Foster + Partners

CIBSE Technical Symposium 2018

Assessing Thermal Comfort and Performance of the Airfloor HVAC System using Multi-Software Coupled Modelling Method

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Outline

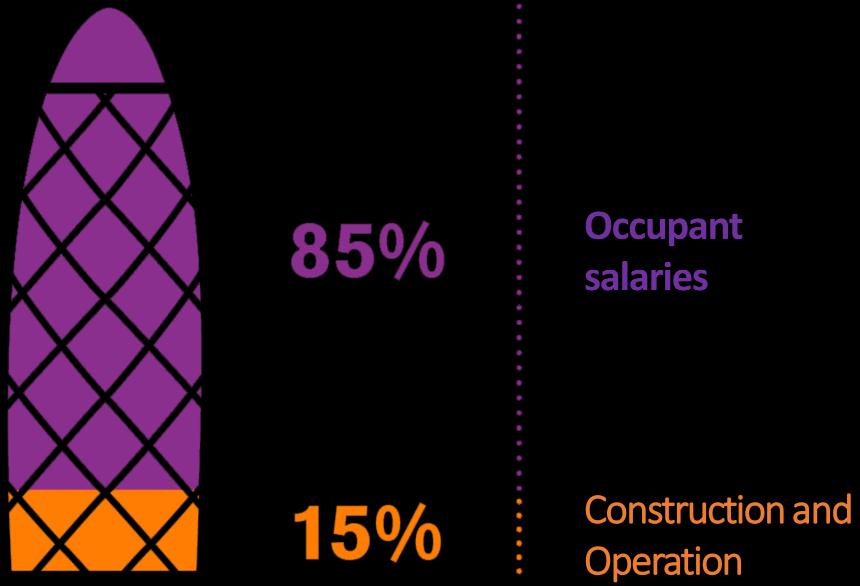
1. INTRODUCTION
Importance of the Healthy and Productive Environments

- We spend 90% of our time indoors.
- The quality of the internal environment has direct impacts on the health and productivity of building users.

Views out allow eyes to rest from screens, and **improve productivity by 7-12%**

Workers' **productivity reduces by 6%** when temperatures are **too warm**

Exposure to distracting **noises can reduce performance by 66%**

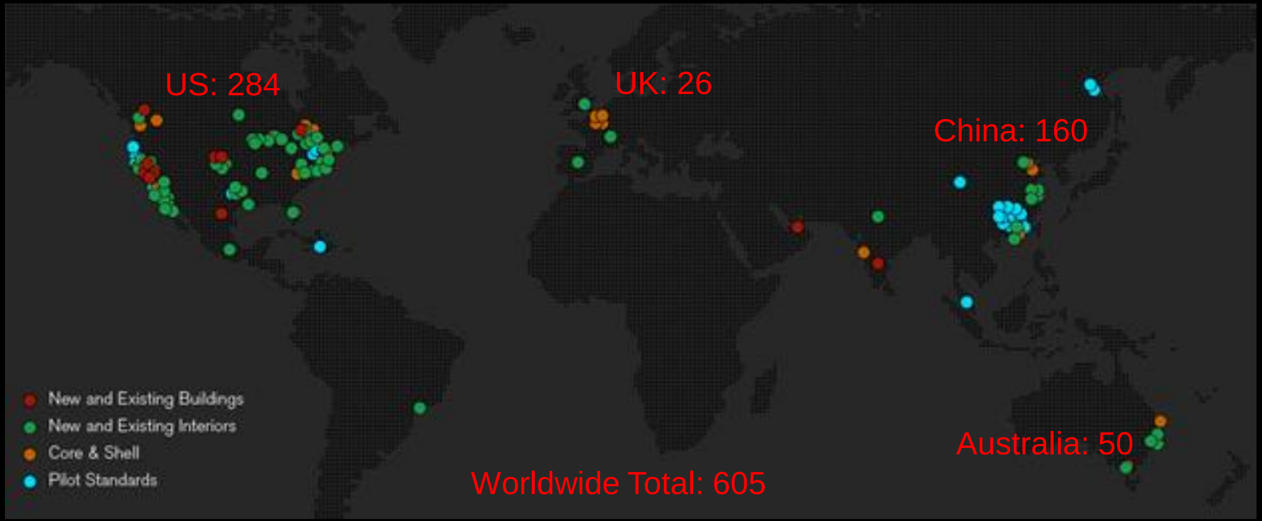


Cost of a typical office building over 25 years

Source: WGBC, 2014. *Health, Wellbeing & Productivity in Offices*

1. INTRODUCTION
Introduction to the WELL Building Standard

WELL registered projects worldwide (as of early 2018)



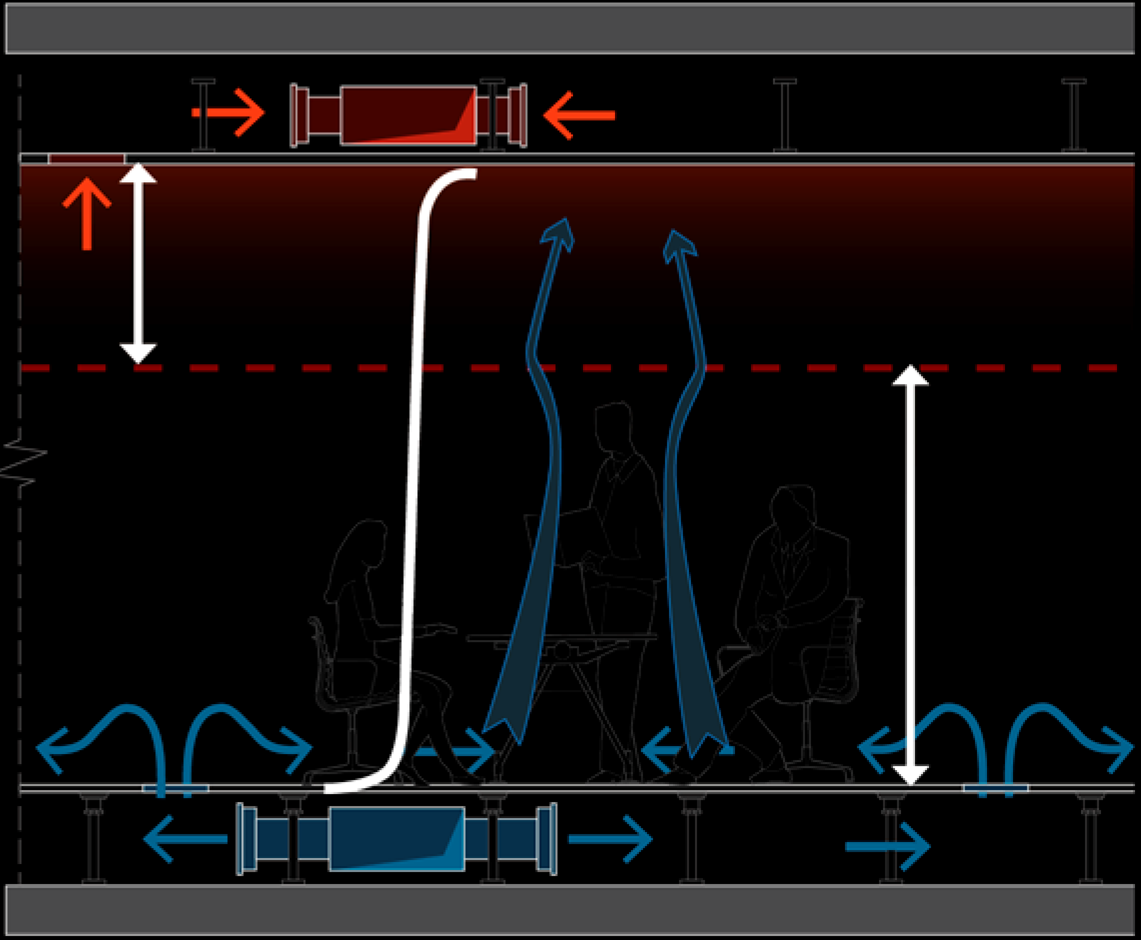
WELL certified projects worldwide (as of early 2018)

Pilot	Silver	Gold	Platinum
6	**28**	**37**	**6**

- Covers 7 concepts related to health and wellbeing
- Evaluates post-occupancy performance
- Maintained by IWBI and has several synergies with other standards such as LEED and BREEAM

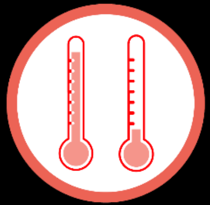
Source: IWBI, 2018. *Browse WELL Projects*

1. INTRODUCTION
Advantages of Displacement Ventilation System



Increased Indoor Air Quality

- Pollutants displaced to stratified zone
- Reduced Sick Building Syndrome
- 20% reduction on absenteeism and sick leave
- 10% increased productivity



Improved Thermal Comfort

- Better room radiant temperature
- Less supply velocity to reduce down-drafts
- Minimise complains regarding thermal comfort which might potentially reduce productivity by 4-6%

Reduced Noise Levels

- Noise level reduced due to lower velocity supplied to the occupied zone
- Elimination of low frequency ventilation noise can increase performance by 8%

Sources:
BCO, 2011. *The Impact of Office Design on Business Performance*
WGBC, 2014. *Health, Wellbeing & Productivity in Offices*

1. INTRODUCTION
Features Distribution and Relationship with the Research

List of WELL Features Favour Displacement System

- AIR
- WATER
- NOURISHMENT
- LIGHT
- FITNESS
- COMFORT
- MIND

Feature 03 – Ventilation Effectiveness
- Ventilation rates comply with ASHRAE 62.1-2013
- Displacement ventilation system has higher ventilation effectiveness in cooling mode

Feature 21 – Displacement Ventilation
- Directly recommend to use side wall displacement system or UFAD system
- System should be validated by CFD simulation

Feature 76 – Thermal Comfort
- Comply with ASHRAE 55-2013
- Mean radiant temperature is part of PMV matrix

Feature 83 – Radiant Thermal Comfort
- Comply with ASHRAE 55-2013
- Use hydronic radiant heating/cooling systems (sometimes coupled with traditional displacement systems)

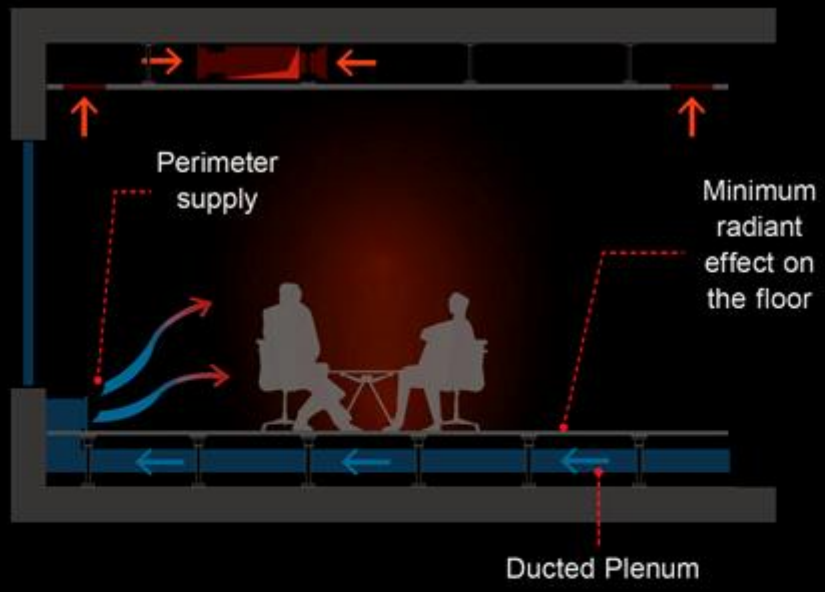
2. AIMS & OBJECTIVES
Research Aims

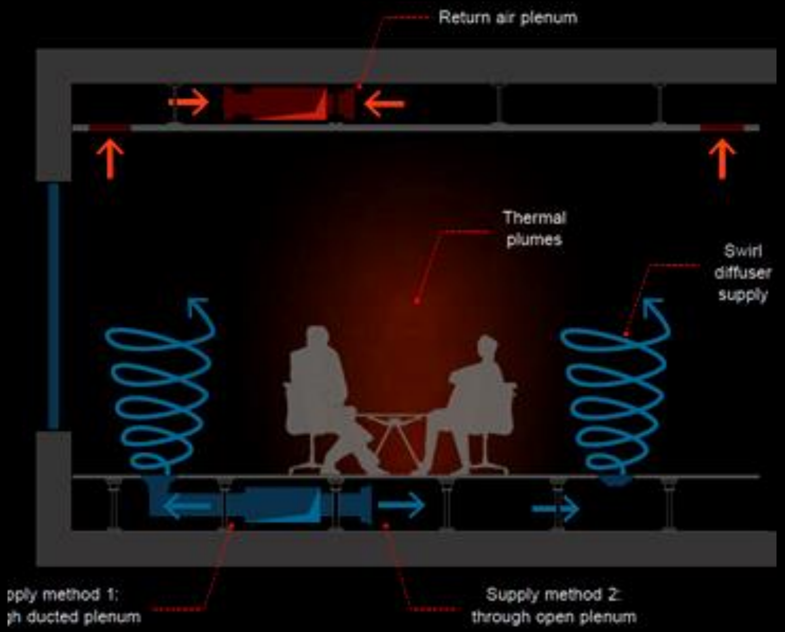
- **Research Aim:** Develop an analytical modelling method to validate complex UFAD design under both peak load and annual part load conditions.

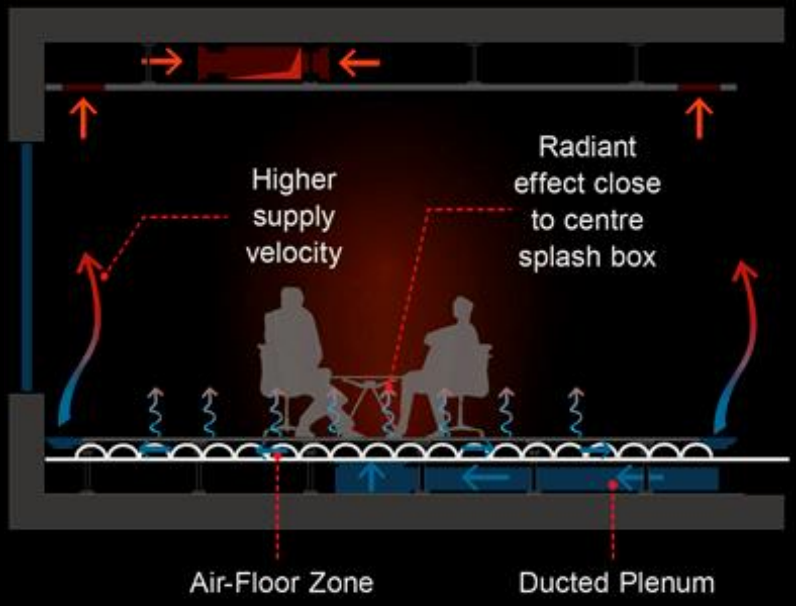
Comparison between Traditional Calculation Workflow and Proposed Modelling Method		
	Traditional UFAD Calculation and Simulation	**Multi-software Coupled Modelling**
Calculation/Simulation Methods	Steady-state calculation, usually using ASHRAE UFAD design guide or CBE UFAD Design Tool	Steady-state calculation for peak sizing (using same method), CFD to validate the peak airflow, and annual dynamic model to predict the part load performance
Major Design Outcomes	- Duct and coil sizing - Diffuser size and layout	- Duct and coil sizing - Diffuser size and layout - Airflow and temperature distribution within the plenum and building itself - Annual energy/load performance and comfort (% hours) distribution
Cons	- Lack of performance validation on the complex UFAD system regarding flow and temperature distribution - Lack of annual system performance prediction and comfort hours distribution	- Longer design time required due to the use of multi-software simulation approach and iterative design optimisation procedures

2. AIMS & OBJECTIVES
System Types Overview

Selected Case Study System







Traditional side-supply DV:

+ Flexible duct locations
+ Easy to adopt in retrofit projects
+ Potential to integrate into structural features
- Limited capacity allowed
- Uneven air distribution to core area
- No radiant effect created

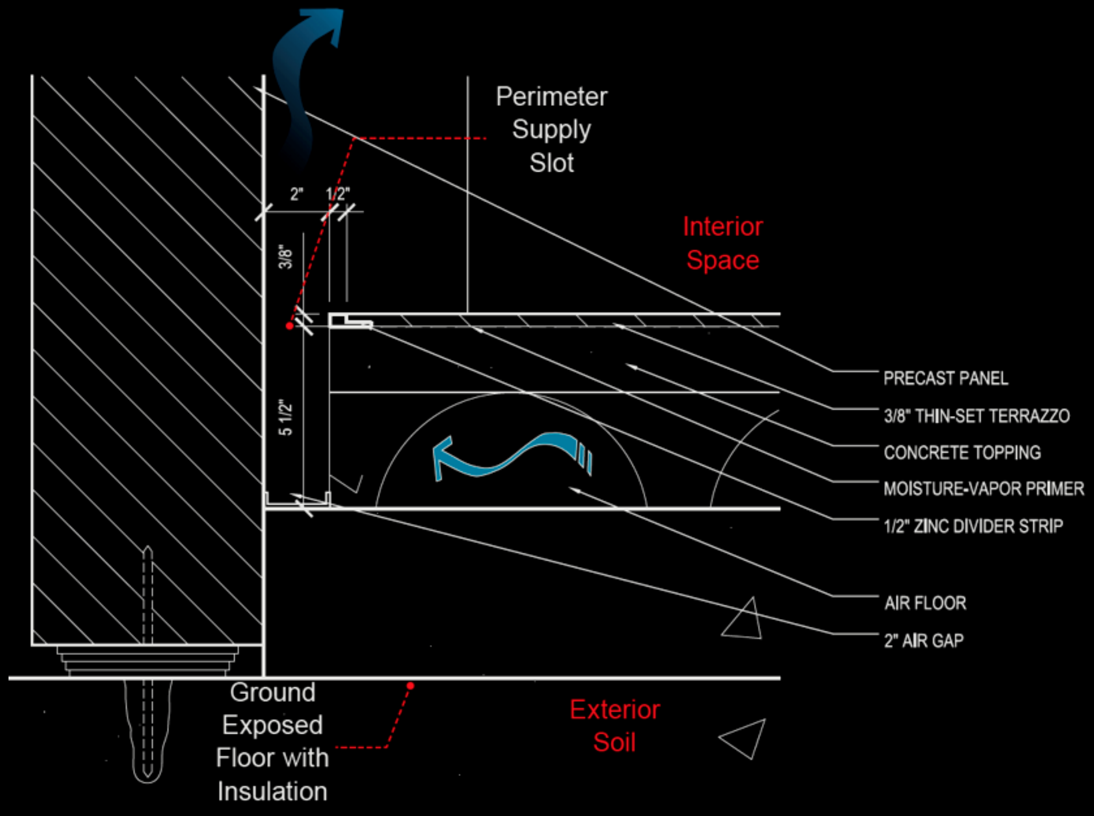
Typical UFAD system:

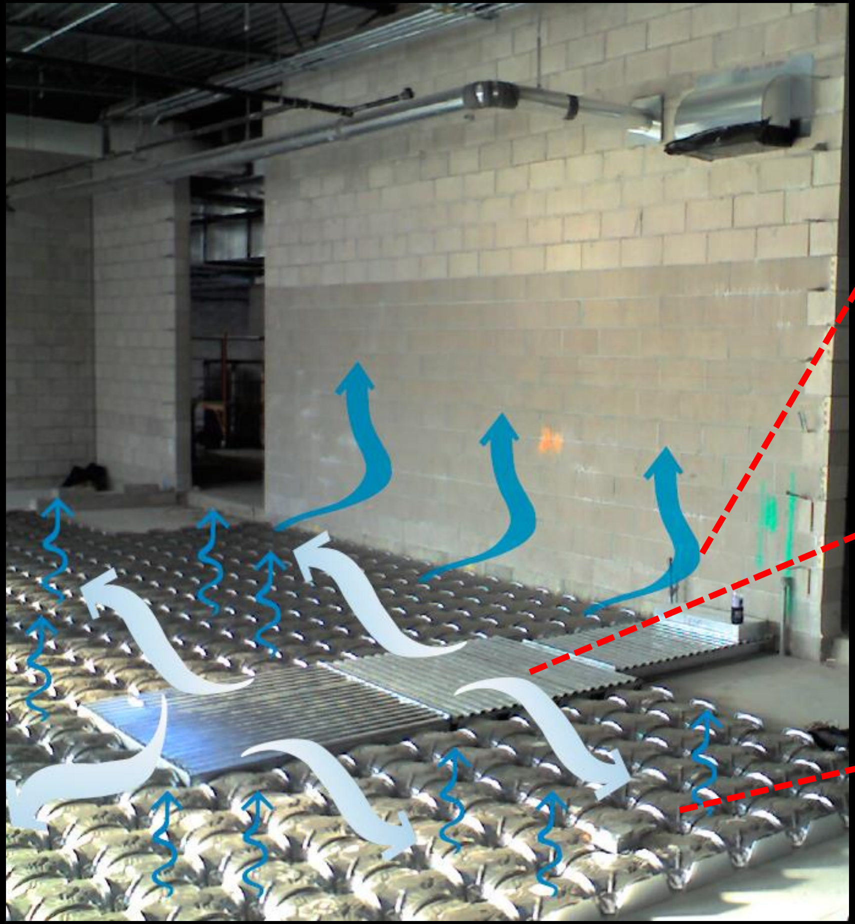
+ Evenly distributed air
+ Open plenum supply creates radiant effect
+ Potentially higher capacity allowed
- Underfloor plenum required
- Floor diffuser is visible

Airfloor System:

+ Strong radiant effect provided
+ Perimeter outlet can be less-visible
+ Suitable for open public spaces
- Less floor plenum flexibility than typical UFAD due to the air-floor structure
- Extra consideration for the floor build-up

2. AIMS & OBJECTIVES
Introduction to the Airfloor HVAC System





Air supply at perimeter floor grilles

Splash box

Radiant effect created by the hollow steel forms embedded in a concrete slab

Image Source:
Airfloor Inc.

2. AIMS & OBJECTIVES
Literature Review

Current Research and Limitations		
	Traditional UFAD System	**Novel UFAD System**
Existing Calculation Guidance	- ASHRAE UFAD design guide - CBE UFAD design tool	- No widely-recognised calculation methods available
Existing Simulation Methods and Performance Validation	- Comparative study between traditional overhead system and UFAD, identified energy benefits of UFAD system (Linden et al, 2009) - Transient multi-dimensional numerical solution for hollow core system (Park, 2016) - Experimentally validated CFD and EnergyPlus coupled model (Webster et al, 2008)	- Simple psychrometry study showing the fundamental steady-state calculation for humidity control (Chapman, 2009) - Steady-state calculation to understand the temperature loss from the system to the ambient ground (Chapman, 2003)
Knowledge Gaps	- Limited studies addressing the optimisation of the HVAC system part load performance	- No detailed analytical CFD model and dynamic thermal simulation carried out for this specific system

Sources:

ASHRAE, 2013. *Design, Construction and Operation of Underfloor Air Distribution Systems*

Chapman, 2003. *Downward Losses in an Unconditioned, Well-Ventilated Space*

Chapman, 2009. *Relative Humidity Impacts of the AirFloor System in the Built Environment*

Linden et al, 2009. *Simulation of Energy Performance of Underfloor Air Distribution (UFAD) Systems*

Park, 2016. *Thermal Analysis of Hollow Core Ventilated Slab Systems*

Webster et al, 2008. *Modeling of Underfloor Air Distribution (UFAD) Systems*

3.0 METHODOLOGY
Case Study Building

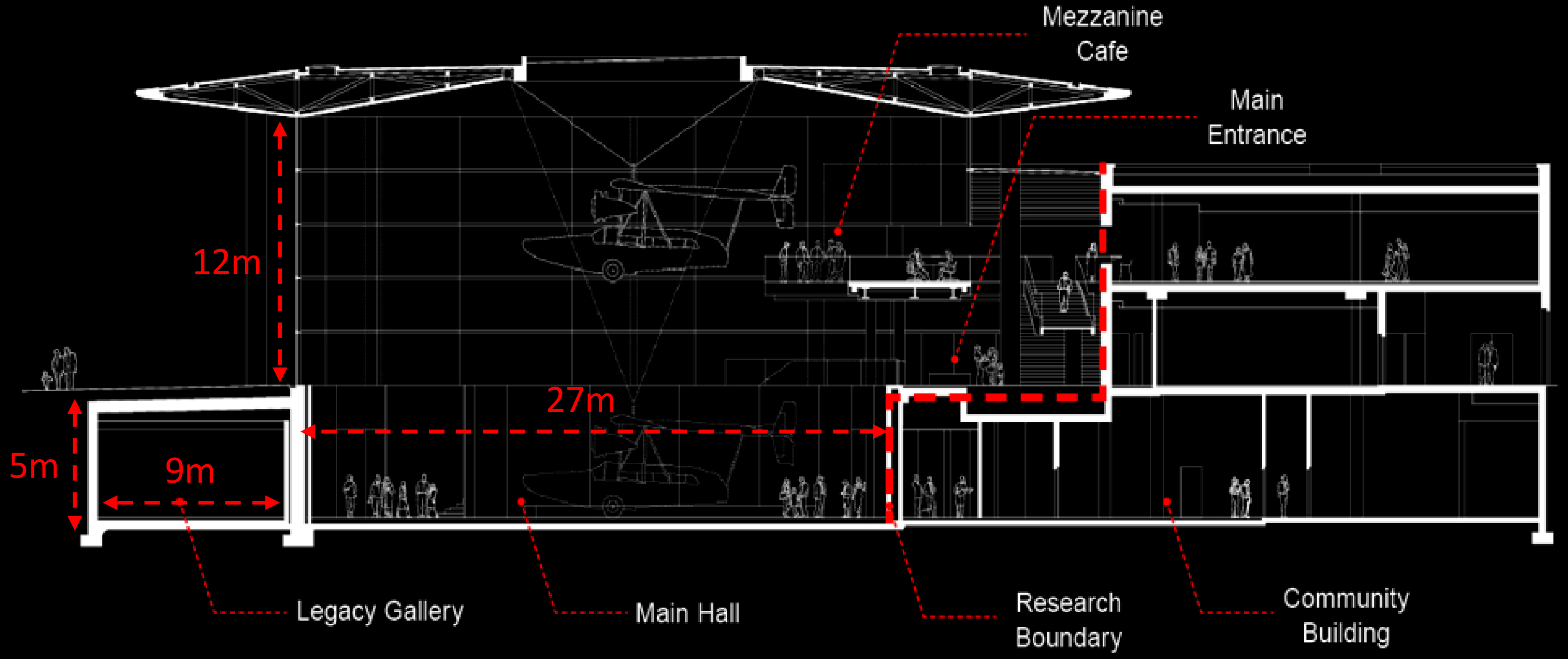
SC Johnson's Fortaleza Hall

- Located at Racine, Wisconsin. Foster + Partners design and completed in 2010.
- Achieved LEED Gold certification in 2011.

Image Source: Gillfoto

3.0 METHODOLOGY
Case Study Building

Building Functional Areas and Research Boundary



- The novel UFAD HVAC System applied in the main hall and legacy gallery.

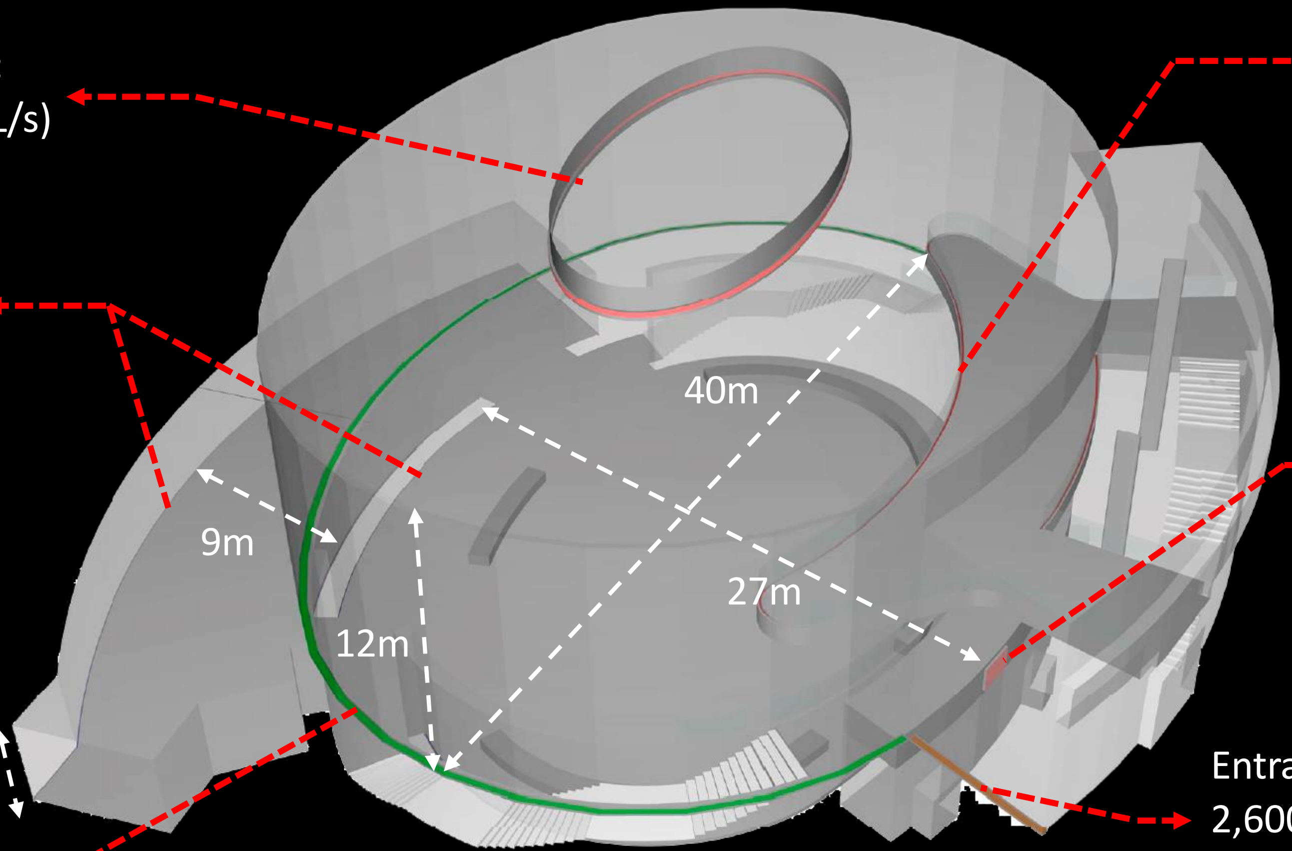
3.0 METHODOLOGY
Case Study Building

HVAC System Overview

High level roof return:
30,000 CFM (14,158 L/s)

UFAD System Perimeter Supply:
22,000 CFM (10,383 L/s)
53.6-86.0°F (12.0-30.0°C)

Mezzanine Café Supply:
3,960 CFM (1,869 L/s)
63.0-86.0°F (17.2-30.0°C)



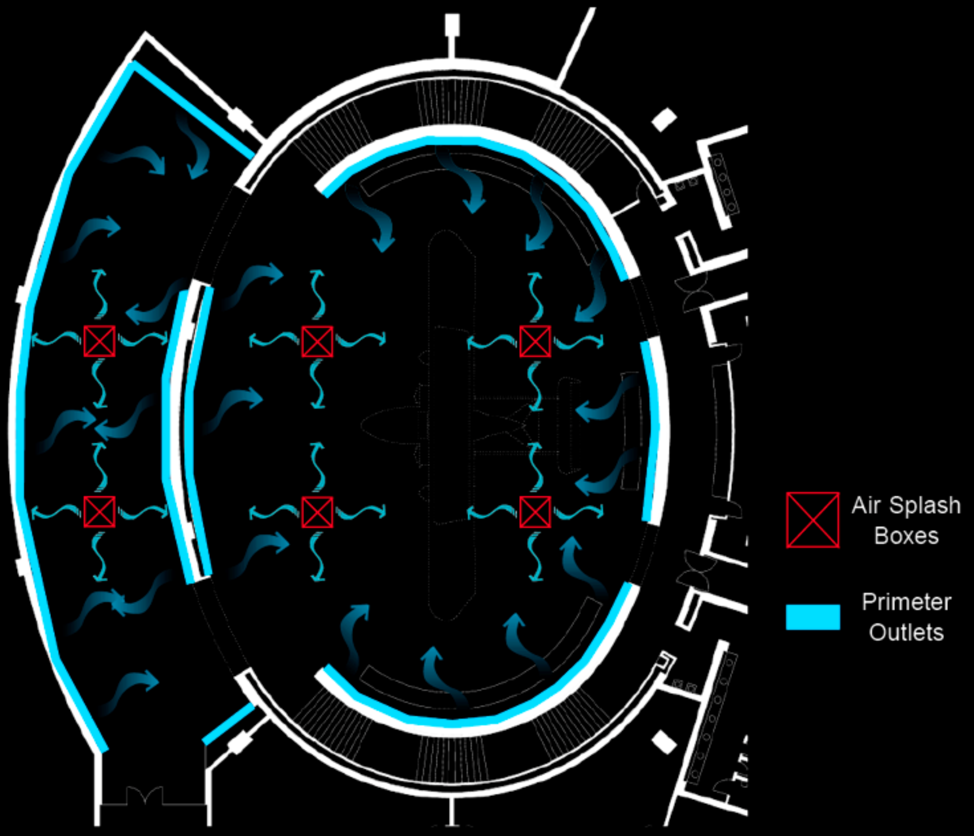
East Corridor Return:
22,000 CFM (10,383 L/s)

Glass Trench Supply:
34,000 CFM (16,046 L/s)
63.0-90.0°F (17.2-32.2°C)

Entrance Trench Supply:
2,600 CFM (1,227 L/s)
63.0-86.0°F (17.2-30.0°C)

3.0 METHODOLOGY
Case Study Building

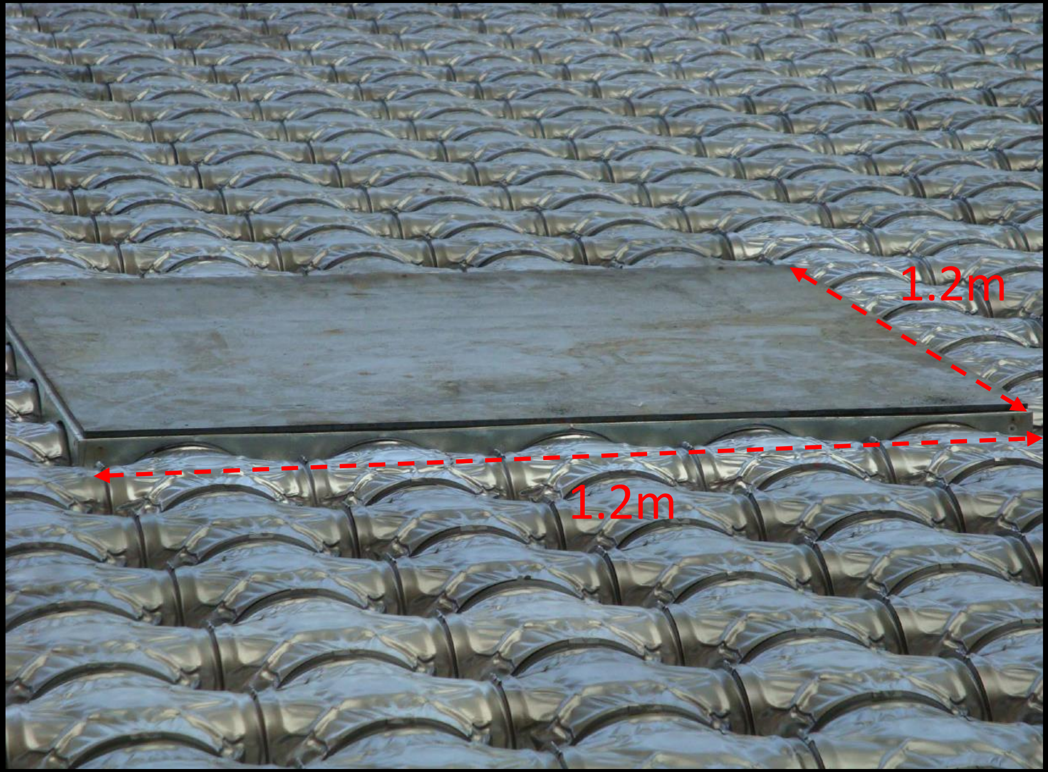
Novel UFAD System Set-up and Internal Conditions



Internal Design Conditions	
Occupancy (Hall)	100 ft²/person (9.29 m²/person)
Occupancy (Café)	25 ft²/person (2.32 m²/person)
Lighting	1.5 W/ft² (16.15 W/m²)
Café Small Power	1.0 W/ft² (10.76 W/m²)
Infiltration	0.10 ACH across all areas
Hall Setpoint	70.0-80.0 °F (21.1-26.7 °C) (±1°K) / 50% RH% (±5%)
Legacy Gallery Setpoint	70.0-75.0 °F (21.1-23.9 °C) (±1°K)
Load Split	50% small power load, 30% occupancy load and 60% of the lighting load were applied to the stratified zones

3.0 METHODOLOGY
Case Study Building

Novel UFAD System Sizes



Air Splash Box Dimensions

Novel UFAD System Capacity within the Case Study Building	
Main Hall Sensible Cooling Load	~70 W/m²
Main Hall Sensible Heating Load	~200 W/m²
Supply Air Flow (Main Hall)	15,000 CFM (7,079 L/s)
Supply Air Flow (Main Hall)	~6.4 ACH
Radiant Heat Pickup/Release	~40 W/m² (based on the research results in this paper)
Off-coil Condition	13°C (Summer) / 31°C (Winter)
Off-coil for Dehumidification	12°C
Perimeter Slot Outlet Size	2 inches (50 mm)
Perimeter Slot Velocity	~0.5-2.2 m/s (based on the research results in this paper)

3.0 METHODOLOGY
Multi-software Coupled Modelling Method

Work Steps	Simulation Software	Main Outcome
Step 1 - Initial Flow Development	OpenFOAM	Flow Regimes Zonal Air Flow Rates
Step 2 - Develop the HVAC Air-side Schematic	IES-VE	Zonal Air Flow Rates Zonal Heat Transfer Rates Annual Hourly Data
Step 3 - Validate the Temperature Distribution	OpenFOAM	Flow Temperature Distribution Outlet Temperature at Peak
Step 4 - CFD Simulation for the Whole Building	OpenFOAM	Peak Summer and Winter Temperature Distribution within the Whole Building
Step 5 - Annual Simulation and Optimisation	IES-VE	Part Load Performance AHU Operation Optimisation Humidity Control Strategies

Use as inputs

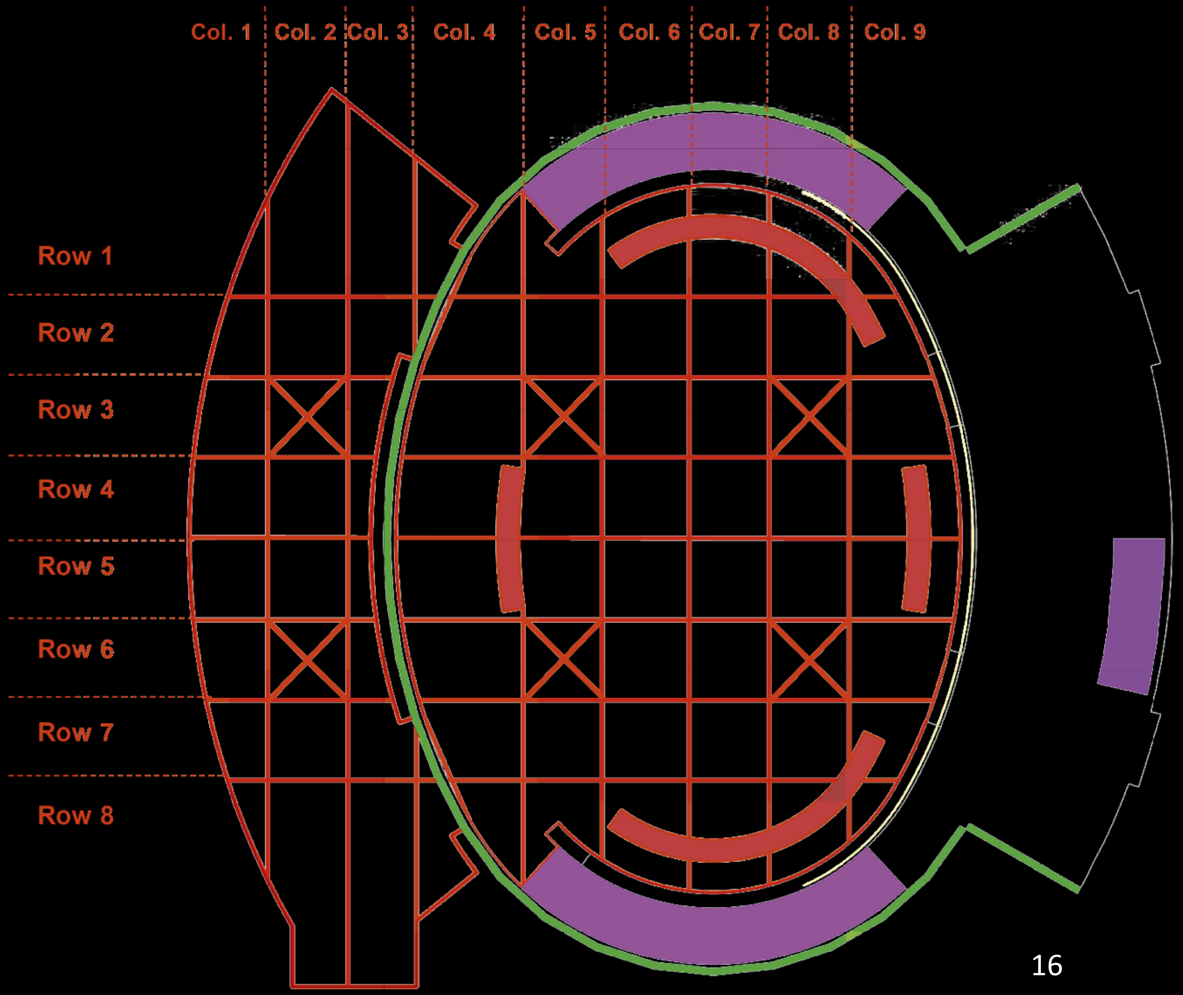
Cross check and validate

Use as boundary conditions

Cross check and validate

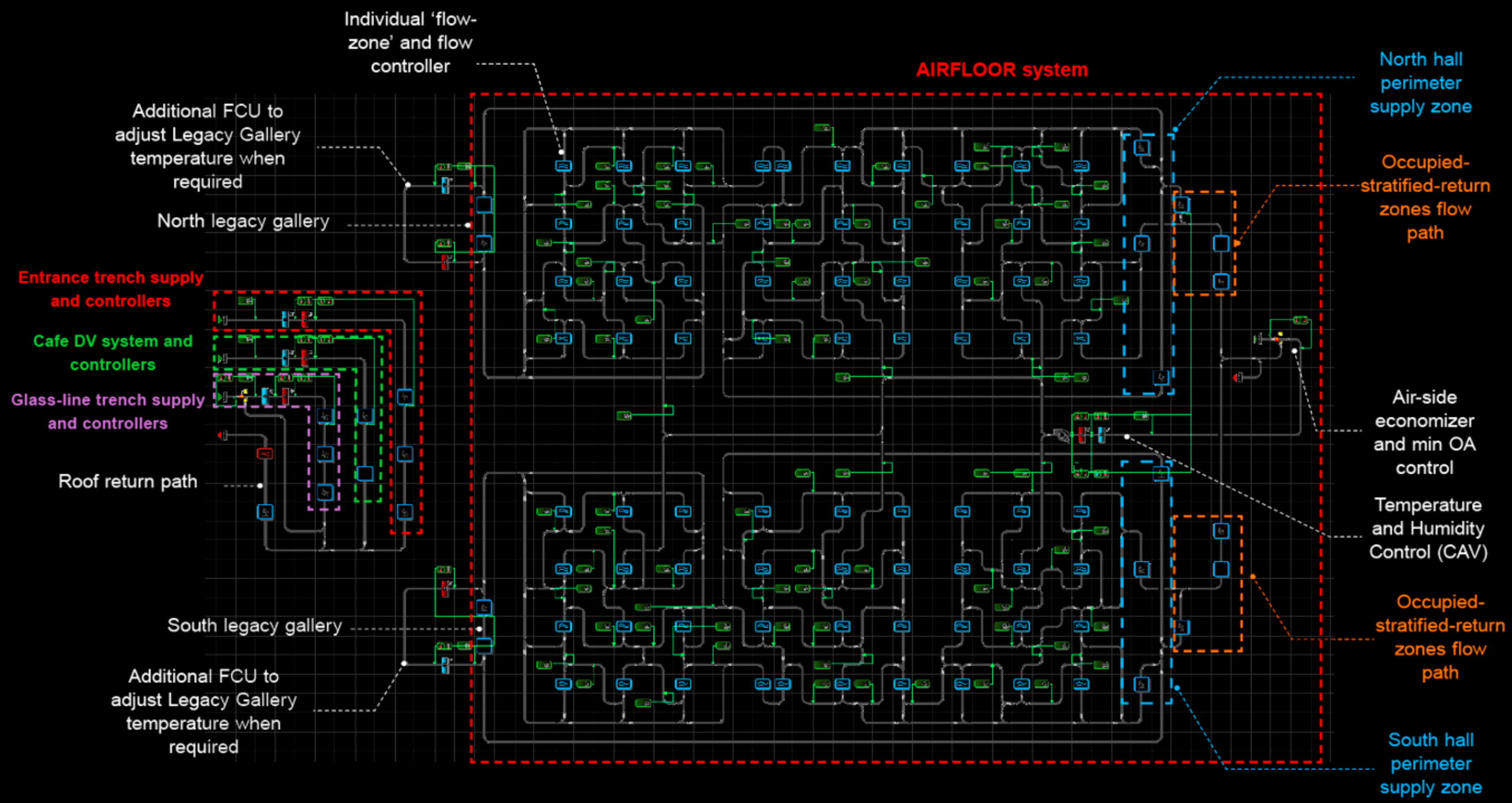
Use as boundary conditions

72 ‘Flow-Zones’ Divided



3.0 METHODOLOGY
Multi-software Coupled Modelling Method

IES-VE ApacheHVAC Air-side Links

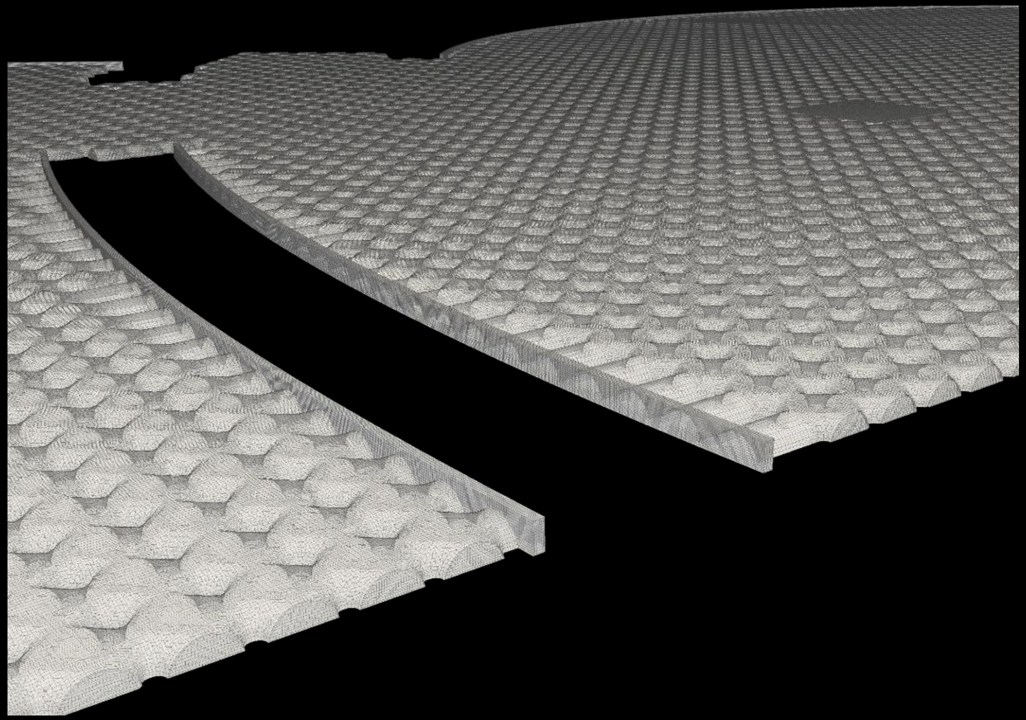


- CAV control to all HVAC systems to ensure adequate air movement in the central area
- Min OA applied to main hall and legacy gallery (4,400 CFM / 2,077 L/s)
- 70°F / 21°C air-side economizer high limit shut-off
- Specific fan power for Airfloor = 1.9 W/(L/s)

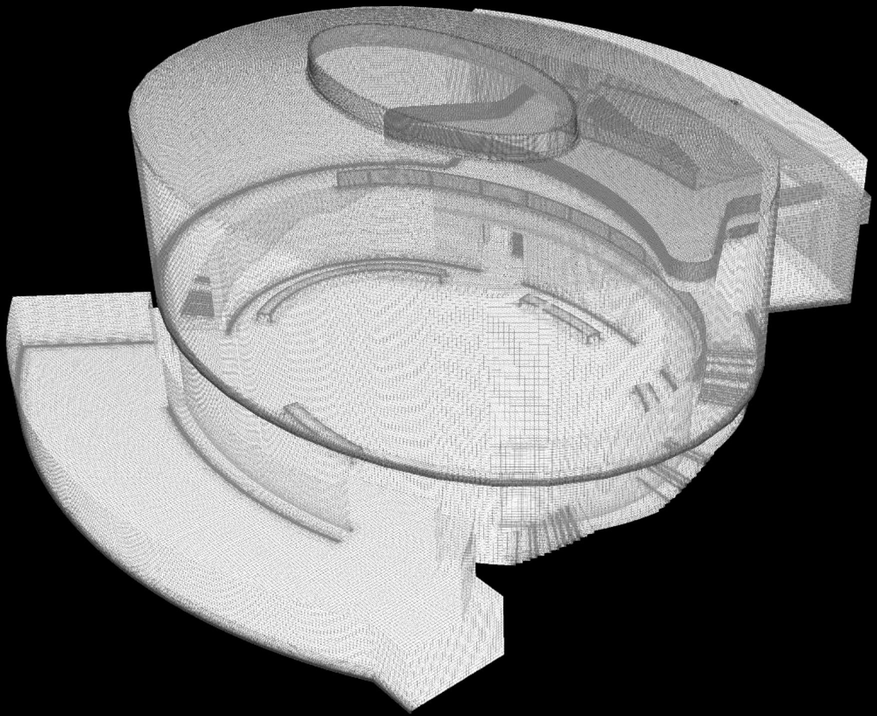
3.0 METHODOLOGY
Multi-software Coupled Modelling Method

CFD Meshing and Solver Settings

OpenFOAM snappyHexMesh containing hexahedra and split-hexahedra cells



Floor cell size: 21 million



Building cell size: 26 million

Solver Settings:

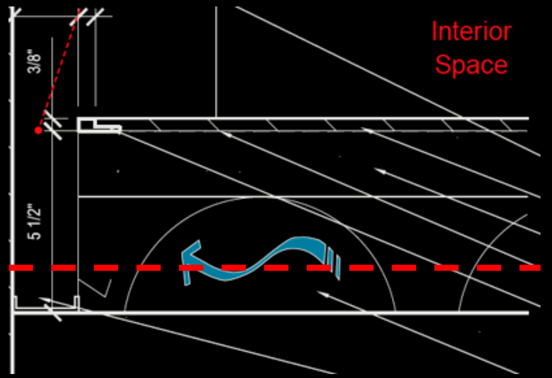
Solver:
RANS Steady-State
BuoyantBoussinesqSimpleFOAM

Turbulence Model:
Realisable k-ε turbulent closure model

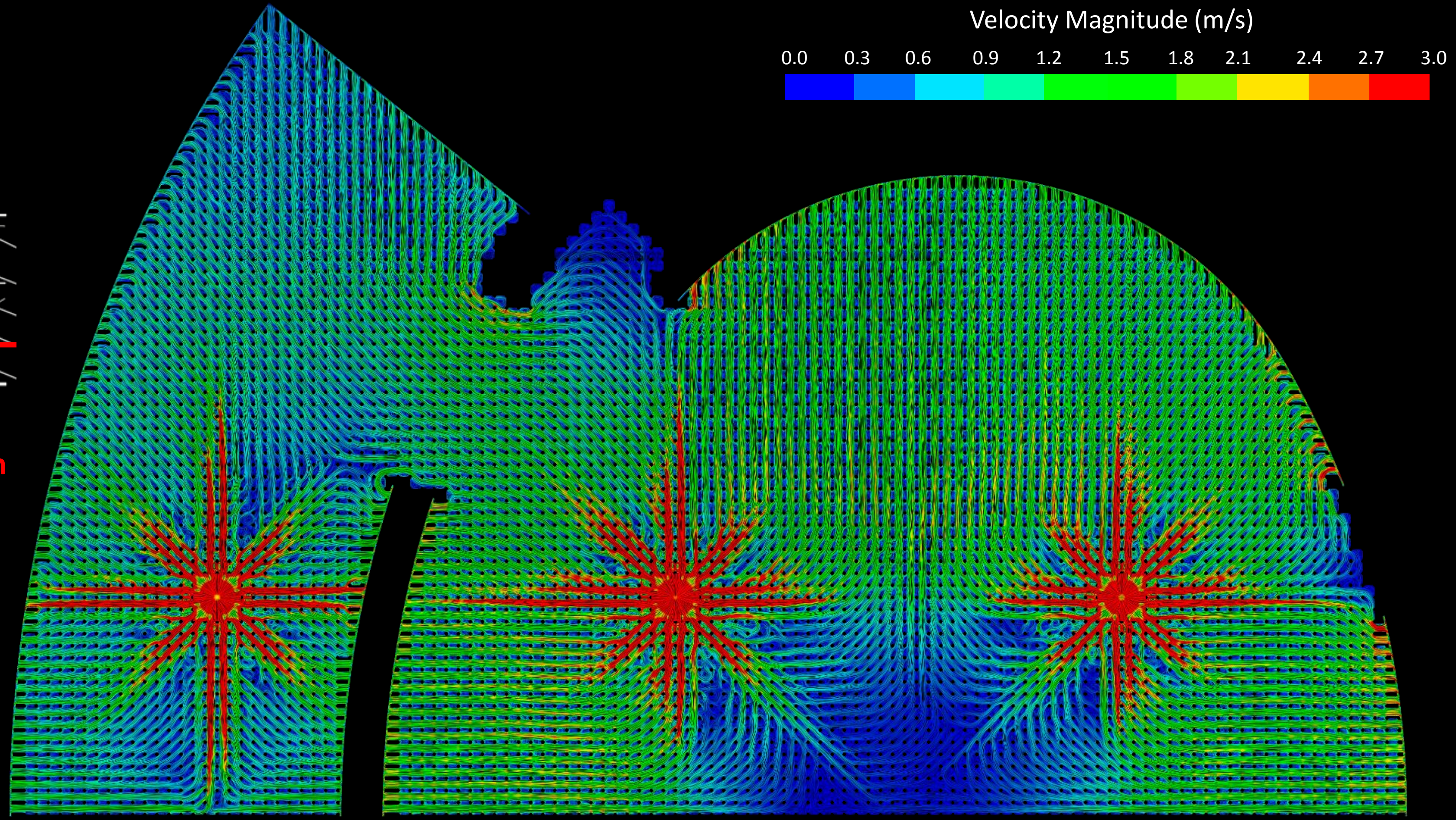
Convergence Criteria:
3000 iterations to reach 10-5 convergence

4.0 RESULTS & DISCUSSIONS
Flow Pattern and HVAC Schematic Development

Floor Plenum Velocity Distribution

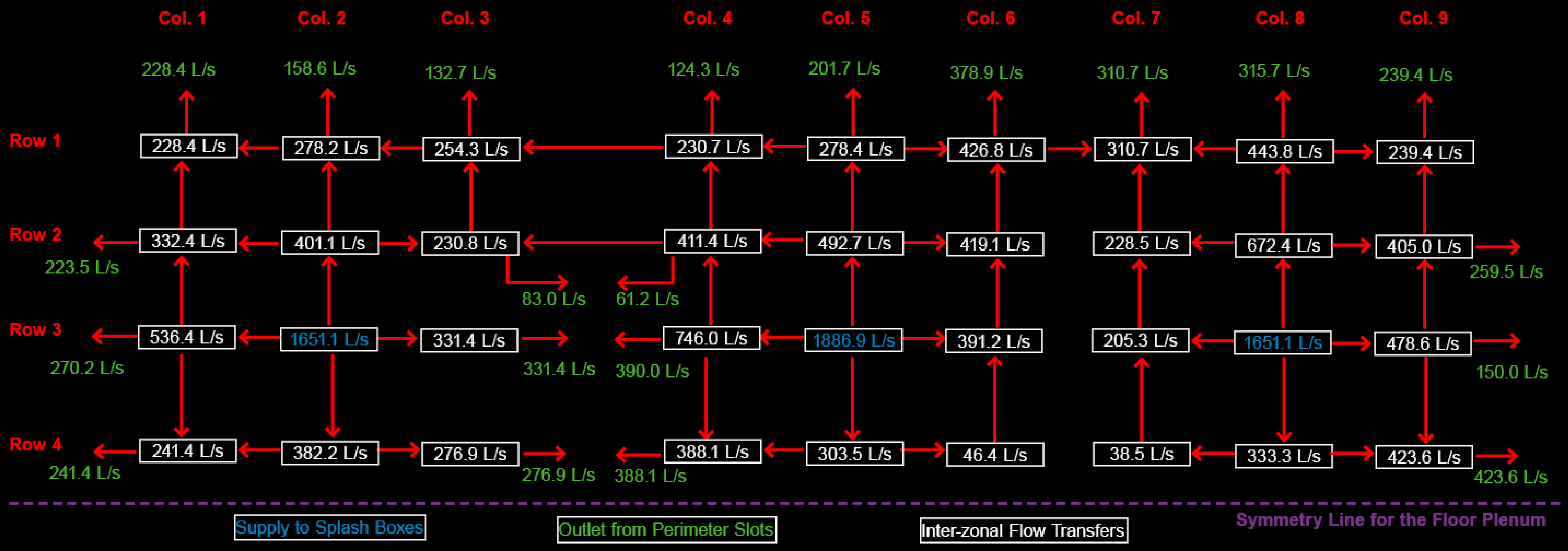


Cutting plane: mid of the plenum



4.0 RESULTS & DISCUSSIONS
Flow Pattern and HVAC Schematic Development

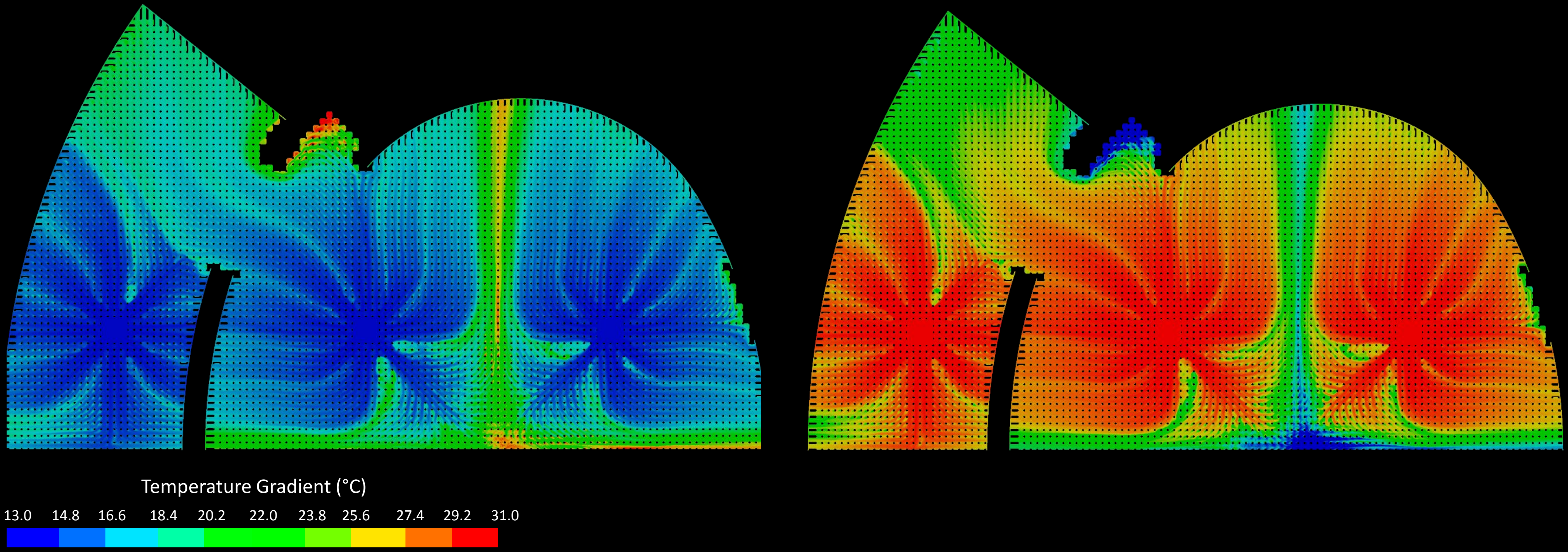
HVAC Schematic Development



4.0 RESULTS & DISCUSSIONS
Temperature Distribution and Range of Error

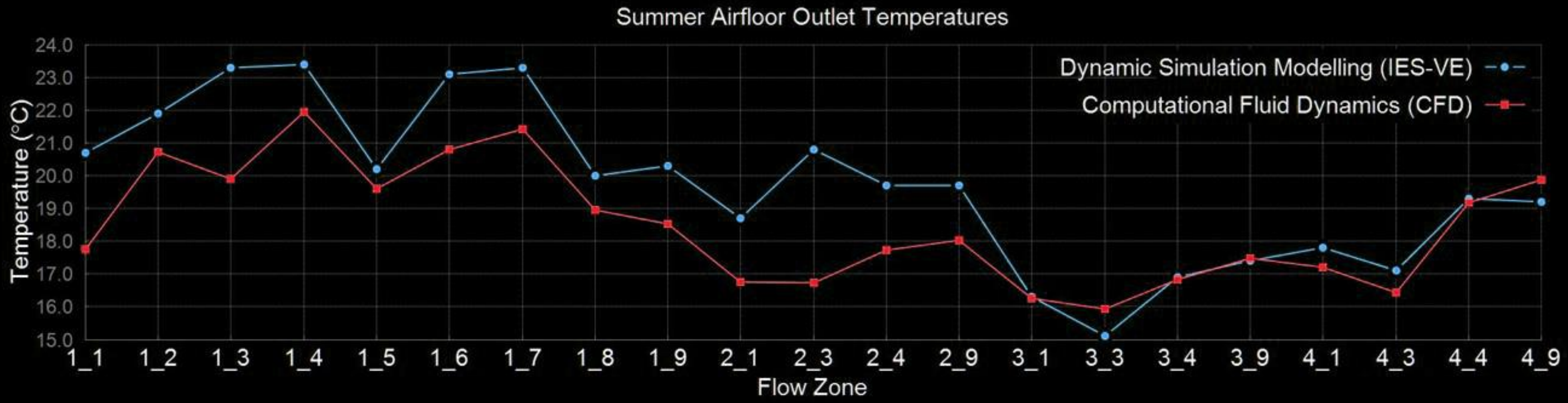
Seasonal Temperature Distribution within the Floor Plenum

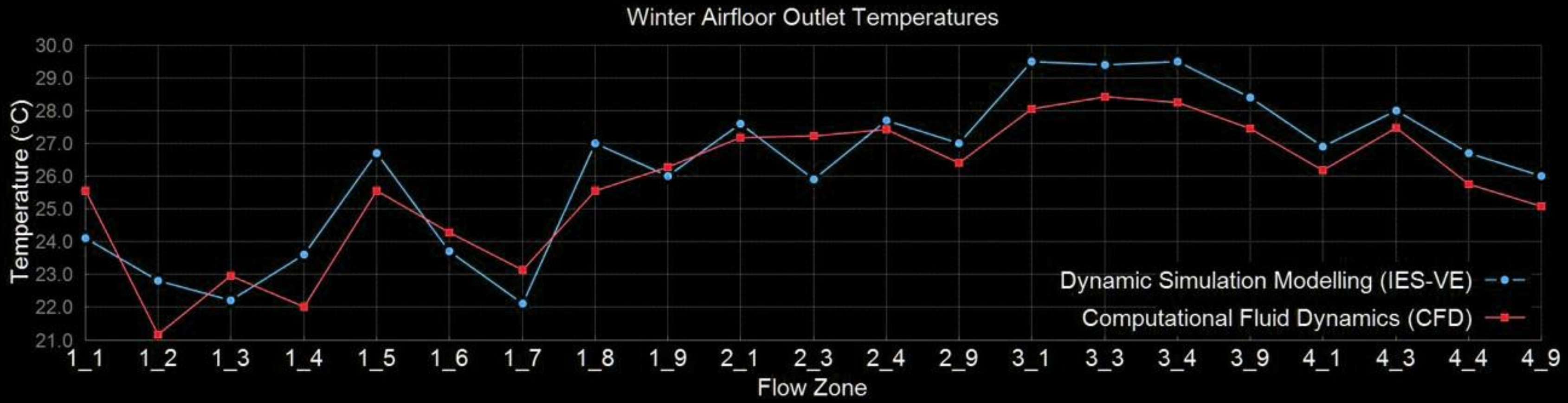
Peak Summer Condition **Peak Winter Condition**



4.0 RESULTS & DISCUSSIONS
Temperature Distribution and Range of Error

Temperature Range of Error Tests





Summer:

Average % error = 6.7%
Max. deviation = 4°C

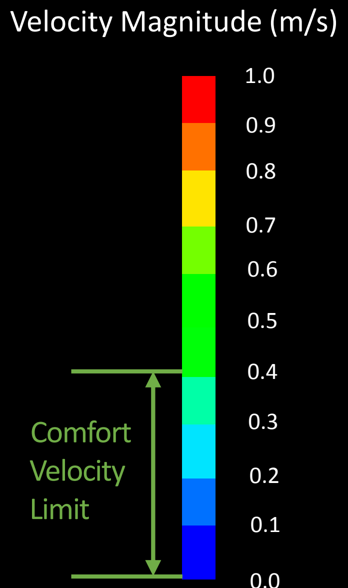
Winter:

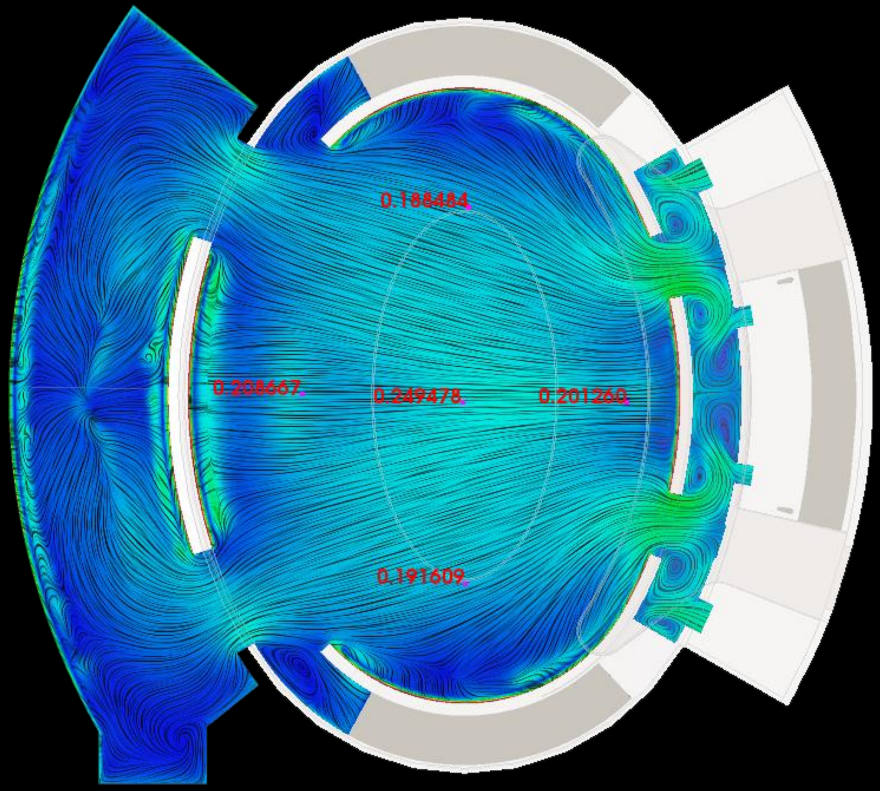
Average % error = 2.5%
Max. deviation = 2°C

4.0 RESULTS & DISCUSSIONS

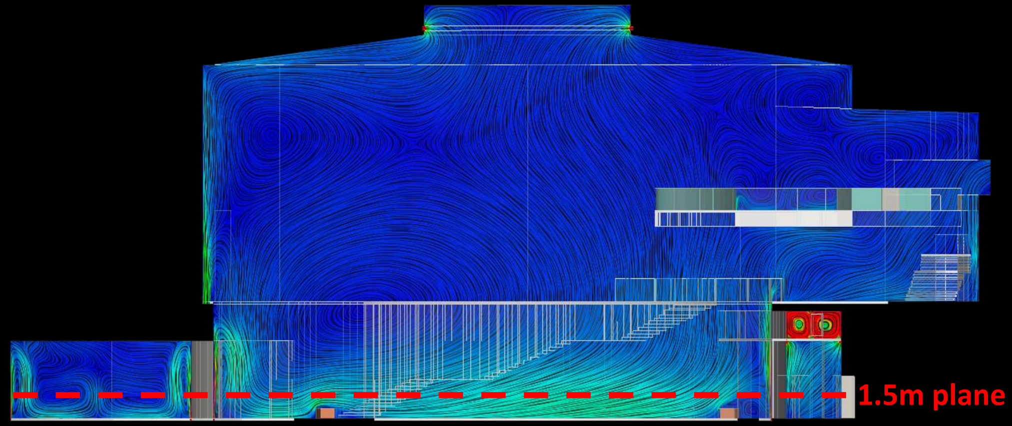
Peak Distribution within the Case Study Building

Summer Velocity Analysis





Velocity Plot @ 1.5m



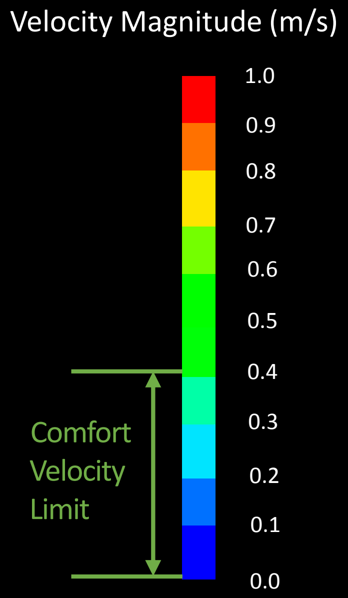
Velocity Plot Section

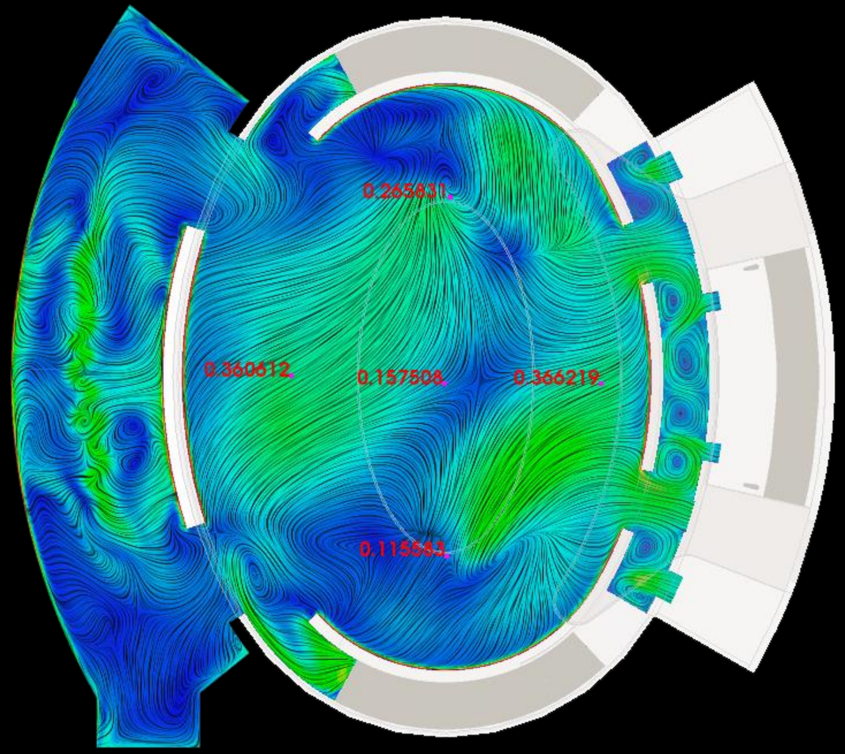
Key Observations:

- Average velocity between 0.19-0.25 m/s
- Airflow organised as cold supplied air remains at bottom and hot stratified air stays at top

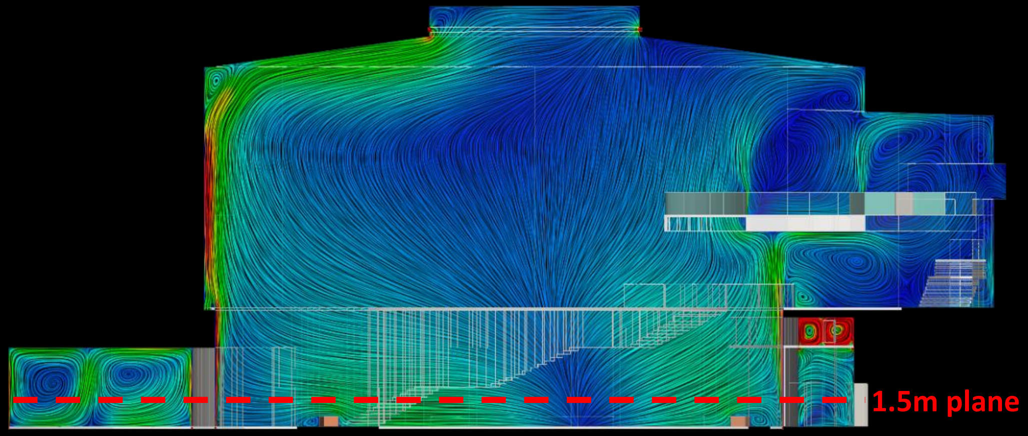
4.0 RESULTS & DISCUSSIONS
Peak Distribution within the Case Study Building

Winter Velocity Analysis





Velocity Plot @ 1.5m



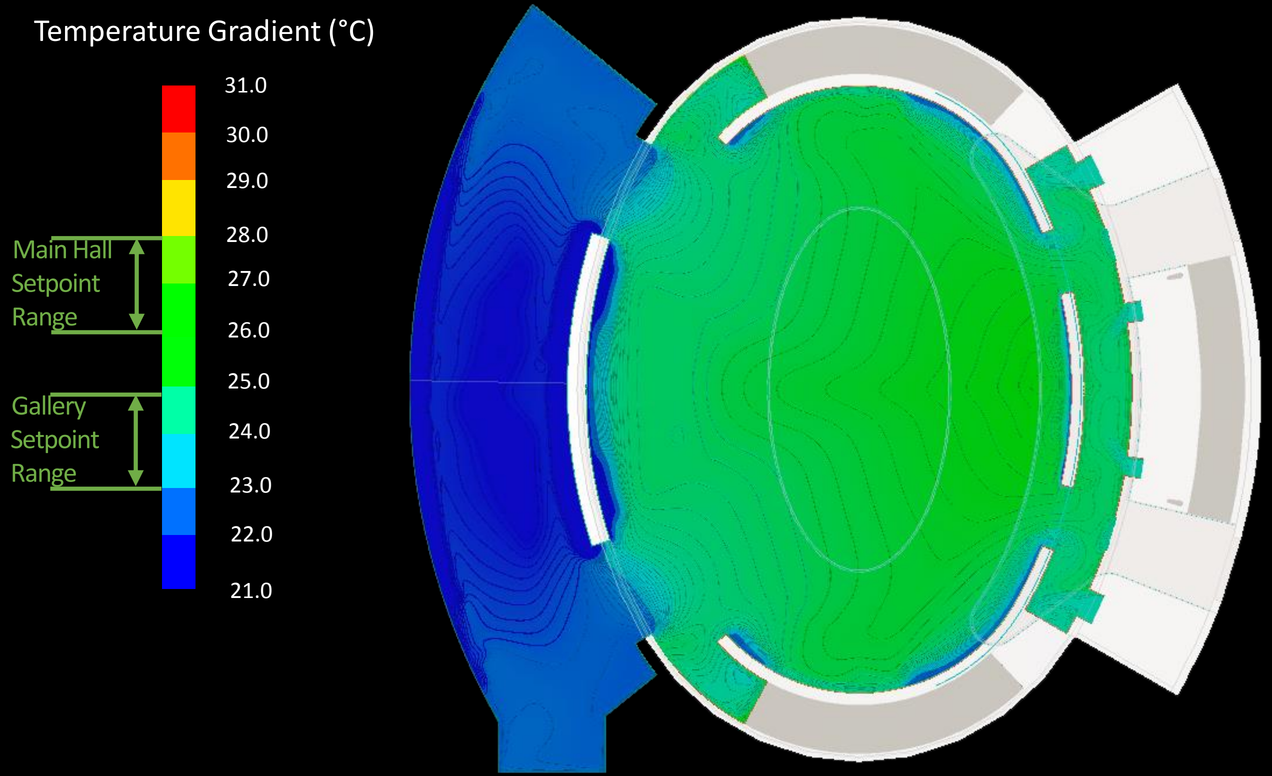
Velocity Plot Section

Key Observations:

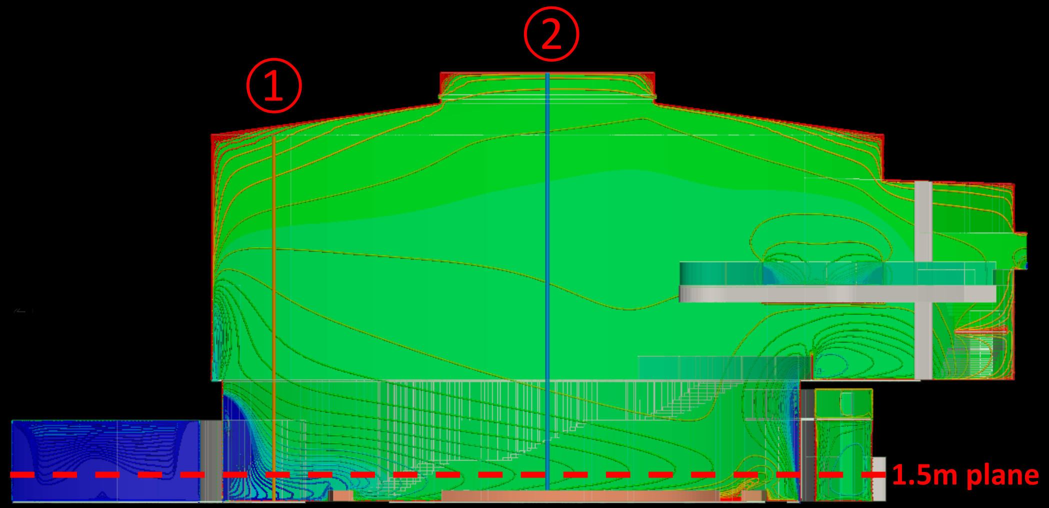
- Average velocity between 0.16-0.37 m/s
- Airflow less organised and more well-mixed due to the less stratification

4.0 RESULTS & DISCUSSIONS
Peak Distribution within the Case Study Building

Summer Temperature Analysis



Temperature Plot @ 1.5m



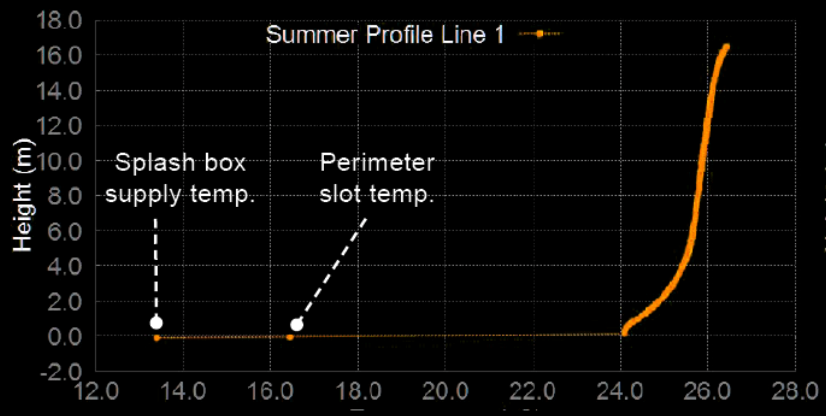
Temperature Plot Section

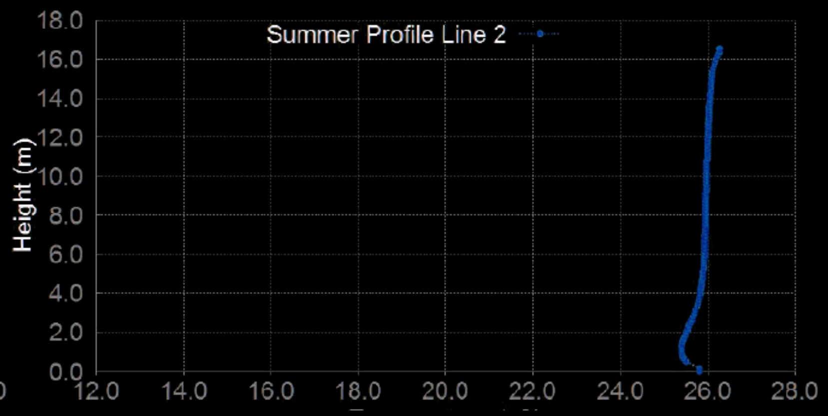
Key Observations:

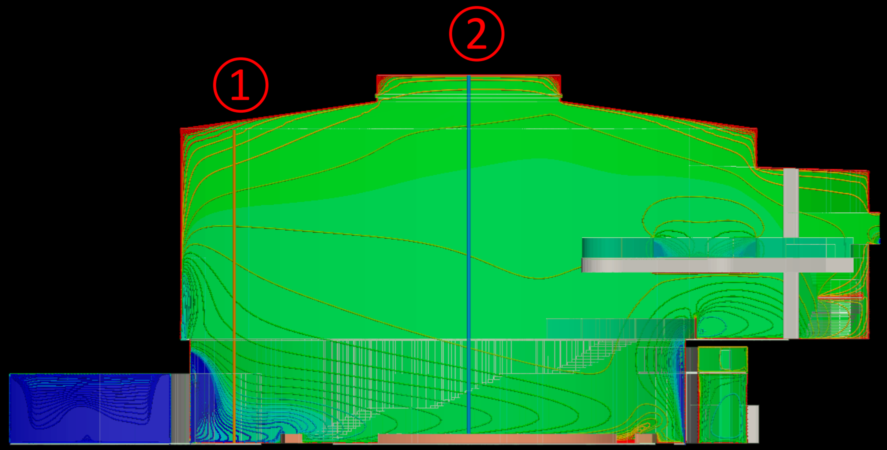
- Comfortable conditions within the hall
- Slightly cooler in legacy gallery, but still within the setpoint in most of the areas
- Stratification is not obvious due to café and trench supply

4.0 RESULTS & DISCUSSIONS
Peak Distribution within the Case Study Building

Summer Stratification Analysis







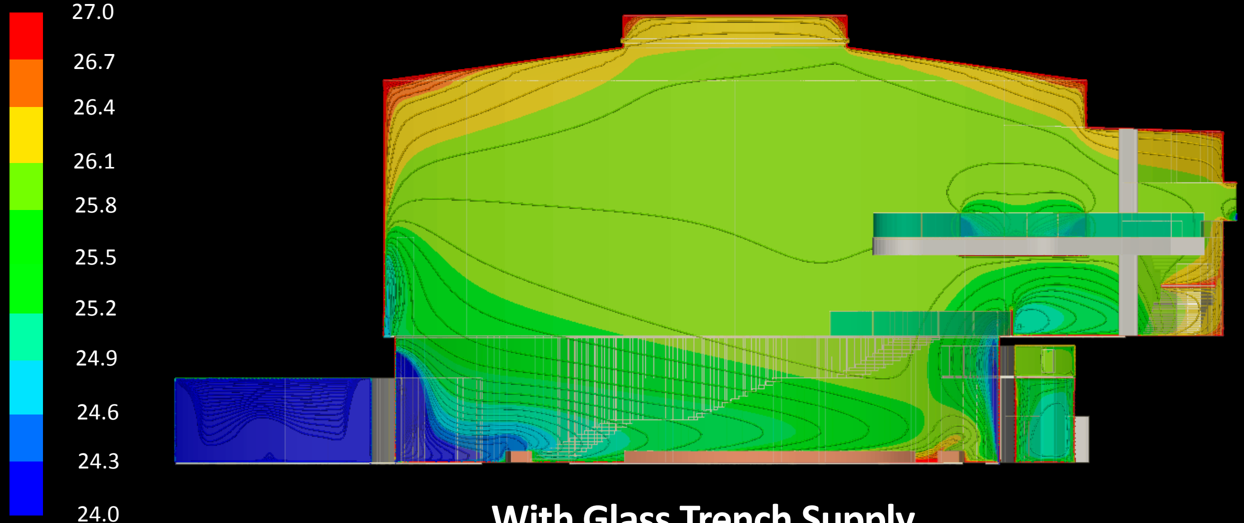
Key Observations:

- Effect heat pick up within the floor causing around 3°C temperature rise
- Ankle-to-head height difference within 3°C, within the ASHRAE 55 comfort limit
- More stratification near glass

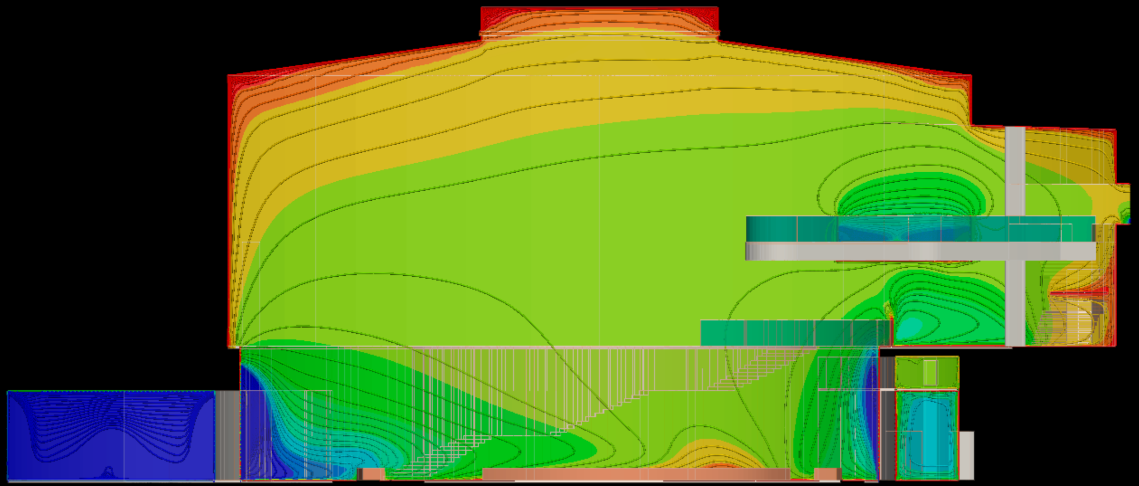
4.0 RESULTS & DISCUSSIONS
Peak Distribution within the Case Study Building

Summer Stratification Analysis

Temperature Gradient (°C)



With Glass Trench Supply



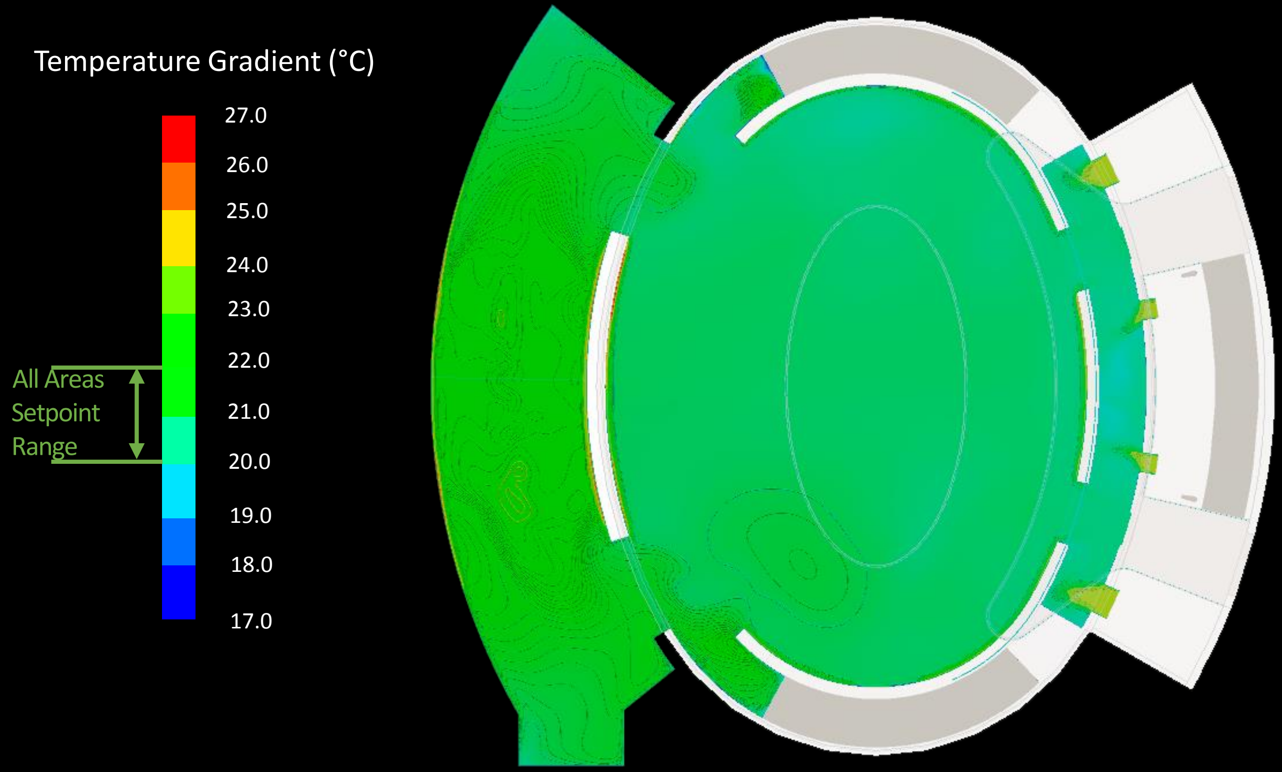
Without Glass Trench Supply

Key Observations:

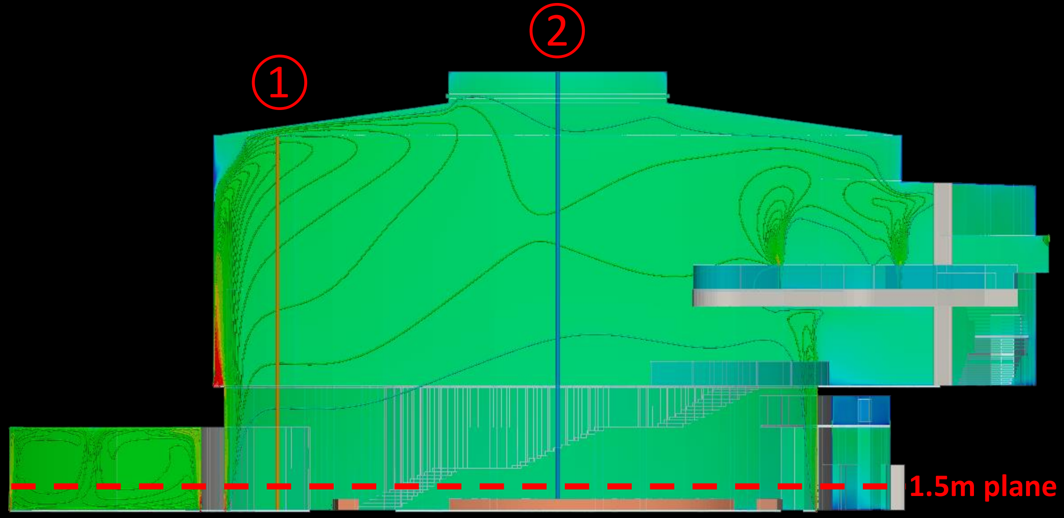
- Trench supply can potentially be turned off as the occupied area is far from glass
- Without glass trench supply, more obvious stratification effect can be observed in the space

4.0 RESULTS & DISCUSSIONS
Peak Distribution within the Case Study Building

Winter Temperature Analysis



Temperature Plot @ 1.5m



Temperature Plot Section

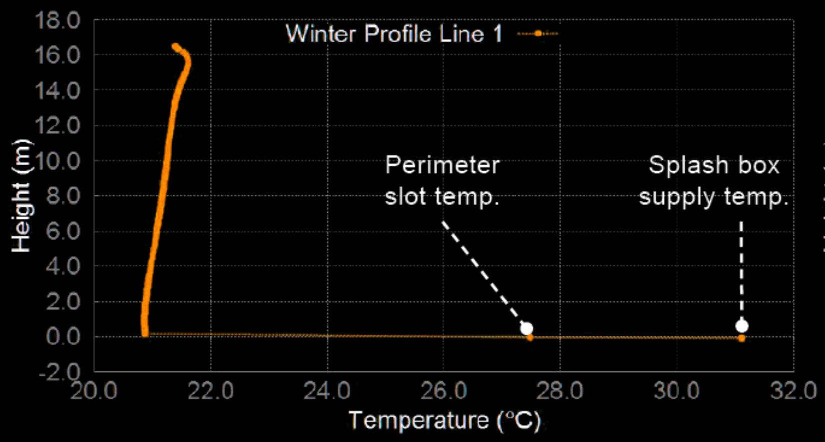
Key Observations:

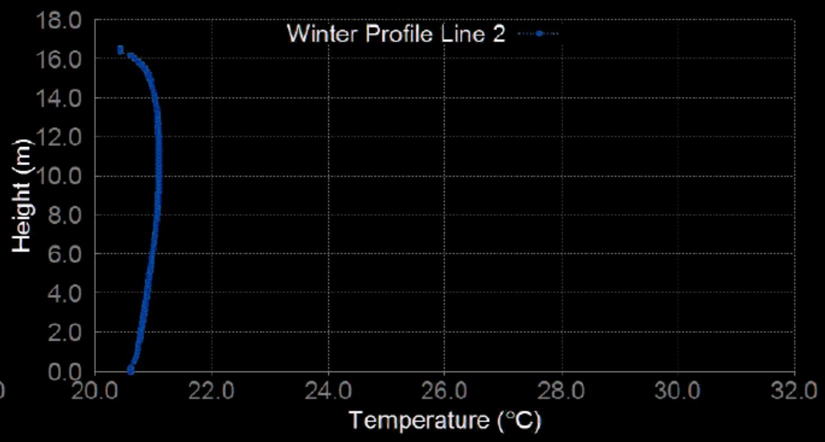
- Overall comfort within all areas
- Slightly cooler entrance area due to skylight heat loss and less trench heater
- Trench heater maintained good near-glass temperature

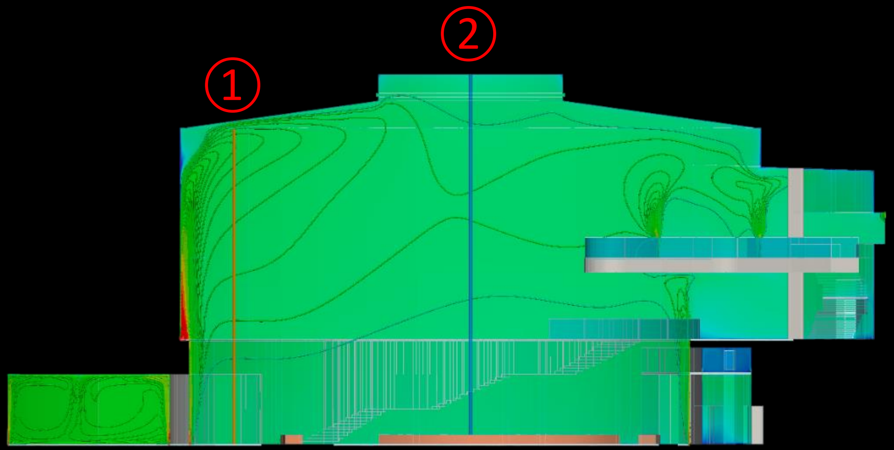
4.0 RESULTS & DISCUSSIONS

Peak Distribution within the Case Study Building

Winter Stratification Analysis







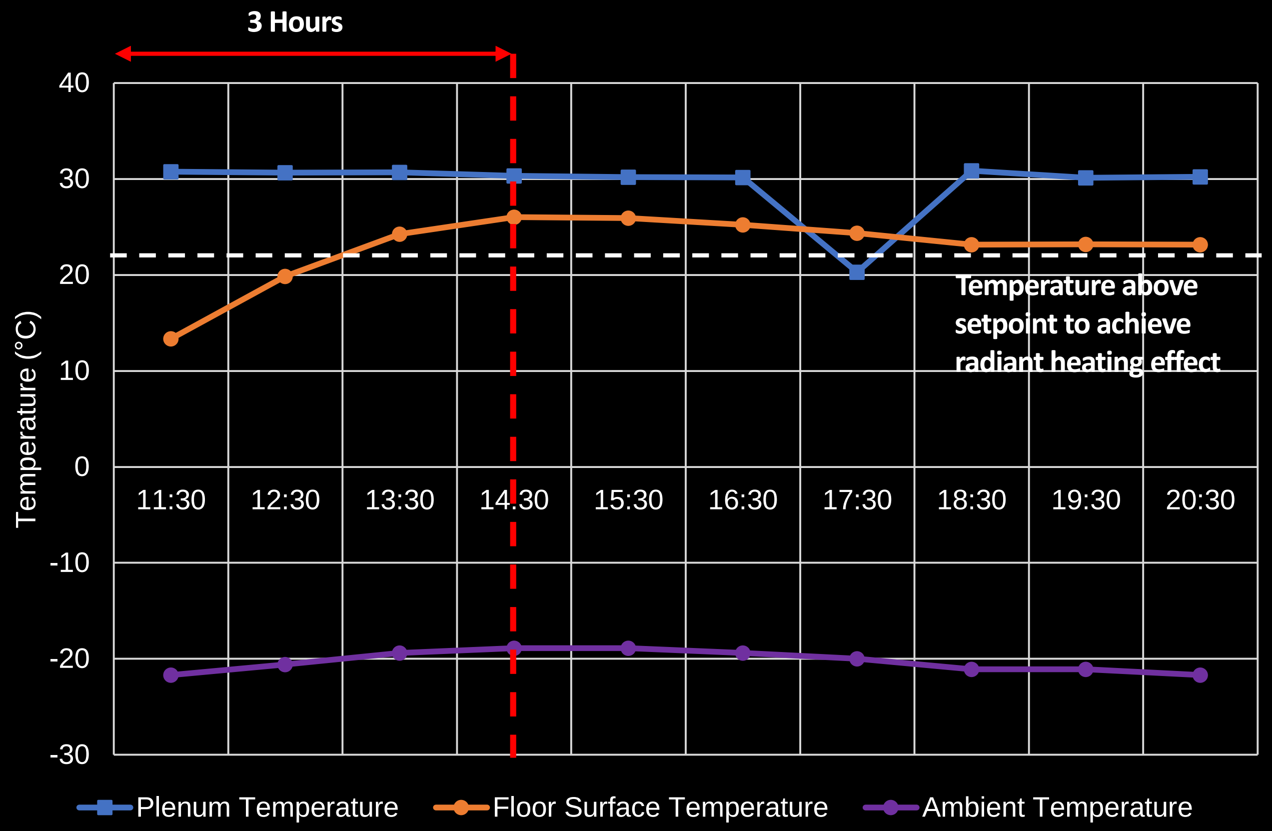
Key Observations:

- Good heat release within the floor plenum
- Less stratification observed, all space within the comfort setpoint of 21°C
- Top temperature drop due to the less reach of trench heater and cold skylight surfaces

4.0 RESULTS & DISCUSSIONS

Annual Dynamic Thermal Modelling and Analysis

Annual Analysis – Thermal Decay Effect (winter example)



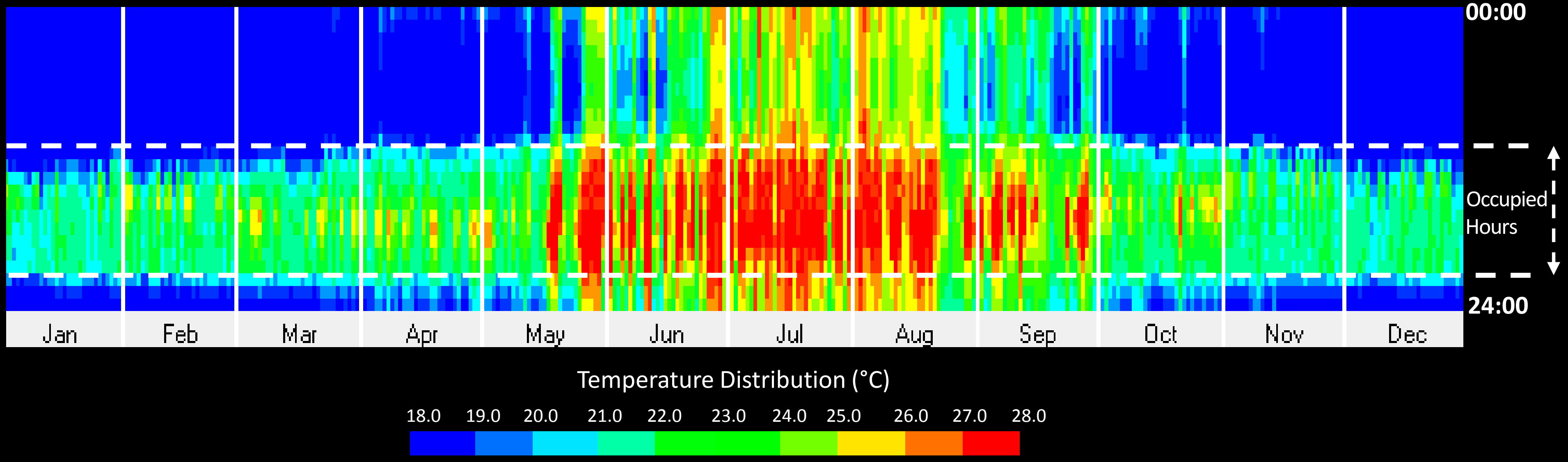
Key Observations:

- Winter example was used to limit the impact of solar load
- Graph plotted above the splash box
- Around 2-3 hours time lag observed
- Can potentially be used in design stage to optimise the thermal mass and build-up

4.0 RESULTS & DISCUSSIONS
Annual Dynamic Thermal Modelling and Analysis

Annual Analysis – Annual % Comfort Hours within the Main Hall

Annual Mean Radiant Temperature Plot



Plotted based on ASHRAE 55-2013

Assumptions:

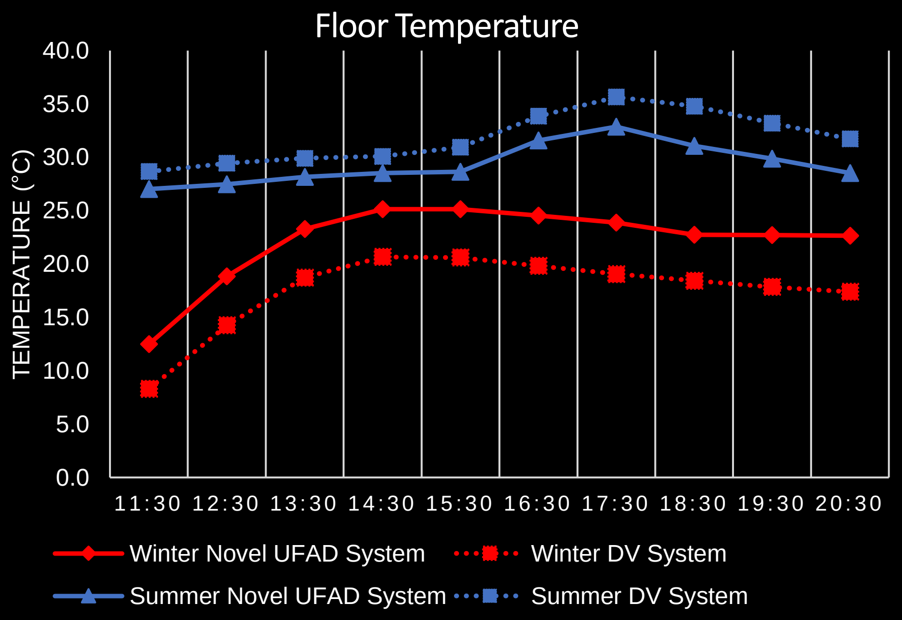
- Setpoint: 21.1-26.7°C
- Mean air velocity: 0.2 m/s
- Relative humidity: 50%
- Metabolic rate: 1.2 met (standing, relaxed)
- Clothing level: 0.5 (summer) – 1.0 (winter)
- **Target MRT to meet -0.5<PMV<0.5: 18.4-28.0°C**

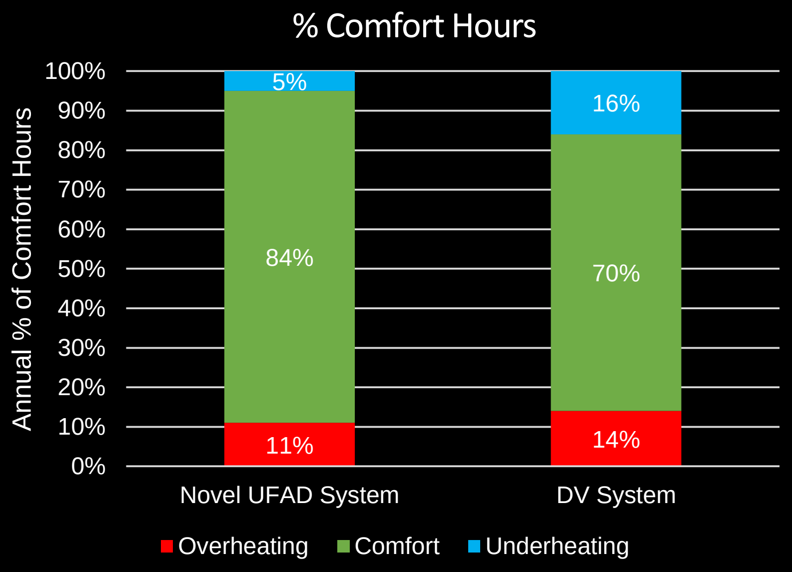
Key Observations:

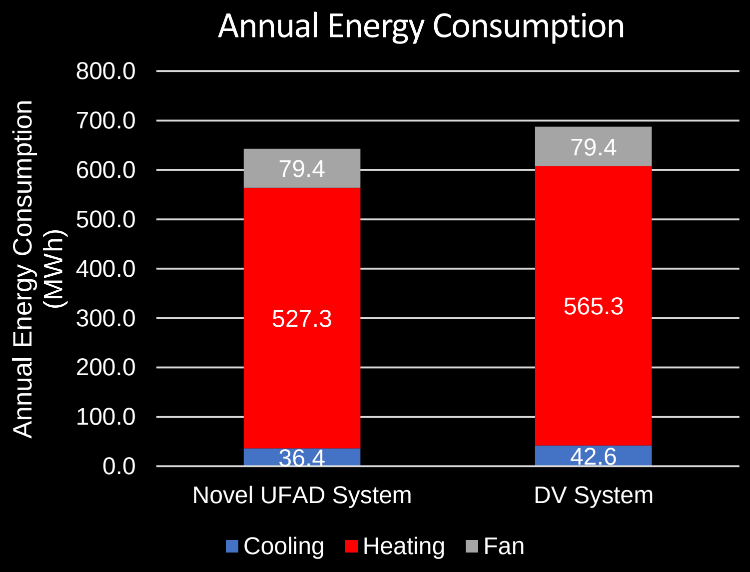
- Overall 84% comfort occupied hours with 11% overheating and 5% underheating
- System has extra capacity to reduce main hall setpoint and eliminate overheating

4.0 RESULTS & DISCUSSIONS
Annual Dynamic Thermal Modelling and Analysis

Annual Analysis – Comparison between Side-Supply DV and the novel UFAD HVAC System







Key Observations:

- Better floor temperatures in both summer and winter when use the novel UFAD system
- Winter temperature difference is larger due to the temperature difference between indoor and outdoor
- Provide around 40 W/m² radiant heat pick-up/release

Key Observations:

- 14% more comfort hours was achieved by the novel UFAD system, mostly due to elevated winter floor temperature

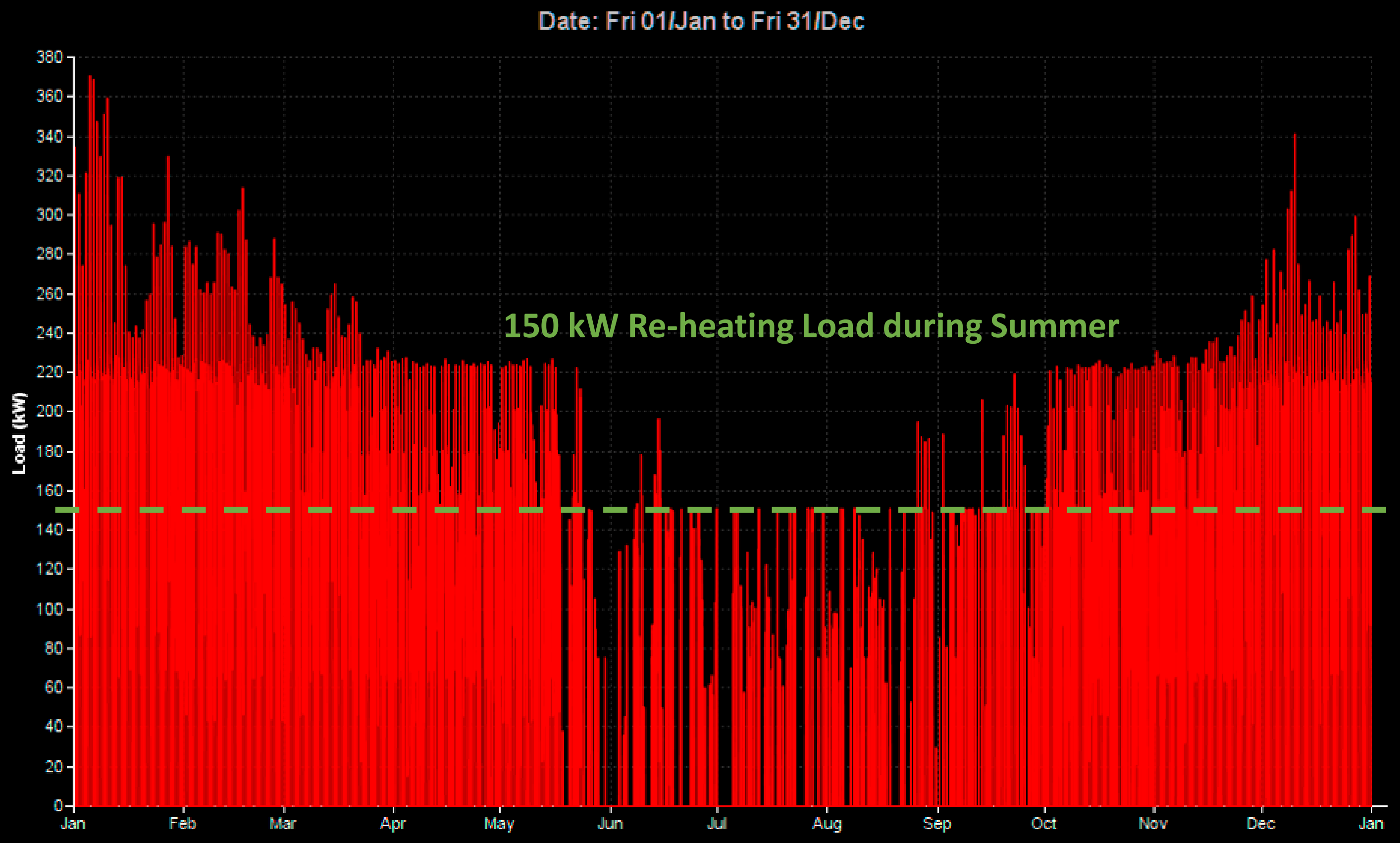
Key Observations:

- 6% annual energy saving could potentially be achieved by the novel UFAD system, mainly due to the heating savings

4.0 RESULTS & DISCUSSIONS

Annual Dynamic Thermal Modelling and Analysis

Annual Analysis – Annual Reheating Load Distribution



Key Observations:

- Around 150 kW re-heating load exists during summer seasons for the dehumidification purposes
- A lot of design considerations can be made to minimise the energy use for re-heating, such as: return air by-pass dampers, solar hot water, condenser water heat recovery and so on.

5.0 CONCLUSION
Conclusions and Further Recommendations

Conclusions

- A multi-software coupled modelling method was used in this research using DSM software IES-VE and CFD software OpenFOAM.
- A self-validated analytical model was developed for the novel UFAD system, within a case study building. The analytical method can potentially be applied to other air-based UFAD systems.
- The main purposes of using this method are to validate the AHU and diffuser design, generate accurate indoor CFD results (potentially for WELL submission), and investigate system's annual performance.
- From the study, 14% more annual comfort hours, with 6% reduced energy consumption can be achieved, comparing to a typical displacement ventilation system.

5.0 CONCLUSION
Conclusions and Further Recommendations

Further Recommendations

- The flow model was developed based on the CAV operation of the system. For potential VAV operation, correction factors or a new analytical model should be developed.
- RANS Steady-state solver was used in the CFD analysis. Potentially, transient Large Eddie Simulation (LES) solver could be used, however the running time will also increase.
- On-site measurement could potentially be carried out to further fine-tune the analytical model, so that modelling feedback can be given to operation team to optimise building’s future performance.

Foster + Partners

Thank You

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