Impact of retro-reflective glass façades on the surface temperature of street pavements in business areas of Singapore and Tokyo

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Abstract. This study evaluates variations in the surface temperature of street pavements caused by retro-reflective glass when applied on highly-glazed façades of high-rise buildings located in Singapore and Tokyo. To accomplish this, simulations are conducted on one experimental site situated in business areas of Singapore and another in the city centre of Tokyo. Incoming solar radiations on street pavements and heat transfers affecting their surface temperature are among the physical phenomena being simulated. As a result of the data analysis, it appears that the use of accordion retro-reflective glass on highly-glazed façades could noticeably reduce the surface temperature of street pavements in business areas of both Singapore and Tokyo, compared with other types of glass. A more significant decrease in the surface temperature can be expected in the experimental site of Tokyo, particularly near the summer solstice. On the other hand, the design optimisation of accordion retro-reflective glass seems to be more effortlessly achieved in Singapore. These outcomes represent an encouraging step towards the reduction of building energy use, as well as the mitigation of the Urban Heat Island effect, from the use of retro-reflective glass façades in business areas of different cities experiencing various climates.

1. Introduction

Over the last century, an important growth in urban areas has been observed in most countries. The Organisation of the United Nations [1] reports that more than 65% of the world population will be living in urban areas by 2050. This elevated concentration of inhabitants in restricted areas is the source of various environmental issues. One of them is known as the Urban Heat Island (UHI) effect.

The UHI effect is characterised by noticeable temperature differences between an urban area and its sub-urban or rural surroundings. In Singapore, the magnitude of the UHI effect can reach 4 Kelvin especially at night-time within business areas [2]. The magnitude of 4 Kelvin in this case refers to the difference in air temperature between the coolest and the hottest spot in the island. Other studies conducted in Seoul, Tokyo, or Beijing [3], for instance, evaluate the magnitude of the UHI effect from the land surface temperature. Based on remotely sensed data, these studies also show considerable Heat Islands occurring at noon during summer seasons. Alike Singapore, business areas appear to be the most affected locations by the UHI effect.
Apart from the various consequences of the UHI effect on outdoor thermal comfort and air quality, this phenomenon also severely affects the building energy use in many places of the world. In the tropics and arid climates, where high temperatures are experienced all over the year, the UHI effect provokes major increases in the use of air-conditioning. While trying to keep indoor conditions within a satisfactory level thermal comfort, most air-conditioning systems release a substantial amount of heat in the outdoor environment of buildings, which further enhance the UHI effect. In temperate climates, like the one observed in Tokyo, the interaction between the UHI effect and the cooling energy demand is highly considered during summer seasons.

Various strategies have been developed to mitigate the UHI effect, as well as minimising the building energy use, in different climatic regions. In the tropics, numerous studies have been analysing the use of greenery on the building envelope or street pavements as a countermeasure of the UHI effect [4, 5, 6]. However, this mitigation strategy often requires an important amount of water to be supplied for irrigation of plants. Because of this, cool materials and cool painting have essentially been considered in dryer climates [7, 8, 9].

Both the use of greenery and cool materials have some limitations when applied to buildings of business areas. In most modern cities, business areas consist of high-rise buildings with highly-glazed façades. Under these conditions, several studies [10, 11] demonstrate that the use of rooftop gardens or cool roofs has a minimal effect on outdoor air temperature at the pedestrian level. In addition, greenery and cool materials can be applied on walls primarily, which makes their use on highly-glazed façades relatively challenging.

As observed by Ichinose et al. [12], a significant portion of incoming solar radiations on highly-glazed façades can be reflected towards the sky by imprinting prisms or triangular shapes on glass surfaces. Referred as retro-reflective glass surfaces, this countermeasure can potentially produce a direct effect on the UHI effect by reducing reflected solar radiation from building façades to the outdoor environment, and an indirect effect by lowering the solar heat gains into indoor spaces through windows. So far, little is known about the direct effect of retro-reflective glass façades on the UHI effect.

From observations made by Ichinose et al. [12], this study intends to provide a better understanding on the direct effect of retro-reflective glass façades on the UHI effect. In other words, it is aimed to determine whether the use of retro-reflective glass façades can substantially minimise the surface temperature of surrounding street pavements of a highly-glazed and high-rise building. The scope of this study is restricted to business areas of Singapore and Tokyo, where numerous highly-glazed and high-rise buildings can be observed. To solve the research problem, the objectives of this study comprises: 1) the evaluation of incoming solar radiations on street pavements based on a 3-D representation of the urban micro-environment of a building; 2) the simulation of reflected solar radiations from various types of glass façades including retro-reflective ones; and 3) the definition of a model for heat transfers through street pavements to calculate their surface temperature in response to the use of different glass façades at the urban microscale.

2. Methodology

To evaluate how significantly the surface temperature of street pavements is affected by the use of retro-reflective glass façades, the methodology consists of an experiment conducted on two sites based on data collected from simulations. An experiment here refers to a research design as defined by Tan [13], where each experimental site (or sampling unit) comprises one reference building which is surrounded by various building blocks and street pavements. One site is selected in the Central Business District of Singapore, and another in the city centre of Tokyo (Japan).

Treatments of the experiment are represented by various types of glass to be applied on façades of the reference building, or alternatively, on the façade of one of the surrounding building blocks. This includes clear glass (SHGC = 0.88), low-E glass (SHGC = 0.44), retro-reflective glass (SHGC = 0.58). Two different designs of retro-reflective glass are considered as in Ichinose et al. [12]: prismatic and accordion retro-reflective glass. Both types of retro-reflective glass are assumed to have a constant diffusive reflection of 5% when sunlight hits the glass surface with any angle of incidence. However,
variations of the retro-reflectivity, as well as the specular reflectivity, with respect to the angle of incidence of sunlight is taken into account and illustrated in Figure 1.

Figure 1. Variation of retro-reflectivity with respect to the angle of incidence of sunlight for prismatic (solid) and accordion (dotted and dashed) designs according to Ichinose et al. [12].

2.1. Experimental sites
The Octagon, which is situated in 105 Cecil Street of the Central Business District, is an excellent example of the type of building that can be observed in business areas of Singapore. This building is about 80 meters tall, and is composed of 26 storeys. The height of the surrounding buildings varies between 55 meters and 85 meters. Although the envelope of the surrounding buildings has an important portion of glazing, their respective façade which is exposed to the Octagon seems to have a relatively low window-to-wall ratio. While the Octagon has a glazing ratio around 80%, surrounding building façades have a glass surface which is between 1/3 and 2/3 the surface covered by walls. Besides this, street pavements exposed to the North, South, West, and East façades of the Octagon consist of 3, 2, 4, and 2 lanes, respectively, which is relatively narrow in comparison with the height of buildings. Figure 2 illustrates the Octagon, as well as its surroundings.

Figure 2. Octagon building of the 105 Cecil Street in Singapore, with its height and this of the surrounding buildings (picture is taken from Google Earth).

The Marunouchi Eiraku is selected as a representative instance of high-rise buildings located in business areas in Tokyo. This experimental site comprises taller buildings than these observed around the Octagon building of Singapore. Furthermore, the use of glass for building façades seems to be more
intense on and around the Marunouchi Eiraku than the Octagon. Larger street pavements can also be
noticed, varying from 15 meters to 40 meters. The Marunouchi Eiraku and its surrounding buildings are
shown in Figure 3.

Figure 3. Marunouchi Eiraku building of the 1-Chrome-4-1 Marunouchi in Tokyo, with its height and this of the
surrounding buildings (picture is taken from Google Earth).

2.2. Calculation of incoming solar radiations on street pavements
Incoming solar radiations on street pavements \( K_{s↓} \) (in W/m\(^2\)) is calculated as linear composition of direct
normal irradiance \( K_{DNI↓} \) (in W/m\(^2\)), diffuse horizontal irradiance \( K_{DHI↓} \) (in W/m\(^2\)), specular reflections
from the building façades \( K_{f→s,spec}↑ \) (in W/m\(^2\)), and diffuse reflections from the building façades
\( K_{f→s,diff}↑ \), that is

\[
K_{s↓} = r_s \cdot \cos(\theta_{s↓}) \cdot K_{DNI↓} + F_{sky} \cdot K_{DHI↓} + \cos(\theta_{s↑}) \cdot K_{f→s,spec}↑ + K_{f→s,diff}↑ \quad (1)
\]

where \( r_s \) is the portion of the shaded area of the street pavement (0-1), \( \theta_{s↓} \) and \( \theta_{s↑} \) the angle of incidence
of direct normal irradiance and reflections from building façades on the street pavement (in degree),
and \( F_{sky} \) the sky view factor of the street pavement (0-1).

A technique relying on computer vision is used to evaluate the portion of the shaded area \( r_s \) of street
pavements at the urban microscale. More precisely, various cells of size \( L_c \times L_c = L_c^2 \) (in m\(^2\)) within a
horizontal grid are individually defined as shaded or not. The horizontal grid actually represents the
surface of street pavements at the urban microscale, whose resolution can be expressed as \( 1/L_c \) (in
pixels/m). Although asymmetric urban street canyons are considered for the approximation of the
portion of the shaded area \( r_s \), as well as for the calculation of other parameters of Equation (1), some
simplifications are yet assumed on the horizontal plan of the urban microscale. As shown in Figure 4, a
reference building with dimensions \( L_{ref} \times W_{ref} \times H_{ref} \) (in m) is presumed to be surrounded by nine
building blocks of height \( H_{N-W}, H_N, H_{N-E}, H_W, H_E, H_{S-W}, H_S, H_{S-E} \) (in m) in good alignment.
From this consideration, the morphology of the urban microclimate is determined by a few other
parameters which are: 1) the width of surrounding street pavements \( w_N, w_S, w_W, \) and \( w_E \) (in m), 2) the
length of West and East building blocks \( L_W \) and \( L_E \) (in m), and 3) the width of North and South building
blocks \( W_N \) and \( W_S \) (in m). From the outcome of simulations of the shading effect in the urban
microclimate, the portion \( r_s \) within a region \( R \), corresponding to the enclosure of a given street
pavement, is calculated as
\[
    r_s = \frac{|\{i_{x,y} \in R | i_{x,y} \text{ is considered to be shaded}\}|}{|\{i_{x,y} \in R\}|}
\]

where \(i_{x,y}\) is a cell of size \(L_c^2\).

A similar technique is used to evaluate the sky view factor \(F_{\text{sky}}\) of each street pavement in the urban microclimate. The difference with the calculation of the shading effect is that each cell corresponds to a parcel of the dome surrounding the centre of a given street pavement. Consequently, the resolution \(1/L_c\) of each cell in the computation of the sky view factor is expressed in pixels per degree instead of pixels per meter. Within a dome \(D\) of resolution \(1/L_c\), the sky view factor is calculated as

\[
    F_{\text{sky}} = \frac{|\{i_{x,y} \in D | i_{x,y} \text{ is considered to be open to the sky}\}|}{|\{i_{x,y} \in D\}|} \quad (3)
\]

where \(i_{x,y}\) is a parcel of size \(L_c^2\) (in degree\(^2\)) on the dome \(D\).

For the calculation of reflected solar radiations \(K_{f \rightarrow s, \text{spec}}\) and \(K_{f \rightarrow s, \text{diff}}\), building façades are also gridded in cells of size \(L_c^2\) (in m\(^2\)). Each cell is first categorised as either wall or glass. Then, whether a cell \(i_{x,y}\) corresponds to a parcel of wall or window, the absorptivity \(\alpha_{x,y}\) (0-1), the transmissivity \(\tau_{x,y}\) (0-1), and the total reflectivity \(\rho_{x,y}\) (0-1) is defined based on the material properties. The total reflectivity \(\rho_{x,y}\) is further decomposed into the specular \(\rho_{x,y}^{\text{spec}}\), diffuse \(\rho_{x,y}^{\text{diff}}\), and the retro- \(\rho_{x,y}^{\text{retro}}\) reflectivity, which varies with respect to the angle of incidence of sunlight on the building façade \(\theta_f\) (in degree), that is

\[
    \rho_{x,y} = \rho_{x,y}^{\text{spec}}(\theta_f) + \rho_{x,y}^{\text{diff}}(\theta_f) + \rho_{x,y}^{\text{retro}}(\theta_f) \quad (4)
\]

where \(\rho_{x,y}\) is assumed to be independent of \(\theta_f\). As for Rossi et al. [14], only first order specular reflections are being considered within the computation of incoming solar radiations. This means \(K_{f \rightarrow s, \text{spec}}\) represents the immediate specular reflections from a building façade \(f\) to the street pavement \(s\). In addition, it is important to highlight that the computational effort related to diffuse reflections \(K_{f \rightarrow s, \text{diff}}\) from a building façade \(f\) to the street pavement \(s\) is particularly intense. The reason is that the
calculation $K_{f\rightarrow s, \	ext{diff}}^1$ requires the evaluation of the view factors between each cell of the façade $f$ and each parcel of the street pavement $s$.

### 2.3. Estimation of the surface temperature of street pavements

As illustrated in Figure 5, a model of heat transfers through a composite slab was developed to assess the surface temperature of street pavements. The outdoor temperature $T_{\text{out}}$ (in °C) and the convective heat transfer coefficient $h_{\text{out}}$ (in W/m²-K) can be evaluated either from measurements or from CFD simulations. Only measurements are however being used to determine the soil temperature $T_{\text{soil}}$ (in °C) and its conductivity $k_{\text{soil}}$ (in W/m-K). The calculation of net longwave radiations $L_s^*$ (in W/m²) relies on estimate of radiative heat exchanges between the surface of street pavements and its environment, including the building façades and sky. The thermal capacitances of $C_{so}$ and $C_{si}$ (in J/K) of the outer and inner layer of pavement, respectively, is assessed from material properties. Finally, and most importantly, conductive heat gains $q_{ko}$ and $q_{ki}$ of the outer and inner surface are calculated based on the lumped thermal assumption, that is

$$
q_{ko} = U \cdot (T_{si} - T_{so}) \quad \text{and} \quad q_{ki} = U \cdot (T_{so} - T_{si})
$$

The overall conductive heat transfer coefficient $U = (\sum d_i/k_i)^{-1}$ (in W/m²-K) is obtained from the thickness $d_i$ (in m) and the conductivity $k_i$ (in W/m-K) of each layer $i$. For time discretisation of heat transfer equations, the Euler explicit method is employed as numerical scheme.

![Figure 5. Model of heat transfers through a composite slab used for the calculation of the outer surface temperature of street pavements ($T_{so}$) from estimates of absorbed solar radiations ($K_{s}^{*} = \alpha_s K_{s}^{\downarrow}$).](image)

### 2.4. Parameters of simulations and baseline configurations

Based on information reported on Google Earth, the dimensions of the Octagon (Singapore) and the Marunouchi Eiraku, as well as their respective surrounding building blocks and street pavements, were approximated as shown in Figure 6. Even though the urban micro-environment of the Marunouchi Eiraku comprises taller buildings on average, most surrounding street canyons of the Octagon have a higher height-to-width ratio, which are around 8 and 10 in the South and East street pavements, respectively. Nonetheless, the largest street canyon around the Octagon has a similar height-to-width ratio as this of the Marunouchi Eiraku.
Figure 6. Morphology of the urban micro-environment of experimental sites of Singapore and Tokyo, where distances are in meters.

The setup for simulations and baselines of experimental sites in Singapore and Tokyo is described in Table 1. To simulate the effect of solar reflections on street pavements within a reasonable computational time, the resolution $1/L_c$ is 2 pixels per meter for the urban micro-environment of the Octagon, and 1 pixel per meter for this of the Marunouchi Eiraku. In both simulations of the experimental sites for Singapore and Tokyo, the time step of calculation of heat transfers is 20 times lower than this of the computation of incident solar radiations to guarantee the stability of the numerical scheme for time discretisation of heat transfer equations. The window-to-wall ratio of the reference building and their surroundings are estimated from information collected on Google Earth. Material properties of street pavements are approximated from the characteristics reported by Zheng et al. [15]. Finally, the soil is presumed to have a constant thermal conductance of 0.2 Watts per square meter.

Table 1. Parameters of simulations and configurations of baselines of experimental sites in Singapore and Tokyo.

| Parameters                                         | Value          |
|----------------------------------------------------|----------------|
| **Experimental site of Singapore (Octagon)**       |                |
| Resolution of sky view factors (in pixels/Deg)      | 2              |
| Resolution of shading effect and solar reflections (in pixels/m) | 2              |
| Time step of calculation of incident solar radiations (in s) | 3600           |
| Time step of evaluation of heat transfers on street pavements (in s) | 180            |
| Walls of buildings                                 |                |
| Absorptivity (0-1)                                 | 0.7            |
| Diffuse reflectivity (0-1)                          | 0.3            |
| Emissivity (0-1)                                   | 0.9            |
| Windows of buildings                               |                |
| Window-to-wall ratio of the North façade of the reference building (-) | 4              |
| Window-to-wall ratio of the South façade of the reference building (-) | 4              |
| Window-to-wall ratio of the West façade of the reference building (-) | 4              |
| Window-to-wall ratio of the East façade of the reference building (-) | 4              |
| Window-to-wall ratio of the exposed façade of the North building block (-) | 0.33           |
| Window-to-wall ratio of the exposed façade of the South building block (-) | 0.67           |
| Window-to-wall ratio of the exposed façade of the West building block (-) | 1.5            |
| Window-to-wall ratio of the exposed façade of the East building block (-) | 0.43           |
| Street pavements                                   |                |
| Upper surface layer                                | Asphalt        |
| Thickness (in cm)                                  | 5              |
| Conductivity (in W/m-K)                            | 0.73           |
| Density (kg/m$^3$)                                 | 2200           |
| Specific heat capacity (J/kg-K)                    | 940            |
| Absorptivity (0-1)                                 | 0.9            |
| Emissivity (0-1)                                   | 0.93           |
| Layer                        | Material                  | Thickness (in cm) | Conductivity (in W/m-K) | Density (kg/m³) | Specific heat capacity (J/kg-K) | Absorptivity (0-1) | Emissivity (0-1) | Base course layer |
|-----------------------------|---------------------------|-------------------|-------------------------|----------------|-------------------------------|-------------------|----------------|------------------|
| Lower surface layer         | Asphalt                   | 10                | 0.73                    | 2200           | 940                           | 0.9               | 0.93           | Cement + aggregates |
| Base course layer           |                           | 50                | 1.7                     | 2400           | 2400                          | 750               |                |                   |

**Experimental site of Tokyo (Marunouchi)**

- **Resolution of sky view factors (in pixels/Deg)**: 2
- **Resolution of shading effect and solar reflections (in pixels/m)**: 1
- **Time step of calculation of incident solar radiations (in s)**: 3600
- **Time step of evaluation of heat transfers on street pavements (in s)**: 180

**Walls of buildings**
- **Absorptivity (0-1)**: 0.7
- **Diffuse reflectivity (0-1)**: 0.3
- **Emissivity (0-1)**: 0.9

**Windows of buildings**
- **Concrete**
  - Window-to-wall ratio of the North façade of the reference building (-): 50
  - Window-to-wall ratio of the South façade of the reference building (-): 50
  - Window-to-wall ratio of the West façade of the reference building (-): 50
  - Window-to-wall ratio of the East façade of the reference building (-): 50
  - Window-to-wall ratio of the exposed façade of the North building block (-): 50
  - Window-to-wall ratio of the exposed façade of the South building block (-): 19
  - Window-to-wall ratio of the exposed façade of the West building block (-): 1
  - Window-to-wall ratio of the exposed façade of the East building block (-): 4

**Street pavements**
- **Asphalt**
  - Upper surface layer
    - Thickness (in cm): 5
    - Conductivity (in W/m-K): 0.73
    - Density (kg/m³): 2200
    - Specific heat capacity (J/kg-K): 940
    - Absorptivity (0-1): 0.9
    - Emissivity (0-1): 0.93
  - Lower surface layer
    - Thickness (in cm): 10
    - Conductivity (in W/m-K): 0.73
    - Density (kg/m³): 2200
    - Specific heat capacity (J/kg-K): 940
    - Absorptivity (0-1): 0.9
    - Emissivity (0-1): 0.93
  - Base course layer
    - Cement + aggregates
    - Thickness (in cm): 50
    - Conductivity (in W/m-K): 1.7
    - Density (kg/m³): 2400

3. Results

The use of different types of glass façades on the Octagon (Singapore) and the Marunouchi Eiraku (Tokyo) is simulated over four days: one near the spring equinox, one near the summer solstice, one near the fall equinox, and one near the winter solstice. The four days selected for the analysis of the Octagon are not identical to those chosen for the Marunouchi Eiraku, due to the fact that one sunny day in Singapore does not necessarily correspond to one day of intense solar exposure in Tokyo. For a proper analysis of the effect of glass façades on street pavements, it is crucial to select typical days with noticeable direct normal irradiance. These days are chosen from yearly typical meteorological measurements, which can be collected from the EnergyPlus Weather Database.

Figure 7 illustrates the elevation of the Sun near the equinoxes and solstices, which is globally higher in Singapore than in Tokyo, except near the summer solstice. It can also be observed that the duration of daytime strongly varies between the summer solstice and the winter solstice in Tokyo. While the Sun
rises around 5 am and shines around 8 pm near the summer solstice, a reduction of 5 hours of sun is experienced near the winter solstice. In contrast, the duration of daytime in Singapore slightly varies between 11 and 12 hours near the two equinoxes and the two solstices.

Direct normal irradiance over a typical meteorological year in Singapore and Tokyo is illustrated in Figure 8. Near the spring equinox and the summer solstice, Tokyo appears to be exposed to more intense direct normal irradiance than Singapore. This difference seems to diminish near the fall equinox and the winter solstice. In contrast with the city of Tokyo, direct normal irradiance during a sunny day in Singapore do not vary drastically over a typical meteorological year. The peak of direct normal irradiance remains between 600 and 800 Watts per square meter.

3.1. Impact of various glass façades on street pavements of the Octagon (Singapore)
Simulations of incoming solar radiations on street pavements around the Octagon are run near the equinoxes and the solstices, and the results obtained based on the baseline configuration are shown in
Figure 9. Near the equinoxes, two observations can be made. First, the North and the South street pavements seem to be highly exposed to solar radiations all over the day. A lower exposure is predicted on the West and East street pavements. Nonetheless, the magnitude of incoming solar radiations on the two street pavements achieves a noticeable peak value around 1 pm, which corresponds to the moment in time where the Sun attains its highest elevation. This peak value experienced in the West and the East street pavements becomes more significant than incoming solar radiations on the North and the South pavements near the solstices. Because of its lower height-to-width ratio, the West street pavement has a more intense peak of solar exposure than this experienced in the East street pavement.

Table 2 illustrates the impact of low-E glass, prismatic retro-reflective glass, and accordion retro-reflective glass when applied on the North, South, West, and East façades of the Octagon. This outcome first reveals that the most significant diminution in the magnitude of incoming solar radiations on street pavements is globally achieved from the use of accordion retro-reflective glass. For some specific cases, like the one occurring near the spring equinox on the North street pavement and the one near the fall equinox on the South street pavement, the use of retro-reflective glass seems to enhance the magnitude of incoming solar radiations due to the augmentation of diffuse reflections.

Then, it can be noticed that the effect of accordion retro-reflective glass façades on the magnitude of incoming solar radiations varies over time. Near the equinoxes, the lowest attenuation of incoming solar radiations is obtained when accordion retro-reflective glass is applied on the West façade of the Octagon. A reduction in their magnitude can yet be achieved from the use of accordion retro-reflective glass on the East façade. Nonetheless, this decrease is not as considerable as the one reached on the West façade.
One particularity of retro-reflective glass, and especially the accordion one, is that imprints can be designed such as maximising the retro-reflectivity around a specific angle of incidence. To determine the angle of incidence around which the retro-reflectivity should be maximised over the façades of the Octagon, a theoretical model of retro-reflective glass façades is simulated near the equinoxes and the solstices. This model assumes that the retro-reflectivity $\rho_r$ of glass with respect to a certain angle of incidence $\theta$ is obtained from a Gaussian kernel $N(\theta; \mu_\theta, \sigma_\theta^2)$, that is

$$\rho_r = \rho_{r,max} \cdot N(\theta; \mu_\theta, \sigma_\theta^2) \quad (6)$$

where $\rho_{r,max}$ is the highest retro-reflectivity (0-1) that can be achieved, $\mu_\theta$ the angle of incidence (in degree) around which $\rho_{r,max}$ is obtained, and $\sigma_\theta = 10$ the standard deviation value (in degree) of the Gaussian kernel.

The average variation in the magnitude of incoming solar radiations with respect to accordion retro-reflective glass with various $\mu_\theta$-values, when applied on the West façade of the Octagon, is shown in Figure 10. According to this illustration, a visible reduction in the magnitude of incoming solar radiations on the West street pavements is obtained from the use of accordion retro-reflective glass, as long as the $\mu_\theta$-value is located between 70° and 75°. This means that the design optimisation of accordion retro-reflective glass to be applied on the West façade can certainly be achieved within a small range of $\mu_\theta$-value at 72.5° ± 2.5°.

The model introduced in Section 2.3. is used to estimate the increase or decrease in the surface temperature of street pavements. Boundary conditions of the model are evaluated from EnergyPlus simulations of the Octagon and its surrounding buildings. Except the magnitude of incoming solar radiation and net longwave radiations, most boundary conditions remain unchanged from the use of one type of glass to another. It could be hypothesized that a reduction (or an escalation) in the surface temperature of street pavements would directly cause a diminution (or an augmentation, respectively) in outdoor conditions like outdoor air temperature or the surface temperature of surrounding building façades. Because of this, simulations of heat transfers through a composite slab in this case provide estimates of the lowest decrease or increase in the surface temperature of street pavements that is provoked from the use of different types of glass on façades of the Octagon.

Estimates of the shortest decrease/increase in the surface temperature of the West street pavement is shown in Figure 11, when different glass films are applied to the façade of the Octagon. Near the solstices, the use of one type of glass or another on the façade seems to have little effect on the surface temperature the street pavement. A more visible effect is however noticed near the equinoxes. Compared with the use of clear glass, a decrease between 0.3 Kelvin and 0.6 Kelvin could at least be achieved from
the use of accordion retro-reflective glass around 3pm near the equinoxes. This corresponds to a reduction not less than 2.5 and 4.5 Kelvin in relation with the use of low-E glass. In short, it is shown that the use of accordion retro-reflective glass on the West façade of the Octagon appears to be capable of cooling the outdoor environment in comparison with other types of glass, particularly near the equinoxes.

![Figure 11. Estimates of the lowest decrease/increase in the surface temperature (min \( \Delta T_{so} \)) of the West street pavement around the Octagon when low-E (solid), prismatic retro-reflective (dotted and dashed), and accordion retro-reflective (dotted) glass is being used on the West façade instead of clear glass.](image)

3.2. Impact of various glass façades on street pavements of the Marunouchi Eiraku (Tokyo)

Incoming solar radiations on street pavements around the Marunouchi Eiraku are simulated as for the experimental site of Singapore. From the outcomes obtained based on the baseline configuration, which are illustrated in Figure 12, it appears that the magnitude of incoming solar radiations is considerably more intense on each street pavement near the summer solstice. Among all street pavements, the one exposed to the North façade of the Marunouchi Eiraku seems to be particularly inclined to considerable solar heat gains over a typical sunny day. Near the spring equinox, as well as near the summer solstice, the magnitude of incoming solar radiations on the West and the East street pavements reaches a significant peak around 12 pm.

![Figure 12. Incoming solar radiations on the North (solid), the South (dashed), the West (dashed and dotted), and the East (dotted) street pavements around the Marunouchi Eiraku building (Tokyo).](image)
Alike the data analysis conducted on the Octagon, incoming solar radiations were initially simulated when different types of glass are applied on façades of the Marunouchi Eiraku only. Over the simulations, it could however be observed that the North façade of the Marunouchi Eiraku has a minimal exposure to sun rays near the equinoxes and the solstices. In other words, a change in the material properties of the North façade appeared to have a negligible effect on solar heat gains of the street pavement. For this reason, different types of glass are analysed on the South façade of the Otemachi Tower instead of the North façade of Marunouchi Eiraku.

Results related to the impact of the use of low-E glass, prismatic retro-reflective glass, and accordion retro-reflective glass on incoming solar radiations around the Marunouchi Eiraku are summarised in Table 3. Near the summer solstice in the North, West, and East street canyons, the use of accordion retro-reflective glass appears to be capable of reducing the magnitude of incoming solar radiations in comparison with the baseline configuration, which is not the case of the use of low-E and prismatic retro-reflective glass. On the other hand, incoming solar radiations seem to be negligibly affected by the use of one type of glass or another near the winter solstice.

Table 3. Average variation in the magnitude of incident solar radiations on street pavements (in W/m²) at daytime around the Marunouchi Eiraku and the Otemachi Tower (Tokyo) when low-E glass (A), prismatic retro-reflective glass (B), and accordion retro-reflective glass (C) are applied on building façades instead of clear glass.

| Street pavement | Near spring equinox | Near summer solstice | Near fall equinox | Near winter solstice |
|-----------------|---------------------|----------------------|-------------------|---------------------|
|                 | A       | B       | C       | A       | B       | C       | A       | B       | C       | A       | B       | C       |
| North           | 28.27   | 17.80   | 0.02    | 52.90   | 15.05   | -2.96   | 4.91    | 3.07    | 0.23    | 2.69    | 1.45    | 1.42    |
| South           | 0       | 1.83    | 1.83    | 0       | 3.04    | 3.04    | 0       | 0.46    | 0.46    | 0       | 0.44    | 0.44    |
| West            | 22.44   | 13.16   | -0.42   | 8.72    | 3.77    | 0.43    | 9.97    | 5.59    | -0.14   | 5.49    | 4.73    | 1.49    |
| East            | 9.22    | 4.41    | 0.40    | 25.49   | 11.84   | -0.35   | 2.06    | 1.06    | 0.07    | 3.54    | 2.58    | 0.63    |

Figure 13 shows the average variation of the magnitude of incoming solar radiations on the street pavement between the Marunouchi Eiraku and the Otemachi Tower, when accordion retro-reflective glass with various $\mu_B$-value is being applied on the South façade of the latter building. For a typical sunny day near the summer solstice, a significant reduction in the magnitude of incoming solar radiations appears to be achievable for a $\mu_B$-value of 80°. Unfortunately, non-negligible increase of solar heat gains on the North street pavement could be expected near the spring equinox, if the maximisation of retro-reflectivity is achieved around this angle of incidence. The highest possible decrease in the magnitude of incoming solar radiations near the spring equinox can apparently be reached for a $\mu_B$-value around 60°, which is significantly apart from the optimal $\mu_B$-value of the summer solstice. In other words, it could be relatively difficult to optimise the design of accordion retro-reflective glass in the case of the Marunouchi Eiraku.

Figure 13. Average variation in the magnitude of incident solar radiations on street pavements (in W/m²) at daytime with respect to various optimisations of retro-reflective glass applied on the South façade of the Otemachi Tower near the spring equinox (solid), the summer solstice (dashed), the fall equinox (dotted and dashed), and the winter solstice (dotted).
The impact of the use of various type of glass on the surface temperature of the North street pavement around the Marunouchi Eiraku is illustrated in Figure 14. These results first suggest that a diminution of 0.75 Kelvin in the surface temperature of the pavement could at least be obtained from the use of accordion retro-reflective glass near the summer solstice around 12pm, which corresponds to a reduction of 7.75 Kelvin compared with the use of low-E glass. A visible cooling effect might also be achieved near the spring equinox. This outcome confirm that the use of retro-reflective glass does not seem to affect the surface temperature of pavement near the fall equinox and the winter solstice. In short, the use of retro-reflective glass might have a minimal indirect effect on the heating consumption of the Marunouchi Eiraku, but a considerable indirect impact on the cooling consumption.

Figure 14. Estimates of the lowest decrease/increase in the surface temperature ($\Delta T_{so}$) of the North street pavement around the Marunouchi when low-E (solid), prismatic retro-reflective (dotted and dashed), and accordion retro-reflective (dotted) glass is being used on South façade of the Otemachi Tower instead of clear glass.

4. Discussion
First of all, this study suggests that street pavements situated in business areas are exposed to important incoming solar radiations, both in the tropics and in a temperate climate. For example, the case of the Octagon demonstrates that incoming solar radiations of high magnitude might considerably affect the surface temperature of street pavements which are connected to the West façade of a highly-glazed and high-rise building in Singapore. It is however important to bear in mind that the West street canyon around the Octagon is the one with the lowest height-to-width ratio, that is, the one with the highest solar exposure potentially. Near the summer solstice, the street canyon with the lowest height-to-width ratio around the Marunouchi Eiraku also seems to be inclined to substantial incoming solar radiations on the street surface. These observations could have been distinct, if street canyons with different dimensions than those around the Octagon and the Marunouchi Eiraku were considered for the data analysis.

Nonetheless, the analysis conducted on the Octagon and the Marunouchi Eiraku show that the use of accordion retro-reflective could reduce the surface temperature of street pavements, in most cases where important incoming solar radiations are experienced. The use of accordion retro-reflective glass on the West façade of the Octagon might produce a reduction of more than 0.6 Kelvin in the surface temperature of street pavements with respect to the use of clear glass. In contrast, the use of low-E glass on the same building façade would cause an increase higher than 4 Kelvin in the surface temperature. The use of different types of glass on the South façade of the Otemachi Tower has an even more significant impact on the magnitude of incoming solar radiations in the North street canyon of the Marunouchi Eiraku. In comparison with the use of clear glass, a decrease higher than 0.75 Kelvin and
an increase higher than 7 Kelvin is predicted from the use of accordion retro-reflective and low-E glass, respectively.

At this point, it is important to remember that the urban micro-environment of the Marunouchi Eiraku consists of buildings which are twice as tall as those around the Octagon. These buildings also have a more important glazed surface covering the façades. It certainly explains why a greater decrease in the surface temperature of street pavements results from the use of accordion retro-reflective glass on façades of the Marunouchi Eiraku. This fact might also be observed comparing most real cases of Singapore and Tokyo. However, it does not mean that a similar decrease in the surface temperature of street pavements could theoretically be achieved from the use of accordion retro-reflective glass in business areas of Singapore and Tokyo, if urban micro-environment comprising buildings of equal height and glazing ratio are considered.

While a visible reduction on the surface temperature of street pavements around the Marunouchi Eiraku could be expected from the use of accordion retro-reflective glass near the summer solstice, a small augmentation is in contrast observed near the winter solstice. In other words, the use of this type of retro-reflective glass seems to be able to indirectly minimise the building energy use in a real case of Tokyo, by considerably mitigating the surface UHI effect near the summer solstice and slightly enhancing it near the winter solstice. This discovery represents a true novelty compared with the study conducted by Ichinose et al. [12]. Among the conclusions of this work, it was deduced that the cooling energy demand during summer seasons could not be reduced from the use of retro-reflective glass as much as from the use of low-E glass. In addition, Ichinose et al. [12] assessed that the use of retro-reflective glass on building façades in Tokyo might imply a non-negligible augmentation of the heating consumption over winter seasons. It is essential to remember that these presumptions were derived from simulations of the direct effect of the use of retro-reflective façades on the building energy use. Considering the indirect effect instead, this study demonstrates that a better performance is achieved by accordion retro-reflective glass compared with low-E glass, prismatic retro-reflective glass, and even clear glass near the summer and winter solstices. To conclude whether the use of accordion retro-reflective glass has a great potential in reducing the energy demand in buildings, as well as mitigating the UHI effect, their influence on anthropogenic heat releases should be simulated based on model of interactions between urban climate and building energy use.

Finally, it is observed that the design optimisation of retro-reflective glass would more easily be achieved on the West façade of the Octagon than the South façade of the Otemachi Tower. While the lowest reduction in the magnitude of incoming solar radiations on the street pavement is achieved for a 𝜇𝜃-values between 70° and 75° on the West façade of the Octagon over the four selected days, more than 20° separates the 𝜇𝜃-values where the smallest decrease is achieved by the use of accordion retro-reflective glass on the South façade of the Otemachi Tower near the spring equinox and near the summer solstice. It would be interesting to see if this fact is corroborated on various real cases of Singapore and Tokyo.

5. Conclusion
This study showed how considerably the use of retro-reflective glass for building façades is liable to minimise incoming solar radiations on street pavements, as well as their surface temperature, in urban micro-environment situated in business areas of Singapore and Tokyo. To accomplish the objectives, an experiment was conducted on one location in the Central Business District of Singapore and one site in the city centre of Tokyo. The effect of retro-reflective glass façades on street pavements was assessed from calculations of incoming solar radiations relying on a 3-D representation of the urban micro-environment, and subsequently, from approximations of heat transfers through a composite slab. This method of data collection actually represents a significant improvement in the field of simulations of retro-reflective façades in an urban context. Studies like the ones conducted by Rossi et al. [14] and Yuan et al. [16] calculated the behaviour of retro-reflective façades based on a 2-D representation of a symmetric street canyon without distinguishing the reflective properties of walls and windows. All these studies, including this conducted by Ichinose et al. [12], did not take into consideration the impact of
heat absorbed by pavements on their surface temperature. In other words, this study is among the first in assessing the true potential of retro-reflective façades in directly mitigating the UHI effect.

Results first demonstrate that the surface temperature of street pavements in business areas of Singapore and Tokyo could be reduced by the use of accordion retro-reflective glass on building façades, compared with the use of other types of glass like low-E glass, prismatic retro-reflective glass, or even clear glass. Because urban micro-environments in business areas of Tokyo seem to be composed of higher buildings with a more significant glazing ratio, the use of accordion retro-reflective glass in this context, as well as any other type of glass, appears to have a more significant impact on the surface temperature of street pavements than in real cases of Singapore. Nonetheless, fewer efforts are certainly required to fabricate accordion retro-reflective glass with an optimal design for building façades in Singapore, which could reduce the surface temperature of street pavements as much as possible.

To give more credit to these primary observations on the effect of retro-reflective glass façades on the surface temperature of street pavements, more experimental sites in business areas of both Singapore and Tokyo should first be considered in the data analysis. Currently, a platform called Virtual Singapore is being developed in order to collect information about buildings and their environment over the entire island of Singapore. After that, models of incoming solar radiations and heat transfers used for the assessment of surface temperature of street pavements should be validated based on field measurements. Lastly, interactions between urban microclimate and building energy use should be taken into account during simulations of the surface temperature of street pavements. From the model of interactions between urban microclimate and building energy use, it could also be obtained more realistic estimates of the impact of retro-reflective glass façades on cooling and/or heating consumption than these given by Ichinose et al. [12].

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