Modelling the Urban Radiant Fluxes Using View Factors

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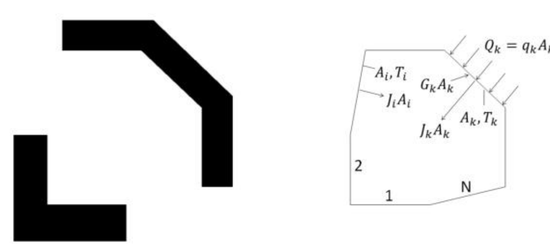
ABSTRACT: The exchange of radiant fluxes between different surfaces in outdoor urban environment can be described based on the theoretical framework of enclosure theory (or net-radiation method) in order to have a general understanding of the relation between different surfaces and consequent radiant fluxes and hence the T_{mrt} within the enclosure. To apply the theory, the required enclosure could be constructed by including the real surfaces of building facade and the imaginary surface of sky dome. The mean radiant temperature at a point within the enclosure could be determined if each surface temperature T_i is solved given a known input energy flux q_i is imposed to each surface. At any instant, the surface energy balance holds for every surface of the enclosure by energy conservation. However, the enclosure theory requires certain assumption, idealizations and computations. For example, each surface of the enclosure are assumed to be gray, diffuse and at a different uniform temperature. But most of the real materials are not black, gray nor diffuse. The area of the enclosure may also be subdivided into smaller areas on a basis of uniform surface temperature over those smaller areas. It may require excessive computational time by dividing an area into too many smaller ones as for each surface there are two equations to be solved (not shown in the text). A system of 2N equations has to be solved if there are N surfaces 'recognized' in the enclosure, or in turn in the urban environment. This has also given rise to the difficulties in 'recognizing' individual 'surface' of uniform temperature in the real outdoor spaces surrounded by buildings with sunlit areas, tress with leaves, and so on. To put it simply, by treating the urban structure as a 'black box' and using regression analysis, the objective of this study is to identify and evaluate the empirical relation between radiant fluxes from directions within urban context in daytime. The urban environment will be captured in fish eye photos and decomposed into different components based on materials and properties. Radiant fluxes will be measured and regressed on those view factors. The preliminary results revealed a simple and significant correlation between view factor of materials and outdoor radiant fluxes.
Keywords: Urban morphology, outdoor thermal comfort, radiant fluxes, Sky view factor (SVF), Sunlit view factor (SLVF)

INTRODUCTION

The exchange of radiant fluxes between different surfaces in outdoor urban environment can be described based on the theoretical framework of enclosure theory (or net-radiation method) in order to have a general understanding of the relation between different surfaces and consequent radiant fluxes and hence the T_{mrt} within the enclosure. To apply the theory, the required enclosure (as illustrated in Figure 1) could be constructed by including the real surfaces of building facade and the imaginary surface of sky dome (Aristide, M., 2000). The mean radiant temperature at a point within the enclosure could be determined if each surface temperature T_i is solved given a known input energy flux q_i is imposed to each surface. At any instant, the surface energy balance holds for every surface of the enclosure by principle of energy conservation. However, the enclosure theory requires certain assumption, idealizations and computations (John R.H, et al, 2010). For example, each surface of the enclosure are assumed to be gray, diffuse and at a different uniform temperature. But most of the real materials are not black, gray nor diffuse. The area of the enclosure may also be subdivided into smaller areas on a basis of uniform surface temperature over those smaller areas. It may require excessive computational time by dividing an area into too many smaller ones as for each surface there are two equations to be solved (not shown in the text). A system of 2N equations has to be solved if there are N surfaces 'recognized' in the enclosure, or in turn in the urban environment. This has also given rise to the difficulties in 'recognizing' individual 'surface' of uniform temperature in the real outdoor spaces surrounded by buildings with sunlit areas, tress with leaves, and so on. To put it simply, by using regression analysis, empirical relation between radiant fluxes and view factors would be evaluated.



a) *b)*

Figure 1: Building envelope in urban environment could be treated as an enclosure of N surface areas each of uniform temperature T_i (a) building blocks shown in plan; and (b) radiative transfer within enclosure formed by building envelope.

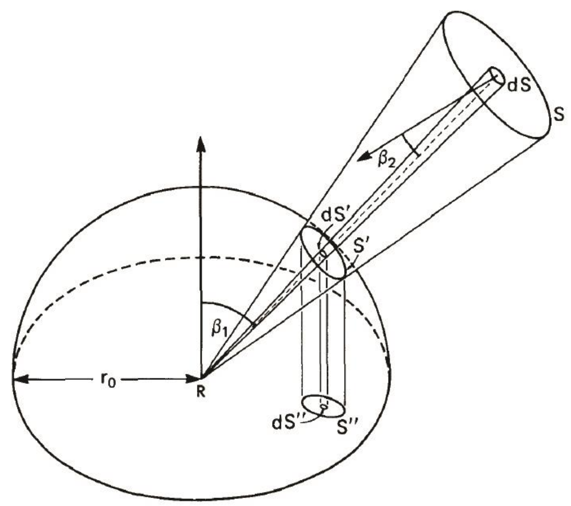


Figure 2: Radiation geometry. View factor of area S, which seen by the centre of the hemispheric, can be projected on a hemispheric surface S' and then projected on a horizontal plane surface S'' as produced by fish-eye len. Figure by Steyn (1980)

URBAN ENVIRONMENT AND VIEW FACTORS

Outdoor environment can be geometrically defined by the building facades and outdoor objects forming an enclosure of N surface areas each of certain temperature (John R.H, et al, 2010; Michael, 2013). The magnitude of radiative heat transfer between any two surfaces of this enclosure depends on their relative surface geometry and orientations. View factor is the geometrical parameter to depict the relative geometric configurations between any two surfaces. It is defined to account for the fraction of radiation energy, emitted or reflected or both, that directly intercepted (viewed) by another surface.

The built environment could also be projected on a hemispheric surface S' and then projected on area S'' as in Figure 2 and the view factor of particular surface could be computed from the integral in equation 1 and 2 respectively for surface S and S''. Moreover, with the fish-eye photographs of urban environment, the view factor of certain surface could be determined by applying Nusselt's "Unit Sphere Method" as given by equation 2 (John R.H, et al, 2010). The view factor of the surface S viewed by an object O located at the centre of the hemisphere surface, for example, the radiation sensor is given by (Steyn, 1980)

$$F_{O-S} = \frac{1}{\pi r_O^2} \int_S \cos\beta_1 \cos\beta_2 \, dS \tag{1}$$

or, using Nusselt's unit sphere method,

$$F_{O-S} = \frac{1}{\pi r_O^2} \int_{S''} dS'' \tag{2}$$

RADIANT FLUXES AND VIEW FACTORS

Consider the object O or surface O with area A_O, without the loss of generality, the irradiation, G_O that incident on object O is the sum of internal irradiation leaving from all other surfaces within the enclosure. The G_O is defined by:

$$A_O G_O = \sum_{i=1}^{N} A_i F_{i-O} J_i \tag{3}$$

where F_{i-O} is the view factor defined as the fraction of radiant energy leaving from the i-th surface A_i and reaching the object O, and J_i, is the radiosity which is the sum of emitted and reflected radiant energy leaving from the i-th surface. If using Reciprocity rule,

$$A_O F_{O-i} = A_i F_{i-O} \tag{4}$$

then equation (3) becomes,

$$G_O = \sum_{i=1}^{N} F_{O-i} J_i \tag{5}$$

where F_{O-i} is the view factor defined as the fraction of radiant energy leaving from the surface A_O and reaching the surface A_i. If there are three kind of surfaces, S_1, S_2 and S_3 which are dominant in the radiative energy transfer in the outdoor built environment, then equation (5) would becomes

$$G_O = F_{O-1} J_1 + F_{O-2} J_2 + F_{O-3} J_3 + \cdots \tag{6}$$

where F_{O-1} is the view factor defined as the fraction of radiant energy leaving from the surface A_O and reaching the surface S_1, and so on. And these view factors are computed by using equation (1) or (2). It should be noted that the irradiation G_O on object O can be regarded as a linear combination of view factors of some surfaces S_i viewed by object O if only radiation energy is considered. There are three types of view factors casted by the urban environment that would be mentioned as follows:

The Sky view factor (SVF), denoted by Ψ_{sky}, is a ratio of radiation received (or emitted) by a planar surface to radiation emitted (or received) from entire hemispheric environment (Watson et al., 1987). SVF is dimensionless quantity ranged from zero to unity meaning a particular point in the canyon completely obstructed to unobstructed, respectively (Oke, 1988). As its name suggests, SVF is the fraction of sky dome can be viewed from a particular point within canyon (Evyatar et al., 2010). It can be used to outline a more complex urban canyon (Johnson et al., 1984; Unger, 2009). It is often associated with the cooling rate of the city at night. A number of studies were done to investigate the effect of SVF on city cooling at night (Chapman et al, 2001).

Similar to SVF, Sunlit View Factor (SLVF), denoted by Ψ_{sunlit}, is a fraction of sunlit area of building facades that can be viewed from a particular point within urban environment. SLVF is also a dimensionless quantity from zero to unity. Theoretically, SLVF should be as important as SVF in determining the radiative energy exchange in urban context. But, it should be associated with the heating rate of city in daytime. Therefore, the effect of SLVF on radiant fluxes in urban morphology is the objective of this study.

The Greenery View Factor (GnVF), denoted by Ψ_{green}, is a fraction of greenery area of the built environment seen from a particular observation point within the built environment. It could be associated with the shadowing effect of trees, or cooling effect (if any) of any greenery, like trees, vertical greening, grass and so on.

With equation (5) and (6), the irradiation G_O, is the sum of radiation energy from different surfaces approaching the radiation sensor, and it could also be regarded as the linear combination of view factors of different surfaces with the coefficients are the respective radiosities of those surfaces. These radiosities are generally unknown or hardly be measured for each differential surface in the built environment. Therefore, the irradiation G_o on the sensor would be measured and regressed on predictors of view factors which can be obtained relatively easier than their corresponding radiosities. Thus, the empirical relation between radiant fluxes and view factors would be evaluated in the outdoor built environment by multiple regression analysis.

STUDY METHODOLOGY

The field measurements were taken between June and October 2015 over 14 measurement points covering a wide range of urban morphology with different combinations of view factors in the outdoor environment under mostly clear sky conditions. Measurements were logged at 10-second intervals during 15:00 -16:00 for each point and each day of measurement.

The three dimensional short-wave and long-wave radiant fluxes were measured by the net radiometers (Kipp & Zonen, CNR4). The three CNR4 net radiometers were mounted on a tripod for capturing radiant fluxes from the six directions namely, the sky dome, the ground, and the four cardinal directions (North, East, South and West). Measurements are taken at a height of approximately 1.5 meters above podium level as shown in Table 2. The newly-purchased net radiometers are calibrated by the manufacturer. The measured radiant fluxes were smoothed out using 5-min mean value.

Fish-eye photos were taken with Nikon CoolPix digital camera and fish-eye lens at the CNR4 station at a height of around 1.5m above podium level for six directions for each 15-min interval from 15:00 to 16:00 on each day. The values of SVF, SLVF, and GnVF were obtained with RayMan software and correlated to long-wave and short-wave radiant fluxes respectively. The algorithm of calculating the three types of view factors is shown in Table 1.

The diffuse sky radiation, K_o, was extracted from Kau Sai Chau (KSC) Automatic Weather Station (22º22'13''N, 114º18'45''E) of Hong Kong Observatory. The effective long-wave radiant fluxes, L_o emitted by the air was then obtained from the air temperature data by using the Stefan-Boltzmann law and assuming the air is a black body. The air temperature was taken from the Manned Weather Station (22º18'07''N, 114º10'27''E) of Hong Kong Observatory. These data provided the 'background' information of radiant fluxes on the days of measurement for reference. These background information would also be used for adjustment in the multiple regression analysis as one of the predictors besides view factors.

Table 1: Algorithm of Sky View Factor and Sunlit View Factor Calculation: first by taking fish-eye photos, and being processed with RayMan software. Similar procedure was done for the Greenery View Factor.

Fish-eye Photo	View Factor	
	Sky	Sunlit
		
		
	SVF = 0.349	SLVF = 0.075

RESULTS AND DISCUSSION

The objective of this study is to investigate the correlation between radiant fluxes and the View Factors casted by the outdoor built environment. Multiple linear regression analysis was performed on long-wave and short-wave radiant fluxes, respectively as function of Sunlit View Factor (SLVF), Greenery View Factor (GnVF) and Sky

View Factor (SVF). With the measured data in summer 2015, mostly under clear sky conditions, summary of regression equations were shown in Table 2 and 3 for long-wave and short-wave fluxes respectively. The regression for long-wave fluxes in the outdoor built environment was given by

$$L_i = -69.28 + 116.59\ SLVF - 37.82\ GnVF - 122.87\ SVF + 1.17\ L_o, \quad (7)$$

where the adjusted R^2 is of 0.6486. This value of adjusted R^2 explained nearly 65% of the sample variation in the measured long-wave fluxes between buildings. The overall significance level of the model is of 0.001 ($p < 0.001$, N = 65). This implied the model was highly significant. The t-tests for all the predictors were all highly significant in the model ($p < 0.01$, N = 65). Besides, the signs of coefficient of SVF, SLVF GnVF and L_o were negative, positive, negative and positive respectively in this model which making sense. For instance, the sky view and adjacency to greenery were believed to have cooling effect and hence less long-wave fluxes would be obtained. The sunlit areas were heated up resulting a higher surface temperature than ambient and giving positive contribution to the long-wave radiant fluxes. The effective long-wave fluxes, L_o emitted by the air was also linear to the long-wave fluxes, L_i measured within the built environment implying the effect of air temperature on the long-wave fluxes was also significant. On the other hand, the regression for short-wave fluxes in the outdoor built environment was given by

$$K_i = -32.62 + 116.42\ SLVF + 33.03\ GnVF + 248.30\ SVF + 0.13\ K_o, \quad (8)$$

where the adjusted R^2 is of 0.6308. This value of adjusted R^2 explained around 63% of the sample variation in the measured long-wave fluxes between buildings. The overall significance level of the model is of 0.001 ($p < 0.001$, N = 62). This implied the model was highly significant. The t-tests for all the predictors were all highly significant in the model ($p < 0.001$, N = 62) except for the GnVF whose t-test was of 0.05 significance level. The signs of coefficient of SVF, SLVF GnVF and K_o were all positive in this model which also making sense. For instance, the area of sky view increased with the amount of diffuse (sky) radiation. The sunlit area might reflected more short-wave fluxes than a non-sunlit one resulting in positive contribution to the short-wave fluxes. The diffuse solar radiation, K_o extracted from the Kau Sai Chau (KSC) Automatic Weather Station (22°22'13''N, 114°18'45''E) of Hong Kong Observatory was also linear to the short-wave fluxes, K_i measured within the built environment implying the background information of the day was adequate for modelling purpose. It was also noted that the coefficient of GnVF was positive but with a smaller magnitude when compared with that of SVF. This might imply that the effect of the greenery (like, tall trees with wide canopies) was only to screen out some of the diffuse (sky) radiation from the sky, i.e. shading effect from diffuse radiation as like as that from direct solar radiation. It was because the greenery would not emit short-wave fluxes by itself as its surface temperature was not high enough to emit a large amount of short-wave fluxes according to the Stefan-Boltzmann law. Therefore, the statistically positive contribution of GnVF might be due to physically the remaining diffuse sky radiation when coming across the gaps between the leaves of the trees.

Table 2: Summary of regression equation of long-wave radiant fluxes regressed on View Factors.

	Coeff.	S.E.	t	p	sign.
Const.	-69.28	75.06	-0.92	0.3597	-
SLVF	116.59	29.00	4.02	0.0002	0.001
GnVF	-37.82	13.84	-2.73	0.0082	0.01
SVF	-122.87	31.67	-3.88	0.0003	0.001
L_o	1.17	0.16	7.54	0.0000	0.001

Table 3: Summary of regression equation of short-wave radiant fluxes regressed on View Factors.

	Coeff.	S.E.	t	p	sign.
Const.	-32.62	7.47	-4.37	0.0001	0.001
SLVF	116.42	31.85	3.66	0.0006	0.001
GnVF	33.03	12.95	2.55	0.0135	0.05
SVF	248.30	30.06	8.26	0.0000	0.001
K_o	0.13	0.03	4.33	0.0001	0.001

IMPLICATIONS FOR URBAN PLANNING

The finding of this study is preliminary. Nonetheless, based on the current findings, recommendations of environmental urban planning for Hong Kong as one of the high density cities in hot and humid regions, might be recommended, but not limited to the followings:

- Appropriate disposition of building envelopes could help the radiative cooling of open spaces, and avoid radiative heating of them;
- Where appropriate, sky view should be preserved and maximized when viewed from the open space at pedestrian level for better radiative cooling;
- Built forms or envelope features that would block solar radiation (either direct or reflected one) towards the open space to minimize the warming effect of the spaces should be considered;
- The use of vertical greening on building envelope that would absorb or screen out part of the solar radiation and minimize solar radiation towards the

open space should be considered, particularly for those sunlit building area.

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