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Urban road and pavement solar collector system for heat island mitigation: assessing the beneficial impact on outdoor temperature

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Abstract. Road renewable energy system has raised much attention from both industrial and academic research on how abundant solar radiation absorbed by road surfaces can be collected while reducing the impact of high surface temperature towards urban environment. Cities consume about 3% of total global land mass with road and parking lots consuming around 35 to 50% of land use footprint. These urban road networks permit the dynamic movement of human activities and physical development of the cities. Remarkably, researches have given much spaces to explore on how roads can contribute to make cities more sustainable. Therefore, ideas on road renewable energy system have surfaced to its audiences. The heat island effect has been reported to raise temperature up to 12 ℃ in urban areas which affects building cooling energy load and simultaneously the people comfort. High discomfort can lead to high energy and cost utilisation, which further worsens the issue. This study assessed the beneficial impacts of urban road pavement solar collector towards reducing outdoor temperature by carrying out de-coupled numerical modelling of an urban canyon model integrated with the pavement solar collector in ANSYS FLUENT, validated with experimental data. Numerical results showed up to 4.67 ℃ air temperature reduction and up to 27.0 % surface temperature reduction after the U-RPSC application. When applying to street canyon with different heights, the concern was highlighted on the system performance in reducing potential UHI effect in deeper canyon during less windy condition and during the night-time. The study also presents the experimental work on the performance of a laboratory-scale U-RPSC system.

1. Introduction and Literature Review

The Urban Heat Island (UHI) effect is a phenomenon whereby urban areas become warmer than their surrounding rural areas (up to 8ºC difference [1]), due to the replacement of vegetation and soil with building surfaces. These increased urban temperatures lead to increased energy demand for cooling buildings, elevated emissions of air pollutants and GHG, compromised health (overheating) and thermal discomfort. However, these temperatures can be used to heat water flowing through buried copper pipe.

In this way, urban road pavement solar collector (U-RPSC) systems collects thermal energy which used to meet increased energy demands and reduce UHI effect.

Several works have studied the potential of road pavement energy harvesting. Nasir et al. [1] investigated the effect of building geometry on U-RPSC system performance using computational fluid dynamics (CFD) modelling. The model allows the air flow and ground surface temperature to be simulated in both urban and rural/flat macro domains, which expands on previous studies that solely considered flat domains. Bobes-Jesus et al. [2] compiles information on the types of studies carried out on asphalt's thermal behaviour and the different methodologies to do so; a mixture of experimental tests under both real atmospheric condition or in asphalt collectors that have already installed and theoretical studies using numerical modelling and simulation (FEM etc) were used. Wang et al. [3] reviewed different energy harvesting techniques used for roadway and bridge for different applications (working principles, examples, prototypes and major findings) to compare their power output, cost-effectiveness, technology readiness etc.

Chiarelli et al. [4] evaluates the optimisation of convection-powered asphalt collectors for the reduction of urban pavement temperatures using experimental trials and CFD simulations. The study concluded that optimal performance is achieved when pipes are installed in a single row under the pavement, allowing for a surface temperature reduction of up to 5.5°C and the energy absorbed and exergy (energy quality). Alsono-Estébanez et al. [5] determined that the energy harvested by the collector increases with the flow rate (non-linear), resulting in higher performances as the flow rate grows and maximum performance value of 74% were obtained for high irradiances (around 800 W/m^2) and medium sizes (approximately 0.27 m^2). Following earlier studies on U-RPSC, Nasir et al. [6] extended their work by investigating the effect of three configurations of urban street canyon (symmetrical [SCH], asymmetrical 1 where building B was taller [AC1] and asymmetrical 2 where building B was shorter [AC2]) on the performance of U-RPSC systems using CFD. Nasir et al. [7] extended their previous work on U-RPSC by investigating the optimisation of the design based on several parameters such as embedment of U-RPSC, water flow velocity and temperature. Nasir et al. [8] also analysed the influence of different urban canyon aspect ratios on the performance of U-RPSC using a CFD approach.

Several works have conducted studies on urban canyons. Huang et al. [9] investigates the impact of shape and height of different roofs on airflow by considering three different roof heights to building height ratios and five different shapes in a numerical model and then validating results against wind tunnel results. Similarly, Karra et al. [10] also investigates the influence of real-world conditions on air flow, specifically heterogeneity and wind variability in urban canyons but used field and laboratory experiments. Memon et al. [11] evaluated the role of wind speed and building aspect ratio (ranging between 0.5 and 8) on air temperatures in an urban canyon using CFD and comparing results with wind tunnel measurments; two diurnal and one nocturnal heating situation were considered.

To date, research has focussed on identifying the effect of U-RPSC systems in reducing surface temperature and considered some parameters that affect its performance. No study has investigated the influence of the U-RPSC on the ambient air temperature and also on the energy consumption of neighboring buildings. Therefore, the aim of this study is to assess the beneficial impacts of U-RPSC towards reducing outdoor temperature by carrying out de-coupled numerical modelling of an urban canyon model integrated with the U-RPSC. The model will be validated with laboratory test data. The U-RPSC performance in terms of reduction of surface temperature and thermal collection will be determined. Furthermore, the potential influence on the energy consumption will be discussed.

2. Methodology

2.1. Numerical modelling

The decoupled approach proposed in [1, 6-7] is employed in the present work. This approach employs a macro- (outdoor) and micro-domain (U-RPSC) to simulate the influence of the external urban environment on the U-RPSC system. The study was conducted using steady-state 3D CFD approach.

The CFD tool ANSYS Fluent with the standard turbulence k–ε model was used for the simulation and analysis. The CFD governing equations including continuity, momentum and energy are solved. The effects of solar radiation within the canyon are simulated using the discrete ordinates (DO) model. The discretized equations were solved by the SIMPLE algorithm was selected while the second-order central difference were utilized for spatial discretization and in temporal discretization. A workstation with dual 32 core processor and 64GB RAM was used for conducting the simulations.

For the macro-domain or the outdoor environment, the urban canyon was modeled based on our previous works [1, 6-7] and the dimensions of the computational domain were based on the best practice guidelines for modelling urban flow (COST 372). The geometry was created using SolidEdge CAD software and then imported into ANSYS DesignModeler to generate the computational domain required for Meshing and CFD analysis in Fluent. The computational fluid domain is comprised of an airflow inlet on one side and an outlet on the opposite side as shown in Figure 1. The outlet of domain was set the gauge pressure to zero. The symmetry conditions were applied to the lateral and top boundary of the domain, which means that any parameter has zero gradients. The ground and building surface were set as stationary wall under no-slip condition. This study will assess the effect of different aspect ratio (AR) of the urban canyon on the system's performance. The base model (Figure 1) urban canyon had an aspect ratio of 1 (width of 20 m and height of 20 m). The length of the two buildings is 100 m. For the macro domain, similar boundary conditions as [12] were applied. An atmospheric boundary layer flow profile was imposed at the inlet. The approach airflow temperature was set to 30 °C. The hybrid meshing method was employed for all the computational models.

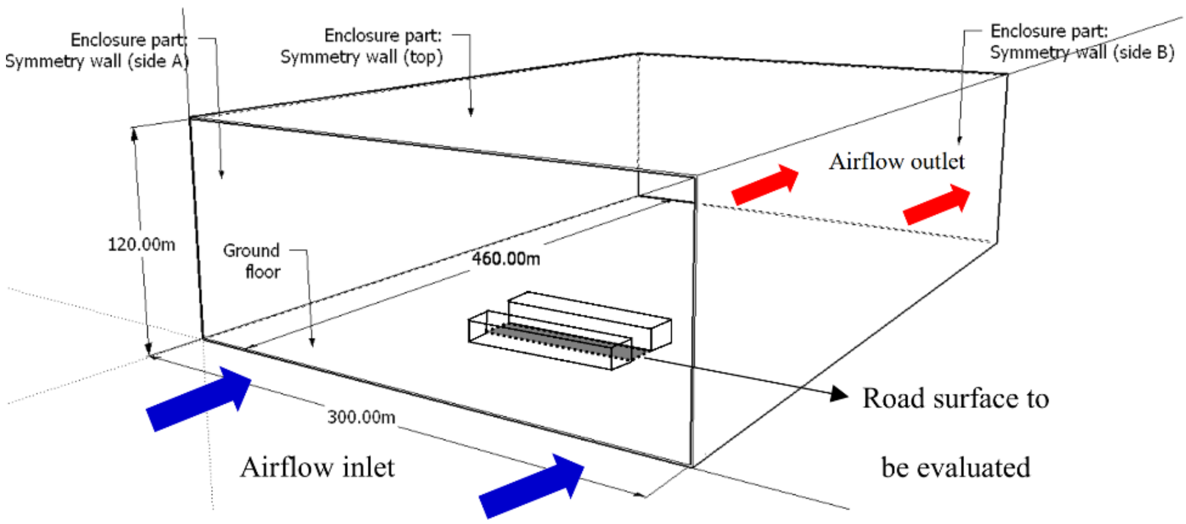

Figure 1. Computational domain and boundary conditions of the urban canyon model with U-RPSC.

The micro domain or the U-RPSC system included 20mm diameter copper pipes embedded within an asphalt slab. The distance between the pavement surface and the centre of the pipe was 150mm. The pipes were parallel to the length of the urban canyon. It should be noted that only the central area (10%) of the urban canyon was covered with the U-RPSC system for simplification. For the micro domain, the boundary conditions included the water flow inlet and outlet, pipe wall and pavement surface. The inlet velocity was set to 0.01 m/s. The inlet temperature was set to 20 ºC. The pipe wall was set as copper and the slab was set as asphalt material.

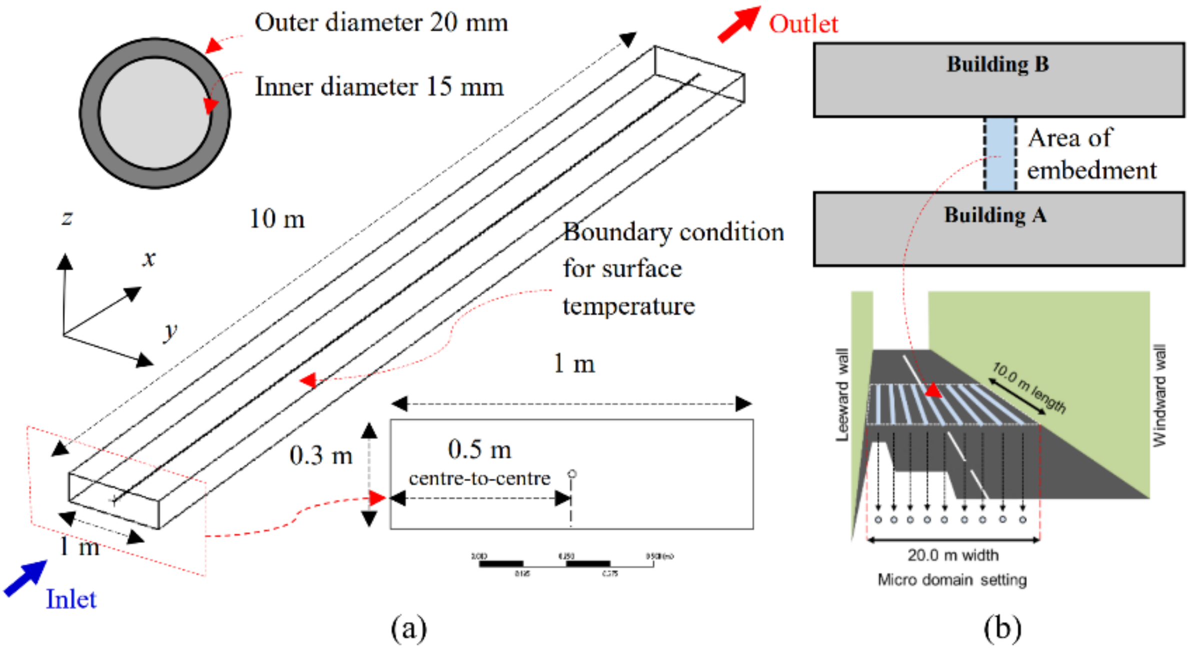

Figure 2. U-RPSC section model with 1 pipe (a) size of domain, pipe and pavement body (b) pipe embedment within street canyon of urban domain.

2.2. *Experimental testing*

Bitumen Macadam (BM) was used in this experiment with the following properties: density $\rho = 2300$ kg/m^3, specific heat $Cp = 920$J/kg K and thermal conductivity $K_p = 1.73$W/m K. Copper pipe was used as the heat pipe for its high thermal conductivity value of $K_c = 385$W/m K, which is favourable for conducting heat. The other pipe properties included are density $\rho = 8978$kg/ m^3 and specific heat $C_c =$ 390J/kg K. The asphalt slab was divided into two sections for data analysis purposes, side A (the water inlet) and B (the water outlet). 3 thermocouples (K-type) were placed on each side to measure the temperature at 3 different pavement depths, which at (i) Top – closer to the asphalt slab surface (ii) Middle – at the centre of the pavement depth (iii) Bottom – closer to the bottom of the asphalt slab.. The temperature range of K-type thermocouples is 0-275 ℃ and accuracy of ± 2.2 ℃. Thermocouples calibration was conducted initially before the start of the experiment. Also, the analysis of the effect of the circulating water on the temperature distribution of RPSC was carried out together with the test on the water leakage within the pavement.

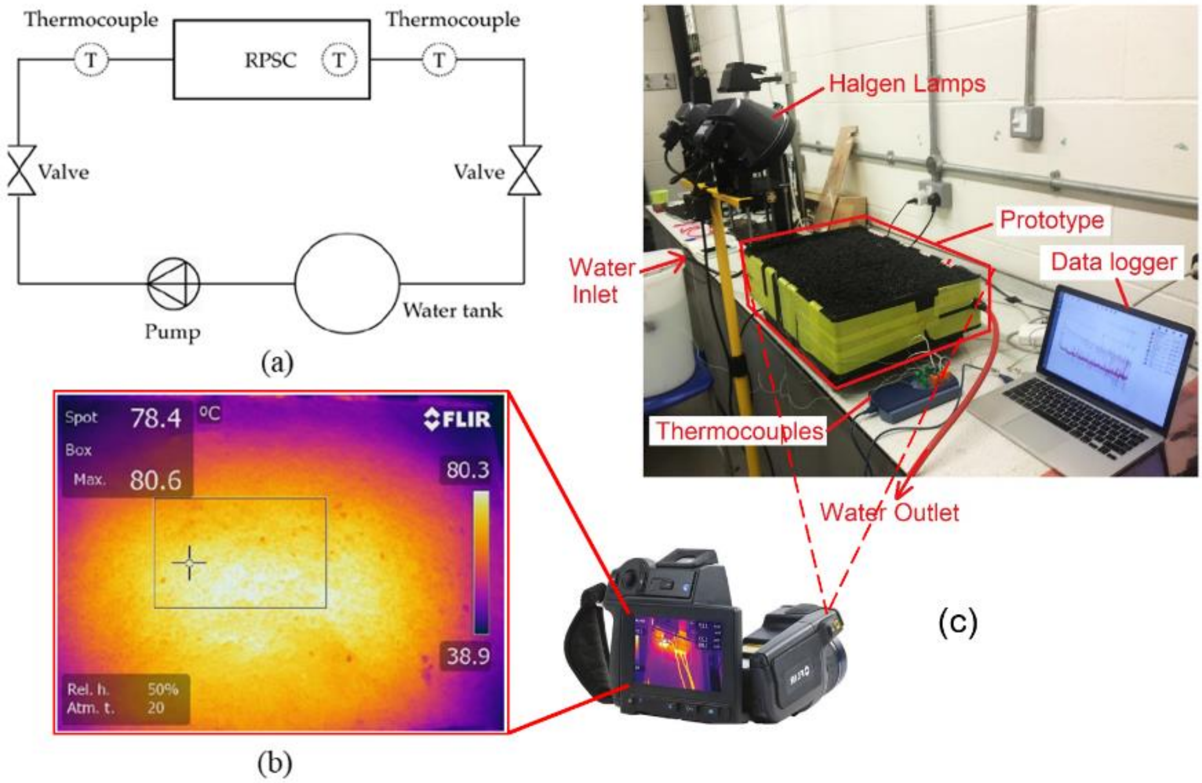

Figure 3. (a) Schematic diagram of the U-RPSC system (b) Initial prototype surface temperature (c) Photo of U-RPSC system.

Two 400W halogen lamps were used to simulate solar radiation and heat the slab surface until the temperature reached ± 80 ℃. FLIR T660, a handheld infrared thermal camera was used to measure and monitor the temperature of the slab surface, It has a temperature range between -40 ℃ and 2000 ℃ and accuracy of ± 2 ℃. PicoLog 6 software was used to record the temperature reading of the thermocouples and the data was utilised for the validation of the computational model. Eachexperiment was conducted within 60 minutes and the data was recorded at 2 minutes' interval. The water pump has 12V DC, 3m maximum head, 240 litres/h maximum flow rate and 8.4W power was used to pump water into the prototype after the surface temperature was preheated up to 2 hours, reaching ± 80 ℃. During the experiment, the halogen lamps were kept on to simulate continuous solar radiation, and to avoid major effect of room air convection on surface temperature reduction. The ambient temperature of the laboratory room was kept 23-25 ℃, meanwhile the supplied water was kept to a constant temperature of 20-21 ℃ with the mass flow rate of the water supply was kept constant at 0.0126 kg/s; see Fig. 3 which describes the laboratory setup of RPSC system. Thermocouples are placed at the inlet and other at the outlet to check the variation in the water temperature.

3. Results and Discussion

The temperature field was validated by comparing the obtained temperature from the simulation with the temperature based on the experimental results. The comparison was carried out by taking the measurement at the similar location where the thermocouples were placed in the RPSC prototype, see the validation results in Fig. 4. The simulation results were underestimated up to 5°C at the top position;

however, the variance became nominal at the middle and bottom positions, by 1-3 °C. The temperature profile across the pavement depth of the simulation was comparable with that of the experiment.

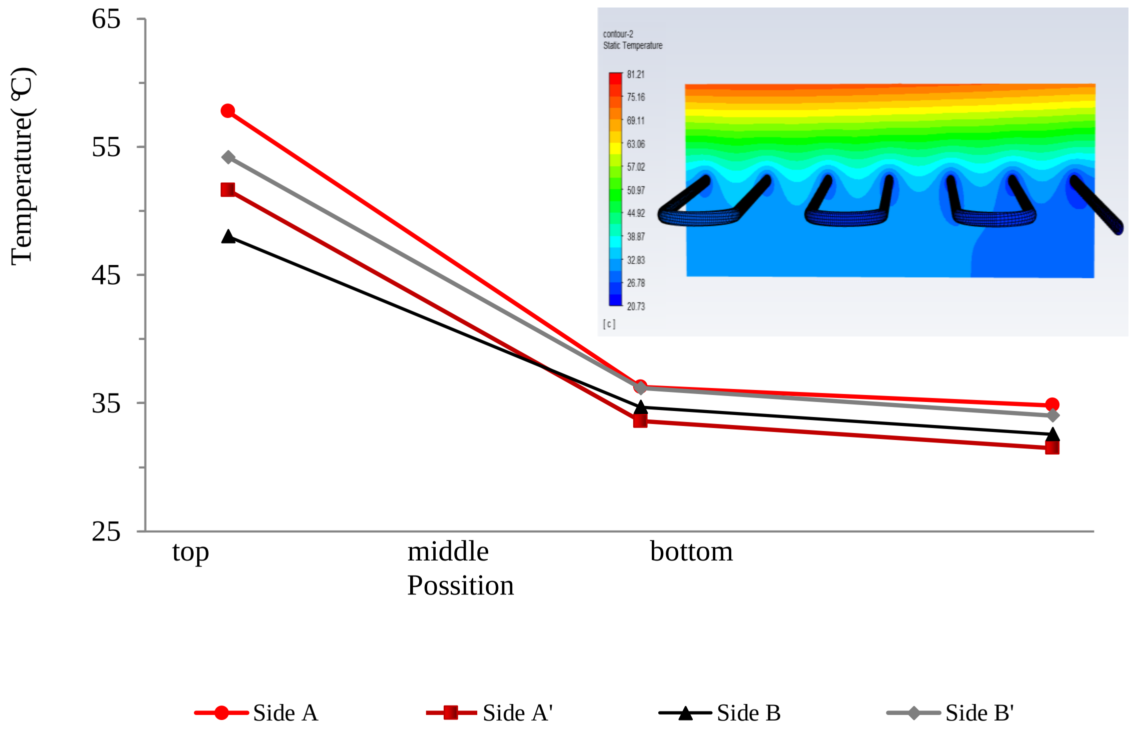

Fig. 4 Validation of the numerical results (Side A' and B') of temperature at different position with experiments (Side A and B).

For the modelling of the U-RPSC system within the urban canyon, a typical hot summer day was simulated [12] with the outdoor air temperature at 30 ºC. The direction of the wind was perpendicular to the urban canyon building's length. It was observed that due to the position of the sun and shadowing effect of the upstream building, the surface near the upstream building had a lower temperature than the surface near the downstream building (Figure 5a-d). This pattern was observed for all the simulated aspect ratio. The percentage of the shaded surface increased with the aspect ratio of the urban canyon. Figure 5e compares the air temperature reduction across the height of the urban canyon (5 metres) for the different aspect ratio with U-RPSC. The largest air temperature reduction was observed in the AR 1 urban canyon. The air temperature was reduced up to 4.7 ºC at 0.5 metres height and 3.1 ºC at 5 metres height. While the lowest reduction was observed for AR 3 urban canyon which had a reduction of 1.7 ºC at 0.5 metres and 0.82 ºC at 5 metres. Lowest variation across the height of 5 metres was observed in the urban canyon AR 4.

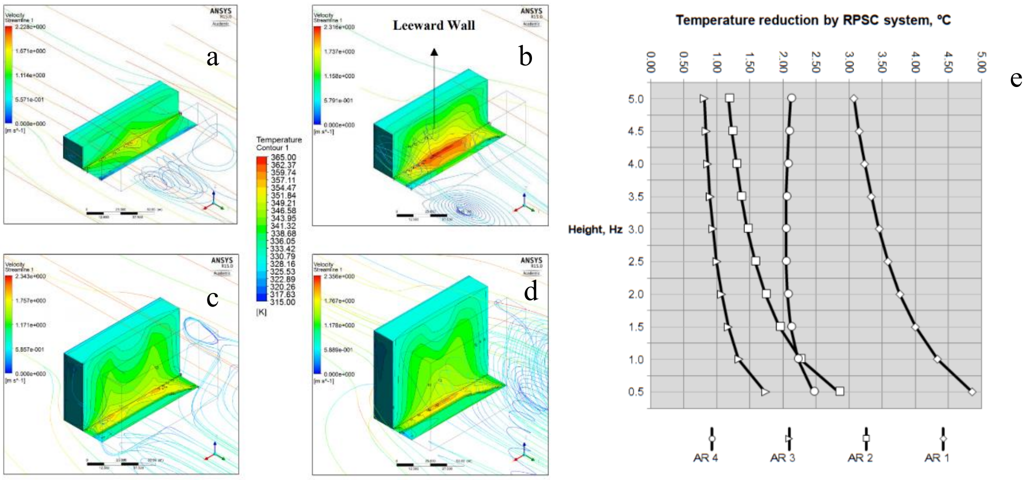

Fig. 5 Surface temperature contour and air velocity streamlines within the urban canyon for (a-d) AR 1-4 and the (e) temperature reduction %.

4. Conclusion and Future Work

Using a de-coupled numerical modelling approach, the present work assessed the beneficial impacts of urban road pavement solar collector (U-RPSC) towards reducing outdoor temperature. The study also presents the experimental data on the performance of a laboratory-scale U-RPSC system which was used to validate the computational model. The measured and predicted pavement temperature results showed good agreement. The values discrepancy may be a result of the employed radiation model and also the uneven distribution of radiation across the pavement in the experimental work. Based on the simulation of the U-RPSC system and the set conditions, the ambient air temperature within the urban canyon was reduced by up to 4.67 ℃ and the surface was reduced up to 27% as a result of the addition of the U-RPSC. When applying to street canyon with different heights, the concern was highlighted on the system performance in reducing potential UHI effect in deeper canyon during less windy condition and during the night-time. Future studies should focus on assessing the influence of RPSC on surrounding buildings energy consumption. Furthermore, the model should be coupled with Building Energy Simulation (BES) to further assess the impact of U-RPSC on surrounding building energy consumption.

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