# Feasibility Study on Using Sunlit View Factor to Model Outdoor Thermal Comfort:
## A Case Study in Sha Tin, Hong Kong

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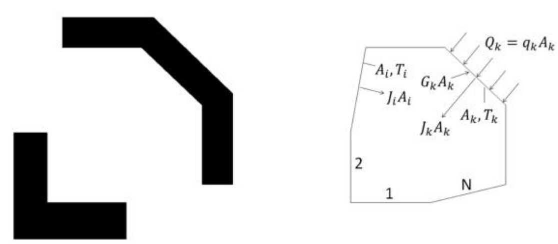
*ABSTRACT: The building facade not only serves as the outer surface of building itself, but also defines the boundaries of outdoor urban environment. This enclosure entraps more short-wave radiation from the sun due to its complex geometry and thermo-physical properties when compared with an unobstructed flat area. Building surface reflects and absorbs short-wave radiation, and is heated up to a higher surface temperature. The heated surface, especially the sunlit one, emits and exchanges more long-wave radiation with surrounding buildings and other outdoor objects. Therefore, to some extent, more long-wave radiant fluxes existing within urban environment could be regarded as one of the consequences of entrapping solar radiation by urban structure. In other words, more sunlit building area casted by urban morphology should lead to more long-wave radiant fluxes within urban environment. With more emitted long-wave and reflected short-wave radiant fluxes by sunlit urban fabric, the resulting mean radiant temperature ($T_{mrt}$) will be higher causing human thermal discomfort in outdoor environment. Thus, it is important to identify and evaluate the empirical relations between the geometrical composition of sunlit urban surfaces and outdoor thermal comfort. By treating the urban structure as a black box, and using simple regression analysis, the objective of this feasibility study is to identify and evaluate the empirical relation between radiant fluxes (especially long-wave fluxes) from six directions within urban context and corresponding sunlit area of adjacent building facades in daytime. Radiant fluxes of both long-wave and short-wave were measured by net radiometers in outdoor space in Wo Che Estate, Sha Tin, Hong Kong. The measured radiant fluxes were smoothed out using 5-min mean value. View factor of sunlit area was captured by using fish-eye lens camera, and corresponding values were obtained with the aid of RayMan software. The radiant fluxes and mean radiant temperature are regressed on sunlit view factor. The results showed a strong correlation between sunlit view factor and outdoor thermal comfort.*
*Keywords: Urban morphology, outdoor thermal comfort, radiant fluxes, Sky view factor (SVF), Sunlit view factor (SLVF)*

## INTRODUCTION

The building facade not only serves as the outer surface of building itself, but also defines the boundaries of outdoor urban environment. This enclosure entraps more short-wave radiation from the sun due to its complex geometry and thermo-physical properties when compared with an unobstructed flat area (Terjung, 1973, Aida, 1982, Oke, 1982). Building surface reflects and absorbs short-wave radiation, and is heated up to a higher surface temperature. The heated surface, especially the sunlit one, emits and exchanges more long-wave radiation with surrounding buildings and other outdoor objects (Givoni, 1976). Therefore, to some extent, more long-wave radiant fluxes existing within urban environment could be regarded as one of the consequences of entrapping solar radiation by urban structure. In other words, more sunlit building area casted by urban morphology should lead to more long-wave radiant fluxes within urban environment. With more emitted long-wave and reflected short-wave radiant fluxes by sunlit urban fabric, the resulting mean radiant temperature ($T_{mrt}$) will be higher causing human thermal discomfort in outdoor environment.

Therefore, by understanding the fundamental physics of microclimate (Nunez, et al., 1977), and using simple regression analysis, the objective of this feasibility study is to identify and evaluate the empirical relation between sunlit area of neighbouring building facades and outdoor thermal comfort within these buildings, i.e. the inter-radiant fluxes, especially long-wave fluxes from six directions within urban context in daytime.




*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.*

## URBAN MOROPHOLOGY AND VIEW FACTORS

Without the loss of generality, the exchange of radiant fluxes between different surfaces in outdoor urban environment can be depicted by enclosure theory so as to have a general understanding of the relation between sunlit surfaces and consequent long-wave radiant fluxes and hence the $T_{mrt}$ within the enclosure. As illustrated in Figure 1, an enclosure is constructed by including real surfaces of building facade and the imaginary surface of sky dome (Aristide, M , 2000). A schematic diagram of an enclosure of N distinct surfaces is formed and shown in Figure 1b (John R.H, et al, 2010; Michael, 2013).

Consider the k-th surface of area $A_k$ in Figure 1b, the irradiation, $G_k$ that incident on the k-th surface is the sum of internal irradiation leaving from all other surfaces within the enclosure. The $G_k$ is defined by:

$$G_k = \sum_{i=1}^{N} F_{k-i} J_i \quad (1)$$

where $F_{k-i}$ is the view factor defined as the fraction of radiant energy leaving from the k-th surface and reaching the i-th surface, and $J_i$, is the radiosity which is the sum of emitted and reflected radiant energy leaving from the i-th surface. Assuming ideally, at the very first moment, there is no other external radiations like solar radiation incident on any surfaces i.e. all $q_i$ are zero for all i, and thus all radiosities do not change, i.e. $J_i$ and $G_i$ are the same as their initial values, respectively. And for the next moment, if the k-th area $A_k$ is the only sunlit surface, then only $q_k$ will be non-zero due to the solar radiation giving a higher $J_k$. As a result, surface $A_k$ is heated up to a higher surface temperature $T_k$ by these two equations:

$$J_i = q_i + G_i \quad (2)$$

$$J_k = \varepsilon_k \sigma T_k^4 + \rho_k G_k \quad (3)$$

In theory, this suggests that more long-wave radiant fluxes will be emitted by a sunlit surface. And consequently, more long-wave radiant fluxes exists within the enclosure will be recorded if there are more sunlit surfaces. Similarly, if there is a large patch of cooler 'surfaces', like the sky, less long-wave radiant fluxes will be measured. In fact, this is the same principle used for explaining the cooling effect of Sky View Factor (SVF). There are two kinds of view factor casted by the urban morphology that will be mentioned in details as follows:

The Sky view factor (SVF), denoted by $\Psi_{sky}$, 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 $\Psi_{sunlit}$, 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.

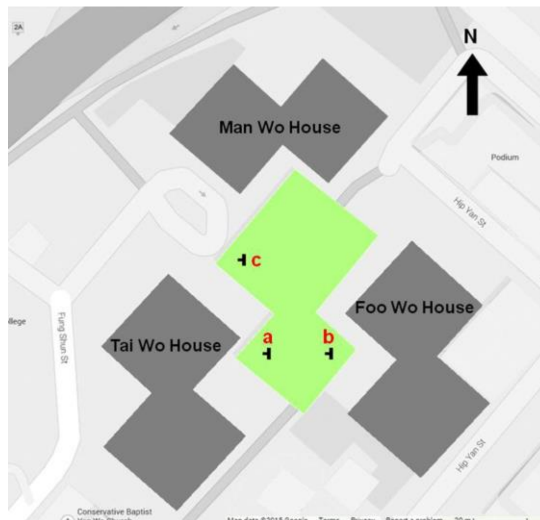



*Figure 2: Three measuring points in Wo Che Estate, Sha Tin in Hong Kong conducted on three sunny and clear sky days: (a) Dec 31, 2014, (b) Jan 2, 2015, and (c) Jan 3, 2015.*

## STUDY METHODOLOGY

The field measurement was performed on a podium of Wo Che Estate (22°23'N, 114°11'E, see Fig. 2), which is a residential area of Sha Tin District in the New Territories, Hong Kong, to eliminate interference from anthropogenic heat produced by traffic. The podium, which is at an elevation of around 5m above ground level, not only provides access to surrounding residential buildings, but also creates open spaces for residents having outdoor activities and exercises. Therefore, outdoor thermal comfort is crucial in such urban environment. The testing points on podium are mainly surrounded by three residential building towers of around 70 meters tall (from ground level), namely, Tai Wo House, Foo Wo House, and Man Wo House.

*Table 1: Description of the measurement locations*

| | Site Description | Time | | SVF |
|---|---|---|---|---|
| | | Start | End | |
| a: | Adjacent to sitting areas | 07:00 | 17:00 | 0.327 |
| b: | Adjacent to sitting areas | 07:00 | 17:00 | 0.319 |
| c: | Adjacent to sitting areas and pedestrian path | 08:00 | 18:00 | 0.349 |

*Table 2: Site Photos and fish-eye photos for each location*

SVF = 0.327

*Point a) Measuring location a on Dec 31, 2014*
*(Tai Wo House is at the back)*

SVF = 0.319

*Point b)* Measuring location b on Jan 02, 2015
(Foo Wo House is at the back)

SVF = 0.349

*Point c)* Measuring location c on Jan 03, 2015
(Man Wo House is at the right)

Three measurement spots were selected for this feasibility study as shown in Figure 2. Measurement points a-c are the outdoor spaces adjacent to the sitting areas and pedestrian path that most frequently used by the residents. The experiment was conducted on three sunny and clear sky days: 31th Dec 2014, 2nd and 3rd Jan 2015 at locations a-c, respectively. Measurements were recorded at 10-second intervals from 07:00 to 17:00 for the first two days, and from 08:00 to 18:00 for the third day (see Table 1).

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.

Fish-eye photographs were taken with Nikon CoolPix digital camera and fish-eye lens at the CNR4 station at a height of 1.5m above podium level for each hour: 09:30, 10:30, 11:30 etc. The values of SLVF was obtained with RayMan software and correlated to radiant fluxes and mean radiant temperature ($T_{mrt}$), respectively. The daytime SLVF values for point a-c are recorded. The algorithm of calculating sunlit view factor is shown in analogy of that of sky view factor is shown in Table 3.

*Table 3: Algorithm of Sky View Factor and Sunlit View Factor Calculation: first by taking fish-eye photos, and being processed with RayMan software.*

| Fish-eye Photo | View Factor | |
|---|---|---|
| | Sky | Sunlit |

| | SVF = 0.349 | SLVF = 0.075 |
|---|---|---|

## MEAN RADIANT TEMPERATURE

The mean radiant temperature, $T_{mrt}$ or MRT, which is a weighted sum of all short and long wave radiant fluxes (including direct, reflected and diffuse components), to which the human body is exposed, is one of the most important meteorological parameters governing human energy balance and the thermal comfort of a man. $T_{mrt}$ is defined as the 'uniform temperature of an imaginary enclosure in which the radiant heat transfer in the actual non-uniform enclosure' (ASHARE, 2013).

Mean radiant temperature is determined by *integral radiation measurements*. This is the most accurate method to obtain outdoor $T_{mrt}$ (Sofia et al., 2007). In order to determine $T_{mrt}$, the mean radiant flux density $S_{str}$ of the human body has to be calculated by multiplying the six individual measurements of the short-wave and long-wave radiant fluxes with the corresponding weights, namely the view factors $F_i$ (i = 1-6) between a person and the surrounding surfaces according to Equation (4) (VDI, 1994):

$$S_{str} = \alpha_k \sum_{i=1}^{6} F_i K_i + \varepsilon_p \sum_{i=1}^{6} F_i L_i \text{ , } i = [1,6] \qquad (4)$$

$K_i$ = the short-wave radiant fluxes
$L_i$ = the long-wave radiant fluxes
$F_i$ = the view factors between a person and surrounding surfaces
$\alpha_k$ = the absorption coefficient for short-wave fluxes (standard value 0.7)
$\varepsilon_p$ = the emissivity of human body. According to Krichhoff's laws $\varepsilon_p$ is equal to the absorption coefficient for long-wave radiation (standard value 0.97)

The angular factor (or view factor), $F_i$, is affected by the position and orientation of a person (Fanger, 1972). To simplify, for a (rotationally symmetric) standing or walking person $F_i$ is set to 0.22 for radiant fluxes from the four cardinal directions (North, East, South, and West) and 0.06 for radiant fluxes from sky and the ground, respectively. For a sphere, $F_i$ is set to be one-sixth (i.e. 0.167) for all six directions. In this study, by setting the values of $F_i$ for a rotationally symmetric standing or walking person, the mean radiant flux density $S_{str}$ is obtained and thus the $T_{mrt}$ (ºC) is calculated from the Stefan-Boltzmann law:

$$T_{mrt} = (S_{str}/\varepsilon_p \sigma)^{0.25} - 273.15 \qquad (5)$$

$\sigma$ = the Stefan-Boltzmann constant (5.67 x $10^{-8}$ $Wm^{-2}K^{-4}$)

## WEIGHTED SUM OF RADIANT FLUXES

In order to identify and evaluate the relationship between radiant fluxes and view factor, the six individual measurements of long-wave radiant fluxes were added to a sum, W. Sum L, with corresponding weight taking into account of both angular factor and emissivity of human body according to equation (6). Similarly, the equation of W. Sum K is given by equation (7).

$$W.SumL = \varepsilon_p \sum_{i=1}^{6} F_i L_i \qquad (6)$$

$$W.SumK = \alpha_k \sum_{i=1}^{6} F_i K_i \qquad (7)$$

## RESULTS AND DISCUSSION

The objective of this study is to identify and evaluate the correlation between view factor of sunlit areas and radiant fluxes, as well as that between Sunlit View Factor (SLVF) and Mean Radiant Temperature (MRT). Simple linear regression was performed on radiant fluxes and MRT, respectively, as a function of SLVF. By using the measured data in three sunny and clear days of measurement, with twenty-eight points, all the trends are upward and highly significant (P < 0.001) as shown in Figure 3 and Table 4. The summary of the regression equations is given in Table 5. These indicate the positive impact of sunlit area on downward long- ($L_{abc,\ downward}$), downward short-wave radiant fluxes ($K_{abc,\ downward}$), the weighted sum of long- ($W.SumL_{abc}$) and short-wave ($W.SumK_{abc}$) from six directions, and MRT, respectively. Taking the effect of SLVF on MRT as an example, the linear relationship was found as:

$$T_{mrt} = 239.030 \text{ SLVF} + 7.055, \quad \boldsymbol{R^2} \text{ of } 0.4767 \qquad (8)$$

The coefficient of SLVF is positive and of the value 239.030 indicating that if SLVF is increased by 0.1, then MRT will go up by around 23.9K. This significant influence of SLVF on MRT is seemingly through its positive impact on both weighted sum of long-wave and short-wave radiant fluxes. At the measurement points with larger SLVF, both W.SumL and W.SumK generally increases. So do the downward long- and short-wave radiant fluxes. As illustrated in Table 4, though the correlation $R^2$ between SLVF and downward short-wave radiant fluxes is 0.3657, it seems that there are two large clusters of data: one is for higher measured short-wave radiation value of around 400 – 800 $W/m^2$; another is for lower value of less than 50 $W/m^2$. This shows more future work is needed to investigate in detail the effect of SLVF on downward or weighted sum of short-wave fluxes in the daytime urban environment while eliminating the intervention of direct sunlight on net radiometers.

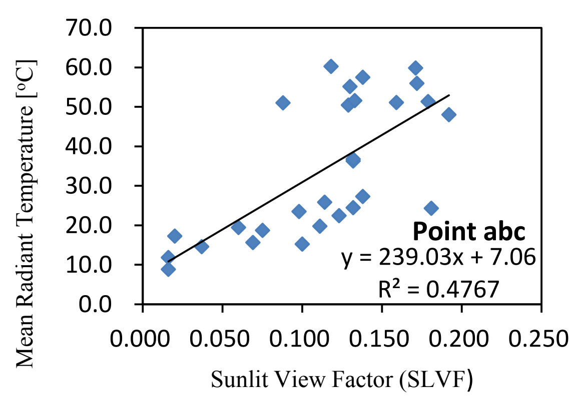
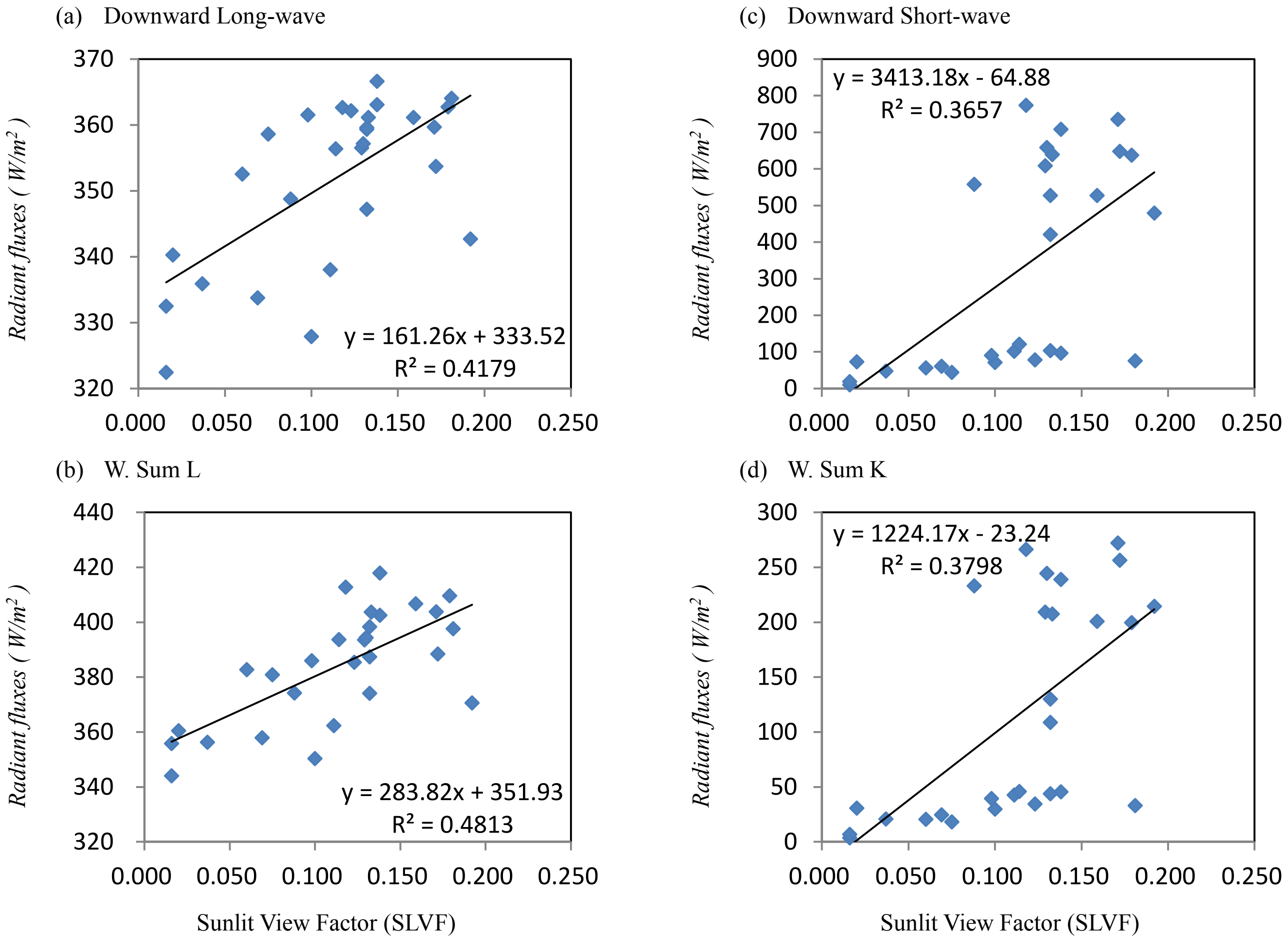



*Figure 3: Scatter plot for Mean Radiant Temperature against Sunlit View Factor using 5-min mean values for the three measurement points a, b, and c.*

*Table 4: Scatter plots for 3D radiant fluxes using 5-min mean values for the three measurement points a, b, and c.*




## CONCLUSION

In theory, the importance of SLVF and SVF should be the same in determining the radiative energy exchange in urban thermal environment, and the outdoor thermal comfort, but the former one is associated with heating effect by radiation, while the latter one is with the cooling effect. Therefore, this study attempts to identify and evaluate empirical relation between radiant fluxes from six directions within urban context and the corresponding sunlit area of adjacent building facades in daytime. The results showed a strong positive association between sunlit view factor and outdoor thermal environment. In other words, the larger sunlit building area in a given urban environment, the more long- and short-wave radiant fluxes measured. Thus, the mean radiant temperature within the open space increases with larger sunlit building area that surrounding the open space. Thus, the desired location of open space should be carefully planned within the building clusters at design stage, or the feature of building envelope should be designed in a way to avoid capturing of sunlight to that open space.

*Table 5: Summary of regression equations of radiant fluxes and MRT regressed on SLVF in the form of Y = aX + b.*

| Y | a | b | $R^2$ | $\alpha$ | SLVF Range |
|---|---|---|---|---|---|
| $L_{abc,\ downward}$ | 161.26 | + 333.52 | 0.4179 | 0.001 | [0.016, 0.192] |
| $K_{abc,\ downward}$ | 3413.18 | - 64.88 | 0.3657 | 0.001 | [0.016, 0.192] |
| W.Sum$L_{abc}$ | 283.82 | + 351.93 | 0.4813 | 0.001 | [0.016, 0.192] |
| W.Sum$K_{abc}$ | 1224.17 | - 23.24 | 0.3798 | 0.001 | [0.016, 0.192] |
| $T_{mrt}$ | 239.03 | + 7.06 | 0.4767 | 0.001 | [0.016, 0.192] |

## IMPLICATIONS FOR URBAN PLANNING

Though this study is a feasibility one, its finding is rather 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 region, might be suggested as follows:

- Shading should be provided to open spaces by suitable disposition of building envelopes to reduce the prolonged exposure of direct solar radiation in hot and/or humid seasons, particularly in the afternoon session;

- Wide gaps should be adequately provided between buildings to maximize the sky view for cardinal cooling effect of open spaces in-between;

- To reduce capturing of reflected solar radiation from sunlit area, shorter buildings should be arranged on the northern side of the open spaces when there is already a tall building at the southern side of the open space

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