# DEVELOPMENT OF ENERGY PERFORMANCE INDICATOR FOR RESIDENTIAL BUILDING ENVELOPE

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**A THESIS SUBMITTED AS A PART OF THE REQUIREMENTS**
**FOR THE DEGREE OF DOCTOR OF PHILOSOPHY**
**IN ENERGY TECHNOLOGY**

**THE JOINT GRADUATE SCHOOL OF ENERGY AND ENVIRONMENT**
**AT KING MONGKUT'S UNIVERSITY OF TECHNOLOGY THONBURI**

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## ABSTRACT

Thailand has been a net energy importing country ever since it began its first Economic and Social Development Plan to embark on a new phase of coordinated economic development in 1964. From 1985 to the present, per capita consumption of oil and natural gas has increased sixfold, while per capita consumption of electricity has increased fivefold. A report of the International Energy Agency (IEA) indicates that the consumption of electricity in commercial and residential buildings constitute 40% of total electricity consumption and the building sector consumes 30% of total energy consumption. Development and implementation of mandatory and voluntary energy performance standards for buildings are necessary and beneficial to society. This study presents the development of Overall Thermal Performance Value (OTTV), or the measure of thermal performance, of building walls enclosing spaces used under bedroom function. This development represents a part of an attempt to develop a building energy performance standard for residential buildings in Thailand. Bedroom function is the major residential function in the use of a residential household. The results of this study indicates that building envelope and interior walls should be constructed by using low thermal mass materials including low solar absorptance of wall surfaces to reduce heat storage from solar radiation during daytime which is major factors of cooling coil load (CCL) of night time function. The exposed wall should be installed with interior insulations and if the wall comprises the window area, the glazing type and shading device should be considered to screen the transmitted solar radiation through window which is much influenced on the performance of building envelopes. The developed OTTV is verified and the results show that the developed OTTV can be used to indicate the performance of building envelopes enclosing residential spaces accurately.

**Keywords:** U-Value, building envelope, cooling load, OTTV

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## NOMENCLATURES

### Acronym and Nomenclature

(Arranged in alphabetical order)

| | |
|---|---|
| $\Delta T$ | temperature different of outdoor and indoor, ˚C |
| Abs | solar absorptance |
| AC space | air-conditioned space |
| ASH | the absorbed solar radiation equivalence to ESR due to heat stored in the interior walls from absorption of transmitted solar radiation during daytime, W/m2 |
| BR | bed room |
| C | convection heat flux, W.m-2 |
| CCL | cooling coil load, the load sensed by the cooling coil, kWh.m-2 |
| $CCL_G$ | cooling coil load due to the heat and solar radiation transfer through glazing and absorbed by internal walls ans masses prior to the bedroom period and heat transfer during the bedroom period, W/m2 |
| $CCL_{OW}$ | cooling coil load due to the opaque part of the wall, W/m2 |
| CTD | the temperature different of outdoor and indoor equivalence to $\Delta T$ due to conduction heat gain through the transparent or glazed section during the bedroom period and that due to heat transferred and stored in the interior walls during daytime, ˚C |
| DSH | density-specific heat product, kJ/(m2·K) |
| ESR | effective solar radiation, W/m2 |
| EXT | insulation on the external surface or externally insulated |
| HF | heat flux, W.m-2 |
| $HF_{ext}$ | Heat flux on exterior wall, W/m2 |
| $HF_{int}$ | Heat flux on interior wall, W/m2 |
| IgloH | horizontal global solar radiation, W/m2 |
| INT | insulation on the internal surface or internally insulated |

## NOMENCLATURES (Cont')

| | |
|---|---|
| Irrad | irradiance or solar radiation, W.m-2 |
| IskyH | horizontal diffuse solar radiation, W/m2 |
| IsunN | beam normal solar radiation, W/m2 |
| LCC | life cycle cost |
| LR | living room |
| LSH | Left hand side |
| LW | long-wave or thermal radiation flux, W.m-2 |
| NI | no insulation or un-insulated |
| OTTV | overall thermal transfer value, W/m2 |
| $OTTV_{br}$ | overall thermal transfer value for bedroom function, W/m2 |
| RH | relative humidity, % |
| $RH_{amb}$ | ambient relative humidity, % |
| RHS | Right hand side |
| SHGC | solar heat gain coefficient |
| STR | studio room |
| T | temperature, oC |
| $T_{amb}$ | ambient temperature, ˚C |
| T-Amb | ambient air temperature |
| T-Back | temperature on the back of a wall section or interior surface, oC |
| $TD_{eq}$ | equivalent temperature different, ˚C |
| $TD_{shw}$ | equivalent temperature different due to conduction heat transfer through wall and that due to stored heat in the wall from solar radiation absorbed during the time prior to the bedroom period, ˚C |
| Temp | temperature, ˚C |
| $T_{ext}$ | Temperature on exterior wall, ˚C |
| T-EXT | temperature on the interior surface of the externally insulated section, oC |
| $T_{int}$ | Temperature on interior wall, ˚C |

## NOMENCLATURES (Cont')

| | |
|---|---|
| T-INT | temperature on the interior surface of the internally insulated section, oC |
| T-NI | temperature on the interior surface of the un-insulated wall section, oC |
| $T_{room}$ | Room temperature, ˚C |
| T-Room | room air temperature, oC |
| $T_{sky}$ | sky temperature, ˚C |
| $U_f$ | value of overall heat transfer coefficient of glazing, W/(m2·K) |
| U-value | overall heat transfer coefficient, W/(m2·K) |
| Uw | overall heat transfer coefficient of wall, W/(m2·K) |
| WWR | window to wall ratio, the ratio of the area of window to the overall wall area |
| αs | solar absorptance |

# CHAPTER 1
# INTRODUCTION

## 1.1 Rationale/Problem Statement

Thai vernacular houses were constructed from low-mass materials. Typically thatch was used for roofs. Walls were constructed from thatch or wood planks or even broad tree leaves. Roof eaves of such houses extend to provide shading of solar radiation. Windows and doors were open to allow good natural air flow for ventilation. Daylight from the sky provides sufficient lighting in the house during daylight hours. Floors were raised up by a full floor height, one consequence of which was the resultant upward flow of cool ventilation air from below. Such vernacular houses located among canals and water ponds were comfortable to live in. No heating or cooling was used. Embedded energy in the materials used for housing was low. Energy consumption to keep the interior environment comfortable was negligible. Artificial lighting was needed during night time only.

At present, electrification has reached over 99% of villages. Bottled liquefied petroleum gas (LPG) has become the most common cooking fuel. Electrical lighting, entertainment, and food preparation each accounts for about 15% of total electricity consumption of 2,680 kWh per annum of an average household. Amenities that include air-conditioning, use of electric fans, hot shower, and refrigeration account for the rest of over 50% of electricity consumption. Overall energy use per household is expected to increase by 2.5 times in 2030, while the number of households will increase by 25% and urbanization will increase from 43% to 64%.

Housing design has diversified greatly, in shape, size, configuration, and composition of materials. Materials for housing are now industrially produced. Low-to-medium income housing can be broadly classified into two category, individual detached house and condominium. In rural areas, low-income earners mostly dwell in detached houses. Most low-income earners also dwell in urban condominium. Most medium-income earners live in urban area and dwell in both types of housing. Medium-income earners will use air-conditioning in one or more rooms (such as the main bedroom and the living room). Low-income earners will use electric fan to achieve comfort. Present housing designs do not pay sufficient attention to ensure that daylight provides sufficient illumination during daytime.

Presently, there is insufficient effort and insufficient body of studies into the issues of low-energy housing for low-income and medium income earners. Even fewer studies have touched on the issue of thermal comfort for low-income housing. Modern housing design does not adequately attempt to utilize daylight fully nor to provide sufficient but energy-efficient electric lighting during night time. Even though a Building Energy Code for mandatory implementation on commercial building exists in Thailand, there is no such code for residential or other types of buildings. It is also perceived that a mandatory code for residential dwellings will not be accepted by the public at this point in time, but some schemes of voluntary energy labeling may be acceptable.

This research first study on criteria and energy performance indicators of building envelope enclosing residential spaces, an experimental and simulation study on comparative thermal performance of walls enclosing spaces that are used to serve three residential functions of bedroom, living room, and studio room are investigated. The study considers different levels of insulation and its placement at the interior and exterior surfaces on walls with and without windows, and for each functional use of a space. Moreover, building envelope performance indicators of opaque walls and glazing are formulated based on the results of the study. Next, it conducts a survey study on housing designs, thermal comfort, efficiency of energy use for lighting and thermal comfort, and the level of use of daylight in existing sample detached houses and condominium for low-to-medium income earners in selected urban areas. Similar studies will be made on sample detached houses in selected rural areas. The results will form baseline information for formulating key performance parameters on energy performance of building envelope, lighting, cooling, and overall energy use of main spaces. The overall results will be used to verify the results of the developed envelope performance indicators in the final part of this report.

Chapter 1 of this report first presents rational and statement of problem of this study. Literature reviews and the past research results are described in this section including the objective and scope of work of this study.

Chapter 2 describes theories related to this study, main attributes influencing energy consumption, and conceptual view on energy consumption in a building space including a hypothesis on the OTTV formulation of residential buildings are presented in this section.

Chapter 3 explains methodology used in this research study. Concept of development of OTTV formulation of residential function of use including method of experimental and simulation study on envelope performance are proposed. Methods of household surveys for housing features and energy use baseline are also presented in this section.

Chapter 4 demonstrates the results of this research study. Firstly, the results of the OTTV function development is presented, the experimental and simulation study results on comparative thermal performance of walls enclosing residential spaces and energy performance indicator of opaque wall and glazing system are reported. Next, the baselines of energy use and housing features obtained from the survey are demonstrated. Finally, results of the baseline from the survey are used to verify the developed OTTV formulation at the final part of this section.

Chapter 5 presents conclusion of this study. The future work of this study are also presented in the final section.

## 1.2 Literature Review

### 1.2.1 Energy performance of wall

In a review of vernacular architecture, Zhai and Previtali [64], assert that for the tropical region, houses were constructed from materials that offer good insulation and of low thermal mass, as evidenced by those of vernacular houses in two locations in Indonesia.  Lindberg et al. [43], describes measured temperatures in walls of 6 test buildings in Tampere University of Technology.  It was observed that for massive walls, heat could be transferred into the room during some periods when exterior temperature was falling.  Thomsen et al. [58], refers to 12 houses in a project of the International Energy Agency (IEA) Task 13 that were designed to mainly demonstrate the effect of insulation and wall mass. The houses were considered low energy houses.  Kalogirou et al. [30], used TRYSYS, a well-known simulation program, to simulate heating and cooling energy consumption for a room module that comprised a massive internal wall behind a glazed window with overhang.  The results show that heating energy as well as cooling energy decrease with increasing wall thickness, although in the latter case less sharply. Zhu et al. [65], report on the study of two identical houses in Las Vegas. The walls of the baseline house were insulated to give an R-value of 2.15 ($m^2.K.W^{-1}$) with standard wall composition, while those of the so-called Zero Energy House (ZEH) comprised thick reinforced concrete with insulation that rendered an R-value of 2.06 ($m^2.K.W^{-1}$). Measurements of wall surfaces temperatures during heating, cooling, and transitional (no heating nor cooling) seasons show that wall temperatures of the massive wall fluctuate much less when ambient air temperature fluctuates diurnally in all seasons. Furthermore, the massive wall was able to store heat sufficiently during winter daytime that no heat flux flowed into interior wall surfaces even during night time. Computer energy simulation using Energy 10 shows much lower heating energy but slightly higher cooling energy consumption from the ZEH. Chiraratananon and Hien [11], experimented with two rooms of 16 $m^2$ each 80 km north of Bangkok and used a computer simulation program called BESim to simulate cooling load in the experimental room when the wall thickness varied. The authors conclude that thick walls may beneficially help delay heat gain for spaces that are used during daytime, the same effect increases cooling load for residential spaces that are used during night time. Bojić and Yik [4], note that cooling is a dominant energy end-use of buildings in Hong Kong. The authors observe that in Hong Kong, like the practice in several countries in hot climate region, insulation is not used on walls. The authors utilized a computer program for building energy simulation called HTB2 to simulate electrical energy and peak electrical demand of housing units in a new high-rise public housing block called 'Harmony'. The authors used investigated 11 alternative constructions. The alternatives include combinations of the use of massive (base case) and light walls, and insulation placed on interior, exterior, and on both wall surfaces. The authors conclude that the simpler case of exterior insulation on massive exterior wall with massive interior wall without insulation offers significant reduction of both annual cooling energy and peak demand. Kossecka and Kosny [34], examined theoretical performance of six configurations of insulation placement in heavy walls. Program DOE 2.1E was used for simulating energy consumption of a ranch house in six climatic regions of USA, where heating or cooling was assumed employed for 24 hours of every day of a whole year They concluded that the wall with exterior insulation performs best, with lowest heating and lowest cooling energy, while the one with interior insulation performs worst. Even though Balocco et al. [3], investigate transient performance of walls with different insulation placement, the authors conclude that the wall with exterior insulation performs best under both cooling and heating climates. Chirarattananon et al. [15], use BESim program to simulate use of insulation on exterior and interior surfaces of exposed walls of a generic building model and report that for spaces that are used during daytime, insulation reduces cooling load and is cost-effective when there is no window on the exposed wall. When there is window, solar radiation gain through window increases cooling load in the interior space predominantly that no conclusion can be drawn on the cost effectiveness of insulation. Tummu et al. [59], conducted physical experiment on the use of insulation on exterior and interior wall surfaces on an experimental room in the Bangkhuntian campus of King Mongkut's University of Technology and report that the results of heat fluxes and temperature agreed well with the results predicted by the BESim program. The authors then use BESim to investigate the use of insulation on exposed walls of residential spaces that are used during evening and night time. The authors conclude that insulation on interior surface improves thermal performance of exposed walls and enhances thermal comfort in the space, but insulation placed at the exterior surface causes the opposite effects.

### 1.2.2 Energy performance of window

A study of the effect of window area on energy saving was undertaken by Krarti et al. [35], using climate conditions in the US. The simulation tool of this study was DOE-2.1E and 4 selected types of glazing were used. These were clear, blue, gray and reflective tint double glazing with different visible transmittances ranging from 0.073 (reflective tint) to 0.781 (clear). It was found that window visible transmittance and window area had significant impact on energy saving from daylighting as increasing glazing transmittance or window area contributed to greater daylight illuminance.

### 1.2.3 Glazed Window and Thermal Comfort

For a period, attaching a layer of spectrally selective transparent film to glazing in the belief that the film would reduce transmission of heat from solar radiation into building interior was popularly practiced in Thailand. Chaiyapinunt et al. [9], reported that the film reduced transmission of solar radiation and improved thermal comfort for the occupants situated near a window. When the film increases reflection of infrared radiation from the glazing, the surface temperature of the glazing with attached film also reduces and helps increase thermal comfort for the nearby occupants.

### 1.2.4 Window with Shading Devices

Discomfort conditions, such as those caused by glare and excessive heat, generally occur when direct sunlight is allowed to enter a space. It is necessary to limit the entry of direct sunlight. Therefore, shading devices are commonly used. Shading devices offer excellent opportunities for energy savings while allowing occupants a visual connection to the outdoor. Shading devices can be designed to blend into the architecture of a building and offer a more comfortable and pleasant visual environment. Also, well-designed shading devices can dramatically reduce building peak heat gain and cooling requirements. Reduction in annual cooling energy consumption of 5% to 15% associated with reduction of solar heat input by 80% to 90% have been reported depending on the area and location of fenestration, Wulfinghoff [62]. The design of a sun shading device may differ and each may evolve to suit local needs and local conditions. In Hong Kong, for instance, the frequently found external shading devices include overhangs and balconies, while side-fins are less common. Projecting windows or so called bay windows has become very popular as it is a way to increase usable space without affecting the land plot ratio, Li et al. [42]. An external shading device may interfere with the view from a window, while some device helps reduce solar glare and heat. External shading is useful in almost all situations where direct sunlight through glazing increases cooling energy requirement substantially. However, an external shading device may have a major effect on the appearance of a building. In a tall building, it must be mounted securely to the building structure to counter wind loads.

#### 1.2.5 Heat Transfer through Roof

Since 1982, Fairey [22], reported that thermal radiation from roofs that absorbed solar radiation was the dominant mode of heat transfer in the attic and was responsible mainly for heat gain across ceiling to the space below. Experiments involving the use of radiant barrier (RB), a thin sheet of thermally reflective surface(s) (single or double sided) at Florida Solar Energy Center found that the temperatures on the surface and in the middle of fiberglass insulation mounted on the ceiling was higher than the temperature of air in the attic space, Levins and Herron [41], indicating that the insulation transferred heat to air and not vice versa. In USA, it was believed earlier that air under roof deck transferred heat to ceiling and that movement of air through the attic would help remove heat from it. Subsequent studies found that use of RB helps reduce cooling energy in summer and heating energy in winter, Levins and Hall [40]. It was also reported that accumulated dust on RB reduced its effectiveness, but it still performed its function. Moser et al. [46], developed a model for calculation of heat transfer in the attic zone that included a computational fluid dynamic model, a thermal radiation exchange model, and conduction heat gain through wall model. The authors applied their model to an atrium model and obtained results for a particular time. Moujaes and Brickman [47], used backward difference for approximating the partial derivative of the heat conduction equation to find solution of energy balance equations they developed for the attic, the zone below the attic, and the whole house. Comparison of numerical results obtained from their model with experimental results show good correspondence. The authors then applied their model to show the results of application of radiant barrier under a number of situations. More recently, Soundhan et al. [52], conducted experiments using four test cells to determine comparative effectiveness of radiant barrier against typical insulation materials used under roofs of different colors and for ventilated and unventilated attic space under roof deck. The authors also developed a model of the mechanisms of heat flow. The authors concluded that thermal radiation heat transfer was dominant during daytime, that the performance of the RB was comparable to that of fiber glass or polystyrene insulation when there was no ventilation and was comparatively superior when there was ventilation. Tang et al. [54], found that vaulted or domed roofs that were traditionally used in the Middle East where the climate was hot and dry were able to thermally radiate well in the night to help reduce temperature in the interior of buildings. Such roofs performed consistently better than flat roofs.

### 1.2.6 Requirements on energy performance

Implementing building energy efficiency standards and codes are effective means to foster energy efficient buildings that lower energy consumption in this sector, Iwaro and Mwasha [27]; [37]. As further noted by Iwaro and Mwasha [27], in almost all countries in Asia and Africa, energy codes and standards for buildings, if exist, apply to non-residential buildings only as not all residential buildings use heating or cooling to control the interior environment.

For countries in hot climate, heat gain though exposed building walls is expected to contribute a significant share of the cooling load of an air-conditioned residential space. It is therefore expected that any energy conservation standards and programs for the residential sector must address energy performance of exposed walls. Chua and Chou [19], note that air-conditioning was increasingly used in residential buildings in Singapore. In order ‘to ensure that building envelope designs are suitable to be operated under air-conditioned environment, the $ETTV_{res}$, and the code requirement on its value for residential buildings was introduced in 2008’. The authors also demonstrate through building energy simulations that cooling loads of two building models vary linearly with $ETTV_{res}$. The

Energy Technology policy Division of the International Energy Agency, IEA Secretariat [26], publishes a document called a ‘Technology Road Map for Energy Efficient Building Envelope’ to assist countries in planning, implementing, and monitoring building envelopes. The document explores existing and emerging technologies for energy efficient (EE) building envelopes and suggests policy directions to transform to EE buildings.

#### 1.2.7 Building energy performance rating

A more energy efficient building uses less energy resources input per productive output, minimizes detrimental environmental impacts and maximizes financial returns. Most countries in Europe and many states in USA require that buildings be assessed by qualified professionals regularly using standard methods and the results must be disclosed, Leipziger [39]. Assessment methods vary with locality and make it difficult to compare results. There is, however, consistency in how to define energy quantification methods and energy types, but little consensus on how to define floor area or what energy loads to be included. The first country in the world to implement mandatory energy rating and disclosure is Denmark in early 1990s, but now the system has spread to all of Europe, USA, China, Brazil, Australia, South Africa, and others. Studies have found that the higher rated houses command higher rental fee and higher valuation for sale, Hyland et al. [25]

## 1.3 Research objectives

The main objective is to develop a building envelop system performance indicator for new residential buildings that comprises

- A study on thermal performance of insulated walls enclosing residential spaces in Thailand,
- a study on energy use and carbon emission of low-income houses in northern Thailand, and
- development of formulation of an OTTV for walls of residential buildings in Thailand.

## 1.4 Scope of work

Scope of this work is set out as follows.

* Only building envelope performance indicators are investigated in this study,
* the indicators are developed for air-conditioned spaces of night time function of use,
* computer simulation namely BESim and TRNSYS are used in building energy simulation, and
* low and medium income house are mainly considered to be used for result verifications.

# CHAPTER 2
# THEORIES

This Chapter describes theories related to this study, main attributes influencing energy consumption, and conceptual view on energy consumption in a building space are presented. Hypothesis on the OTTV formulation of residential buildings are proposed in the final part of this Chapter.

## 2.1 Main attributes influencing energy consumption of air-conditioned space

To design a potentially energy efficient building, the designer must be aware of the attributes of the building and the environment that influence eventual energy consumption of that building.

There are many attributes of a building that influence its energy consumption that include the building itself, technology used with the building systems (envelope system, air-conditioning system, lighting system, and others) exterior environment of the building, and management of the building. This chapter will examine the phenomena in a broad perspective.

The purpose of air-conditioning in buildings in a tropical zone such as those in Thailand is to provide thermal comfort for the occupants that will allow occupants to concentrate and continually perform. However, the mechanism of air-conditioning includes cooling and dehumidifying air while air supplied into a zone receives heat and moisture from equipment, human occupants, and other interior loads that lead to high level of energy consumption. To define appropriate thermal condition that lead to thermal comfort but that does not lead to excessive energy consumption is important and will be described later.

Figure 2.1 illustrates the situation in an air-conditioned zone. The zone occupant requires the of use equipment in the zone for which electrical energy is required. Electrical energy supplied to equipment contributes to heat and to increasing temperature of the environment around the equipment. The heat is transferred to air in the zone and eventually contributes to cooling load in the zone. Some equipment used such as electric water heater produces heat and humidity that contributes sensible and latent heat to the cooling coil. Even though electric lamps have good energy efficiency, even fluorescent lamps are able to convert only 25% of electricity supply into light. Most electrical energy is converted into heat and contributes to cooling load of the air-conditioning system. Even light that is a part of electromagnetic radiation in the visible band and is a form of radiative energy that is absorbed by surfaces in the room will eventually contribute heat to the air-conditioning system. Electrical equipment and lighting system consumes electricity directly and contributes load to the air-conditioning system that indirectly causes additional consumption of electricity. Human occupants contribute both sensible and latent loads to the air-conditioning system by thermally radiates to the surrounding, by convecting heat body heat to air, and by contributing moisture to air from the respiration and perspiration.

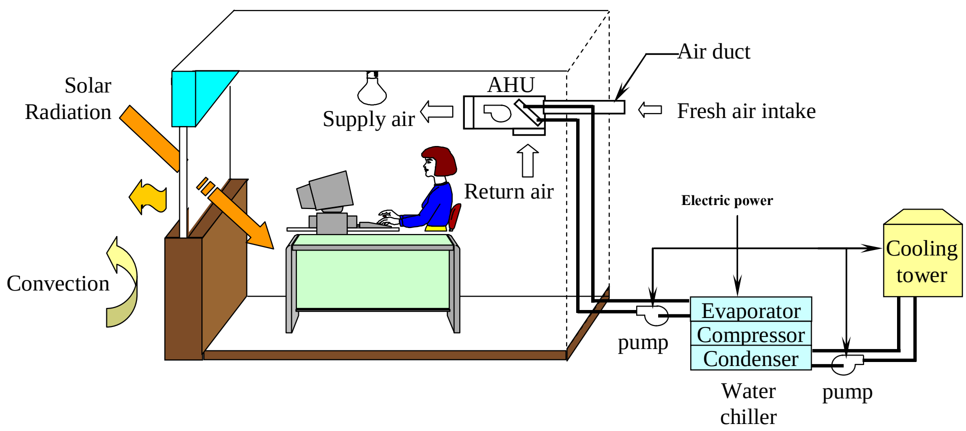



**Figure 2.1** The situation in an air-conditioned space

When examining the exterior environment, it is found that solar radiation is an intensive energy source and the exterior air is warmer and more humid than those of the interior air. Solar radiation transmits through glazing directly into the interior at the level of 250 $Wm^{-2}$ which contributes substantially to heat gain into the air-conditioned space. Shading devices could be used to shade beam radiation, but in most cases diffuse radiation from sky can still penetrate into the interior space. Apart from direct transmission of solar radiation, absorbed solar radiation on the glazing raises the glazing temperature and causes additional heat gain into the interior space through both convection and thermal radiation mechanisms. Transmitted solar radiation is absorbed by surfaces of walls, floors and of objects in the space and increases temperatures of the surfaces. Thermal radiation from surfaces in the space comprises radiation in the long-wave range that cannot transmit through glazing. Thus an air-conditioned space that is enclosed to prevent air leakage and that comprises glazed window becomes a green house where solar radiation can enter but the accompanying energy from solar radiation is trapped.

A part of solar radiation falls on opaque wall surfaces and a part is reflected, with the remaining absorbed by the exterior surface. The absorbed energy causes a rise in the temperature of the exterior surface to drive heat into the interior surface of wall. Eventually, the absorbed energy from solar radiation is convected and thermally radiated into the building interior. This contributes to the thermal environment of the space that in turns contributes to cooling load of the cooling coil of the air-conditioning system. The cumulative effect on the cooling coil over a period of time (such as a year) can be identified as follows

Cumulative load of cooling coil = cumulative load from external sources
+ cumulative load from internal sources

On the other hand, the same relationships can be written for the average load as

Average load of cooling coil = average load from external sources
+ average load from internal sources.

The cooling coil load eventually reflects on electricity consumption by the air-conditioning system. Figure 2.2 illustrates the relationships that external environment drive energy and heat through opaque and transparent wall components that contributes load to the air-conditioning system. Human occupants and other internal sources contribute heat that contributes as internal load to the air-conditioning system.

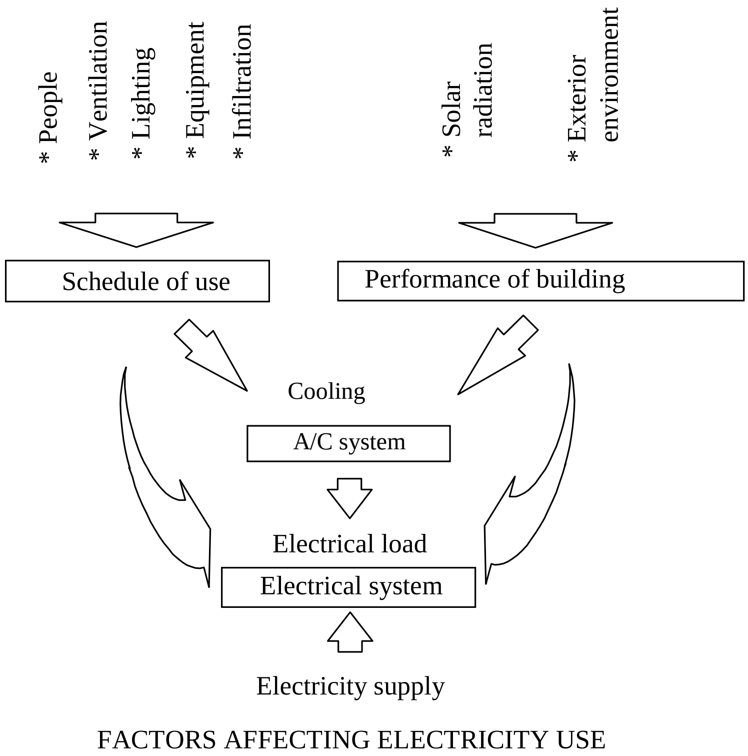



**Figure 2.2** Relationship between the driving forces and eventual electricity consumption

## 2.2 Building shape orientation and solar radiation

The points to be made in the followings apply particularly to air-conditioned buildings or air-conditioned spaces, but most of the content is also applicable to unconditioned spaces.

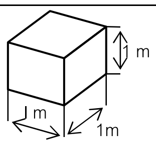
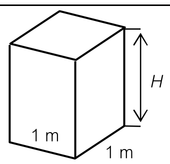
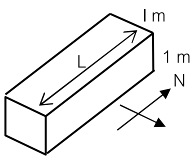
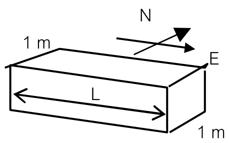
### 2.2.1 Building Shape

**a) Building Shape Orientation and Solar Radiation**

In tropical region, tall buildings receive less solar radiation. Table 2.1 shows rectangular blocks used to represent different building shapes that illustrate the relative values of received solar radiation per unit surface area and per unit volume.

If the cubic shape is taken as the reference, it is found that tall building receives least radiation where the surfaces receives 18% less radiation per unit area. For the long building that is oriented along the East-West direction, the surfaces receives 9% less radiation per unit area, while the long building oriented along North-South receives 13% more radiation per unit area.

**Table 2.1** Annual average solar radiation on rectangular buildings

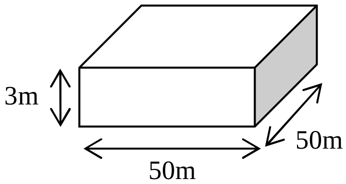
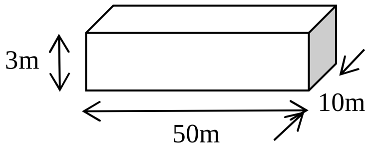
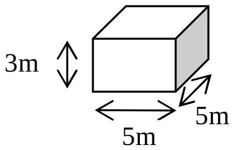
| Building shape | Building type | Varied dimension | Total radiation on all surface | |
|---|---|---|---|---|
| | | | per unit surface area ($W/m^2$) | per unit building volume ($W/m^3$) |
|   | Cubicle | - | 242 | 1211 |
|   | Tall, Square | Height, *H*<br>5m<br>10m | 199<br>193 | 836<br>789 |
|   | Long, along N-S | Length, L<br>5m<br>10m | 273<br>279 | 927<br>981 |
|   | Long, along E-W | Length, L<br>5m<br>10m | 265<br>269 | 900<br>861 |

**b) Effect of Wall to Floor Ratio**

A large building with large floor area per storey and with square shape of large dimensions has relatively low level of external heat gain that results in lower energy consumption per floor area. Buildings with such shape have relatively lower heat gain per floor area resulting in lower level of cooling load. However, daylight through windows cannot penetrate beyond the peripheral space into the interior and the deep space would not be amenable to space heat removal by natural ventilation.

Table 2.2 illustrates the varying ratios of wall area to floor area for buildings of different shapes.

**Table 2.2** Ratio of wall area to floor area for Buildings of different shapes

| **Building Shape** | **Attribute** | **Ratio of Wall Area to Floor Area** |
|---|---|---|
|  | Long and wide | 0.24 |
|  | Long and narrow | 0.72 |
|  | Narrow and short | 2.4 |

### 2.2.2 Solar Radiation

The amount of solar radiation reaching a horizontal surface in Thailand is considered high because Thailand is situated near the Equator. The amount of solar radiation reaching angles. vertical surfaces in different directions differ but not to any significant extent. Surface in the Southern direction receives more radiation than those in other direction since the location of Thailand is above the Equator. For surfaces that have different inclination angles with respect to the horizontal plane, the amount of solar radiation decreases with increasing inclination angle. Figure 2.3 illustrates patterns of values of solar radiation for planes in different orientation and different inclination

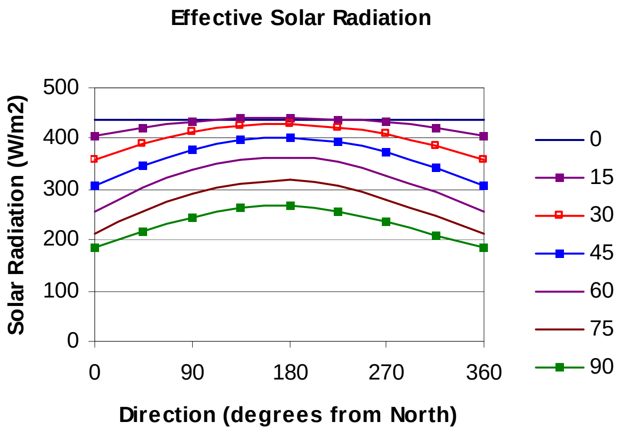



**Figure 2.3** Solar radiation on inclined planes

Each curve represents the amount of solar radiation falling on to a plane of given inclination angle and given direction. The line at the bottom corresponds those for solar radiation on vertical planes of different directions. The top most line corresponds to solar radiation on horizontal plane.

### 2.2.3 Opaque Wall

Opaque walls are commonly constructed from cement plastered brick, cement plastered cement block, plastered light weight cement, casted concrete slabs, and others that offer sufficient strength and may or may not be insulated.

**a) Influence of Color and Thermal mass on Exterior Wall**

The paint on an exterior wall affects the absorption of solar radiation and heat transfer into the interior. Pale color surface absorbs less solar radiation than darker one. Solar absorptance of surfaces varies of 0.3 to 0.8. The coefficient of solar absorption of a wall painted with white color may increase when dust accumulates.

The mass of a wall and its specific have multiplying effect in delaying transmission of heat through the wall. The capacity to delay heat transmission is proportional to the product of wall thickness, density of wall material, and specific heat of wall material. This product is called thermal mass. During the night, a wall will dissipate heat into the atmosphere, thus reducing temperature of the wall. If the wall has appropriate thermal mass, it would be able to delay transmission of heat into the interior during day time. In a space that is air-conditioned and is used only during morning period, a wall with high thermal mass is able to delay transmission of heat into the interior and thus reducing cooling load due to external factor in this period

The value of equivalent temperature difference for building, $TD_{eq}$, that is used to calculate the overall thermal transfer for wall described in Chirarattananon and Taveekun [17] can be used to compare the difference in the level of heat transmission through walls that have different solar absorptance of surfaces and different thermal masses. Figure 2.4 and Figure 2.5 show graphs of the value of $TD_{eq}$ as functions of solar absorptance and of thermal mass respectively for walls of office.

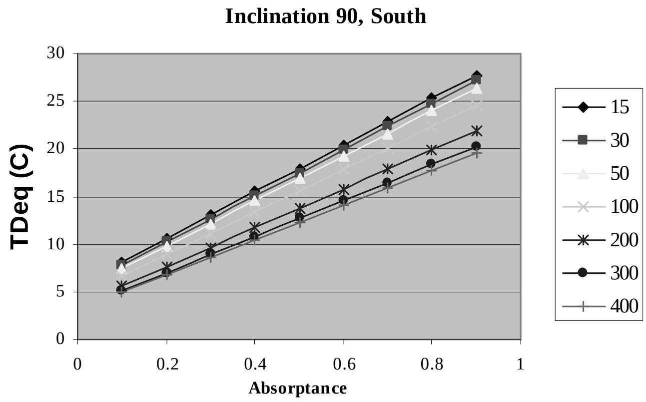



**Figure 2.4** Graphs of the equivalent temperature difference as a function of solar absorptance, office

Each line of graph in Figure 2.4 corresponds to the *equivalent temperature difference* for a wall of office with the indicated thermal mass (from 15 to 400 $kJm^{-2}K^{-1}$). The uppermost line is for the wall with the lowest thermal mass. The graphs are for vertical walls that orient southward. The lines of graphs appear to be straight. *The value of the equivalent temperature difference varies along the line from over 25 for wall solar absorptance of 0.9 to about 8 for wall solar absorptance of 0.1 for the uppermost line.* Such large variation underpins the significance of solar absorptance.

Each line of graphs in Figure 2.5 shows value of the *equivalent temperature difference* for a wall of office with indicated solar absoptance and thermal mass. The graphs are for vertical walls that orient southward. The uppermost line corresponds to the case of solar absorptance of 0.9. The graphs show weaker variation of the equivalent temperature difference as a function of wall mass. For the case of office buildings, *the higher the thermal mass the lower the value of the equivalent temperature difference*.

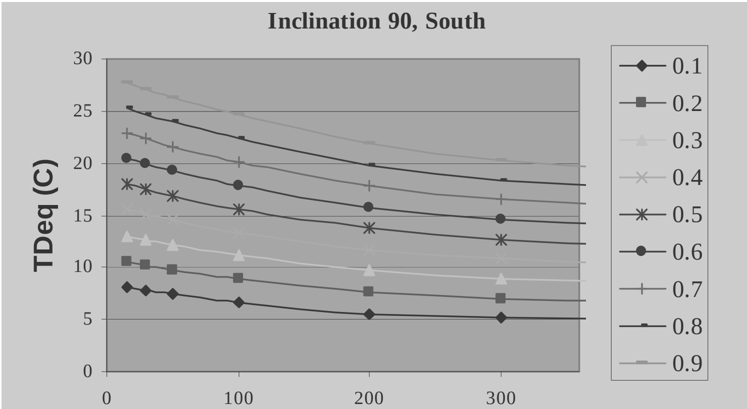



**Figure 2.5** Graphs of the equivalent temperature difference as a function of thermal mass, office

Table 2.3 shows selected values of the equivalent temperature difference for walls of office, department store, and hotel for vertical walls that orient southward. The values of the equivalent temperature difference in each case are shown against the wall thermal mass and solar absorptance. Examining those values for a fixed value of solar absoptance, for example at 0.9, the values decrease as the wall thermal mass increases for the case of office. This means, for office, increasing thermal mass decreases heat gain. But for department store, heat gain becomes maximum at a mid value of thermal mass. For hotel, higher thermal mass leads to larger heat gain.

**b) Heat Transfer Coefficient (U-value)**

The value of heat transfer coefficient or U-value also directly determines the size of heat transfer across an opaque wall in the same way as the equivalent temperature difference. The U-value of a wall is basically a function of the thermal properties of wall material. If a wall comprises more than one layer, thermal resistance of each layer adds to increase the thermal resistance of the composite wall. Walls of cement plastered brick, of cement block, and of concrete slab all have similar U-values in the range of 3-5 $Wm^{-2}K^{-1}$. For light weight concrete, the values are in the range 1-4 $Wm^{-2}K^{-1}$ depending on the type and thickness of the concrete block.

**Table 2.3** Equivalent Temperature difference for a vertical wall facing south.

| **Thermal mass,** | **Solar absorptance** | | | | |
|---|---|---|---|---|---|
| **(*kJ.m*$^{-2}$*.K*)** | 0.3 | 0.5 | 0.7 | 0.9 | |
| **Office** | | | | | |
| 15 | 13.0 | 18.0 | 22.9 | 27.8 | ↓ |
| 30 | 12.7 | 17.5 | 22.3 | 27.1 | |
| 50 | 12.2 | 16.9 | 21.6 | 26.3 | |
| 100 | 11.1 | 15.6 | 20.1 | 24.6 | |
| 200 | 9.7 | 13.7 | 17.8 | 21.9 | |
| 300 | 8.9 | 12.7 | 16.5 | 20.3 | |
| 400 | 8.6 | 12.2 | 15.9 | 19.5 | |
| **Department store** | | | | | |
| 15 | 9.8 | 13.1 | 16.4 | 19.7 | ↑ |
| 30 | 9.9 | 13.3 | 16.6 | 20.0 | |
| 50 | 10.0 | 13.4 | 16.9 | 20.3 | |
| 100 | 10.1 | 13.7 | 17.2 | 20.8 | ↓ |
| 200 | 9.8 | 13.3 | 16.9 | 20.4 | |
| 300 | 9.1 | 12.5 | 15.9 | 19.3 | |
| 400 | 8.5 | 11.8 | 15.0 | 18.3 | |
| **Hotel** | | | | | |
| 0 | 5.6 | 7.7 | 9.7 | 11.8 | ↑ |
| 30 | 5.6 | 7.7 | 9.8 | 11.8 | |
| 50 | 5.7 | 7.7 | 9.8 | 11.9 | |
| 100 | 5.7 | 7.8 | 9.9 | 12.0 | |
| 200 | 5.8 | 8.0 | 10.1 | 12.3 | |
| 300 | 5.9 | 8.1 | 10.3 | 12.5 | |
| 400 | 5.9 | 8.2 | 10.4 | 12.6 | |

The size of heat transfer across an opaque wall is the product of its heat transfer coefficient and its equivalent temperature difference. Therefore, for a wall in any direction, and used for any function, heat transfer across it can be reduced by choosing wall material of low thermal conductivity, or by addition of insulation layer of low thermal conductivity. For buildings in tropical zone, the use of heavy wall with high thermal mass does not always lead to desirable results (of reducing heat gain) but may even produce adverse effects.

**c) Insulation**

Materials used as insulation for walls and roofs should have low thermal conductivity that will render low heat transfer coefficient. Some insulation products comprise a thermally reflective surface on one side. If such product is placed with the reflective side towards the side of the wall of higher temperature without being in physical contact with the adjacent surface, the reflective surface will reduce absorption of thermal radiation and improves the overall performance of the assembly. Insulation used with wall could reduce the overall heat transfer coefficient of the assembly to the level of 0.3 – 1.0 $Wm^{-2}K^{-1}$ depending on the type and thickness of insulation.

Thailand is located in tropical zone where air temperature and solar radiation are high, the use of thermal insulation under roof and on walls of air-conditioned space is highly cost-effective. The configuration where insulation is used and the type of space usage determines how cost-effective the insulation is.

### 2.2.4 Glazing

In the current practice, glazing has found heavy use. Curtained walling, where glazing is used to cover almost the entire wall, has become a popular feature and is used in many buildings. In general, heat transfer through glazing, inclusive of transmission of solar radiation, is much larger than that through opaque wall. In normal situations, heat transfer through glazing is 5 times that for opaque wall. In tropical climate, transmission of solar radiation through glazing into the interior of buildings is generally undesirable, but the ability to transmit daylight offers an opportunity for daylighting.

Flat glass that is use on window is made from sand under a float glass process. A glass with low impurities appears white. Addition of appropriate impurities gives color to a glazing. When iron oxide is added, the glass appears greenish and is able to transmit more visible radiation than infrared radiation, thus rendering such glass suitable for daylighting. Most tinted glass attenuates all parts of solar radiation of different frequency ranges equally.

Special coating has been introduced to improve transmission properties of glass. Three broad categories of coatings are currently available. Coating in the first category enhances absorption of solar radiation on the glass. This is not suitable for hot climate. Coating in the second category reflects solar radiation. Such coating allows low level of transmission of solar radiation. The transmittance of solar radiation is rather uniform across its spectrum. The coating thus also reduces transmission of the visible part of solar radiation. The third type of coating enhances transmission of visible radiation and limits emission of thermal radiation. Glazing with such coating is commonly used in insulating glass. There are 3 derived properties for a glazing, which are U-value, solar heat gain coefficient, and visible transmittance.

**Overall Heat Transfer Coefficient (U-value)**

This coefficient represents heat transfer across the glass per unit area and per degree of temperature difference between the environments on each side of the glass. It accounts for the thermal and physical properties of a glass pane and of the coating on the glass, as well as the thermal environments on both sides of the glass pane. The value for a given glass type and thickness is given based on standard condition of the environment and based on standard calculation procedure. For a single glazing, the value is given at around 5 – 6 $Wm^{-2}K^{-1}$. For an insulating glass with two layers of glass enclosing a gas layer, the value is around 2 – 3 $Wm^{-2}K^{-1}$depending on the thickness of the gap between glass panes and the type of gas. Even for an insulating glass, the overall heat transfer coefficient is comparable to that of a common opaque wall without insulation.

**Solar Heat Gain Coefficient (SHGC)**

This coefficient represents heat transmission across a glass pane due to solar radiation per unit of radiation and per unit area. It accounts for direct transmission of solar radiation and the inward fraction of heat from solar radiation absorbed on the glazing. For clear glass, its value of SHGC is around 0.7, and for tinted and coated glass, its value is around 0.25. This property of glazing is important for countries in tropical zone that receive strong solar radiation.

**Ratio of Visible Transmission to Solar Heat Gain Coefficient ($T_V$/SHGC)**

Coefficient of transmission of visible radiation, $T_V$, represents the ratio of transmitted visible radiation from impinging solar radiation. The ratio represents the relative amount of visible part of solar radiation or the light part in solar radiation that is transmitted to total transmitted heat from solar radiation. In simple terms, this is the light to heat transmission ratio. In utilization of daylight in buildings, a glazing with a value of this ratio greater than one is able to transmit more light than heat from solar radiation. Some green glass and some blue glass types that are coated to reduce thermal emissivity have high values (more than one and approaching two) of this ratio and is suitable to be used in area planned for daylighting.

**a) Glazed Window**

Glazed windows are areas in buildings that are used for viewing the exterior environment from a confined space. In natural ventilated buildings, windows are open to allow air flow. In air-conditioned buildings, glass is used to cover windows to allow viewing of the exterior and to prevent air leakage through windows. Glazed windows have high potential to bring heat into buildings, but also offers potential for daylighting.

Glazed windows should extend from floor to the height of d desks or from 0.7 m, but should not reach the ceiling except when it is a part of daylighting design. Daylight transmitted below the desks does not contribute to useful daylight significantly.

Venetian blinds or similar internal shading devices should be used on glazed windows to allow occupants to adjust the amount of daylight suitable to the space and to limit the thermal effect of solar radiation in the space. The use of venetian blinds enclosed between two glass panes can shade off radiation from the sun but allows some diffuse light from the sky to pass through. This arrangement should be intentionally designed and if it is used with automation could lead to cost-effective daylighting while minimizing the adverse effect of solar heat.

**b) The Use of Shading Devices**

External shading devices can be more effective in shading beam solar radiation from a window than internal shading such as curtain or blinds. Absorbed or reflected solar radiation due to external shading device will manifest as heat gain in the exterior and will not transfer directly into building interior.

Horizontal shading device is effective for shading of beam radiation when the sun is at high altitude angle, so it is suitable to be used on the north and south facades for locations in Thailand since the facades in these two directions do not face the sun during sunrise and sunset times. In taller buildings, the desire to fully shade out radiation of the sun from a window may render a shading device too large to be acceptable. Multiple slat shading devices in Figure 2.6 where the width of each slat can be limited could be considered instead of that in Figure 2 that is normally used. The multiple slat shading device is effective in shading beam radiation from the sun and still allow diffuse light from the sky to enter. The upper surface of the slats could be designed to reflect and increase additional daylight into the interior. The device in Figure 2.7 may not be able to shade out radiation from the sun effectively, but instead obstructs view from the interior and shade out a large part of diffuse light from the sky.

For the East and West facades, movable vertical shading devices could be considered.

Every shading device obstructs view to the sky to an extent, but a properly designed device obstructs view minimally while still being effective in shading radiation from the sun.

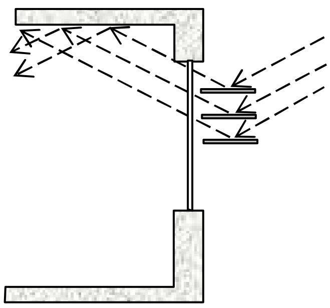


**Figure 2.6** Horizontal shading device comprising multiple slats

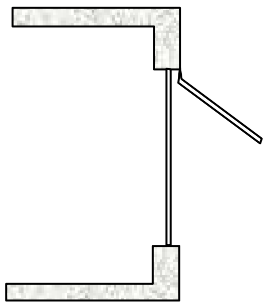


**Figure 2.7** Horizontal shading device commonly used

### 2.2.5 Air Leakage

Air leakage into or out from an air-conditioned space contributes load to an air-conditioning system, the effect is identical to introduction of exterior air for ventilation.

## 2.3 Conceptual view on energy consumption in a building space

The starting point in the development of the energy performance standard for building envelope and the equation for computation of whole building energy consumption is the consideration of the dynamic relationships relating to cooling coil load and heat gain and energy storage components in a zone. The relationship leads to a consideration of linearity in the relationship and the use of effective performance coefficient of air-conditioning system in the calculation of energy consumption in the zone.

### 2.3.1 Dynamic Cooling Requirement and Energy Use in Building

The mechanisms of heat transfer into an air-conditioned zone, and the eventual transfer to the cooling coil could be illustrated by a consideration of the situation in Figure 2.1. The load that the cooling coil receives from air comprises a sensible and a latent component. The air receives such load from heat convection from sources in the zone that include heat from equipment, lighting system, occupants, ventilation air and leakage air.

The air receives latent heat from occupants, ventilation air and leakage air, and other sources.

The mechanism of change of sensible heat of air can be represented by Equation (2.1)

$$Mc_p \frac{dT_i}{dt} = \sum_{j=1}^{j=n_c} \dot{Q}_{sj} + \sum_{j=1}^{n_s} A_j h_j (T_j - T_i) + \sum_{j=1}^{n_z} \dot{m}_j c_p (T_{zj} - T_i) + \dot{m}_f c_p (T_o - T_i) + \dot{Q}_{exs} \qquad (2.1)$$

where $M = \rho V$ is the mass of air in the zone,

$\rho$ is the density of air,

$V$ is the volume of air,

$c_p$ is the specific heat of dry air, 1.006 $\mathrm{kJkg^{-1}}$,

$Mc_p \frac{dT_i}{dt}$ is the rate of increase of sensible heat of air in the zone,

$\sum_{j=1}^{j=n_c} Q_{sj}$ is the total sensible heat loads in the zone,

$\sum_{j=1}^{n_s} A_j h_j (T_j - T_i)$ is the sum of heat convected from surfaces in the zone to air,

| | |
|---|---|
| $\sum_{j=1}^{n_z} \dot{m}_j c_p (T_{zj} - T_i)$ | is the sensible heat of air that leaks into the room from other zones, |
| $\dot{m}_f c_p (T_o - T_i)$ | is the sensible heat of exterior air that leaks into the room and |
| $\dot{Q}_{exs}$ | is the rate of removal of sensible heat of the air-conditioning system. |

For the latent heat, a similar equation can be written, as in Equation (2.2)

$$M \frac{dW_i}{dt} = \sum_{j=1}^{n_L} \frac{\dot{Q}_{Lj}}{h_w} + \sum_{j=1}^{n_s} A_j h_{Lj} \rho_i (W_{sj} - W_i) + \sum_{j=1}^{n_z} \dot{m}_j (W_{zj} - W_i) + \dot{m}_f (W_o - W_i) + \dot{m}_s (W_s - W_i) \quad (2.2)$$

where

| | |
|---|---|
| $W_i$ | is the humidity ratio of air in the room, |
| $\sum_{j=1}^{n_L} \frac{\dot{Q}_{Lj}}{h_w}$ | is the rate of addition of water vapor due to latent loads in the space, |
| $\dot{Q}_{Lj}$ | is the latent load *i* in the space, |
| $h_w$ | is the heat content of water vapor at 25°C, approximated at 2500 $kJkg^{-1}$, |
| $\sum_{j=1}^{n_s} A_j h_{Lj} \rho_i (W_{sj} - W_i)$ | is the term related to rate of vapor transmission through walls, |
| $\sum_{j=1}^{n_z} \dot{m}_j (W_{zj} - W_i)$ | is the rate of vapor addition due to air exchanges between zones |
| $\dot{m}_f (W_o - W_i)$ | is the rate of vapor addition due to air leakage, and |
| $\dot{m}_s (W_s - W_i)$ | is the rate of vapor contribution from the cooling coil. |

The two equations above exhibit essentially linear relationships of coiling coil load and the component loads with embedded weak non-linearity. These two equations merely express the part of heat balance of air. Figure 2.8 illustrates a broader perspective on the overall balance in the system.

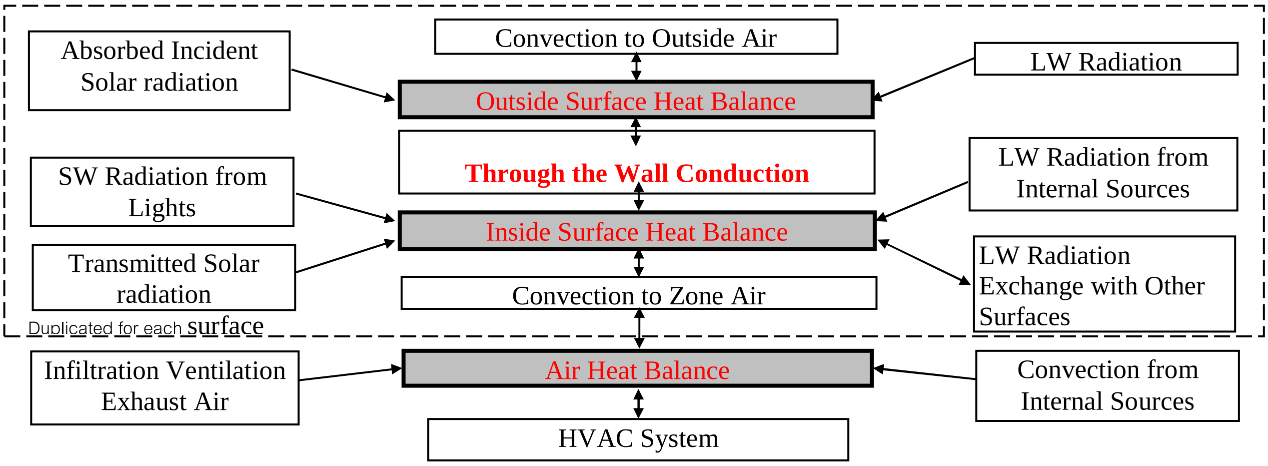



**Figure 2.8** Overall energy balance in a zone.

Energy balance equations at all nodes are also largely linear. The energy balance equations involving components with thermal masses such as that of wall would be dynamic, the solutions of which would exhibit thermal inertia.

The overall cooling coil load over a period could be represented by the following relationship

| | | | |
|---|---|---|---|
| Cooling coil load over a period | = | external factors of heat gain through building envelope<br>+ thermal storage load of envelope<br>+ internal factors (lighting, equipment, occupants, ventilation and air leakage)<br>+ thermal storage load of interior walls, floors and furniture | (2.3) |

**a) Thermal Mass and Its Effect on Cooling Coil Load**

The resultant effect of the thermal masses of wall, air, and objects in the zone is not apparent in relationships (2.1) and (2.2), but could be illustrated in Figure 2.9 and described in the followings.

Suppose the room in Figure 2.1 is used during 13.00 and 17.00 and air-conditioning is on during the corresponding time

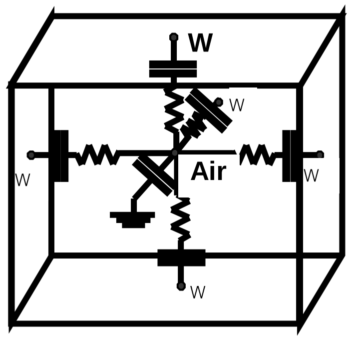



**Figure 2.9** A model that illustrates the effect of thermal masses in the zone.

In the morning that the room is unoccupied and air-conditioning is off, the room received heat from various exterior driving sources without an active removal of heat, the heat will cause temperature of wall and interior surfaces to rise. Prior to turning the air-conditioner on at 13.00, the surfaces of wall and other objects in the room will rise beyond the set-point temperature for the air in the room. The cumulated heat will contribute to the load due to heat gain at the given moment. The situation could be illustrated by Figure 2.10

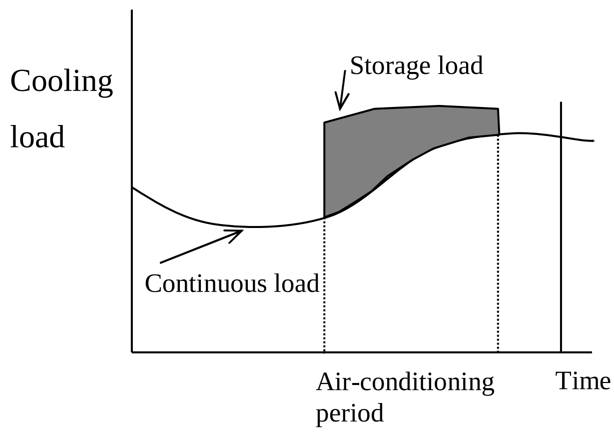



**Figure 2.10** An illustration of the contribution of cumulated load to the normal load.

**2.3.2 The Relationship between Average Cooling Coil Load and the Overall Thermal Transfer Value and Other Loads in the Zone**

In the development of energy performance standards for buildings of countries in tropical climate where air-conditioning is required to reduce temperature in the interior space to achieve thermal comfort and where no zone heating is required, past experience allows making a postulate that the average cooling coil requirement (CR) over a period could be related to the average heat from heat gain through external wall, electric lighting, and other sources in the form shown in Equation (2.4) as follows

$$CR = \frac{A_w}{A_f}[OTTV(wall\ storage)] + C_L(LPD) + C_E(EQD) + C_O(OCCU) + C_V(VENT) \qquad (2.4)$$

where

| | |
|---|---|
| *CR* | is the cooling requirement, |
| $A_w / A_f$ | is the ratio of wall area to floor area of that zone, |
| *OTTV* | is the overall thermal transfer value, $Wm^{-2}$ |
| *LPD* | is the lighting power per unit floor area in the zone (Lighting Power Density), $Wm^{-2}$, |
| *EQD* | is the equipment power per unit floor area in the zone (Equipment Power Density), $Wm^{-2}$, |
| OCCU | is the rate of heat generation by occupants in the room, $person.m^{-2}$ |
| *VENT* | is product of rate of flow of ventilation air with the difference between enthalpy of exterior air and that of interior air; this term represents ventilation load, $l.s^{-1}.m^{-2}$ |
| $C_L$, $C_E$, $C_o$, *and* $C_V$ | are coefficients that relate heat contribution to cooling requirement from lighting, equipment, occupancy, and ventilation. |

Note that *OTTV* is the only term that is rated per unit wall area, all other terms are rated in terms of per floor area.

The study of Chirarattananon and Taveekun [17], found that the effect of heat storage in wall depends on thermal properties of wall materials, wall orientation, and wall inclination and the time of use of the zone. In all cases, it was found that the effect was substantial and must be accounted for in the parameters of OTTV. On the other hand, thermal storage effect of floor and internal partition and other objects in the zone is small for typical construction and climate condition of Thailand. Exterior driving forces exert direct influence on the wall that faces exterior environment, but the influence does not extend sufficiently into the interior space.

The first term in (2.4) represents load from external influence while other terms represent load from internal influences. The linearity of the equation is consistent with the pattern exhibited in (2.1) and (2.2).

Chirarattananon and Taveekun [17], presents a study of the development of minimum energy performance requirements where a building model comprising 5 zones shown in Figure 2.11 was used in computer simulation.

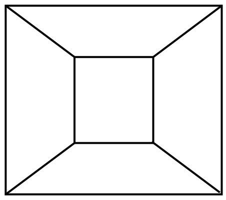


**Figure 2.11** Model used in the parametric study in the development of OTTV formulation.

In the study, the authors used heavy insulation between partition and ceiling to minimize the effect of heat transfer between zones and through roof. The authors also use the 3-term formulation for OTTV as in (2.5)

$$
\begin{aligned}
OTTV &= (1\text{-}WWR)\,(TD_{eq})\,(U_w) \\
&+ (WWR)\,(\Delta T)\,(U_f) \\
&+ (WWR)\,(SHGC)\,(SC)\,(ESR)
\end{aligned}
\qquad (2.5)
$$

where $WWR$ = window area to overall wall area,

$TD_{eg}$ = equivalent temperature difference of opaque wall,

$U_w$ = thermal conductance of opaque wall,

$\Delta T$ = temperature difference for glazed window,

$U_f$ = thermal conductance of glazing,

$SHGC$ = solar heat gain coefficient of glazing,

$SC$ = shading coefficient of shading device, and

ESR = effective solar radiation.

To obtain the value of $TD_{eq}$ in this case, the value of $U_w$ was varied each time to produce one pair of values of cooling coil load and $U_w$, while all other parameters were kept constant. A collection of several pairs of such values were then used to regress for the value of $TD_{eq}$, the equivalent temperature difference. A large number of parametric runs were conducted to obtain complete formulations of $TD_{eq}$ for each building category. Three building categories were adopted in the study. The time duration of use of building in each category of commercial buildings were defined as shown in Table 2.4. A set of values of $TD_{eq}$ and $\Delta T$ were given for each category of buildings. For each category of building, $TD_{eq}$ is a function of solar absorptance of the wall surface, a function of wall orientation and inclination, and a function of thermal mass represented by the sum of the products of material density, specific heat, and thickness of each layer that forms the wall.

**Table 2.4** Time duration of use of each of the three building categories.

| **Building Category** | **Time Duration of Building Use** | **Buildings in This Category** |
|---|---|---|
| Office | 08.00 – 17.00 | Office and school |
| Department store | 10.00 – 22.00 | Department store, hypermarket, restaurant, club house |
| Hotel | 24 - hour | Hotel, hospital, convalescence home, condominium |

### 2.3.3 Equation for Whole Building Energy Calculation

The authors in Chirarattananon and Taveekun [17], derive a relationship between average energy use in a zone and the lighting and other energy uses in the form shown in (2.6)

$$Energy\ use\ in\ a\ zone = \left(\frac{CR}{COP} + LPD + EQD\right) \times zone\ \ floor\ area \times duration(hours) \qquad (2.6)$$

where the coefficient of performance (COP) is the measure of the performance of the whole air-conditioning system that serves the zone. A similar equation scheduled to be used as a part of energy labeling scheme of Hong Kong called HK-Beam for calculation of reference energy consumption of office buildings appears in the HK-Beam document, HK-BEAM Society [24].

The above result, and the results of the study in the development of building energy code commissioned by the Department for Alternative Energy Development (DEDE) has been used in the whole building energy compliance procedure. The procedure specified that Equation (2.7) be used as a part of calculation of the whole building energy requirement for new building not yet constructed. From (2.7), the equation of whole building energy requirement is then obtained in the form

$$E_{pa} = \sum_{\substack{i=1 \\ i \neq j}}^{n} \left[ \frac{A_{wi}(OTTV_i)}{COP_i} + \frac{A_{ri}(RTTV_i)}{COP_i} + A_i \left\{ \frac{C_l(LPD_i) + C_e(EQD_i) + 130C_o(OCCU_i) + 24C_v(VENT_i)}{COP_i} \right\} \right] n_h + \sum_{i=1}^{n} A_i(LPD_i + EQD_i) n_h \qquad (2.7)$$

This equation assumes that the occupants fully occupy the zone during the whole duration, and lighting, air-conditioning, and other equipment in are fully utilized during the specified duration of each zone.

The requirements of the Building Energy Code has been embodied in the Ministerial Regulation for Design of New Large Buildings announced in the Royal Gazette on 20 February 2009 and has come into force on 20 June 2009. Even though minimum energy performance requirement for hot water production is also included in the Ministerial Regulation, only calculated energy consumption of the three principal systems are allowed to be exchanged.

**An illustration of the Use of the Whole Building Energy Equation**

Equation (2.7) could be used to illustrate the effect of efficiency of systems or of the relative significance of the contribution from given systems on the overall energy consumption of a building.

Suppose an air-conditioned space is used as an office space. The space is used 2.340 hours per annum and the values of load contribution from lighting, air-conditioning, equipment, and occupants, are shown in Table 2.5.

**Table 2.5** Coefficients of contribution to cooling from different sources.

| Categories of Buildings | $C_l$ | $C_e$ | $C_o$ | $C_v$ |
|---|---|---|---|---|
| Office education Department store | 0.84 | 0.85 | 0.90 | 0.90 |
| Hotel hospital, convalescence home | 1.0 | 1.0 | 1.0 | 1.0 |

Table 2.6 illustrates results of application of relationship (2.7) in the calculation of energy consumption of the sample office space.

The table shows the ratio of external wall area to floor area for the zone, value of coefficient of performance (*COP*), lighting power density (*LPD*), equipment power density (*EQD*), occupancy (*OCCU*), and ventilation (*VENT*) that assume reference values shown in column 2.1, and when one parameter assumes a new value in columns 2.2 to 2.7. The resultant energy consumption per unit floor area calculated from application of relationship (2.7) for each case (each column) appears in rows 8 to row 15. In the last column 2.8, *OTTV*, *COP*, and *LPD* assume values that differ from the reference values simultaneously.

In column 2.2, only *OTTV* assumes a value that differs from the reference value, the resultant cooling coil load, and energy consumption related to cooling load from external factor changes.

**Table 2.6** Resultant energy consumption indices for reference case and for other cases.

| Column → | Base Case ↓ 1 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 |
|---|---|---|---|---|---|---|---|---|---|
| **Row ↓** | **Item** | **Parameter values and results** | | | | | | | |
| 1 | *OTTV, W/m²* | 65 | **25** | 65 | 65 | 65 | 65 | 65 | **25** |
| 2 | $A_w/A_f$, $m^2$ | 1 | 1 | **0.24** | 1 | 1 | 1 | 1 | 1 |
| 3 | *COP* | 2.2 | 2.2 | 2.2 | **3.5** | 2.2 | 2.2 | 2.2 | **3.5** |
| 4 | *LPD, W/m²* | 20 | 20 | 20 | 20 | **10** | 20 | 20 | **10** |
| 5 | *EQD, W/m²* | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| 6 | *OCCU* | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | **0.2** | 0.1 | 0.1 |
| 7 | *VENT, l/s* | 1 | 1 | 1 | 1 | 1 | 1 | **2** | 1 |
| 8 | *CCL*, $W_{th}/m^2$ | *140.6* | *100.6* | *91.2* | *140.6* | *132.2* | *152.3* | *162.2* | *92.2* |
| 9 | *Ext, %* | *46* | *25* | *17* | *46* | *49* | *43* | *40* | *27* |
| 10 | *Int, %* | *54* | *75* | *83* | *54* | *51* | *57* | *60* | *73* |
| 11 | $AC_E$, $kW_h/m^2Y$ | *149.5* | *107.0* | *97.0* | *94.0* | *140.6* | *162.0* | *172.5* | *61.6* |
| 12 | $L_E$, $kW_h/m^2Y$ | *39.3* | *39.3* | *39.3* | *39.3* | *19.7* | *39.3* | *39.3* | *19.7* |
| **13** | $\boldsymbol{E_n}$, $kW_h/m^2Y$ | ***214.4*** | ***171.8*** | ***161.8*** | ***158.8*** | ***185.8*** | ***226.8*** | ***237.3*** | ***106.8*** |
| 14 | $AC_E/E_n$ | *69.8* | *62.3* | *59.9* | *59.2* | *75.7* | *71.4* | *72.7* | *57.7* |
| 15 | $L_E/E_n$ | *18.3* | *22.9* | *24.3* | *24.8* | *10.6* | *17.3* | *16.6* | *18.4* |

Note
- *CCL* = cooling coil load ($W_{th}/m^2$)
- *Ext* = the fraction of external factor of cooling coil load, %
- *Int* = the fraction of internal factor of cooling coil load, %
- $AC_E$ = air-conditioning energy use per unit area, ($kW_h/m^2Y$)
- $L_E$ = lighting energy per unit area, ($kW_h/m^2Y$)
- *En* = total energy use per unit area ($kW_h/m^2Y$)
- $AC_E/E_n$ = the ratio of air-conditioning energy to total energy, %
- $L_E/E_n$ = the ratio of lighting energy to total energy, %

Total energy consumption of the building changes from 214.4 $kWhm^{-2}Y^{-1}$ to 171.8 4 $kWhm^{-2}Y^{-1}$. When each relevant parameter assumes a value that differs from the reference value, the relevant energy terms change accordingly. In column 2.8, the values of the performance coefficients of three principal parameters assume values that differ from reference values simultaneously, in this case overall energy consumption changes substantially from 214.4 $kWhm^{-2}Y^{-1}$ to 106.8 $kWhm^{-2}Y^{-1}$.

**2.3.4 A Hypothesis on the OTTV formulation of residential buildings**

For Singapore, OTTV represents overall heat gain across a given building envelope, Chua and Chou [19]. For Thailand, OTTV for commercial buildings in Thai BEC represents cooling coil load (CCL) of the air-conditioning system due to heat gain across the envelope per unit area of the envelope, Chirarattananon and Taveekun [17]. Such CCL is obtained from computer simulation using a generic building model. The values for $TD_{eq}$, $\Delta T$ and *ESR* are obtained from regression procedure using (2.5) when *WWR*, $U_w$, $U_f$, and *SHGC* on the RHS of (2.5) are varied and the resultant values of CCL per unit envelope area is used on the LHS of (2.5). In applying such procedure, it is assumed that $TD_{eq}$ is independent of $U_w$, and *ESR* is independent of *SHGC*, etc.

For the present case of residential space used under the bedroom function, there is no solar radiation present on the building envelope throughout the duration of the bedroom function. However, studies in Chirarattananon et al. [15] and Tummu et al. [59] illustrate that solar radiation on the exposed wall and its transmission into the interior space during daytime is stored as heat in the exposed wall and in the interior walls. This stored heat will be transferred to air and contributes to CCL during the bedroom period. The OTTV formulation for the bedroom function should reflect this storage effects.

The hypothesis on the formulation of a thermal performance measure for a wall enclosing a space serving the bedroom function is that it takes the form

$OTTV_{br}$ = (1-*WWR*)(CCL due to conduction heat gain and stored heat in opaque wall)
+ (*WWR*)(CCL due to conduction heat gain through glazing and stored heat in the interior room mass)
+ (*WWR*)(CCL due to heat stored in the interior room mass due to absorbed transmitted solar radiation). (2.8)

The thermal performance measure for the bedroom function, $OTTV_{br}$, comprises three terms where each term is considered independent of the other. The first term represents the CCL due to conduction heat gain through the opaque section during the bedroom period and that due to stored heat from absorption of solar radiation on the section during daytime. The second term represents CCL due to conduction heat gain through the transparent or glazed section during the bedroom period and that due to heat transferred and stored in the interior walls during daytime. The third term represents CCL due to heat stored in the interior walls from absorption of transmitted solar radiation during daytime.

# CHAPTER 3
# METHODOLOGY

This Chapter explains common methodology used in this research study. For experimental researches in this research, experiments and computer simulations were undertaken to obtain results under each specific objective. The experiments was conducted mainly at Bangkhuntian campus. A computer program called BESim that has been developed to an extent earlier was used for calculation and simulation.

Experiments to be carried out under each specific objective were utilize measured data from a solar radiation and daylight measurement station at Bangkhuntian and three experimental rooms near the station. Some common equipment and measurement procedures are described in the followings, detailed methodologies of each research topic are described in each Chapter.

## 3.1 Solar Radiation and Daylight Measurement Station

This station is located on the roof of the main building of the School of Bio-resource Technology in Bangkhuntian campus (Figure 3.1). All components of solar radiation and solar illuminance, air temperature and relative humidity, sky temperature, wind speed and direction are measured by individual sensors and logged by a dedicated data logger that transfers all data to a dedicated computer automatically. A UPS is used to back up power to all sensors and recording instruments.

**Figure 3.1.** The meteorological station in Bangkhuntian campus.

## 3.2 Experimental buildings

The figure below shows photographs of the experimental building. The experimental buildings are full scale. For daylighting experiments, scaled models of buildings are also used.

**Figure 3.2.** The meteorological station and experimental house in Bangkhuntian campus.

## 3.3 Measurement of Heat Flux through an Opaque Wall and an opaque Ceiling

A surface transfers heat from it by convection to air and radiation to other surfaces. Opaque wall surfaces are assumed to have high thermal emissivity, therefore heat flux sensors of appropriate range could be used to measure total heat fluxes through such surfaces. A temperature sensor should be attached to the surface in proximity of the heat flux sensor, and another to measure air temperature near the surface to yield temperature values for calculation of convection heat transfer. Infrared thermometer can be used for inspection of thermal radiation from or temperature of a surface. Temperature sensors will be used to measure surface temperatures of all sections that are recorded for use in calculation of transfer of thermal radiation.

## 3.4 The BESim program

This computer program is used in the simulation runs. It was developed earlier and was described in a number of researches reported in Chiraratananon and Hien [11]; [12; 15; 16; 59]. The program uses local meteorological data to calculate dynamic heat transfers under the principle of energy balance. It accounts for solar, short wave, and long wave radiation heat transfers using numerically calculated view factors. Raytracing is also used with beam radiation when a surface has a specular reflectance component. A zone can be air-conditioned or naturally ventilated. Outputs of the program include: i) temperatures on and components of heat fluxes from zone surfaces and temperatures of air in each zones on user-specified time and dates, and ii) cooling coil load of air-conditioning system and electricity cost. The calculation method used in BESim program are presented in APPENDIX.

# CHAPTER 4
# A STUDY ON THERMAL PERFORMANCE OF INSULATED WALLS ENCLOSING RESIDENTIAL SPACES IN THAILAND

## 4.1 Introduction

Thailand is located in a tropical region and its climate is hot and humid. In the long past, residential houses were built for natural ventilation and light natural materials were used for walls. Air-conditioning for cooling is now common. Heat gain through walls is believed to contribute substantial load to an air-conditioner. With strong solar radiation and high ambient temperature typical of a tropical location, heat gain through opaque wall is expected to contribute significantly to such load. Reference [14] shows that insulation improves thermal performance of walls enclosing spaces used under commercial functions (office, department store, and hotel) and is highly cost effective for walls that have no window. But residential spaces are mainly occupied during evening and night time when solar radiation is no longer present and temperature of ambient air declines, it is of interest to learn if insulation can improve performance of walls in such situations. No insulation is used with walls of residential buildings in Thailand up to the present.

Bojić and Yik [4], note that cooling is the dominant energy end-use but insulation is not used on walls in Hong Kong. The authors use HTB2, a simulation program, for study of application of insulation on walls of high-rise buildings to conclude that exterior insulation on massive wall offers significant reduction in annual cooling energy. Kossecka and Kosny [34], evaluate six configurations of insulation placement on heavy walls of a ranch house model under continuous use in six climatic regions of USA and conclude that exterior insulation leads to lowest cooling and heating energy. Balocco et al. [3], investigate different insulation placements on walls and conclude that exterior insulation performs best under both cooling and heating climates. Masoso and Grobler [45] note that there are six instances reported in literatures that the use of insulation leads to increased energy use and call the phenomenon ‘anti-insulation behaviour’. Chiraratananon and Hien [11], utilizes the same simulation program and the same meteorological data used in this paper to study the effect of wall mass to conclude that wall of high mass is not cost effective for tropical climate. Aktacir et al. [1], investigate cooling energy requirements of building models with walls insulated to three levels and conclude that the cost of air-conditioning is reduced significantly from application of insulation at all three levels. Optimum insulation thicknesses for walls of buildings requiring heating and cooling in a city of Turkey is reported by Ozel [48], to be at 55 mm for south wall and 60 mm for other orientations. Saha [51], reports a study on application of different levels of insulation to residential buildings with typical wall construction under the climate of Sydney, Australia. The author claims that cooling and heating cost savings of 79% is achieved from application of insulation on walls.

This paper first notes the salient feature of the Thai climate and materials used for walls of traditional residential buildings and of present air-conditioned buildings. The results of a set of experiments and calculations on thermal performance of insulated exposed walls in an experimental room conducted consecutively for three residential functions are then presented. The paper then present results from simulation using a generic building model to show that insulation placed on interior surface improves wall performance for all functional uses of a space.

## 4.2 Climate and building shell

Building design is influenced by the climate and the culture of people at a location, [64].

### 4.2.1 The climate of Thailand

The climate of Thailand is hot and humid. Dry-bulb temperature varies between 25 to 35$^{o}$ C every day, except for the cool season during November to February where the temperature drops by an average of 2$^{o}$C. Relative humidity ranges from 40 to 80%. The air is dryer and the sky is clearer in the cool and the hot seasons, resulting in higher radiation from the sun. Global solar radiation and air temperature are highest in the hot season with insolation at slightly higher than the average of 18 MJ per day. The sky temperature remains above 20$^{o}$C for most times of a year. Figure 4.1 a) shows graphs of ambient air temperature (T-Amb), relative humidity (RH), beam normal (IsunN), diffuse horizontal (IskyH), and global (IgloH) solar radiation of 20 August 2011, a rather cloudy day and is one of the days when the experiments described in Section 4.3 were conducted. The graphs exhibit typical pattern of weather in the rainy season (late May to October) in the central region of Thailand. Similar graphs for 9 May and 2 February 2000, the warmest and coolest days of the year 2000 are also shown.

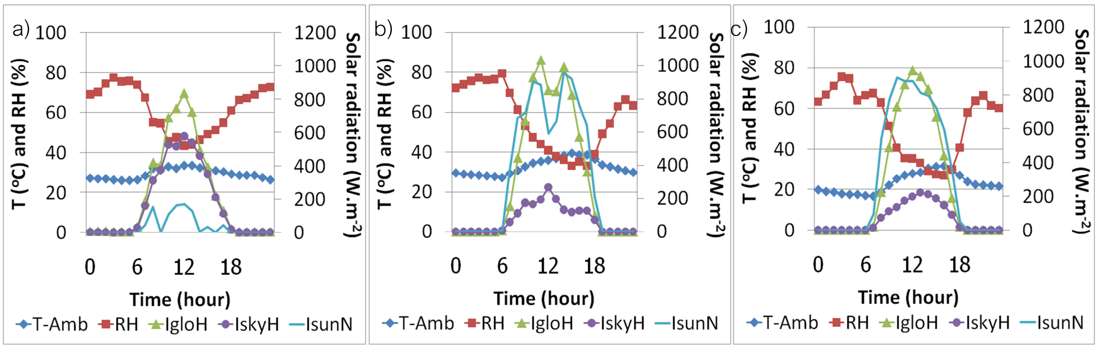



**Figure 4.1** Graphs of solar radiation, air temperature and relative humidity of the given dates, a) 18 August 2011, b) 9 May 2000, c) 2 February 2000

### 4.2.2 Traditional and modern residential building shells

Traditional Thai houses are constructed from materials of low thermal mass, are well shaded and well ventilated with open windows and door. Thin wood boards or other natural materials with moderate thermal conductivity are used for walls. No insulation is used.

Modern residential buildings in Thailand now rely on air-conditioning to achieve thermal comfort. Two decades and earlier, the opaque part of walls of such buildings was predominantly constructed from local bricks that were plastered on both sides with cement mortar. Concrete blocks and light weight concrete blocks are now also commonly used. Typically air-conditioning accounted for up to 70% of electricity consumption in a household and it is surmised that heat gain through wall is responsible for a significant part of the cooling load. However, no insulation is used with walls in modern residential buildings.

## 4.3 Experiment and calculation

A set of experiments on heat gain through un-insulated and insulated walls were conducted in an experimental room to validate results of calculation from a computer program. The calculation utilized measured weather data of the days of experiments from a nearby station.

**4.3.1 A solar measurement station and an experimental room**

A station equipped with global, beam, and diffuse solar radiation measuring equipment was elected on top of a 7-story building in a seaside campus of the university that is located 10 km south of Bangkok. The station also measures air temperature and relative humidity, and wind speed and wind direction and stores all data via a data logger.

A small experimental building comprising five square rooms of identical dimensions, with the five rooms forming a cross, was constructed on the ground near the building where the station is located. A set of experiments were conducted in August 2011 in a room where its exposed windowed wall faces south. The width and length of the room are each 3m and its height is 2.65m. The exposed walls are constructed from brick of 80mm thick that is plastered over with cement mortar on both sides to a total thickness of 100mm. The opaque part of the southern exposed wall is divided into three equal sections. One section is externally insulated, one is internally insulated, and the section in the middle is un-insulated. The area of the window that is glazed with clear glass accounts for 60% of the total wall area. Figure 4.2 shows photographs of the interior and the exterior views of the wall. Thermal properties of the opaque wall sections, of the polyethylene foam insulation, and of the glazing are shown in Table 4.1. Solar transmittance of the glazing is 0.83.


**Figure 4.2** Photographs of interior and exterior configurations of the southern windowed wall, a) Interior, b) Exterior

**Table 4.1** Thermal properties of the exposed wall, of the insulation, and of the glazing.

| Wall component | Thermal properties | | | Thickness, m |
|---|---|---|---|---|
| | conductivity, $W.m^{-1}.K^{-1}$ | density, $kg.m^{-3}$ | specific heat, $J.kg^{-1}.K^{-1}$ | |
| Brick wall | 1.102 | 1700 | 790 | 0.1 |
| polyethylene foam | 0.029 | 45 | 1,210 | 0.025 |
| Clear glazing | 0.960 | 2,500 | 880 | 0.006 |

### 4.3.2 The BESim program

A computer program called 'BESim' was used to calculate results for comparison with those from experimentation. This program was developed earlier and was used in the development of the building energy code of Thailand, [16] and was used in the works described in [11; 14]. The program uses local meteorological data to calculate dynamic heat transfers under the principle of energy balance. It accounts for solar, short wave, and long wave radiation heat transfers accurately using numerically calculated view factors. Raytracing is also used with beam radiation when a surface has a specular reflectance component. A zone can be air-conditioned or naturally ventilated.

Outputs of the program include: i) temperatures on and components of heat fluxes from zone surfaces and temperatures of air in each zones on user-specified time and dates, and ii) cooling coil load of air-conditioning system and electricity cost.

### 4.3.3 Experimental and calculation results

The experimental room was assumed to serve consecutively three residential functions of bedroom (BR), living room (LR) and studio room (STR). The usage schedules of the three functions are shown in Table 4.2. Even though residential houses are also used during daytime, evening and night time usages only are considered here. During each functional use, air-conditioning is turned on in the zone or room with a set-point temperature of 25°C. Outside the functional period, the air is allowed to float to its balanced condition. In the experiment and in BESim calculation, there was no internal cooling load. Type K thermocouple sensors with the accuracy of 1.5°C for the range of measurement of 0-200°C were used for temperature measurements while heat flux sensors model MF-180 with the reproducibility of 2% were used for measurements of heat fluxes from the wall sections. All measurements were logged by a data logger at an interval of one minute and were averaged to give 15-minute data. Meteorological data from the station were also averaged to give synchronized 15-minute data. Figure 4.1a) illustrates sample patterns of solar radiation and air temperature and relative humidity obtained from the station for a day of experiment.

**Table 4.2** Usage schedule of each function.

| Functional use of zones | Time of use |
|---|---|
| Bedroom (BR) | 21:00-06:00 |
| Living room (LR) | 18:00-21:00 |
| Studio room (STR) | 18:00-06:00 |

**Results for the bedroom (BR) function**

Figure 4.3a) shows graphs of heat fluxes (HF) at the interior surfaces of the section with no insulation (NI), of the section with insulation on the interior surface (INT), and of the section with insulation on the exterior surface (EXT), obtained from experiments for the BR function, while Figure 4.3b) shows corresponding graphs of results from BESim calculation. Figure 4.4 a) shows graphs of measured temperatures (T) of the interior surface (room side) of the NI section (T-NI), of the INT section (T-INT), of the EXT section (T-EXT), of room air (T-Room), and of ambient air (T-Amb), also for the BR function. Figure 4.4 b) shows the corresponding graphs from calculation. The calculation results exhibit reasonable correspondence with the experimental results.

Examining the graphs of heat flux gains into the room at the interior wall sections in Figure 4.3 a), it is seen that from 6.00 hour on the heat gains into the wall sections steadily increase as solar radiation (a small part from beam and a large part from diffuse radiation for this south-facing wall in late August) fell on the exterior surface. Part of solar radiation transmitted through the window would also be reflected on to the interior surfaces of the wall sections, although to a lesser extent. From 6.00 to late afternoon when the air-conditioner was off, heat was continuously stored in the wall (negative heat fluxes), but started to be released (positive heat fluxes) from late afternoon with a peak at 18.00 hour and then is observed to decline. From 18.00 solar radiation was no longer present and the ambient air temperature began to fall. When the air-conditioner was turned on at 21.00 the heat fluxes are observed to rise immediately to almost 35 $W.m^{-2}$ for the NI section, 25 W.m$^{-2}$ for the EXT section, and about 5 W.m$^{-2}$ for the INT section. These fluxes then decline steadily as seen in Figure 4.3 a) as the surface temperatures fall towards the room air temperature as seen from Figure 4.4 a). Figure 4.4 a) and b) both show clearly that T-INT of the INT wall section follows T-Room closely at all times, while T-EXT exhibits the highest inertia and drops very slowly from its initial value at 21.00 towards T-Room. Even by 6.00 of the next morning, T-EXT still remains significantly higher than T-Room.

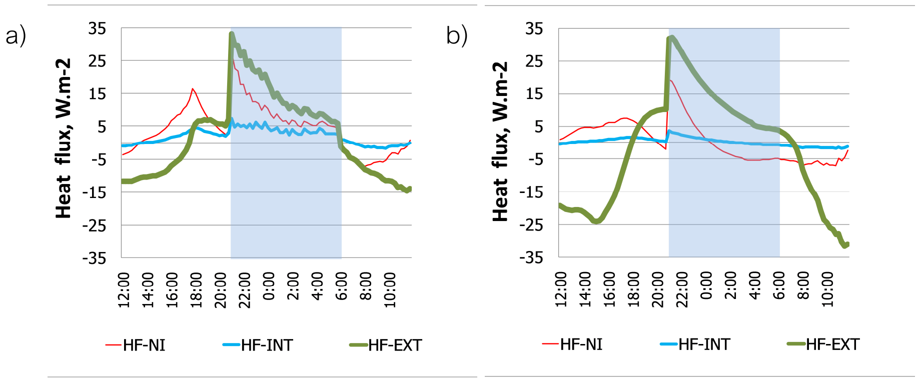



**Figure 4.3** Graphs of heat fluxes and temperatures on the interior surfaces and ambient temperature from experiments and from calculation for the BR function, a) Experiment, b) Calculation

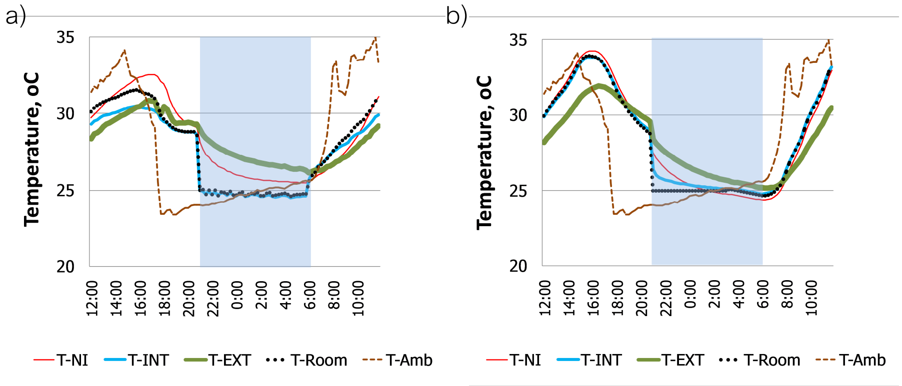



**Figure 4.4** Graphs of temperatures on the interior surfaces and air, a) Experiment, b) Calculation.

**Results for the living room (LR) function**

Figure 4.5 shows graphs of the same quantities and configuration as those in Figure 4.3, but for the LR function. The calculation results exhibit reasonable correspondence with the experimental results. The salient features of temperature variations are similar to those of the BR case and are not presented here.

Under this function, air-conditioning is turned on in the zone immediately after solar radiation disappears and the temperature of ambient air starts to fall. The heat flux gains into the zone for the NI and EXT wall sections are observed to immediately rise to about 60 W.m$^{-2}$ while that for the INT section rises to less than 10 W.m$^{-2}$ at 18.00 hour. The stored heat is released partially up to 21.00 hour. During 21.00 to 18.00 hours of the next day, there are gradual heat gains into the wall at different levels for all cases.

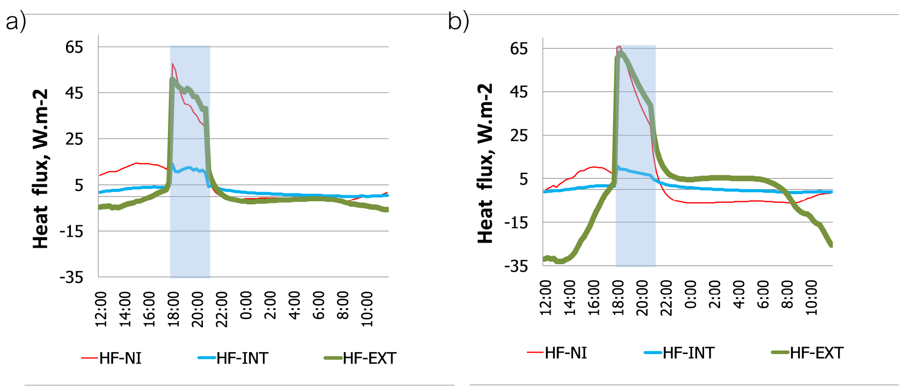



**Figure 4.5** Graphs of heat fluxes on the interior surfaces from experiments and from calculation for the LR function, a) Experiment, b) Calculation

**Results for the studio room (STR) function**

Figure 4.6 shows graphs of the same quantities and configuration as those in Figure 4.3 and Figure 4.5, but for the STR function. The calculation and experimental results exhibit reasonable agreement. Similar to the LR case, graphs of temperatures are also omitted here.

Under this function, air-conditioning is turned on in the zone immediately after 18.00. The heat gains into the zone for the NI and EXT wall sections are observed to immediately rise to about 60 W.m$^{-2}$ while that for the INT case rises to less than 10 W.m$^{-2}$. The stored heat is released almost completely by 6.00 of the next day. During daytime, there is net heat storage in the wall.

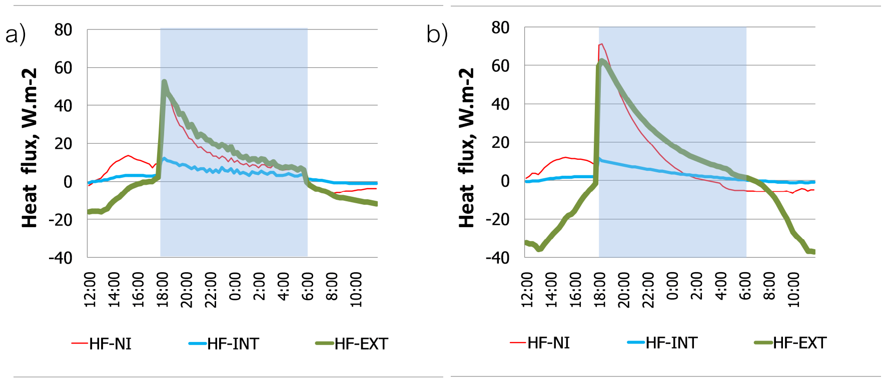



**Figure 4.6** Graphs of heat fluxes on the interior surfaces from experiments and from calculation for the STR function, a) Experiment, b) Calculation

Two observations are made for all the cases above. First, heat gains into the zone under all functional uses of the zone for the INT configuration are clearly smaller while heat gains in the EXT configuration may even exceed those of NI configuration in some functional usages. Second, calculated heat gains into and heat storage into wall are slightly larger than those from the experiments. It is believed that the cause for this is that the presence of trees in front of the experimental room, as seen in Figure 4.2, may have reduced solar radiation incident on the windowed wall. This effect is not accounted in the calculation.

### 4.4 Simulation results and discussion

In order to investigate long-term thermal performance of insulation used on walls enclosing spaces used for residential functions, the BESim program was used to calculate heat gain through walls and annual cooling coil loads of a three-storey generic building model. The spaces in all three floors are assumed to serve same function in each set of simulation runs, but only the results from the middle floor are used in the followings. The model is identical to that used in [11; 14] and is shown in Figure 4.7. The peripheral zones are all identical. The central core zone is unconditioned. The window appears as the color-shaded upper section of each external wall.  Each building façade faces a cardinal direction.

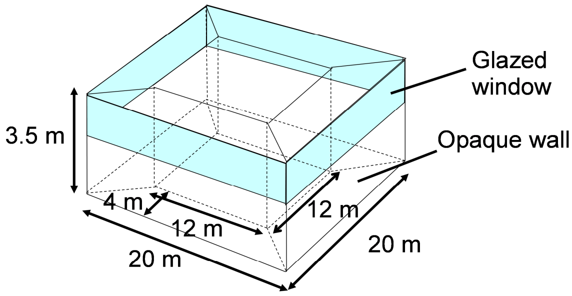



**Figure 4.7** The configuration of the middle floor of the building model.

For all the simulation runs, weather data of Bangkok for the year 2000 is used. Solar absorptance values of all external and internal opaque surfaces are at 0.4. Thermal emittance values of all opaque surfaces are 0.91 and for glazing it is 0.84. Table 4.3 shows summary thermal properties of the opaque wall and of the polyurethane foam insulation. The thickness of the insulation varies from 25 to 75 mm. For glazing, the properties in Table 4.1 are used.

The standard U-values of the un-insulated and the insulated walls in the table are calculated based on exterior air film resistance of 0.044 $m^2 .K.W^{-1}$ and interior air film resistance of 0.12 $m^2 .K.W^{-1}$. BESim does not use the standard values, instead it uses correlation formulas for air film resistances and does dynamic calculation. The U-values of the wall assembly are given for information only.

**Table 4.3** Thermal properties of wall and polystyrene foam and the U-values.

| Wall component | Thermal properties | | | Thickness, m | | | |
|---|---|---|---|---|---|---|---|
| | k | ρ | $c_p$ | | | | |
| Concrete wall | 0.546 | 2210 | 920 | 0.1 | 0.1 | 0.1 | 0.1 |
| PS foam | 0.028 | 30 | 1,380 | 0.0 | 0.025 | 0.05 | 0.075 |
| Overall standard U-value of wall, $W.m^{-2}.K^{-1}$ | | | | 2.881 | 0.806 | 0.469 | 0.330 |

In the followings, annual cumulative cooling coil loads (CCLs) of each insulation configuration and for each functional use is presented. Then the annual average heat flux (HF) and convection (C) flux of the opaque parts of the four exposed walls are presented.

Finally, detailed heat gains from relevant surfaces in the west zone for a particular day are presented to show salient points of interest on the relative performance of walls with different insulation configurations.

**4.4.1 Effects of insulation on cooling coil load**

Since the air-conditioned spaces of the building model in Figure 4.7 do not have internal load, the CCL in each space comprises load from heat gain through its exposed wall only. Thermal performance of exposed walls of the air-conditioned spaces could be examined from the CCLs.

**Effects of insulation on walls with no window, WWR = 0**

Figure 4.8 show plots of the average (over the four zones) of cumulative (one full year) CCLs of each insulation configuration for each functional use of the AC spaces for the case WWR = 0, or no window. The figures show that the average CCL for the LR, BR and STR functions could be ranked according to the duration of each functional use of the spaces, with the larger values corresponding to those functional uses of longer duration. Insulation appears to reduce CCL with the internally insulated configuration appearing to give slightly lower CCL than that of the externally insulated configuration.

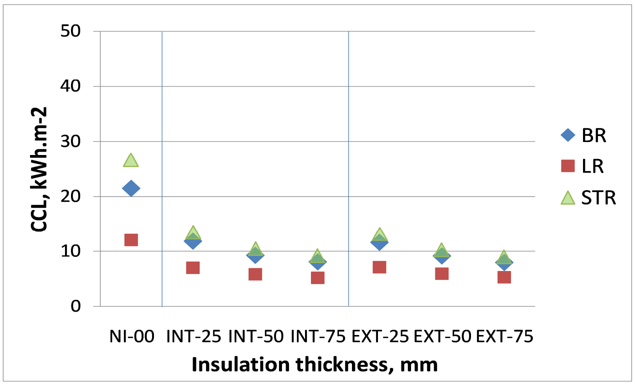



**Figure 4.8** Average CCLs for each insulation configuration and for each functional use for the case WWR = 0.

It appears that both INT and EXT reduces cooling load significantly. In order to evaluate the cost effectiveness of both cases, the costs of polystyrene foam (PS foam) type of insulation are obtained from manufacturers and are shown in Table 4.4. These include labor cost and the cost of adhesive for affixing the foam to wall. The costs of exterior insulation include weather proofing of the exposed surface.

**Table 4.4** Cost of wall insulation, Bahts.m$^{-2}$

| Thickness, mm | 25 | 50 | 75 |
|---|---|---|---|
| Interior | 175 | 197.5 | 222.5 |
| Exterior | 750.5 | 783.5 | 816.5 |

Assuming a life of 25 years and a discount rate of 7%, the present worth factor is 11.65. For simplicity, the cost of electricity is assumed to be 4 Bahts (one US$ = 30 Bahts) per kWh. In Thailand, residential electric tariff is progressive. The given value is close to marginal tariff rate. The graphs in Figure 4.9 show life cycle costs (LCCs) from application of the respective insulation configurations for all functions. It is seen that only the INT configuration for STR has lower LCC than that of NI case for all insulation levels and is cost-effective. For the BR function, the INT configuration has lower LCC for the two upper levels of insulation. For the LR function, even INT is not cost-effective for any insulation level. The EXT configuration for any residential function is not cost-effective for any insulation level.

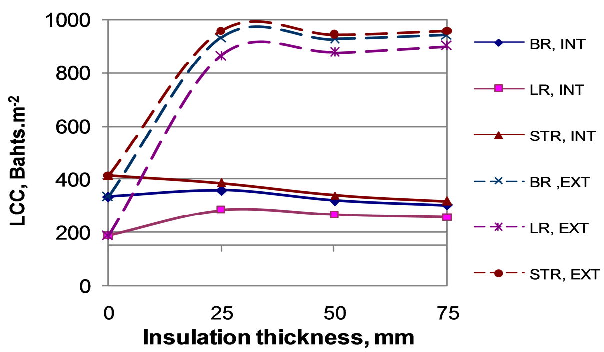



**Figure 4.9** Life cycle costs for all functions and for all insulation configurations for the case where WWR = 0.

**Effects of insulation on walls with windows, WWR > 0**

Figure 4.10 a) show plots of the average of cumulative (one full year) CCLs of each insulation configuration for each functional use of the AC spaces for the case WWR = 30% and Figure 4.10 b) shows the case for WWR = 60%.

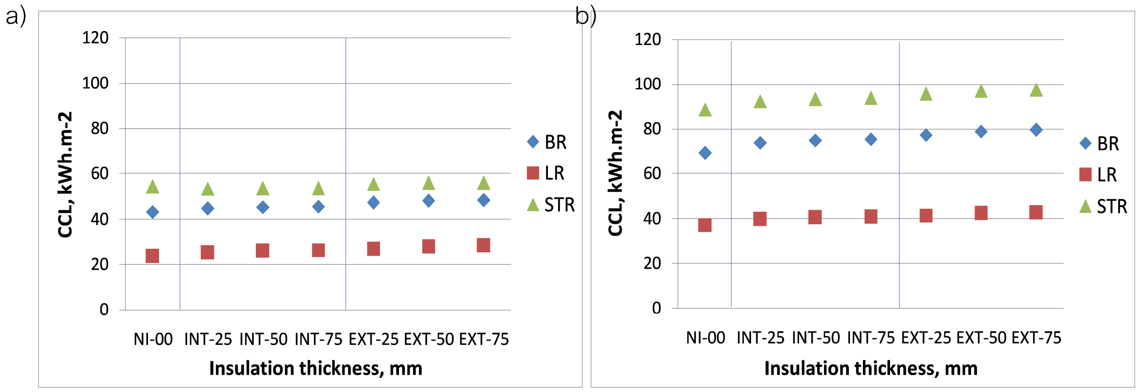



**Figure 4.10** Average CCL for each insulation configuration and for each functional use for the cases where WWR > 0, a) WWR = 30%, b) WWR = 60%

For the cases here, CCLs appear to rank from the lowest for the un-insulated configuration through the INT configuration to the EXT configuration for all functional uses of spaces. These are clear evidence of 'anti-insulation behavior' coined by the authors in [45] and observed in [14]. In all cases of non-zero WWRs, the higher the value of WWR, the CCLs become higher. Heat gain through window appears to be more significant than the level or placement of insulation. The sizes of CCLs can no longer be used to compare thermal performance or cost-effectiveness of insulation configurations since the effect of heat gain through windows obscures the effect of heat gain through opaque walls.

### 4.4.2 Effects of insulation on heat flux and convection gains

In order to examine thermal performance of the opaque part of the wall in isolation, heat flux and convection gain across the opaque section are considered.

Heat flux (HF) from the wall to the interior surface of an exposed opaque wall section is in energy balance with thermal or long-wave radiation (LW) and convection (C) heat transfers out from the interior surface, ie. HF = LW + C. For all residential functions, solar radiation is absence and short wave radiation from electric light is assumed absent or negligible. Figure 4.11 shows the sizes of average (over all four zones and over all usage time in a year) heat flux and convection components at opaque wall sections for all residential functions and all insulation configurations and levels for the case of WWR = 30%.

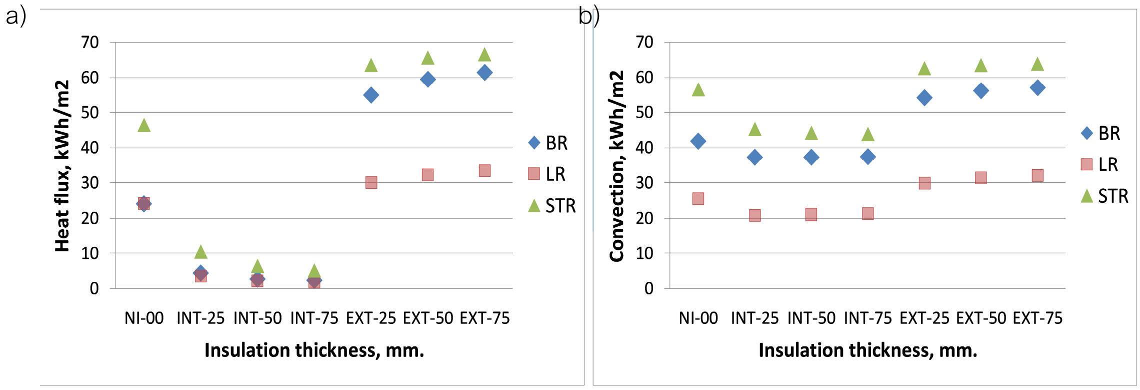



**Figure 4.11** Heat flux into an opaque wall surface and convection from the surface for the case WWR = 30%, a) Heat flux, b) Convection

From the figure, the sizes of HFs differ substantially between the different insulation configurations with the INT configuration possessing the lowest values, and those of the EXT configuration even exceed those of the NI configuration. The ranking of the sizes of convection fluxes is similar but the differences are moderate. The patterns of heat fluxes and convection fluxes for the case where WWR = 60% is similar to those in Figure 4.12. In each insulation configuration and each functional use, the average Cs are more relevant to HFs as in each case the convection heat transfer contributes to air-conditioning load. Table 4.5 give sample values of average HFs for the case WWR = 0, 30%, and 60%. Table 4.6 gives average Cs also for the three values of WWRs. The interior surface temperatures that essentially follow T-Room, which are low, under INT configuration in Figure 4.4 imply that LW must be negative. While the Cs are positive, Cs and LWs balance to give low HFs for the INT configuration as seen in Figure 4.11 a) and in Table 4.5. The opposite effects are observed for the EXT configuration.

**Table 4.5** Sample values of average heat fluxes for insulation thickness of 50 mm.

| Function | WWR = 0 | | | WWR = 30% | | | WWR = 60% | | |
|---|---|---|---|---|---|---|---|---|---|
| | NI | INT | EXT | NI | INT | EXT | NI | INT | EXT |
| BR | 25.42 | 6.60 | 11.54 | 24.12 | 2.69 | 59.59 | 20.68 | -1.30 | 109.74 |
| LR | 24.15 | 3.99 | 8.15 | 24.13 | 2.13 | 32.32 | 23.03 | 0.39 | 52.00 |
| STR | 48.76 | 10.96 | 14.39 | 46.43 | 6.37 | 65.66 | 41.00 | 1.23 | 124.04 |

**Table 4.6** Sample values of average convection fluxes for insulation thickness of 50 mm.

| Function | WWR = 0 | | | WWR = 30% | | | WWR = 60% | | |
|---|---|---|---|---|---|---|---|---|---|
| | NI | INT | EXT | NI | INT | EXT | NI | INT | EXT |
| BR | 22.22 | 7.49 | 8.78 | 41.88 | 37.30 | 56.19 | 67.78 | 66.17 | 103.17 |
| LR | 15.41 | 5.03 | 6.29 | 25.60 | 21.15 | 31.34 | 38.31 | 34.51 | 51.34 |
| STR | 32.14 | 9.10 | 9.87 | 56.57 | 44.21 | 63.51 | 89.49 | 81.54 | 122.09 |

The figures of convection fluxes in Table 4.6 imply that INT improves thermal performance of opaque parts of walls in all functional uses and for walls with any window sizes. With the presence of window, EXT configuration reduces thermal performance of opaque part of a wall for all functional uses at an extent that is related to the size of the window.

### 4.4.3 Heat transfer relationships on the interior surfaces

In order to gain more insight into the heat transfer mechanisms for each insulation configuration, the relevant heat gain components on the interior surfaces of the glazing, the opposite wall, and the exposed wall for the *west zone* for the BR function on 9 May 2000, the warmest day of the year, are to be examined for the case where WWR = 30%. Figure 4.12 a) show solar radiation (irrad), HF, LW, C, T-Amb and temperature on the *interior surface of the glazing* (T-Back) at the window. Solar radiation on the glazing (Irrad) is the net of solar radiation transmitted through the glazing and the reflected solar radiation from other surfaces in the room on to the glazing in the west zone. During daytime, peak values of HF, LW, and C exceed 100 $W.m^{-2}$. During BR hours, T-Back stays almost equal to interior set-point temperature of air (T-Room). The values of HF and LW are negative while C is slightly positive throughout the duration. Figure 4.12 b) shows similar quantities on the surface of the *wall opposite the window*. Sizeable solar radiation (Irrad) falls on the surface during daytime, particularly during afternoon, that raises T-back to over 40$^{o}$C and causes storage of heat in the wall. During the BR hours, the wall surface temperature declines from about 35$^{o}$C but remains above 30$^{o}$C. The values of HF and C are highly positive, whereas LW is also positive but the size is lower.

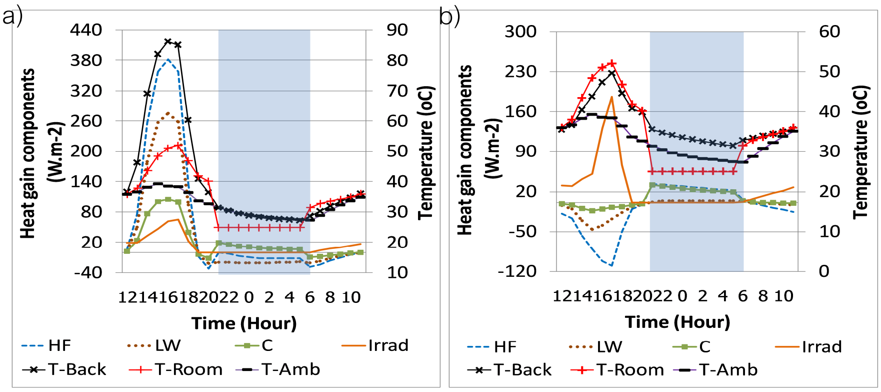



**Figure 4.12** Temperature and heat gain components at glazing and at the opposite wall, a) Glazing, b) Opposite wall.

Figure 4.13 a) shows the temperatures and heat gain components at the *exposed wall in NI* configuration. Reflected solar radiation on the surface in the afternoon reaches 60 W.m$^{-2}$.. The surface temperature T-Back reaches 45$^{o}$C resulting in heat being stored during the afternoon. This temperature declines in the evening but still reaches close to 35$^{o}$C at the start of the night and eases to 30$^{o}$C by the end of the BR function period. The values of HF and C drop from 40 to 20 W.m$^{-2}$ while LW falls to negative value towards the end of the period.

Figure 4.13 b) shows same quantities at the *exposed wall for the INT* (50 mm) configuration. The thermal environment in the room, except those at the exposed wall, does not differ to any significant extent to that of the NI configuration. Even though T-Back exceeds 45$^{o}$C in the afternoon, it falls sharply to slightly over 30$^{o}$C at the start of the BR function period and steadily falls to 29$^{o}$C by the end of the period. These changes result from the use of interior insulation that shields the surface from the heat gain and loss in the wall. Long-wave (LW) radiation is clearly negative while C drops from 20 to 15 W.m$^{-2}$.

Figure 4.13 c) shows same quantities at the exposed wall for the EXT (50 mm) configuration. During the afternoon, the surface temperature reaches higher than those of the

NI or the INT configuration, but throughout the BR function period the surface temperature remains above 30°C and are higher than those of the NI and INT configurations. Long-wave (LW) radiation is positive and C is larger than those of the other two configurations. The external insulation prevents heat stored in the wall to transfer out to the exterior surface during the BR function period.

The conclusion that can be drawn from detailed examination of Figure 4.13 clearly concurs with the results in Table 4.6 that INT reduces C, but EXT does the opposite. Another significant benefit of INT configuration is revealed in Figure 4.13 that the interior surface of the exposed wall is kept closer to the set-point air temperature (T-Room) because of the presence of the insulation.

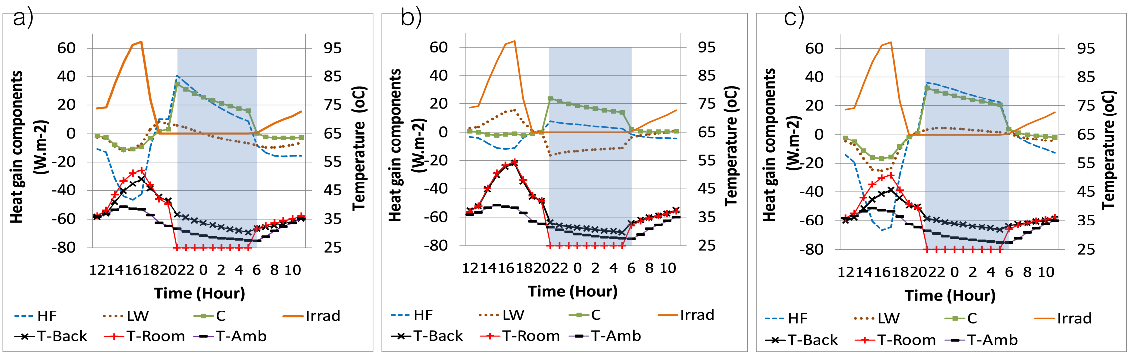



**Figure 4.13** Temperature and heat gain components at the exposed wall, a) NI, b) INT, c) EXT.

## 4.5 Conclusion

Cooling in commonly occupied spaces in residential houses has become widely practiced in many countries in tropical climate including Thailand, but insulation is not used and it has not been clear if it is cost effective or that it gives any benefit. This paper specializes on night residential functions and shows conclusively that in the case where there is no window, insulation placed at the interior surface of an exposed wall enclosing any residential functions improves thermal performance of walls and is cost-effective in room functions of longer duration, while insulation placed on the exterior surface improves wall performance but is not cost-effective. When window is present, solar radiation gain during daytime changes the situation. Insulation on the interior surface still improves thermal performance of an exposed wall and enhances thermal comfort in the space by enabling the surface temperature to follow set-point air temperature more closely in all residential spaces. However, insulation placed on the external surface of an exposed wall causes the opposite effects by raising temperature of the interior surface and increasing convection heat transfer to the air in the room, under all night residential functions.

# CHAPTER 5
# A STUDY ON ENERGY USE AND CARBON EMISSION OF LOW-INCOME HOUSES IN NORTHERN THAILAND

## 5.1 Introduction

This study reports first results from a multi-partner research project entitled 'Energy and Low Income Tropical Housing' funded under the Energy Programme of the UK Research Council. Partners in this project include Warwick and Cambridge University in the United Kingdom and organizations in China, Tanzania, and Uganda. Essentially, it is intended that the eventual outcome of the project will lead to reduction of energy use and carbon emission in low to medium income households while improving the quality of interior environment and the quality of life of residents. The results reported here pertain to an attempt to obtain baseline data on energy used, carbon dioxide emitted, household construction, thermal comfort and lighting conditions in interiors of houses. The requisite data are mainly obtained from a survey of houses of low income earners in rural areas. The next step in the project is to define a set of qualitative and quantitative criteria for energy efficient and environmentally benign house design. The results from the survey will be used to set a reference baseline design.

Thailand is located in the tropical region of Southeast Asia. The climate is hot and humid, although the northern part of the country is further away from the sea than the rest and thus is slightly less humid. Nevertheless, cooling for thermal comfort is becoming common. With electrification reaching over 99% of households, air-conditioning now penetrates to 18.4% of residential households nationally and 44.5% of those in the Greater Bangkok area (Bangkok and five adjacent provinces). Electric hot water heaters used for shower also penetrates to 9% and 19% respectively, Bureau of Social Statistics [5]. Both air-conditioning and the use of electric hot water heater are highly energy intensive and are growing annually at over 4% nationally and 6% in Greater Bangkok. The same source reports that electric fans, fluorescent lamps, television sets, refrigerators, electric rice cookers penetrates to over 90%, while electric iron, electric kettle, DVD player, and washing machine penetrate to over 60% of households nationally. These common household appliances will eventually reach saturation. Kidhen et al. [31] identifies 4 categories of end-uses in households that require electricity; lighting, entertainment, amenity, and cooking. Amenity that includes air-conditioning and the use of hot water heater is responsible for about 55% of total electricity consumption and the rest about 15% each in 2011. The average household electricity consumption is 2,680 kWh per year in 2011. The 2010 Power Development Plan, an official plan used for planning addition of electric generation plants to meet forecasted load in 2030, The Energy Policy and Planning Office [55], expects the electric load of residential households to grow from 33.3 TWh in 2010 to 68.0 TWh in 2030, more than twice of that in 2010. These figures imply that energy use in Thai households would still grow significantly. Many factors could be identified as causes for this phenomenon. These include the fact that common household appliances have not reached saturation and that there are significant proportion of families still living under poverty line that will emerge from it and become more energy intensive. Also, there is a continuing trend of increase in the number of families due mainly to reduction of family size. Moreover, the load forecast is likely to under estimate the growth in electricity consumption due to air-conditioning and electric hot water heating as the load forecast on which the Power Development Plan is based does not yet specifically account for such growth.

According to the report of the Department for Alternative Energy and Energy Efficiency referenced by the Bureau of Statistical Forecasting [7], emission of carbon dioxide from energy use in Thai households in 2010 was estimated at 6,895 kton. Depending on fuel mix for power generation in 2030, the amount could more than double. There has not been report of survey of emission of carbon dioxide during construction or during production of construction materials used in houses, although some studies of such emission have been taken on specific residential and other buildings, Jaranpong and Chiarakorn [29]; [44].

## 5.2 Macro indicators of socio-economic conditions of Northern Region of Thailand

In order to examine what is meant by low income housing, here the situation of income, poverty, shares of types of dwelling, and materials used for housing construction are first examined.

**Population**

The results of population and housing census conducted in 2010 shows that Thai population has reached 65.98 million. The comparative data from 1990, 2000, and 2010 also show that the population growth and family size have steadily declined to 0.8% and 3.1 persons, while the number of households has grown to 20.36 million as shown in Table 5.1, Bureau of Statistical Forecasting [8]. The size of aged population, those over 60 years, also increases significantly. There is also a marked increase in the number of families with only one member. Urbanization has reached 44.2% nationally. Similar trends are observed for the Northern Region of Thailand except for the population growth which is observed to be lower than national average. This is due largely to migration of people in the region to Greater Bangkok due to better job opportunity.

**Table 5.1.** Changes of population and size of households over two decades to 2010.

| Description | 1990 | | 2000 | | 2010 | |
|---|---|---|---|---|---|---|
| *Demography* | National | North | National | North | National | North |
| Population (million) | 54.55 | 10.39 | 60.92 | 11.22 | 65.98 | 11.66 |
| Population in urban area (%) | 29.4 | - | 31.1 | - | 44.2 | 34.6 |
| Population growth (%) | 1.96 | - | 1.05 | - | 0.80 | - |
| Aged population (%) | 6.80 | - | 9.78 | - | 11.6 | 2.36 |
| *Household* | | | | | | |
| Number of households (million) | 12.32 | - | 15.88 | 3.26 | 20.36 | 3.74 |
| Member per household | 4.4 | - | 3.8 | 3.5 | 3.1 | 3.1 |
| Share of single-member family (%) | 5.1 | - | 9.1 | - | 18.3 | - |

### Income and Poverty

The census mentioned above, Bureau of Statistical Forecasting [8], reveals that annual average household income reaches about 300,000 THB or about USD 10,000 in 2010 and the share of income from agricultural activities is 14.5% nationally and 21.6% for the Northern Region, as shown in Table 5.2.

**Table 5.2.** Monthly income per household in 2013.

| Geographical area | Total (THB) | Wage and Salary (%) | Small Business (%) | Agriculture (%) | Others (%) |
|---|---|---|---|---|---|
| Whole Kingdom | 25,194 | 40.8 | 18.5 | 14.5 | 26.2 |
| Greater Bangkok | 43,058 | 58.5 | 21.2 | 0.3 | 20.0 |
| North | 19,267 | 28.7 | 19.7 | 21.6 | 30.0 |

The World Bank defines poverty line as the income level below the level necessary to meet basic needs. This level is not absolute. From a publication of the World Bank, the poverty head count ratio at USD 2 a day (PPP) as percentage of Thai population is 3.5% in 2010, but is *none* at USD 1.25 a day in 2013, Development Economics Data Group [21].

The National Economic and Social Development Board (NESDB) of Thailand, the authority on poverty and its alleviation, defines Thai poverty line on the assumption that food accounts for 60% of overall consumption of people at the line. At the poverty line, 60% of its value is the amount required to satisfy basic need for food per person per month, Bureau for Development of Database and Social Indicators, 2008. Table 5.3 shows the poverty lines and poverty ratios at national and regional level from 2007 to 2011, Bureau of Statistical Forecasting [6]. The Northern Region has higher poverty ratio, at 16%, than the national average. The Thai poverty line is higher than USD 2 a day and most rural people at poverty line have their own houses.

**Table 5.3.** Poverty line and poverty ratio at national and regional level from 2007 to 2011.

| Poverty line | 2007 | | 2008 | | 2009 | | 2010 | | 2011 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | THB | Ratio, % | THB | Ratio, % | THB | Ratio, % | THB | Ratio, % | THB | Ratio, % |
| National | 2,031 | 20.94 | 2,170 | 20.49 | 2,220 | 19.08 | 2,305 | 16.91 | 2,422 | 13.15 |
| Bangkok | 2,565 | 3.55 | 2,677 | 2.26 | 2,722 | 2.89 | 2,778 | 2.43 | 2,910 | 1.83 |
| North | 1,792 | 26.53 | 1,925 | 28.68 | 1,974 | 24.79 | 2,055 | 22.85 | 2,160 | 16.04 |

**Low income housing**

From the 2010 national census, the Bureau of Statistical Forecasting reports that 77% of families in the whole kingdom and 90% of families in the Northern Region live in detached houses as shown in Table 5.4. The same census also records that almost all dwellings are constructed with concrete block and cement only (54%), wood only (23%), and a combination of concrete block and cement and wood (22%).

**Table 5.4.** Types of dwellings, percent.

| Type of dwellings | National | Bangkok | North |
|---|---|---|---|
| Detached house | 77.3 | 45.7 | 90.2 |
| Twin/town house | 7.3 | 25.3 | 1.5 |
| Shop house/row house | 12.9 | 25.6 | 6.3 |
| Flat/condominium | 1.8 | 2.8 | 1.3 |
| Others* | 0.7 | 0.6 | 0.7 |

*Includes raft, room in office, dormitory, prison, and welfare homes.

After the Second World War, there was a period of high population growth. The government at the time invested heavily to improve utilities, sanitation, and infrastructures in cities, especially in Bangkok. The policies created economic opportunities that attracted rural people to Bangkok and that started informal settlement into vacant land plots, often near job sites in cities. In 1972, the National Housing Authority (NHA) was created to solve housing shortage by providing welfare housing to low-income people. A number of schemes were operated including some heavily subsidized housing projects, site and services scheme (where the NHA provided prepared site completed with access road, electricity, water supply, drainage, and sanitation services and clients design and construct their own houses), and semi-commercial scheme. In 2002, the government mandated NHA to provide 600,000 units of ‘Ban Eau Arthorn (BEA)’. These are constructed with the same designs for 4 types of housing, which are detached houses, twin houses, shop houses, and flats (4-storeyed multiple unit). The sites are chosen from different locations in the country, but more than half of them in Bangkok. The government subsidized about a quarter of the cost of each unit of about THB 400,000 and size of 30 $m^2$. Eligible Thai nationals are those that do not own land, having lived near the area where the site is located, and earning less than THB 15,000 per month (This was later increased to 30,000.). Eventually 270,466 units were built, some are still unoccupied, Usavagovitwong [60]. All houses built by NHA are located in urban or suburban areas and none in rural area.

An agency called 'Community Organization and Development Institute (CODI)', an off-shoot of NHA, was created in 1992 to improve slum dwellings and prevent further slum creation. The scheme called 'Ban Mankong (BMK)' as operated by CODI is to involve direct participation by each occupant in each site to secure the land for redevelopment into permanent, more livable, 'homes'. This scheme has been hailed as a successful 'demand driven' solution to low-income housing problems, Archer [2].

## 5.3 Objective scope and methodology of the surveys

The immediate objective of this project is to identify criteria and features for low energy, low emission, thermally, and visually comfortable designs of houses for low and medium income earners. The results are intended to be used for developing a rating scheme of house design that possesses such desirable features. It is also intended that the outputs from the project be utilized widely. Towards this end, the National Housing Authority (NHA) was invited to participate in this project (with NHA's own resources) from the beginning. Results obtained from each step are expected to be disseminated to NHA personnel and to the public. Furthermore, it is expected that the NHA would adopt the scheme and use it to rate designs of the houses that they construct. In the long run, it is hoped that the scheme could be used by the NHA to rate designs of houses of commercial developers on a voluntary basis.

In order to gain detailed baseline data of households of low income earners, it was decided to conduct surveys in all major regions of Thailand. For the Northern Region, it was decided that 3 units each of the four types of BEA housing from Chiangmai Province would be included in the survey. Another 10 detached houses in the same province deemed to belong to low income earners and selected by a local village head were also included. The survey would obtain baseline data to be used for analysis in order to develop criteria and features for improved designs. So the BEA designs are one set of baseline designs and the 10 selected detached houses, from which common features would be identified, form another baseline design. This paper reports only results from the survey of the 10 selected detached houses.

The survey acquired specific data listed in Table 5.5.

**Table 5.5.** Data acquired from the survey of sample houses.

| Required data | Details |
|---|---|
| General information | Income, education, age, family size, etc. |
| Energy uses | Appliances and time duration of use for lighting, cooking, entertainment and, amenity. |
| Trends in energy use | Occupants' views on trend on acquisition and replacement of appliances and switching of fuels used, e.g. for cooking |
| House history, configuration and materials | Configurations, dimensions and material used on roof, glazing and walls. |
| Indoor thermal and lighting condition | Visual and thermal sensation at the time of interview when illuminance, air temperature, relative humidity, wind speed, radiant temperature (from globe thermometer), and $CO_2$ were simultaneously measured. |

The survey took place in September 2014. The occupants were interviewed based on prepared questionnaire. The interviewers carried with them prepared information on electric power rating of types and makes of appliances and inspected each appliance during the interview. Lighting and data pertaining to thermal environment were measured by sensors and recorded on data logger. The measuring instruments, except the illuminance meter, were housed on a stand placed near the interviewee(s). Photographs were also taken on both interior and exterior of the house. In all cases, photographs were taken in the living quarter where the interview took place. In some cases, photographs were taken in all quarters of a house.

Each survey team comprised two groups. One group conducted interview while the other group inspected and photographed appliances used in different quarters and took note of the dimensions and materials used for roof, wall, windows, and floor. Representatives of the NHA took part in all surveys.

## 5.4. Results and discussion

Results from the survey are generally consistent with those from the census report published by the Bureau of Statistical Forecasting of the National Statistical Office.

*House design and features*

The traditional Thai house known as 'Ruen Thai Derm' is a wooden house on a platform raised on posts up by a floor height and comprises a gabled tapering roof. The house is well ventilated by open windows and doors and is well shaded by extended roof. Such house is commonly situated near river, water ways, or close to ponds of water, Jaijongrak [28]; [61]. Scarcity of hard wood and the changes in environment due to construction of roads and other factors influence tremendously the features of and materials used in modern houses.

The selected houses in the survey belong to low income earners in rural area. The older houses (more than 20 years), 2 out of the 10 surveyed, are constructed of wood and retain general features of 'Ruen Thai Derm'. However, the original platform or floor has been lowered almost to the ground level while the original walls and pitched roof are retained. Corrugated fiber cement tiles are used as roofing material (available since more than 40 years ago). Figure 5.1 shows photograph of one such house where it has a single story. It was discovered from the interview that as the owners aged, it was difficult to climb up the steep traditional stairs used in the old houses. Besides, the families were becoming smaller, so there was no need to retain 2 floors.

**Figure 5.1.** A wooden house.

All houses surveyed have only one floor. Two of the remaining 8 houses are constructed of concrete block and cement, and wood and are more than 10 years old. The parts of the walls under windows are constructed of concrete block and cement, and the upper parts comprise wood salvaged from original wooden walls (Figure 5.2 a)). The wall is laid up layers by layers of concrete block, bonded by cement mortar and plastered on both sides with cement mortar to form a smooth surface. The remaining 6 houses are less than 10 years old and are all constructed of concrete block and cement (Figure 5.2 b)). Hard wood suitable for housing construction is now scarce. The sample houses in the survey show clear trend that concrete block and cement was the choice in recent past. Such houses are sturdy and promote a sense of security. To some owners, such construction represents modern trend.

**Figure 5.2.** A house constructed with wood and concrete block and cement (a) and a house constructed with concrete block and cement (b).

The ratio of the number of houses constructed with concrete block and cement only, wood only, and concrete block and cement and wood from the survey is 3:1:1, while the ratio reported by the Bureau of Statistical Forecasting from the 2010 census in Section 5.2 is 2:1:1.

**Floor shape and area**

The common feature of all the houses surveyed is that the layout or the shape the floor is rectangular. Among the older houses there are no partitions into rooms (for example bedrooms). The owners used a part of the house as living quarter. At night, mattresses are laid on floor and mosquito nets are strung above the mattresses. Kitchen and toilet are located in opposite spaces on an extended area at the back of the house.

The floor area of the houses surveyed varies from 32 to 90 $m^2$. The average floor area is 72 $m^2$ and the average area per person is 34.4 $m^2$.

**Family size age distribution income and occupation of family members**

The number of members in a family in the surveyed households varies from 1 to 6 as in Table 5.6. It is noted that there are two distinct groups, where the family sizes in the first group are only up to 2, and the family sizes in the second group are at least 5. In the former group, the family members are either an elderly single person or two elderly persons, whose working age offspring are employed in the cities. The second group comprises extended families where elderly grandfathers and/or grandmothers live with the families. The occupation of such families is farming. These insights can be used to partially explain the statistics in Table 5.1. Availability of jobs in the cities is drawing away working age families from homes and the number of farmers is still shrinking. The average family size from the survey is 3.3. This figure is comparable to the figure of 3.1 for northern region in Table 5.1.

**Table 5.6.** The number of households in each family size.

| Family size, persons | Number of households |
|---|---|
| 1 | 2 |
| 2 | 4 |
| 5 | 1 |
| 6 | 3 |

Table 5.7 shows the number of persons in each age range of the surveyed households. The number of persons at age below 15 equals that of the elderly people (over 60 years old), and each constitutes 15% of the total. The same proportion of elderly people and the phenomenon of population aging are also observed regionally and nationally, Statistics Group 4 [53]. Moreover, an increasing percentage of old age people live alone, as can be observed in Table 5.6 and noted in Knodel [32]; [33] also notes that education and employment opportunities draw children and working age people away and leaving elderly

parents at homes. Also, there are many instances that elderly persons are emotionally attached to their homes and refuse to move to live with their offspring in another location.

**Table 5.7.** Age distribution of the surveyed houses.

| **Age, year** | **Persons** |
| --- | --- |
| <15 | 5 |
| 16-30 | 4 |
| 31-45 | 9 |
| 45-60 | 10 |
| >60 | 5 |

In terms of family income, 90% of the surveyed families earn less than THB 15,000 per month as shown in Table 5.8. Examining the figures in Table 5.1 and 5.2, the families fall into the category of low-income earners. Table 5.9 shows that 55% of household members are unemployed (retired persons and students), only 26% are privately employed near where they live and 7% are farmers with low income.

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**Table 5.8.** Family income distribution of the surveyed houses.

| Family Income | Number of households |
| --- | --- |
| Less than 5000 | 4 |
| 5001-15000 | 5 |
| 15000-30000 | 0 |
| More than 30000 | 1 |

**Table 5.9.** Occupation of persons in the surveyed houses.

| Occupation | Number of persons |
|---|---|
| Unemployed (retired) | 8 |
| Farmers | 2 |
| Students | 9 |
| Government employees | 2 |
| Small commercial | 2 |
| Employees (private) | 8 |

**Electricity consumption**

This paper reports only electricity consumption as it is the main interest of the project. Information on consumption of electricity by household appliances was obtained by reading electric bill of each household and from electricity used with each appliance in the household. The interviewer(s) would ask the house occupant(s) on the duration of use of each appliance and noted the type, size, and make of the appliance. Electricity consumption of each appliance is obtained from calculating the duration of use and its electric power rating. The power rating data of each appliance was comprehensively compiled from many sources, including information from laboratory tests. The value of electricity consumption (kWh) corresponding to each appliance from the 10 households appears in the third column of Table 5.10. Each value for each appliance is the collective value of the 10 households. The average electricity consumption per household per month is 191.7 kWh which is slightly lower than the 2011 national average of 223 computed from the annual value mentioned in Section 5.1. The average expense on electricity is THB 460. In the table, the appliances are grouped in accordance to the 4 main end-use categories of lighting, entertainment, amenity, and cooking. The proportion of each end-use category in Table 5.10 is similar to those reported by Kidhen et al. [31]. The use of personal computer, air-conditioner, and electric water heater among this group of low income households is rather unexpected.

The number of households that use air-conditioning is 3 while those that use electric hot water heating is 4. It is noted that a household that uses air-conditioning also uses electric hot water heating. One household uses electric water heating without using air-conditioning. The need for hot water for personal cleansing among elderly persons is one possible cause in this instance. Among the households that has air-conditioning and hot water heating, the average electricity consumption due to these two items per household is approximately180 kWh/month. This figure means that there was one air-conditioner that was turned on during night time.

**Table 5.10.** Electricity consumption of each appliance obtained in the survey.

| End-use Category | Appliance | Electricity consumption, kWh/month | Percentage of total | Percentage for each category |
|---|---|---|---|---|
| Lighting | Lamp | 190.1 | 9.9 | 9.9 |
| Entertainment | DVD player | 0.6 | 0.0 | 8.8 |
| | TV | 168.7 | 8.8 | |
| | CD player | 0.2 | 0.0 | |
| Amenity | Personal computer | 46.8 | 2.4 | 65.6 |
| | Washing machine | 44.9 | 2.3 | |
| | Vacuum cleaner | 22.4 | 1.2 | |
| | Water heater | 182.0 | 9.5 | |
| | Air- conditioner | 357.3 | 18.6 | |
| | Refrigerator | 293.2 | 15.3 | |
| | Iron | 48.0 | 2.5 | |
| | Printer | 2.4 | 0.1 | |
| | Fan | 260.2 | 13.6 | |
| Cooking | Toaster | 20.3 | 1.1 | 15.6 |
| | Electric stove | 28.0 | 1.5 | |
| | Microwave | 35.7 | 1.9 | |
| | Rice Cooker | 45.8 | 2.4 | |
| | Kettle | 170.1 | 8.9 | |
| Total | | 1916.7 | 100.0 | 100 |

Figure 5.3 shows plots of electricity consumption against floor area of household, family size, and family income. All three plots exhibit certain degree of correlation between electricity consumption and each of the three parameters, but its correlation with family income is clearest. The top electricity consumers are also the households that have air-conditioning and electric hot water heating.

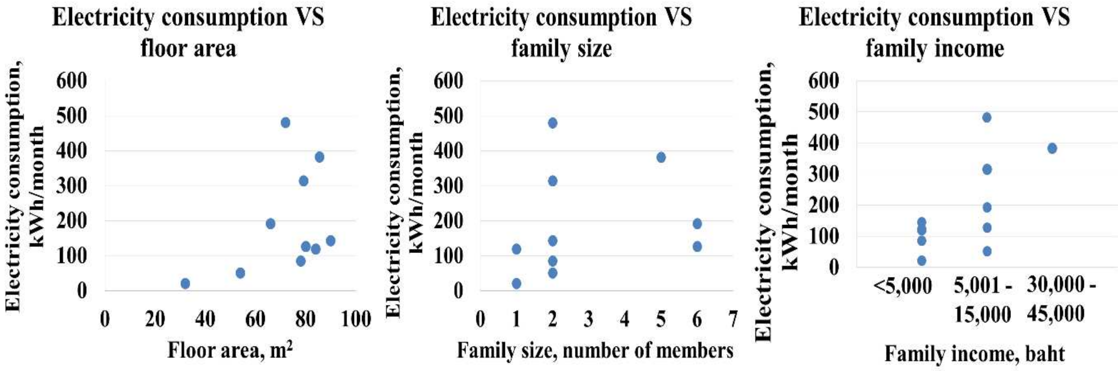


**Figure 5.3.** Plots of electricity consumption against floor area (a), family size (b) and family income (c).

**Thermal environment and thermal comfort assessment**

Major features of traditional houses, of extended roofs that shade solar radiation well and open windows and doors that allow air to flow through, were present in the houses surveyed. In addition, most houses have ceiling under roofs that help reduce thermal radiation from the roofs into the spaces below. During the time of visit, the interior air temperature and radiant temperature did not differ to significant extent from the exterior ambient temperature. This condition prevailed in most houses and was sufficiently amenable for residents to live in the houses. September month is in the late rainy season, the air would be humid and hot as the sun is near the zenith at noon. Table 5.11 shows results of measurement of interior environmental parameters. The range of air temperature recorded during the time of visit (daytime only) is typical for the time of the year. The non-zero air speed implies that fans were turned on and the houses were well ventilated. The relatively low level of carbon dioxide recorded implies that the spaces were sufficiently naturally ventilated.

**Table 5.11.** Values of thermal environmental parameters.

| Range | Air temperature, ˚C | Relative humidity, % | Radiant temperature, ˚C | Air speed, m/s | Carbon dioxide, ppm |
|---|---|---|---|---|---|
| Maximum | 34.1 | 70.3 | 34.5 | 0.8 | 537 |
| Minimum | 30.6 | 58.9 | 31.1 | 0.2 | 460 |
| Mean | 32.4 | 65.1 | 32.6 | 0.6 | 494 |

For thermal comfort assessment, the ASHRAE 7-point scale was used. The interviewee(s) would be told to equate the +3 point to the condition that he/she would feel when he/she is seated at the same position during daytime in the month of April (warmest in Thailand), and the -3 point to the December month (coolest). Figure 5.4 shows plots of the thermal sensation values (TSV) obtained against operative temperature, $T_{o.}$ As is expected, most respondents reported 'warm and too warm' sensations even when electric fans were on. For this group of respondents, the neutral temperature is obtained as 29.2$^o$C. This is the projected value and is outside the range of air temperatures measured, but is not unexpected.

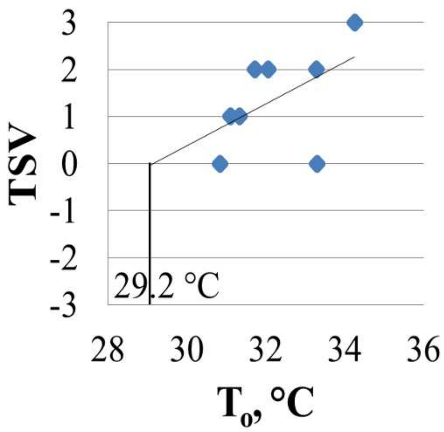


**Figure 5.4** A plot of thermal sensation values against operative temperatures.

**Lighting condition**

Daylight illuminance at work plane level in the living quarters and bedroom of households was measured by an illuminance meter. Table 5.12 shows the resulting values.

Most values are as expected but deemed to be on the slightly low side. Wooden walls are not painted and the color of the surfaces appears dull brown and has low reflectance for light. Spaces enclosed by such walls would tend to be less illuminated. No measurement was recorded in three houses. The values corresponding to those of house no. 7 and 8 appear to be too low. One occupant in house no.7 was ill and so windows were intentionally closed to reduce light. The occupant in house no.8 did not reside in the house and windows were closed.

**Table 5.12.** Values of illuminance at work plane level, lux.

| Space | House number | | | | | | | | | | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
| Living quarter | - | 225 | 200 | 740 | - | - | 42 | 70 | 250 | 424 | 278 |
| Bedroom | - | - | - | - | - | - | - | - | - | 265 | 165 |

**Carbon dioxide emission**

This paper considers carbon dioxide emission from a house in two parts. One part is indirect carbon dioxide emission due to the use of electricity, and carbon dioxide emission from generation of electricity. The other part is carbon dioxide emission during production of materials used to construct the house.

The houses surveyed comprise some houses that are constructed from wood, and the combination of wood and cement. However, it is clear that the trend in the near future is the preference for concrete block and cement for walls. Materials for construction are readily available, the time required for construction is short, and the finished wall is economic. In the followings, a house model is used that is envisaged as a representative detached house of the Northern Region. Calculation will be made on carbon dioxide emission from construction materials used and indirect emission from the consumption of electricity of the model house.

Figure 5.5 shows a perspective rendering of the model house. There is an external space under roof in front of the house. This space is used to welcome casual guests or for casual relaxing activities in the early morning or early evening.

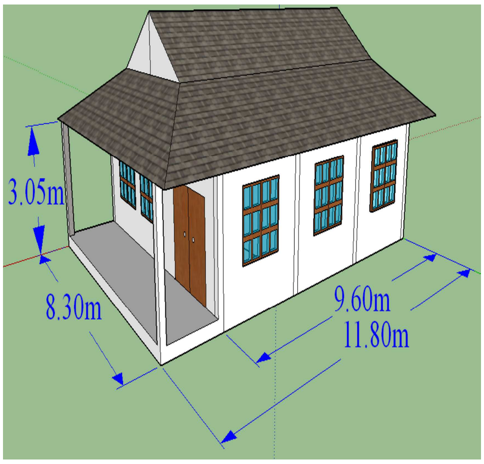


**Figure 5.5.** Perspective view of the house model.

The house has an interior dimension of 9x8.3 = 74 $m^2$ and height of 3 m. The house has two bedrooms.  Kitchen, cloth washing, restroom (toilet and bathroom) are located on a separate but immediate space at the back of the house. The supporting columns are steel-reinforced concrete. The walls are constructed from plastered cement blocks. The pitched roof comprises corrugated fiber cement tiles laid on metallic support. Ceiling comprises fiber cement panels. Windows comprises flat 5 mm glass with wooden frame. Doors are made of wood. The floor is reinforced concrete.

Table 5.13 shows quantities of building materials used, emission factors with references, and calculated carbon dioxide emissions. Total carbon dioxide emission from construction materials (so-called ‘embedded carbon dioxide’) is 12,699 kg or 12.7 ton. The top major contributors to the emission are concrete, cement, and steel. Here, wood is not counted where in some situation it could be considered to contribute negatively.

**Table 5.13.** Quantity and type of construction material, emission factor and $CO_2$ emission.

| Item | Quantity, kg | Emission factors, kg $CO_2$/kg material | Reference | Emission, kg $CO_2$ |
|---|---|---|---|---|
| Sand | 7,472 | 0.0037 | TGO | 28 |
| Concrete block | 41,135 | 0.130 | University of Bath (2008) | 5,347 |
| Cement | 6,432 | 0.490 | TGO | 3,152 |
| Steel | 968 | 1.25 | SimaPro 7.1 | 1,210 |
| Roof tiles | 2,182 | 0.353 | SimaPro 7.1 | 770 |
| Fiber cement panels | 736 | 1.09 | University of Bath (2008) | 803 |
| Lime | 532 | 0.740 | University of Bath (2008) | 394 |
| Glass | 881 | 1.130 | SimaPro 7.1 | 996 |
| Total | | | | 12,699 |

TGO (Thailand Greenhouse Gas Management Office) is a Thai government unit, University of Bath is the university bearing this name in the United Kingdom, and SimaPro is a computer-database software.

The electricity consumption of the surveyed households per month in Table 5.10 is 191.7 kWh or 2,300 kWh per household per year. The Thailand Greenhouse Gas Management Organization – the officially designated organization for matters on greenhouse gas, TGO (2010), uses an emission factor of 0.6093 kg $CO_2$/kWh for the present mix of fuels used in electric power generation. Total emission for the model house throughout its life is then

35.02 + 12.7 = 47.72 ton $CO_2$, if the life of the house is 25 years, or

70.04 + 12.7 = 105.74 ton $CO_2$, if the life of the house is 50 years.

The Finance Ministry allows a life of 25 years for buildings for the purpose of depreciation calculation, but there is no consensus in Thailand on the economic life time of a house.

The resulting extent of energy use carbon emission obtained above will be the reference values for the Northern Region in the project. However, in future it is more likely that the low-income earners would become middle income earners and consume electricity at a rate that is more than twice the figure used here, as they will have air-conditioning and use electric hot water heating.

## 5.5 Conclusion and Policy Implications

The survey conducted meets the set objective. The socio-economic conditions of the surveyed houses match with those from national census, so that a model house with detailed features and construction could be formed to represent contemporary (and immediate future) houses of low income earners of the Northern Region. From the surveyed results on electricity consumption and construction materials identified, carbon dioxide emission from construction materials used (‘embedded carbon dioxide’) and from occupants’ daily activities while occupying the house have been quantified. The investigation on thermal comfort illustrates that rural houses are reasonably comfortable with natural ventilation, at least during the duration of the survey. Present house design and features also allow natural daylight into the interior during daytime without the need for electric lighting.

Thailand has adopted an energy conservation plan since 2011, The Energy Policy and Planning Office [56]. The plan for residential buildings dwells mainly on voluntary programs for energy efficient appliances, especially air-conditioners and hot water heaters. There is no specific program on the house design and construction since no suitable information was available during the plan development. Implementing building energy standards and codes are effective means to foster energy efficient buildings, Lauston [38], Iwaro and Mwasha [27]. Adopting and enforcing a mandatory code on residential buildings is unlikely to be accepted in Thailand soon. Introducing and promoting a voluntary rating scheme for design of residential houses is plausible. Granadeiro et al. [23] consider that the most significant component that affects energy performance of a building is the building envelope. The energy and environmental rating scheme for house design will therefore addresses building envelope. This will include development of an energy performance indicator for thermally efficient and cost effective walls and roof. The scheme will include a requirement on design that enhances sufficient natural flow of air for ventilation and thermal comfort and entry of daylight for lighting. The rating scheme will utilize information from the survey to form baseline design and include guidelines to achieve more efficient and more environmental benign cost-effective design.

# CHAPTER 6
# A STUDY ON FORMULATION OF AN OTTV FOR WALLS OF RESIDENTIAL BUILDINGS IN THAILAND

## 6.1 Introduction

In Thailand, air-conditioning penetrates up to 18.6% in households country-wide and 37.4% in Greater Bangkok (Bangkok and 3adjacent provinces) and is steadily increasing [5] in all areas at a rate close to 6% per year. Air-conditioning contributes to electricity consumption substantially in households that possess air-conditioners. Residential sector consumes electricity at 22.3% and together with commercial sector consume 57% of total in Thailand [20], where this extent is similar to that observed globally [49]. Chan et al. [10] assert that buildings consume 89% of electricity in Hong Kong and air-conditioning contributes a substantial proportion. These figures underscore the importance of energy efficiency in residential buildings.

Implementing building energy efficiency standards and codes are effective means to foster energy efficient buildings that lower energy consumption in this sector [27; 38; 57]. As further noted by Iwaro and Mwasha [27], in almost all countries in Asia and Africa, energy codes and standards for buildings, if exist, apply to non-residential buildings only. At present, all large commercial buildings in Thailand and other ASEAN countries are air-conditioned, while a certain percentage of residential buildings are air-conditioned.

For countries in hot climate, heat gain though exposed building walls is expected to contribute a significant share of the cooling load of an air-conditioned residential space. It is therefore expected that any energy conservation standards and programs for the residential sector must address energy performance of exposed walls. Overall thermal transfer value (OTTV) as energy performance indicator for building walls has been used in Singapore [19], in Hong Kong [63], and in Thailand [13]. Chua and Chou [19] note that air-conditioning was increasingly used in residential buildings in Singapore. In order ‘to ensure that building envelope designs are suitable to be operated under air-conditioned environment, the $ETTV_{res}$ (effective thermal transfer value for residential buildings) and the code requirement on its value for residential buildings was introduced in 2008’. The authors also demonstrate through building energy simulations that cooling loads of two building models vary linearly with $ETTV_{res}$ . In another paper, the same authors show results of an energy simulation on two sample residential blocks that each unit reduction in the $ETTV_{res}$ of each block brings about savings of cooling loads of 3.5-4.0% [18]. A division of the IEA publishes a document to assist countries in planning, implementing, and monitoring building envelopes [36]. The document explores existing and emerging technologies for energy efficient (EE) building envelopes and suggests policy directions to transform to EE buildings. Sadineni et al. [50] examine passive means for building energy savings and review the effectiveness of past and existing means to improve components of building envelopes. Chiraratananon and Hien [11] investigate thermal performance of massive walls enclosing commercial and residential spaces in Thailand and reports that thermally massive walls retain more heat during daytime and release it into the enclosed space during the night. The authors conclude that thermally massive walls are not cost-effective. Chirarattananon et al. [15] examine use of insulation on exposed walls of buildings serving commercial functions while Tummu et al. [59] investigate the use of insulation on exposed walls of residential buildings under Thai climate and both conclude that insulation on the interior surface of an exposed wall improves its thermal performance, but its cost-effectiveness depends on the wall and window configuration as well as the function the enclosed space serves. Granadeiro et al. [23] consider that the most significant component that affects energy performance of a building is the building envelope, the authors then proceed to formulate an indicator for design of building envelope based on the use of heating and cooling degree days, total solar radiation in the heating and cooling seasons, envelope parameters such as U-value, solar heat gain coefficient, shading coefficient, and window area, and set-point temperature for the interior.

This paper presents a functional formulation for OTTV as the measure of thermal performance of building walls enclosing spaces used under bedroom function. This development represents a part of an attempt to develop a building energy performance measures for residential buildings in Thailand. Bedroom function is the major residential function in the use of a residential household. Presently there is a statutory building energy code (BEC) for commercial buildings in which OTTV is used as the thermal performance measure for walls. The impetus for the present work partly arises from a project called 'Energy and Low-income Tropical Housing', a multi-partner project funded under Energy Programme of the UK Research Council. The project will develop a scheme for rating energy and carbon performance of designs of residential buildings in which envelope performance constitutes a major part. Surveys undertaken within the project found that existing houses are well-shaded so overall exposure to solar radiation is limited. In consonance with the existing practice, bedrooms with only one exposed wall are considered. Furthermore, effective total window area is restricted to 30% of total exposed wall area.

## 6.2 Thermal environment and residential building model for simulation

The method used in this paper to obtain the desired OTTV formulation is to perform simulation using a generic building model where its main interior spaces are used under the bedroom function. The building is assumed located in the central region of Thailand and the weather data of the whole of year 2000 is used.

### 6.2.1 Thermal environment and building shell

The Thai climate is hot and humid. For the central region, which is our reference location, annual average temperature is 28.63 $^{o}$C, daytime (06.00-18.00) average is 30.76, night time (18.00-06.00) average is 26.10, and the average for the duration of our bedroom function (21.00-06.00) is 25.58. Solar radiation and relative humidity are high all year. Figure 6.1 shows graphs of global, $I_{gloH}$, diffuse horizontal, $I_{skyH}$, and sun normal, $I_{sunN}$, solar radiation and ambient dry-bulb temperature, $T_{amb}$, relative humidity, $RH_{amb}$, and sky temperature, $T_{sky}$, for 3$^{rd}$ and 4$^{th}$ March 2000. These two days at the beginning of hot and dry season are rather clear and are the days used for illustration in Section 6.4.

As noted in [11], traditional Thai dwellings are constructed from natural materials of low mass. Modern residential buildings are constructed with materials produced by the construction industry. Walls typically comprise concrete blocks, concrete slabs, or light weight concrete, which are more massive than those used in the past. Lighter walling materials are also available such as wood-like fiber board, but these are typically used as decorative panels. Windows are glazed with single-pane clear float glass, but green glass and even manufactured two-layer insulating glasses are also used. Wall configurations and values of material properties used in the simulation conform to those used in the construction industry.

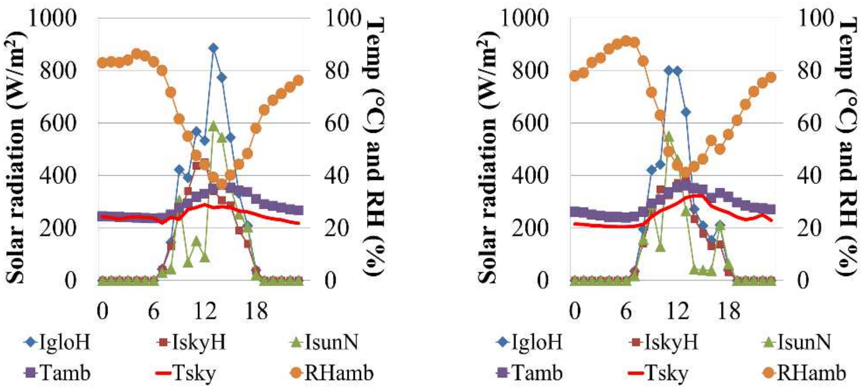


**Figure 6.1.** Solar radiation and temperature of 3rd and 4th March 2000,

a) 3 March 2000, b) 4 March 2000.

### 6.2.2 Building model

A generic building model comprising three floors where the main spaces are all assumed to serve bedroom function is used. The model is identical to that used in [15; 59]. In order to avoid the effect of heat transfer through roof and floor, only results of the middle floor are used in the present study. The configuration of the middle floor is shown in Figure 6.2. The shape of the building is square with dimensions shown. The peripheral zones are identical, are air-conditioned during the bedroom hours, and each face a cardinal direction. The core zone is un-conditioned. The windows appear as the color-shaded upper section of the walls.

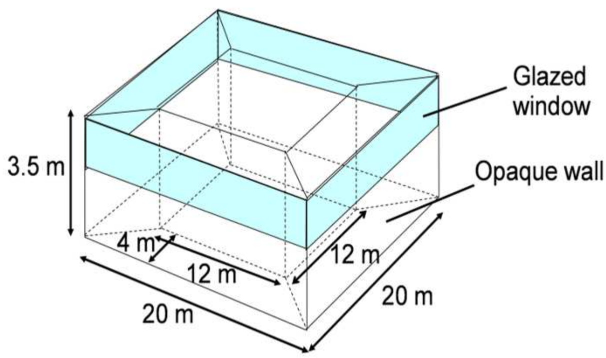


**Figure 6.2.** The configuration of the middle floor of the building model.

In order to obtain parameters for each exposed wall in the OTTV formulation, its thermal properties will be varied. In addition to changing optical and thermal properties, placement of insulation will be considered for each wall surface. Optical and thermal properties of windows will be varied as well. As will be seen later, thermal properties of interior wall surfaces will also be varied.

### 6.2.3 The BESim program

This computer program is used in the simulation runs. It was developed earlier and was described in a number of researches reported in [11; 15]. The program uses local meteorological data to calculate dynamic heat transfers under the principle of energy balance. It accounts for solar, short wave, and long wave radiation heat transfers using numerically calculated view factors. Thermal radiation exchanges between interior surfaces are accounted. A zone can be air-conditioned or naturally ventilated.

## 6.3 A Hypothesis on the OTTV formulation

The standard form of OTTV is

$$OTTV = (1 - WWR)(U_w)(TD_{eq}) + (WWR)(U_f)(\Delta T) + (WWR)(SHGC)(ESR) \qquad (6.1)$$

where $U_w$ is to be calculated based on wall compositions using ASHRAE thermal condition for summer,

$TD_{eq}$ represents the equivalent average temperature difference across the opaque wall section that accounts for solar radiation, thermal radiation exchanges at the surfaces, and temperatures of ambient and interior air,

$U_f$ is to be calculated based on standard thermal condition for summer,

$\Delta T$ represents effective temperature difference across the glazing,

SHGC is to be calculated in accordance with optical and thermal properties of glazing using standard condition, and

ESR represents effective solar radiation on the glazed window.

For Singapore, OTTV represents overall heat gain across a given building envelope [19]. For Thailand, OTTV for commercial buildings represents cooling coil load (CCL) of the air-conditioning system due to heat gain across the envelope per unit area of the envelope [13]. Such CCL is obtained from computer simulation using a generic building model. The values for $TD_{eq}$, □□□ and ESR are obtained from regression procedure using (6.1) when WWR, $U_w$, $U_f$, and SHGC on the RHS of (6.1) are varied and the resultant values of CCL per unit envelope area is used on the LHS of (6.1). In applying such procedure, it is assumed that $TD_{eq}$ is independent of $U_w$, and ESR is independent of SHGC, etc.

For the present case of residential space used under the bedroom function, there is *no solar radiation present on the building envelope throughout the duration of the bedroom function*. However, *studies in [15; 59] illustrate that solar radiation on the exposed wall and its transmission into the interior space during daytime is stored as heat in the exposed wall and in the interior walls*. This stored heat will be transferred to air and contributes to CCL during the bedroom period. The OTTV formulation for the bedroom function should reflect this storage effect.

The hypothesis on the formulation of a thermal performance measure for a wall enclosing a space serving the bedroom function is that it takes the form

$OTTV_{br}$ = (1-WWR)(CCL due to conduction heat gain and stored heat in opaque wall)

+ (WWR)(CCL due to heat stored in the interior room mass due to absorbed transmitted solar radiation) (6.2)

+ (WWR)(CCL due to conduction heat gain through glazing and stored heat in the interior room mass).

The three terms are postulated to be independent of the other. The first term represents CCL due to conduction heat gain through the opaque section during the bedroom period and that due to stored heat from absorption of solar radiation on the section during daytime. The second term represents CCL due to heat stored in the interior walls from absorption of transmitted solar radiation during daytime. The third term represents CCL due to conduction heat gain through the transparent or glazed section during the bedroom period and that due to heat transferred and stored in the interior walls during daytime.

### 6.4. Proof of the hypothesis and elaboration of the terms of $OTTV_{br}$

Each term in (6.2) is considered consequentially as follows.

#### 6.4.1 Opaque wall term

Consider Equation (6.2), let WWR = 0 and let the product ($U_w$) ($TD_{shw}$) represents CCL during the bedroom period of the building model in Figure 6.2, i.e.

$$CCL = (U_w)\,(TD_{shw}). \tag{6.3}$$

Here, $TD_{shw}$ is the equivalent temperature difference due to conduction heat transfer through wall and that due to stored heat in the wall from solar radiation absorbed during the time prior to the bedroom period. In order to obtain its values for different wall compositions, properties of the opaque wall material and of its surface are varied to obtain different values of CCL during the bedroom period. A layer of 50-mm polystyrene foam insulation is added at the *interior wall surface* as an option on wall compositions. Table 6.1 lists the ranges of variation of relevant properties and values of $U_w$. The thickness of the wall is 0.1m. The entry in the second column, DSH, is 'density-specific-heat-wall-thickness product, or thermal mass of wall.

**Table 6.1.** Variation of wall properties and values of $U_w$.

| **Wall orientation** | **DSH, kJ/m$^2$** | **Solar absorptance** | **Thermal conductivity, W/(m·K)** | **Values of $U_w$, W/(m$^2$·K)** |
|---|---|---|---|---|
| North, south, east, west | 25.2 – 252.0 | 0.1 – 0.9 | 0.3 – 2.0 | 0.34- 3.63 |

Results in [59] conclude that insulation placed on the exterior surface of an exposed wall of bedroom can adversely affect its thermal performance, so this study considers only *placement of insulation on the interior surfac*e. Figure 6.3 shows plots of CCL of the bedroom period against values of $U_w$ of walls in each direction and for three values of wall thermal mass.

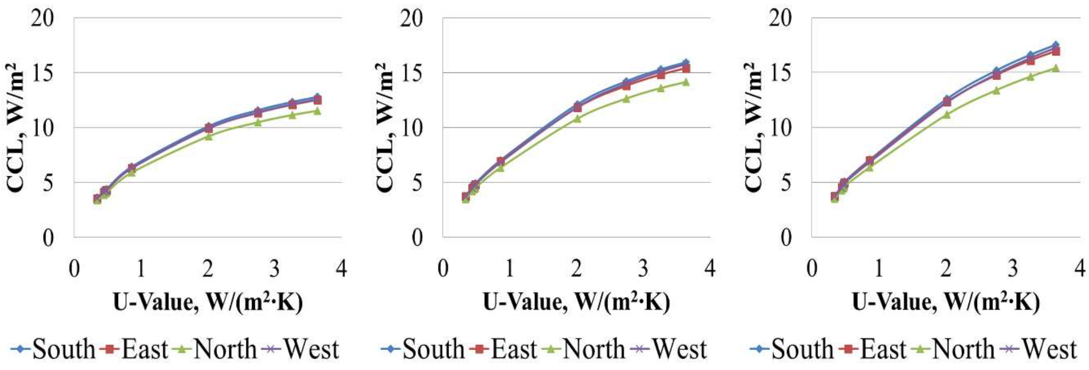


**Figure 6.3.** Plots of CCL of walls of four directions against $U_w$ for three values of wall thermal mass, a) DSH = 25.2 kJ/m$^2$, b) DSH = 148.0 kJ/m$^2$, c) DSH= 252.0 kJ/m$^2$.

The plots show a saturation effect of CCL. In the case of commercial spaces this effect is unexpected. In order to understand this phenomenon in the present case, there is a need to examine the situation in some detail. Figure 6.4 shows plots of heat gain components across walls of thermal mass of 148 kJ/m$^2$, solar absorptance of 0.3, oriented towards south, and of three values of $U_w$, The plots cover the duration between 06.00 hours of 3$^{rd}$ March and 10.00 of 4$^{th}$ March 2000. The value of $U_w$ of Wall 1 in the left most figure is 0.86, and those for Wall 2 and Wall 3 are 2.245 and 3.63. The value 2.245 is half of the sum of 0.86 and 3.63. *The solid line in each graph represents net heat flux gain into the wall*. Two periods can be distinguished from the plots. The first period of charging heat into the walls (when net heat flux gain into wall is positive) spans from 06.00 to around 17.00 of the 3$^{rd}$ of March and the second period of discharging heat from the walls is from around 17.00 to the end of the bedroom period. The magnitude of heat charging during the first period, and that of discharging during the second period, increases with the value of $U_w$ of a wall. Also, the charging period becomes shorter for the cases with higher value of $U_{w.}$ Moreover, for walls with higher values of $U_w$, the higher magnitude of heat charging during the morning and afternoon is followed by higher level and longer duration of heat loss from the same wall during late afternoon and evening prior to the bedroom period. Table 6.2 gives a summary of the net heat gain of each wall before and during the bedroom period.

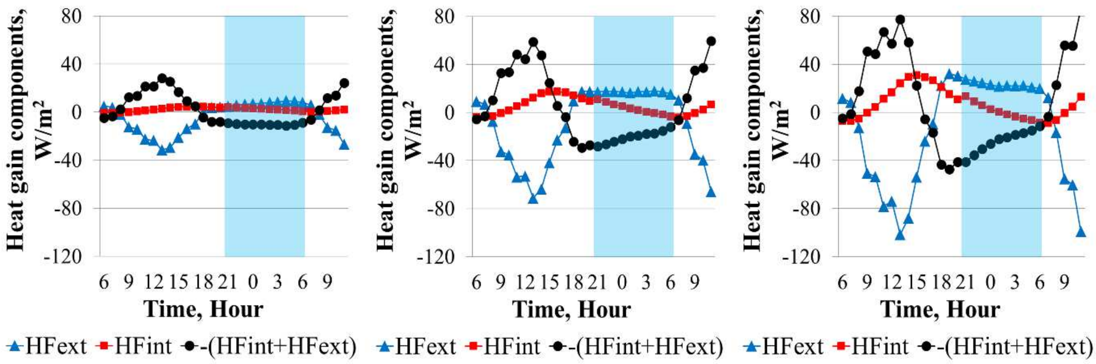


**Figure 6.4.** Heat gain components on the walls of three values of $U_w$, a) $U_w = 0.86$ $W/(m^2 \cdot K)$, b) $U_w = 2.245$ $W/(m^2 \cdot K)$, c) $U_w = 3.63$ $W/(m^2 \cdot K)$.

**Table 6.2.** Net heat gain on each wall and the difference during the two periods.

| **Wall →** | **Wall 1** | **Wall 2** | | **Wall 3** | |
|---|---|---|---|---|---|
| **Quantity →** **Period** | **Net gain, $Wh/m^2$** | **Net gain, $Wh/m^2$** | **Increase over Wall 1** | **Net gain, $Wh/m^2$** | **Increase over Wall 2** |
| Duration 06.00 – 21.00 | 127.6 | 213.3 | 85.7 | 239.7 | 26.4 |
| Duration 21.00 – 06.00 | -92.3 | -191.0 | -98.7 | -226.1 | -35.1 |

The values from the table show that all walls have net positive gains during the first period and negative gains or losses during the bedroom period. The losses contribute to the air-conditioning load. The figures also show that for the first period, there is diminishing increase of net heat gain of Wall 2 over Wall 1to that of Wall 3 over Wall 2. Similar effect is observed on the losses during the bedroom period. This pattern is consistent with what is observed from Figure 6.4. These results that include diminishing increase in heat loss from walls as $U_w$ increase are consistent with the observed saturation effect of CCL in Figure 6.3.

From results such as those in Figure 6.3 and using the relationship (6.3), the values of $TD_{shw}$ are obtained and plotted in Figure 6.5.

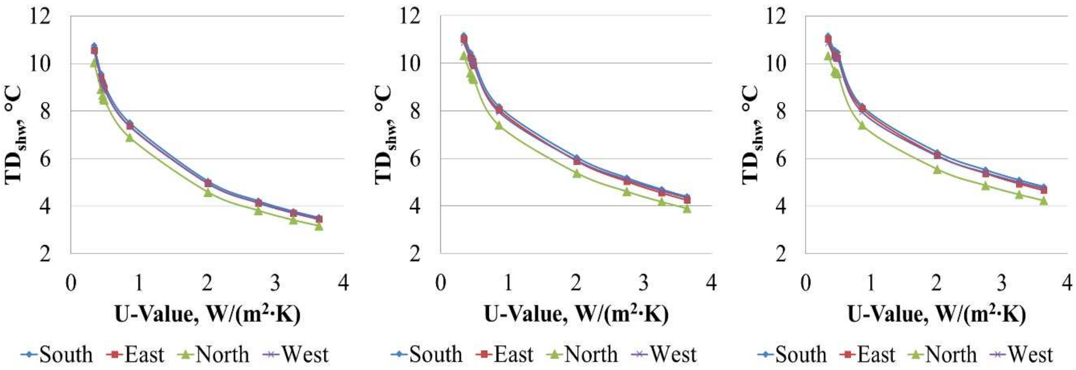


**Figure 6.5.** Plots of $TD_{shw}$ against U-value of walls of varying density, a) DSH = 25.2 kJ/m$^2$, b) DSH = 148.0 kJ/m$^2$, c) DSH = 252.0 kJ/m$^2$.

The plots in Figure 6.5 imply that $TD_{shw}$ is a nonlinear, decreasing function of $U_w$ and is a weak function of wall orientation. However, it varies strongly and linearly with solar absorptance of the exterior surface of wall as shown in Figure 6.6. The patterns of $TD_{shw}$ in Figure 6.5 and 6.6 imply that it should vary weakly with wall thermal mass. The pattern in Figure 6.7 confirms this observation. The effect of thermal mass is more pronounced for walls of higher $U_w$ and higher solar absorptance.

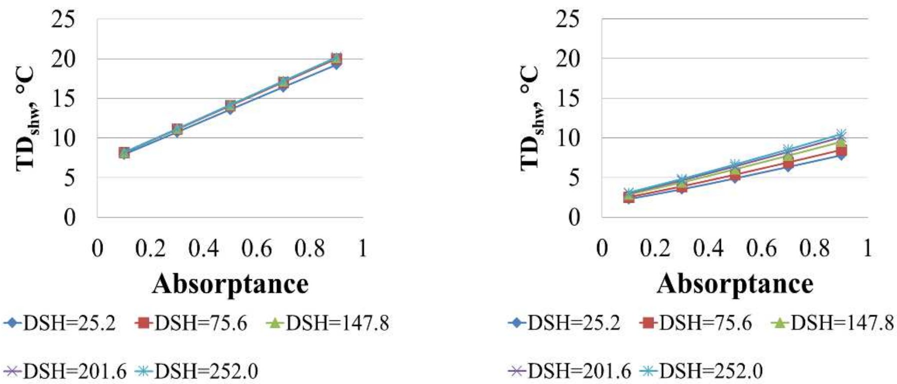


**Figure 6.6.** Plots of $TD_{shw}$ against solar absorptance of wall surface,
a) $U_w$ = 0.34 W/(m$^2$·K), b) $U_w$ = 3.63 W/(m$^2$·K).

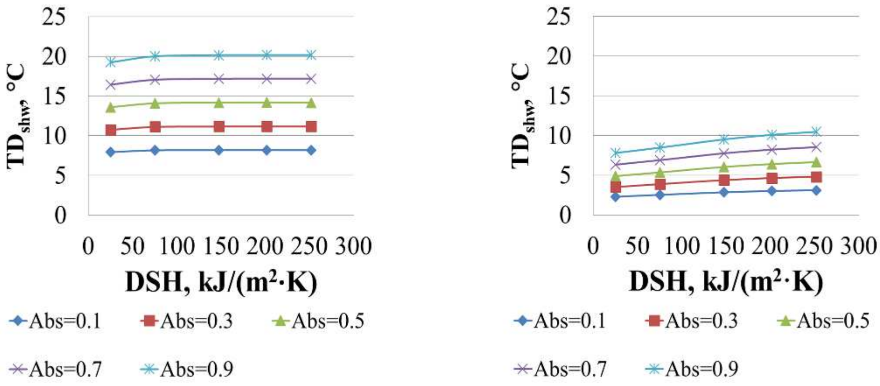


**Figure 6.7.** Plots of $TD_{shw}$ against wall density, a) $U_w = 0.34$ W/(m$^2$·K), b) $U_w = 3.63$ W/(m$^2$·K).

The pattern of $TD_{shw}$ in Figure 6.5 appears to resemble exponential decay function. Indeed, the following functions are derived from least squares curve fitting for the south and north oriented walls.

$$TD_{shw} = (10.48\alpha_s + 5.79)e^{(0.265\alpha_s - 0.692)U_w} + 5.41\alpha_s + 0.0075DSH + 0.574 \quad \text{for south,}$$
$$TD_{shw} = (8.79\alpha_s + 5.78)e^{(0.218\alpha_s - 0.700)U_w} + 4.15\alpha_s + 0.0061DSH + 0.819 \quad \text{for north,} \quad (6.4),$$

where $\alpha_s$ is the solar absorption coefficient.

### 6.4.2 The window and glazing terms

Consider the case where there is a window on each exposed wall in Figure 6.2. Now CCL that occurs during the period of bedroom function is postulated to comprise two independent sources. The first source is the conduction heat transfer through the exposed opaque wall and heat stored in it prior to the bedroom period. This first part is dealt with and characterized in Section 6.4.1. The size of CCL due to this source can be calculated as product of (1-WWR), $U_w$, and $TD_{shw}$. The second source includes the heat and solar radiation transfer through glazing and absorbed by internal walls and masses prior to the bedroom period and heat transfer during the bedroom period. The CCL due to the second source is represented by two terms as follows

$$CCL_G = (SHGC)(ASH) + (U_f)(CTD) \quad (6.5)$$

where $CCL_G$ is the glazing term or the CCL due to the second source, here with window of size WWR. The first term in (6.5) represents CCL due to heat from solar radiation transmitted and absorbed prior to the bedroom period while the second term represents conduction heat transfer through glazing both prior to and during the bedroom period.

**Extraction and separation of the glazing term**

First consider a specific case where the exposed opaque wall and all internal walls, floor and ceiling have identical thermal properties shown in Table 6.3.

**Table 6.3.** Thermal properties of the exposed wall and interior walls.

| **Thermal conductivity,** W/(m·K) | **DSH,** kJ/m² | **Solar absorptance** | **Thermal absorptance** |
|---|---|---|---|
| 0.7 | 1,760 | 0.5 | 0.9 |

With the given thermal conductivity, $U_w$ of the exposed wall is obtained as 3.26, and the CCL/m$^2$ due to the given exposed opaque wall is given in Table 6.4.

**Table 6.4.** CCL/m$^2$ due to the exposed opaque wall, W/m$^2$.

| **South** | **East** | **North** | **West** |
|---|---|---|---|
| 21.05 | 20.14 | 17.88 | 20.64 |

**The term related to transmitted solar radiation**

In the next step, a series of simulation runs was conducted to obtain CCLs during the bedroom period of the model in Figure 6.2 when the exposed wall comprise an opaque wall section of properties given in Table 6.3 and a glazed window section with a fixed U-value of 5.822. In the set of simulation runs, the size of the window, i.e. WWR, and its optical properties, the solar heat gain coefficient (SHGC), take on successive values in column 1 and 2 in Table 6.5. The resulting CCLs with the given wall and windows with given glazing are shown in column 3, 5, 7, and 9 *under the heading* 'W&G' for the given wall orientation in Table 6.5.

**Table 6.5.** CCLs, W/m$^2$**,** of bedroom with given combination of opaque wall and windows.

| *SHGC* | *WWR* | **South** | | **East** | | **North** | | **West** | |
|---|---|---|---|---|---|---|---|---|---|
| | | **W&G** | **G only** | **W&G** | **G only** | **W&G** | **G only** | **W&G** | **G only** |
| **0.387** | **0.15** | 29.19 | 11.29 | 27.74 | 10.63 | 24.33 | 9.13 | 28.42 | 10.88 |
| **0.507** | **0.15** | 30.87 | 12.98 | 29.31 | 12.20 | 25.72 | 10.52 | 30.04 | 12.49 |
| **0.606** | **0.15** | 32.98 | 15.08 | 31.27 | 14.16 | 27.38 | 12.17 | 32.03 | 14.49 |
| **0.693** | **0.15** | 34.45 | 16.55 | 32.63 | 15.52 | 28.56 | 13.36 | 33.43 | 15.89 |
| **0.834** | **0.15** | 36.96 | 19.06 | 34.96 | 17.85 | 30.56 | 15.36 | 35.82 | 18.27 |
| **0.387** | **0.30** | 30.53 | 15.79 | 28.97 | 14.87 | 25.34 | 12.82 | 29.70 | 15.25 |
| **0.507** | **0.30** | 32.65 | 17.91 | 30.93 | 16.83 | 27.07 | 14.56 | 31.74 | 17.29 |
| **0.606** | **0.30** | 35.29 | 20.55 | 33.38 | 19.29 | 29.16 | 16.64 | 34.26 | 19.81 |
| **0.693** | **0.30** | 37.13 | 22.39 | 35.08 | 20.98 | 30.64 | 18.12 | 36.03 | 21.58 |
| **0.834** | **0.30** | 40.26 | 25.53 | 37.98 | 23.88 | 33.14 | 20.62 | 39.03 | 24.58 |

In order to obtain values of CCL due to glazing only, the portion of CCL due to the opaque part of the wall must be removed. According to the postulate, this portion of CCL can be obtained proportionately to wall area from the CCL of exposed opaque wall in Table 6.4. The size of this CCL is $CCL_{OW}$ where

$$CCL_{OW} = (1\text{-}WWR)(\text{CCL in Table 6.4}). \qquad (6.6)$$

The CCL due to the glazing of given size and given optical and thermal properties is then obtained as $CCL_G$ where

$$CCL_G = (\text{CCL under'W\&G' in Table 6.5}) - CCL_{OW}. \qquad (6.7)$$

The resulting values of $CCL_G$ is shown under the heading ‘G only’ in Table 6.5. Figure 6.8 shows a plot of the values of $CCL_G$ for the *north wall* against the product (SHGC*WWR). These values represent *fractions of CCL due to transmitted solar radiation across window of size WWR of the wall area and glazing with given SHGC*. The corresponding quantity in (6.1) is a linear function of (SHGC*WWR). In the present case, the relationship is not strictly linear. The power function that fits the plot under the least-square criterion is

$$CCL_G \approx f_{CG}(SHGC, WWR) = 41.994(SHGC * WWR)^{0.5284} \tag{6.8}$$

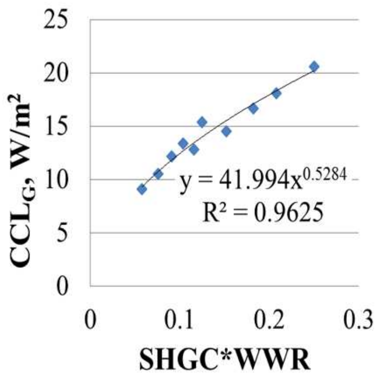


**Figure 6.8.** Plots of $CCL_G$ against SHGC*WWR.

Since $CCL_G$ in (6.7) and (6.8) is obtained as cooling coil load due to window of relative size WWR and glazing of given SHGC, the value of ASH, the absorbed solar radiation heat equivalence of ESR in (6.1), is then obtained as the slope of the curve in Figure 6.8, i.e.

$$ASH = \left.\frac{d(41.994(SHGC * WWR)^{0.5284})}{d(SHGC * WWR)}\right|_{(SHGC*WWR)*} \tag{6.9}$$

where (SHGC*WWR)* is the value at the middle of the range in Figure 6.8. Evaluating this value using the power function gives, for the north wall, ASH = 54.3.

This value is comparable to those obtained by Chua and Chou of 58.6 in [18].

**The glazing conduction term**

To obtain the parameter CTD of the glazing conduction term (term 2) in (6.5), a series of simulation runs was again conducted to obtain CCLs during the bedroom period when the walls possess properties shown in Table 6.3. The WWR and SHGC of the glazing were fixed at 0.3 and 0.606, and the glazing U-values, $U_f$, varied in the range shown in Table 6.6.

**Table 6.6.** CCLs, W/m$^2$, of bedroom with given walls, window, and U-value of glazing.

| $U_f$ | $U_f$*WWR | South | | East | | North | | West | |
|---|---|---|---|---|---|---|---|---|---|
| | | W&G | G only | W&G | G only | W&G | G only | W&G | G only |
| **3.52** | **1.056** | 38.23 | 23.49 | 36.17 | 22.08 | 31.50 | 18.98 | 37.06 | 22.61 |
| **5.44** | **1.632** | 35.78 | 21.04 | 33.84 | 19.75 | 29.54 | 17.02 | 34.73 | 20.28 |
| **5.80** | **1.740** | 35.38 | 20.65 | 33.47 | 19.37 | 29.23 | 16.71 | 34.35 | 19.90 |
| **5.88** | **1.764** | 35.29 | 20.55 | 33.38 | 19.29 | 29.16 | 16.64 | 34.26 | 19.81 |
| **5.95** | **1.785** | 35.22 | 20.48 | 33.31 | 19.22 | 29.10 | 16.58 | 34.20 | 19.74 |

The same procedure was used to obtain $CCL_G$ due to the conduction terms per unit glazing area under 'G only' in column 4, 6, 8, and 10 in Table 6.6. Figure 6.9 shows graphs of $CCL_G$ with $U_f$ on the horizontal axis. The slopes of the graphs which are the CTD parameters for the glazing facing the cardinal directions are all comparable. The negative value of CTD implies that the glazing conduction term represents net heat loss from the interior to the exterior through the glazing.

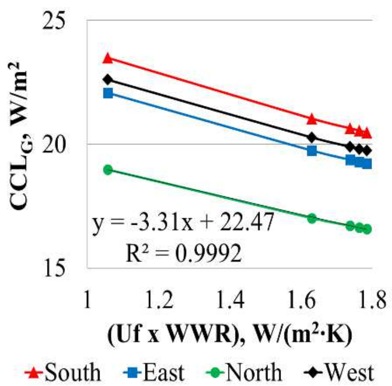


**Figure 6.9.** Graphs of $CCL_G$ against $U_f$.

In order to understand this phenomenon, there is a need to examine the temperatures on the surfaces of the glazing, $T_{ext}$ and $T_{int}$ , of ambient air. $T_{amb}$, of air in the room, T-Room, and of sky, $T_{sky}$, on 3 March 2000 in Figure 6.10 a) for $U_f$ 5.95 and b) for $U_f$ 3.52. For all hours, the temperatures on the exterior and interior surfaces almost overlap and are higher than ambient air temperature and sky temperature. The situation implies that there is convection to ambient air and thermal radiation from the glazing to the sky. Figure 6.10 c) shows that there is a net positive heat flux from the exterior surface of the glazing for all hours of the day p to the end of bedroom period and the size is larger for glazing of higher $U_f$ value. The heat fluxes for the interior surfaces are consistently negative during bedroom period, meaning there is heat loss from the room interior through the glazing to the exterior. The implications from the three figures are consistent and correspond with the negative value of CTD obtained.

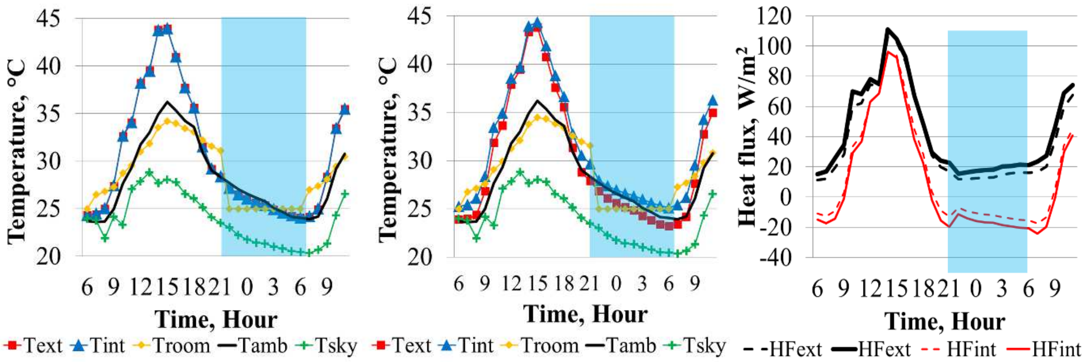


**Figure 6.10.** Temperatures and heat fluxes relationships for the south zone on 3 March 2000, a)Temperatures of $U_f$ = 5.95 W/(m$^2$·K), b) Temperatures of $U_f$ = 3.52 W/(m$^2$·K), c) Heat fluxes of $U_f$ = 5.95 W/(m$^2$·K) (Solid) and $U_f$ = 3.52 W/(m$^2$·K) (Dashed).

Table 6.7 shows values of ASH and CTD for the reference walls with thermal properties shown in Table 6.3 and interior walls of solar absorptance of 0.5 and density 1,760 kg/m$^3$.

**Table 6.7.** Values of ASH and CTD for the reference walls.

| **Item** | **Direction** | | | |
|---|---|---|---|---|
| | **South** | **East** | **North** | **West** |
| ASH, W/m$^2$ | 67.1 | 62.6 | 54.3 | 64.7 |
| CTD, $^o$K | -4.2 | -3.9 | -3.3 | -3.9 |

The values of ASH and CTD in the table show that both vary weakly with vertical solar radiation prevailing in each direction.

### 6.4.3 Independence of the glazing terms from the opaque wall term

Section 6.4.2 illustrates extraction of the CCL due to glazing from that due to an exposed opaque wall and glazing combination of specific thermal properties, and then separating the glazing term further into an absorbed and stored solar heat term and a conduction through glazing term.

In the following steps to prove the relative independence of the glazing term from the opaque wall term, the solar absorptance, the density, and the conductivity and hence the U-value, of the exposed opaque wall is altered by one value at a time from the corresponding reference value. The resulting values of ASH and CTD due to each alternative wall composition are then shown for comparison to those from the original opaque wall. Table 6.8 shows the resulting values.

**Table 6.8.** Values of ASH and CTD for alternative values of opaque wall property.

| **Alternative opaque wall property** | **OTTV parameters** | **South** | **East** | **North** | **West** |
|---|---|---|---|---|---|
| Solar absorptance, 0.1 | ASH, W/m$^2$ | 63.7 | 59.4 | 51.9 | 61.6 |
| | CTD, $^o$K | -3.3 | -3.2 | -2.6 | -3.2 |
| DSH, 25.2 kJ/m$^2$ | ASH, W/m$^2$ | 66.0 | 61.7 | 53.6 | 63.7 |
| | CTD, $^o$K | -4.3 | -4.1 | -3.4 | -4.1 |
| U-value, 0.83 W/(m$^2$·K) | ASH, W/m$^2$ | 74.8 | 70.0 | 61.1 | 72.0 |
| | CTD, $^o$K | -4.9 | -4.7 | -3.9 | -4.6 |

The table show that values of ASH and CTD are reduced by the smaller solar absorptance of the wall surface slightly, changed by the smaller thermal mass slightly, and increased by the smaller U-value slightly. The variations are not significant and so the values of ASH and CTD in Table 6.7 will be used.

### 6.4.4 The OTTV formulation

Based on the elaboration in 6.4.1 to 6.4.3 the OTTV formulation for the bedroom function of a residential building (in Thailand) is,

$$OTTV_{br} = (1 - WWR)(U_w)(TD_{shw})+(WWR)(U_f)(CTD)+(WWR)(SHGC)(ASH), \quad (6.10)$$

where $TD_{shw}$ is given in (6.4), and CTD and ASH are given in Table 6.7.

The pattern of $TD_{shw}$ in Figure 6.5 implies that there is diminishing reduction in cooling coil load through opaque component of an exposed wall when insulation is added, but using lighter or more reflective color is effective. Reducing solar heat gain through glazing is also effective, but use of double glazing to reduce the U-value of window will adversely result in higher $OTTV_{br}$.

## 6.5 Validation of the OTTV formulation

The formulation in (6.10) is intended as the measure of thermal performance of an exposed wall of residential buildings. It is derived from the CCL of a model used under bedroom function, and is thus interpreted as thermal (cooling coil load, $W_{th}$) load due to heat gain per unit area of the exposed wall of the space. The validity of the formulation is important as it is intended to be used as one the main measure of thermal performance of residential buildings in an energy and carbon rating scheme for residential houses in Thailand in the project mentioned in Section 6.1. Two residential models are to be used in the validation exercise. One is a bedroom in a residential condominium and another one is the bedroom in a detached house.

Figure 6.11 shows photographs of a residential condominium and a house taken from the survey in the project. Figure 6.12 shows floor plan of a residential unit on the middle floor of the condominium and that of the detached house. The condominium was built by the National Housing Authority (NHA) of Thailand. The unit in the condominium has an area of 31.2 $m^2$ while its main bedroom has a length of 3.25m, a width of 3m, and a height of 2.8m. The detached house has a length of 9m, width of 8m, and height of 3m. Its bedroom has the same floor dimensions as those of the main bedroom in the condominium unit. In each of both units, only the bedrooms that has a window on west-facing exposed wall is assumed air-conditioned during 21.00 to 06.00.

**Figure 6.11.** Building models used, a) NHA condominium, b) single detached house.

The configurations of the condominium unit and the detached house were coded into the input files of two programs, BESim and TRNSYS, the latter a well-known transient simulation software. The same weather data used by BESim was coded and used by TRNSYS. Property and parameter values for the exposed wall of the bedrooms in both cases are shown in Table 6.9. Three cases of wall and window properties were simulated,' light', 'medium' or 'reference', and 'heavy'. The corresponding value of $OTTV_{br}$ in each case is shown on the last row in the table.

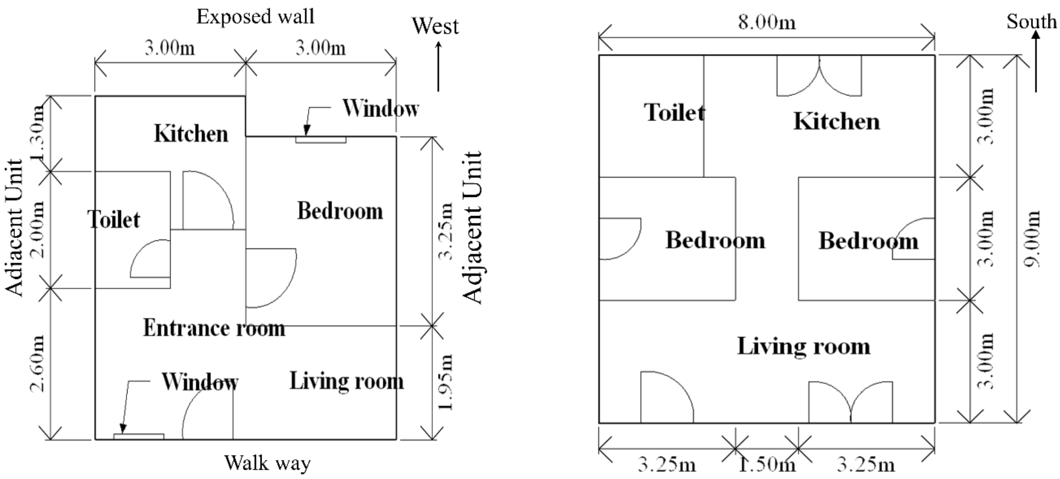


**Figure 6.12.** Floor plan of a unit in the condominium (a) and of the detached house (b).

Note that the value of WWR in the case of condominium unit is 0.18 while that of the detached house is slightly larger at 0.25. The values of $OTTV_{br}$ for the house are then larger than those for the condominium unit. Property values of all other walls in both units were the same as those of the medium wall of the exposed bedroom wall.

**Table 6.9.** Property and parameter values of the walls.

| **Item** | **Light** | **Medium** | **Heavy** |
|---|---|---|---|
| $U_w$ | 0.86 | 3.26 | 3.63 |
| DSH | 25.2 | 148 | 252 |
| $\alpha_s$ | 0.1 | 0.5 | 0.9 |
| $TD_{shw}$ | 10.2 | 6.33 | 5.11 |
| $U_f$ | 5.8 | 5.8 | 5.8 |
| SHGC | 0.39 | 0.61 | 0.83 |
| ASH | 64.7 | 64.7 | 64.7 |
| CTD | -3.9 | -3.9 | -3.9 |
| WWR, condo | 0.18 | 0.18 | 0.18 |
| WWR, house | 0.25 | 0.25 | 0.25 |
| $OTTV_{br}$, condo | 13.0 | 28.9 | 44.8 |
| $OTTV_{br}$, house | 16.4 | 32.1 | 47.9 |

*Note: condo = condominium.

The annual cooling coil loads of the bedrooms of both units for the three cases are shown in Figure 6.13.

In both housing units, the cooling coil loads change in correspondence with the values of $OTTV_{br}$ linearly. There are slight differences in the cooling coil loads obtained by the two simulation programs. The properties of opaque walls and glazing in the three cases in Table 6.9 differ substantially that result in substantial differences in the values of $OTTV_{br}$, yet the same proportionate changes occur to annual cooling coil loads obtained by both simulation programs. The results of simulation from both computer software affirm that the OTTV formulation accurately reflects thermal performance of an exposed wall of a bedroom.

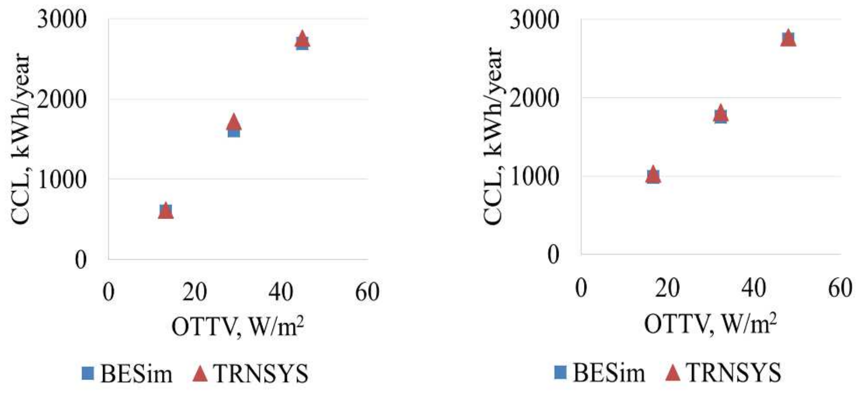


**Figure 6.13.** Annual CCL from simulation plotted against $OTTV_{br}$. a) Condominium, b) Detached house.

### 6.6 Conclusion

The OTTV form of measure of thermal performance of wall that comprises three terms, one accounting for cooling coil load due to heat gain through opaque wall, one for solar radiation gain through glazing, and one for heat conduction through glazing applies well to the case of space used to serve bedroom function. However, the unexpected negative value of the conduction temperature difference (CTD) terms shows that this third term represents heat conducted out from the space through glazing. The validation exercise affirms that the OTTV formulation correctly and accurately accounts for relevant thermal components of heat transfer through exposed building wall that contribute to cooling coil load in the space.  The results in this paper that is reflected in the OTTV formulation confirms that high thermal mass of wall can be adverse to thermal performance or wall, insulation on wall interior surface reduces heat gain albeit with diminishing reduction for higher level of insulation, solar gain prior to the bedroom period contributes to cooling coil load in the bedroom period, and reducing U-value of glazing contributes negatively to reduction of cooling coil load.

# CHAPTER 7
# CONCLUSION AND FUTURE WORK

## 7.1 Conclusion

Thailand was a net energy importing country ever since it began its first Economic and Social Development Plan to embark on a new phase of coordinated economic development in 1964. From 1985 to the present, per capita consumption of oil and natural gas has increased six folds, while per capita consumption of electricity has increased five folds. A report of the International Energy Agency (IEA) indicates that consumption of electricity in commercial and residential buildings constitute 40% of total electricity consumption and the building sector consumes 30% of total energy consumption. Development and implementation of mandatory and voluntary energy performance standards for buildings are necessary and beneficial to society. This study presents the development of an OTTV, or the measure of thermal performance, of building walls enclosing spaces used under bedroom function. This development represents a part of an attempt to develop a building energy performance standard for residential buildings in Thailand. Bedroom function is the major residential function in the use of a residential household. The results of this study indicates that building envelope and interior walls should be constructed by using low thermal mass materials including low solar absorptance of wall surfaces to reduce heat storage from solar radiation during daytime which is major factors of CCL of night time function. The exposed wall should be installed interior insulations and if the wall comprises window area, the glazing type and shading device should be considered to screen the transmitted solar radiation through window which is much influenced with the performance of building envelopes. The developed OTTV is verified and the results indicate that the developed OTTV can be used to indicate the performance of building envelopes enclosing residential spaces precisely.

## 7.2 Future Work

A study on building envelope performance of non-air conditioned residential spaces considering of thermal comfort, visual comfort and energy consumption in houses are recommended. The results may enhance thermal comfort condition in houses without the use of air-conditioner which can reduce energy consumption significantly.

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# APPENDIX

# THE CALCULATION METHODS USED IN BESIM PROGRAM

# THE CALCULATION METHODS USED IN BESIM PROGRAM

## 1. SURFACE ENERGY BALANCES

This document is written to give theoretical background on the algorithms and procedures used by BESim in the calculation. Although standard methodologies and algorithms are used in most modules, there are also specific methodologies and algorithms in some subject areas that the authors have contributed to the community of building energy science that are specific to BESim. This document is organized in a way that it presents a logical flow of the subject matters.

### 1.1 A Physical Overview

Figure A.1 is presented to illustrate the complex interactions of driving forces and heat transfer mechanisms in a zone or space and the surroundings.

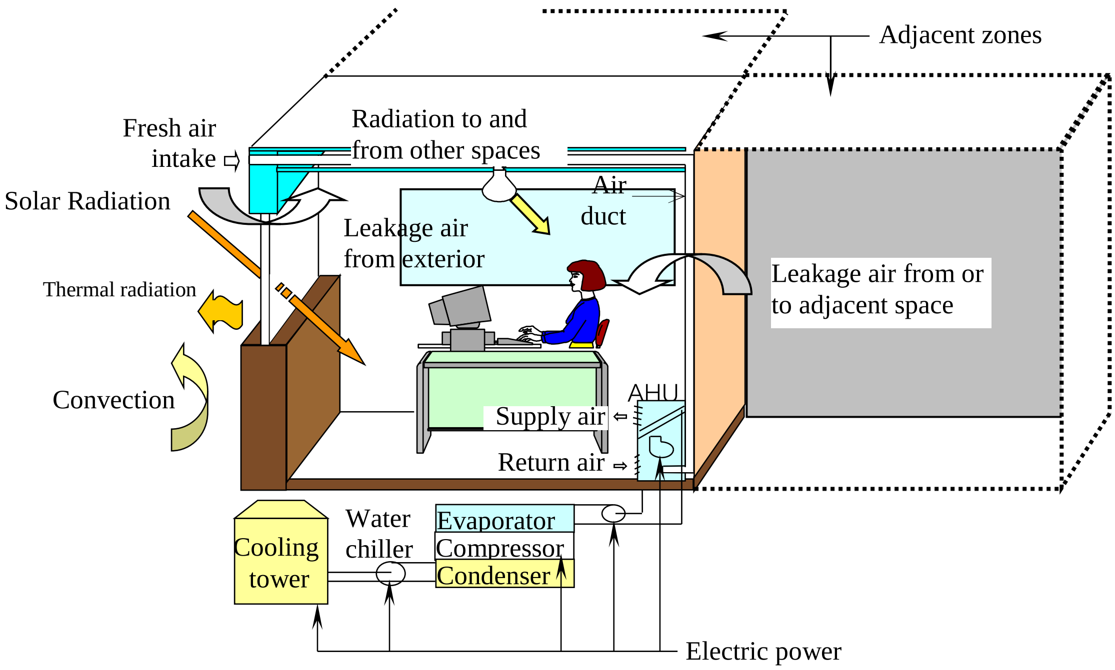


**Figure A.1.** Complex interactions of driving forces, heat, and human and equipment operations in a space

At a given instant, solar radiation falls on the external façade. A part of solar radiation is transmitted through glazing into the building interior. The part of solar radiation falling on an opaque surface is partly reflected and partly absorbed on to the outer surface of the opaque wall. The absorbed energy will increase the internal energy of the wall material and slowly increases the surface temperature. The speed of temperature increase depends on the intensity of solar radiation absorbed, thermal properties of wall materials that can dictate the rate of conduction heat transfer through the wall, and the temperature of the opposite surface of the given wall. Heat transfer through wall is dynamic. Exterior air temperature also convects heat to the surface. At the same instant, the exterior surface exchanges thermal radiation with surrounding surfaces. Surrounding surfaces "seen" by the exterior surface may comprise a part of ground, a part of sky and a part of surfaces of other buildings. Cloud, particulates and the general atmosphere of the sky form an "equivalent" sky surface that can exchange thermal radiation (at wavelength longer than 3 μm), apart from imparting diffuse solar radiation (at wavelength less than 3 μm) to the exterior surface. While heat is being conducted from the exterior surface through the wall material into the interior surface, the interior surface of the external wall exchanges thermal radiation with other surfaces in the room. Air in the room also convects heat away from the interior surface.

Although we have focused our attention on the external wall, there are similar heat exchanges on all internal walls. In Figure A.1, light from the lamp in the room is illustrated to be transmitted to an adjacent room through an internal, glazed window. This contributes radiation of short wavelength, similar to solar radiation, through direct transmission to the adjacent space.

Electric power is supplied to lamps in order for it to produce light, or visible radiation. But in all lamps in use, less than 25 % of such power is converted into visible radiation. The other 75 % or more of supplied power is turned into thermal energy that increases the temperature of a lamp and its complementary component (such as a ballast). Part of this thermal energy is radiated to other surfaces in the room, but part of it is convected to air. Computers and other equipment in the room also generate heat from its operation.

Some equipment and human occupants in the room contribute both sensible heat and latent heat. Sensible heat is transferred as thermal radiation to other surfaces in the space and convected to air. Latent heat is transferred to air directly.

Fresh, outside air introduced into the space for ventilation is mixed with return air at the air-handling system. This adds load to the cooling coil. Leakage air from exterior and from adjacent spaces will mix with the air in the room and increase or decrease the space cooling load in the room.

The speed of dynamics of operation of the air-conditioning system is generally higher than that of heat gain through walls. Some of the salient features of the phenomena described and some assumptions normally made are noted here in the followings.

- The air in an air-conditioned zone is assumed *well mixed* so that the property of air everywhere in the zone is represented by one condition. An air-conditioned zone is served by an air-conditioning system. This system responds to a temperature control device such as a thermostat. The control device operates the cooling coil of the air-conditioning system to keep the air temperature at the set-point value of the zone.

In the case of displacement ventilation or natural air low, the flow of air may not be well mixed. Specific method for dealing with heat transfer and air flow is needed when the assumption of air being well-mixed is lifted.

- The phenomena of heat gain, radiation and air leakage described in the foregoing suggests that all phenomena and mechanisms in every space in the building occur simultaneously and interactively. Electromagnetic radiation emanating from one space affects energy balance in another space. The condition of air in one space may differ from that of another space. When this air leaks from a space at that instant, it interactively affects the space that it leaks into. Viewing from a broad perspective, the phenomena in a space systemically affects the whole building. This situation implies that if mathematical equations are written to describe the evolution of air properties or other state variables in the buildings, the equations are all related. A set of equations written for a set of state variables in one space would contain state variables representing properties or conditions of another space in the building. Thus the set of equations of states of all spaces in the building become very large. The equations are nonlinear, dynamical and simultaneous. The solution of such set of equations can present a real challenge even for a building of few spaces, when each space is expected to be served by an air-handling system to achieve an independent and distinct condition. In practice, it would be necessary to consider isolating each space and solving the corresponding set of equations separately and using some means to relate the results for the whole building.

- For the purpose of calculating thermal radiation exchange, surfaces in a building are assumed to be diffuse and the temperature of a section of a zone is assumed uniform so that one temperature represents the entire surface of the section. (The temperatures of the surfaces on two sides of a section differ, though.). This assumption of diffuse surface property is also made for the case of diffuse light. However, in calculating direct or beam daylight, a surface may have certain specular property. In lighting calculation, the surface of a section is divided into several segments to allow more accurate calculation of daylight distribution in building interior.

**Energy Calculation**

In order to calculate energy use in a building, the starting point is to examine heat gain into a space or a zone.

Heat is gained into a space through external walls. Air in the space then receives this heat through convection process. The air at higher enthalpy level then transfers heat to the cooling coil of an air-handling system. Heat from the air is transferred to water in a chilled water air-conditioning system in this process. The return chilled water that now carries heat from the air-conditioning zone then transfers heat to the primary refrigerant in the water chiller. The performance of the water chiller is influenced by the temperature of the supply and return chilled water, and by the temperature of the entering condenser water. The temperature of the condenser water when it returns from the cooling tower is related to the temperature of this condenser water as it enters the cooling tower, and the prevailing ambient air condition used to cool this water.

In order to relate all these processes and phenomena to electricity use of a building, energy balance equations are written at each stage. These equations are developed from a consideration of the interactions of energy components at that stage. The resulting equations are eventually solved to obtain the value of energy use.

## 1.2 A Modeling Overview

BEsim uses interactive energy balance procedure in its calculation. There are specialized modules that BESim uses to generate data for subsequent calculation. Figure A.2 illustrates the main procedural flow of computation. The starting point is the energy balance at the exterior surface of each section of wall or fenestration. The resultant heat flows into and through the section, by conduction for opaque section, and by transmission of short-wave radiation and conduction for transparent section. There is another energy balance at the interior surface of the section. The interior surface participates in thermal radiation exchanges with other surfaces. Heat from the surface of the section is also transferred to air. Within a zone, the air transferred energy to the air-conditioning system under an energy balance condition.

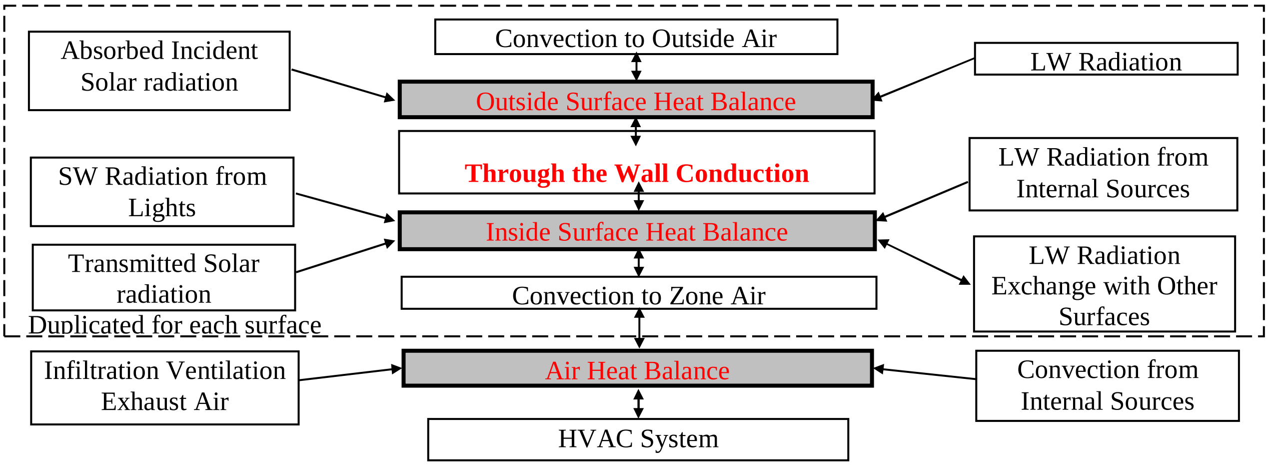


**Figure A.2** Steps or flow of computation with energy balance at the junctions or node of a section.

Figure A.3 shows the program components of BESim. Essentially, the integrated solution manager is the program manager that brings in input data and manages flow of data into computation modules. The main blocks that data flow through are shown enclosed in the box bordered by dotted lines.

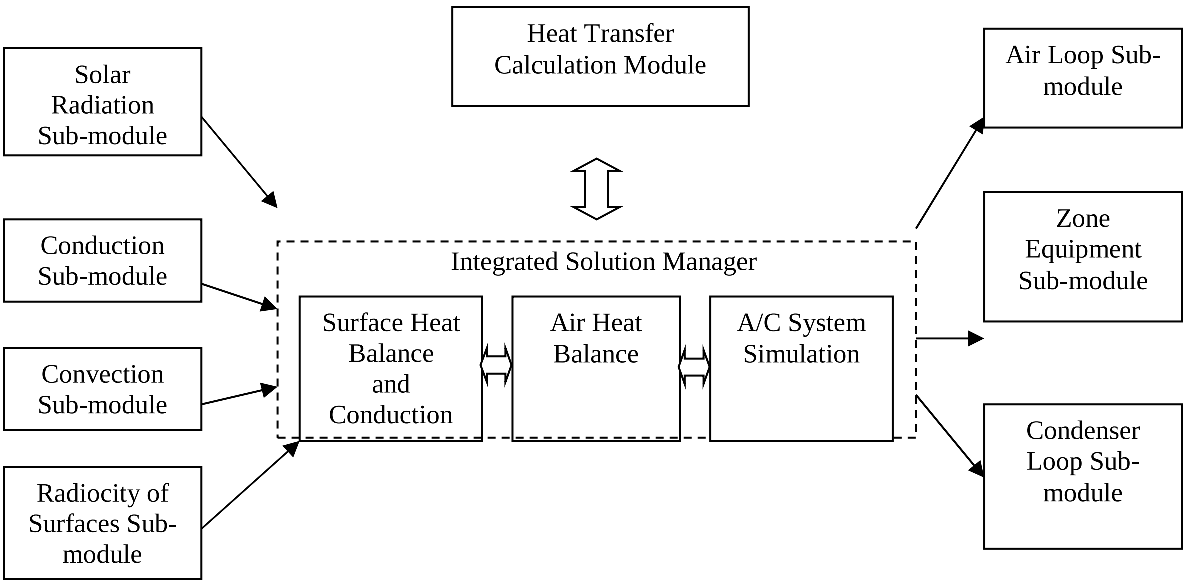


**Figure A.3** Program components of BESim.

The program manager calls procedure for calculation of solar radiation using solar radiation data read from meteorological input file. It also calls other program procedures to calculate convection heat and thermal radiation that are balanced at the exterior surface also using data read from meteorological input file.

The principle of balance applies not only to energy at a node, but also to the states of air and water across the whole procedure. As the air passes its heat to the air handling system, the response from the system is fed back to air iteratively until a balanced condition is reached between the zone air and the system. The same balancing procedure is applied between the system and plant. Figure A.4 illustrates the principle.

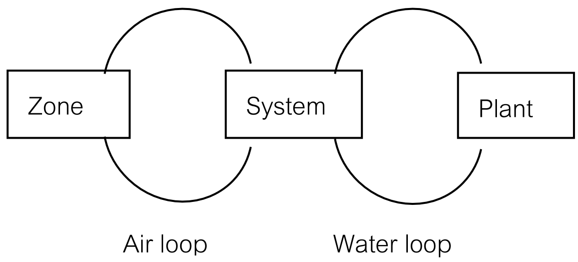


**Figure A.4** Balance in the air and in the water loop