AMCA International Large Diameter Ceiling Fan Study

AMCA *insite*™ Webinar Series | January 5, 2022 | www.amca.org

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Michael Ivanovich

Senior Director, Global Affairs, AMCA International

- Joined AMCA in July 2011
- Coordinates advocacy in N. America, Asia, Europe, and Middle East
- Leads AMCA energy efficiency initiatives involving codes, standards and regulations
- M.Sc. Civil Engineering (Building Systems)
- Project manager for the AMCA COVID Ceiling Fan Project

Christian Taber

Principal Engineer – Codes & Standards, AMCA Member Company

- M.S. in mechanical engineering & biosystems engineering; B.S. in chemical engineering
- ASHRAE certified High-Performance Building Design Professional and Certified Energy Manager
- Air Movement Code Action and Review Committee (AMCARC), Chair
- Served on AMCA committees 230, 214, 211, 208 and 11
- ASHRAE – Standards Committee, SSPC 90.1

Dr. Leon Wang

Associate Professor, Concordia University Quebec

- Member of Centre for Zero Energy Building Studies (CZEBS) at Concordia
- Previously the Concordia University Research Chair (CURC) in Building Airflow and Thermal Management
- Ph.D. in Mechanical Engineering from Purdue University
- Vice-chair of ASHRAE TC 4.10- Indoor Environmental Modeling
- Contributions to IECC, AMCA, ASHRAE, CDC and others

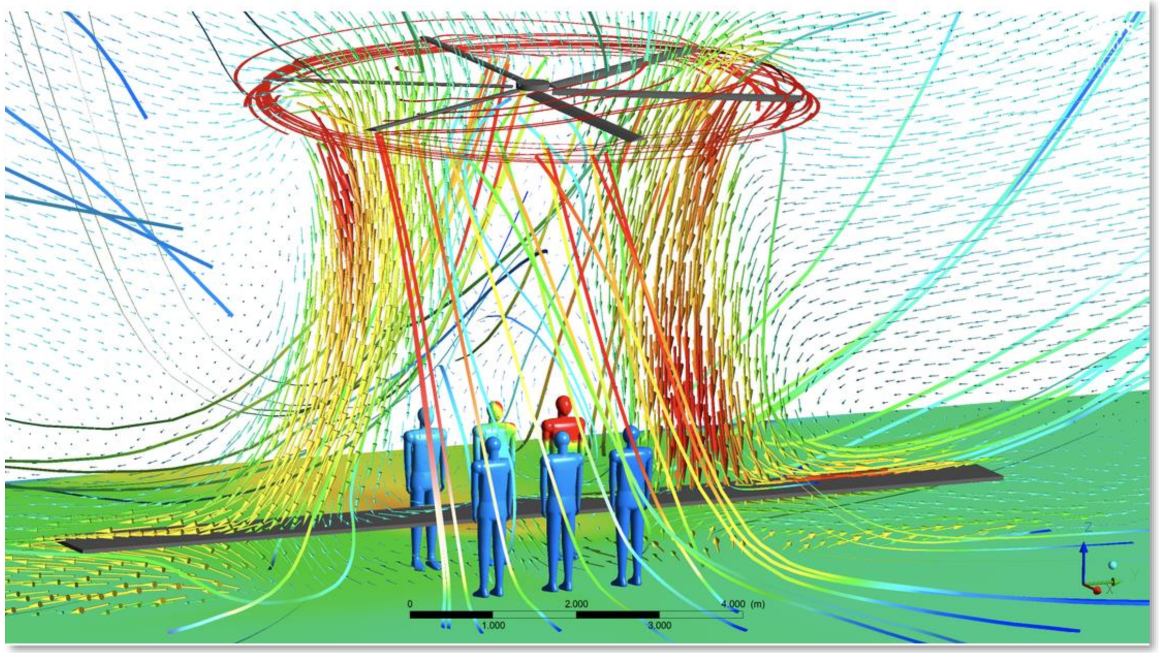
Dr. Paul Raftery

Professional Researcher, Center for the Built Environment, UC Berkeley

- Performs research on advanced HVAC systems and controls
- Ph.D. in engineering from National University of Ireland, Galway; Bachelors of Mechanical Engineering from Cork Institute of Technology
- Fullbright Fellow; active member of ASHRAE
- Decades of experience in HVAC engineering, building automation systems and controls, full-scale laboratory experiments, new technology development, and measurement and verification of technology demonstrations

Outline

- Purpose of study (Ivanovich)
- Description of building, application, and fans (Taber)
- Model limitations and assumptions (Wang)
- Model description and results (Wang)
- Guidance for operators (Raftery)
- AMCA Communications and Project Resources (Ivanovich)



AMCA International LDCF Study

Purpose and Learning Objectives

The purpose of this presentation is to describe why and how the AMCA COVID Ceiling Fan Project was conducted; present the results of the modeling effort; present guidance stemming from the study; summarize feedback from COVID-guidance organizations thus far.

At the end of this presentation you will be able to:

1. Identify COVID-exposure guidance from public and private organizations
2. Describe the AMCA COVID Ceiling Fan effort at a high-level
3. Explain the guidance for operating large diameter ceiling fans in relevant spaces and occupancies
4. Outline AMCA communications discussing the project and guidance.

Purpose of Study

Michael Ivanovich

Project Team

Today's Presenters

SCIENCE TEAM			
Name	Title	Affiliation	Project role/contribution
Liangzhu (Leon) Wang, PhD, P.Eng.	Associate professor, Department of Building, Civil, and Environmental Engineering	Concordia University	Principal investigator
William P. Bahnfleth, PhD, PE	Professor, architectural engineering Chair, ASHRAE Epidemic Task Force	The Pennsylvania State University	Science-team leader
Edward A. Nardell, MD	Professor, departments of Environmental Health and Immunology and Infectious Diseases	Harvard T.H. Chan School of Public Health	Infectious diseases and study of ceiling fans for control of infectious diseases
Jovan Pantelic, PhD	Research scientist, building science	Well Living Lab Inc.	Infectious diseases
Paul Raftery, PhD	Professional researcher	Center for the Built Environment, University of California, Berkeley	Ceiling-fan modeling
Geoff Sheard, DSc	President	AGS Consulting LLC	Computational-fluid-dynamics modeling and fan engineering
Pawel Wargocki, PhD	Associate professor, departments of Civil Engineering and Indoor Environment Chair, ASHRAE Epidemic Task Force Science Applications Committee	Technical University of Denmark	Indoor-air-quality expertise
INDUSTRY TEAM			
Michael Ivanovich	Senior director, global affairs	AMCA International	Project manager
Eddie Boyd	Chief executive officer	MacroAir Technologies	LDCF performance
Marc Brandt	Director, domestic industrial	Hunter Industrial	LDCF performance
Thomas Catania, Esq.	Board member	Institute for Energy Innovation	Regulatory communications
Aaron Gunzner	Senior manager, advocacy	AMCA International	Staff liaison
Mark Stevens	Executive director	AMCA International	Member relations
Christian Taber	Principal engineer, codes and standards	Big Ass Fans	Warehouse model, LDCF modeling
Mike Wolf, PE	Director, regulatory business development	Greenheck Fan Corp.	Regulatory communications

Project Team

Project Funding

- AMCA International
- Big Ass Fans
- Greenheck Fan Corp.
- Hunter Industrial
- MacroAir Technologies

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Purpose of Study

- Some COVID-19 guidance includes operation of ceiling fans
  - Guidance does not seem to apply to HVLS fans or warehouses
- **To contribute to the body of COVID-19 guidance for commercial and industrial facilities, with focus on the role of large-diameter ceiling fans (LDCF) without supplemental air treatment**
  - LDCF: U.S. Department of Energy defined product class for ceiling fans having a blade span greater than 7 ft (2 m)
  - High Volume, Low Speed (HVLS) fans; some LDCF are not HVLS
- U.S. only because of regional construction and occupancy characteristics
  - Some slides to not have metric equivalents

Purpose of Study

- Warehouses selected as subject building type/application
- Warehouses are critical to supply chain, and increasingly so
  - Second largest building type in USA based on square footage (office bldg. #1)
  - https://www.constructiondive.com/news/warehouse-construction-boom-to-continue-next-year/513592/
  - https://www.globest.com/2019/06/21/e-commerce-demand-pushes-us-warehouse-construction-to-record-levels/?slreturn=20210920114228

- COVID outbreaks happen in warehouses
  - https://www.wsws.org/en/articles/2021/08/30/pdx9-a30.html
  - https://www.thestar.com/business/2021/10/06/at-warehouses-construction-sites-and-manufacturers-vaccine-mandates-are-rare-and-they-dominate-outbreaks-on-the-job.html

Purpose of Study

- Examples of Current Guidance
  - CDC: https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html
    - Question 11: Can fans be used to decrease risk of COVID-19 transmission indoors.
      - "Use ceiling fans at low velocity and potentially in the reverse-flow direction (so that air is pulled up toward the ceiling)"
  - WHO: https://www.who.int/news-room/q-a-detail/coronavirus-disease-covid-19-ventilation-and-air-conditioning
    - Can fans be used safely inside?
      - The use of ceiling fans can improve the circulation of air from outside and avoid pockets of stagnant air forming indoors. However, it is critical to bring in air from outside when using ceiling fans, such as by opening windows
  - Minnesota Department of Health: https://www.health.state.mn.us/diseases/coronavirus/indoorair
    - Use portable fans and ceiling fans with caution. The impact of fans on the risk of spreading the virus are unknown. They may help reduce risk, but must be positioned to avoid blowing air from one person in the direction of another person. Adjust ceiling fans to pull air up rather than down. For example, tilt blades upward, if possible.

Purpose of Study

- ASHRAE ETF Guidance (current)
  - Commercial Buildings: Unitary fans: Different configurations: ttps://www.ashrae.org/technical-resources/commercial
    - For ceiling fans, if possible, reverse the flow direction to blow upward.
    - For pedestal and horizontal fans, beware of the nature of air flow and avoid prolonged cascades of air flow from the face of a person onto others.
    - If the space has good filtration efficiency (>= MERV 13) but poor air mixing or low air change rate, then run fans to promote good mixing.
    - If there is good ventilation air and poor air mixing, then run the fans to promote good mixing.
    - If there is poor filtration efficiency and poor ventilation, then run the fans and put in portable air cleaner with HEPA filter units.
    - If fans are the only HVAC in the room then either open a window, provide portable air cleaner with HEPA filter units or avoid using the room

Structure of Study

- Assembled an international team of experts on building science, IAQ science, infectious diseases, modeling
- Assembled an industry team of experts to provide HVLS expertise and funding
- Goal was to peer review the study from start to finish
- Science team governed research design, modeling, interpretation of results, and final report
- Industry team helped tune the fan model and operationalize guidance
- Winter and summer conditions were modeled; emphasis on summer conditions

Structure of Study

- Project conceived in September 2020
- Project final report delivered in August 2021
- Setting up to communicate results and guidance
  - ASHRAE ETF was first external audience for this project
  - Centers for Disease control was present for ASHRAE ETF and communicated with separately
  - *AMCA inmotion* article published November 1, 2021
    - https://www.nxtbook.com/nxtbooks/ashrae/ashraejournal_amca_2021november_v2/
    - https://www.amca.org/educate/articles-and-technical-papers/amca-inmotion-articles/amca-covid-19-guidance-for-large-diameter-ceiling-fans.html

AMCA COVID-19 Guidance for Large-Diameter Ceiling Fans

Over a 12-month period, Air Movement and Control Association, in collaboration with an international team of scientists, engineers, and researchers, executed a series of numerical simulations to investigate the impact of large-diameter ceiling fans on COVID-19 exposure in a warehouse.

Photograph courtesy of Greenheck Fan Corp.

BY **MICHAEL IVANOVICH**, **AARON GUNZNER**, AND **SCOTT ARNOLD**, AMCA INTERNATIONAL

Numerous studies of airflow and performance characteristics of circulating fans have been undertaken.[1,2,3,4,5,6] Relatively few, however, are focused on aerosol transmission of airborne pathogens in large industrial spaces, a shortage all the more noticeable during the coronavirus disease 2019 (COVID-19) pandemic.

To contribute to and improve the body of COVID-19-prompted guidance for the operation of circulating fans, Air Movement and Control Association (AMCA) International commissioned numerical-simulation studies of airborne-particle and aerosol transmission with large-diameter (greater than 2.1 m [7 ft]) ceiling fans (LDCF). The focus of the studies was warehouses in the United States, in which LDCF commonly are used for comfort cooling and destratification. The results, however, also are applicable to many manufacturing/industrial facilities.

To promote integrity in the design and execution of the research and ensure the conclusions drawn from the study are valid, AMCA assembled "industry" and "science" teams (Table 1). Consisting of representatives of AMCA member companies and members of the AMCA staff, the industry team provided expertise in the application and performance of products, while the science team, made up of authorities in infectious diseases, indoor-air quality, fans, and computer modeling, including two leading members of the ASHRAE Epidemic Task Force, advised on the project setup and reviewed the intermediate and final results. Because COVID-19 infection rates are poorly understood and varying with mutations, the study focused on particle concentrations as an indicator of exposure risk.

Following is a high-level summary of the project's findings and resultant guidance. For information on the simulation methodology, setups, assumptions, validations, and results, see the final report, "AMCA COVID Guidance for UNDUCTED Fans – Modeling Ceiling Fans," prepared by Liangzhu (Leon) Wang, PhD, P.Eng.; Senwen Yang; Runzhong (Alvin) Wang; Mohammad Mortezazadeh, PhD; Jiwei Zou; and Chang Shu of Concordia University, at https://bit.ly/COVID_LDCF.

The Building

Based on the U.S. Department of Energy (DOE) commercial reference building for warehouses (Figure 1a), the warehouse in the study measured 100 m (330 ft) long by 46 m (150 ft) wide by 8.5 m (28 ft) tall with two AMCA-certified 6.1-m- (20 ft) diameter ceiling fans installed 36.6 m (120 ft)

Building, Application, and Fans

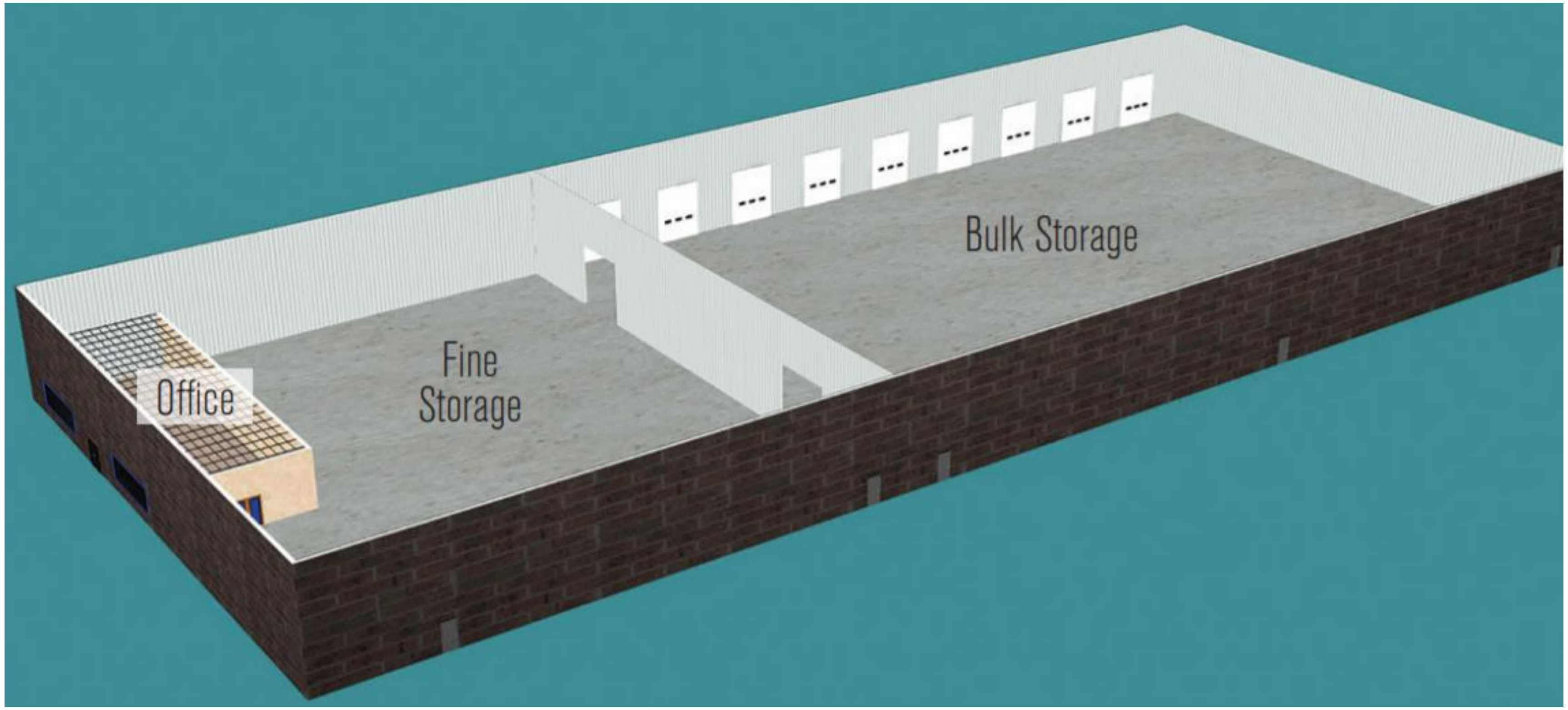
Christian Taber

Building Overview - Warehouse

Building Overview - Warehouse

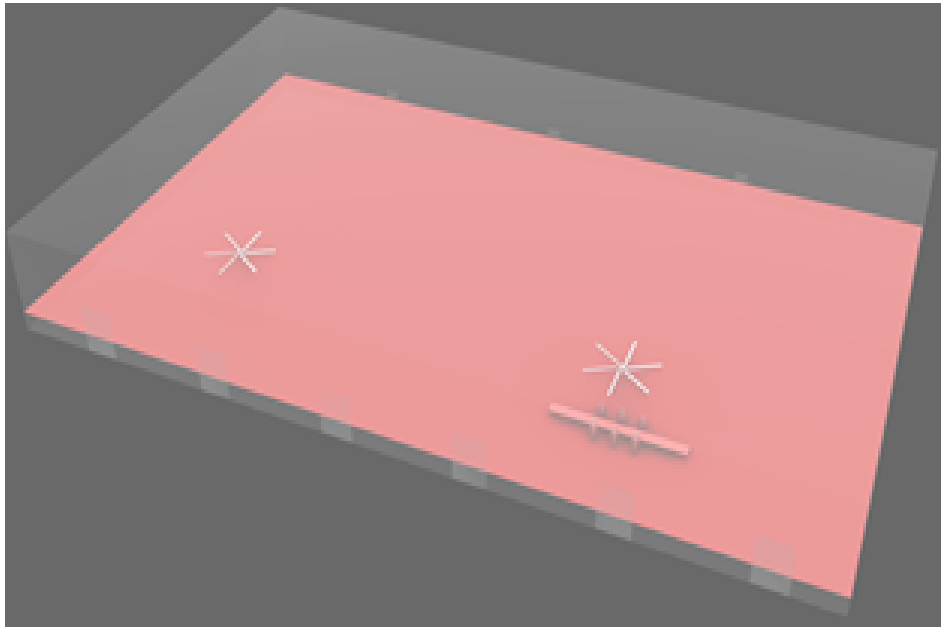
Warehouse - Building Overview

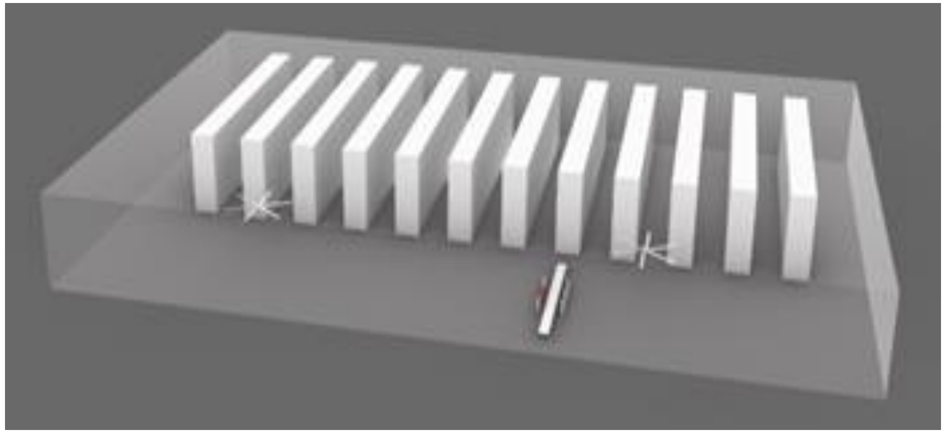
- Based on U.S. Department of Energy commercial reference building for warehouses
- Dimensions - 100m (330 ft) x 46m (150ft) x 8.5m (28ft)
- Chicago, IL USA



Warehouse Bulk Storage

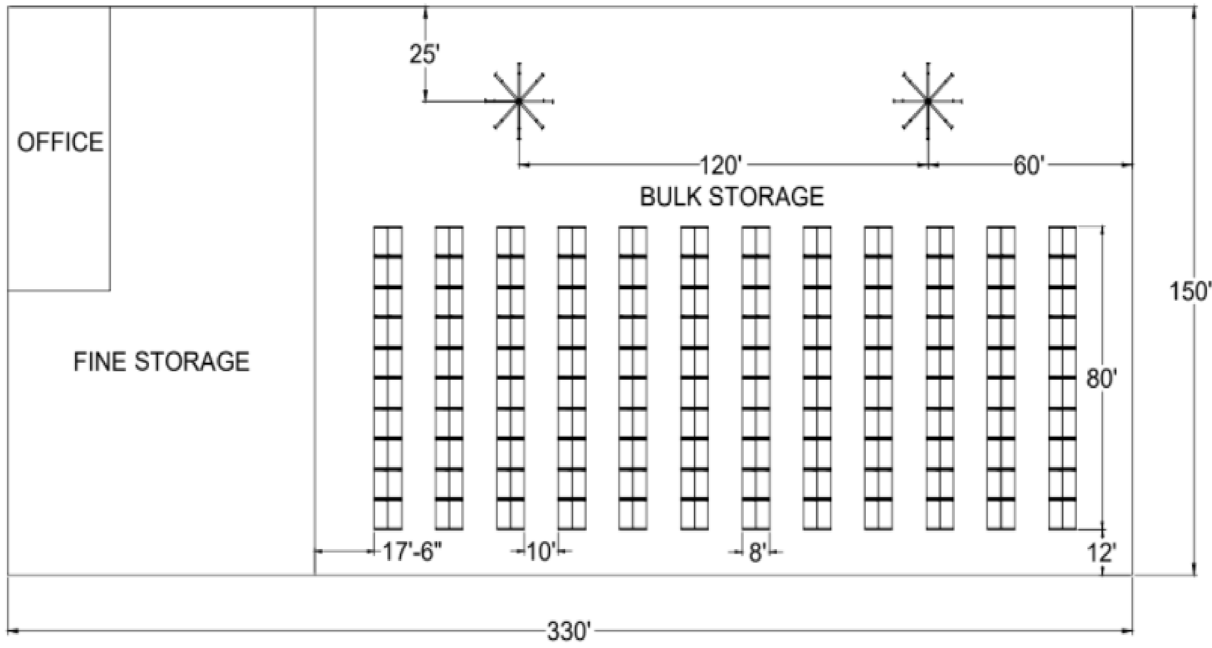
- Dimensions
  - 70-m (230-ft) x 46-m (150-ft) x 8.5-m (28-ft)
- Mechanical System
  - Heating - Unit heaters, constant volume, 55-F setpoint
  - Ventilation - Exhaust fans, 85F on-point
  - Air Conditioning - None
- Envelope
  - Based on ASHRAE 90.1 - 2016
  - Six dock doors, Three standard doors
- Thermal conditions modeled using EnergyPlus
- Occupancy is very low-density





Bulk Storage - Airflows

- Ventilation
  - Minimum = 2,907 cfm
  - Comfort = 24,150 cfm (1.5 ach)
- Infiltration
  - 5,228 cfm
- HVLS Fans
  - Two 6.1-m (20-ft) impeller diameter
  - AMCA-certified performance data
    - 91 m^3/s (192,000 cfm)
    - Test procedure in accordance with U.S. Code of Federal Regulations 10 CFR 430 Appendix U
  - 6.1-m (20-ft) blade height



Comparison of Air Volumes & Dilution Airflow Rates

	Office Space	Breakroom	Warehouse - Winter	Warehouse - Summer
Outdoor Air (cfm/person)	5	5	10	
Outdoor Air (cfm/ft^2)	0.06	0.12	0.06	0.7 cfm/ft^2
Infiltration (cfm/ft^2)	0.054	0.054	0.152	
Occupants (person/1k ft^2)	5	50	0.333	0.333
Room Air Volume (ft^3/person)	2,000	200	84,000	84,000
OA + Infil (cfm/person)	27.8	8.5	646	2,100

Assumptions: 3,000 ft^2 per space type, 10-ft ceiling in office and breakroom, 28-ft ceiling in warehouse
Source: ASHRAE Standard 62.1-2019 Table 6-1, ASHRAE AEDG Warehouses & Small Office Buildings

Model Design

Leon Wang, PhD

Study Design

- Drift Flux model
- Fan model
- Validations of models
- CFD simulations
- Data analysis
- Guidance development
- Final report

Assumptions

- Modeled the particle droplets generated from an infector and their distributions in the warehouse.
  - The actual absolute values of COVID-19 infection risks are not the focus of this study. Therefore, all the results, the conclusions, and the associated guidelines should be interpreted **on a relative basis.**
- Considers the particle release from **loud speaking** and does not consider other respiratory scenarios.
- Based on **the Drift-flux model** with limitations to interpret particle-air interactions and particle-particle interactions.
  - For example, a particle is with **one-way coupling** with the airflow, and no particle accumulation, coagulation, resuspension are modeled, although the gravitational and surface depositions have been addressed.
  - All the **particles are spherical** with constant density and diameter; the **model does not consider natural particle decay** or any virus-related biological decay behavior, so the particle concentrations could be overestimated.

Assumptions

- **The effects of occupant and warehouse vehicle movements on the airflow are not considered**, although the airborne particle transmission is modeled for an 8-hour transient process.
  - In addition, the **thermal plume from an occupant is considered stably established**. So, the thermal plume in this study could be overestimated, and horizontal particle spreading could be underestimated.
- The **fan operation does not affect the ventilation rates** through docks and doors in the simulations, and the **internal surface temperatures are constant**.
  - In reality, fan operation may likely increase or reduce ventilation airflows through openings in the building envelope compared to a scenario without a fan operating.
- The **particle deposition to porous rack surfaces is not considered**, so that the spatial particle concentrations could be overestimated for cases with racks.
- The **fan is assumed to be constantly running**, so intermittent operation or dynamic speed changes are not considered.

Limitations

- The proposed LDCF guidelines are based on the relative reduction of the whole-warehouse breathing zone and working zone particle concentration levels.
  - Therefore, they do not imply any safe/unsafe conditions but suggest the fan operation strategy for a relatively lower particle concentration in the space.
- Still air (Fan Speed = 0) cases are more dependent on the assumptions than the other cases, as the fan momentum-driven airflows tend to dominate the air distribution in the space when the fan operates.
  - Therefore, a slight change to these assumptions (less effective thermal plume, more mixing effects from people/vehicles movements, different or unsteady ventilation flows through windows and doors) could have a relatively large impact on these FS-0 cases' results which would affect the overall conclusions.

Limitations

- As we have modeled, the significant reduction in concentrations for the “high speed” scenarios is primarily due to dilution and losses through depositions.
  - Therefore, the results depend on the accuracy of the deposition model, without which the predicted concentrations would be higher, and the conclusions could be different.
- The warehouse has a large volume space and is sparsely occupied.
  - Therefore, the conclusions may not apply to other cases otherwise, such as a space with a small volume and/or densely occupied.

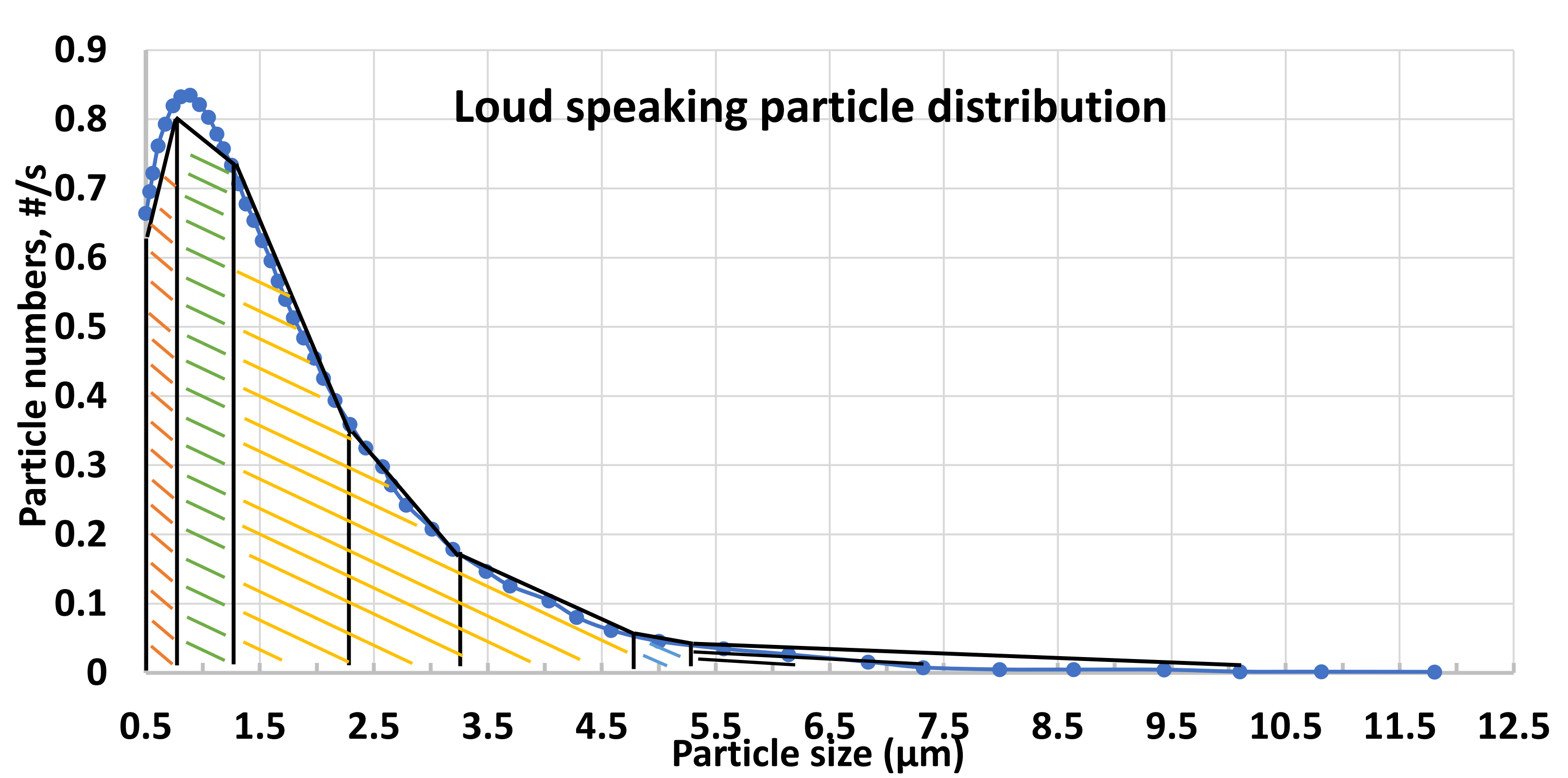
Model Results

Leon Wang, PhD

Key Inputs

Key Parameters	Settings
Mouth opening area	227 mm^2 (0.35 in^2); 17 mm (0.67 in) diameter circle [42,43]
Exhale velocity	3.4 m/s (11.2 ft/s) (loud speaking/shouting) [44]
Exhale temperature	34 °C (93.2 °F) [45]
Number of infectors	One infector at different locations
Infector location	Case dependent – see Fig. 7
Particle diameter	Particle bins (0.5 µm, 1µm, 3 µm, 5 µm, 10 µm)
Particle surface deposition	Particle sinks by UDF [23]
Airborne decay rate	No measurable decay rate [46]
LDCF rotating speed	78 rpm (100% speed); 16 rpm (20% speed); no fan running
LDCF maximum volume flow rate	Q= 90 m^3/s (192,000 CFM) at 78 rpm from AMCA
Fan diameter	6.1 m (20 ft)
Fan locations	Two fans 36.6 m (120 ft) apart; 7.6 m (25 ft) from the south wall; 18.3 m (60 ft) from the west wall surfaces; 2.1 m (7 ft) under the ceiling
Outdoor dry bulb temperature	Summer 32 °C (89.6 °F) and Winter -17.5 °C (0.5 °F) [47]
Body temperature	33 °C (91.4 °F) [44]
Surface temperatures	From EnergyPlus simulation (see Fig. 6)
Inlet ventilation rate	0.37 m^3/s (780 CFM) per dock
Steady or Transient	See simulation scenarios
Turbulence model	Standard k-ε [48]
Species transient timestep	Adaptive 0.1s to 60 s
Mesh size near the fan	10 mm (0.39 in)
Mesh size near the mouth	2 mm (0.08 in)
Rack geometry	24 m × 6 m × 2.4 m (80 ft × 20 ft × 8 ft)
Packing line	12 m × 0.9 m × 0.1 m (40 ft ×3 ft × 0.3 ft)
Fan speed type	3 (7 additional speeds for selected case - U-H-D-3)
Reverse fan speed	2
Total simulations	223
Total mesh grids/case	14.6 million
Computing time/case	6 hrs (steady-state airflow only); 8 hrs (transient Drift-flux)

Particle Distribution Loud Speaking



Particle size bin (µm)	0.5~0.75	0.75~1.25	1.25~4.75	4.75~5.25	5.25~10
Bin width (µm)	0.25	0.5	3.5	0.5	4.75
Particle generation (#/s)	4.47	9.33	23.31	0.54	2.35
Particle number fraction	11.17%	23.34%	58.27%	1.36%	5.87%
Mass generation (kg/s)	2.92E-16	4.89E-15	3.29E-13	3.55E-14	1.23E-12
Mass generation (lb/s)	6.44E-16	1.08E-14	7.25E-13	7.83E-14	2.71E-12
Mass fraction	0.02%	0.31%	20.59%	2.22%	76.87%

*S. Asadi, A.S. Wexler, C.D. Cappa, S. Barreda, N.M. Bouvier, W.D. Ristenpart, Aerosol emission and super-emission during human speech increase with voice loudness, Sci. Rep. 9 (2019) 1–10. https://doi.org/10.1038/s41598-019-38808-z.

Centre for Zero Energy Building Studies
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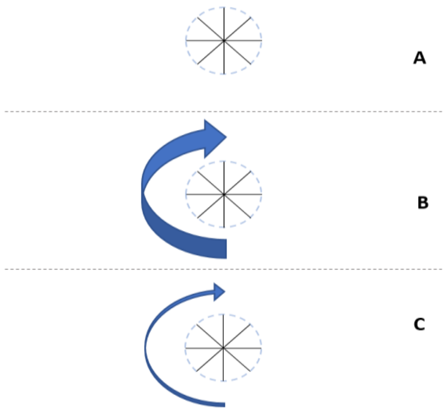
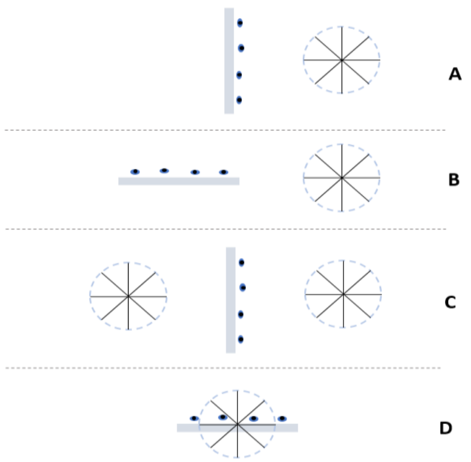
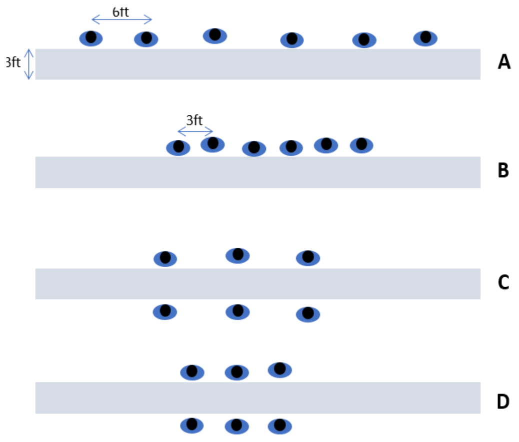
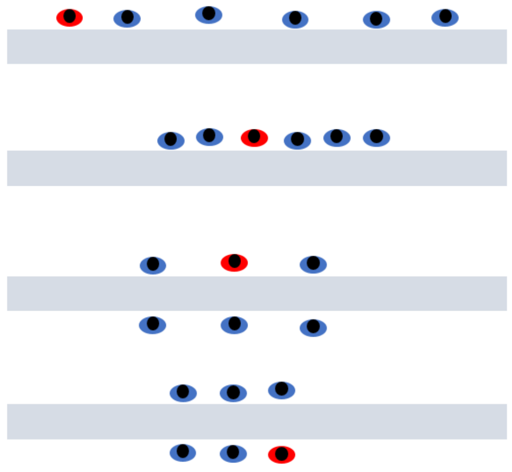
Simulation Scenarios

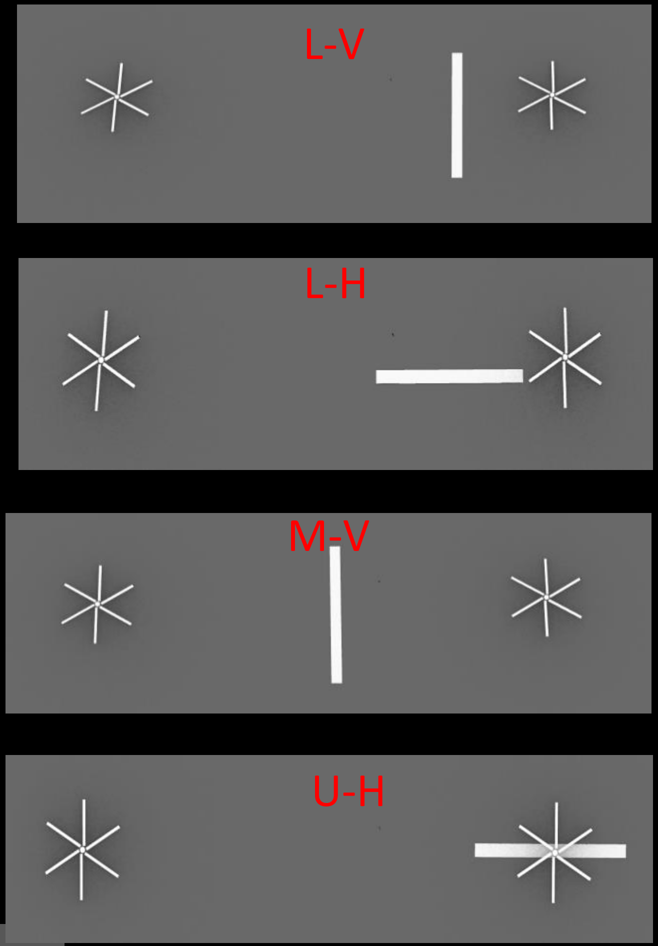
Packing line scenarios based on Dr. Paul Raftery's Suggestion		
Factors	**Levels**	**Descriptions**
Fan Speed (S)	3 levels, in order of priority: • A: No fan – still air conditions with buoyancy-driven flow • B: Maximum fan speed • C: 20% max fan speed	Note: level A gives the same result regardless of the subsequent fan location factor level (as that is almost irrelevant to the still air simulations), which will reduce # of simulations required. 
Fan Location (F)	4 levels, in order of priority: • A: Perpendicular to fan airflow • B: Parallel to airflow • C: Converging, and perpendicular to fan airflow • D: Directly overhead	

Occupant Location (O); Infectious Person Location	4 levels, in order of priority: • A: In one line, ≥ 6ft • B: In one line, ~3ft • C: Across from one another • D: Across from one another, ~3ft	
	Do not need to simulate – using unique tracers per occupant simultaneously in every simulation	
Viral Emission Factor (E)	4 levels, in order of priority: ▪ A: Breathing ▪ B: Shouting (directional, toward neighbor) ▪ C: Shouting ▪ D: Coughing/sneezing	

Fan, Packing Line Location Definitions

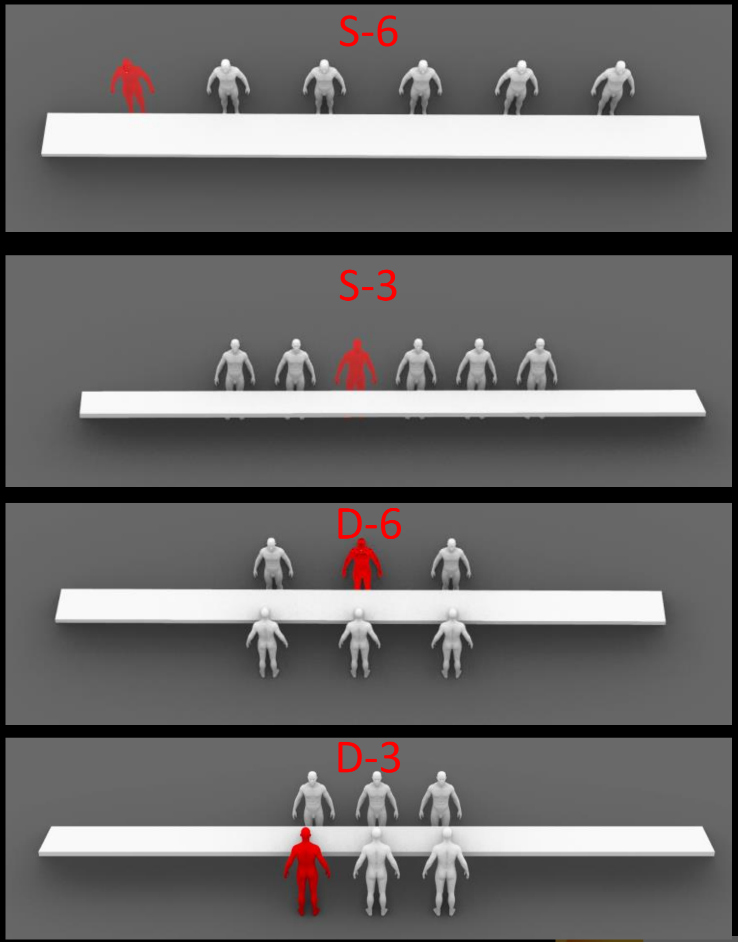
Packing line location

M=Middle L=Left U=under V=Vertical H=Horizontal



Worker location

D=double row S=single row 6=6 ft 3=3 ft



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Fan Speeds Nomenclature

Fan-speed label	Fan speed (% max. rpm)	Fan speed rpm	Air speed exiting fan m/s (fpm)
FS-0.6	20	16	0.6 (118)
FS-0.9	30	23	0.9 (177)
FS-1.2	40	31	1.2 (236)
FS-1.5	50	39	1.5 (295)
FS-1.8	60	47	1.8 (354)
FS-2.1	70	55	2.1 (413)
FS-2.4	80	62	2.4 (472)
FS-2.7	90	70	2.7 (531)
FS-3.0	100	78	3.0 (591)

[1]The side of the cylinder of the fan zone colored by yellow in Figure 5c.
[2]A cylinder around the fan center at a height of 1.7 m (5.6 ft).

TABLE 2. Fan air speed and airflow rate in the fan zone for a case of U-H-D-3.

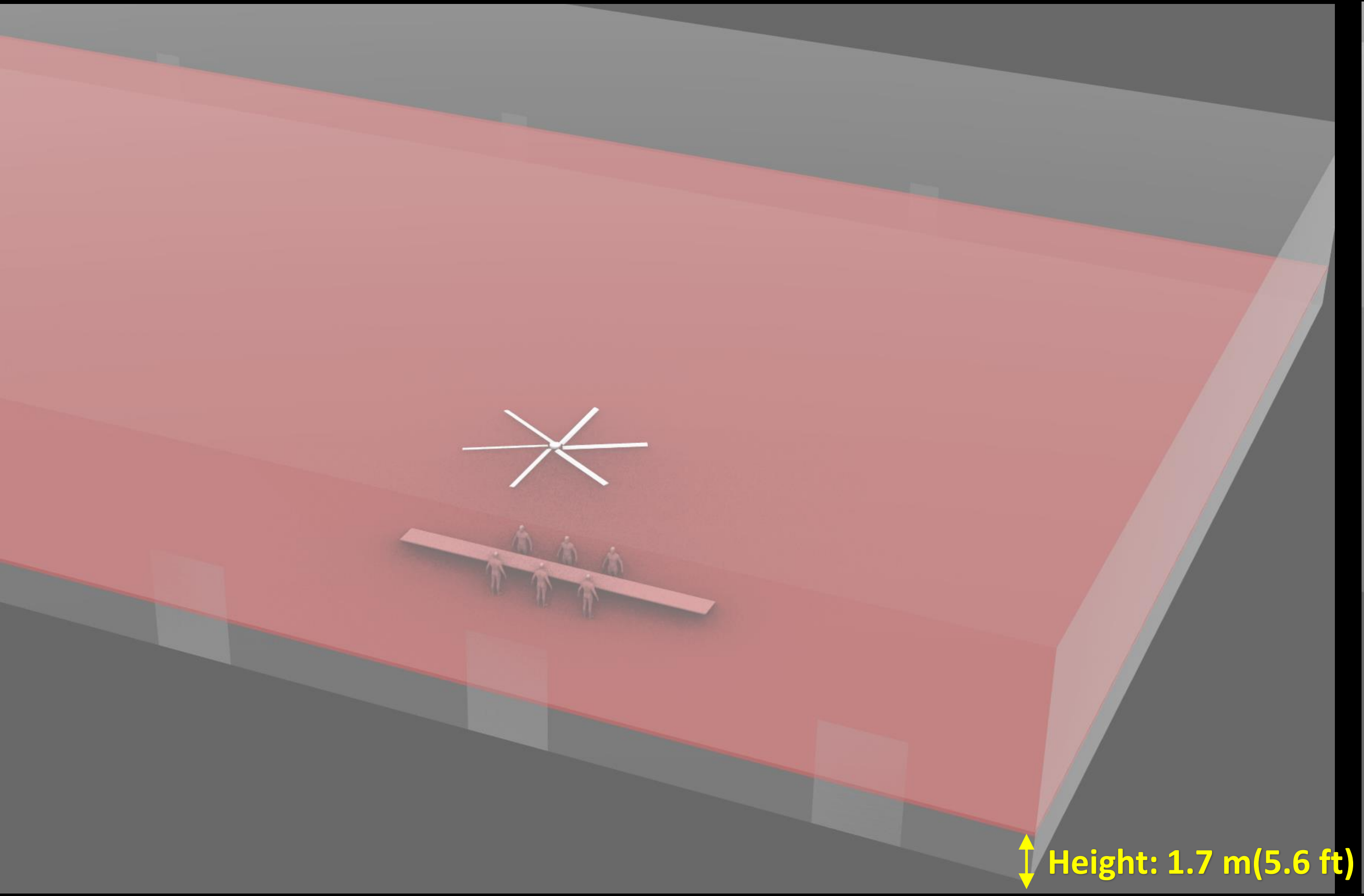
Note: Bonus Slide has more columns to the table

Primary fan speeds modeled in study:

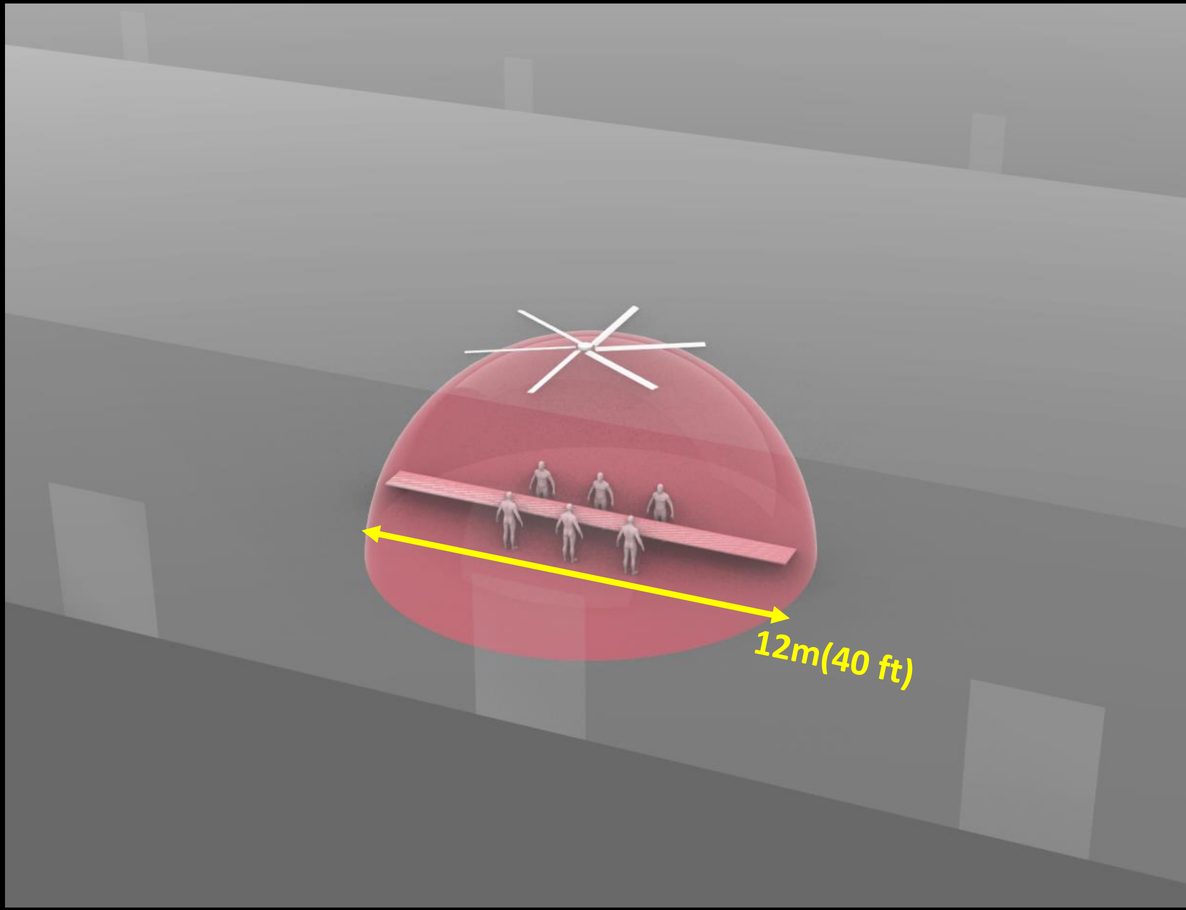
- **FS-0** = Fan Not Running
- **FS-0.6** = 0.6 m/s (118 fpm)
- **FS -3.0** = 3.0 m/s (591 fpm)

Result Zone Definitions

Whole-warehouse Breathing Zone

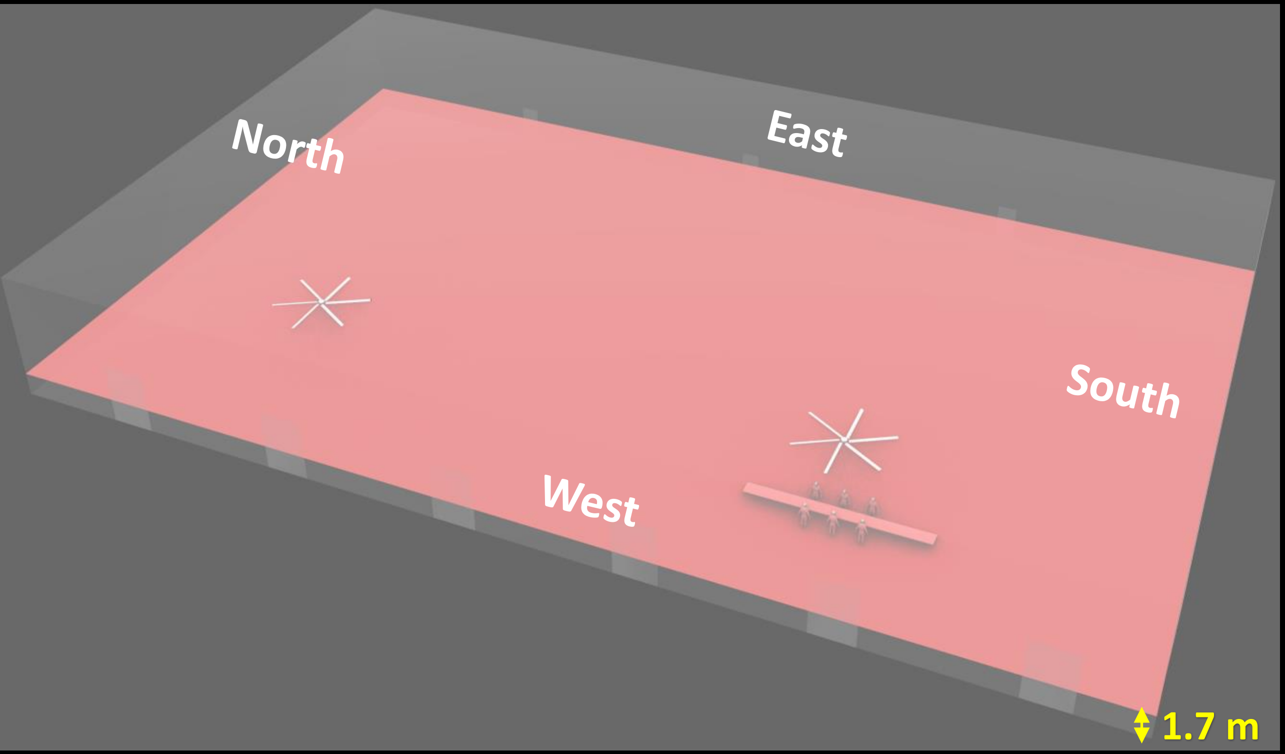


Working Zone

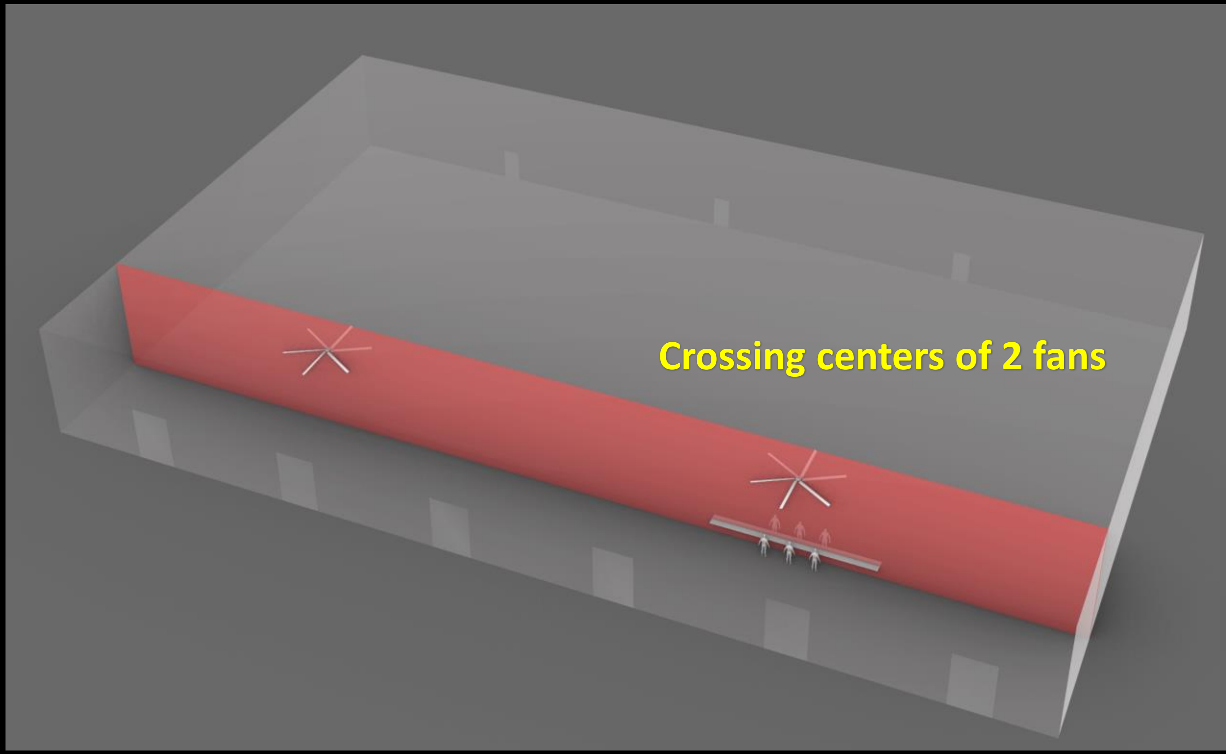


Result Plane Definitions

Horizontal Plane Location
(whole-warehouse breathing zone)



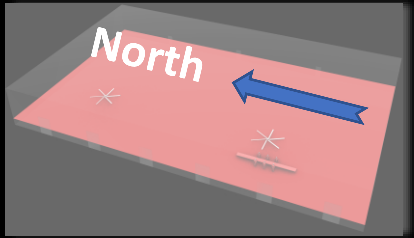
Vertical Plane Location



FS-0 = Fan not running
FS-0.6 = Fan running at 20% speed

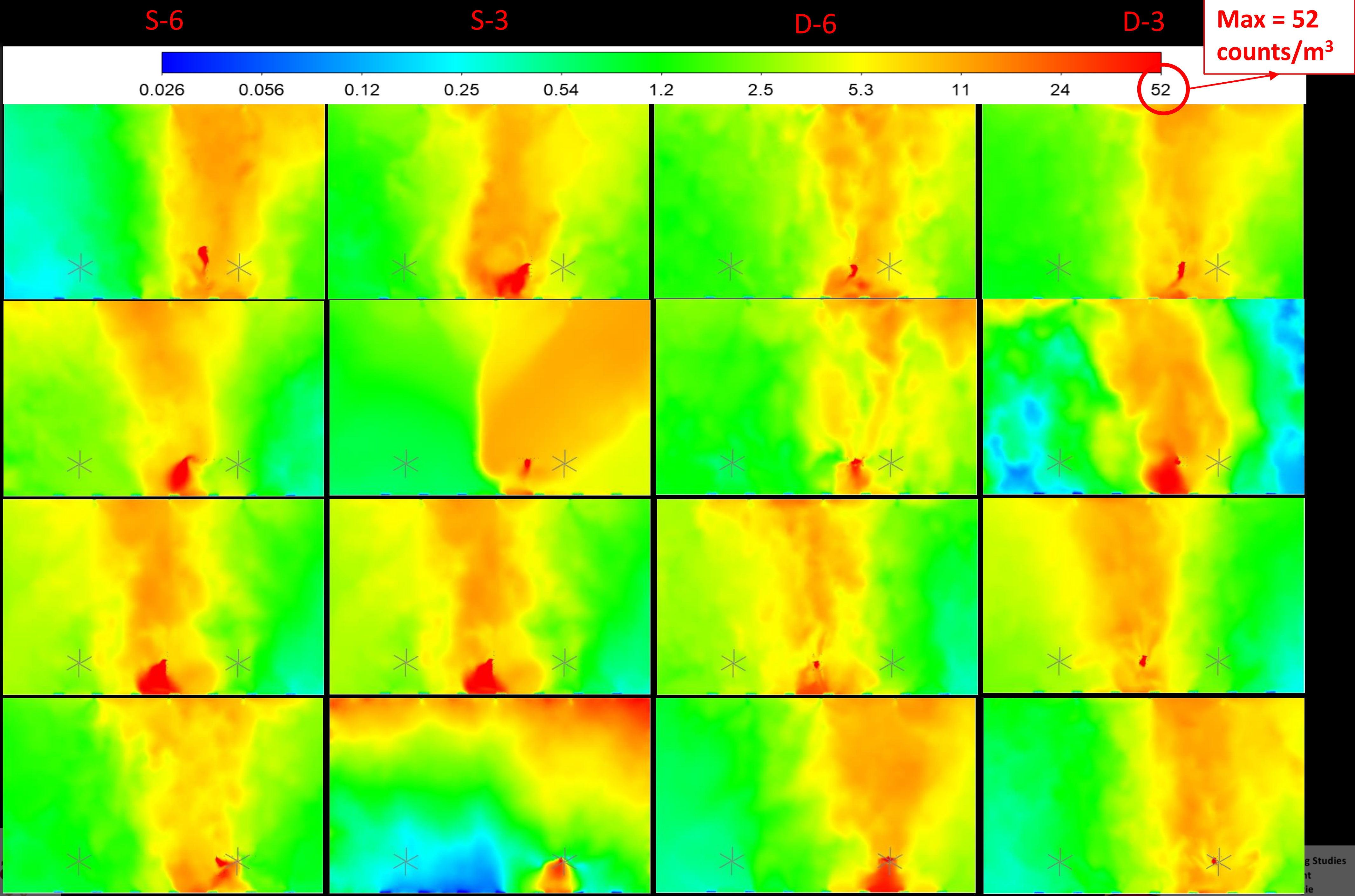
FS-3 Fan/FS-3 = Fan running at 100% full speed
Reverse Fan = Fan blowing air upwards

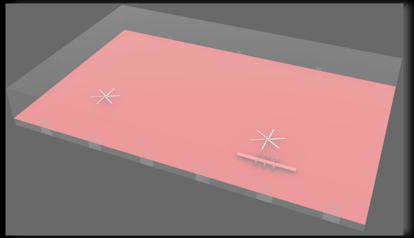
Fan air speed (FS): 0.6 = 0.6 m/s; 3 = 3 m/s



Whole-warehouse breathing zone concentration, **FS-0**, counts/m³ (8 hr)

Airflow/particle moving West to East





L-V

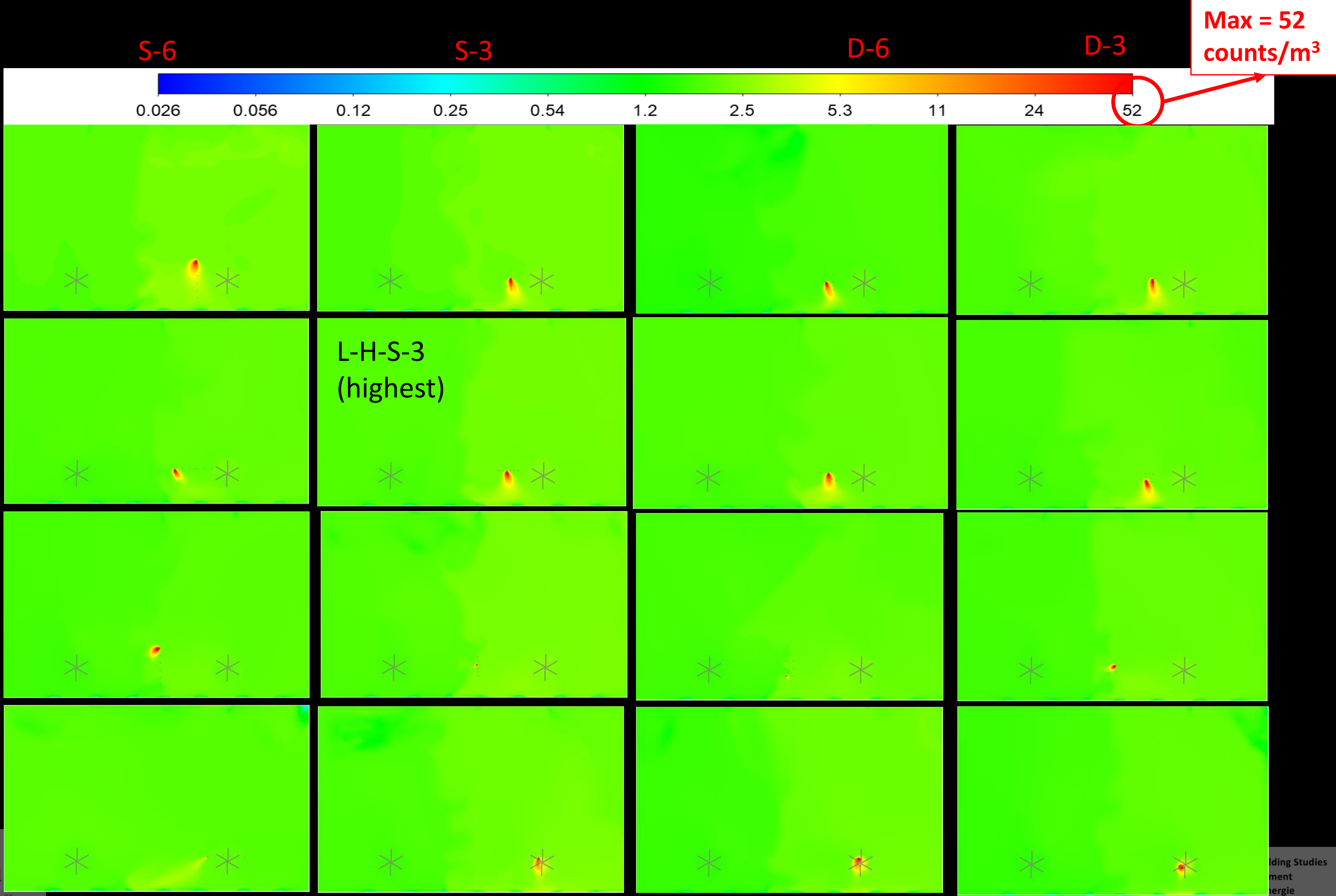
Whole-warehouse breathing zone concentration, FS-3, counts/m³ (8 hr)

L-H

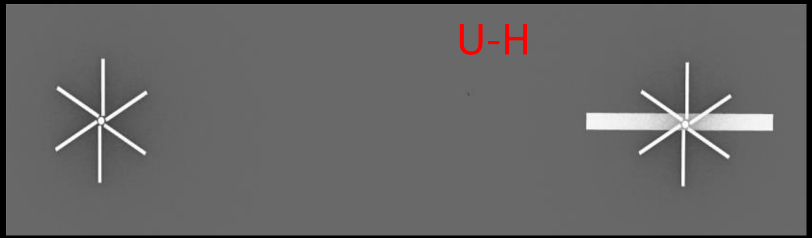
Fan at high speed

M-V

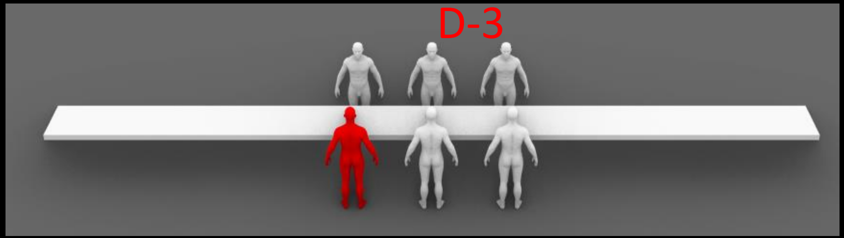
U-H



Investigate the Case (U-H-D-3) Summer Conditions



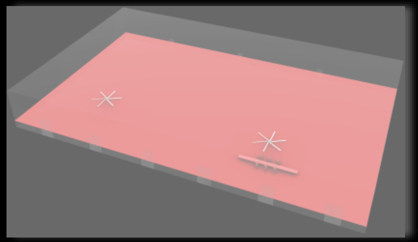
Packing line **U**nder the fan
Horizontal placement

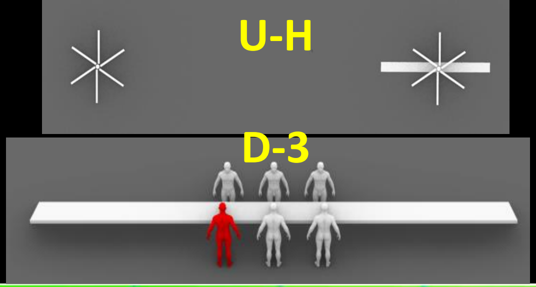


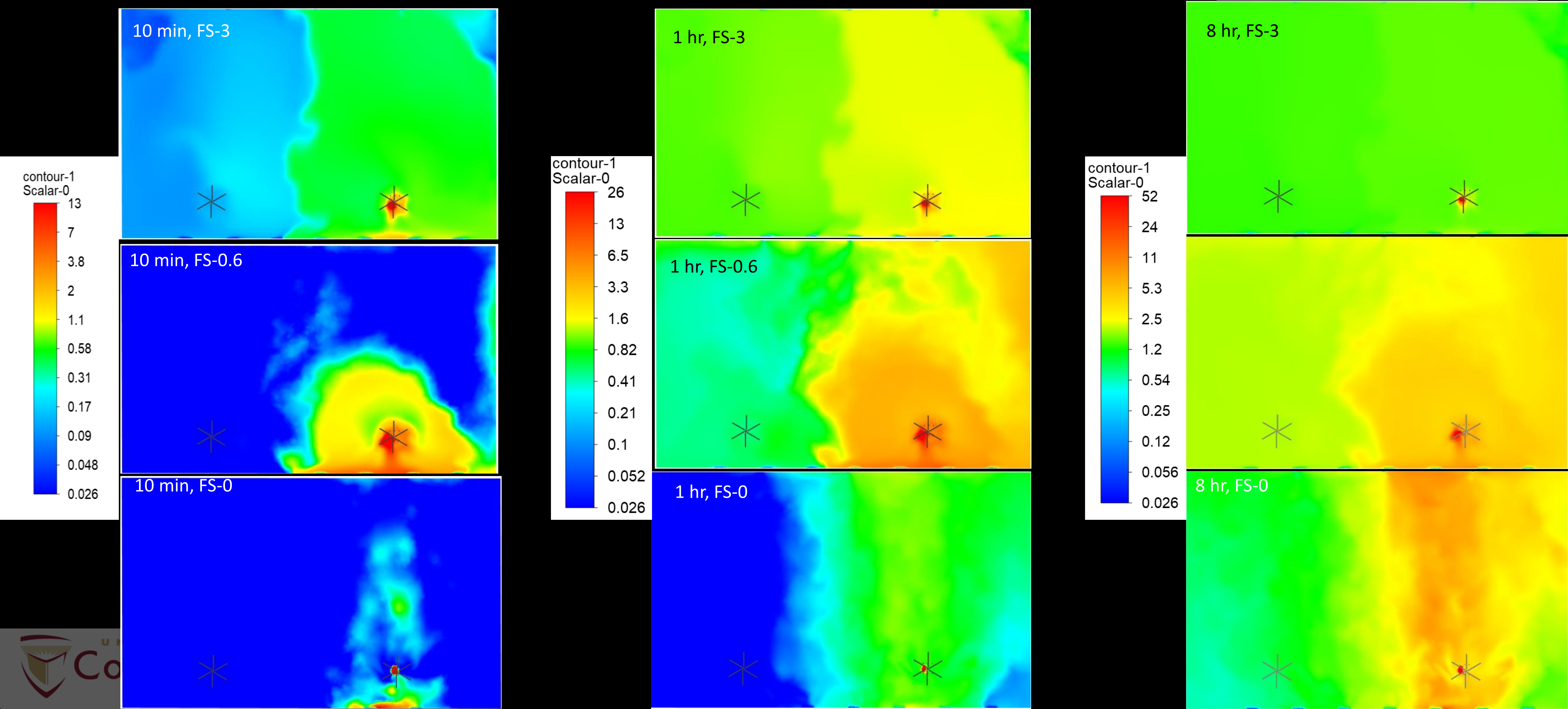
Double line workers with **3** feet apart

because it results in lowest whole-warehouse beathing zone concentration

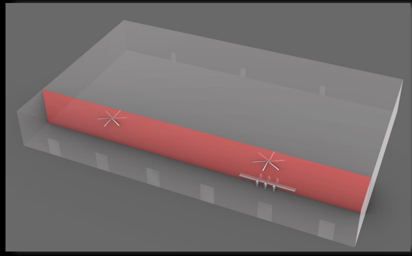
Compare Fan Operations (U-H-D-3) – Horizonal Plane



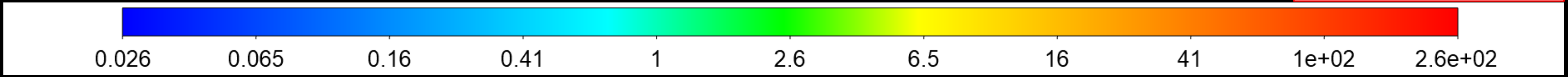


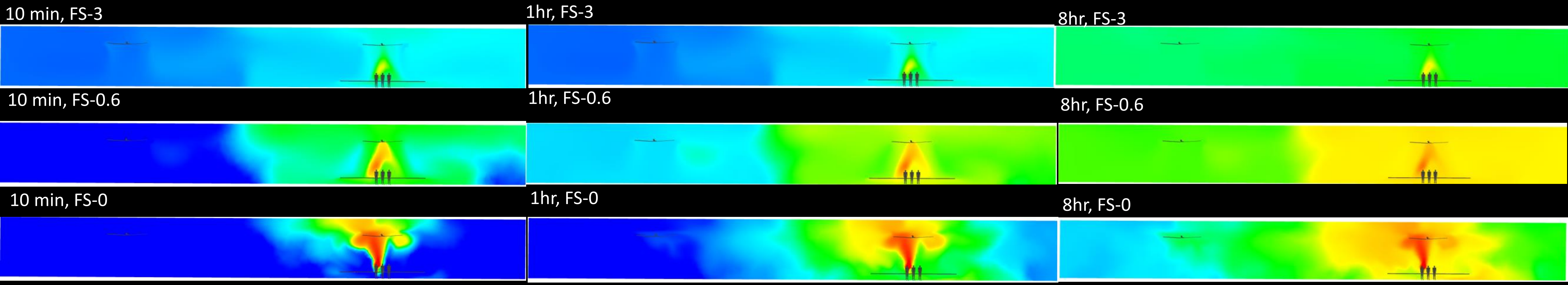


Compare Fan Operations (U-H-D-3) – Vertical Plane



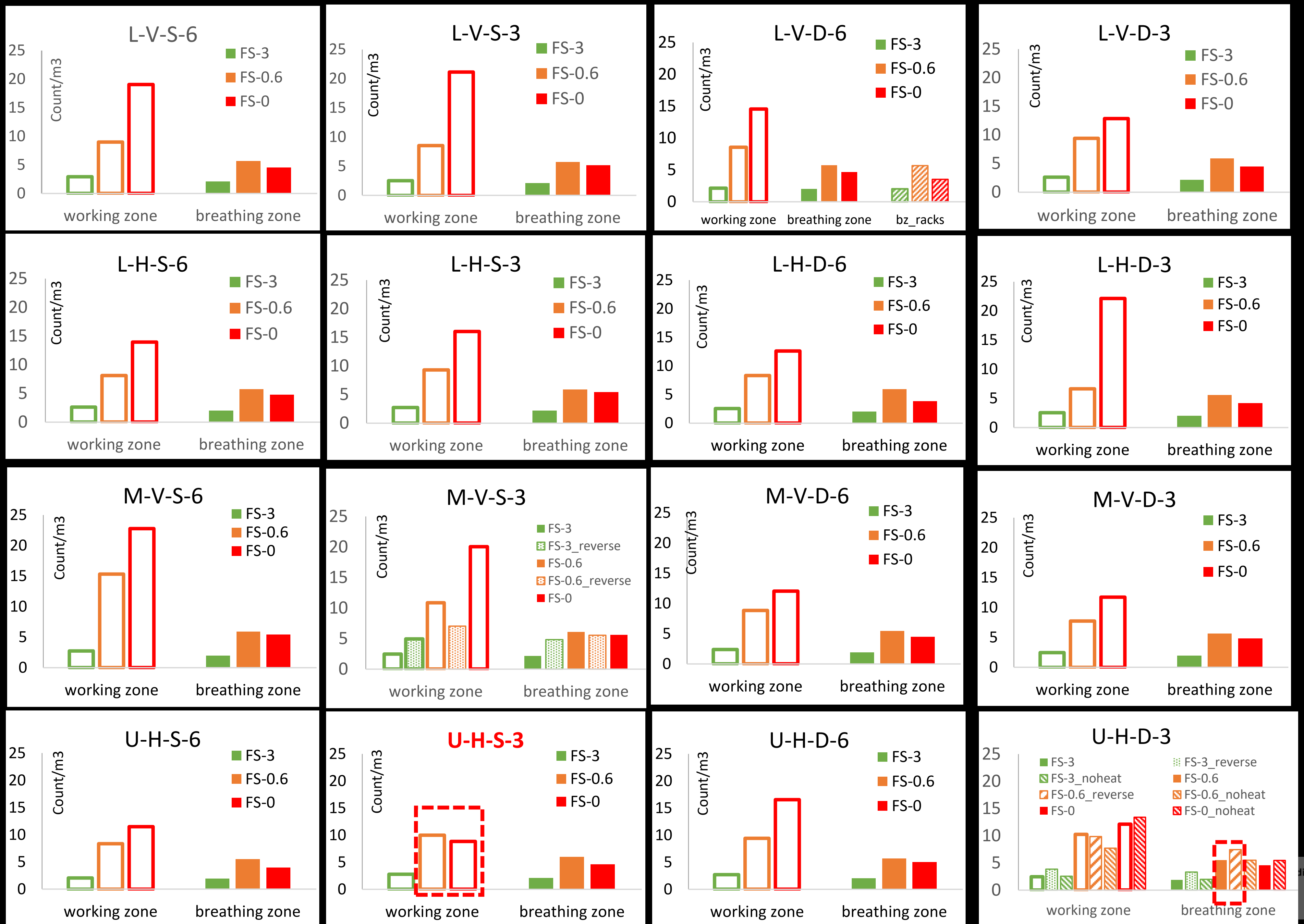
Max = 260 counts/m^3



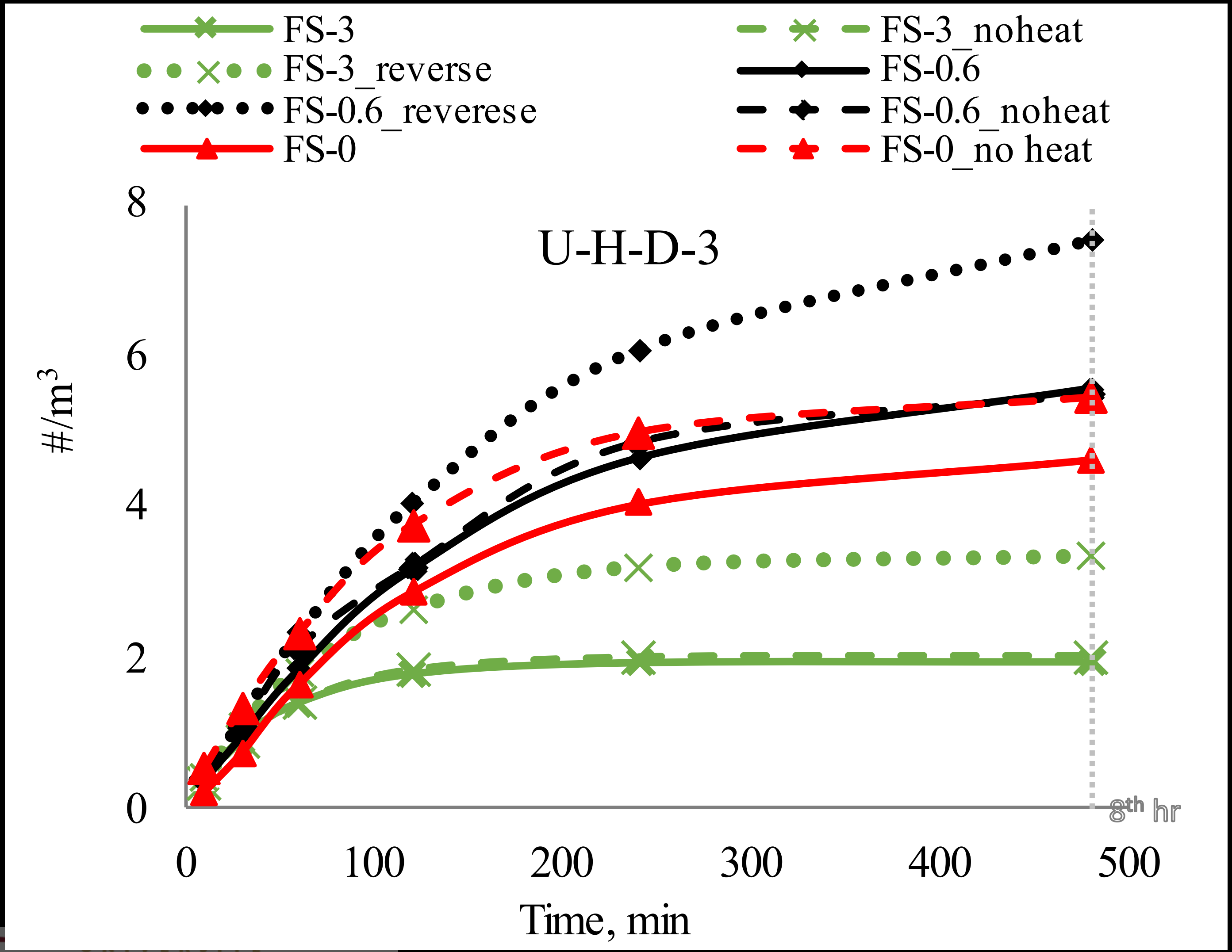


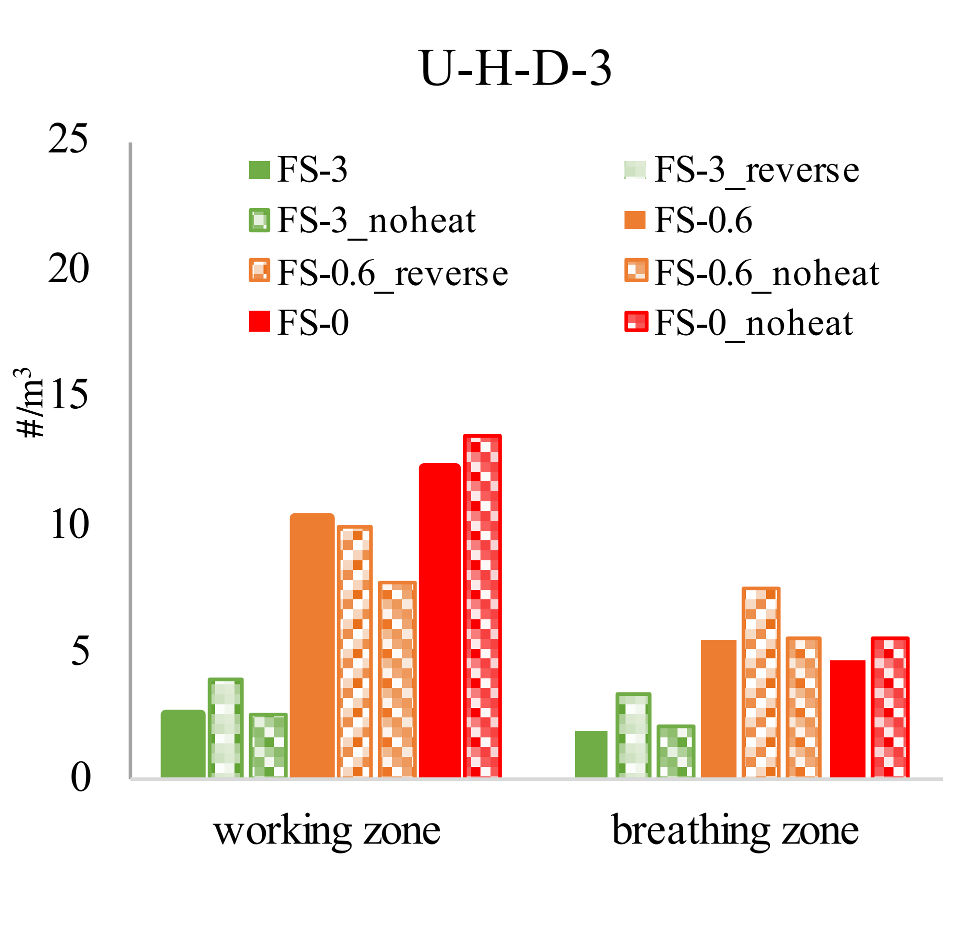
Working zone and whole-warehouse breathing zone concentrations (8 hr), counts/m³

1. Fan speed at 3 m/s (FS-3) has the highest dilution effect on whole warehouse breathing zone and working zone concentrations
2. Fan speed at 0.6 m/s (FS-0.6) performs mostly better for working zone, but slightly worse for whole warehouse breathing zone than 0% speed fan
3. Fan speed at 3 m/s (FS-3) performs worse after reversing
4. Fan speed at 0.6 m/s (FS-0.6) performs better after reversing for working zone but could perform worse for warehouse breathing zone
5. Thermal plume is very important: without thermal plume, 0% fan worsens, and FS-0.6 performs better in working zone (see U-H-D-3)



Whole warehouse breathing zone and working zone comparison





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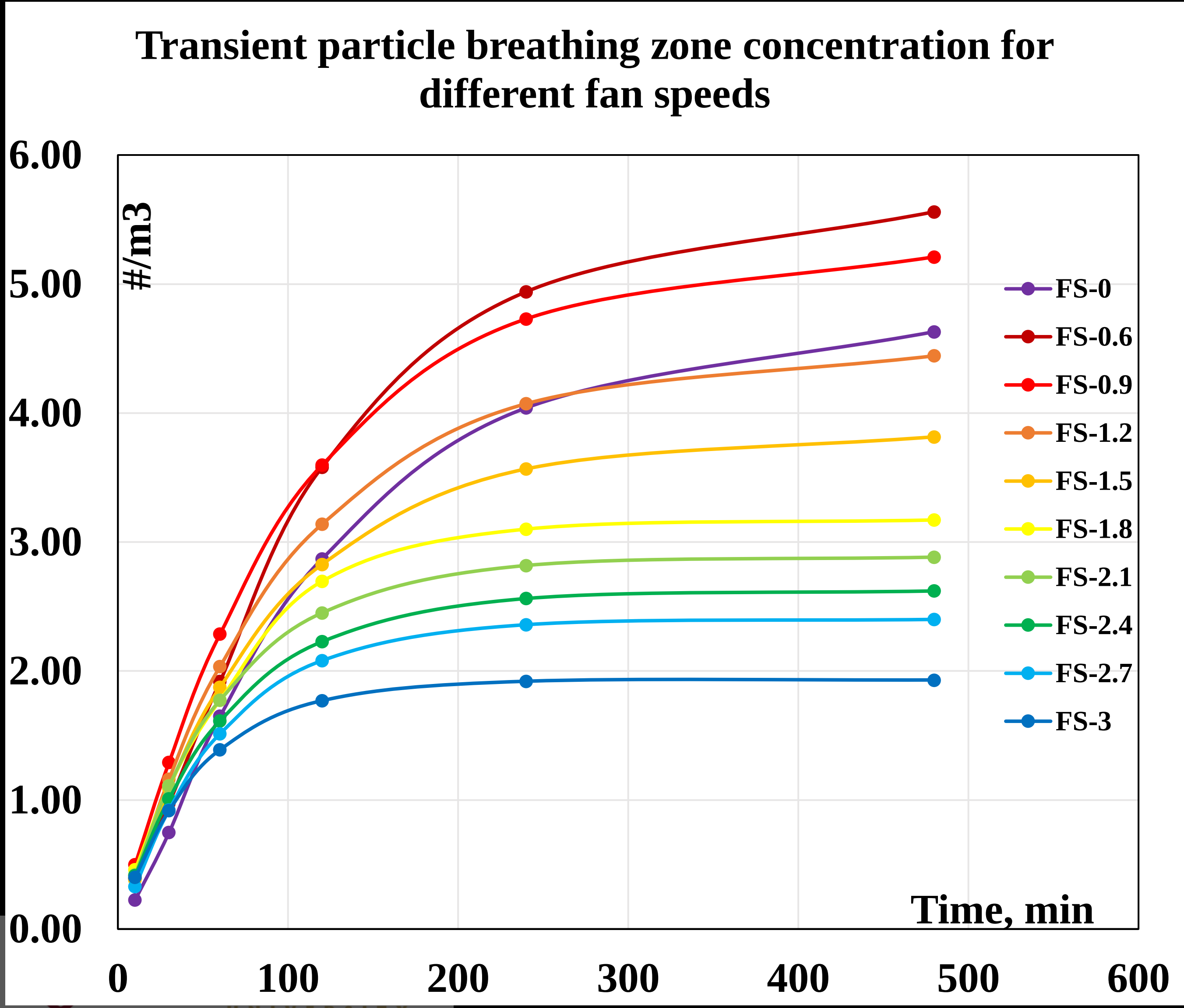
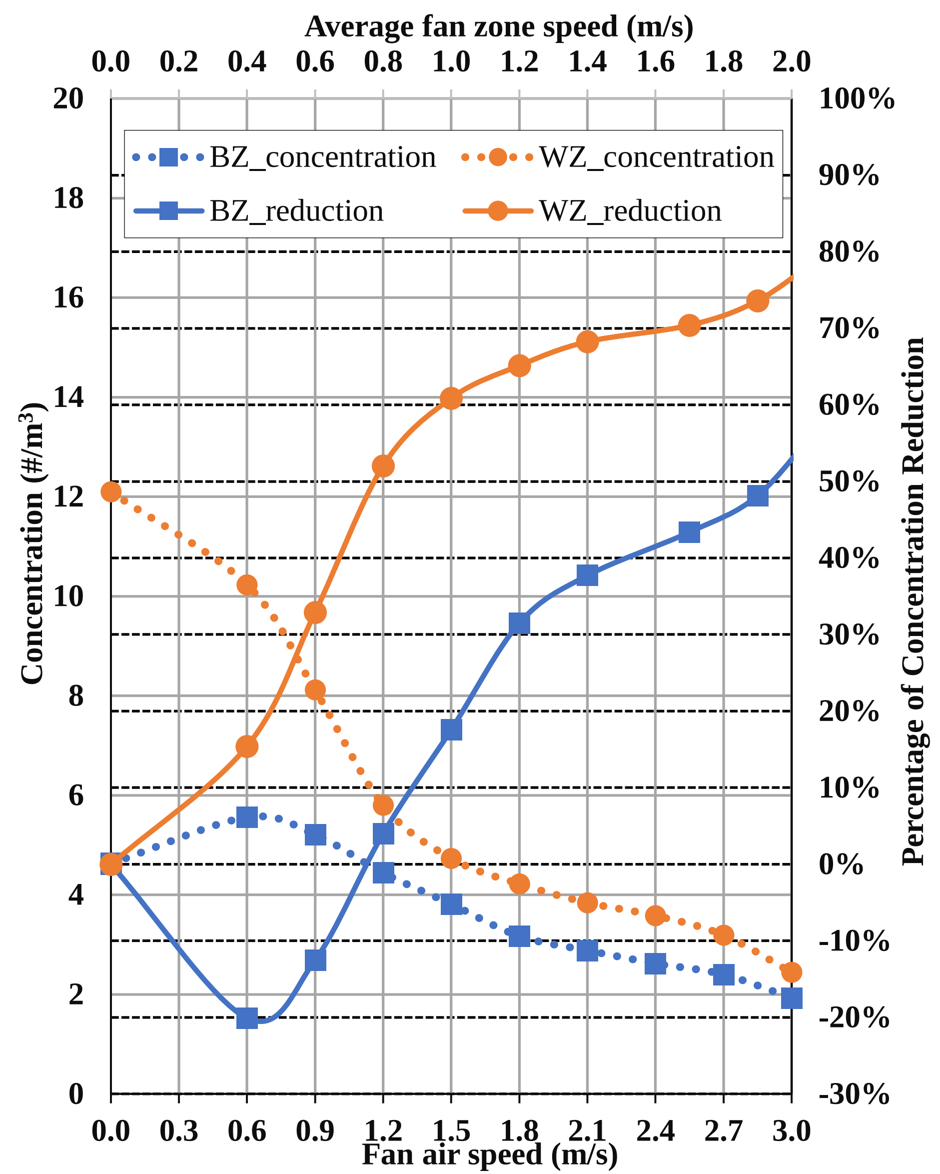
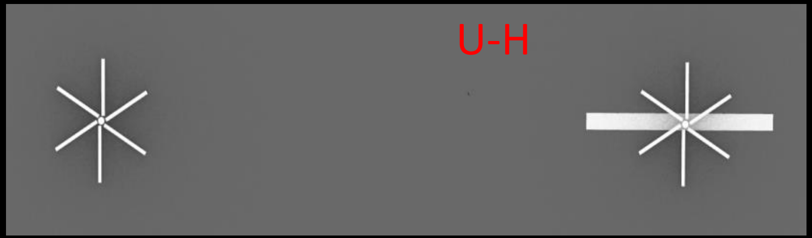
U-H-D-3 – Whole warehouse breathing zone and working zone concentration at different fan speeds

0%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% 100% fan speeds

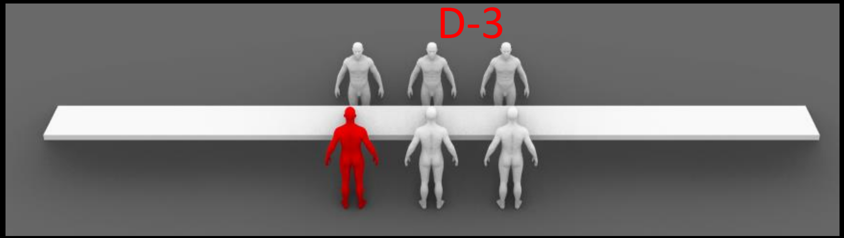




Winter Conditions (U-H-D-3)



Packing line **U**nder the fan
Horizontal placement



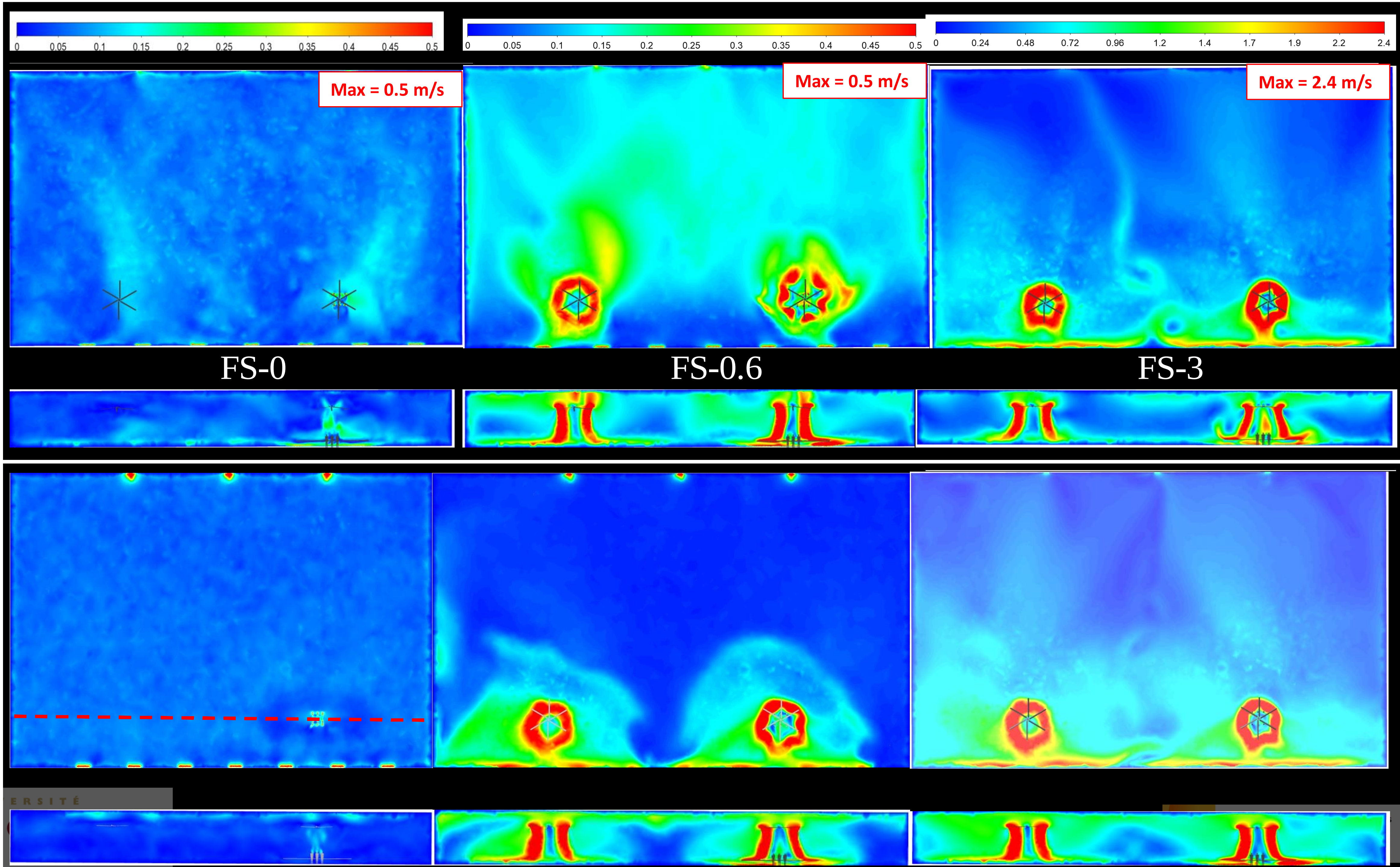
Double line workers with **3** feet apart

because it results in lowest whole-warehouse beathing zone concentration

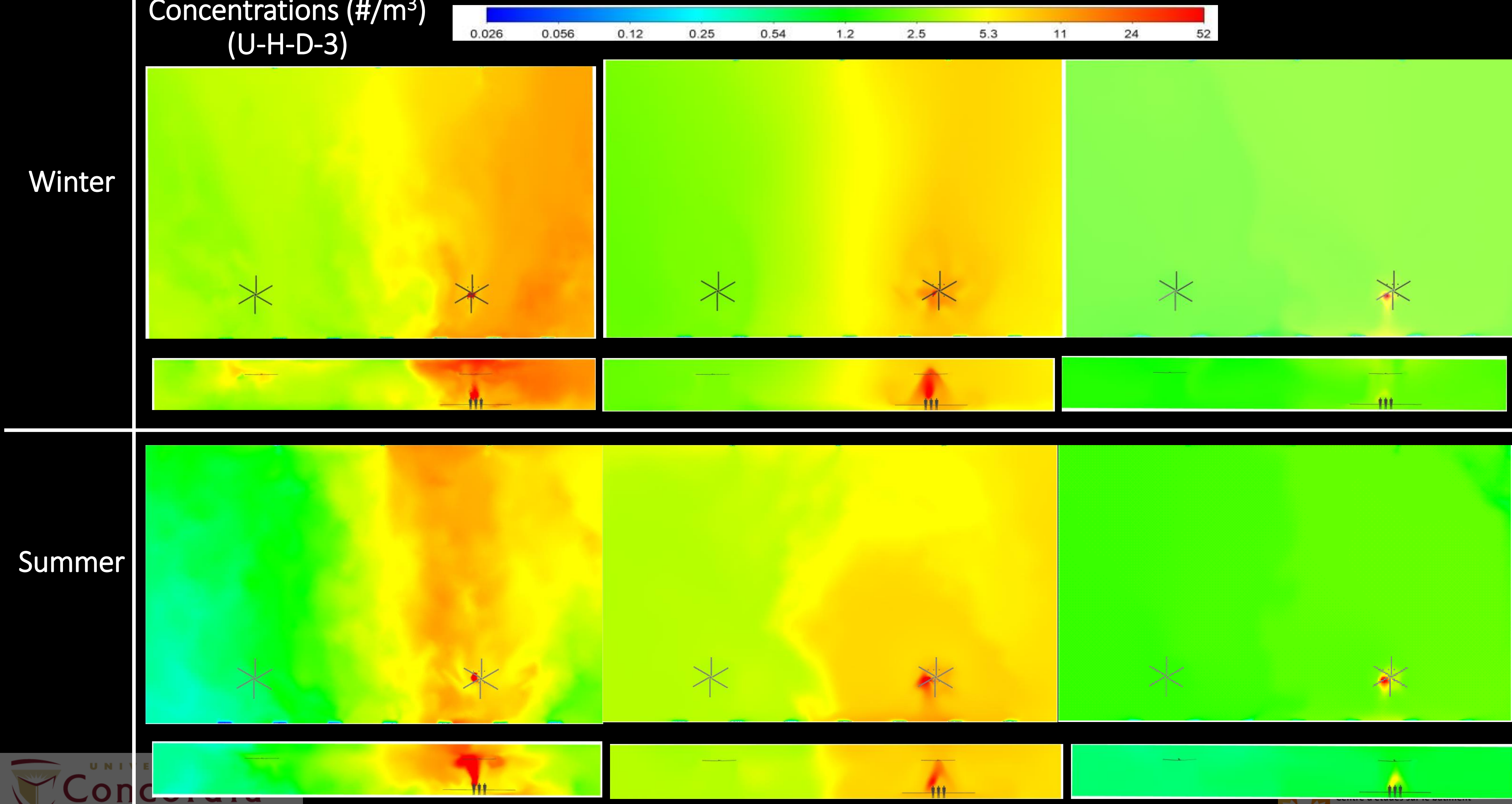
Airflow Speeds (U-H-D-3)

Winter

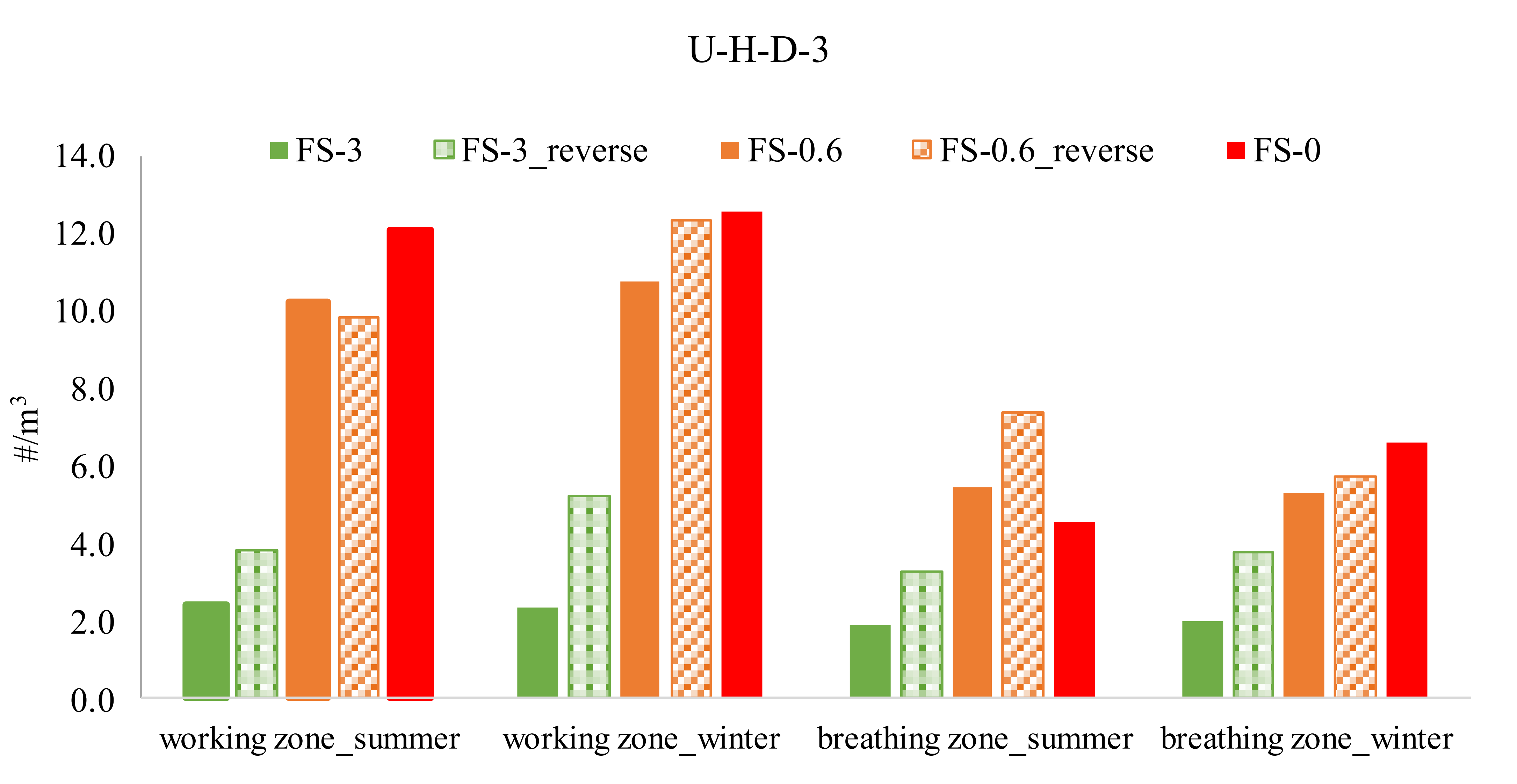
Summer



Concentrations (#/m³)
(U-H-D-3)



Comparison of concentrations ($\#/m^3$) (U-H-D-3)



Conclusions

1. FS-3 (3.0 m/s) speed fan is always the best;

2. If lower fan speed is preferred: FS-3 fan *reverse* is a good option, but not as good as FS-3 fan with downward flow;

3. Reverse fans at higher fan speed (e.g., FS-3 fan) reduces the performance compared to before reversing;

4. Reverse fan at lower fan speed (e.g., FS-0.6 = 0.6 m/s) may reduce the whole warehouse airflow speed and thus lower diluting effect, so the whole warehouse concentration could become higher.

5. To protect whole warehouse, increasing the whole warehouse overall airflow speed may improve dilution and deposition, and loss through open doors, e.g., running fans at higher speed

6. To protect working zone, increasing local airflow speed and thus dilution to higher sections of the warehouse, for example, through thermal plume or through local air moving devices (portable fans), will help

7. Thermal plume are quite essential especially for still air cases; local air mixing and movement could help to dilute and reduce the chance of creating local hotspots

Guidance for Operators

Paul Raftery, PhD

Simplified guidance

- Guidance based on season and worker-location with respect to fans:
  - Operate fans at the highest feasible speed while maintaining occupant comfort in the space.
  - Where possible, avoid locating occupants immediately downstream of each other for extended periods of time.
  - At high fan speeds (e.g., summer conditions) the simulations show a notable reduction in concentrations.
  - At low fan speeds (e.g., winter conditions) the simulations show a slight reduction in concentration in the region close to the fan (e.g., within three fan diameters), and no practical difference outside that region.

Logic behind the guidance

Where are most occupants located?	Summer conditions	Winter conditions
Close to the fan(s)	Operate fans downwards, at high speed	Operate fans at highest feasible speed that does not cause discomfort in either forward or reverse direction, whichever approach was used pre-pandemic[1]
Far from the fan(s)[3]	Operate fans downwards, at high speed	Operate fans at highest speed in either forward or reverse, whichever approach was used pre-pandemic[2]

Notes: Green/yellow/red color coding is an approximate indicator of how clear the effect was in the scenarios we simulated.

1: Simulations show slightly lower concentrations with reverse flow than with forward flow at a given low speed, but this is based on a much smaller number of simulated scenarios (two as opposed to the 16 for a typical forward-direction scenario) and is a small effect given simplifications and assumptions in the model. For simplicity, retaining the pre-pandemic direction is advised—unless reversing the fan allows for substantially higher fan speeds while avoiding draft at the occupied level.

2: Although simulations show a slight *increase* in average warehouse breathing concentration for fans at low-speed vs off, the distribution is far more uniform across the entire warehouse (i.e. no 'hot spots'). Based on feedback from the science team, overall this homogeneity is a net advantage as more mixing (i.e., dilution) is beneficial for times when workers who may be far apart for much of the workday meet and interact more closely. Lastly, the still-air results depend highly on model assumptions and simplifications (e.g., plume effectiveness, lack of local mixing, the presence of racks, etc.), and this small difference could be an artifact of those.

3: e.g. Most occupants located more than 3 fan diameters from the center of a fan for the majority of the day.

Considering other scenarios

- Large spaces with high ceilings and few occupants may be comparable
  - Hangars
  - Manufacturing facilities
  - Indoor sporting facilities without an audience (e.g. basketball court)
  - i.e., very high ventilation airflow/person and typical or low air changes per hour.
- Large spaces with dense occupancy are not comparable, further research needed
  - Churches and similar venues
  - Gymnasiums
  - i.e., typical ventilation airflow/person and typical or low air changes per hour.

AMCA Communications and Project Resources

Michael Ivanovich

AMCA Communications

- U.S. Based Guidance Agencies/Organizations
  - ASHRAE ETF √
  - Centers for Disease Control √
  - NIH (Feb. 2022)
  - ACGIH
  - Minnesota Dept. of Health
  - Others
- Other Public Communication
  - AMCA inmotion (global *ASHRAE Journal* audience) √
  - Social Media √
  - AMCA Public Webinars (Jan 5, 2022) √
  - Public Seminars (AHR Expo, Las Vegas; January 2022)
  - Trade Press Technical Articles
    - In progress

Resources

- Project Final Report
- Warehouse Model Background
- AMCA Communications and Resources

Final Report

- Project Final Report:
  - AMCA COVID Guidance for UNDUCTED Fans – Modeling Ceiling Fans, https://bit.ly/COVID_LDCF

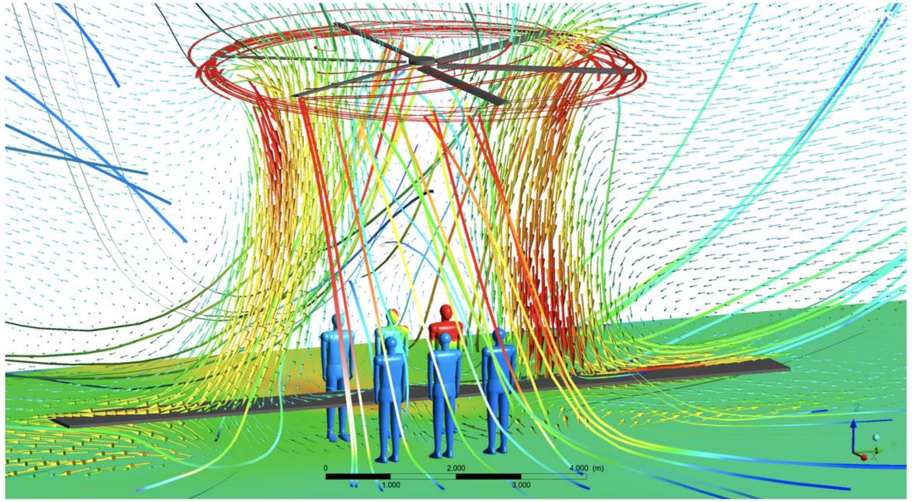
AMCA COVID-19 Guidance for Large-Diameter Ceiling Fans

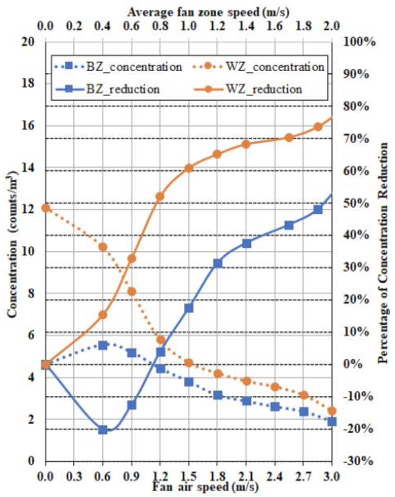
by Leon Wang - Tuesday, 26 October 2021, 10:50 AM

AMCA COVID Guidance for UNDUCTED Fans_LDCF_Final.pdf

Over a 12-month period, Dr. Wang (Principal Investigator) was in collaboration with Air Movement and Control Association (AMCA), and an international team of scientists, engineers, and researchers, executed a series of numerical simulations to investigate the impact of large-diameter ceiling fans (LDCF) on COVID-19 exposures in warehouses. An AMCA COVID-19 Guidance for LDCF is proposed on how to operate these devices to mitigate COVID-19 infections in large warehouses.

The full final report can be downloaded from **HERE**.



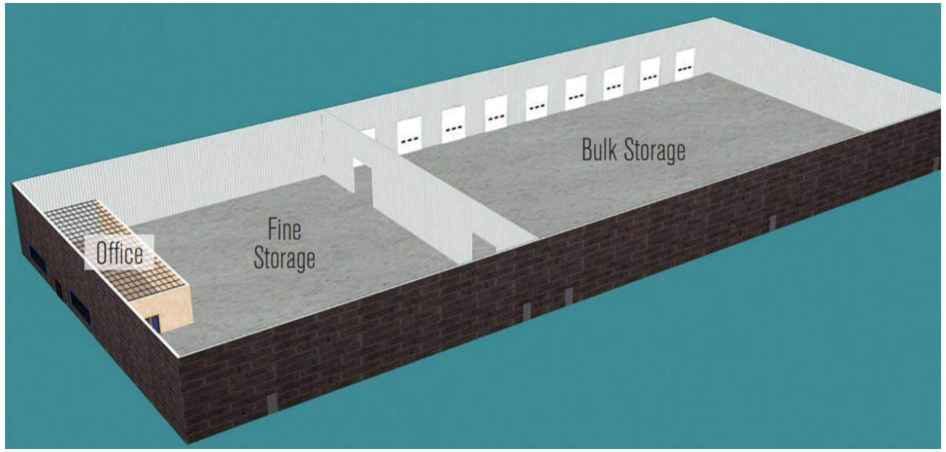


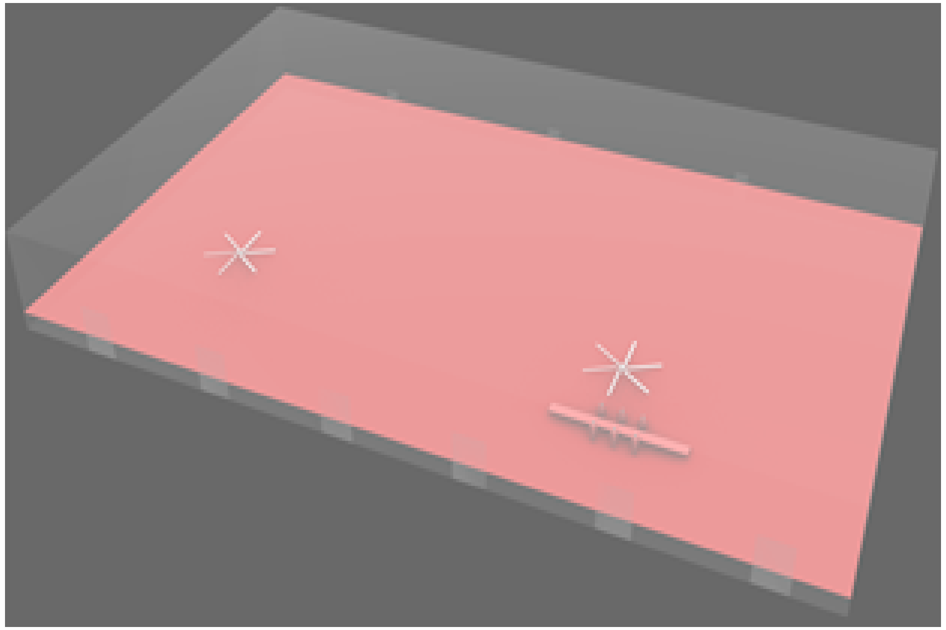
Prepared by Liangzhu (Leon) Wang, PhD, P.Eng.;

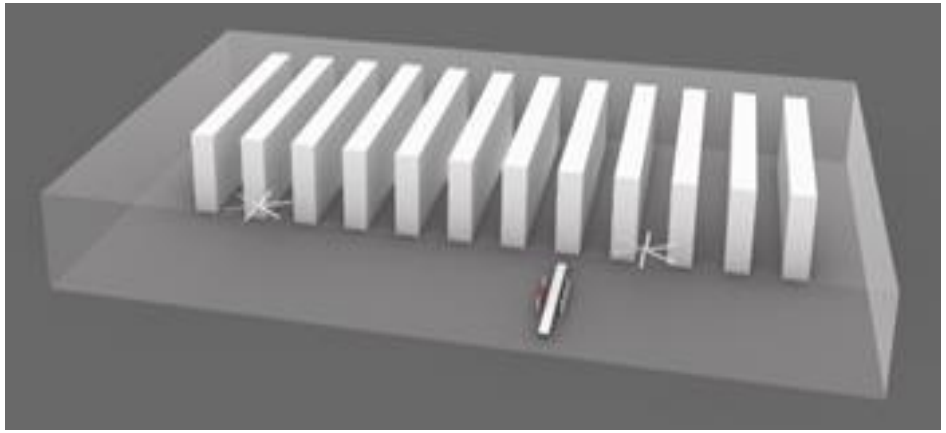
- Senwen Yang; Runzhong (Alvin) Wang;
- Mohammad Mortezazadeh, PhD;
- Jiwei Zou; and
- Chang Shu

All from Concordia University - Montreal

Warehouse Model







- https://www.energy.gov/eere/buildings/commercial-reference-buildings
- https://www.energycodes.gov/determinations
- https://www.nrel.gov/docs/fy11osti/46861.pdf
- https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-17056.pdf

AMCA Resources and Hyperlinks

- *AMCA inmotion* article
  - https://www.nxtbook.com/nxtbooks/ashrae/ashraejournal_amca_2021november_v2/
  - https://www.amca.org/educate/articles-and-technical-papers/amca-inmotion-articles/amca-covid-19-guidance-for-large-diameter-ceiling-fans.html
    - Article provides additional references with hyperlinks

- AMCA Web Page for LDCF
  - www.amca.org/LDCF

Thank you for your time!

To receive PDH credit for today's program, you ***must*** *complete the online evaluation, which will be sent via email 1 hour after this webinar.*

PDH credits and participation certificates will be issued electronically within 30 days, once all attendance records are checked and online evaluations are received.

Attendees will receive an email at the address provided on your registration, listing the credit hours awarded and a link to a printable certificate of completion.

Questions

Michael Ivanovich, AMCA International

Christian Taber, Big Ass Fans

Leon Wang, PhD, Concordia University - Montreal

Paul Raftery, PhD, U-Cal-Berkley, Center for the Built Environment

Contact: Michael Ivanovich, mivanovich@amca.org

Bonus Slides

Warehouse Construction Increasing

- **CB Richard Ellis Study**
  - https://www.cbre.us/research-and-reports/2021-US-Real-Estate-Market-Outlook-Industrial-Logistics
  - Year-over-year e-commerce growth surged to 44.5% in 2020 Q2 from 14.8% in Q1.
  - $1 billion in incremental e-commerce sales generates 1.25 million sq. ft. of warehouse space demand.
  - Net absorption is projected to reach nearly 250 million sq. ft. in 2021, **more than the previous five-year annual average** of 211 million sq. ft.

Theory – Drift-flux Model

$$\frac{\partial(\rho C)}{\partial t} + \nabla \cdot \left(\rho(\vec{V} + \vec{V_S})C\right) = \nabla \cdot [(D_P + \varepsilon_P)\nabla C] + S_C$$

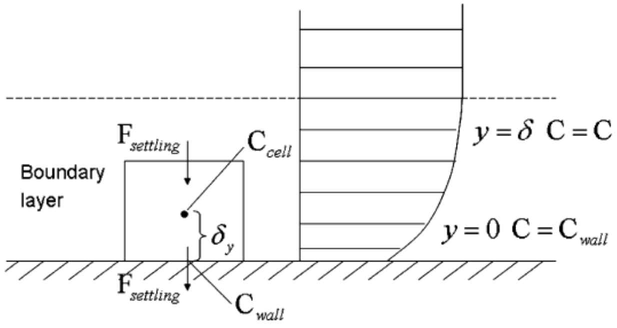
$$|V_S| = C_c \sqrt{\frac{4}{3}\frac{g d_P(\rho_P - \rho)}{C_D \rho}}$$

$$J = v_d C_{cell} = \left(D_p + \varepsilon_P\right)\frac{dC}{dy} + i v_s C_{cell}$$

$$J_{cell} = V_d C_{cell} \rho_{cell} A_{cell}$$

$$V_d = \begin{cases} \dfrac{V_s}{1 - e^{-V_s I}} (upward) \\ \dfrac{V_s}{e^{-V_s I} - 1} (downward) \\ \dfrac{u^*}{I} (vertical) \end{cases}$$

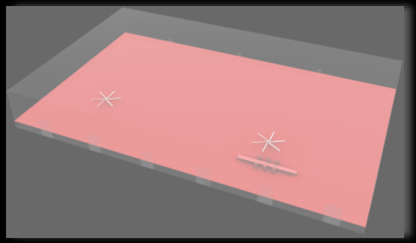
$\vec{V_S}$ = gravitational settling velocity from the Stokes equation
μ_{eff} = effective viscosity of air, $\mu_{eff} = \mu + \mu_t$
μ = molecular viscosity of air
μ_t = turbulence viscosity, determined from turbulence model
σ_C = turbulent Schmidt number,$\sigma_C = \frac{\mu_t}{\varepsilon_P}$
D_P = particle Brownian diffusion coefficient
ε_P= particle turbulent diffusivity
C_D = drag coefficient; $=\frac{24}{Re}$ for $Re < 1$; $= \frac{24}{Re}(1 + 0.15 Re^{\frac{2}{3}})$ for $1 < Re < 1000$
$Re = \frac{\rho_a d_P |V_a - V_P|}{\mu_a}$
ρ_a= air density
d_P= particle diameter
V_P = particle velocity
V_a = air velocity
μ_a=dynamic viscosity of air



$u^* = \sqrt{\frac{\tau_W}{\rho}}$; I is an integral factor

- N.P. Gao, J.L. Niu, **Modeling particle dispersion and deposition in indoor environments**, Atmos. Environ. 41 (2007) 3862–3876.
- A.C.K. Lai, W.W. Nazaroff, **Modeling indoor particle deposition from turbulent flow onto smooth surfaces**, J. Aerosol Sci. (2000).
- S. Zhu, J. Srebric, S.N. Rudnick, R.L. Vincent, E.A. Nardell, **Numerical modeling of indoor environment with a ceiling fan and an upper-room ultraviolet germicidal irradiation system**, Build. Environ. 72 (2014) 116–124.

Whole-Warehouse BZ Concentration



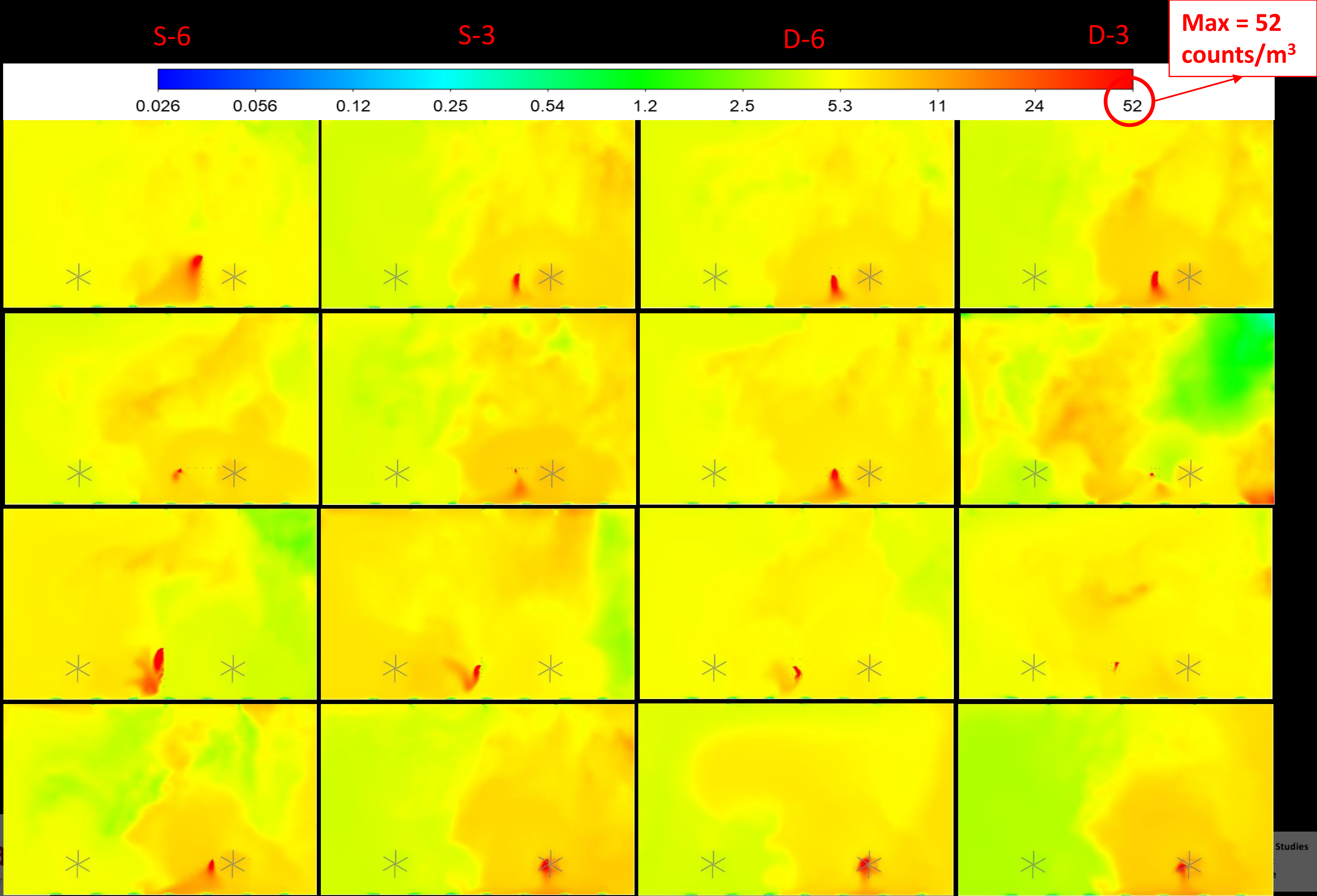
L-V

Whole-warehouse breathing zone concentration, FS-0.6, counts/m^3 (8 hr)

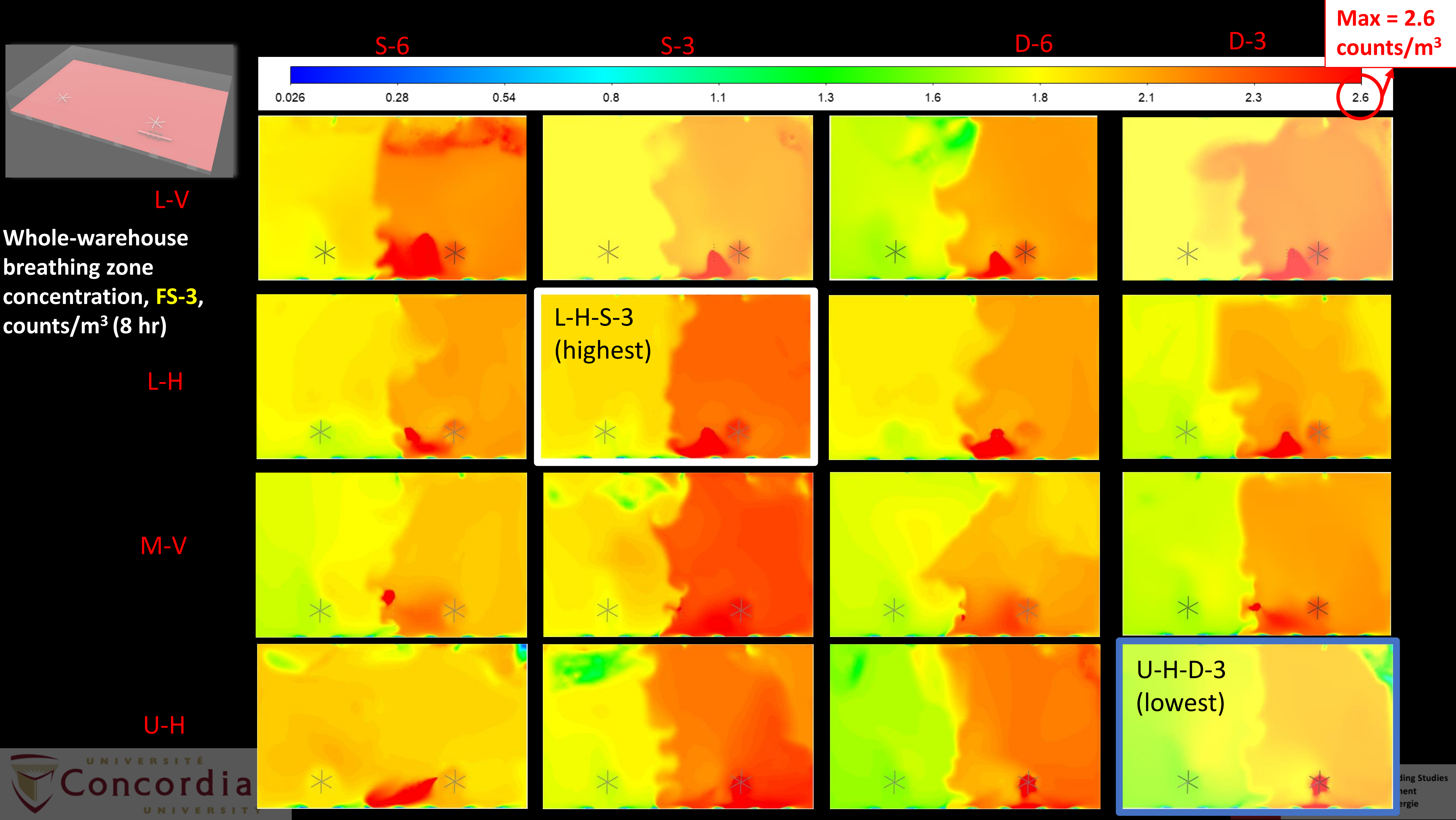
L-H

M-V

U-H

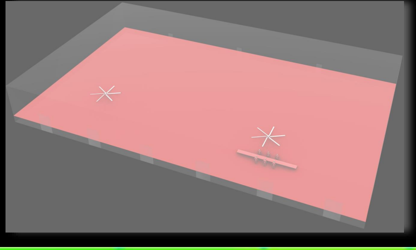


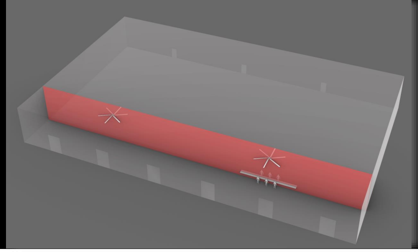
Whole-warehouse breathing zone concentration, FS-3, counts/m³ (8 hr)



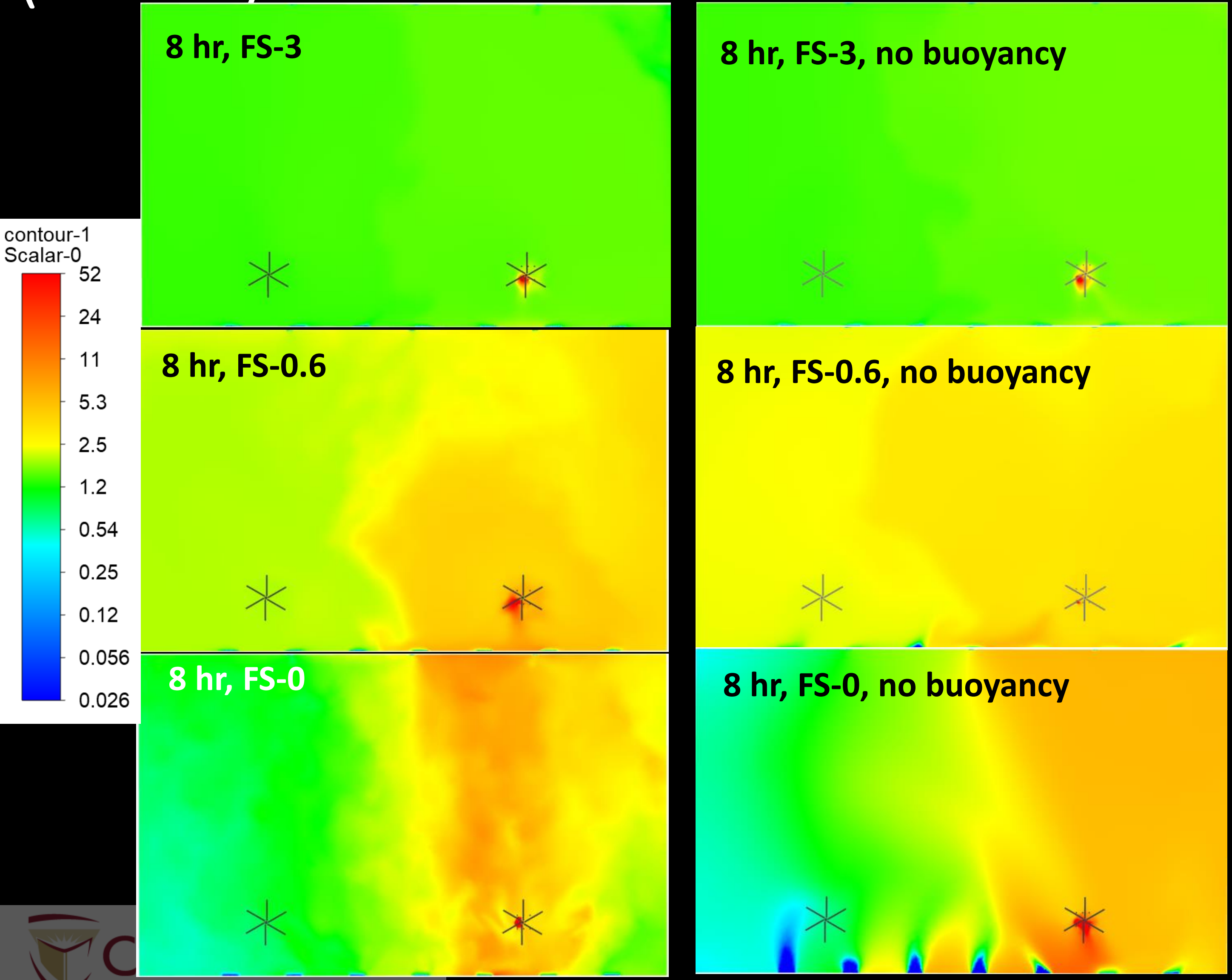
Effects of thermal plume

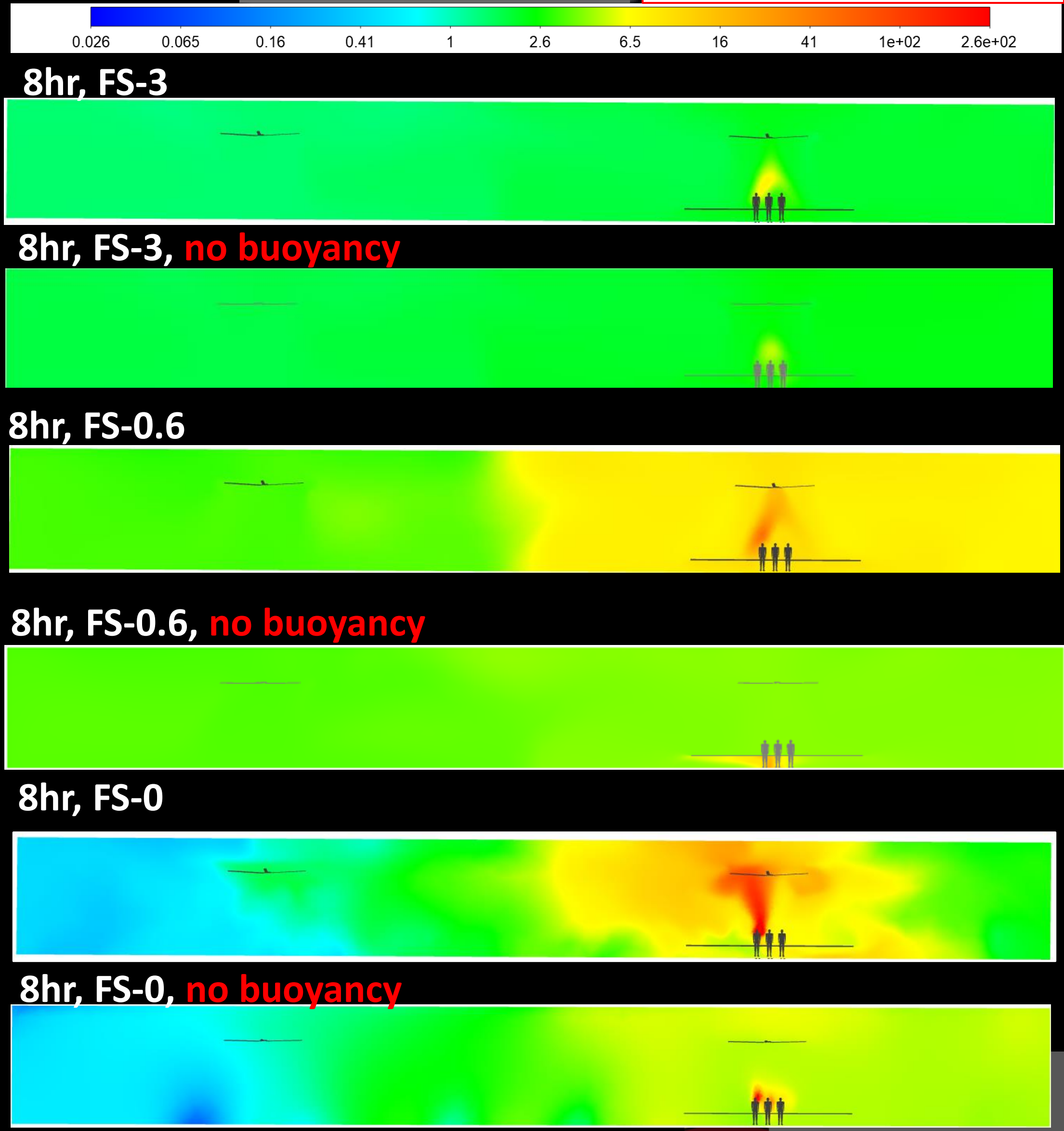
Compare impact of thermal buoyancy, counts/m^3 (U-H-D-3)



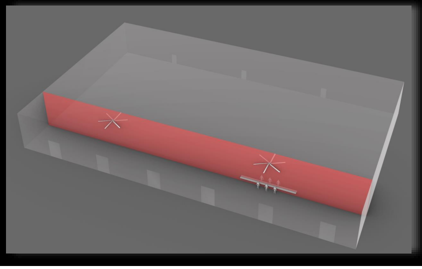


Max = 260 counts/m^3

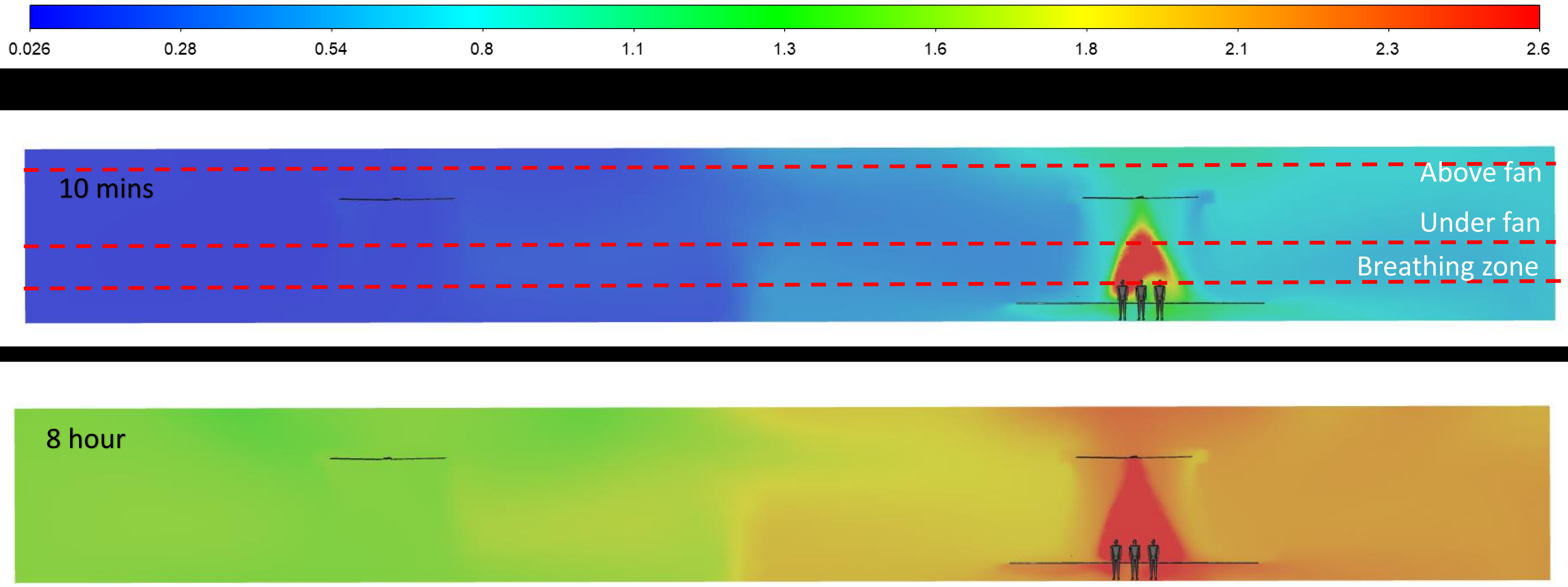




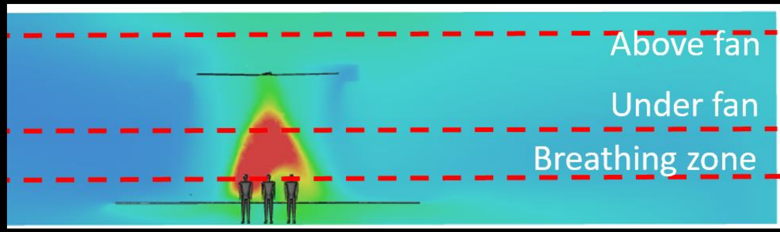
Vertical plane concentration, FS-3,counts/m^3 (U-H-D-3)



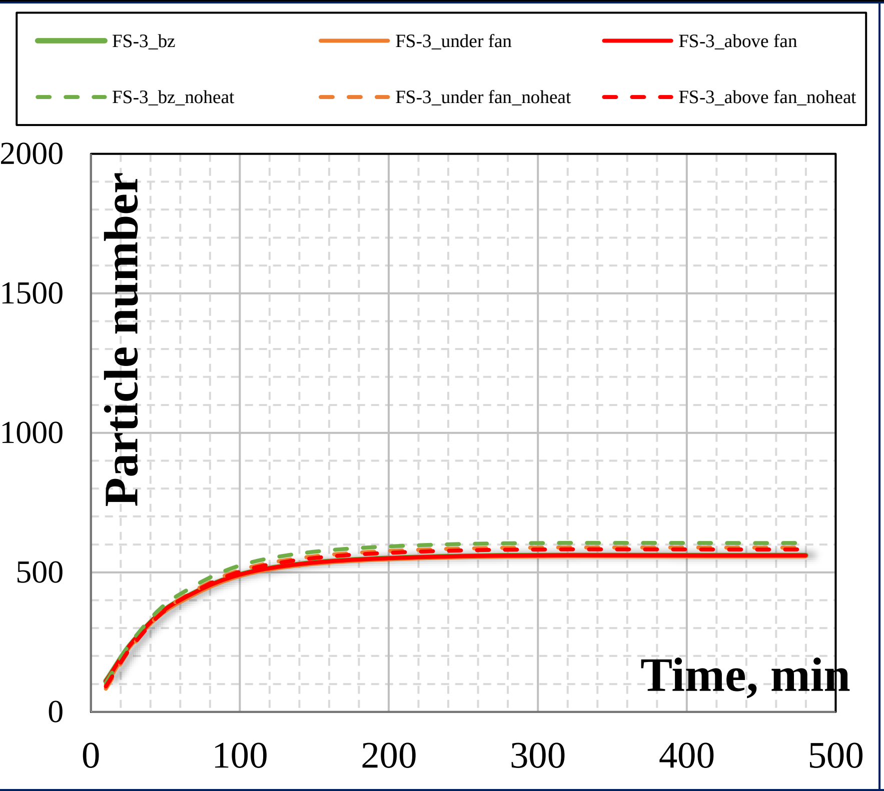
Max = 2.6 counts/m^3



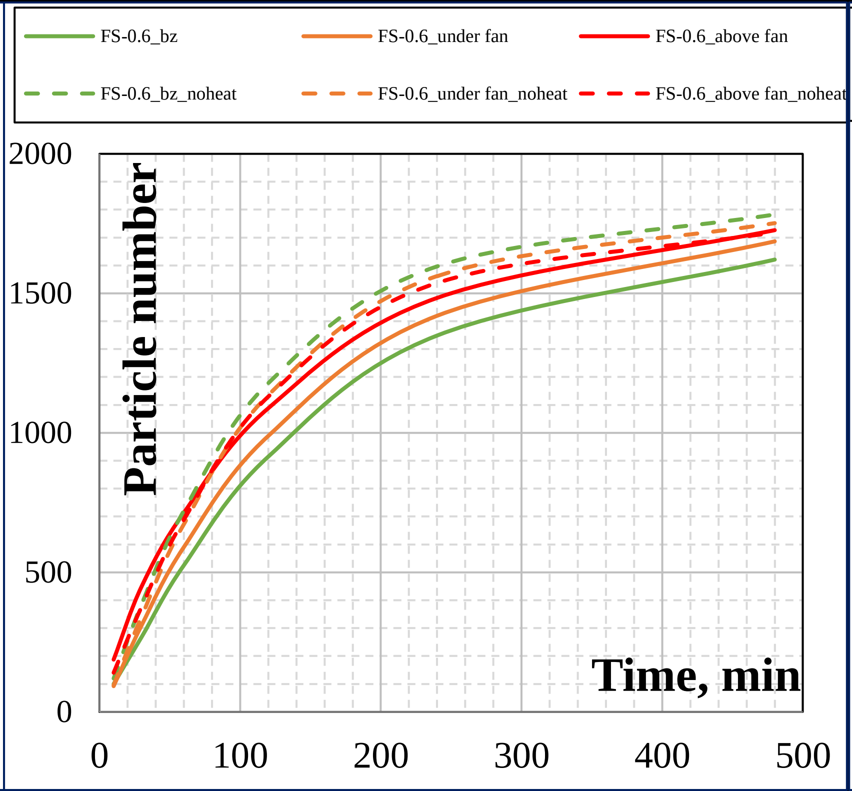
Transient average particle concentrations at whole-warehouse breathing-zone plane, under-fan plane, above-fan plane, U-H-D-3



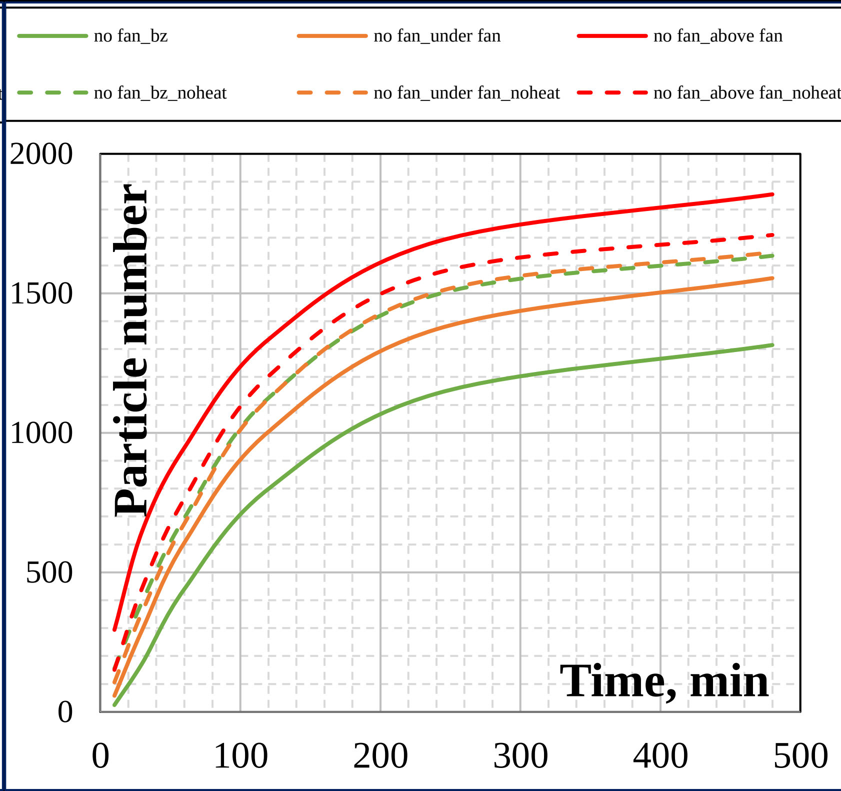
FS-3



FS-0.6



FS-0



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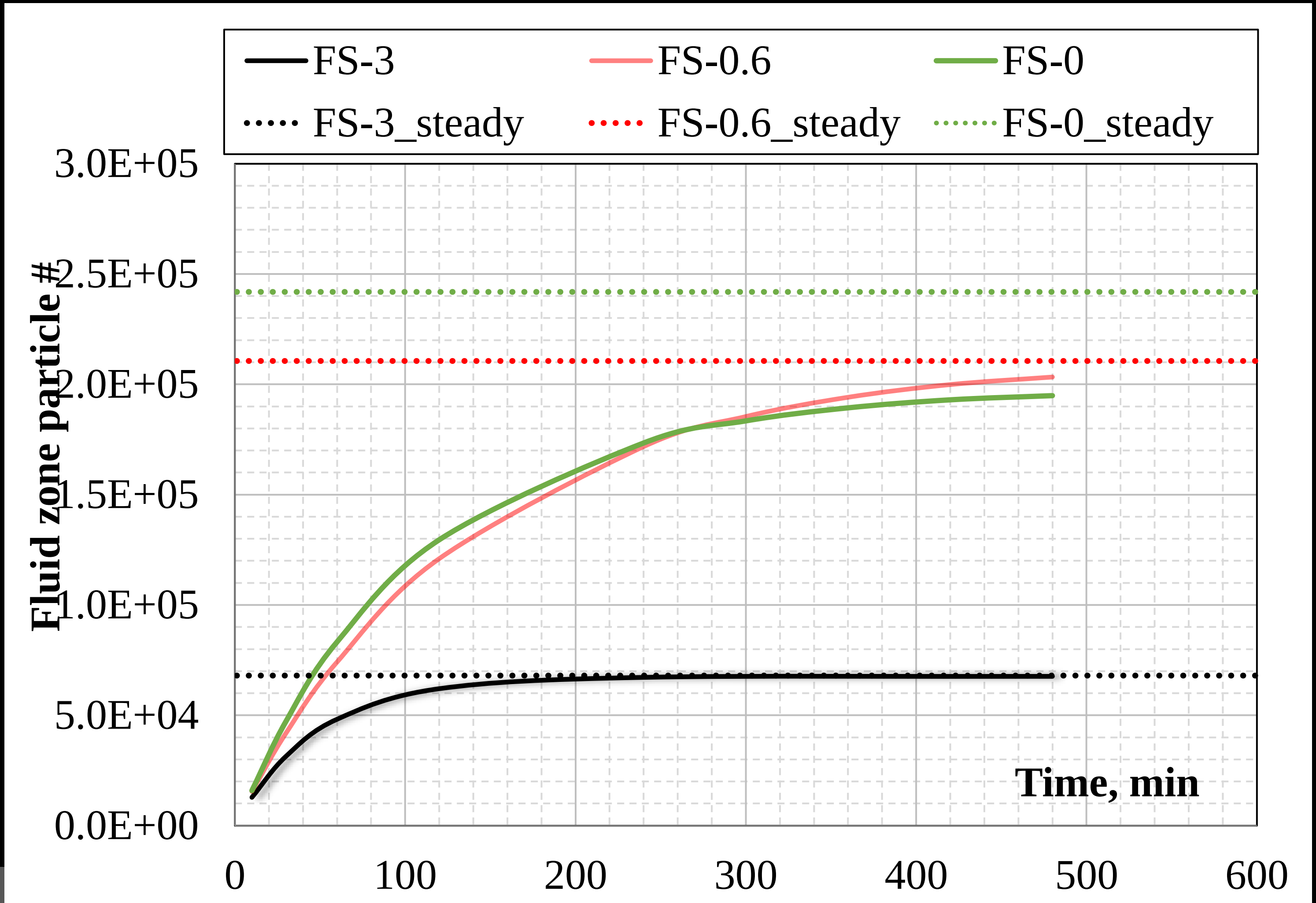
Slow speed operation

Transient whole-warehouse total particle counts – (U-H-D-3)



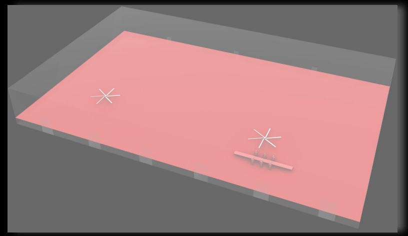
Why FS-0.6 is the worst?

- the FS-0.6 cause less surface deposition compared to FS-3 speed case
- the FS-0.6 whole warehouse breathing zone concentration is higher than FS-0 case (due to higher thermal plume for no-fan condition)

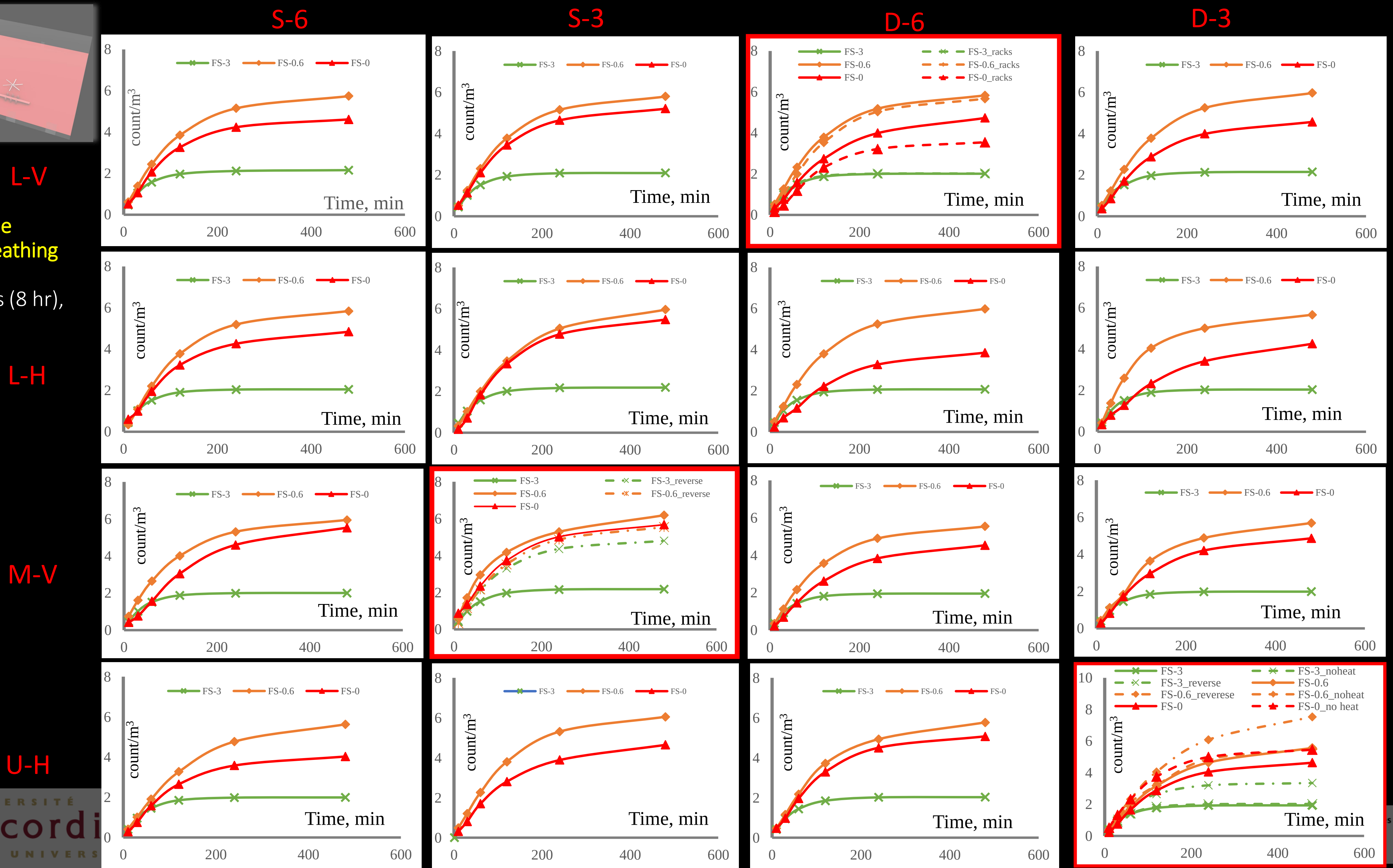
$$A_{si}\frac{dL_{si}}{dt} = v_{di}A_{si}C_z(t)$$

where:

- C = particle concentration in air [kg/m^3], subscripts: zone, outdoor air, and supply
- Q = volumetric airflow rate [m^3/s], subscripts: supply, return, infiltration, air cleaner, and local exhaust
- L_{si} = surface loading for surface i [kg/m^2]
- V = zone volume [m^3]
- A_{si} = deposition surface area for surface i [m^2]
- v_{di} = particle deposition velocity for surface i [m/s] ($v_d = k_d\, V/A_s$)
- N_s = number of surfaces (floor, walls, and ceiling)
- η_{ac} = particle filtration efficiency of air cleaner [-]
- k_d = particle deposition rate [1/s]
- G = particle generation rate [kg/s]
- P = particle penetration factor [-]
- t = time [s]



Transient **whole warehouse breathing zone** particle concentrations (8 hr), counts/m^3

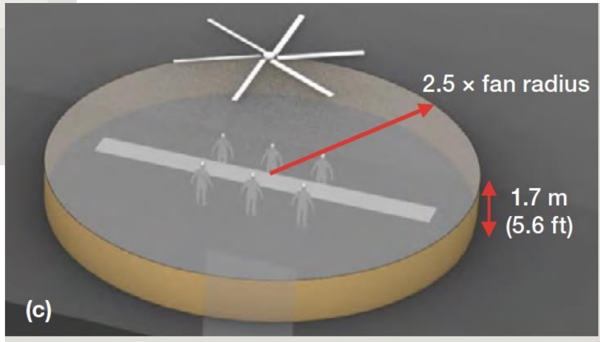


Fan Parameters for Design Guidance

Fan-speed label	Fan speed	Fan speed	Air speed exiting fan	Airflow exiting fan	Average air speed at side surface[1]	Average fan-zone[2] air speed	Maximum air speed in fan zone
	(% max. rpm)	rpm	m/s (fpm)	m^3/s (cfm)	m/s (fpm)	m/s (fpm)	m/s (fpm)
FS-0.6	20	16	0.6 (118)	18 (38,400)	0.2 (39)	0.4 (79)	1.0 (197)
FS-0.9	30	23	0.9 (177)	27 (57,600)	0.3 (59)	0.6 (118)	1.3 (256)
FS-1.2	40	31	1.2 (236)	36 (76,800)	0.4 (79)	0.8 (157)	1.7 (335)
FS-1.5	50	39	1.5 (295)	45 (96,000)	0.5 (98)	1.0 (197)	2.2 (433)
FS-1.8	60	47	1.8 (354)	54 (115,200)	0.6 (118)	1.2 (236)	2.5 (492)
FS-2.1	70	55	2.1 (413)	63 (134,400)	0.7 (138)	1.4 (276)	2.9 (571)
FS-2.4	80	62	2.4 (472)	72 (153,600)	0.8 (157)	1.7 (335)	3.4 (669)
FS-2.7	90	70	2.7 (531)	82 (172,800)	0.9 (177)	1.9 (374)	3.8 (748)
FS-3.0	100	78	3.0 (591)	91 (192,000)	1.0 (197)	2.1 (413)	4.4 (866)

[1]The side of the cylinder of the fan zone colored by yellow in Figure 5c.
[2]A cylinder around the fan center at a height of 1.7 m (5.6 ft).

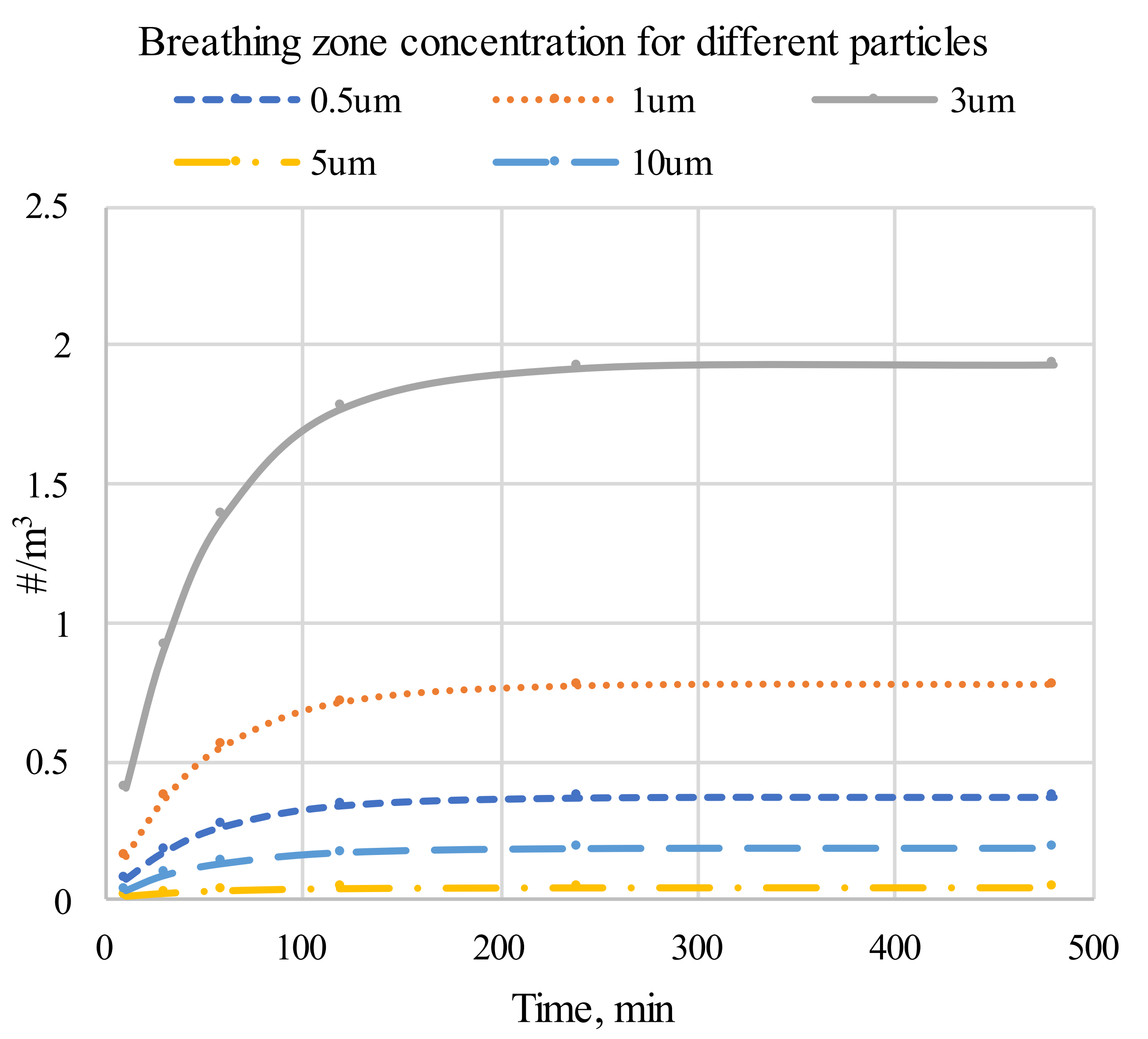
TABLE 2. Fan air speed and airflow rate in the fan zone for a case of U-H-D-3.

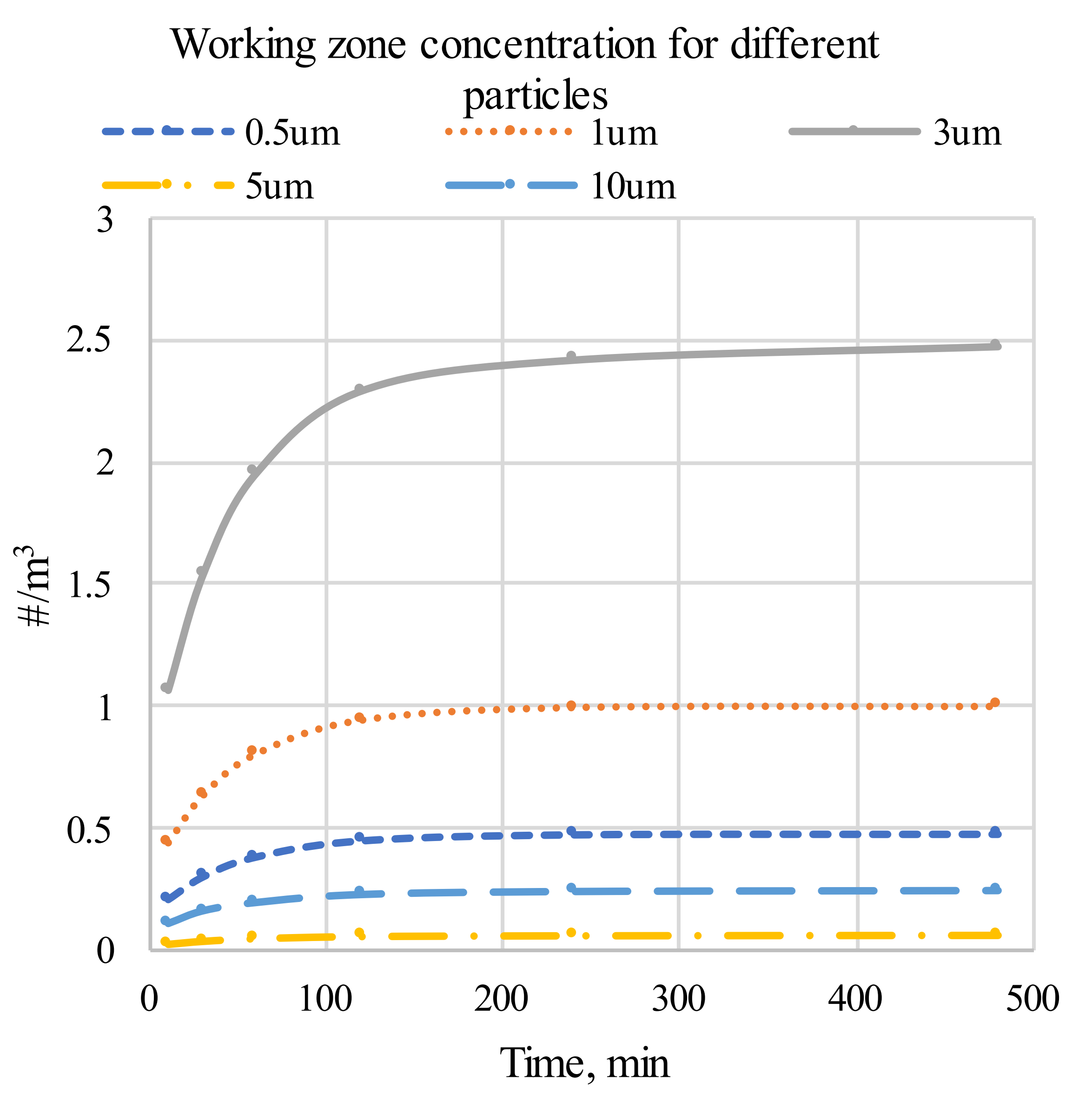


Note: Figure from AMCA inmotion article at www.amca.org/inmotion

Impact of particle diameters

Particle concentration for different particle diameters (U-H-D-3, FS-3) (Summer)

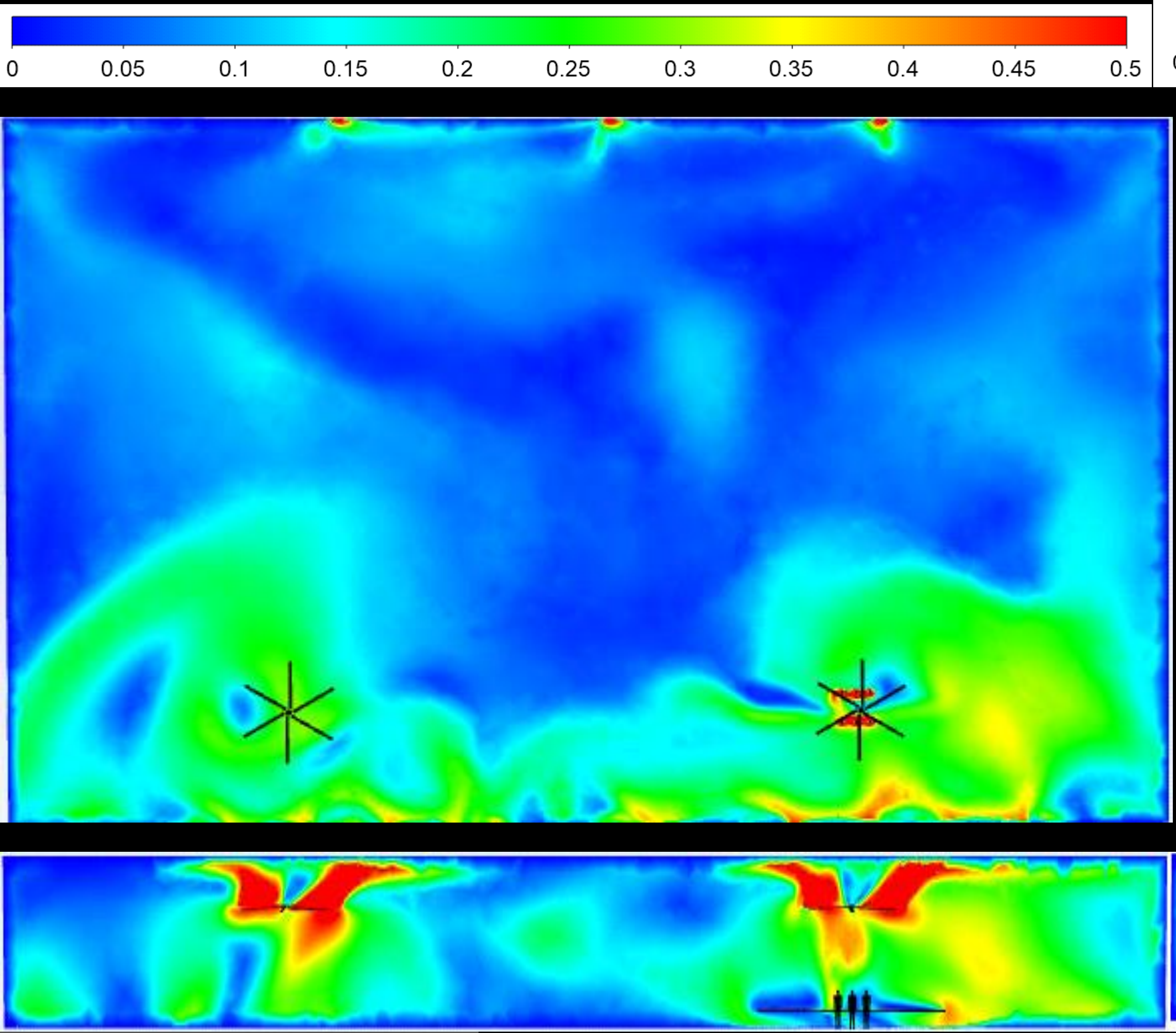




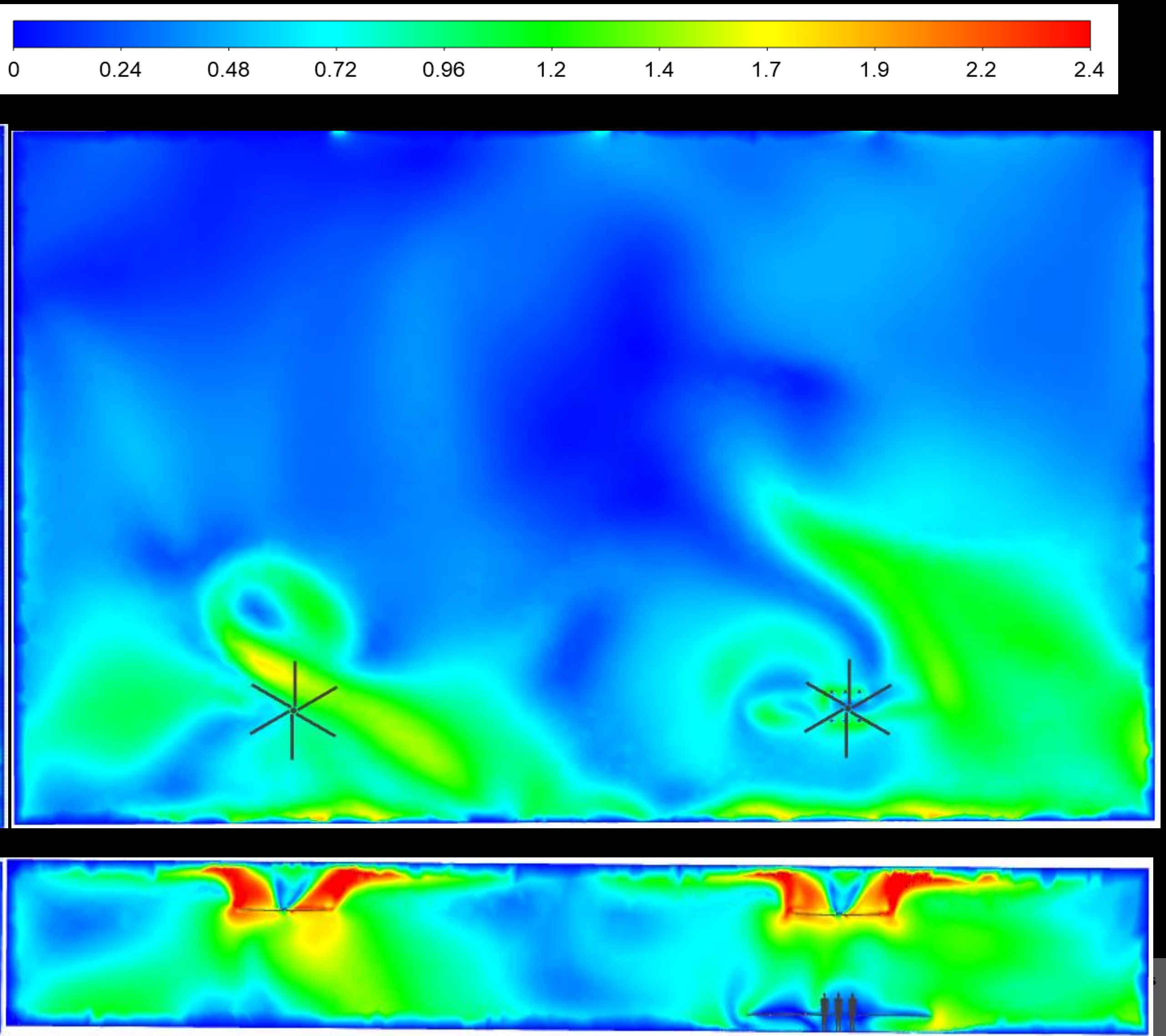
Impact of fan reverses

Airspeeds (m/s) after reverse (U-H-D-3) (Summer)

FS-0.6_reverse

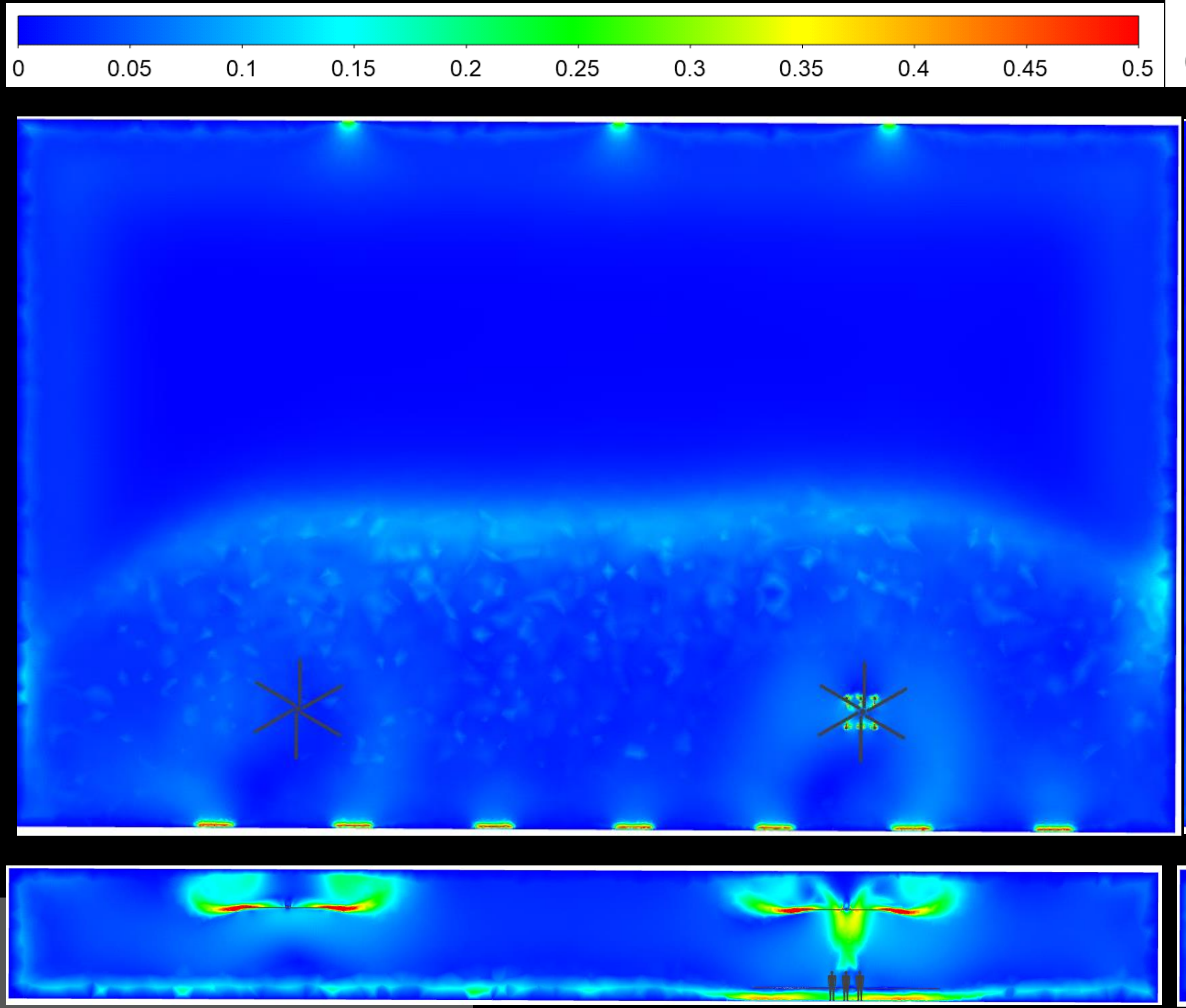


FS-3_reverse

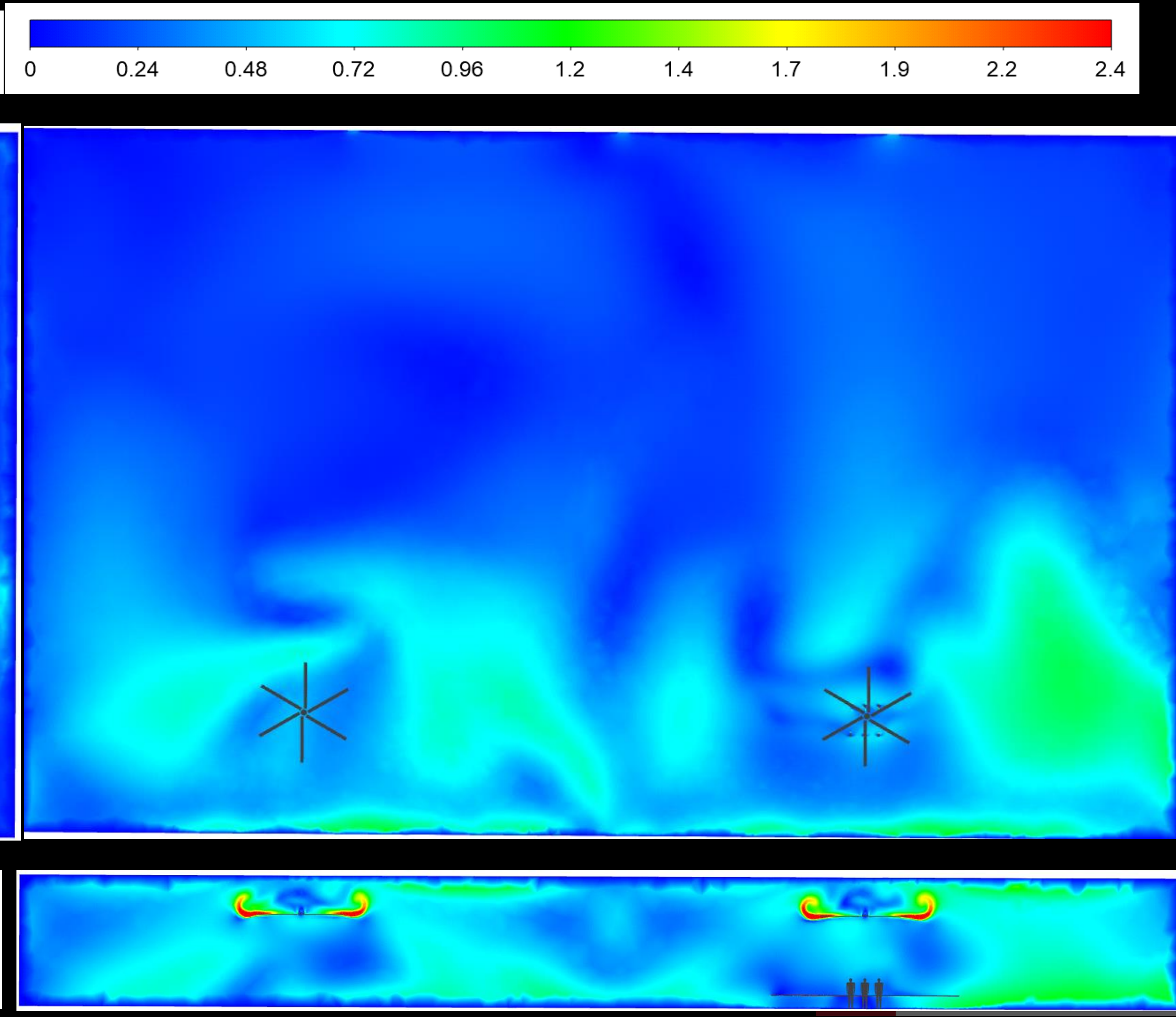


Airspeeds (m/s) after reverse (U-H-D-3) (Winter)

FS-0.6_reverse



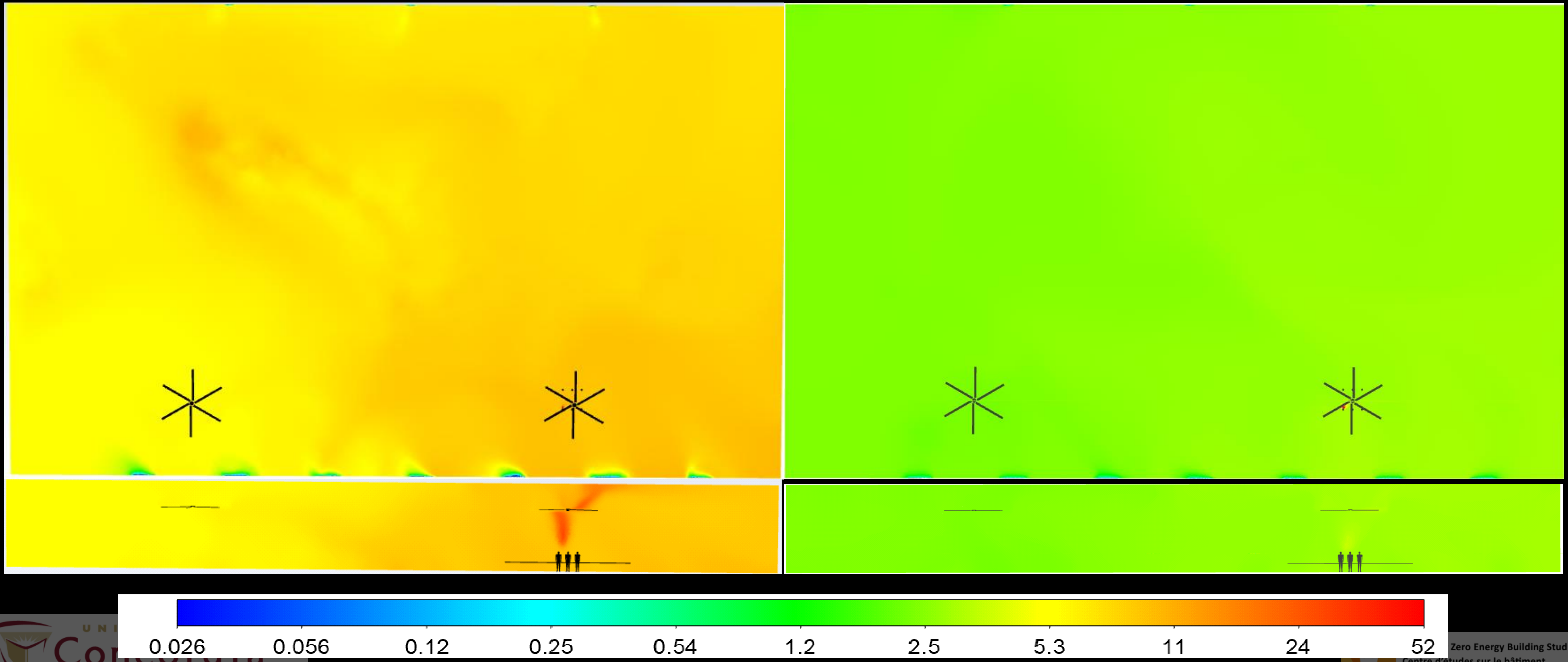
FS-3_reverse



Concentrations (#/m^3) after reverse (U-H-D-3) (Summer)

FS-0.6_reverse

FS-3_reverse



Concentrations (#/m^3) after reverse (U-H-D-3) (Winter)

FS-0.6_reverse

FS-3_reverse