

Envelope colour on thermal load in hot humid Hong Kong: Effect of hue, value, and chroma

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Abstract: Cooling energy consumption of a building can be significantly reduced by limiting solar heat gain through envelope, in which depends on the intensity of impinging solar radiation and on the colour of external surface. Albedo, from the thermal point of view, is the prime parameter of interest; however, it does appear to be too conceptual in practice. Architects, when considering choices of envelope colour, the actual decision is between various colours: yellow, blue, or green rather than a single numerical albedo. This study is to investigate the effect and magnitude of colour, in terms of visual qualities hue, value (lightness), and chroma (saturation), on thermal load of buildings. In the experiment, air temperatures inside test cells painted into different colours were measured, the results suggest that colour attribute: chroma has negligible effect on thermal performance of building envelope, while value has significant thermal effect. The effect of hue, as shown in this study, was insignificant, however further study might be needed as to obtain a clearer picture of its effect.

Keywords: colour; thermal load; hot humid climate

1. Introduction

Cooling energy consumption of a building can be significantly reduced by limiting solar heat gain through envelope, in which depends on the intensity of impinging solar radiation and on the absorptivity (colour) of external surface. Jones [1] performed early experiments on influence of colour on heat absorption in Arizona, Tucson. He measured surface temperatures of metal plates painted with different colours, exposed to midday sun. He found that for colours with the same visual brightness and saturation, those with middle wavelength, such as green and yellow absorb more heat, resulting in higher temperatures, about 70°C with ambient temperature of about 38°C. Colours with longer or shorter wavelengths, such as red on one hand, and blue on the other hand, had equally lower temperatures, about 60°C. This finding is surprising as conventionally, from the thermal point of view, colour lightness is the prime attribute of interest. This paper presents the results of several experiments conducted during mid-summer in Hong Kong, which investigate in-depth the influence of colour, in terms of visual attributes: hue, value, and chroma on thermal load of buildings.

1.1 Munsell colour system

In describing colour in this study, the Munsell Colour System is applied. The system was developed

by Albert H. Munsell in the 1900s, the system organizes colour into a three-dimensional arrangement known as hue, value, and chroma. Hue, defined by Munsell as “The quality by which we distinguish one colour from another, as a red from a yellow, a green, a blue, or a purple”, it is the name of the pure state of a colour or chromatic group, determined by wavelengths. In the Munsell system, there are five principal hues: red (R), yellow (Y), green (G), blue (B), and purple (P) arranged in a circular form. All the principal hues are coded with the number 5. The second dimension of colour is Value, which according to Munsell, “The quality by which we distinguish a light colour from a dark one”; it is a description of the degree of lightness. The system contains value levels from 0 to 10, where value 0/ indicates absolute darkness (black) of 0 percent reflectance and value 10/ represents absolute white of 100 percent reflectance. The third dimension is Chroma, which defines the grayness ratio of the colour, in other words, the attribute of saturation that describes the amount of weakness or strength of a hue at a certain value. The grayer –or less colourful –the colour, the closer its position is to the neutral or achromatic gray. The Munsell system identifies colours by the three attributes, with notation in the sequence: hue, value/chroma (H V/C) [2, 3]. Fig. 1 shows the three-dimensional relationship of hue, value, and chroma in Munsell System.

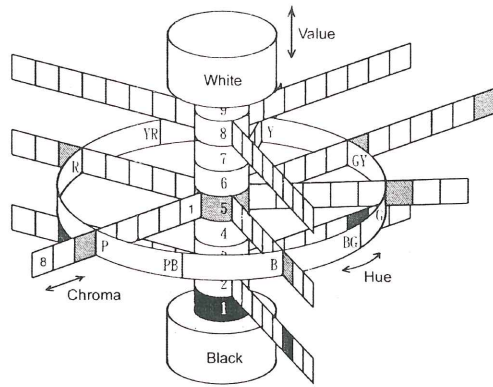


Fig. 1: Munsell colour sphere: Shaded regions (including N9) represent positions of colours involved in this study (Section 2.0).

2. Experimental set-up

The experiment was conducted on the roof of the section of the Architecture Department at The Chinese University of Hong Kong, HKSAR. Identical wooden test cells, each 310 mm long, 225 mm wide, 225 mm high, and 120 mm thick were constructed for the experiment. Iron-Constantan type J thermocouple wires with PVC/PVC insulation made from the same thermocouple wire roll have been used throughout. In this case, we assume if there was any bias in this type of thermocouples, it was the same of all the measurement points. Each test cell has a thermocouple suspended in the internal space that measures air temperature. Ambient dry bulb temperature was recorded with a shielded thermocouple. A device, according to Givoni, dubbed Solarimeter Substitute (SolSub) was installed for measuring indirectly the solar radiation on horizontal surface. The device is a tiny cube 70mm long, 70mm wide and 70mm high. It was made of clear acrylic plastic plate 6mm thick. Inside the cube was a thermocouple attached between a black aluminum plate and a 25 mm thick Styrofoam. It was found in other experiments that the differences between temperatures measured by the device and the concurrently air temperature (DBT) are closely correlated with the intensity of the solar radiation striking the surface. Fig. 2 shows the correlation between the device and solar radiation.

The data acquisition system was placed inside a thermal insulated house. A desktop personal computer, fitted with a Fluke 2635A Hydra Data Buckets, with 21 analog input channels each, was used for data acquisition. Input data from the channels was sampled once every 10 seconds, and data from each data bucket

was automatically stored in a data file, auto rollover everyday.

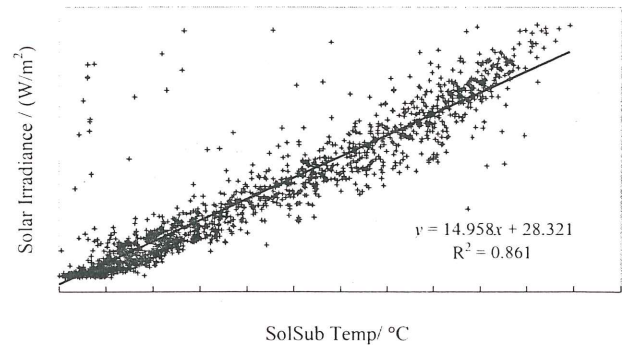


Fig. 2 Correction between SolSub temperature and solar radiation.

2.1 Experiment 1: Effect of hue

Eight test cells were painted into three neutral value scales: white (N9), medium gray (N5), black (N1) and five principal hues: grayish red (5R 5/6), grayish yellow (5Y 5/6), grayish green (5G 5/6), grayish blue (5B 5/6), and grayish purple (5P 5/6). Colours were selected such that hue was the unique variable under test, while the level of value and chroma were kept constant.

2.2 Experiment 2: Effect of value

Nine test cells were painted into three principal hues, with each hue further evolved into three different levels of value: dark red (5R 2/6), grayish red (5R 5/6), light pink (5R 8/6), dark olive green (5GY 2/6), grayish yellow green (5GY 5/6), light yellow green (5GY 8/6), dark blue (5B 2/6), grayish blue (5B 5/6), and light blue (5B 8/6). These colours were selected such that for certain hue, value is the unique variable under test, while the level of chroma was kept constant.

2.3 Experiment 3: Effect of Chroma

This experiment included two test cells painted into grayish yellow green (5GY 5/6) and strong yellow green (5GY 5/12) for studying the effect of chroma, with hue and value kept constant.

Positions of the selected colours in the Munsell Colour Sphere could be found in Fig. 1.

2.4 Experiment 4: Performance of typical envelope colour in Hong Kong

This experiment contains five test cells painted into colours: moderate pink (10R 9/6), pale yellow (2.5Y 8/4), light bluish green (2.5BG 9/4), light greenish blue

(5B 7/4), and white (N9). They are typical envelope colours of high-rise residential buildings in Hong Kong. Measurements were taken for ten days with each experiment.

3. Analysis and conclusions

3.1 Effect of hue

Fig. 3 shows air temperatures inside test cells, over the background of ambient air temperature (DBT) in the first experiment with test cells painted into three neutral values and five principal hues. It could be seen from the figure that with ambient air temperature at around 37°C, maximum air temperature inside white test cells (39.5 °C) is much lower than that of other colours (49°C). Air temperatures inside test cells with five principal hues were almost the same and that they followed closely the air temperature inside test cell of medium gray. The maximum air temperature inside black test cell was about two degrees slightly higher than that of medium gray and the five principal hues. This result suggests that the colour attribute hue has no influence on indoor air temperature.

3.2 Effect of value

Fig. 4 shows air temperatures inside test cells, together with ambient air temperature (DBT) in the second experiment with test cells painted into three principal hues and three level of values. As seen from the figure, with ambient air temperature at around 37°C, maximum air temperature inside test cells with lowest value (2/) was about seven degrees higher than that with highest value (8/). The elevation of temperature from ambient air was about six degrees for test cells of value 8/ while that of thirteen degrees for test cells of value 2/, which is a double of value 8/. The result reveals that colour attribute value has significant effect on indoor air temperature.

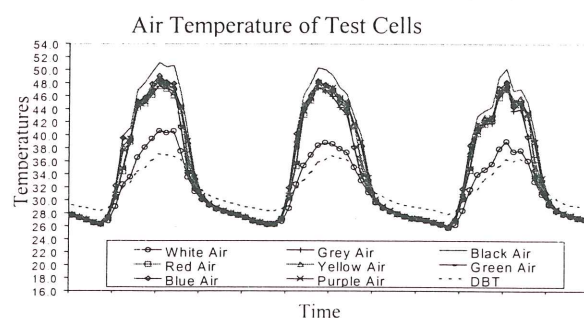


Fig.3: Effect of hue.

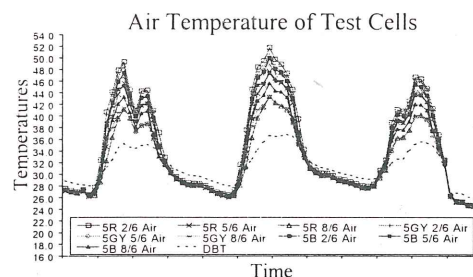


Fig. 4. Effect of value.

3.3 Effect of chroma

Fig. 5 shows air temperatures inside test cells over the background of ambient air temperature in the third experiment with two test cells of higher (stronger) and lower (weaker) level of chroma. It could be seen from the figure that air temperatures inside both test cells were the same, about ten degrees higher than ambient air temperature. The result suggests that the colour attribute chroma has no effect on indoor air temperature.

3.4 Performance of typical envelope colours in Hong Kong

Fig. 6 shows air temperatures inside test cells, together with ambient air temperature in the fourth experiment with test cells painted into five typical envelope colours of high-rise residential buildings in Hong Kong. As can be seen from the figure, with ambient air temperature at around 37°C, maximum air temperature inside test cell of light greenish blue was about 48°C, while that of white test cell was about 39°C –nine degrees lower than the former. Air temperatures inside test cells of moderate pink were similar to that of pale yellow; both of them were about five degrees higher than ambient air. Air temperature inside test cell with light bluish green was in between that of greenish blue and pink, about seven degrees above ambient air. In general, the pattern follows the level of value.

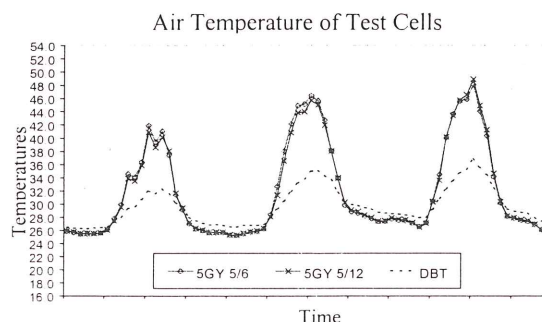


Fig. 5: Effect of chroma.

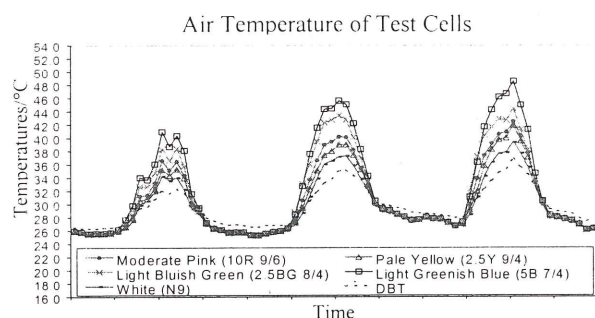


Fig. 6: Performance of typical envelope colours.

3.5 Predicting Air Temperatures of Test Cells

This section describes the method for development of predictive formulas of maximum air temperature inside test cells (T , dependent parameter), on the basis of experimental data. Since solar heat gain through envelope mainly depends on the intensity of impinging solar radiation, it is reasonably assumed that the elevation of temperature measured by Solarimeter Substitute (SolSub) from ambient air (Δ , independent parameter) has significant effect to the dependent parameter. The procedure starts with the presentation of T over the background of Δ . As an example, Fig. 7 shows the air temperature inside test cells of dark red (5R 2/6) and light pink (5R 8/6) in experiment 2, over the background of temperature elevation of SolSub from ambient air.

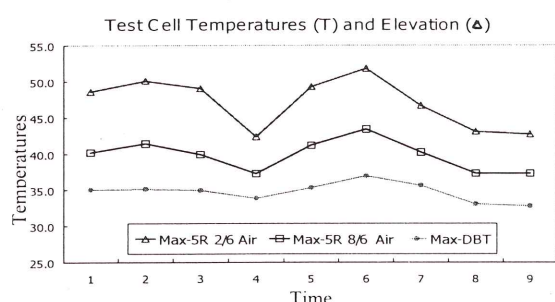


Fig.7 Maximum air temperatures inside test cells and SolSub temperature elevation

It can be seen from the figure that the pattern of maximum air temperature inside test cells follows the pattern of SolSub elevation maxima. Accordingly, the predictive formula for air temperature of test cell was developed on the basis of the corresponding SolSub elevation.

The predictive formula has a general form:

$$T = K_1 G(\Delta) + (1-K_1) \Delta + K_2$$

where T is maximum air temperature inside test cell; $G(\Delta)$ is average, over a given period, of maximum solsub elevation; Δ is the corresponding maximum SolSub elevation; and K_1 and K_2 are Coefficients expressing the effects of colour obtained from experimental data.

Predictive formulas for experiments illustrated previously were developed. Table 1 presents the numerical value of parameters involved in each formula. These values are specific for the particular configuration of experiments which are detailed in the section of experimental setup.

Fig. 8 shows the agreement between measured and computed maximum temperatures inside test cells of dark red and light pink in experiment 2. It can be seen from the figure that good correlation has been obtained between measured and predicted values.

Table 1: Numerical values of K_1 and K_2 .

		N9	N5	N1	5R 5/6	5P 5/6
1	K_1	0.722	0.588	0.531	0.532	0.576
	K_2	-8.3	-1.5	+1.3	-1.5	-0.8
1		5Y 5/6	5B 5/6	5G 5/6		
	K_1	0.565	0.565	0.574		
	K_2	-0.5	-0.6	-0.6		
2		5R 2/6	5R 5/6	5R 8/6	5GY 2/6	5GY 5/6
	K_1	0.631	0.731	0.790	0.652	0.710
	K_2	-0.1	-3.4	-7.4	-1.1	-2
2		5GY 8/6	5B 2/6	5B 5/6	5B 8/6	
	K_1	0.739	0.789	0.735	0.768	
	K_2	-7.2	-0.8	-3.3	-5.2	
3		5GY 5/6	5GY 5/12			
	K_1	0.660	0.630			
	K_2	1	0.6			
4		10R 9/6	2.5Y 9/4	2.5BG 8/4	5B 7/4	N9
	K_1	0.736	0.739	0.727	0.654	0.774
	K_2	-4.1	-5.1	-2	0.6	-6.6

Also, as seen from table 1, numerical values of coefficient K_1 are comparable in all cases (from 0.531 to 0.790) while larger fluctuations are found in K_2 . Therefore, it is assumed that K_2 could be a factor that reflects the effect of colour on air temperatures. The

numerical values of K_2 in experiment 1 with test cells in the five principal hues and gray are similar (from -0.6 to -1.5), while the deviation from white test cell is large (-8.3). The circumstance matches exactly the trend shown in Fig. 3.

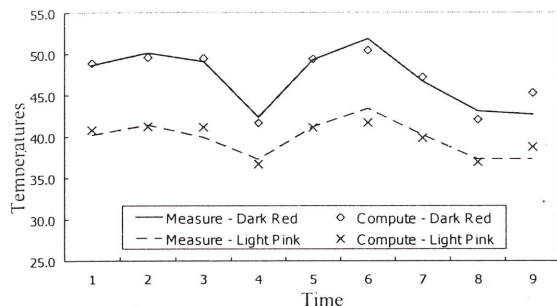


Fig.8 Measured and computed maximum temperature of test cells.

Furthermore, according to the result of experiment 2, the higher level of value the colour, the more negative the coefficient K_2 . Further, there is a linear relationship between the level of value and the coefficient K_2 . Fig. 9 shows the relationship between the level of value and coefficient K_2 for red test cells of experiment 2. As can be seen from the figure, the numerical value of coefficient K_2 could be expressed, in terms of the level of value (V) as below:

$$K_2 = -1.22 V + 2.45$$

Similar procedures were repeated for test cells: blue and yellow-green in experiment 2 and neutral value scale in experiment 1. The results are shown in table 2.

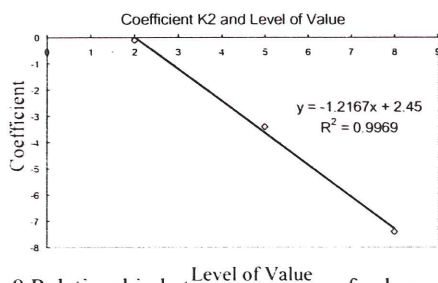


Fig.9 Relationship between the level of value and coefficient K_2

Table 2: Equation of K_2

Colour	Equation of K_2	R^2
Red	$K_2 = -1.22 * V + 2.45$	0.997
Blue	$K_2 = -0.73 * V + 0.57$	0.994
Yellow-Green	$K_2 = -1.02 * V + 1.65$	0.858
Gray	$K_2 = -1.20 * V + 3.17$	0.945

4. Discussion

The results of this study suggest that both colour

attributes: hue and chroma have negligible effect on the thermal performance of building envelope. This means that in the consideration of envelope colours, architects and engineers are free to select between different chromatic groups such as red, yellow, blue and different levels of saturation such as pale, moderate, vivid, without sacrifice the environmental performance. It seems that the finding disagrees with Jones experiment; in fact, the divergence is probably due to different research objectives. Jones conducted the experiment to investigate the thermal effect of colour; consequently, he measured surface temperatures of metal plates painted into different hues but all with the same level of value and chroma (6/6). Since metal has direct and marked response to solar heat gain, the result obtained was distinct and impressive. Whereas this study concerns about the thermal performance of envelope colour, instead of surface temperatures, air temperatures inside wooden test cells (correlated to indoor air temperature) were measured, in this way, the result is better for illustrating the thermal performance of building envelope. In general, Jones finding shows explicitly the response of different colours to solar radiation, while this study shows the effect of envelope colour on indoor air temperatures.

Colour lightness: value, on the other hand, has significant influence on thermal performance of building envelope and that the level of value is linearly related to the coefficient K_2 , a factor which reflects the effect of colour on air temperatures. The result is anticipated because the term value (V) in Munsell System describes the lightness of colour, which is tightly related to reflectance (R):

$$R \approx V * (V - 1) \%$$

Colours such as grayish red (5R 5/6), grayish blue (5B 5/6), and grayish yellow green (5GY 5/6) have been tested in different experiments. For instance, grayish red and grayish blue appeared in both experiment 1 and 2, however one might be aware that the numerical values of K_1 and K_2 (Table 1) in both cases were not consistent, in fact, one of the possible causes for inconsistency would be the duration of measurement. Section 3.5 describes the method of how the predictive formulas were developed, as climatic information: ambient air temperature and solar radiation have significant influences on coefficient K_1

and K_2 , weather changes during the period of experiment could greatly alter the values of K_1 and K_2 . In this study, each experiment was conducted for around ten days; therefore, the predictive formulas obtained in each experiment might not be representative enough for other weather conditions. Longer period of experiment (a year) and more variations in climate (seasons and sky conditions) could result in better predictive formulas.

Table 2 shows equation of K_2 for test cells with different colours in experiment 2. One might be surprised that each colour has its own equation, while experiment 1 suggests that hue should not have affect the results. When substitute level of value (V) equals to one, five, and ten into equations of red and blue, differences of K_2 between two colours were 1, 0.6, and 3 respectively. This reveals that colour (hue) has minor

or no effect on air temperatures at level of value equals to five, which matches the results of experiment 1. However, its effect might occur in colours of high level of value. Experiment with test cells in the five principal hues at high level of value should be further studied, in order to obtain a clearer picture of the influence of colour attributes hue.

References

- 1 B. Givoni. (1998). Climate considerations in building and urban design. New York: John Wiley & Sons, Inc.
- 2 F. Birren. (1969). A grammar of color: a basic treatise on the color system of Albert H. Munsell. New York: Van Nostrand Reinhold Co.
- 3 IES Color Committee. (1992). Color and illumination. New York: Illuminating Engineering Society of North America.