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Analysis of the impact of urban pavement solar collector on urban air temperature and thermal collection: a coupled modelling approach

Weijie Xu[1*], Carlos Jimenez-Bescos[1], Conrad Allan Jay Pantua[1], John Calautit[1] and Yupeng Wu[1]

1 Department of Architecture and Built Environment, University of Nottingham

* Corresponding Author: Weijie.xu@nottingham.ac.uk

ABSTRACT

The asphalt pavement surfaces tend to absorb a large amount of heat through solar radiation and increase the urban air temperature. The thermal energy can be collected by water circulated through buried copper pipes and cool down the pavement surface, which decreases the air temperature and building cooling energy demand. This work aims to develop a method for determining the optimum areas to locate pavement solar collector (PSC) systems and simulate the reduction of ambient air and surface temperature by using a coupled computational modelling approach. A prototype of the PSC was developed, and lab-scale experiments were carried out for validation. Based on the simulated conditions, in the unshaded area, the near-surface temperature of the asphalt slab was reduced by up to 10℃, and the outlet water temperature increased by about 5 ℃. At the pedestrian height level, the reduction of air temperature was up to 4.6℃. This study further expands the investigation of the system by varying water velocity, inlet water temperature and air temperature. The proposed method could be used to optimise the positioning of the PSC to reduce urban surface and air temperature.

Keywords: Pavement solar collector, Computation Fluid Dynamics (CFD), urban street canyon, Urban Heat Island (UHI), thermal collection, heat mitigation

NONMENCLATURE

CFD	Computational Fluid Dynamics
DO	Discrete Ordinate
PSC	Pavement Solar Collector
UHI	Urban Heat Island

1. INTRODUCTION AND LITERATURE REVIEW

Pavements take up a large proportion of urban areas, conventional pavement or asphalt pavements can absorb a large amount of light and radiation, and the heat is dissipated to the surrounding air, which further aggravates the UHI effect. Pavement solar collectors (PSC) showed higher potential to mitigate urban overheating than other solutions [1]. PSC can harness the heat energy and use it in multiple applications such as water heating for neighbouring buildings and snow melting [2].

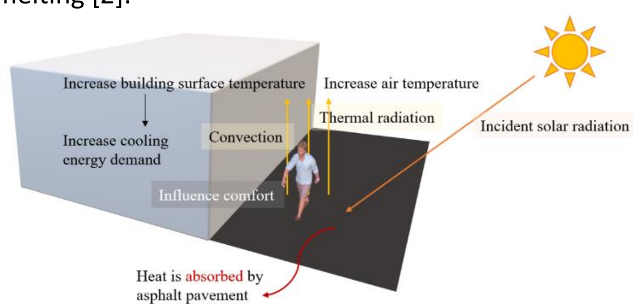

Figure 1. Typical heat transfer in an urban area with a standard pavement [3]

Asphalt pavement absorbs the solar radiation, the heat is stored in the pavement and then radiated to the air and building external walls, which heats the street air temperature and building surfaces. The water pipes of the PSC system can remove the heat from the pavement and cool down the pavement surface temperature. The building cooling energy demand will also decrease because of the lower air temperature. When the adjacent air temperature decreases, it can provide a better thermal environment for pedestrians in summer. The study by Papadimitriou et al. [4] highlighted the potential of PSC to provide thermal energy requirements of the urban environment. The influence of building

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geometry, urban street canyon aspect ratio and urban form on the PSC system have been analysed in the previous works [5-7].

1.1 Novelty

Due to the high requirements for computing power and resource to carry out such simulations which were not available previously. There is no study evaluated the integration of urban street canyon and the PSC system in a computational domain or using a coupled approach for analysing the impact of the PSC systems on the surface-air temperature reduction and thermal collection. It is envisaged that the proposed approach will also help the development of future models to assess the influence of the PSC on the energy demand of the neighbouring buildings.

1.2 Aims and objectives

This work aims to investigate the combined effect of the PSC system on building, air and road temperatures by modelling an urban street canyon with pipes embedded under the pavement. Computational Fluid Dynamics (CFD) simulation was used for this research which is widely used for analysing the aero-thermal environment of urban street canyons and pavement solar collectors [8]. The weather data of Milan, Italy, was selected for this study and 20% of the road was embedded with the pipes. The study will compare the influence on the surface temperature and the ambient environment of pavement with and without the PSC system. Different water inlet velocities and temperatures were compared to show how it affects the PSC system's thermal performance. The asphalt slab prototype of PSC was built and tested in a laboratory setup to obtain the real-time temperature distribution across an asphalt pavement and validate the CFD modelling approach.

2. METHODS

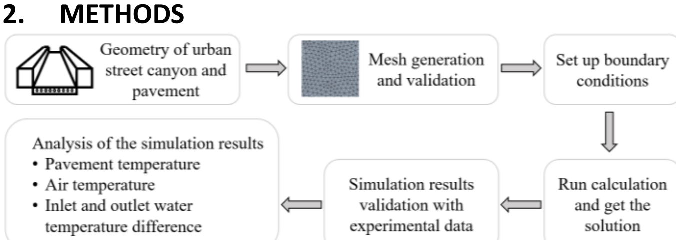

Figure 2. Methodological chart of the process

The study developed a coupled approach to combine the urban street canyon domain and pavement with the PSC system domain in the same model and simulate the heat transfer between the two solid-fluid domains. ANSYS FLUENT v18 was used to model the thermo-fluid properties of the system. The geometry of both street canyon and pavement parts were generated in Solid Edge, and then the model was imported to ANSYS for computational domain and mesh generation, boundary condition set up and simulation process. The simulated results were validated with experimental data. ANSYS Fluent was also used for the post-processing and visualisation of results.

Urban domain. The urban street canyon domain is illustrated in Figure 3. The whole domain was divided into two regions: (1). 0.3m thickness solid pavement region and (2). air-fluid region (wind). The total macro domain of this model was defined as 100.0m length × 80.0m width × 30.3m height.

PSC domain. To find the temperature difference of road surface and air of the canyon, the pipes were not embedded for the whole pavement but only covered 20% of the pavement length. The pipes were made of copper, and the wall thickness was 0.009m. The pipes were located in the centre of the pavement with the length of 20.0m and diameter of 0.02m. The embedded depth was 0.15m, and there were 9 pipes in the pavement, with an interval of 1.0m (Figure 3).

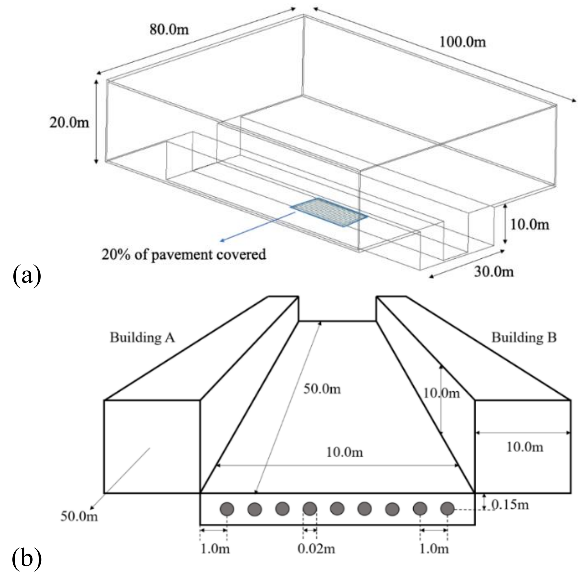

Figure 3. (a) Geometry of the whole domain and (b) location of the pipes (section from Figure 3 (a), not to scale)

2.1 Mesh and sensitivity analysis

Patch conforming method was applied to canyon sections, which including building walls, building roofs and ground road surfaces. The mesh sizing for the PSC area was set to High, which can calculate more accurate output value than Coarse and Medium.

2.2 Boundary conditions

The boundary conditions were set based on the local environment and material properties [6, 9]. Base on the previous studies [5-7, 9], in this research, the urban street canyon was located in Milan, Italy, for result validation, the latitude is 45.47° and longitude is 9.18°. The selected time and date are 14:00 on 26th June, on that day the sunshine factor is 0.25. The wind came from the south direction with a temperature of 303K and velocity of 2m/s. Water at a lower temperature was circulated through the copper pipes and brought away the heat from the pavement slab. The initial inlet water temperature was set to 293K [10]. Copper was used as the pipe material. The top slab of the pavement was made of asphalt. The material for building walls is brick.

To analyse how the inlet water velocity influences the PSC system performance, the inlet water velocity was set between 0.25m/s and 2m/s while the water temperature and other parameters were kept constant. Then the inlet water temperature was set between 288K and 298K to investigate how the temperature affects the system performance. The water inlet velocity was set to 0.25m/s, and other conditions were remaining the same.

Asphalt pavement can be heated up after absorbing a large amount of solar radiation, the sun position and air temperature are changing with the time. So eight different times of 26th June 2016 in Milan, Italy [11] were selected for analysing the PSC system performance under different environmental conditions. The water velocity was 0.25m/s with a temperature of 293K.

2.3 Numerical model validation

For the validation of the PSC numerical model, a laboratory experiment was conducted in the Energy Technologies Building, University of Nottingham, UK. The validation of the urban canyon modelling was carried out and fully detailed in previous works [8].

3. THEORY

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 discretised equations were solved by the SIMPLE algorithm was selected while the second-order central difference were utilised for spatial discretisation and in temporal discretisation. To investigate the temperatures and wind flow pattern, the energy model was set, and the viscous model was set to k-epsilon (2 equations). The steady RANS equations simulated urban turbulent airflow with the standard k-ε model, which based on the principle of heat conversion, continuity and momentum. In this model, the transport equation for turbulence kinetic energy (k) and dissipation rate (ε) allows the airflow to be fully turbulent solved [12]. Discrete ordinate (DO) and solar ray tracing were used as the radiation model for evaluating the impact of solar radiation on the surface temperature and PSC system performance.

4. 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 profile of the temperature distribution across the pavement depth of the simulation was compatible with the temperature profile across the pavement depth of the experiment. It implies from the validation that the temperature field of the constructed model in this study can be used for further analysis.

4.1 Urban and road surface temperature

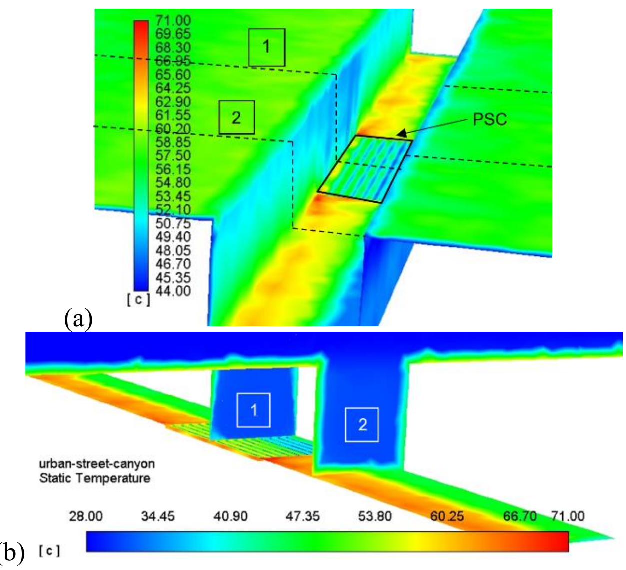

Figure 4. (a) Surface temperature contour of the street canyon and surrounding buildings and (b) cut section temperature contour of the urban street canyon

Figure 4 shows the temperature distribution of the urban canyon ground and building surfaces. Due to the shadowing effect caused by the windward building, the lower surface temperature was (45-50℃) was observed near the windward building. It can also be observed that the pavement had about 10℃ higher temperature than the building sidewalls and air. It can be clearly observed that the PSC system reduced the temperature of the pavement surface in the middle of the canyon (20% of the canyon). Section 1 is the area above the pipe-embedded-pavement and section 2 is the area without the PSC system. The near-ground-air in section 2 had about 10℃ higher temperature than that of section 1. When the PSC cooled down the pavement temperature and air temperature, there would be less convective heat transfer between walls and air because of the smaller temperature differences. In this way, the building cooling energy demand would decrease.

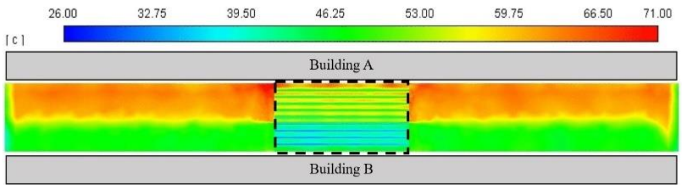

Figure 5. Temperature contour of pavement with PSC with inlet water velocity of 0.25 m/s

Figure 5 shows that the temperature of the pipe-embedded-pavement section was about 28% lower than the areas without pipes. The temperature difference between shaded and unshaded area was about 15°C. The central pavement area which was embedded with the cooling pipes had a much lower surface temperature in both shaded and unshaded areas; the cooling effect was more significant especially in the unshaded area, the temperature was reduced up to 20°C. The ambient air would have a lower temperature when it was close to the cool surfaces, which could improve the thermal environment for pedestrians in summer. The cool pavement could help to reduce the cooling energy demand, as well as reducing the high-temperature damage to car tyres.

4.2 Air temperature and building surface temperature

Figure 6 shows horizontal cross-section contours of the air temperatures at different heights. Without the PSC system, the overall air temperature decreased with the height increasing, which indicates that high-temperature pavement mainly affected the air temperature at a low height.

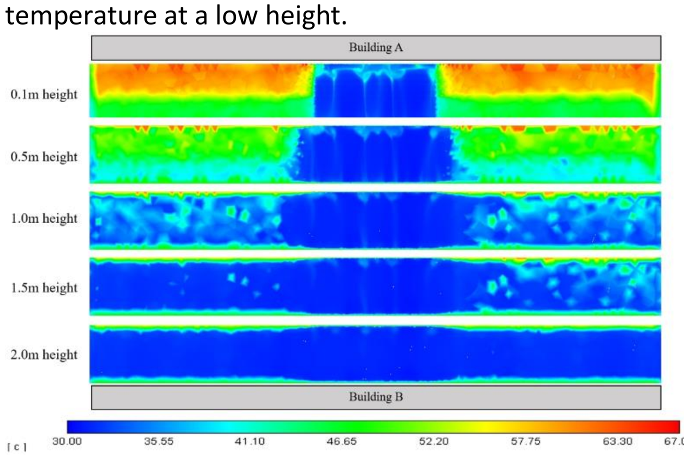

Figure 6. Air temperature distributions in different heights: horizontal cross-section contours from 0.1m to 2m

As observed in Figure 6, the air temperature near the ground surface (0.1m) can be as high as 67 °C and reduces with the height. The cooling effect provided by the PSC system was significant at the lower height areas; the air temperature can be cooled down up to about 30°C. For the spaces which were lower than 1.5m, the air temperature of the pipe-embedded-pavement section was 5°C to 10°C lower than other areas.

Six points were selected to investigate the relationship among the air temperature, location and height for the positions point a, b, c, d, e and f as shown in Figure 7 and the air temperatures were plotted in Figure 8. For this analysis, the case of the inlet water velocity of 0.25m/s was chosen, and the pavement material was asphalt.

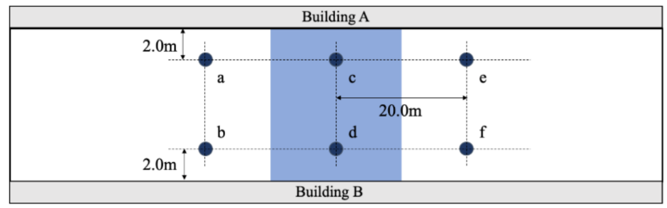

Figure 7. Selected point locations (not to scale)

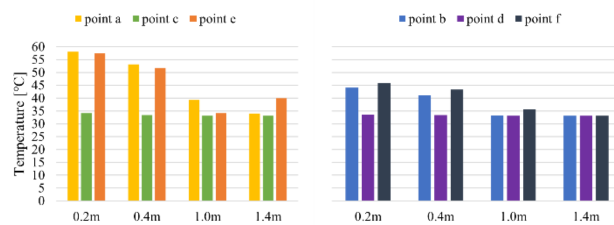

Figure 8. temperature profile at the six locations

Below the height of 1.0m, the air temperatures at point c and d were much lower than those at point a, b, e and f. The gradients show that the temperature decreased much faster at point c and d than other points. The figure shows the cooling effect by the PSC system was notable at the low height spaces. In the unshaded area, with the PSC system, the air temperature can decrease up to 33.9°C at a height of 0.2m. However, at this height without the PSC system, the air temperature was up to 57.5°C.

4.3 Influence of water velocity on pipe outlet water temperature/ potential thermal energy collection

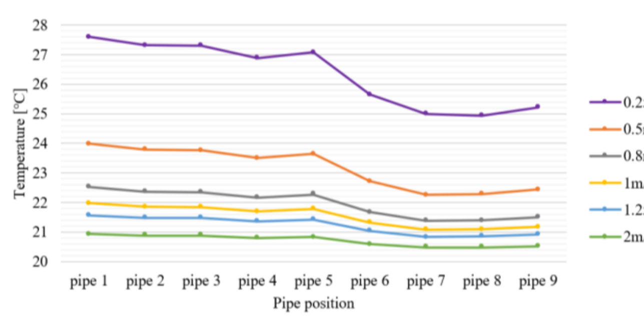

Figure 9. Outlet water temperatures of the nine pipes

The nine pipes had the same inlet water temperature (19.85°C), Figure 9 shows that the six lines had the same tendency. Lower inlet water velocity can dissipate more heat from the pavement, When the inlet water velocity was 0.25m/s, in the unshaded area, the highest outlet temperature was 27.60°C, and the percentage increment was 39.03%. The smallest increment was caused by the most considerable inlet velocity, which was 0.63℃ in the shaded area, which increased the water temperature by up to 3.18%. Compared to other sets of data, when inlet water velocity decreased from 0.5m/s to 0.25m/s, the water temperature increment developed from 20.82% to 39.03%, so the cooling effect provided by the PSC system increased significantly.

4.4 Influence of inlet water temperature on pipe outlet water temperature/ potential thermal energy collection

Inlet water with the lowest temperature had the most significant temperature difference, which means more heat was absorbed by the water. When the inlet water was 15°C, the maximum temperature difference was 9.5℃, and the minimum temperature difference was 6.7 ℃. The water temperature increment was between 44.8% and 63.8%. However, when the inlet water temperature was 25 ℃, the maximum temperature difference was 6.0°C, which means it was still smaller than the minimum temperature difference caused by the 15 ℃ inlet water. With the inlet temperature decreased every 2.5℃, the temperature difference would increase about 0.80°C to 0.86°C.

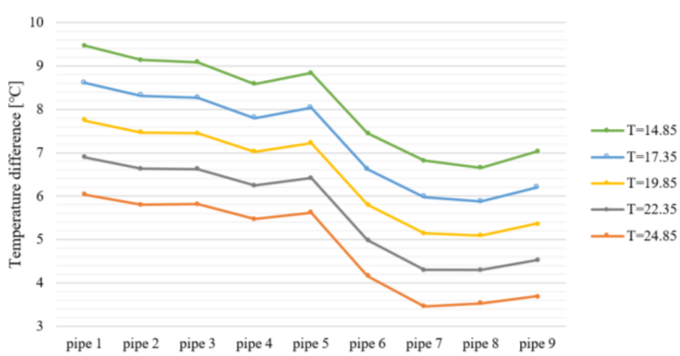

Figure 10. The temperature difference between outlet and inlet water

4.5 Influence of time and air temperature on pipe outlet water temperature/ potential thermal energy collection

At a different time, the air temperatures and solar conditions are different. When there was direct solar radiation coming to the pavement, the outlet water temperatures were much higher than the inlet temperatures. At 12 am, the water temperature average increment of the nine pipes was 7.02°C, while at 8am the average increment was 3.05°C. At 2 pm, the temperature maximum of increment was 7.8°C. For the pipes which were in the unshaded area, the inlet and outlet temperature differences are about 7°C, which means the circulating water temperature increased by 35%. It is necessary to consider the PSC system operating time to obtain higher efficiency.

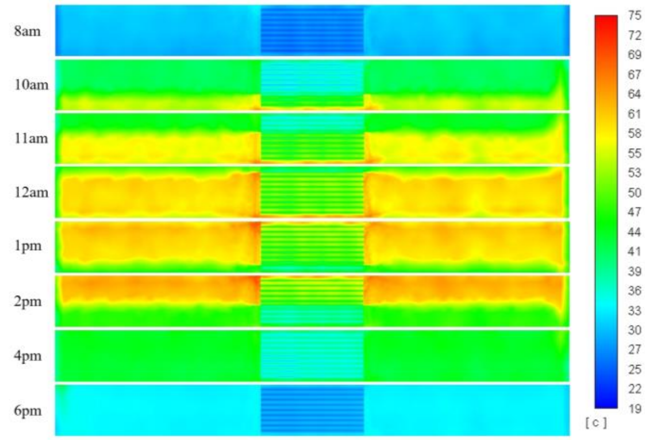

Figure 11. Pavement surface temperature contours at different times

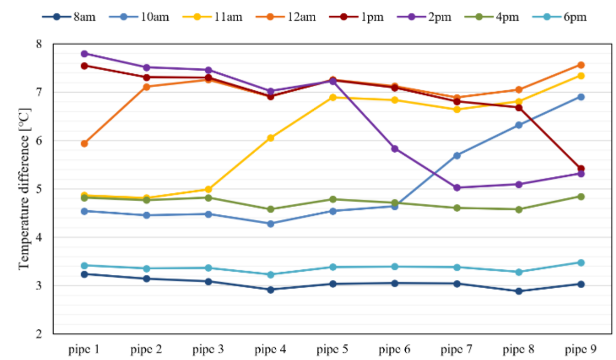

Figure 12. The temperature difference between outlet and inlet water – at different times

5. CONCLUSIONS AND FUTURE WORKS

A coupled approach was developed in this research to combine both the urban street canyon domain and the PSC domain. The numerical modelling of the PSC was validated against experimental data and showed good agreement. Analysis of the PSC system was performed for a section of the whole urban canyon pavement.

Based on the set conditions, the surface temperature of unshaded pavement could be reduced up to about 10 ℃ in the unshaded area with the PSC system embedded under the road. The PSC system also reduced the wall surface temperatures significantly, the air temperature of the region above the pipe-embedded-pavement area had a lower temperature than other areas at the height below 1.5m.

Inlet water with low velocity and the low temperature had a better cooling effect for the pavement. When the inlet velocity was 0.25m/s, the water temperature could increase by up to 39.03%. The pipes with 14.85℃ inlet water can dissipate up to 14.2% more heat from the pavement than those with 24.85℃ inlet water. The pipes with 14.85℃ inlet water can dissipate up to 14.2% more heat from the pavement than those with 24.85℃ inlet water.

With higher air temperature and direct solar radiation, the PSC system could provide more cooling effect. In the early morning, the water temperature increment was 15.2% and at noon can be 35.1%. When the system was operating under the condition which had the same air temperature but at a different time, the solar condition also can lead to a 15.5% difference in water temperature increment.

According to the analysis, the main benefit of the PSC system is to reduce air temperature and improve a comfortable thermal environment for pedestrians, as well as protecting the car tyres during hot days. Other parameters such as pipe position, pipe depth and working system period need to be explored in future studies.

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