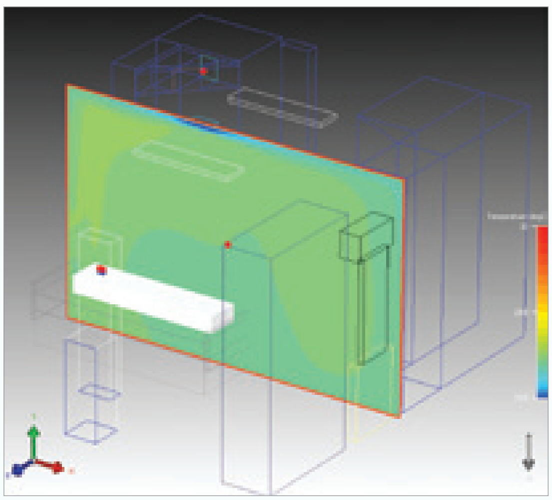


Figure 13:
Velocity profile for OHV at 6 ACH

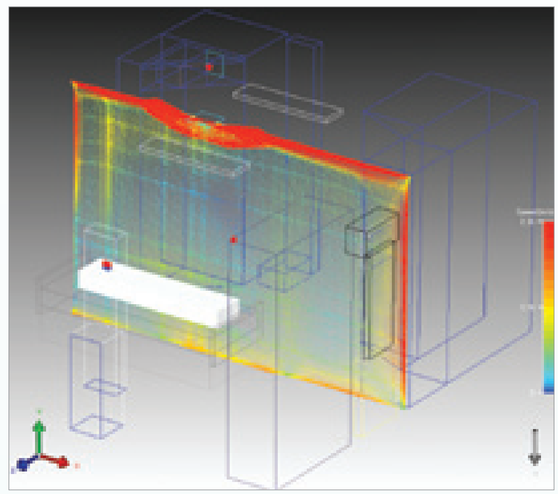


Figure 14:
3ppm Iso-Surface for DV at 4 ACH

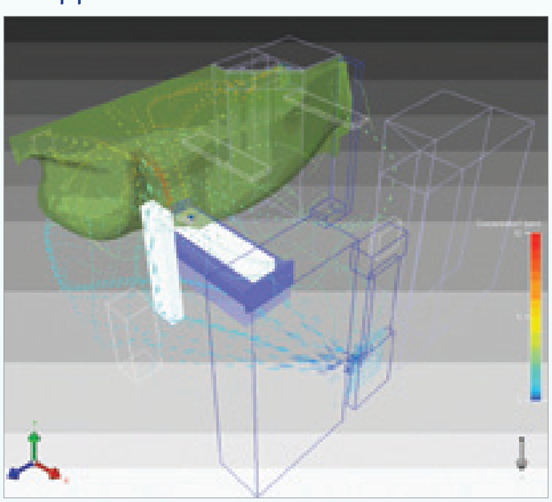


Figure 15:
3ppm Iso-Surface for OHV at 6 ACH

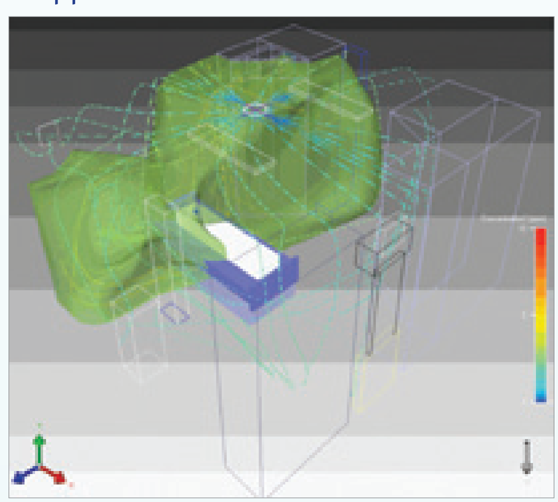


Figure 16:
DV with Warmer Temperature Supply

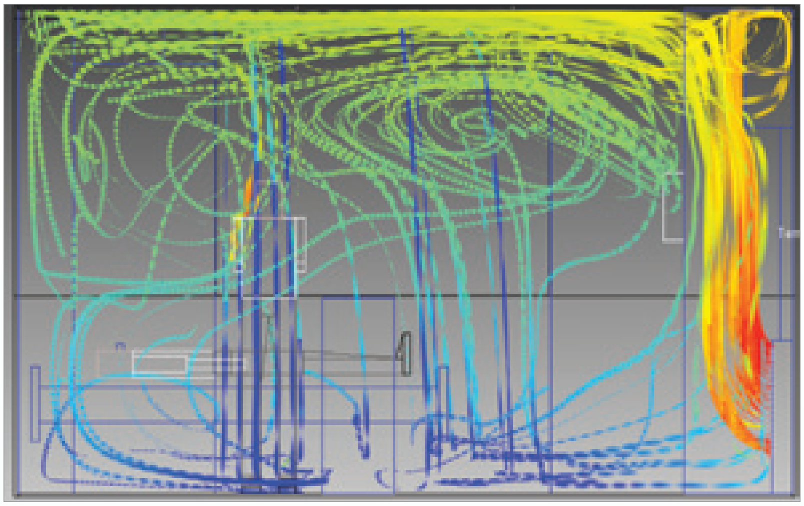


Figure 17:
3ppm Iso-Surface for DV at 4 ACH with
High Supply Air Temperature

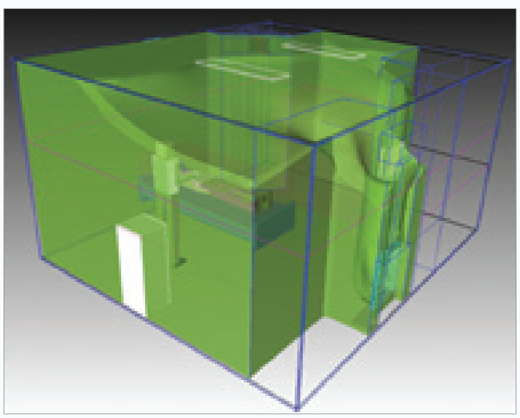


Figure 18:
3ppm Iso-Surface for DV at 4 ACH with
Radiant Heating Panels

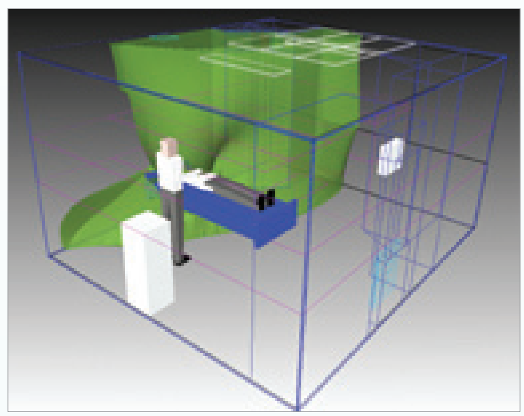


Figure 19:
3ppm Iso-Surface for DV at 4 ACH with
Baseboard Heating

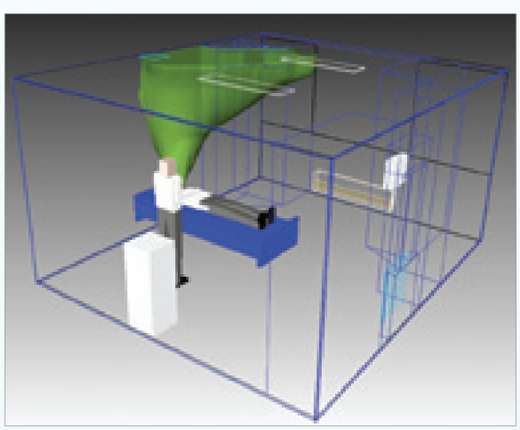


Figure 20:
Normalized tracer gas concentration profiles (comparison of low and high level auxiliary exhaust with 4 ACH and 6 ACH respectively)

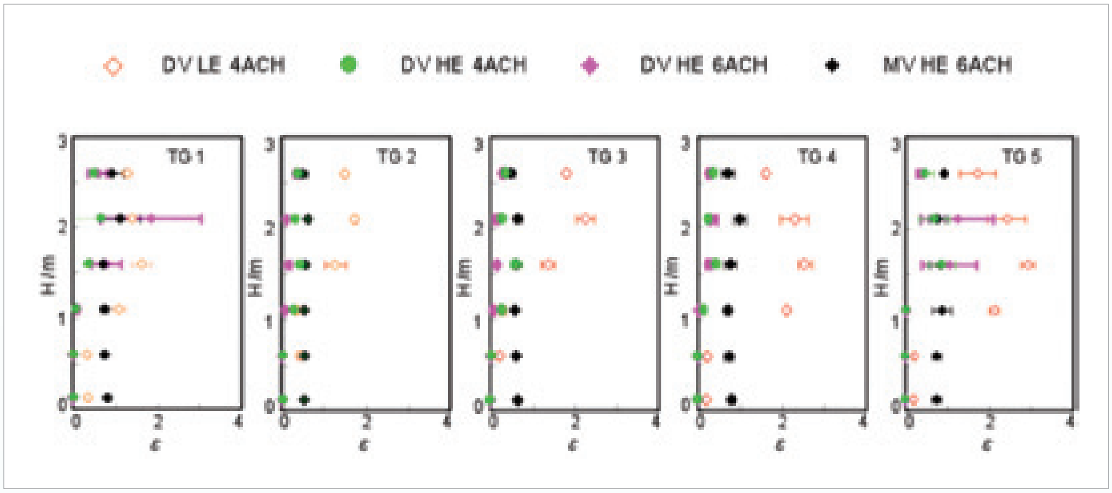


Figure 21:
3ppm Iso-Surface for OHV at 6 ACH

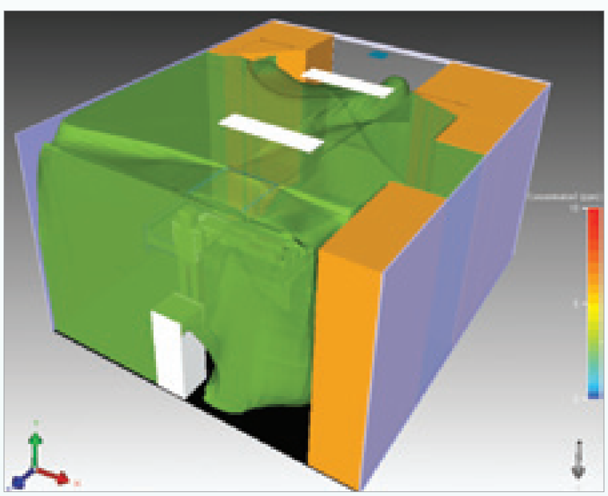
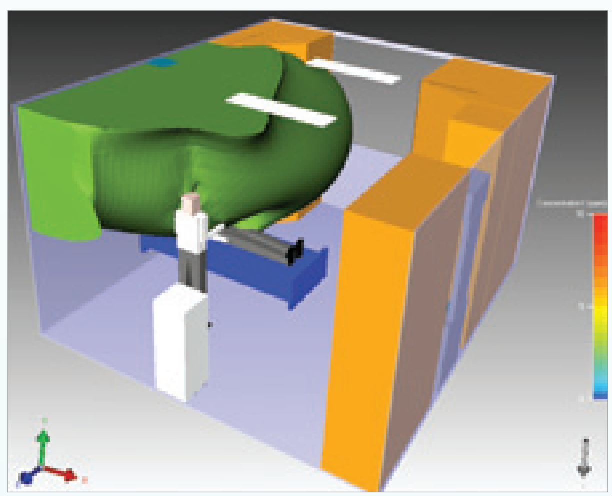


Figure 22:
3ppm Iso-Surface for DV at 4 ACH



4.2.3 Testing and Validation

Numerical validation testing was conducted to create data for comparison to the empirical study, using the boundary conditions (wall temperatures, room geometry, room loads, and airflow values) from the empirical analysis. Two base cases were used for validation of the numerical model: one for an OHV system at 6 ACH and one for a DV system at 4 ACH.

An early subset of the research was to construct a patient breathing model that simulated the effect of real breathing and was consistent with empirical testing. The purpose of this analysis was to evaluate whether the numerical simulations should be performed assuming a constant rate of exhalation (constant breathing) or actual breathing (inhalation and exhalation). The result of the analysis was that "constant breathing" would accurately represent the rate of particle release of actual breathing. Appendix 7.4 includes a summary of the testing and verification of a "constant breathing" numerical model that assisted in subsequent modeling.

The validation period was extended due to many iterative runs to fine tune the boundary conditions, of which heat transfer through the envelope and velocity profiles from the supply diffusers proved most challenging. The boundary conditions were refined to the point of good correlation of numerical to empirical data.

Figures 6-9 on page 13 (and Figures 12-16 in Appendix 7.4 available in the online version) show the comparison.

4.2.4 Statistical Comparison

An independent statistical comparison of the empirical and numerical data was conducted by Dr. Farhad Memarzadeh, to determine the level of agreement between the empirical and numerical models and confirm that the numerical model could serve as an appropriate representation of the empirical test. Appendix 7.5 includes the complete statistical comparison.

The results between the two models demonstrated acceptable agreement, particularly in terms of trending of the outputs in the breathing zone, allowing for extended use of the developed numerical model for more complex testing and comparison of DV and OHV.

4.3 Parametric Numerical Testing

After the numerical model was validated, Dr. Manning and Dr. Xu set up numerical (CFD) models that varied a number of key parameters to test the research initiative's central hypothesis.

4.3.1 Objectives

The overall objective of this research project – and of this portion of the project - was to study and compare the performance of OHV and DV systems in a single-bed hospital patient room. The distinct emphasis of a patient room ventilation system is the ability to remove contaminants while maintaining acceptable thermal comfort, and the parametric numerical testing was designed to evaluate these parallel goals.

4.3.2 Metrics

Two main sets of metrics were established to compare performance, as follows:

a. Thermal Comfort

   There are three standard measures for determination of the suitability of an environment for human occupation:

   - Fanger's comfort equations for Percentage Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). PMV and PPD were empirically derived from human responses to test conditions, in which individuals reported their level of comfort from very cold to very hot. The indices were then developed to describe a set of room conditions in terms of the percentage of occupants who are likely to be dissatisfied with those conditions. These indices do not account for the discomfort experienced when moving from one region to another with different conditions (the Air Distribution Performance Index described below addresses movement effects).

- Comfort (Resultant) Temperature. The thermal comfort of a room depends, to a significant degree, on the radiative exchange between the occupants and their surroundings. The concept of mean radiant temperature is used to describe this radiative exchange, and is dependent upon the surface temperature of the surroundings. The resultant temperature, by extension, describes the combined effect of mean radiant temperature, air temperature, and velocity.
- Air Diffusion Performance Index (ADPI). ADPI is a parameter that measures the uniformity of the space in terms of the proportion of the volume with a velocity lower than 0.35 m s^{-1} (70 ft min^{-1}) and draft temperature between -1.7 °C and +1.1 °C from the mean temperature. Uniformity is normally considered good in the occupied region of a mixed flow design if the ADPI for that region exceeds 80%. Although this measure was designed for establishing whether cooling jets from mixed flow ventilation systems are well dissipated, this measure can be cautiously applied to determine the general uniformity of other environments.

PPD was chosen as the only thermal comfort index for this study since it is the one most widely used and understood.

b. Ventilation Effectiveness/Contaminant Removal

There are two main categories of indices to measure the contaminant control capability of ventilation systems:

- Ventilation Effectiveness, or the ability of a ventilation system to remove internally generated pollutants from a building, zone, or space. Ventilation Effectiveness (as defined by ASHRAE 62.1) is calculated for the caregiver, visitor, and whole room. A further refinement of Ventilation Effectiveness is the Personal Exposure Index, which reflects the contaminant concentration at the exact breathing location of the caregiver, versus simply the contaminant concentration at the general breathing zone.
- Air Change Effectiveness, or the ability of a ventilation system to distribute ventilation air to a building, zone, or space. Air Change Effectiveness is defined by ASHRAE Standard 129-1997. A refinement of Air Change Effectiveness is "Air Distribution Effectiveness", which specifically addresses displacement cooling systems and is currently under consideration by ASHRAE.

Four indices were thus used to evaluate the results from a contaminant removal perspective:

- Ventilation Effectiveness
- Personal Exposure Index
- Air Change Effectiveness
- Air Distribution Effectiveness

4.3.3 Testing

In order to systematically investigate the characteristics of DV and OHV systems, a series of cases were developed to test (using CFD modeling) the following parameters:

- Impact of hot summer conditions (including solar gain)
- Impact of supplemental cooling
- Impact of varying supply air temperatures
- Impact of cold winter conditions
- Impact of supplemental heating
- Impact of air diffuser and grille locations
- Impact of ceiling height
- Impact of movement on DV
- Impact of coughing on DV

Table 2 summarizes the cases.

Table 2: Parametric Numerical Cases

#	Description/ Purpose	Ventilation Type	Main Return	Weather	Load	ACH	Supply Temp (degF)	Additional Cooling/ Heating
1	DV Limit with Solar Load	Displacement	Above Patient	Summer LA 105F	Standard	4	Adjustable, 60F low limit	No
2	Overhead	Overhead	Close to Window	Winter Chicago -10F	Reduced	6	Adjustable, up to 105F	No
3	DV with Radiant Heating Panel	Displacement	Above Patient	Winter Chicago -10F	Reduced	4	67.1	Radiant Heating
4	DV with Baseboard Heater	Displacement	Above Patient	Winter Chicago -10F	Patient, Caregiver only	4	67.1	Baseboard Heater
5	Overhead 4ACH	Overhead	Close to Window	Summer LA 105F	Standard	4	Adjustable, 55F low limit	No
6	Overhead 4ACH	Overhead	Close to Window	Winter Chicago -10F	Patient, Caregiver only	4	Adjustable, up to 105F	No
7	DV at 4 ACH - w Radiant Cooling Panel	Displacement	Above Patient	Summer LA 105F	Standard	4	67.1	Radiant Cooling
8	Overhead 6 ACH in Summer	Overhead	Close to Window	Summer LA 105F	Standard	6	Adjustable, 55F low limit	No
9	DV 4 ACH w Solar Loading	Displacement	Above Patient	Summer Reduced Temp 97F	Standard	4	60	No
10	DV 4 ACH w High Supply Temperature	Displacement	Above Patient	Winter Chicago -10F	Patient, Caregiver only	4	87F	No
11	DV 4 ACH w 12' Ceiling Height	Displacement	Side wall above Patient	Summer LA 105F	Standard	4	60F	No
12	DV 4 ACH w 12' Ceiling Height	Displacement	Above Patient on the ceiling	Summer LA 105F	Standard	4	60F	No

Standard Load = Load from Patient, Caregiver, TV, Equipment. Reduced Load: Patient, Caregiver only

5. KEY FINDINGS

The key findings of the Phase II research are summarized in this section. Complete results are detailed in individual research papers, referred to throughout this document and included as Appendices.

5.1 Empirical Testing Results

In the course of establishing a robust set of boundary conditions for the numerical model, the empirical testing yielded interim results that informed the final set up of the patient room that was then used for complex numerical testing.

The three key results of the empirical testing were as follows:

a. DV did not perform well when the transfer grille to the toilet room was located at low level. With more than half of the supply air transferred via the toilet room, supply air was short circuited reducing the DV effectiveness in the room. When the transfer grille was located at high level, DV performance significantly improved, even at a reduced air change rate.

b. SF_6 tracer gas was a valid surrogate for 1 and 3 micron airborne particles.

c. With the high toilet transfer grille, DV at 4 ACH performed equally or better than OHV at 6 ACH for environmental comfort, ventilation effectiveness, and tracer gas concentration.

5.2 Parametric Testing Results

The numerical testing results for the base cases showed that DV at 4 ACH performed equally or better than OHV at 6 ACH for thermal comfort, ventilation effectiveness, and contaminant concentration.

The base case results are illustrated in the figures 10-13 (see page 14).

The modelers developed a visual concept to display areas of constant contaminant concentration within the patient room. Figures 14 and 15 (see page 14) show through the use of an iso-surface, the extent to which contaminants spread in the DV and OHV scenarios. As the iso-surface demonstrates, the DV airflow pattern results in a more contained contaminant concentration at high level.

The numerical modeling was also used to test more complex parameters beyond the scope of the base cases used for validation. The results for these tests are summarized in Table 3.

Table 3: Summary of Parametric Study Results

#	Description /Purpose	PPD Patient Area Visitor Area	VE for caregiver at 1.1m 1.7m	VE for visitor at 1.1m 1.7m	VE Whole room at 1.1m 1.7m	PEI	ADE	ACE
#	Description /Purpose	PPD Patient Area Visitor Area	VE for caregiver at 1.1m 1.7m	VE for visitor at 1.1m 1.7m	VE Whole room at 1.1m 1.7m	PEI	ADE	ACE
1	DV Limit with Solar Load	8.61 8.91	1.22 1.05	1.45 1.38	1.31 1.18	1.36	1.62	0.95 0.91
2	Overhead	7.06 21.1	0.99 0.87	1.12 1.09	1.04 1.00	1.07	N/A	0.84 0.82
3	DV with Radiant Heating Panel	5.89 9.84	1.67 1.48	1.39 1.37	1.71 1.63	1.89	N/A	1.60 1.18
4	DV with Baseboard Heater	7.05 8.37	3.24 2.58	2.53 2.37	3.07 2.61	3.26	N/A	0.85 0.71
5	Overhead 4 ACH	5.9 6.64	0.97 0.80	1.19 1.19	1.01 0.90	0.99	N/A	0.92 0.91
6	Overhead 4 ACH	5.75 14.99	1.03 0.94	1.09 1.08	1.06 1.03	1.10	N/A	0.75 0.74
7	DV at 4 ACH - w Radiant Cooling Panel	12.53 11.57	1.65 1.35	1.91 1.60	1.77 1.53	1.94	1.81	1.08 1.28
8	Overhead 6 ACH in Summer	8.17 8.74	0.80 0.76	0.94 0.94	0.81 0.79	0.84	N/A	0.79 0.80
9	DV 4 ACH w Solar Loading	9.3 13.18	1.25 1.06	1.57 1.51	1.35 1.20	1.45	1.62	0.87 0.84
10	DV 4 ACH w High Supply Temperature	5.8 12.33	0.90 0.90	0.94 0.98	0.94 0.98	0.97	N/A	0.75 0.85
11	DV 4 ACH w 12′ Ceiling Height	8.25 8.5	1.23 1.06	1.45 1.38	1.31 1.19	1.39	1.62	0.83 0.80
12	DV 4 ACH w 12′ Ceiling Height	7.19 7.86	1.14 0.99	1.26 1.16	1.19 1.08	1.30	1.84	0.97 0.93

See section Summary of Metrics for definition of PPD, VE, PEI, and ACE.

5.2.1 Impact of Hot Summer Conditions and Supplemental Cooling

The metric PPD (Percentage of People Dissatisfied), described in section 4.3.2 above, determines the thermal comfort of a space based on temperature and draft components. PPD indicates the percentage of people that would be uncomfortable given the air temperature and velocity conditions. ASHRAE Standard 55 indicates that values of 20 or less are acceptable, meaning that the air temperature and velocity would be acceptable for more than 80% of occupants.

The standard further states that for non-mixing systems, such as DV, air temperature stratification should not exceed 3.6°F for seated occupants and 5.4°F for standing occupants to ensure thermal comfort.

The summer base case results are summarized in Table 3, Cases 1 and 8. The baseline supply air temperature was set at 67°F with an assumed maximum temperature at 44 inches above the floor of 73°F. The results for increasing solar gains are reflected in Cases 1 and 9.

The room air temperature and thermal comfort were significantly affected by the increase in direct solar gains with a fixed supply air temperature, while the cooling capacity of DV was limited by the acceptable supply air temperature.

The DV system's ventilation effectiveness was reduced by direct solar gain. However, thermal comfort proved to be the limiting factor, meaning that, as long as thermal comfort is maintained, ventilation effectiveness requirements will be met. Thus, the room's direct solar heat gains should not exceed levels that compromise thermal comfort.

Although the thermal comfort was maintained in Cases 1 and 9, the 5.4°F air temperature stratification requirement was not satisfied due to the required low supply air temperature of 60°F to achieve that level of thermal comfort. Thus, a supplemental cooling strategy, such as is used in Case 7 (with radiant cooling), may be required to simultaneously satisfy both requirements of the Standard for certain climates.

The results of the supply air temperature sensitivity analysis were used as the basis for determining the effectiveness of ceiling mounted, radiant cooling panels to provide supplementary cooling (Case 7). For this analysis, the DV system supply air temperature was fixed at 67°F and the room thermal gains were increased. The analysis shows that radiant cooling panels effectively maintained occupant thermal comfort with increasing thermal gains.

5.2.2 Impact of Cold Winter Conditions and Supplemental Heating Modes

Case 10 (Table 3) studied the impact of increasing supply air temperature.

Due to the same buoyancy principles that allow the DV system to work in cooling mode, supplying air into the room that is warmer than the room air's temperature results in the air immediately rising as it enters the space. The warmer supply air cannot drop toward the floor to form stratified layers. Figure 16 (see page 15) illustrates the airflow pattern of the DV system using a higher supply air temperature than that of the room's.

The lower ventilation effectiveness and longer mean age of air in the occupied region indicate a reduction in performance of the DV system in terms of indoor air quality.

Because of the ineffectiveness of heating via the supply air in a DV system, two different strategies for supplemental heating were tested: baseboard convectors and ceiling mounted radiant heating panels. Refer to Cases 3 and 4 in Table 3.

Figures 17 through 19 (see page 15) show the iso-surface comparison between the high supply air temperature case (Case 10) and the supplemental heating strategies (Cases 3 and 4).

5.2.3 Impact of Air Diffuser and Grille Locations

a. Room to Toilet Transfer Grille

Initial empirical testing used a transfer grille low in the toilet room door as the means to make up air to offset exhaust. This arrangement was intended to represent air transferred via a grille, a door undercut or both. After early results demonstrated poor displacement performance, it was determined that a high percentage of the supply air was short circuiting via the toilet room, limiting the displacement mechanism in the room. At 4 ACH, the total supply air to the patient room was 114 CFM. With 78 CFM exhausted via the toilet, 68% of the supply air was being short circuited. The transfer grille was relocated high on the toilet room wall, above the occupied zone, and the performance of the DV system improved dramatically.

Figure 20 (see page 16) shows that the performance of the DV system at 4 ACH, with a low-level transfer grille to the toilet, is less desirable as compared with an OHV system at 6 ACH. When the transfer grille is located at high level, however, the performance is better than that of the OHV system.

This research did not evaluate the comfort or ventilation effectiveness in the toilet room. This research also did not evaluate the effects of an open toilet room door for either displacement or overhead supply. It is anticipated the performance would be similar to a larger room with two exhaust grille locations.

b. Main Room Exhaust Grille

The main room exhaust (or return) grille was located in the ceiling above the head of the patient bed for all numerical cases. This location was selected based on the assumption that particle dispersion would be controlled to some extent by the location of the grille. Numerical modeling demonstrated the effectiveness of the exhaust grille location.

Figures 21 and 22 (see page 16) compare particle concentrations of the standard overhead arrangement at 6 ACH vs. displacement at 4 ACH, and show that the selected exhaust location effectively limits the dispersion of particles in the occupied zone and above.

5.2.4 Impact of Ceiling Height

Two numerical cases were conducted to test the impact of room ceiling height on thermal comfort and ventilation effectiveness. Refer to Cases 11 and 12 on Table 3.

It was found that increasing the ceiling height from 9 to 12 feet in the base case only slightly reduced the ventilation effectiveness; however, thermal comfort was improved.

The additional volume in the upper level of the room allows contaminants more space above the occupied zone in which to collect before being vented out, while creating a larger volume for the air to fill overall (when evaluating air change effectiveness for the whole space). Placing the room exhaust grille as close to the patient as possible (i.e., directly above the patient bed), regardless of ceiling height, will result in the most direct path for contaminant removal.

5.2.5 Impact of Movement on Displacement Ventilation

A discrete study was completed to test the impact of moving objects on contaminant concentration distribution in a single-bed patient room with DV at 4 ACH. The investigation also evaluated a case of OHV with 6 ACH for comparison. The full test details and results are included in Appendix 7.6.

Four different moving objects in the room were considered, for up to four seconds of movements: a visitor walking near the bed end; a caretaker walking along the bed side; a sheet being changed over the patient bed, and a swinging door.

The study found that:

1. The moving objects can carry the contaminant in their wakes. The movements can cause swings in the contaminant concentration in the breathing level of sitting and standing positions for 10 to 90 seconds. The variation of the averaged contaminant concentration due to the moving objects was within 25% for all the cases studied. The variation at the breathing level was lower in the sitting position than in the standing position. Since the variation lasted for less than 90s, it would not likely change the risk level in the patient room.
2. At most times, the DV system with 4 ACH provided better air quality than the OHV system with 6 ACH. The walking visitor and caretaker could experience a large swing in contaminant levels due to body movements in the ward. However, the swing was generally short (about 30s) so it was not likely to change the risk level for the visitor and caretaker.
3. Around the bed region or close to the contaminant source, the DV system had a higher contaminant concentration than the OHV system. However, in most parts of the room, the concentration was lower.

5.2.6 Impact of Coughing on Displacement Ventilation

A study was completed to test the impact of coughing on airflow in a single-bed patient room. The full test details and results are included in Appendix 7.4.

The simulation results showed that although the coughing only lasted a very short period of time (about 0.73s), a much longer time period (up to 5 min) needed to be simulated in order to capture the effect of the coughing activity.

Around the bed, where a caregiver is most likely to stand, the DV case showed a higher contaminant concentration for a short period of time, while at the end of the simulated 5 minutes, the concentration was lower than that with the OHV system. This can be explained by the fact that DV 'confines' or 'contains' the concentration around the patient, while OHV - given its mixing nature and higher ACH - is able to dilute the contaminant better around the bed. Consistent with the above discussion, DV delivers a better concentration in the visitor area, as it is further away from the patient.

When looking at the room as a whole, the results achieved by the two ventilation system in terms of response to coughing were comparable.

6. RECOMMENDATIONS

6.1 General Recommendations

This research effort has led to the following general recommendations for a 4 ACH DV system in a single-bed patient room:

1. In summertime warm climate conditions, acceptable ventilation effectiveness and contaminant control can be achieved, provided that thermal comfort is maintained.
2. When the internal thermal gains exceed the cooling capacity of the DV system, supplementary cooling, such as radiant cooling, will have to be added to maintain the required room air temperature and corresponding thermal comfort.
3. Supplemental heating is recommended when heating is required.
4. The transfer air to the toilet room needs to be high, above the occupied zone.
5. While multiple alternative main exhaust grille locations were not tested for displacement ventilation, the location above the head of the patient bed is recommended unless an alternate location can be shown to be an improvement via numerical modeling.

6.2 Design Strategies

The results of the numerical and empirical analysis showed that the particle removal efficiency and thermal comfort of DV is dependent on an integrated design approach to address both whole system optimization and thermal comfort. The study identified the following room layout and system design issues that need to be carefully considered:

1. The cooling capacity of a DV system is limited by the minimum allowable supply air temperature required to maintain thermal comfort.
2. Room thermal gains and losses must be controlled if the performance of the DV system is to be maintained, i.e.:
   a. Facades should be designed to minimize the thermal gains and losses to prevent warm and cold surfaces, especially with respect to glazing. The warm surfaces could affect the DV air flow.
   b. Manual or automatic solar shading devices should be installed to minimize/ eliminate direct solar gains. The field tests showed that floor surfaces warmed up by direct solar gains can act as a thermal hot spot, creating localized thermal chimneys, and causing most of the displacement supply air to short circuit the breathing level.
   c. Lighting and medical equipment loads should be minimized.
3. DV should not be used for space heating, i.e.:
   a. Providing supply air from the low sidewall displacement diffuser at a higher temperature than the room's temperature will result in decreased performance of the DV system.
   b. When using a supplemental heating method such as radiant or convective baseboard heating, the performance of the DV can be maintained, if not improved.
4. The placement of the DV supply air diffuser is not critical, but should be coordinated with the room design. The diffuser should be located at low level in a location that will not be blocked with solid furniture such as a storage cabinet.
5. The toilet transfer grille should be located at high level. The empirical experiments showed that the DV effect/ pluming/ high level removal of air borne particles can be seriously affected if the supply air is allowed to short circuit at low level, directly into the toilet room.

7. APPENDICES

7.1 Terminology and Abbreviations

Terminology and Abbreviations

Term	Definition
ACH	Air Changes Per Hour
AHJ	Authority Having Jurisdiction
CFD	Computational Fluid Dynamics
CFM	Cubic Feet Per Minute
DV	Displacement Ventilation
FGI	Facilities Guideline Institute
FPM	Feet Per Minute
HVRC	Healthcare Ventilation Research Collaborative
OHV	Overhead Ventilation
PPD	Percentage of People Dissatisfied
PPM	Parts Per Million

7.2 HVRC Advisory Committee

HVRC ADVISORY COMMITTEE

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Appendices 7.3-7.6 are available in the online version. To view these appendices, go to http://www.noharm.org/lib/downloads/doc_index.php

- 7.3 Empirical Testing
- 7.4 Numerical Testing
- 7.5 Statistical Analysis
- 7.6 Movement Study

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