Research Article
Optimization of Wind Driven Rain Barrier for Tropical Natural Ventilated Building

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Abstract: Wind Driven Rain (WDR) is an inherent problem especially on open corridors and open areas like courtyard, balconies and terraces of naturally ventilated tropical buildings. The WDR can cause the building floor to be slippery and even flooding during heavy rain and strong wind. It also eventually caused damages on building materials if exposed over a long period of time. Unfortunately, until to date there are not many researches conducted on WDR in tropical natural ventilated buildings. An experimental and CFD simulation analyses were taken into consideration to predict the percentage of water on a floor of case study building. Different types of rain barrier designs have been proposed to reduce the amount of wind driven rain entering the building. The CFD simulation results showed that the water percentage on the floor caused by the wind driven rain can be reduced from 78% of the floor area to about 42% using titled overhang rain barrier design.

Keywords: CFD Simulation, natural ventilated building, rain barrier, tropical climate, wind driven rain

INTRODUCTION

Wind Driven Drain (WDR) is one of the most critical factors that affect building open spaces like exposed corridors and terraces in tropical regions (Mirrahimi *et al*., 2015). Moreover, this problem is even more serious when there is a semi-enclosed outdoor eating areas like cafes and seating spaces whereby the occupants are subjected and exposed to large amount of rain water penetration (Abuku *et al*., 2009). WDR also affects the performance and durability of a building especially the erosion of external paint and other external cladding of building materials. Hence, it is important to analyze the effects of WDR on tropical buildings in countries like Malaysia where building areas like corridors and facades are frequently exposed to tropical rainstorm throughout the year.

WDR is defined as the amount rain water impinges on the façade of the building, or the amount of water rain that causes the floor of an open area to be wet inside a building (Baheru, 2014). There are two major parametersthat are used in the calculations of wind driven rain (Blocken and Carmeliet, 2007a). The two main parameters are namely the weather parameters and the building parameters (Blocken *et al*., 2010). The weather parameters that affects the WDR are wind direction, wind speed, the amount of rain intensity and its duration. While the building parameters are the building geometry, orientation of the building façade and the sheltering distribution (Blocken, 2004). The most effective methods in WDR calculations is by using the Computational Fluid Dynamics (CFD) simulation, while other methods are considered as an empirical method or field measurements (Blocken and Carmeliet, 2006b).

Measurements method is widely known as the first WDR solution tool, but recently this method is not used in the research field as researchers discovered it has many errors (Blocken and Carmeliet, 2006a). On the other hand, the CFD solution provides more flexibility in modelling the geometry of the building and identification of areas that are influenced by the WDR effect (Choi, 2001). The first model using CFD in the wind driven rain research was presented by Blocken and Carmeliet (2004), where the CFD results obtained have a good agreement with the experimental data. The study represented different geometry types of different buildings with the analysis of the wet pattern as a function of rain and wind speed (Nore *et al*., 2007). Therefore, the numerical method can be classified as an effective research tool to understand the effect of WDR on a building comprehensively. The first correlation of the WDR in the building with the utilization of weather data was made using the empirical method. The first driving rain map was developed by Boyd (1963) and Blocken and Carmeliet (2004), by using the empirical method which include the meteorological data of Canada (Blocken and Carmeliet, 2007b). The driving rain index (DRI) indicates the wetness factor in the building, was calculated based on the annual average amount of rain and the annual average amount of wind

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speed at the same location. The DRI was improved by Robinson and Baker (1975), as they used hourly data of rain and wind speed. In 1995, Fazio *et al*. (1995) further developed on the DRI, whereby the orientation of the building's walls was taken into consideration (Hooff *et al*., 2011).

Further WDR research development has included the Rain Admittance Factor (RAF) as the factor that transformed WDR from the free field into an actual building field. Straube (2006) and Overton (2013) studied the influence of both terrain and topography factors. The British Standard BS-8104 gives a detailed procedure about WDR assessment in buildings. The quantity of WDR impinges on the wall of a building was presented in this procedure (Montazeri *et al*., 2015). The procedure uses the meteorological weather data obtained by weather station to investigate some parameters such as topography, the roughness of the ground, impediments and the geometry of the building (Choi, 2001). The empirical methods of WDR analysis is limited in terms of studying the effect of adding overhang components to the building design (Abuku *et al*., 2009).

Recent studies on the effect of adding overhangs to building to reduce the WDR is very limited. In 1995, Inculet and Surry (Baheru, 2014) studied the effect of adding overhangs to the building. The new improvement in building geometry consists of adding an overhang to each balcony and corner. The study used a scale down prototype of the building showing some corners and balconies with and without overhangs and the scale down models were tested inside a wind tunnel. The influence of adding overhangs to some parts of the building shows some effectiveness of these overhangs to reduce the WDR effect on the corners and balconies of the building. CFD modelling of the same building was proposed by Surry in 2000 (Ge and Krpan, 2007) and the analysis of a medium height building analysed based on the boundary conditions used before shows that the addition of overhangs could produce better protection to these parts of the building.

In order to study the effect of wind driven rain on the building with some open areas that exposed to the rain, especially in continuous heavy rain weather like Malaysia (Selbin *et al*., 2014); a CFD modelling of a building with different design configurations of rain barriers to reduce the WDR effect was presented in this study. The objectives of this study is to find the optimum design of overhang that could be used for an open corridor area of a building to reduce WDR in tropical climate.

PROBLEM STATEMENT

Most of the naturally ventilated buildings in Malaysia and other tropical countries will have some open areas like corridors and open terraces or deck spaces. These open areas have the tendency to be exposed to continuous heavy rain throughout the year especially

Fig. 1: Snapshots of the floor in the case study building

during the monsoon seasons. The open corridors normally were designed as linkages between building blocks and have two sides opening (front and back). Therefore, during the rain, all the floors of these areas are usually covered with rain water and the wetted percentage generally is more than 90% of the floor area. Figure 1 represents some snapshots of these open corridors taken after the rain of the case study building.

In order to address the WDR problem, this study undertook to analyze different design of overhangs and louvers to reduce the effect of WDR on these open areas. The analysis of the effectiveness of the overhang design also takes into consideration of the building orientation and the actual onsite weather data obtained using onsite weather station.

Building and site description: The proposed case study building for this research is an academic building located within the vicinity of the UniversitiKebangsaan Malaysia (UKM). The building consists of two main blocks with five stories height and each floor to floor height is 4 m. Each storey of the building has a long corridor linking the office rooms to a center core where a lift and staircase is located. Generally, these long corridor spaces were exposed to WDR during heavy rain due to its openess in design. Figure 2a shows the orientation of the case study building, while Fig. 2b illustrates the front façade of the building with the corridor linkage.

Figure 2a shows that the building front façade is facing the North West (NW) orientation and the rear facade is facing South East (SE) direction. The case study building is also located at the foot of a hill with the rear façade facing the hill slope.

Measurement procedure: In order to get an accurate boundary conditions for this study, a weather station was installed on the top roof of the building to collect the wind speed and directions that will be used as input parameters in the CFD simulation. The weather station included an anemometer and wind vane to monitor the wind speed and direction surrounding the building. The data was automatically logged into the datalogger every 1 min for 24 h per day for one year.

Figure 3a and b shows the weather station with two components, namely the outdoor anemometer and the indoor wireless data acquisition system. Another instrument used in this study was the horizontal rain gauge as shown in Fig. 3c. Fourteen units of rain gauge

(a)
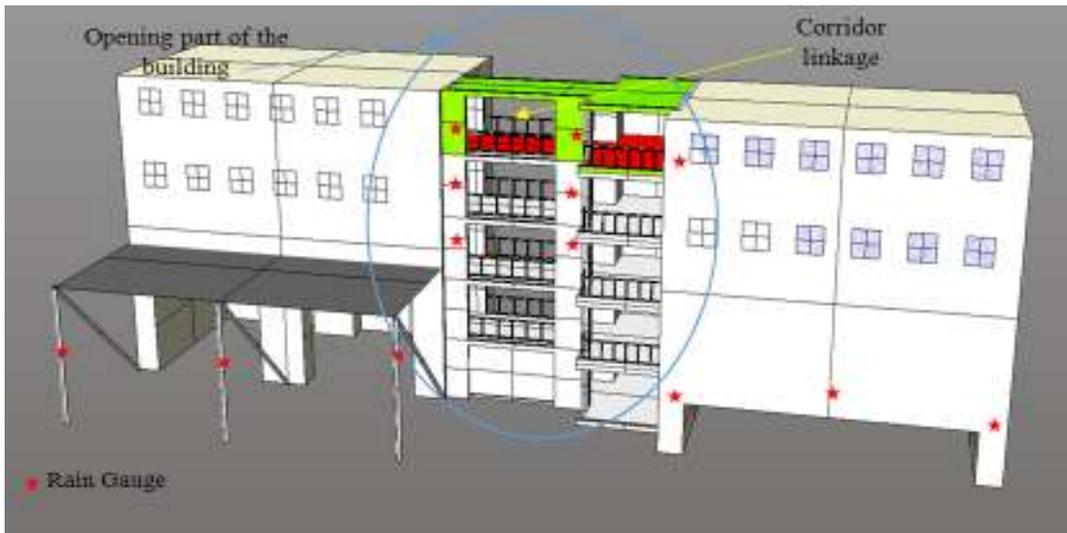
(b)

Fig. 2: (a): Google earth picture showing the building orientation; (b): Schematic drawing of the building showing the rain gauges positions, opening part and corridor linkage

were fitted in different positions of the building and in each storey to calculate the amount of rain for 1 h. The rain gauge consists of a bottle shape rain water collector and a square rain catcher, which can be fitted on the wall or façade of the building. Each time it rains, a stop watch was used to determine the duration of 1 h on the amount of rain water that can be collected in the bottle. Different locations of rain gauges were installed on the building façade to ensure accurate and thorough readings. Subsequently, an average reading of the amount of rain water was derived from the fourteen units of horizontal rain gauge and used as input parameter in the CFD simulation. All the measured parameters obtained from the weather station were also used as inputs in the CFD simulation. Figure 2b indicated the different locations of the rain gauges installed on the building façade.
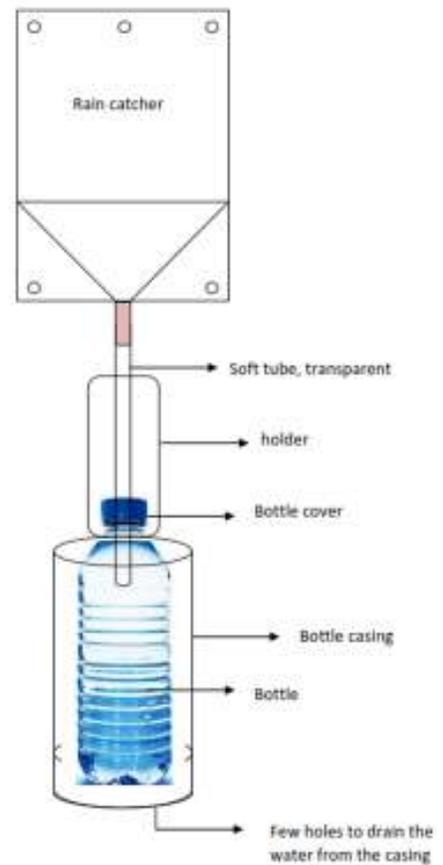
Fig. 3: (a): Wireless Data logger of the weather station; (b): Weather station (anemometer); (c): Horizontal rain gauge

A windrose was derived based on the collected data from the anemometer and wind vane. Figure 4 shows the average annual wind speed and directions around the vicinity of the case study building. The windrose revealed that the prevailing wind is flowing from the NW direction which is directly perpendicular to the building's front facade. It was anticipated that the incoming prevailing wind from the NW will cause more WDR impinging on the front building facade because the case study building is also located on higher eleveation of a hill and this will also cause most of the corridor linkages to be unusable during heavy rain. The prevailing wind was from NW direction and the wind speed is approximately 3 m/s.

CFD Simulation: The WDR analysis has some defined parameters that were very important in the analysis and estimation the amount of rain. As mentioned before, the geometry of the building an important parameter since it will influence the amount of the rain driven by the wind towards the building. Due to the open concept design of the corridor linkage, it is anticipated that both sides of the corridor will be fully exposed to WDR as shown in Fig. 2b.
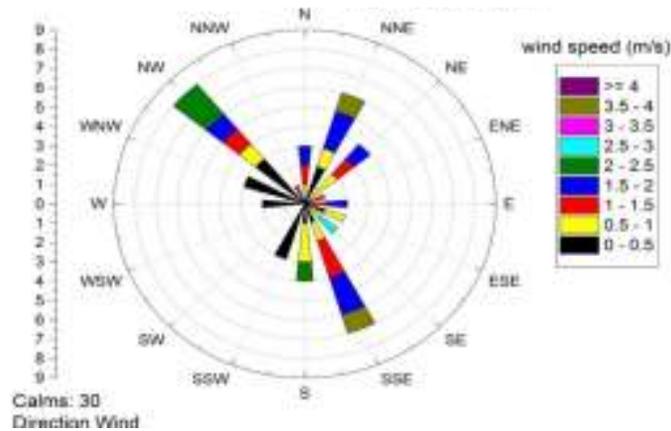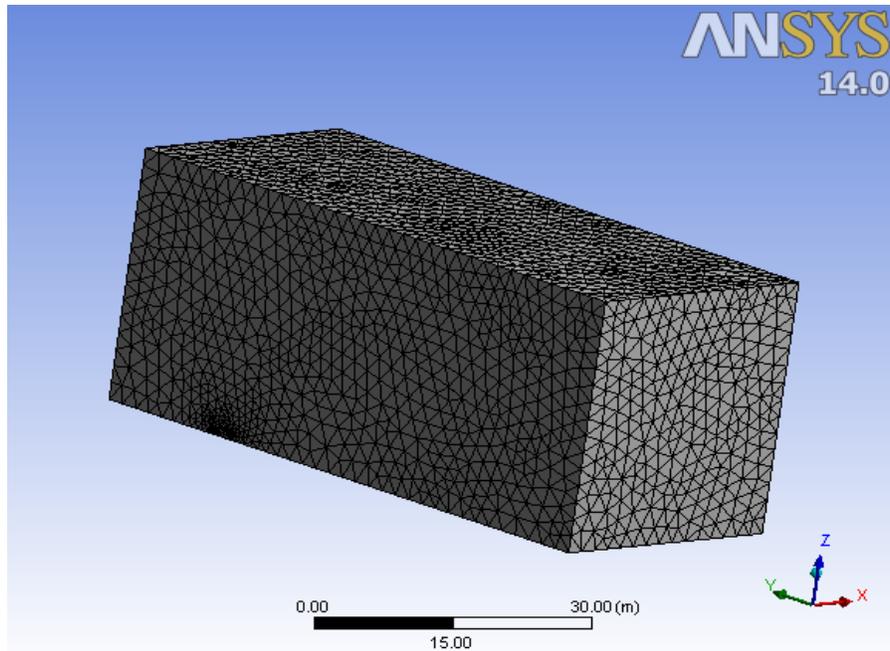

Fig. 4: Average annual wind speed and wind direction taken from weather station on roof top of the building
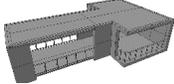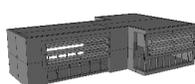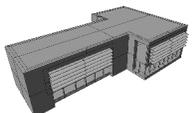

(a)
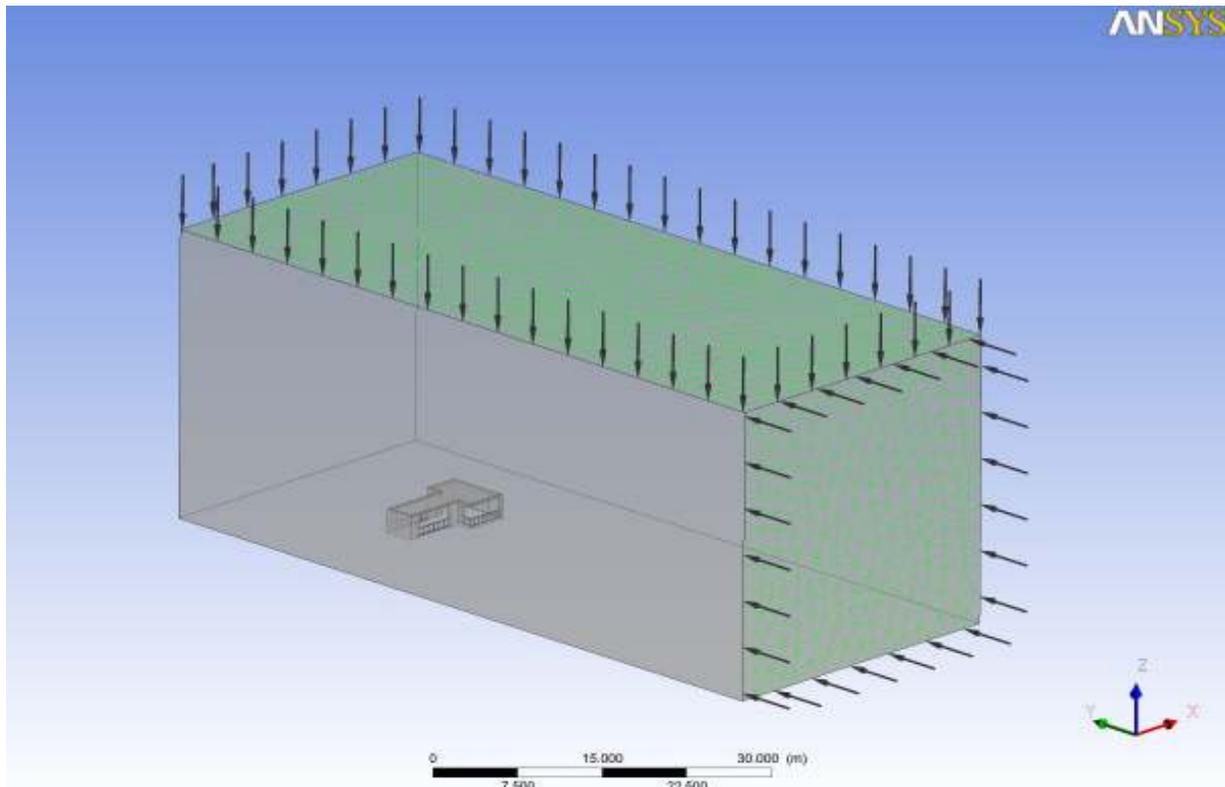
(b)

Fig. 5: (a): Domain analysis and boundary conditions; (b): Meshing analysis of the base model

Table 1: Description of different model with meshing elements number

Type of design configurations for rainwater barrier	Description	Number of elements (Mesh)
	The basic design of the building without adding any configuration	1682047
	1m overhangs were added to both opening sides of the basic building model	1992296
	2m overhangs were added to both opening sides of the basic building model	2143304
	Two 30° tilted overhangs were added to the basic model of the building model	2147822
	Half grid of louvers were added to both sides of the basic building model	2798961
	Full grid of louvers were added to both sides of the basic building model	3157362

Different geometric models of the opening part of the building were simulated using ANSYS 14 CFD simulation tool. A base model and the modified models with overhangs for the building were designed and modelled with actual building dimensions using the Rhinoceros v.4 design and modeling tool. The geometry file was then exported to the ANSYS 14 Workbench and linked to (Fluid Flow CFX) Modeling to be processed. In the CFX modeling interface, a domain surrounding the case study building was created and the settings of the boundary conditions for the simulation process was made. Figure 5a illustrates the domain and the boundary conditions of the building model.

The domain size is very important to determine the accuracy of the CFD simulation process. Hence, the domain size of the simulation was modelled at 20 m width×50 m length ×20 m height, which was 4 times bigger than the volumetric size of the building. In order to solve the two-phase flow of WDR, the Eulerian Lagrangian method was used for the CFD simulation. The trajectories of the rainwater droplets is computed and tracked in Lagrangian frame. The flow regime was based on droplet flow. The Eulerian multiphase model was used to solve the continuity, momentum and energy equations for each phases. The upper face of the domain represents the inlet of the rain drops, while the right side of the domain represents the inlet of the wind.

The meshing of subjected part of the building reached approximately 1.7 million meshing elements for the basic design of the building using the advanced sizing function with a medium relevance center as shown in Fig. 5b.

Different design configurations have been taken into consideration and each model was compared to the base model of the building. The design configuration consists of adding 1 m overhang, 2 m overhang, tilted overhangs, half louvers and full louvers to the opening sides of the corridor linkage of the building. Table 1 below shows the number of elements in the meshing process for each model.
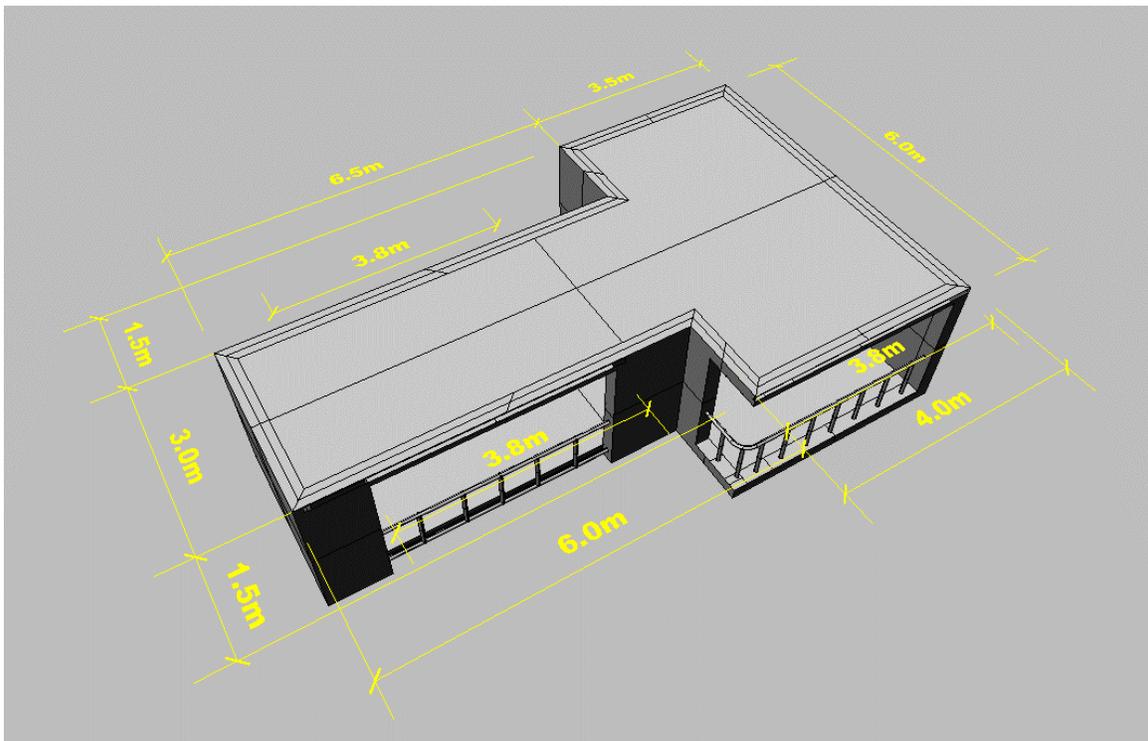
Simulation parameters and boundary conditions: In order to obtain high accurate CFD results from the simulation, the boundary conditions should be modelled very close to the actual ambient conditions. The simulation takes into consideration the effect of the rain droplets driven by the wind speed flowing towards the direction of the case study building. Two phase flow simulation has been proposed in this study with the influence of the water intensity coverage of the floor area of the opening sides of the building. The simulation parameters and boundary conditions were set to the following values shown in Table 2 below:

The simulation process using the Fluid Flow CFX model was applied to all the different design developments of the building to get the best results. Beside the two phase flow analysis of water and air, the continuous fluid for the two fluids also havebeen selected. The CFX simulation setup was set to be a homogeneous model with isothermal heat transfer and k-epsilon turbulence model.
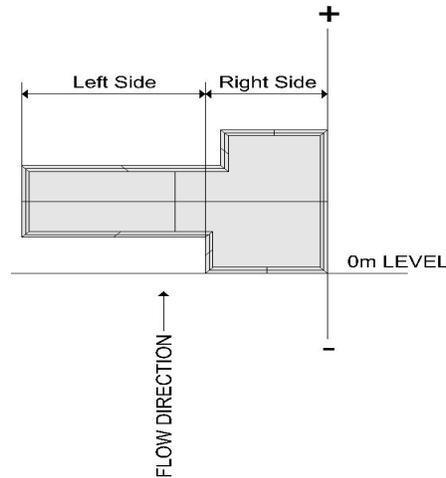
(a)

(b)

Fig. 6: (a): Schematic drawing of the top view of the building; (b): Schematic drawing of the subjected building with dimensions

Table 2: Simulation parameters and boundary conditions

Parameter	Value	Description
Inlet wind speed	5.5 m/s	Assumed to be facing the same direction of the building façade
Inlet rain speed (Terminal velocity)	4 m/s	With variable rain flow rates calculated from the weather station and rain gauges
Intensity at the air side inlet (volume fraction)	0.9 Air 0.1 Water	Assuming that the air side inlet contains small amount of water
Intensity at the water side inlet (volume fraction)	0.2 Air 0.8 Water	Assuming that most of the fluid inlet is water
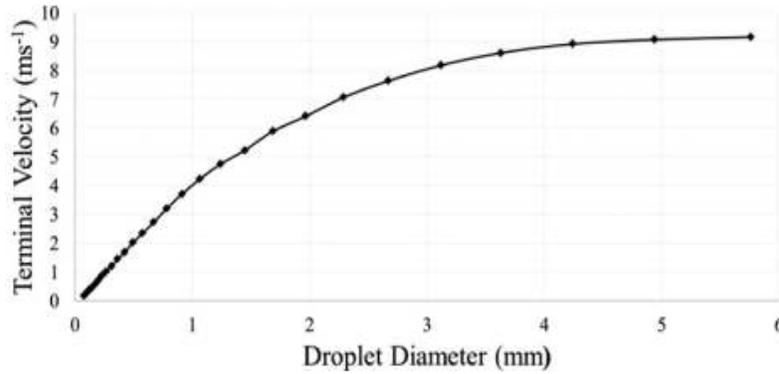
Fig. 7: Equivolume diameter of rain drops

SIMULATION RESULTS AND DISCCUSION

The CFD simulation results for six different geometry models: base model, 1 m overhangs, 2 m overhangs, 1.5 m tilted overhangs, half grid louvers and full grid louvers in the water volume fraction contour form on the floor plane with the percentage of wet area covered by the rainwater. Another simulation setup was obtained in transient model to obtain the accumulated water percentage on the floor area of the building after 4 h of non-stop raining, where the resultant graphs represent the flow direction as shown in Fig. 6a and b illustrate the flow direction from negative (-) to the positive (+) side. The water volume fraction represents the percentage of the water volume to the water and air volume in the building as shown in Eq. (1) below:

$$Water\ Volume\ Fraction = \frac{Water\ Volume}{Water\ Volume + Air\ Volume}$$
(1)

The wind driven rain is usually created by the effect of the drag force generated by the high wind velocity impressing on the droplets of the rain flowing downwards due to the gravity force. This drag force influences on the rain droplets is shown in Eq. (2):

$$F_D = C_D \times \frac{1}{2}\rho_{air}U^2 A$$
(2)

where,
F_D = The drag force
C_D = The drag coefficient
ρ_{air} = The density of air
A = The cross sectional area of the rain droplets
U = The relative velocity between air and rain drop

When the rain drop falls freely due to the gravitational effect, the drag force will equal to the weight of the droplets and therefore, the velocity of the droplets in this case are known as the terminal velocity.

The terminal velocity can be expressed in the following equation, which is a function of droplet diameter:

$$U_{terminal} = 4.5\ D^{0.5}$$
(3)

where, D is the equivolume diameter of the drop in mm as shown in Fig. 7.

Base model: The base model of the opening area in the case study building has the dimensions shown in Fig. 6b. The basic model consists of two opening areas namely (left side and right side), in which these openings were subjected to wind driven rain.

During the raining hours, the prevailing wind from the NW direction will blow towards the building with an average wind speed of 6 m/s. At the same time, the rain flowing down as droplets particles in the vertical direction will be influenced by the wind blowing at horizontal direction and the mixture flow of both water and air will reach the opening areas of the exposed corridor of the building. The first CFD simulation was made to validate the building base model to conclude the effective area of the subjected part of the building. Figure 8a shows the CFD simulation result of the water volume fraction on the floor of the case study building.

Based on the CFD simulation result as shown in Fig. 8a, it revealed that the wind driven rain can reach an overall percentage of 78.77% of the floor area. In other words, approximately 78.77% of the floor area
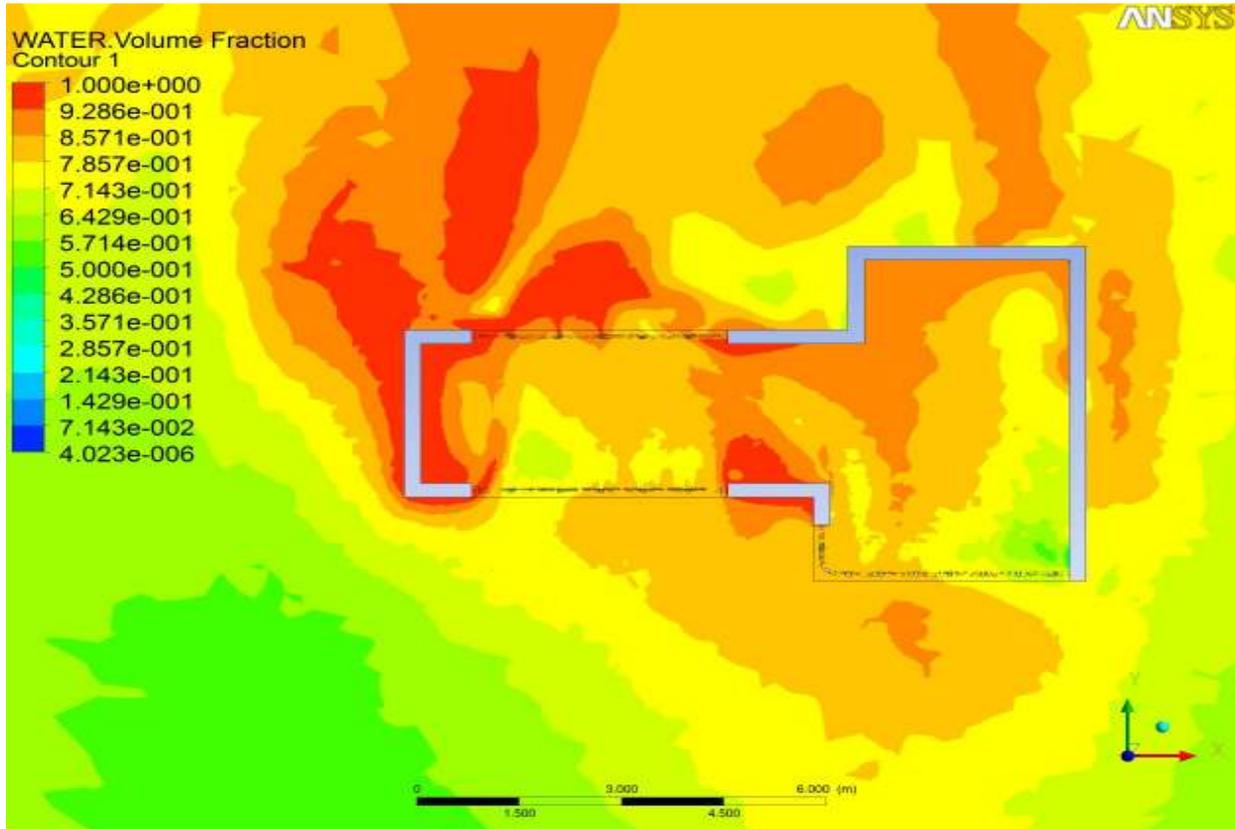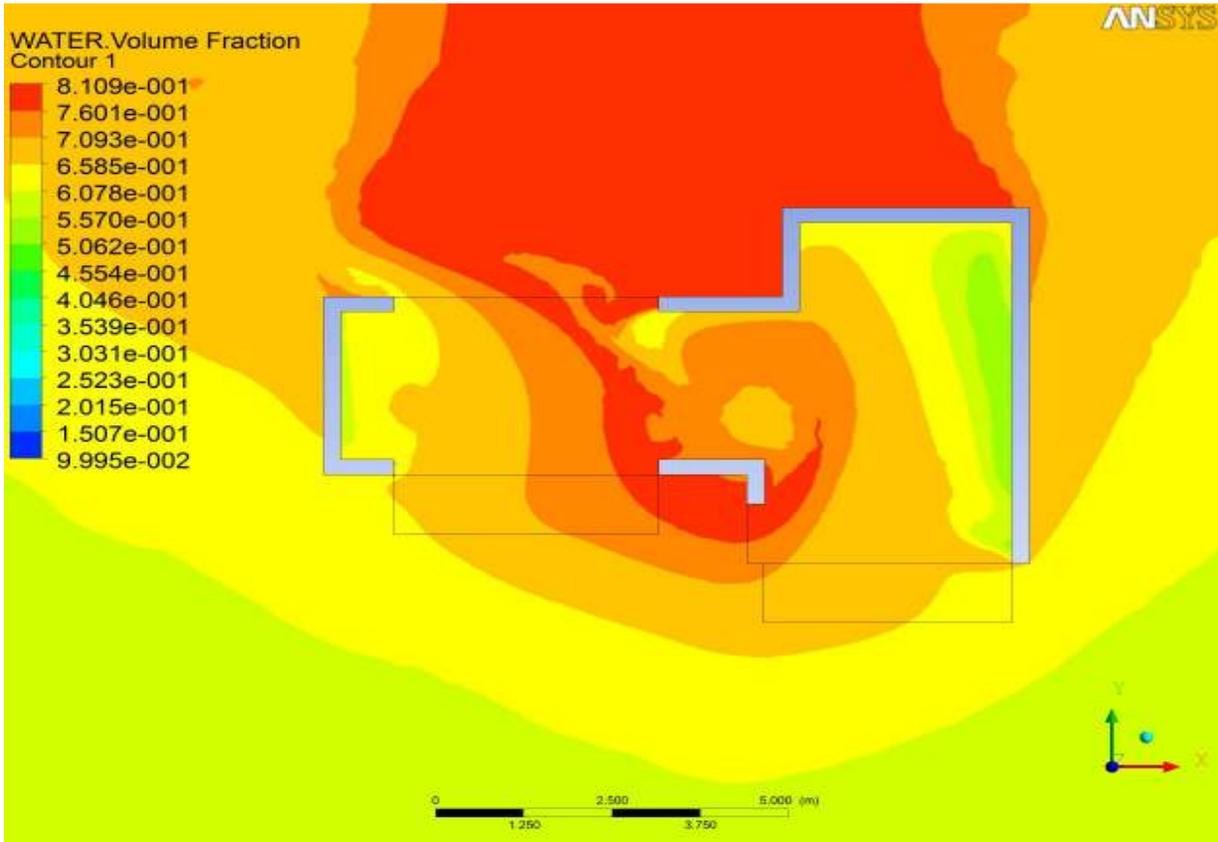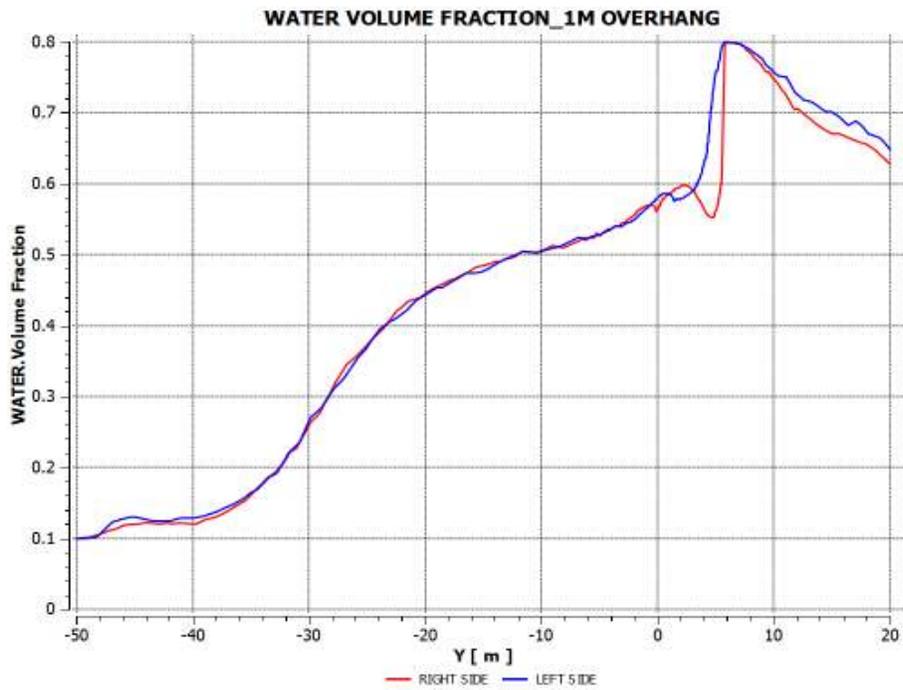
(a)
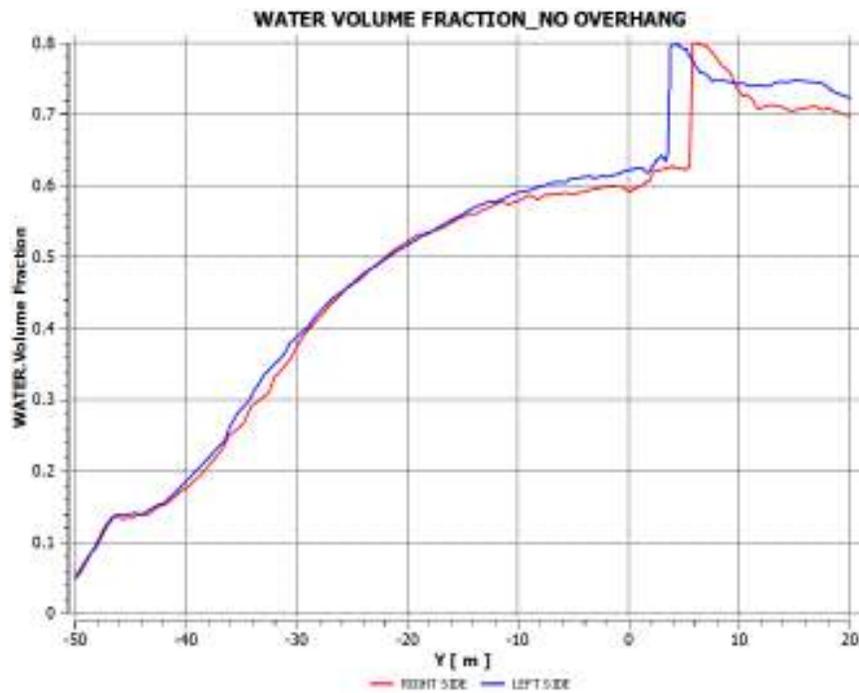
(b)

Fig. 8: (a): Water volume fraction contour (percentage) on the floor of base model; (b): 4 h accumulated rain water percentage of the base model of the building floor

(a)

(b)

Fig. 9: (a): Water volume fraction contour (percentage) on the floor of 1m overhangs model; (b): 4 h accumulated water percentage of 1 m overhangs geometry building floor
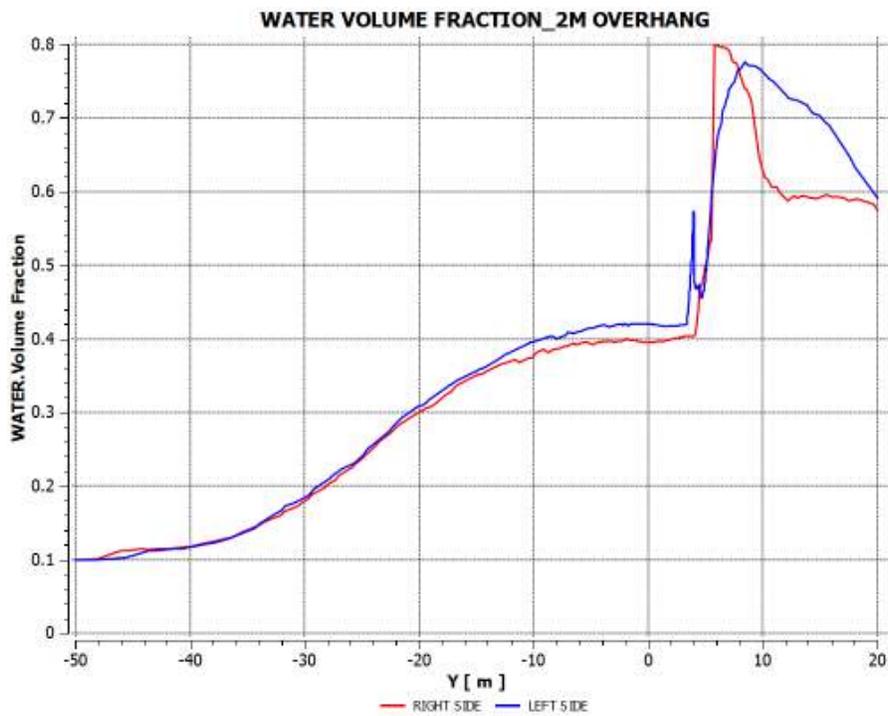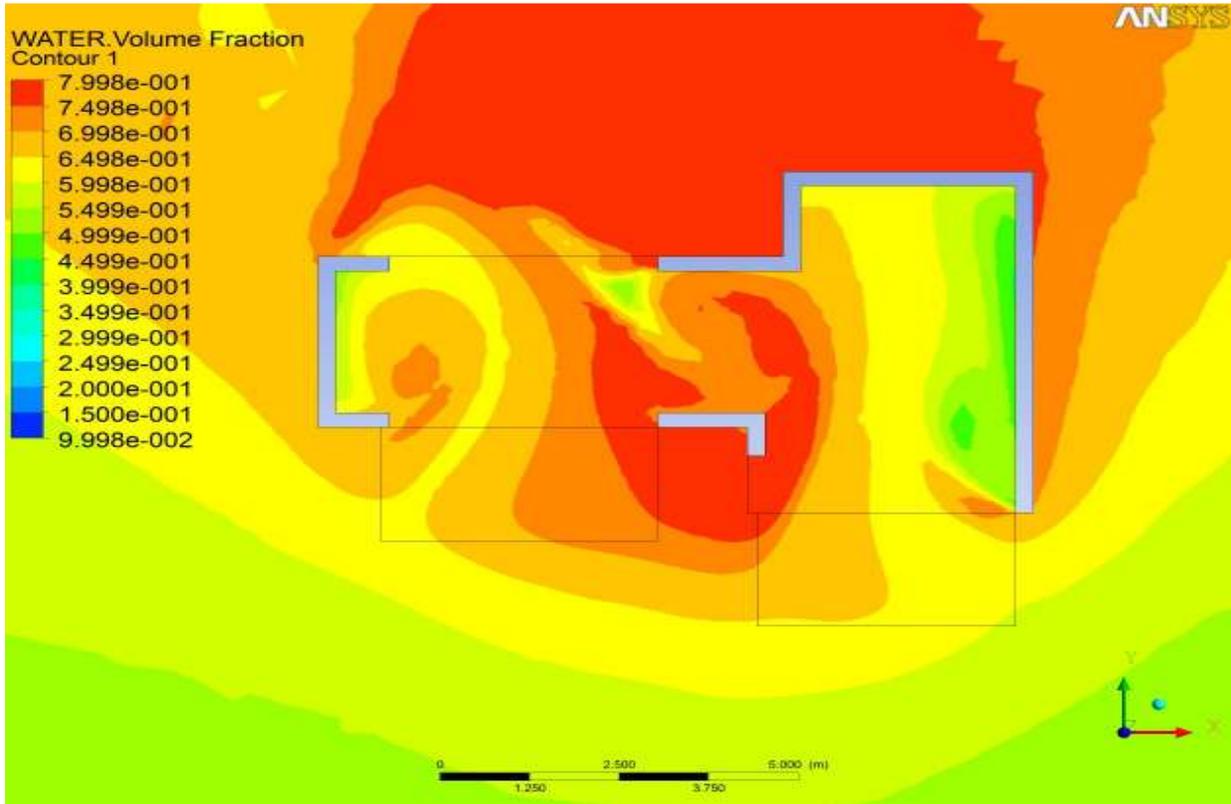
(a)

(b)

Fig. 10: (a): Water volume fraction contour (percentage) on the floor of 2 m overhangs model; (b): 4 h accumulated water percentage of 2 m overhangs geometry building floor

was covered by rain water. The accumulated water volume fraction on the floor of the case study building after 4 h of continuous rain for both right and left opening sides are shown in Fig. 8b.

1m overhang model: In order to identify an optimum design solution to shade the WDR for the building, the base model was added with 1 m overhangs to both opening sides of the building. The CFD simulation results obtained for this model shows that the water volume fraction on the floor can be reduced to approximately 72.01% as shown in Fig. 9a.

Figure 9a revealed that the rain water droplets distribution on the floor of the left side is more than the right side. This is due to the corridor has both opening sides compare to the right side which has only single side opening. Figure 9b represents the accumulated water percentage of the wet area on the floor.

2m Overhangs model: In this model, the geometry of the rain barrier was increased from 1 m to 2 m length on both the right and left sides of the openings. The CFD simulation results revealed that the wet area of the floor can be reduced up to 63.90% as shown in Fig. 10a. With an accumulated time of 4 h continuous rain,

Fig. 10b shows the percentage of the water on the floor of the building has been reduced significantly.

Tilted overhangs model: Another alternative solution to reduce the WDR on the case study building was to use a tilted overhangs to both opening sides. The titled overhangs protrusion from the facade of the building is 1.5 m. The CFD simulation results showed that the wetted area of the floor was decreased from 78.77 to 48.25%. Figure 11a and b represent the water volume fraction percentage and the accumulated water percentage on the floor of the tilted overhangs model. The CFD simulation results also shows that the tilted overhangs model is more effective in reducing the WDR compared to the conventional 1 m and 2 m length overhangs.

Half and full grid louvers model: A series of louvers were designed to fit the two opening sides of the case study building to reduce the WDR effect on the floor. Two louvers arrangements have been designed for this study which are the half grid louvers and full grid louvers. Figure 12a and b illustrate the geometry and arrangement of these different louvers designs.
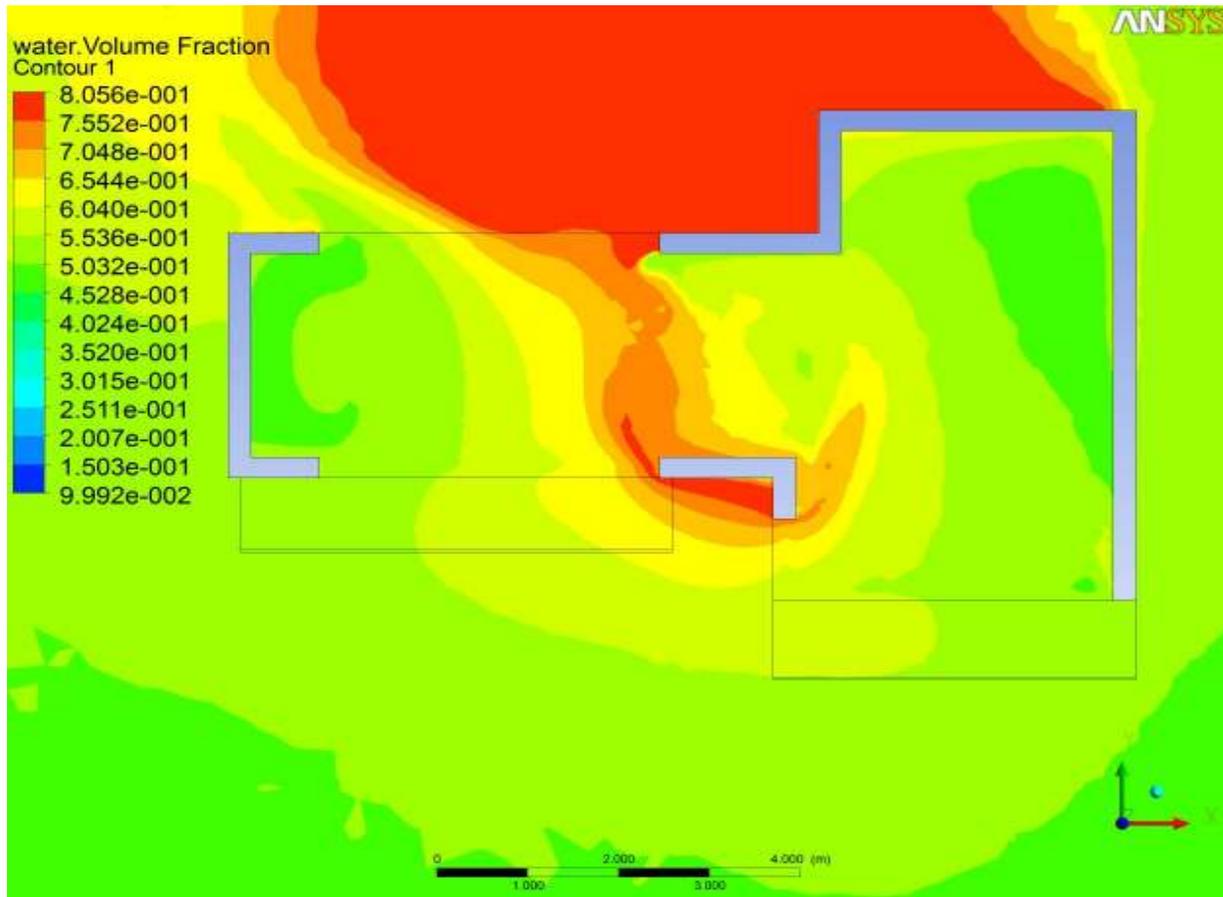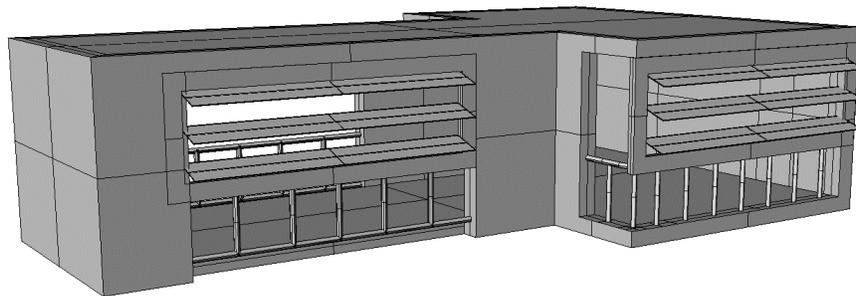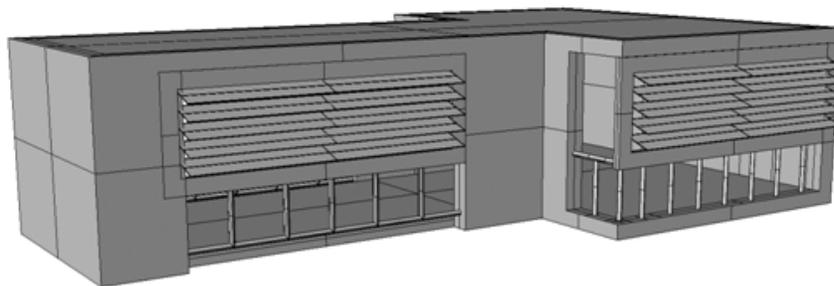

(a)
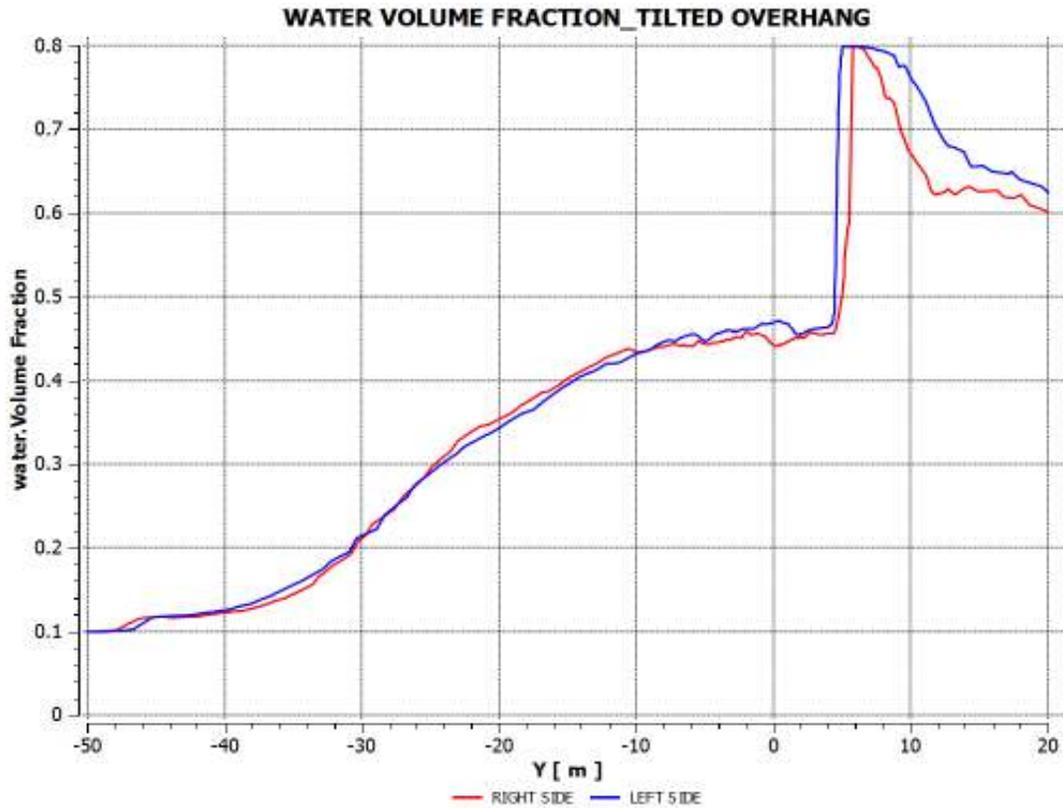
(b)

Fig. 11: (a): Water volume fraction contour (percentage) on the floor of tilted overhangs model; (b): 4 h accumulated water percentage of tilted overhangs geometry building floor
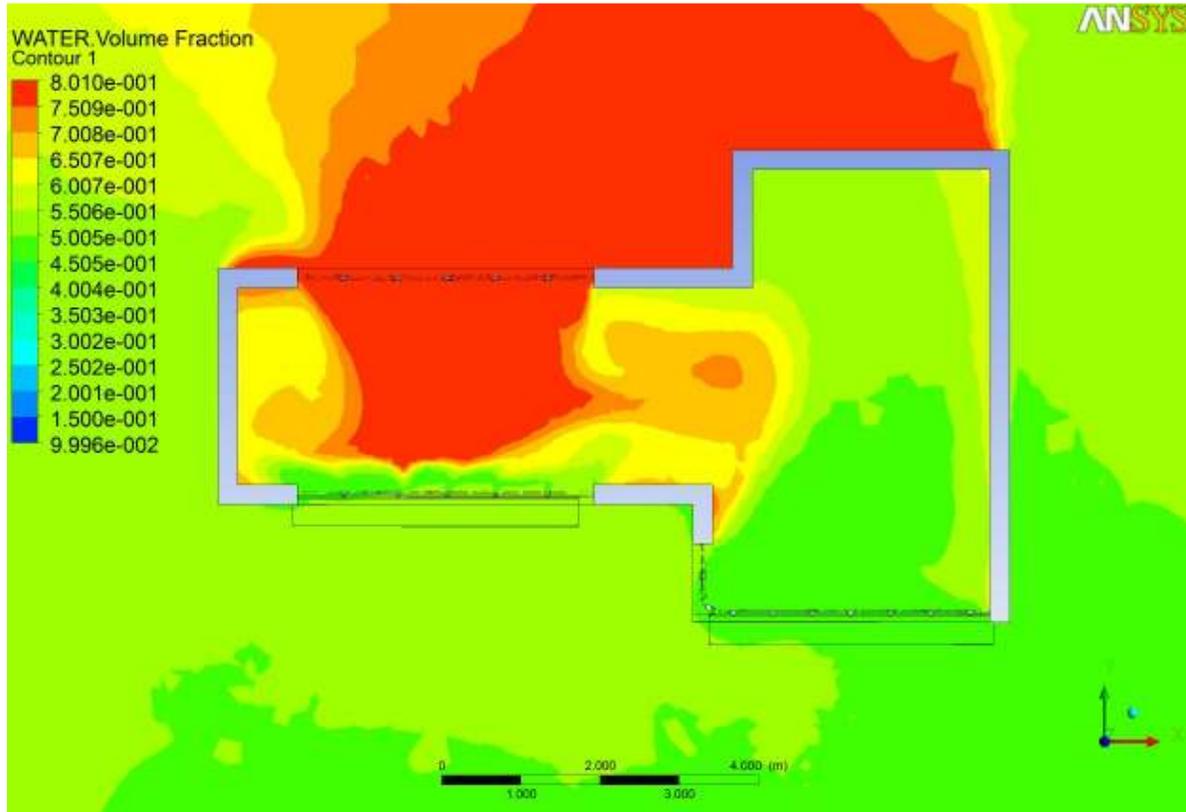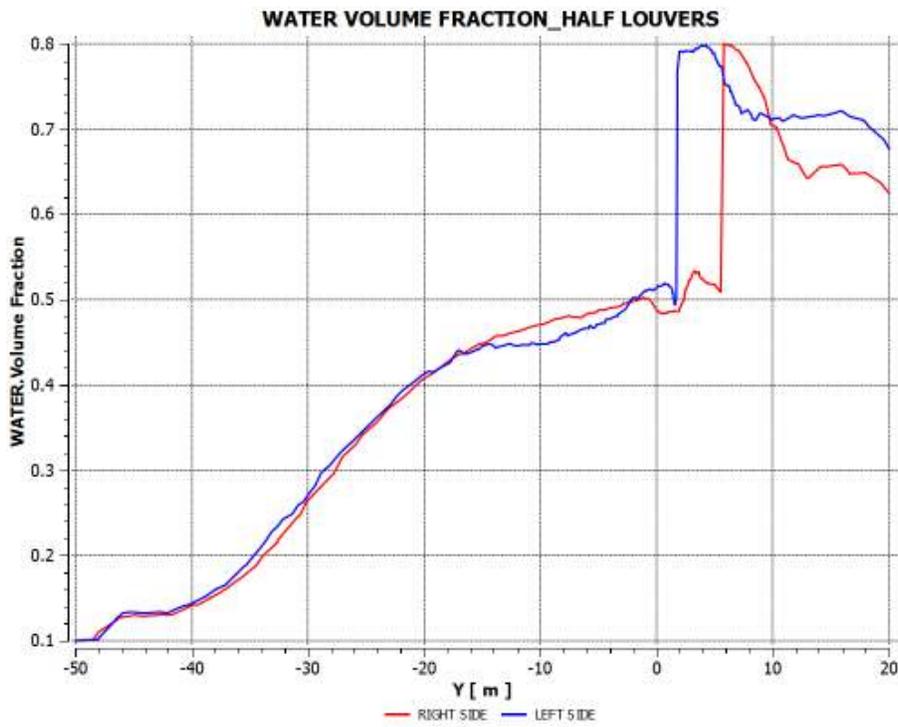

(a)

(b)

Fig. 12: Schematic drawing of the louvers arrangement for the subjected building; (a): Half louvers configuration; (b): Full louvers configuration
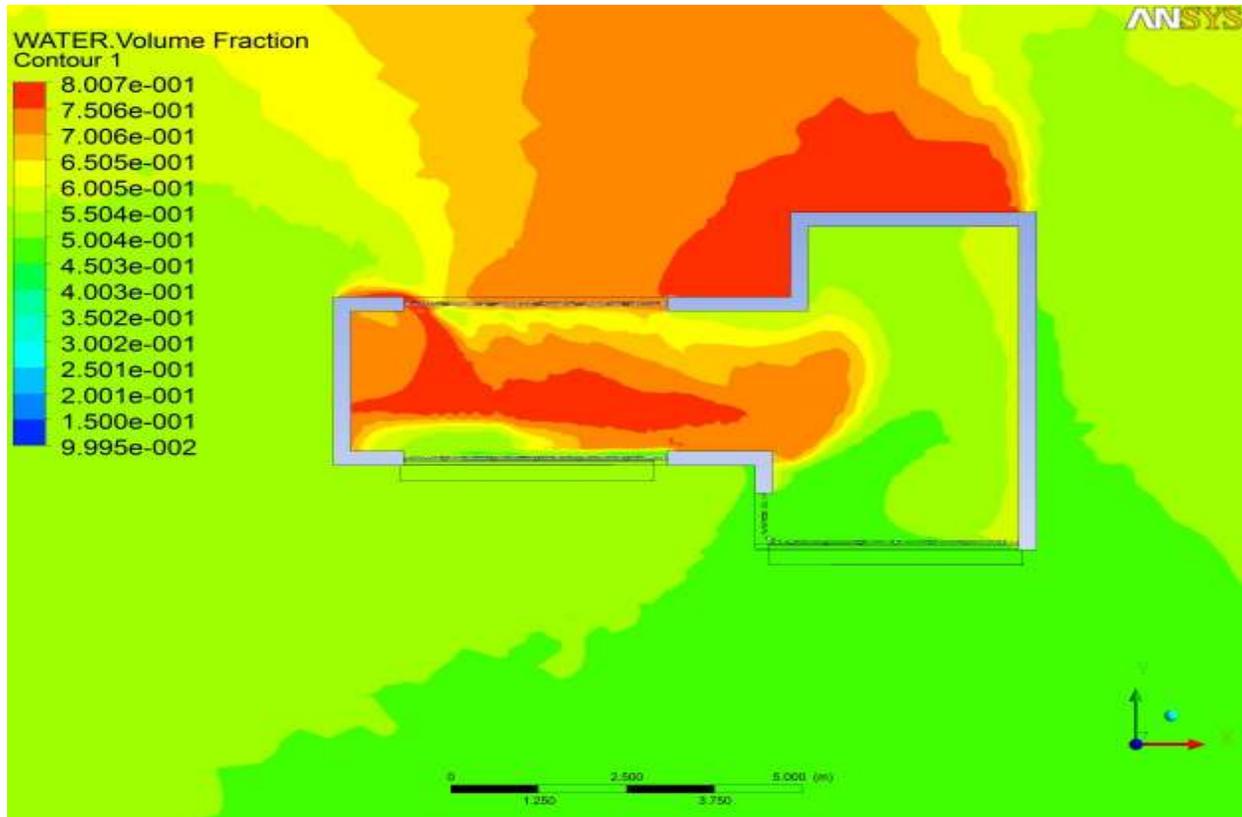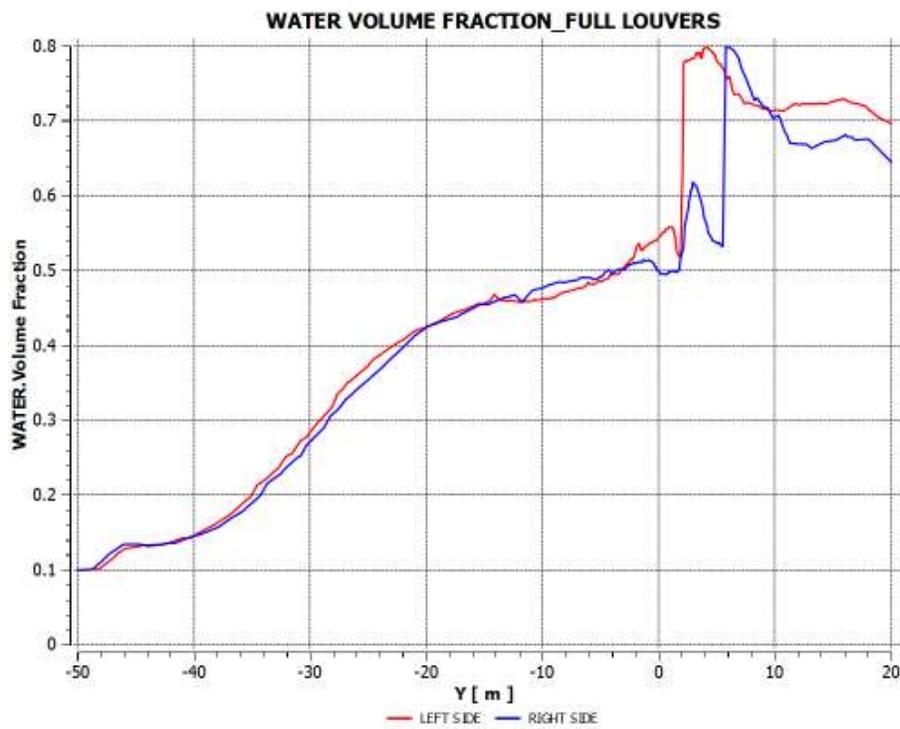
(a)

(b)

Fig. 13: (a): Water volume fraction contour (percentage) on the floor of half grid louvers model; (b): 4 h accumulated water percentage of half grid louvers geometry building floor

(a)

(b)

Fig. 14: (a): Water volume fraction contour (percentage) on the floor of full grid louvers model; (b): 4 hours accumulated water percentage of full grid louvers geometry building floor
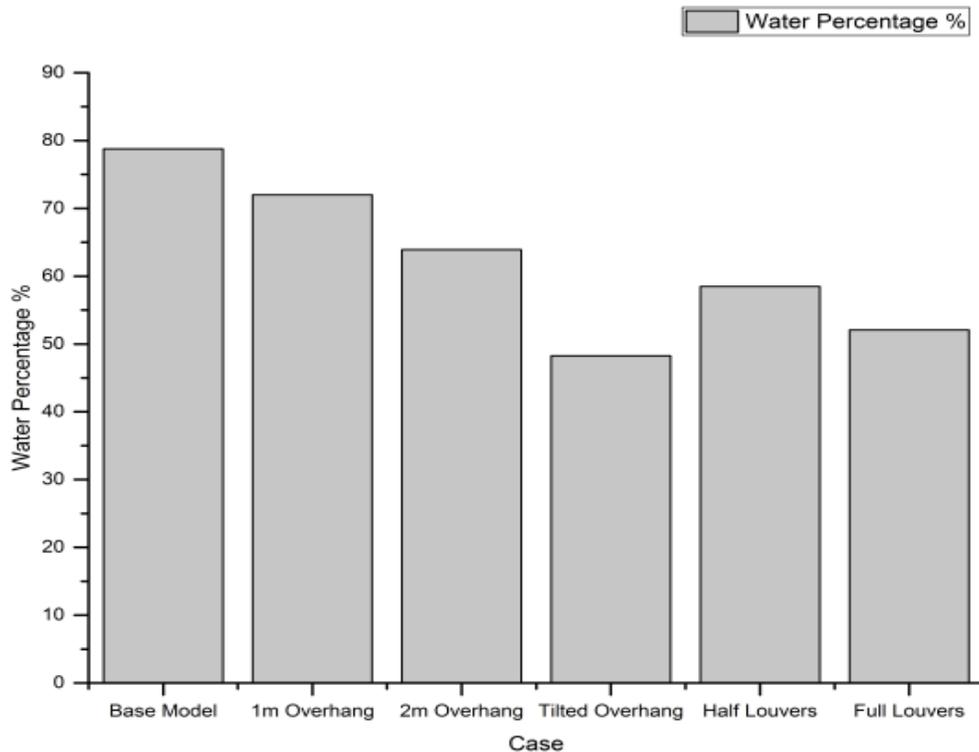
Fig. 15: Water Percentage in the floor plane of the subjected building

The louvers on the building revealed significant results of WDR reduction on both opening sides. The CFD simulation results of the half grid louvers model shows that the wet floor could be reduced to 58.50% as shown in Fig. 13a and b. While the full grid louvers model could reduce the wet floor area percentage to 52.08% as shown in Fig. 14a and b.

Figure 15 shows the summary of the CFD simulation results of the water percentage accumulated on the floor plane for all the different design configurations of the WDR barriers. Based on Fig. 15, the most effective WDR barrier design is the titled overhang whereas the 1m overhang is least effective design. The titled overhang and the full louvers design configurations have the closest effectiveness to prevent the rainwater penetration into the building with only 48.25 and 52.08% of wet floor area respectively.

CONCLUSION

Until today there is still lack of studies on WDR in naturally ventilated tropical buildings. The consequence on WDR has tremendous effect on open and semi-open spaces like corridors, courtyard, terraces and balconies of buildings. Most of these spaces cannot function and be utilized if there is a WDR occurrence. Hence, this study embarked on a research to predict and estimate the penetration of WDR based on various design configurations of WDR barriers. In this study, there were total of 5 models of different WDR b arriers

namely the '1 m overhang', '2 m overhang', 'tilted overhang', 'half louvers' and 'full louvers' and 1 base model without any overhang that were simulated using Computational Fluid Dynamics (CFD). The CFD simulation results revealed that the 'titled overhang' configuration was the most effective WDR barrier compared to the other design configurations with the rainwater distribution on the floor decreased from 78.77% of the base model to 48.25%. Hence, based on this particular case study of a five stories building in tropical climate, the titled overhang is the most effective WDR barrier.

ACKNOWLEDGMENT

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