Overall Thermal Transfer Value Control of Building Envelope Design Part 2 – OTTV Parameters

Joseph C. Lam,
Sam C. M. Hui
and Apple L. S. Chan

Building Energy Conservation Unit
Department of Building and Construction
City Polytechnic of Hong Kong

Concept of Overall Thermal Transfer Value (OTTV) and characteristics of the OTTV equation and parameters have been examined. Parameters for the calculation of OTTV for Hong Kong have been derived. These parameters are based on measured weather data from 1980 to 1989 for a 6-month period (May-October). A reference building envelope has been developed. Based on this reference envelope, OTTV limits of 21 W/m² and 14 W/m² have been proposed for wall and roof, respectively. It is proposed that building envelopes meeting these limits are considered reasonably energy-efficient, in terms of limiting heat gain into buildings.

Introduction

Energy and the environment have become issues of concern to the building professions. As a first step to encourage more energy-efficient design of building and building services systems, in October 1990 the Hong Kong Government commissioned a consultancy study [1] on the possibility of legislative control of new design of air-conditioned commercial buildings via the overall thermal transfer value (OTTV) method. There has been concern about the OTTV study, particularly the proposed OTTV limits and the OTTV parameters for OTTV calculation [2-4].

This paper is the second part of a series of articals on issues relating to "OTTV Control of Building Envelope Design" in Hong Kong. Part 1 [5] deals with OTTV limits for air-conditioned buildings. Starting from first principle, this paper examines the OTTV concept and characteristics of OTTV equations and OTTV parameters used in the OTTV calculation. An alternative set of OTTV parameters different from those given in the Draft Handbook [6] have been derived for Hong Kong.

OTTV concept

OTTV is a measure of heat transfer from the outdoor to indoor environment through the external envelope of a building. Three components of heat gain are considered – conduction through opaque surface, conduction through glass and solar radiation through glass.

OTTV is an index of the overall thermal performance of the building envelope. Smaller the OTTV value, smaller the heat gain in summer, and hence less energy will be required for cooling. OTTV can be used to compare the thermal performance of different building schemes. For example design A with an OTTV of 40 W/m² would admit twice as much heat as design B with an OTTV of 20 W/m², and hence would consume more energy for cooling. The usual practice is to have two separate OTTVs – one for external walls (including windows) and the other for the roof (including skylights, if any).

OTTV equation for walls

As walls at different orientations receive different amounts of solar radiation, the general procedure is to calculate first the OTTVs of individual walls with the same orientation and construction, then the OTTV of the whole exterior wall is given by the weighted average of these values. Thus:

$$\mathrm{OTTV}_i = (Q_w + Q_g + Q_s) / A_i$$

$$= \frac{(A_w \times U_w \times TD_{eq}) + (A_f \times U_f \times DT) + (A_f \times SC \times SF)}{A_i} \quad \text{.........................(1)}$$

where

OTTV_i = overall thermal transfer value of walls with same orientation and construction (W/m²)
Q_w = heat conduction through opaque walls (W)
Q_g = heat conduction through glass windows (W)
Q_s = solar radiation through glass windows (W)
A_w = area of opaque wall (m²)
U_w = U-value of opaque wall (W/m²)
TD_{eq} = equivalent temperature difference (K)
A_f = area of fenestration (m²)
U_f = U-value of fenestration (W/m² -K)
DT = temperature difference between exterior and interior design conditions (K)
SC = shading coefficient of fenestration = $SC_1 \times SC_2$ (dimensionless)
SC_1 = shading coefficient of glass (dimensionless)
SC_2 = solar shade factor of external shading devices (coefficients for 8 orientations for Hong Kong have been derived and are shown in Figure 1) (dimensionless)
SF = solar factor for that orientation (W/m²)
A_i = gross area of the walls (m²) = $A_w + A_f$

and, $$\mathrm{OTTV}_{wall} = \frac{\Sigma\,(\mathrm{OTTV}_i \times A_i)}{A_{tw}} \quad \text{...................(2)}$$

where

OTTV_{wall} = OTTV of the whole exterior wall (W/m²)
A_{tw} = Σ(Ai) = total gross exterior wall area (m²)

Parameters TD_{eq}, DT and SF depend on the climatic conditions. TD_{eq} also varies with the types (densities) of construction and colour of the external surface finish.

Alternatively, equation (1) can be expressed in terms of window-to-wall ratio, WWR. Thus:

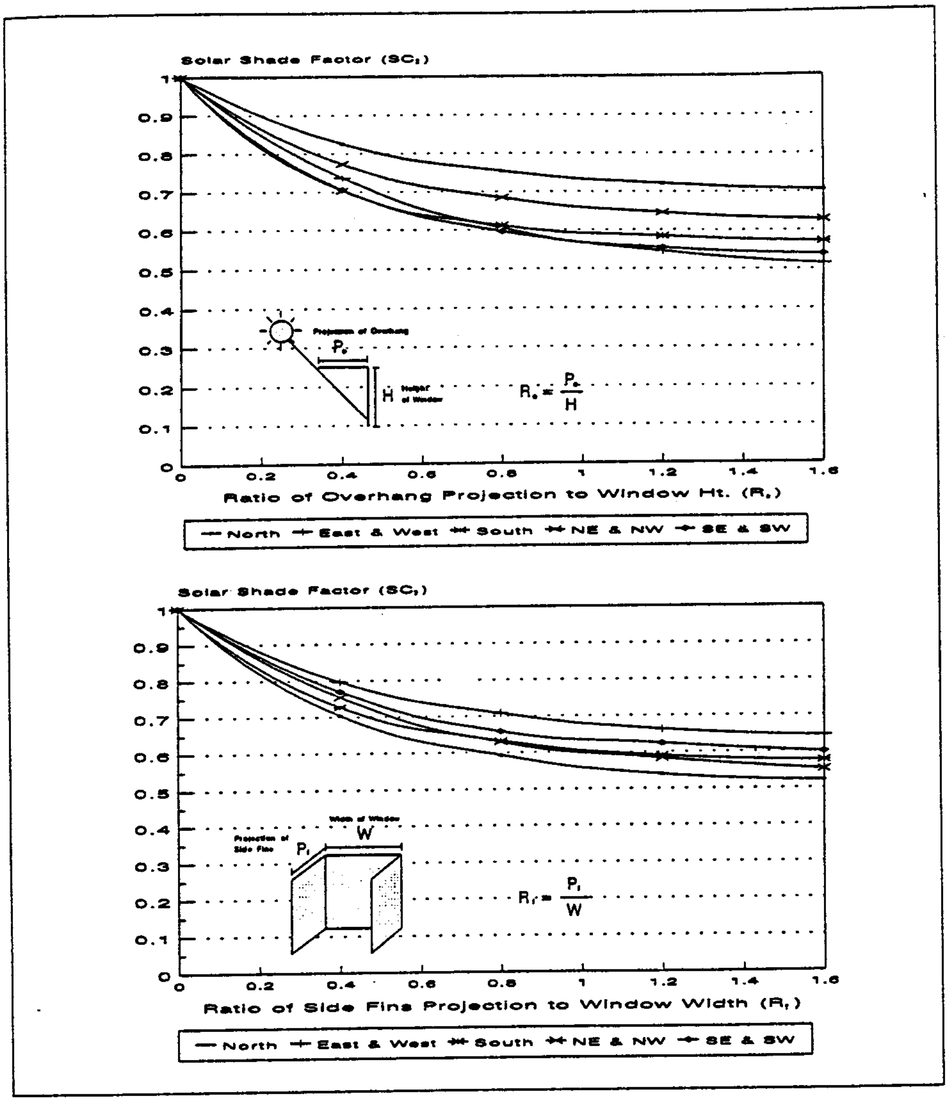

Fig. 1 Solar Shade Factors for Overhang and Fins

$$\text{OTTV}_i = (1-\text{WWR}) \times TD_{eq} \times U_w + \text{WWR} \times DT \times U_f + \text{WWR} \times SC \times SF \quad \text{.......... (3)}$$

where

WWR = the ratio of window area to gross wall area = A_f / A_i

The approach and equations for calculating roof OTTV are similar to those for walls. The calculation for roof is often much simpler because roof usually does not contain large amount of glazing (except skylights over an atrium).

Characteristics of OTTV equation and OTTV parameters

Although OTTV is basically a measure of heat transfer through the external building envelope, its precise characteristics and implications for energy consumption depend very much on how the parameters TD_{eq}, DT and SF have been derived. From equation (1), OTTV is strictly speaking an indication of the average heat gain through the building envelope and the OTTV parameters (TD_{eq}, DT and SF) are obtained from average weather data. One would, however, ask, average over what time period ?

Average period

Figure 2 shows the monthly electricity consumption profiles for residential and commercial buildings in Hong Kong in 1990. It can be seen that consumption begins to rise in May/June and falls off in October/ November, The rise in electricity consumption during those hot summer months is mainly due to air-conditioning. As most of the air-conditioning occurs between May and October, it is, therefore, argued that, as far as heat gain into buildings and the corresponding cooling requirement are concerned, the crucial time period is the 6 hot summer months from May to October.

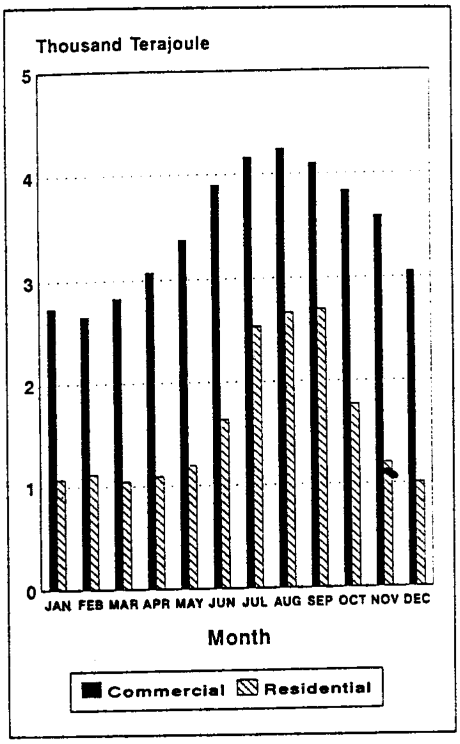

Fig. 2 Electricity Consumption Profiles for the Commercial and Residential Sectors in Hong Kong (1990)

Values for TD_{eq}, DT and SF

Weather data from 1980 to 1989 have been obtained from the Royal Observatory Hong Kong. Hourly records (4416 per year) of air temperature and solar radiation for those 6 hot summer months (i.e., May to October) have been analysed; and the OTTV parameters TD_{eq}, DT and SF have been determined by considering the conduction heat gain through opaque wall, conduction through glass and solar radiation through glass.

Heat conduction through opaque surface and TD_{eq}

$$Q'_w = U_w \times A_w \times (T_{eo} - T_{ai}) \quad \text{.......... (4)}$$

where

Q'_w = heat gain through opaque walls at a particular time (W)

T_{eo} = sol-air temperature (°C) = $T_{ao} + \alpha \times R_{so} \times I_t - \varepsilon \times R_{so} \times I_l$

T_{ao} = outdoor air temperature (°C)

T_{ai} = indoor air temperature (°C)

α = absorptance of the surface for solar radiation (dimensionless)

R_{so} = outside surface resistance (m^2K/W)

I_t = solar irradiance incident on the surface (W/m^2)

ε = emissivity of the surface (dimensionless)

I_l = net long-wave radiation heat loss (W/m^2)

Assuming that U_w is constant, average heat gain, Q_w, over a time period $\Sigma(hr)$ is given by:

$$Q_w = \frac{\Sigma Q'_w \times 1\ hour}{\Sigma(hr)}$$

$$= \frac{U_w \times A_w \times \Sigma[(T_{eo} - T_{ai}) \times 1\ hour]}{\Sigma(hr)} \quad \ldots (5)$$

$$\text{i.e. } Q_w = \frac{U_w \times A_w \times \Sigma[(T_{ao} - T_{ai}) + R_{so} \times (\alpha \times I_t - \varepsilon \times I_l)]}{\Sigma(hr)} \quad \ldots\ldots (6)$$

Assuming constant T_{ai}, R_{so}, α and ε, Equation (6) becomes:

$$Q_w = U_w \times A_w \times \{[avg(T_{ao} - T_{ai}] + R_{so} \times [\alpha \times avg(I_t) - \varepsilon \times avg(I_l)]\} \quad \ldots\ldots (7)$$

where

$avg(T_{ao})$ = $\Sigma(T_{ao}) / \Sigma(hr)$ = mean outdoor air temperature (°C)

$avg(I_t)$ = $\Sigma(I_t) / \Sigma(hr)$ = mean solar irradiance (W/m^2)

$avg(I_l)$ = $\Sigma(I_l) / \Sigma(hr)$ = mean net long-wave radiation loss (W/m^2)

Comparing equations (1) and (7), we have:

$$TD_{eq} = [avg(T_{ao}) - T_{ai}] + R_{so} \times [\alpha \times avg(I_t) - \varepsilon \times avg(I_l)] \quad \ldots\ldots (8)$$

Equation (8) applies to both walls and roof. In ASHRAE Fundamentals Handbook [7], for horizontal surfaces that receive long-wave radiation mainly from the sky, a clear sky condition is assumed and the long-wave correction [$R_{so} \times \varepsilon \times avg(I_l)$] term is estimated to be about 3.9 °C; and for vertical surfaces, long-wave radiation gain from the ground is assumed to balance the long-wave radiation loss to the sky (i.e. I_l=0). In CIBSE Guide [8], long-wave radiation is expressed in terms of cloudiness. In the present study, it is argued that the long-wave correction is not too important for Hong Kong because most buildings are high-rise with some degree of thermal insulation to the roofs. Consequently, heat conduction through the opaque roof is very small compared with the total heat gain. For simplicity, net long-wave radiation is assumed negligible for both vertical and horizontal surfaces. Equation (8) thus becomes:

$$TD_{eq} = [avg(T_{ao}) - T_{ai}] + R_{so} \times \alpha \times avg(I_t) \quad \ldots\ldots (9)$$

Hourly outdoor air temperature and global solar radiation for the 10-year period between 1980 and 1989 have been taken from the weather data tapes supplied by the Royal Observatory Hong Kong. Hourly solar irradiance on horizontal and eight vertical surfaces are computed from the direct and diffuse radiation derived from the measured global solar radiation using the correlations outlined in Kreith and Kreider [9].

Values of TD_{eq} for the eight orientations and the horizontal surface have been computed and are shown in Table 1. These values are based on an indoor air temperature of 25.5 °C, an absorption coefficient of 0.7 and an outside surface air resistance of 0.044 m^2K/W.

Heat conduction through glass windows and DT

$$Q'_g = U_f \times A_f \times (T_{ao} - T_{ai}) \quad \ldots\ldots (10)$$

where

Q'_g = heat gain through glass windows at a particular time (W)

If U_f and T_{ai} are assumed constant, then the average heat gain, Q_g, over a time period $\Sigma(hr)$ is given by:

$$Q_g = \frac{U_f \times A_f \times \Sigma[(T_{ao} - T_{ai}) \times 1\ hour]}{\Sigma(hr)}$$

$$= U_f \times A_f \times [avg(T_{ao}) - T_{ai}] \quad \ldots\ldots (11)$$

From equations (1) and (11), we have:

$$DT = avg(T_{ao}) - T_{ai} \quad \ldots\ldots (12)$$

Equation (12) applies to both windows and skylight. Mean outdoor air temperature for the 6-month hot season between 1980 and 1989 are shown in Table 2. DT has been found to be 1.8 °C.

Solar radiation through glass windows and SF

$$Q'_s = A_f \times SC \times SHGF \quad \ldots\ldots (13)$$

where

Q'_s = solar heat gain through glass windows at a particular orientation at a particular time (W)

SHGF = solar heat gain factor for that orientation (W/m^2)

Assuming constant SC, the average solar heat gain, Q_s, over a time period $\Sigma(hr)$ is given by:

$$Q_s = \frac{A_f \times SC \times \Sigma(SHGF \times 1\ hour]}{\Sigma(hr)} \quad \ldots\ldots (14)$$

Assuming standard summer conditions with angles of incidence less than or equal to 30°:

$$SHGF = 0.87 \times I_t \quad \ldots\ldots (15)$$

For angle of incidence greater than 30°, solar heat transmittance will be less than 87% and Equation (15) will over-estimate the SHGF. This is considered acceptable because, firstly, solar irradiance is relatively small when the angle of incidence is larger than 30°; and secondly, OTTV is an index for comparative study only. Consequently, the degree of accuracy is not crucial.

From Equations (14) and (15), we have:

$$Q_s = 0.87 \times A_f \times SC \times avg(I_t) \quad \ldots\ldots (16)$$

		N	NE	E	SE	S	SW	W	NW	Horizon
*TD_{eq} (°C)	< 100 kg/m²	3.4	4.0	4.5	4.4	4.1	4.4	4.5	4.0	7.1
	100-300 kg/m²	2.8	3.3	3.8	3.7	3.4	3.7	3.8	3.3	5.9
	< 100 kg/m²	2.4	2.8	3.1	3.1	2.8	3.1	3.1	2.8	4.9
SF (W/m²)		47	63	78	75	66	75	78	63	152
DT (°C)		1.8								

* Based on 0.7 absorptivity (α), for other α, new $TD_{eq} = 1.8 + (TD_{eq} - 1.8) \times \alpha / 0.7$

Table 1 **Parameters for OTTV Calculation**

	May	Jun	Jul	Aug	Sep	Oct
1980	24.6	28.4	28.7	28.8	27.3	25.5
1981	25.2	26.9	28.4	29.1	27.2	24.8
1982	25.3	27.2	28.6	28.3	27.5	25.8
1983	26.0	28.6	29.4	29.0	28.3	26.4
1984	24.6	27.9	29.0	28.2	27.3	25.3
1985	26.8	27.2	28.4	28.0	26.8	25.8
1986	25.9	28.0	28.5	29.0	27.8	25.0
1987	25.0	27.5	28.9	28.6	27.3	25.7
1988	26.6	28.6	29.0	27.8	27.6	24.4
1989	25.1	27.5	28.8	28.9	28.1	25.1

Table 2 Monthly Mean Outdoor Air Temperature (in °C) from May to October (1980-1989)

From Equations (1) and (16), we have:

$$SF = 0.87 \times \text{avg}\,(I_t) \quad \text{.......} (17)$$

Equation (17) applies to both window and skylight. Solar factors, SF, for horizontal surface and vertical surfaces have been determined and are shown in Table 1. It can be seen that horizontal surface has the largest SF as expected. For vertical surfaces, SFs for fenestration facing E, SE, W and SW are higher than the other four orientations, mainly due to low solar altitudes of the early morning and late afternoon sun. Similar finding was reported by Shillinglaw and Chen [10]. Some asymmetries in the actual hourly data have been noted. The SF for E and W shown in Table 1 is an average between the calculated SFs for E and W. Similarly, SFs for NE and NW, and SE and SW are averages.

Implications for energy consumption

The total amount of heat gain into a building through the exterior walls, $Q_{t,\,wall}$, during the 6-month hot summer months is given by:

$$Q_{t,\,wall}\ (\text{kWh}) = OTTV_{wall}\ (\text{W/m}^2) \times A_{tw}\ (\text{m}^2) \times 4416\ (\text{hr}) \times 10^{-3} \quad \text{.......} (18)$$

Similarly, total heat gain through the roof, $Q_{t,\,roof}$, during the same time period can be obtained by:

$$Q_{t,\,roof}\ (\text{kWh}) = OTTV_{roof}\ (\text{W/m}^2) \times A_{tr}\ (\text{m}^2) \times 4416\ (\text{hr}) \times 10^{-3} \quad \text{.......} (19)$$

It should be pointed out that the parameters derived for OTTV calculation in the present study has been based on heat gain; and the resulting OTTV is a measure of the average heat gain through a building envelope during the 6-month period from May to October. It is for comparative studies on thermal performance of building envelopes, in terms of their abilities to limit heat gain into buildings. The argument is that smaller the OTTV, smaller the heat gain, and as a result lower cooling load. It, however, cannot give the actual cooling load, nor the energy consumption for cooling. It is indeed the approach adopted by the ASHRAE standard [11] and Singapore OTTV Regulation [12].

For fully air-conditioned buildings with central plants and fixed operating schedules (e.g. hotel and office buildings), attempts have been made to extend the original OTTV concept to cover cooling load. Parameters for OTTV calculation are derived from computer energy simulation and regression analysis of cooling load rather than heat gain [1, 13 and 14]. The resulting OTTV, when multiplied by the external wall/roof area and operating hours of the air-conditioning plant would give an indication of the cooling load due to heat gain through the building envelope during those operating hours. Despite its ability to indicate cooling load, for simplicity and practicability, OTTV based on heat gain is preferred because:

(i) For cooling load OTTV, different sets of TD_{eq}, DT and SF are required for buildings with different operating hours. It is interesting to see that in the Draft Handbook [6], TD_{eq} is different for commercial buildings and hotels, but SF is the same for both.

(ii) TD_{eq}, DT and SF derived from computer simulations and regression analysis are based on a particular computer programme and sometimes (as in the consultancy study [1]) the particular HVAC systems. Different computer programmes and different HVAC systems used in computer simulations could give different values for TD_{eq}, DT and SF.

(iii) OTTV is intended for comparative study on the ability of the building envelope to limit heat gain into a building, particularly during the initial design stage. Smaller the OTTV, smaller the heat gain and hence less energy would be required for cooling. If one wants to estimate the actual energy consumption for cooling, then a more appropriate approach would be to use a computer package (e.g. DOE-2) to carry out hour-by-hour energy calculation, instead the cooling load OTTV method.

OTTV limits for Hong Kong based on new OTTV parameters

In part 1, a reference building envelope has been developed, which is considered reasonably energy-efficient in terms of its ability to limit heat into the building [5]. Building variables for the reference building envelope used in the OTTV calculation are shown in Table 3. Based on these building variables and the OTTV parameters shown in Table 1 (assuming light weight structure), OTTVs for wall and roof have been found to be 20.9W/m^2 and 13.1W/m^2, respectively. Of the 20.9 W/m^2 for wall, heat conduction through opaque wall accounts for 27%, heat conduction through window 23% and solar radiation 50%. Of the 13.1 W/m^2 for roof, heat conduction through opaque roof accounts for 27%, heat conduction through skylight 12% and solar radiation 61%.

It is proposed that OTTV limits of 21 W/m^2 and 14 W/m^2 would be appropriate for air-conditioned buildings in Hong Kong. It should be pointed out point these limits are based on OTTV parameters shown in Table 1. As shown in Part 1 [5], if the OTTV parameters in the consultancy study [1] is used, the OTTV limits would be different.

There could be many different ways to meet the OTTV limits. Together with the provision for trade off between wall and roof OTTVs (as outlined in Part 1 [5]), there should be adequate flexibility, and the proposed OTTV limits should not impose too much constraints on the architectural design and construction practice.

Wall				
Opaque Wall		Window		WWR
U-Value (W/m^2K)	Absorptivity	U-Value (W/m^2K)	Shading Coefficient	
2.5	0.7	6	0.35	44%
Roof				
Opaque Roof		Skylight		SRR
U-Value (W/m^2K)	Absorptivity	U-Value (W/m^2K)	Shading Coefficient	
0.6	0.7	6	0.35	15%

Table 3 **Summary of Variables for Proposed Reference Building Envelope**

Discussion and conclusion

The basic concept of OTTV and OTTV equation have been highlighted. Parameters for the calculation of OTTVs of building envelopes have been presented for the 6-month hot season (May-October). Among the three components of heat gain (conduction through opaque surface, conduction through glass and solar radiation through glass) through a building envelope, solar radiation through glass is by far the largest and most important.

The parameters derived are based on heat gain and the OTTV calculated would give a good indication to the likely heat gain through the building envelope, and could be used to compare the relative energy efficiency of different building designs in terms of their abilities to limit heat gain into buildings.

It is proposed that OTTV limits of 21 W/m^2 for wall and 14 W/m^2 for roof would be appropriate for Hong Kong. Any building that admits 21 W or less of heat per m^2 of its gross external wall area and 14 W or less of heat per m^2 of its gross roof area is considered energy-efficient, in terms of limiting heat gain into the building.

OTTV only deals with building envelopes. Cooling load due to heat gain through envelope is usually 10 - 20% of the total cooling load. Direct energy savings through OTTV control might not be too significant. This would, however, generate interests in energy efficiency and would help create a more energy conscious environment among the building professions.

Acknowledgement

Work presented in this paper is funded by the Croucher Foundation. Hourly weather data for the ten year period (1980 - 1989) for Hong Kong have been supplied by the Royal Observatory Hong Kong.

References

[1] "Final Report on the Feasibility Study on Introduction of Overall Thermal Transfer Value (OTTV) to Air-Conditioned Buildings in Hong Kong", J. Roger Preston & Partners (Asia Pacific), Volume I, August 1991.

[2] "HKIA's Position Paper on Overall Thermal Transfer Value (OTTV) Control in Buildings", The Hong Kong Institute of Architects, June 1992.

[3] "Motion Debate on Energy Policy", HKIA Newsletter, August 1992, pp. 26-27.

[4] Lam, J.C., "OTTV and its Implications for Energy Consumption in Buildings", presented at the HKIE - Gas and Energy Division Technical Meetings, September 1992.

[5] Lam, J.C., Hui, S.C.M. and Chan, A.I.S., "Overall Thermal Transfer Value Control of Building Envelope Design Part 1 - OTTV Limits", Hong Kong Engineer, Vol. 21, No. 8, 27-31 (1992).

[6] "Draft Handbook - Recommendations on Overall Thermal Transfer Value (OTTV) Calculations in Buildings," Building Authority, Hong Kong, 1992.

[7] ASHARE Handbook - Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1989.

[8] CIBSE Design Guide A2, "Weather and Solar Data", Chartered Institution of Building Services Engineers, London, 1979, p. A2-69.

[9] Kreith, F. and Kreider, J.F., "Principles of Solar Engineering", Hemisphere Publishing Corporation, Washington, 1978, p.81.

[10] Shillinglaw, J.A. and Chen, K.T., "Overall Thermal Transfer Value - Skin-Deep Quantifying of Energy Gain and Conservation", Building Journal Hong Kong China, April, 1978, pp. 84-93.

[11] ASHARE Standard 90A-1980, "Energy Conservation in New Building Design", American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlantia, 1980.

[12] "Handbook on Energy Conservation in Buildings and Building Services", The Development & Building Control Division, Ministry of National Development, Singapore, 1979.

[13] Chou, S.K. and Lee, Y.K., "A Simplified Overall Thermal Transfer Value Equation for Building Envelopes", Energy, 13(8), 657-670 (1988).

[14] Turiel, I., Curtis, R. and Levine, M.D., "Analysis of Energy Conservation Standards for Singapore Office Buildings", Energy, 10(1), 95-107 (1985).