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Effect of urban street canyon aspect ratio on thermal performance of road pavement solar collectors (RPSC)

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Abstract

Studies on RPSC (road pavement solar collectors) have shown the potential of reducing the urban heat island effect by dissipating the heat from the pavement for energy harness. In our previous work, performance analysis of RPSC system was carried out to compare the RPSC embedment in two scenarios; within an urban street canyon and within suburban or rural area. The current study expands the analysis of the RPSC system in urban areas by assessing the impact of varying canyon aspect ratios on the performance of RPSC. De-coupled Computational Fluid Dynamic (CFD) approach was proposed to investigate the integration of RPSC system in an urban canyon. The CFD tool ANSYS Fluent 15.0 was used to simulate the fluid flow and heat transfer on the pavement/road surface by enabling three models: (i) energy model, (ii) standard *k*-epsilon model, and (iii) coupled DO-solar load radiation model. The results showed that a significant pavement surface temperature increase was found when the aspect ratio (AR) was increased from 1 to 2 while minimal increase was observed for the canyon with AR above 2. At the particular simulated time (13:00) and location, it was found that the overall performance of the RPSC system significantly increased by up to 13.0 % when AR was increased from 1 to 2, but the performance of RSPC in shadow area (due to the shading effect of building) had significantly dropped (up to 30.0 %) from AR 3 to 4. Findings of this study showed that the canyon aspect ratio had a significant impact on the temperature distribution of the ground surface and should be taken into consideration when assessing the performance of RPSC in urban areas.

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Keyword: Road solar collector; canyon aspect ratio; computational fluid dynamic (CFD); urban heat island (UHI); street ventilation

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1. Introduction and literature review

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The urban heat island (UHI) effect is a form of accumulated heat caused by urbanisation when buildings, roads and other infrastructure elements replace open land or water areas. These elements tend to absorb the heat from the sun rather than reflect it, causing the surface temperature and air temperature to elevate. Several studies suggested that one of the causes of the UHI effect is the reduction of the air velocity in narrow space in between buildings (courtyards and street canyons) which decreases convective heat transfer and urban ventilation [1-4]. Studies [5, 6] on RPSC (road pavement solar collectors) have highlighted the potential of reducing the UHI effect by dissipating the heat from the pavement for energy harness. The study [5] suggested that using RPSC or a hydronic pipe system for pavement heat reduction can potentially extend the lifecycle of pavements up to 5 years by reducing surface temperature by 5°C. In the authors' previous study [6], the effect of urban street canyon on the RPSC performance was investigated and compared against the simulation without the street canyon (replicating rural area). Results have shown higher potential thermal collection (PTC) and surface temperature reduction (STR) was obtained by RPSC in urban conditions. The study also highlighted the reduction of the convective heat transfer from the surface due to the wind flow pattern across long facades which can significantly lower the air circulation in the canyon. In this study, investigation of the impact of various canyon geometries on the RPSC performance was carried out, extending the study of [6] which showed improved thermal performance of RPSC in urban as compared to suburban or rural.

2. Research methodology

In this study, two building blocks (100.0 m length × 20.0 m width × 20.0 m height) were located in the domain (See Fig. 1) perpendicular to the direction of airflow. The computational domain (macro domain) was sized based on the guideline for environmental wind flow modelling [1]. For simplification, the domain size was reduced between the canyon sidewalls) and the domain side walls (to be treated as symmetry in FLUENT); see Fig. 1(a) and 1(b).

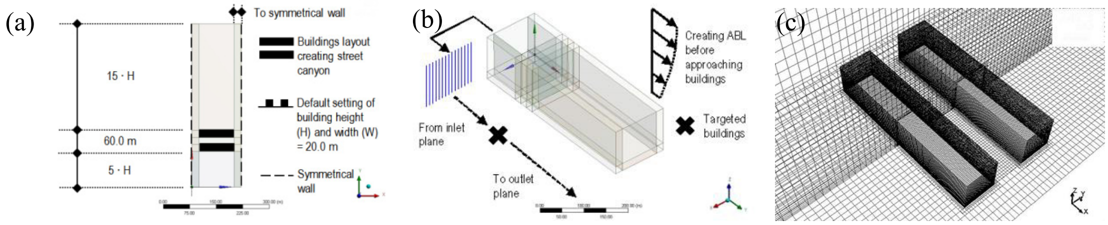


Fig. 1 (a) Plan view of domain; (b) domain was sliced in several volumes; (c) hexahedral mesh technique with grid refinement

The height of the canyon buildings was the factor in determining the size of the flow domain. Four aspect ratios (AR) were used for the RPSC analysis; AR 1-4. The aspect ratio is the height of canyon building, H over the width in between the canyon buildings, W [7]. The essential requirements for the setting of the domain size were followed: (i) the dimension between the airflow inlet plane and the first approaching wall in windward position was set five times the height, 5H; (ii) the dimension between the outflow plane and the building wall (outside canyon) was set three times longer than the dimension of (i), 15H; (iii) the dimension between the topmost building roof(s) to the topmost domain wall was set five times the height, 5H; (iv) the width between the two buildings was set default to 20.0 m for all aspect ratios, (v) the height, H was set 20.0 m, 40.0 m, 60.0 m and 80.0 m for AR 1- 4, respectively. Simulating the airflow in an urban environment requires the atmospheric boundary layer (ABL) profile; thus a growing cell height in z-direction was employed to generate finer cells closer to the ground surface. Full structured hexahedral grid meshing was applied for all domains; see Fig 1(c). Grid verification was carried out to compare three meshes (coarse, medium, fine) to determine an ideal mesh model for the later use. Fig. 2(a) and 2(b) compares the plotted temperature points 1.0 m away from leeward and windward walls. Based on Fig. 2, it can be observed that refining the cells of the building facades and canyon ground surfaces has reduced the difference in temperature values between the grid adapted meshes. The temperature results were in good correlation with the experimental data of [1]: (i) the temperature at the centre of canyon point 1.0 m away from leeward wall ($PC_{windward}$ was 348 K, and (ii) the temperature at centre of canyon point 1.0 m away from windward wall ($PC_{leeward}$) was 305 K. The lower temperature in $PC_{leeward}$ was due to receiving higher air velocity and building shadow. Medium with grid adaption {2} was found to be the most accurate and was applied for all simulations. Validation of the air velocity and air temperature profiles was carried out against the wind tunnel experiment of [1, 8]. The z-height profiles of 0.002 m - 0.2 m above ground surface were plotted in the very centre of the long canyon (70.0 m, x-direction). Based on Fig. 2(c), it can be observed that the plotted air velocity profile showed good agreement with the experimental results excluding the plotted points near the ground surface and above building roofs which were slightly overestimated. In this study, simplification of the urban geometry was made by not including blocks around the canyon street. Due to this, a slight variation in the plotted values of air velocity and air temperature was possible to occur. For the air temperature profile as shown in Fig. 2(d), it can be observed that the plotted CFD values for the profile at the centre canyon location has satisfied the validation specifically near to the ground.

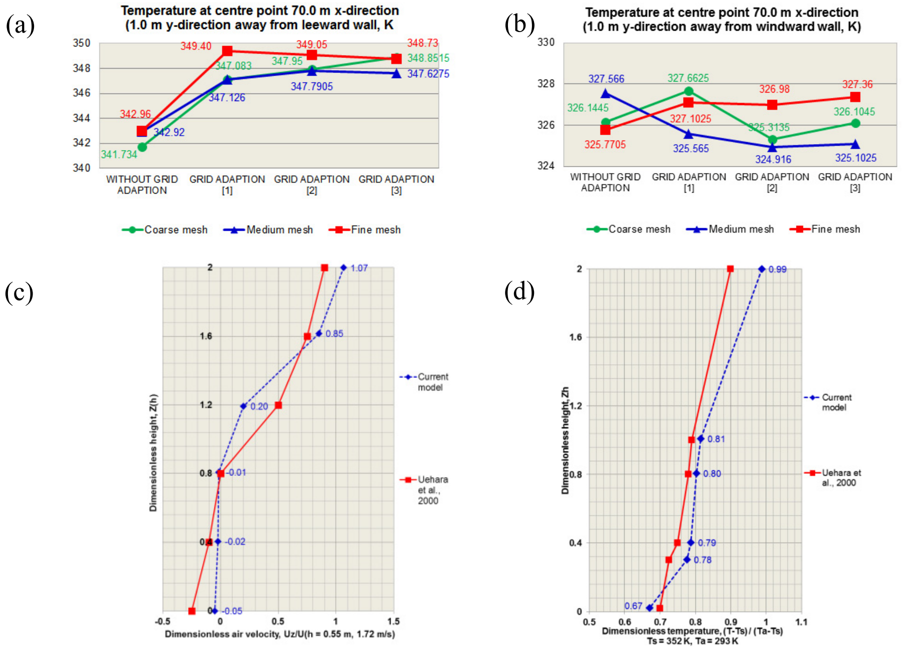


Fig. 2. (a) Temperature against location at 1.0 m away from leeward wall; (b) against location at 1.0 m away from leeward wall; (c) Profile of dimensionless height against dimensionless velocity; (d) against dimensionless air temperature

2.1. Domain setting for micro domain simulation

The RPSC system was characterized by circular hollow horizontal copper pipes with 10.0 m length, 0.005 m (5.0 mm) wall thickness and 0.02 m (20.0 mm) nominal diameter to be embedded 0.15 m (150.0 mm) below the road surface. The gap between the pipes was assumed 1.0 m and the pipes were layered to be parallel with the road direction (north to south). Simplification of the model was carried out by placing the RPSC pipes at the central areas; approximately 10.0 % area was covered out of the total road surface area. The total area of the pipe embedment was 10.0 m length × 20.0 m width. For the micro domain, a 10.0 m width × 0.3 m ground depth. RPSC performance was quantified based on *Delta T* (K) which is the difference between water temperature inlet (T_{wi}) and outlet (T_{wo}), PTC (%) which is (*Delta T* / T_{wi}) × 100% and STR (%) which is ($T_{surface}$-T_{wo} / $T_{surface}$) × 100% [6].

2.2. Boundary condition

Following the study of [1], the simulation was set based on Milan urban centre with longitude 9.18°E, latitude 45.47°N and UTC +1 during the summer month of 21st June at 13:00 hour. It should be noted that the current model considered the sunshine fraction as 0.25, derived from the average cloud cover in the area. The ABL profile in [1] was used as inlet velocity and the inlet temperature was set as 303 K. The turbulent intensity was set as 10.0 % and the turbulent length scale was set as 4.91 m, 7.82 m, 10.38 m and 12.82 m for AR 1-4, respectively. Based on the FLUENT 15.0 User Guide [9]; the diffuse fraction of all surfaces was set to 0.5, indicating that the obtained heat flux is partially diffused and partially reflected. Table 1 displays the material properties applied for the façade and ground surfaces.

Table 1. Boundary condition applied to wall surfaces and computational domain [1, 8]

	Surface description	Temperature (K)	Roughness condition (m)	Thickness (m)	Density (kg/m^3)	Specific heat (J/kg K)	Thermal conductivity (W/m K)	Emissivity
Against wind tunnel	Ground	352	K_s 0.005 C_s 0.0025	NA	700	2310	0.17	NA
	Façade	NA	NA	NA	1030	1300	0.03	NA
Current simulation	Ground	288	K_s 1.0	5.0	2000	1000	0.9	0.9
	Façade	299	NA	0.3	2000	1000	0.9	0.9
	Water	293	NA	NA	998.2	4182	0.6	NA
	Copper pipe	NA	NA	NA	8978	381	387.6	0.8

2.3. Simulation models

The Discrete Ordinate (DO) model coupled with Solar Ray Tracing was used to include the effect of solar radiation in the 3-D simulation. To calculate the solar radiation, the global sun location in the sky at a specified date, time zone, longitude-latitude position and sunshine factor were set as detailed in 2.2. The principle of momentum, continuity and heat conservation that used pressure and steady RANS equations were considered in order to simulate urban turbulent wind/air flow. The standard steady-state k–ε model was used with assumption the wind flow is fully turbulent based on model transport equation for turbulence kinetic energy (k) and dissipation rate (ε) The simulation involved the conductive and convective heat transfer from the ground surface to the bottom layer(s) consisting of pavement solid and the pipe body with flowing medium water.

3. Results and discussion

Fig. 3(a) displays the simulated temperature contour of the ground surface in the urban canyon with various aspect ratios. At the particular simulated time (13:00), it was observed that the windward building was blocking the solar radiation and shadowing the ground near the windward building wall while refracting some radiation on the surface closer to the leeward building wall as per Fig. 3(b). Although the obtained maximum temperature was increased according to the height; it was also observed that the percentage area of receiving solar radiation was reduced accordingly; estimated from 80.0 % for AR 1 to 66.0 %, 50.0 % and 33.0 % for AR 2, AR 3 and AR 4. Fig. 3(c) demonstrated the contour of the air temperature distribution inside the canyon AR4 which shows higher temperature closer to the ground surface. Fig. 4

compares the effect of varying the canyon aspect ratios on the surface temperature values along the length of the canyon surface at three locations as per Fig. 3(b). Based on the result, it was observed that increasing the aspect ratio (based on height of the canyon) also increased the surface temperature with more noticeable difference between AR 1 and AR 2. For AR 1, it can be observed that the temperature trend (A) and (B) had its peak at the centre of the canyon. For AR 2- 4, the peak was observed between 0 and 20.0 m away from the canyon opening ends. A noticeable drop in temperature values was observed from AR 3 to 4 specifically for the trend plotted at the centre; between 30 and 60.0 m of *x*-direction. The predicted performance of the RPSC pipes in various locations is summarised in Table 2.

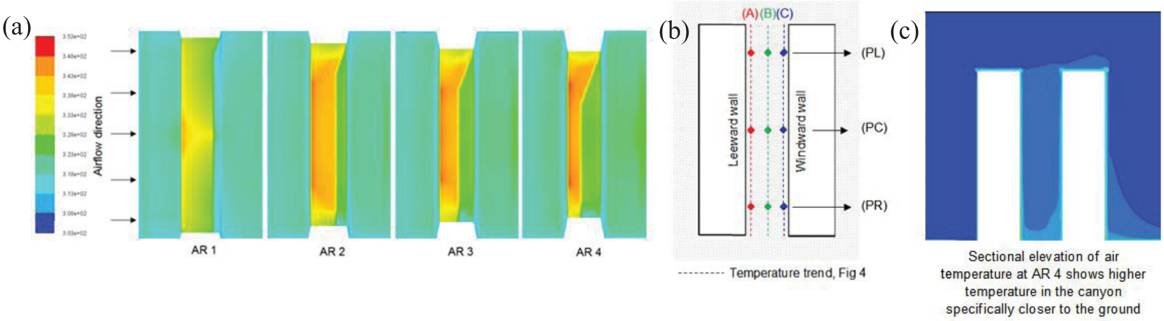


Fig. 3. (a) Temperature contour of canyon surface according to the aspect ratio in top view; (b) measurement location, and (c) section elevation of airflow temperature contour

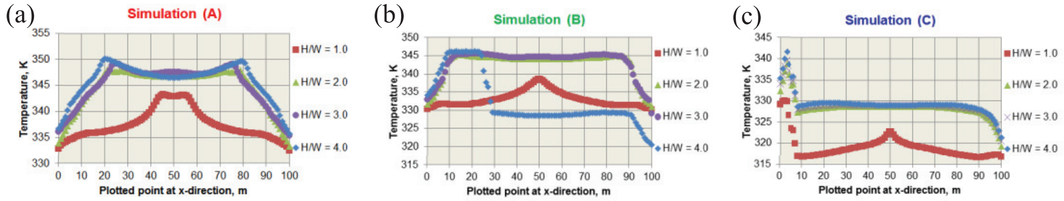
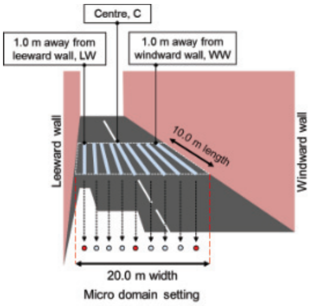


Fig. 4. Temperature trend at (a) 1.0 m away from leeward wall; (b) centre of canyon width; (c) 1.0 m away from windward wall (Red H/W or AR = 1.0, Green H/W or AR = 2.0, Purple H/W or AR = 3.0, Blue H/W or AR = 4.0)

Table 2. *Delta T*, PTC (%) and STR (%) values



H/W	Description	*Delta T*, K	PTC, (%)	STR, (%)
1.0	Pipe LW	6.73	2.30	12.62
	Pipe C	5.98	2.04	11.41
	Pipe WW	3.81	1.30	7.64
2.0	Pipe LW	7.23	2.47	13.42
	Pipe C	6.86	2.34	12.84
	Pipe WW	4.79	1.63	9.38
3.0	Pipe LW	7.33	2.50	13.58
	Pipe C	6.94	2.37	12.96
	Pipe WW	4.85	1.66	8.88
4.0	Pipe LW	6.94	2.37	13.46
	Pipe C	4.77	1.63	9.35
	Pipe WW	4.90	1.67	9.44

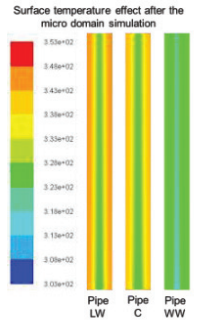


Table 2 displays the calculated values of *Delta T*, PTC and STR for three RPSC pipes (LW, C and WW) which have 10.0 % embedment of overall surface area. It was observed that in terms of thermal collection, the RPSC (LW) performance increased by 13.0 % as the aspect ratio increased from AR 1 to 2 and only 1.4 % from AR 2 to 3. A 5.5 % drop in performance was observed from AR 3 to 4. For Pipe C, a significant reduction in performance (30.0 %) was observed from AR 3 to AR 4 due to the shadows caused by the windward building.

4. Conclusion and future work

This study expands the investigation of the RPSC system in urban areas by assessing the impact of the urban form on the system performance in terms of *Delta T* of inlet-outlet, potential thermal collection (PTC) and surface temperature reduction (STR). De-coupled Computational Fluid Dynamic (CFD) approach was used to simulate the effect of outdoor environment (macro domain) on the RPSC system (micro domain). Based on the simulations of the RPSC system during a typical hot summer day, a significant increase in the surface temperature was observed when the aspect ratio was changed from AR 1-2 while a nominal change in temperature was observed above AR 2. Performance of the RPSC system in terms of thermal collection was increased by 13.0 % specifically from AR 1 to AR 2 but the performance of RSPC below shadow area reduced up to 30.0 % from AR 3 to 4. Findings of this study showed that the canyon building height had a significant impact on the performance of RPSC as it influenced the refraction of the solar radiation which then determined the temperature distribution on the ground. A more detailed analysis is necessary to further investigate the effect of the urban form on the RPSC which includes the investigation of the RPSC performance based on various date, time zone, longitude-latitude position and sunshine factor. Investigation of the effect of buildings with asymmetrical height on system performance and system embedment in several street canyon rows should be carried out.

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Biography

Diana SNM Nasir is currently pursuing PhD with interest in the effect of urban configuration on thermal performance of road pavement solar collector (RPSC) system. She is also interested on renewal energy system with purpose to mitigate the urban heat island (UHI) effect. Received her BSc Arch and MSc Urban Development and Management from Universiti Teknologi MARA (UiTM), Malaysia.