Preserving Overall Performance of Air Conditioners by Incorporation of Wind-Permeable Floor in Buildings

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Outline

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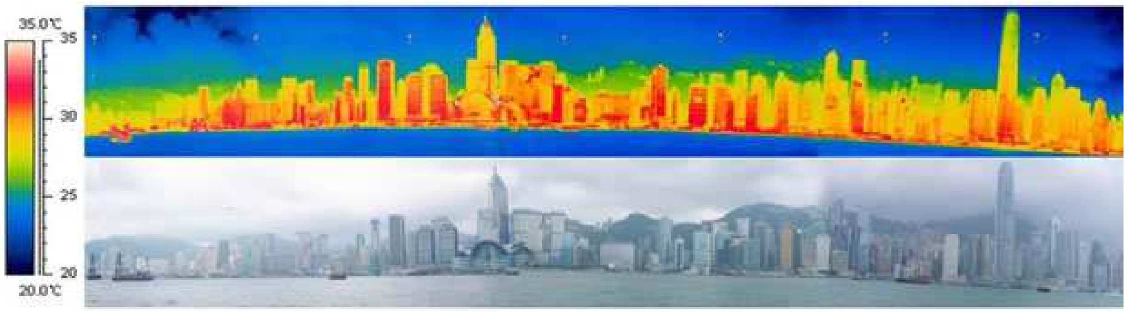
- Methodology
- Homogeneity of Profiles
- Model Geometry Settings
- Results and Conclusion
- Future Work

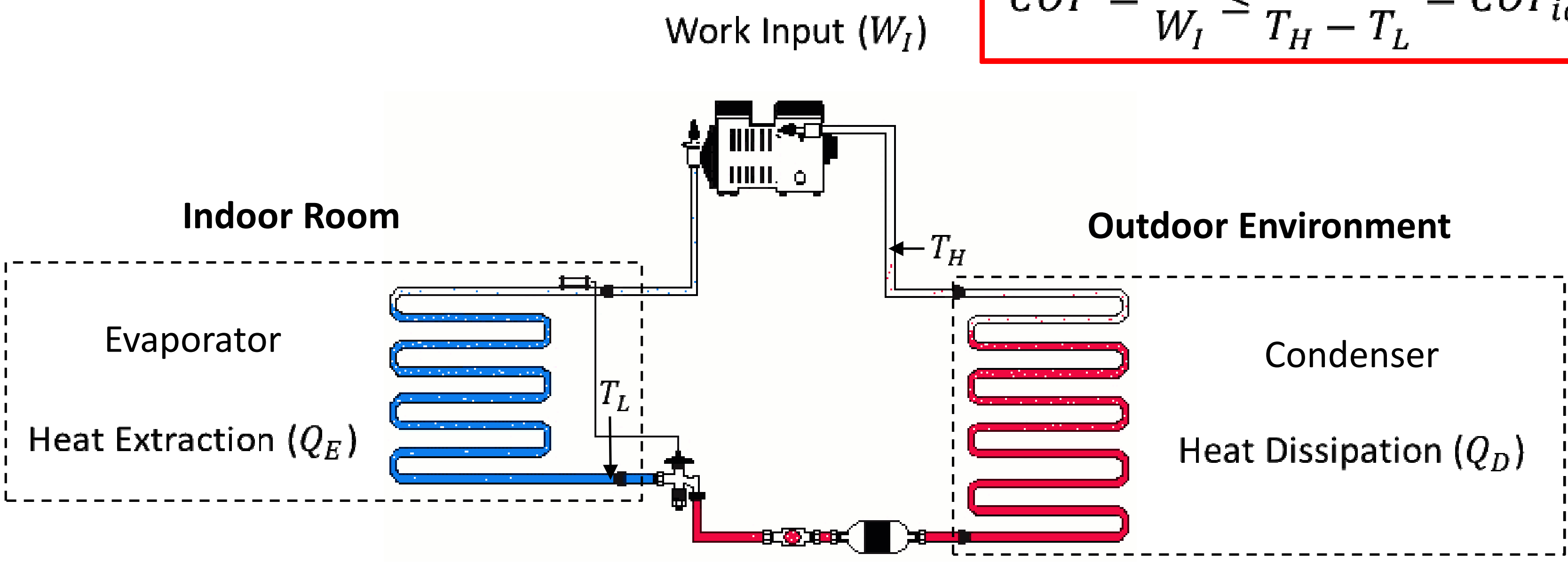
- Hong Kong is one of the most extensively urbanized areas in the world with high population density. Seven and a half million inhabitants live in an area of about a thousand kilometers square
- Large amount of heat generated from the streets and buildings without enough air-ventilation causes the Urban Heat Island (UHI) phenomenon



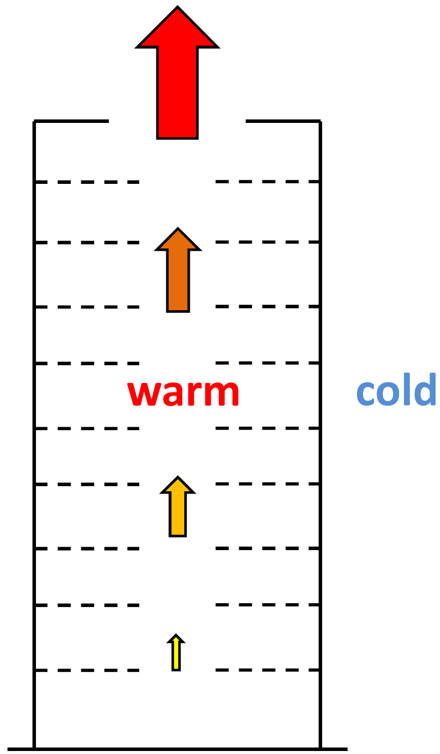
Source: (Photo extracted from research studies by Prof. Yuguo Li)

- Large portion of energy consumption (>30%) and heat production in the residential area is by the refrigeration cycle of air-conditioning. The outdoor temperature determine the cycle efficiency, coefficient of performance (COP)

$$\boxed{COP = \frac{Q_E}{W_I} \leq \frac{T_L}{T_H - T_L} = COP_{ideal}}$$



- Thermal stack effect is formed when heated air is driven upward and accumulated through the semi-enclosed building developed by thermal buoyancy
- Field measurement reveals there could be a temperature difference of at least 10°C over a 24 storeys building
- Overall percentage drop in COP of air conditioners could reach a maximum of 26% under no-wind condition.



Building acts like a perforated tub

Aim of the Study

1. Investigate the effectiveness of the implementation of an open permeable floor in designs of buildings to alleviate the residual heat ejected by outdoor condensing units that is accumulated within semi-enclosed re-entrants of buildings
2. Investigate the group performances of air conditioners after the implementation of the open permeable floor
3. Aid the developers/architects during building design stage to achieve a “greener” building

$k-\varepsilon$ Model with Corrective Terms

Continuity Equation: $\rho \frac{\partial u_i}{\partial x_i} = 0$

Momentum Equation: $\rho u_j \frac{\partial u_i}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\tau_{ij} - \rho \overline{u'_i u'_j}\right) - \frac{\partial p}{\partial x_i} + \rho g_i$

Turbulent Kinetic Energy Equation: $\rho u_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon + \boxed{S_k}$

$\boxed{T}$

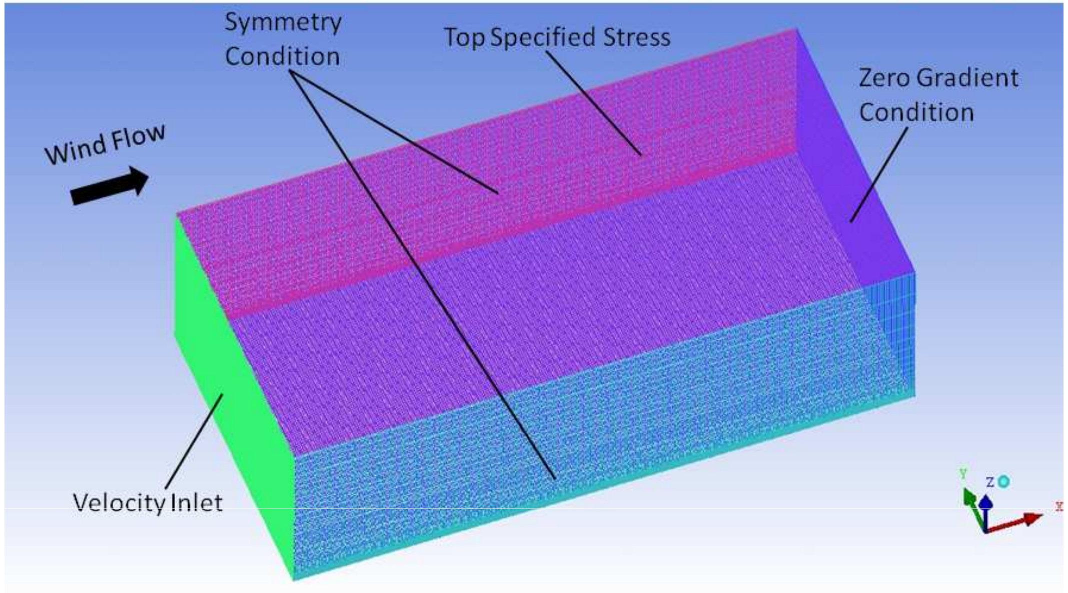
Turbulent Dissipation Rate Equation:

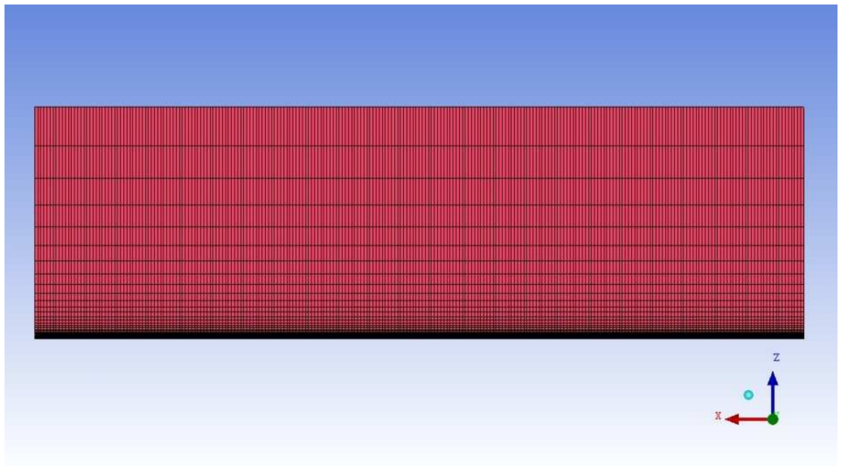
$\boxed{S_\varepsilon = (C_{1\varepsilon} S_k \,\varepsilon / k)(1 - C_{3\varepsilon})}$

Energy Equation:

Work Input (W_I) $\boxed{S_T = -g\left(\frac{\partial \mu_t}{\partial z}\right)/\sigma_T}$

Homogeneity of Profiles





- Simulation is carried on an empty fetch with dimensions 2000 m (L) x 1000 m (W) x 600 m (H)
- Around 1.5 million structure cells are created with first cell size of 0.5m
- Grid Expansion Ratio of at most 1.2 in both horizontal and vertical directions
- Standard Wall Function with roughness height set to $20z_0$ where z_0= 0.002m

Inflow Profiles for Empty Fetch

Inflow Velocity Profile: $u(z) = \frac{u_*}{\kappa}[\ln(\frac{z}{z_0}) - \psi_m(\frac{z}{L})]$ where $L = \frac{u_*^2 \vartheta_0}{\kappa g \vartheta_*}$

Inflow Temperature Profile: $\vartheta(z) = \vartheta_0 + \frac{\vartheta_*}{\kappa}[\ln(\frac{z}{z_0}) - \psi_h(\frac{z}{L})]$ where $\vartheta_* = \frac{-q_0}{\rho c_p u_*}$

Inflow TKE Profile: $k(z) = \frac{u_*^2}{\sqrt{C_\mu}}\sqrt{\frac{\varphi_\varepsilon(z/L)}{\varphi_m(z/L)}}$

Inflow TDR Profile: $\varepsilon(z) = \frac{u_*^3 \varphi_\varepsilon(z/L)}{\kappa z}$

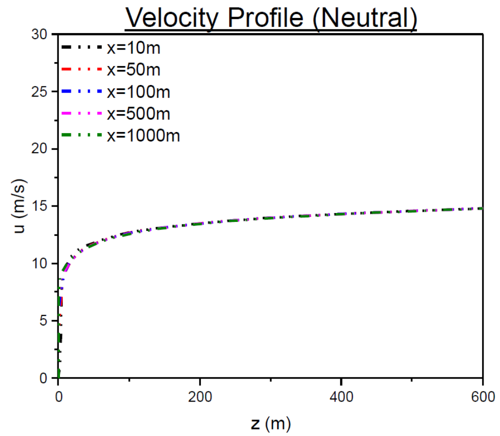
where $\varphi_\varepsilon = 1 - \frac{z}{L}$ for $L < 0$

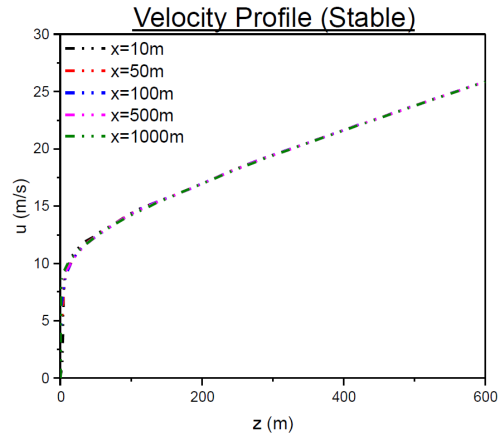
$\varphi_\varepsilon = \varphi_m - \frac{z}{L}$ for $L > 0$

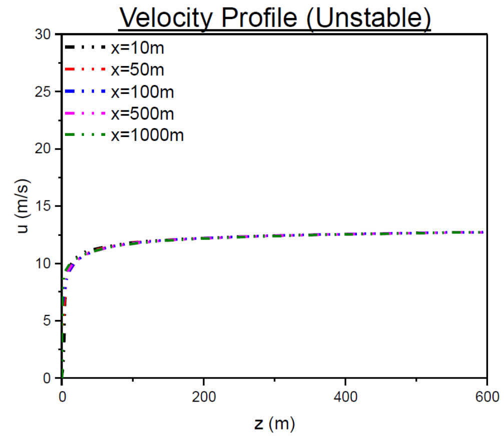
where $\varphi_m = \varphi_h = 1 + 5(\frac{z}{L})$ for $L > 0$, $\varphi_m = (1 - 16\frac{z}{L})^{-0.25}$, $\varphi_h = (1 - 16\frac{z}{L})^{-0.5}$ for $L < 0$

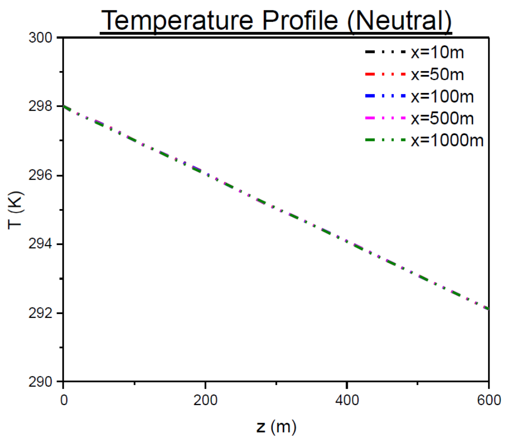
	Stability Class	z_0 (m)	u_* (m/s)	q_0(W/m^2)	ϑ_0 (K)	L (m)
1	Neutral	0.002	0.4815	0	298	∞
2	Stable	0.002	0.473	-30	283	306.0
3	Unstable	0.002	0.5085	100	313	-126.1

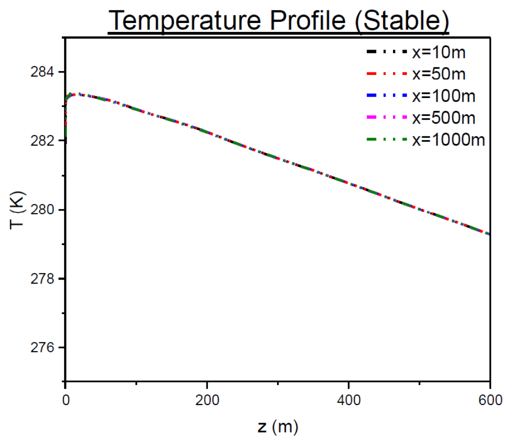
Velocity and Temperature Profiles at Various Locations along Centre Line

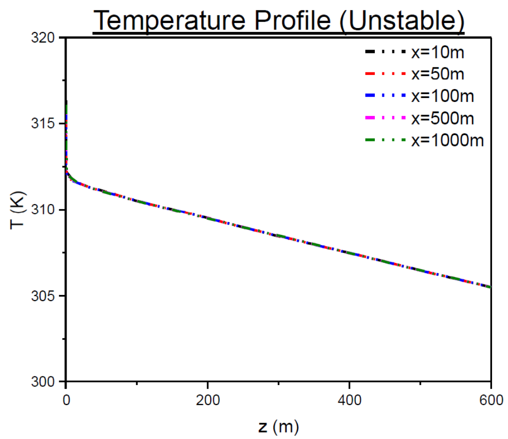




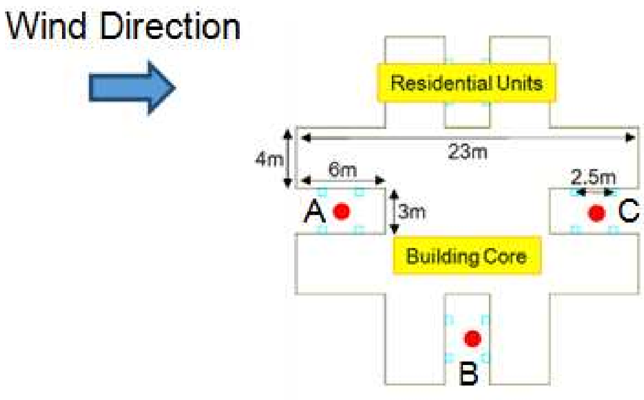


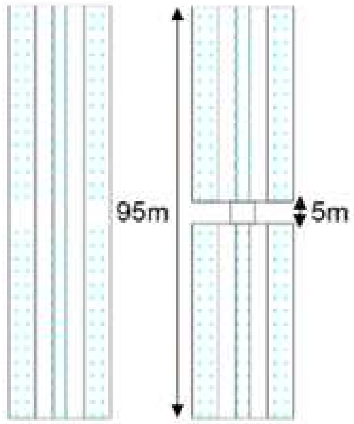


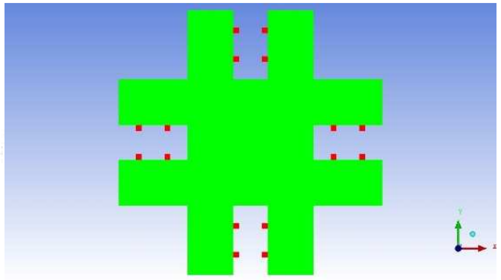


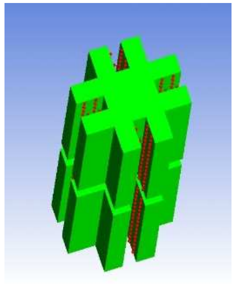


Model Geometry Settings



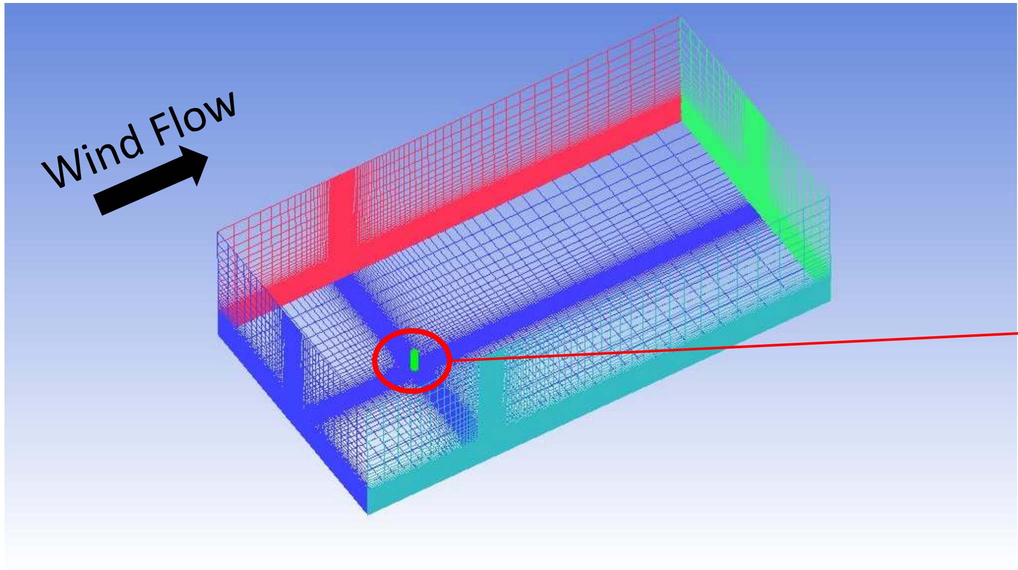


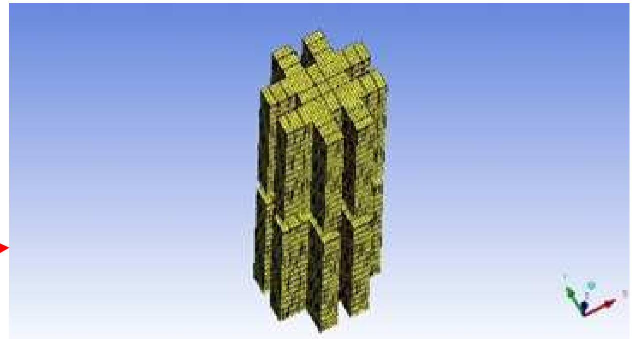




- Typical 30 storey (3 meters per floor) cross shaped residential building with air conditioners installed at re-entrants is investigated
- Two buildings, with/without permeable floor at mid-level are created for comparison
- 4 air conditioners are placed at each re-entrant location of the building
- Each air conditioner is modeled as a volumetric heat source, generating 2500W of heat
- Temperature Data are extracted at three locations A, B and C

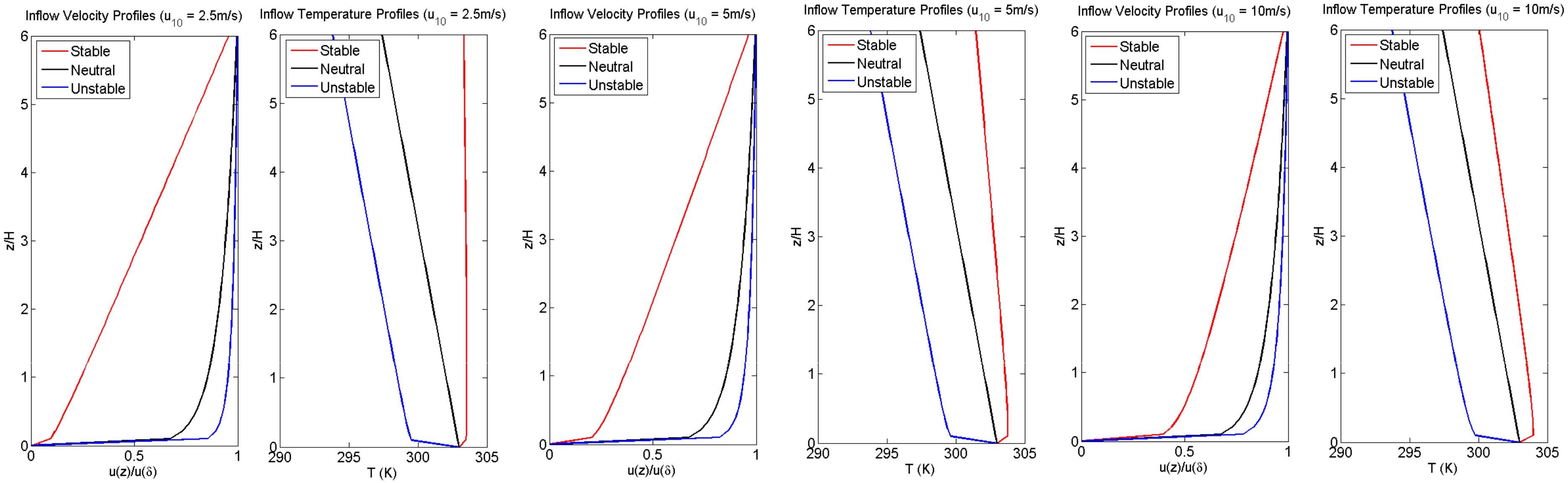
Model Geometry Settings





- Approximately 3 million structure cells are created
- Target building is set 5H away from the inflow, lateral, top sides and 15H away from outflow face where H=95m
- Boundary conditions are same as the empty fetch case
- Second Order upwind schemes are used for the discretize the advection terms
- Scaled residuals of flow and turbulence quantities dropped below 1 x 10^{-5}

Inflow Profiles

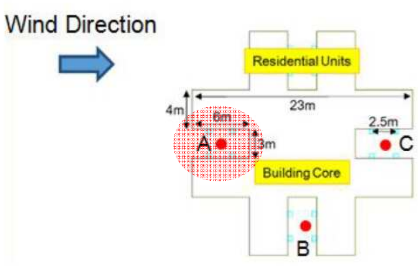


	Stability Class	z_0 (m)	u_* (m/s)	u_{10} (m/s)	q_0 (W/m^2)	ϑ_o (K)	$\Delta\vartheta$ (K)	L (m)
1	Neutral	0.002	0.1205	2.5	0	303	0.98	∞
2	Neutral	0.002	0.2405	5	0	303	0.98	∞
3	Neutral	0.002	0.4815	10	0	303	0.98	∞
4	Stable	0.002	0.102	2.5	-3.04	303	-0.57	32.42
5	Stable	0.002	0.227	5	-11.14	303	-0.57	97.52
6	Stable	0.002	0.473	10	-30	303	-0.57	327.62
7	Unstable	0.002	0.1545	2.5	40.5	303	4.52	-8.46
8	Unstable	0.002	0.2745	5	61.4	303	4.52	-31.29
9	Unstable	0.002	0.5085	10	100	303	4.52	-122.12

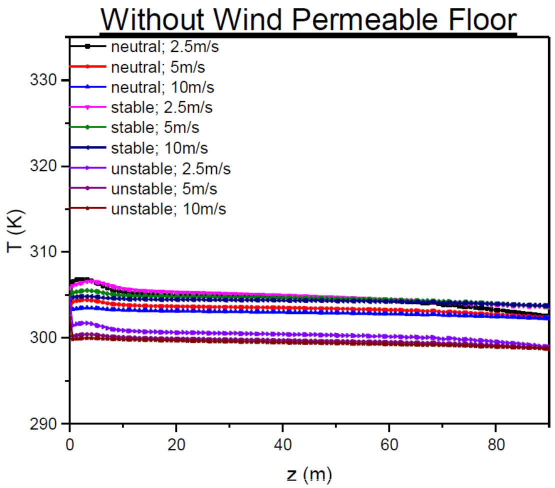
Summary Table of the CFD model

	CFD model
Computational domain size	5H for inflow buffer, lateral and vertical region
	15H downstream region (H=95 meters)
Boundary conditions	Symmetry condition for the two side boundaries Top specified stress
	Wall boundary condition for the ground
	Velocity inlet condition for the inflow boundary
	Zero gradient condition for the outlet boundary
Turbulence model	k-ε model with corrective source terms
Mesh Grids	Approximately 3 million structure cells
Numerical scheme for pressure term and advection terms	PRESTO! for the pressure term Second order upwind schemes for advection terms
Wall function	Standard wall function
Convergence criteria	Scaled residuals dropped to below 1×10^{-5}
Air Conditioner Heat Source	2500W per air conditioner

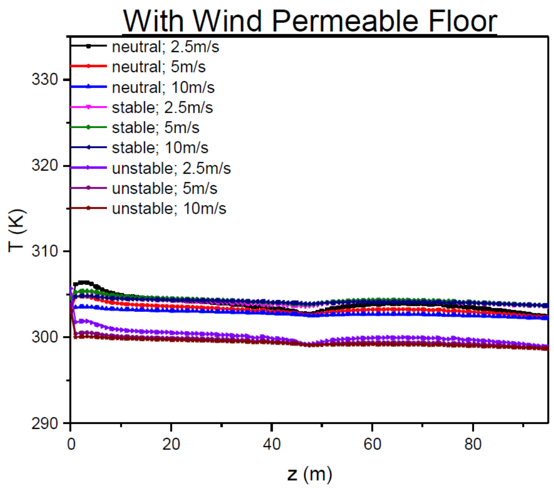
Temperature Profiles



Windward Re-entrant

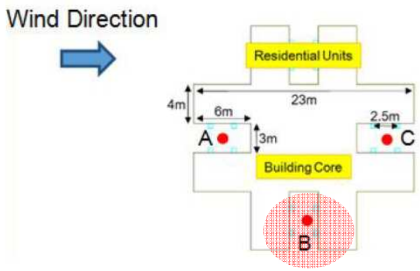


Windward Re-entrant



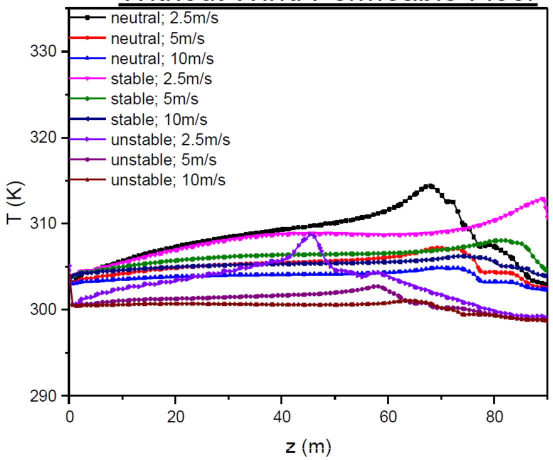
- Similar behavior of the temperature profiles are observed for both cases with/without permeable floor under different atmospheric conditions
- Different wind speed have minor influence on the magnitude and shape of temperature profiles at the windward side

Temperature Profiles



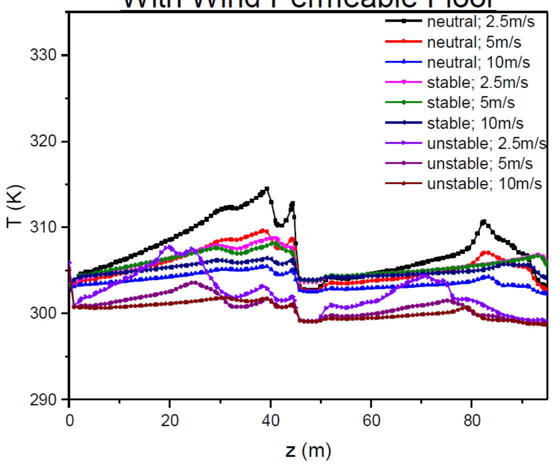
Sideward Re-entrant

Without Wind Permeable Floor



Sideward Re-entrant

With Wind Permeable Floor



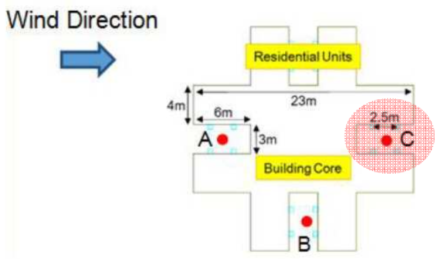
With Permeable Floor:

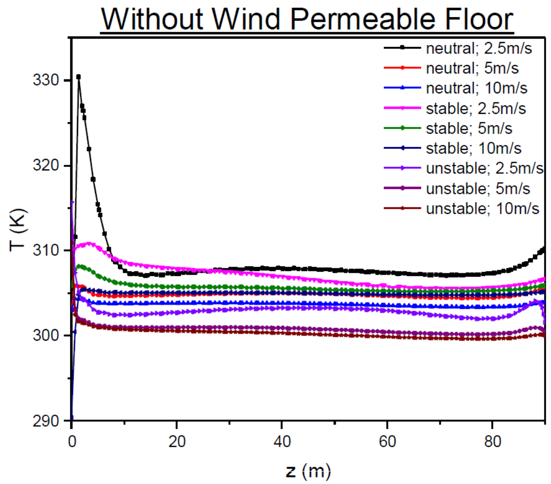
- A temperature drop of approximately 5°C with the implementation of the permeable floor
- A drop of temperature from 314K to 305K is observed under the neutral atmosphere with low inflow wind speed
- Under the stable and unstable atmospheric conditions, temperature decline is also observed but relatively not significant
- Difference in magnitude in wind speed has minor effect on the temperature profiles near the permeable floor location under unstable atmospheric environment

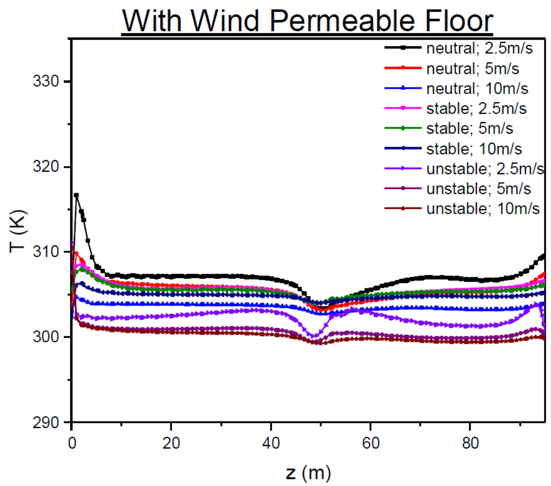
Without Permeable Floor:

- Temperature maintains an increment trend (Evidence of the continuous accumulation of heat emitted from the air conditioners)

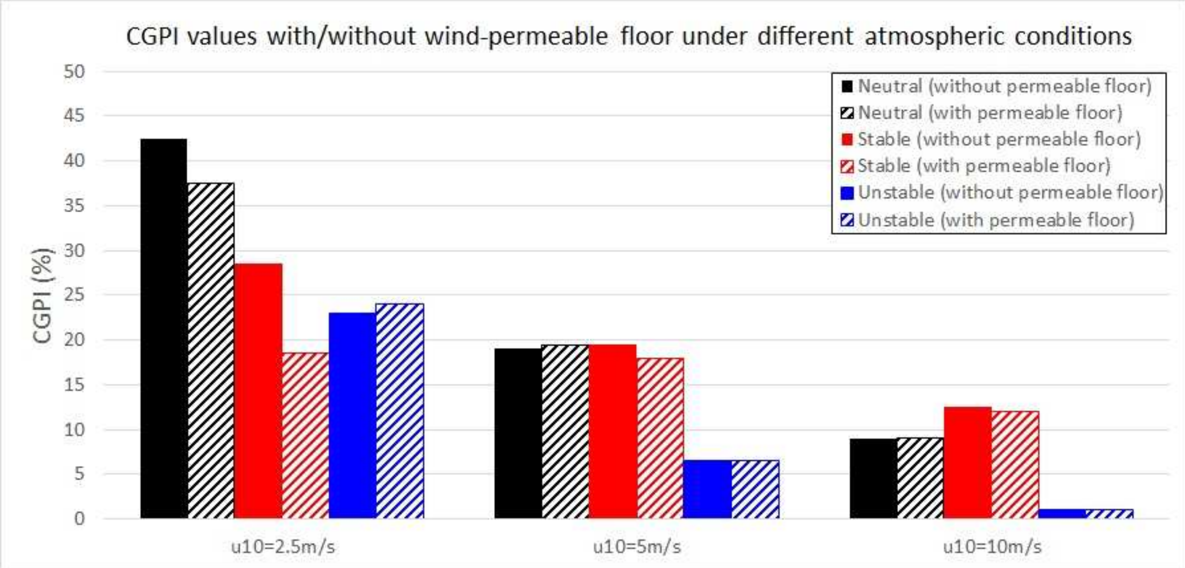
Temperature Profiles







- Under stable atmosphere, the temperature drop at location of the open permeable floor are not as obvious those cases under the neutral and unstable atmosphere
- Under neutral/unstable atmosphere, a minor drop of 0.5 ^{o}C is observed for the cases with mid/high inflow wind magnitude and drop of approximately 1 ^{o}C to 2 ^{o}C is observed for the low wind cases
- Despite there is decline in temperature at location C, the drop is not as sharp when compared to the sideward re-entrant at location B



CGPI for n air conditioners working together is defined as:

$$CGPI_{T_r}(T_{ref}) = \frac{100}{n}\sum_{i=1}^{n}\{1-[\frac{COP_{T_r}(T_{coil})}{COP_{T_r}(T_{ref})}]_i\}$$

where $T_{ref} = 303K$ and T_{coil} extracted from the simulated temperature at geometric center of air conditioners

$$COP_{T_r}(T_{coil}) = 5.15 - 0.0738(T_{coil} - 273)$$

- Smaller the CGPI, the better the efficiency of air conditioners
- Improvement in CGPI is significant particularly under neutral and stable stratifications with low inflow wind
- Open Permeable Floor is relatively useful to alleviate thermal stack effect under neutral/stable low wind environment compared to other atmospheric conditions with higher wind speed

Conclusions

1. After Implementation of Open Permeable Floor in residential blocks:
   - Elevated air passing through the floor is cooled by natural means
   - Residents above the permeable floor are expected to benefit from better thermal comfort than those below
   - Performance of air conditioners (particularly above the Permeable Floor) are retained with lower operating temperature
   - Over 10% enhancement in CGPI (reflecting group performances of the air conditioners) is achieved.
2. The cooling effect by permeable floor is shown to be more significant under neutral/stable atmosphere with low wind speed compared to other atmospheric stability cases with higher wind speed

Future Work

- Influence of location of Permeable Floor on Temperature Profiles and CGPI values will be investigated
- Influence of different inflow wind angle of attack on the results will also be investigated
- Study would be further carried out on a model of a real urban area with topography and clusters of buildings with different shapes and heights

THANK YOU!