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CFD Simulation of Integrating Solar Roads in Urban Canyon

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Abstract

A 3-D computational modelling analysis of a road pavement solar collector (RPSC) system was used in two different macro domains; a standard urban canyon domain and a flat domain (no buildings). The computational model was developed in ANSYS Fluent to consider the temperature effects of solar radiation and radiative exchange between canyon air and surfaces. Good agreement was observed with average error 4.19% validated from the previous CFD model. The simulation of 21st June at 13:00 demonstrated the RPSC system in the urban canyon domain performed 36.08% more effectively in thermal collection with 27.11% more surface temperature reduction as compared to its performance in the flat domain.

Keywords Computational fluid dynamic; Hydronic pipes; Road solar collector; Urban canyon; Urban Heat Island (UHI).

1. Introduction

The application of road pavement solar collectors (RPSC) within an urban compound was studied to benefit these dual functions: (i) as an energy system [1] and (ii) as an Urban Heat Island (UHI) mitigation system [2]. Under the management of public city councils, such systems have the potential to be fully maintaned with less involvement of private stakeholders. Horizontal and vertical installations of solar collector systems have been extensively applied on building roofs and facades; nevertheless these types of system performance can only be achieved within small boundaries of the particular building. In previous literature, the RPSC system works underneath the horizontal road surface by considering climatic factors that influence the workability of the system. Such high solar radiation and heavy rain can increase and reduce the road temperatures respectively. System installation within urban compounds can be more complicated with tall buildings which will overshadow the road and lower the surface temperature but conversely shadows are important in reducing the surface UHI effect which limits the prospects of the system installation. Recent literatures of street canyon geometries found the wind blocking buildings decreased the wind speed within the street canyon as a function of the building height, thus increasing the air temperature [3]. This was explained as a result of air UHI effect which depicted the situation in the very dense urban environment. In reality, building facades also emit additional heat flux to the surroundings, but are very complex. Within this context, this paper investigates the performance of RPSC typed water pipes system in a simplified urban street canyon by comparing the de-coupled approach of an urban scenario with a no-building scenario.

2. Computational Method and Meshing

3D Computational Fluid Dynamic (CFD) models of a de-coupled approach to combine RPSC system and street canyon in the composition of macro and micro domains, respectively as shown in Fig. 1. The macro urban domain as Figure 1(a) represented an urban flow domain consisting of two buildings with dimensions 100 m length × 20 m width × 20 m height situated side by side with a gap of 100 m length × 20 m width, forming a street canyon. Full macro domain size was applied as per the Figure 1(b).

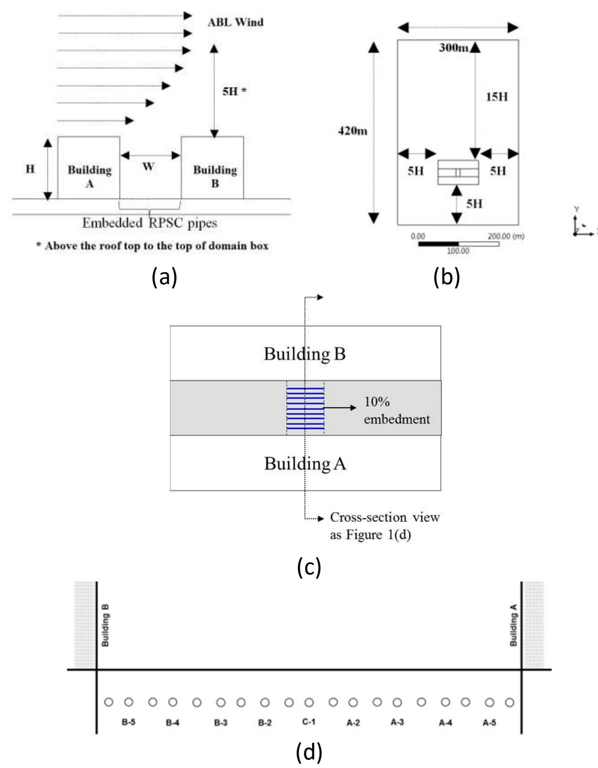

Figure 1. Geometry description of integrated RPSC system with canyon.

To simplify the model, an RPSC copper water pipe system was installed at the very centre of canyon with dimensions of 10 m length × 20 m width with only 10% embedment in the very centre of the road surface as Figure 1(c). 19 pipes depicted embedded 0.15 m deep within the road surface of micro domain with 1 m gaps between the pipe centres. Only 9 pipes were selected based on every two pipes gap (2m) as labelled in Figure 1(d). Surface temperatures were measured based on average temperature at the central surface location of every pipe, Ts before each of the surface temperature was exported as the temperature profile of the topmost surface of micro domain. The micro domain simulates the *Delta T* of every pipe; considering the difference between inlet and outlet water temperatures (K).

The micro domain was sized for the embedment of one pipe, with dimensions 10 m length × 1 m width × 0.3 m depth. For meshing type, patch independent hybrid meshing technique was introduced to ensure refinement at essential areas but retain larger elements where feasible to achieve high computational times. Inflation of First Layer Thickness was applied indicating 0.1m height of the first layer thickness with growth rate 1.2 with maximum of 20 layers. Hexahedral meshing was generated for both building walls. Similar meshing technique was applied for flat macro domain but without the meshing of canyon building geometries.

3. METHOD VALIDATION AND BOUNDARY CONDITIONS

The macro domain was validated against a similar domain and settings as S. Bottillo (2014) [4] by using Solar Load model in Milan urban centre at longitude 9.18, latitude 45.47 and UTC +1 with sunshine factor 0.25 at time 13:00 on 21st June to portray a summer day. Both methods and boundary conditions were applied similar for macro flat modelling (no building). The result was validated with average error 4.19% [5]. The Discrete Ordinate (DO) radiation model was introduce to be coupled with Solar Load model to solve transport equation for fluid flow and energy equation caused by radiation and heat sources in a fluid phase. Upstream wind inlet was located in y-axis 100 m from the first windward wall meanwhile the downstream wind outlet was located 300m away the second leeward wall. A constant velocity of 2 m/s was set at the inlet boundary with standard steady-state $k - \varepsilon$ turbulence model and SIMPLE algorithms. For spatial discretisation, Finite Volume Method (FVM) was set based on cell-average value solution. This simulation developed full turbulent flow towards the blocking canyon wall was based on the principle of second order momentum, continuity and heat conservation with two transport equations; first order turbulence kinetic energy k and first order dissipation rate ε [6]. For wall surfaces, the boundary conditions were set as Table 1.

Table 1. Boundary conditions applied to wall surfaces.

Surface type	Surface Temp. K	Density ρ kg/m3	Heat capacity C_p (J/kgK)	Emissivity ϵ	Therm. Cond. W/mK
Road	NA	1000	1000	0.9	2
Soil	288	1000	1000	0.9	2
Facades	299	1000	1000	0.9	0.15
Copper	NA	8978	381	0.8	387.6
Water	293	998.2	4182	NA	0.6

4. RESULTS AND DISCUSSION

Comparative results of the surface temperature contours can be observed in the Fig. 2; which displayed obvious temperature change for urban macro model at the central location. At time 13:00, the sun refraction influenced higher temperature approaching Building A; but it was noticeable that the x-axis wind penetrated from both open ends of the canyon. The wind penetration assisted in reducing the temperature on the sides of the road surface but not the central location. Different situation was found for flat domain in Figure 2 when no-building scenario causes constant temperature distribution all over the selected surfaces. Based on the measured average Ts from the contours, the Delta T results were summarised in Table 2.

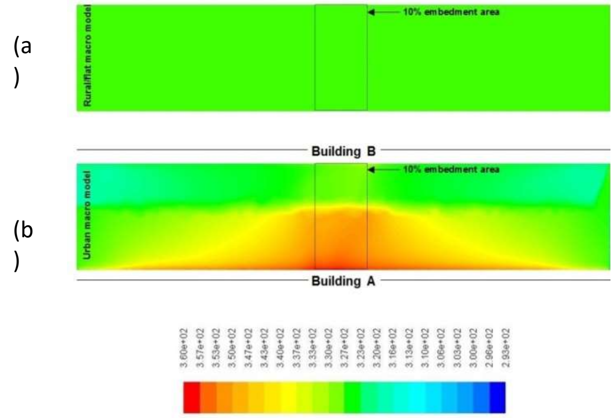

Figure 2. Road surface contours in macro domains: **(a)** Flat **(b)** Urban

Table 2. Delta T of RPSC pipes in urban (U) and flat (F) domains.

Description	Inlet water temperature, $T_{w(i)}$ (K)	Outlet water temperature, $T_{w(o)}$ (K)	*Delta T,* $T_{w(o)}$ (K) - $T_{w(i)}$ (K)
RPSC-F all pipes	292.99	301.52	8.53
RPSC-U C-1	292.99	305.71	12.72
RPSC-U A-2	292.99	305.85	12.86
RPSC-U A-3	292.99	305.98	12.99
RPSC-U A-4	292.99	306.24	13.25
RPSC-U A-5	292.99	306.91	13.92
RPSC-U B-2	292.99	303.99	11.00
RPSC-U B-3	292.99	302.14	9.15
RPSC-U B-4	292.99	302.14	9.15
RPSC-U B-5	292.99	302.14	9.15

5. CONCLUSIONS

In summary, the summarised Delta T of RPSC pipes in urban domain demonstrated average 36.08% more dominant as compared to the flat domain due to the effect of unblocking building geometry. This study found the significant impact of higher temperature simulated from the integration of RPSC system with urban geometry through de-coupled simulation approach. This study aims to aid the decision of the system application when urban environments are considered as an important variable.

REFERENCES

1. Bobes-Jesus V, Pascual-Muñoz P, Castro-Fresno D, Rodriguez-Hernandez J. Asphalt Solar Collectors: A Literature Review. 2013; 102: 962
2. Yue W S, QiYang Z, YingNa D, PeiDong S. Unidirectional Heat-Transfer Asphalt Pavement for Mitigating the Urban Heat Island Effect. 2014; 26: 813
3. Memon, R.A., D. Y.C. Leung, C. Liu, Effects of Building Aspect Ratio and Wind Speed on Air Temperatures in 24 Urban-Like Street Canyons, Building and Environment 45 (2010) pp. 175-188
4. Bottillo S, Vollaro D L, Galli G, Vallati A. Fluid Dyamic and Heat Transfer Parameters in an Urban Canyon. 2014
5. Nasir, D. SNM., Hughes, B.R. and Calautit, J.K., The Impact of Urban Canyon on the Thermal Performance of Solar Roads, In: 3rd Sustainable Thermal Energy management Conference (SusTEM 2011), 7-8th July 2015, Newcastle Upon Tyne, United Kingdom
6. ANSYS Fluent Academic Version 15.0.7 Users' Guide, 2014.