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INVESTIGATIONS OF COOLING LOADS IN HIGH-RISE RESIDENTIAL BUILDINGS IN HONG KONG

M. Bojic, F. Yik, K. Wan, and J. Burnett
Department of Building Services Engineering
The Hong Kong Polytechnic University
Hung Hom, Kowloon,
Hong Kong SAR,
China

ABSTRACT

To minimize yearly cooling loads of high-rise residential buildings in Hong Kong, it is essential to take into account special space and time cooling pattern that exists in their apartments and then determine proper thickness, composition, and location of walls and doors in apartments. In these apartments, some rooms are cooled as dining rooms and bedrooms, and some are not cooled as bathrooms and kitchens. The dining rooms and bedrooms have different cooling schedule. Yearly cooling loads are determined by using the multi-zone HTB2 software. In the apartments during these investigations, the basic design of some walls is modified with 5 cm of thermal insulation and/or 10 to 30 cm of concrete, and the basic design of some doors is modified with 5 cm of thermal insulation. These modified walls and doors are placed in eight different locations within the apartment envelope and partitions. Calculation results show that the yearly cooling load is minimized in several cases: 1.when thermally insulated walls and doors are located optimally, 2.when thermal insulation of walls is applied together with proper thickness of concrete, 3.when concrete is uniformly distributed within apartment walls.

INTRODUCTION

Two facts are well known for Hong Kong. First, the Hong Kong Housing Authority and private sector have the parallel production target amounting to an average total of 85,000 new residential flats in high-rise buildings a year (Anonymous, 1995). Second, electricity use in residential buildings accounted for just near quarter of the total electricity consumption and represented about one-sixth of the total primary energy requirement in Hong Kong. These facts yield concerns to find ways to decrease this electrical energy consumption and at the same time its environment load. To fulfill this goal one available strategy is to optimize envelope and partitions of residential high-rise buildings.

Energy consumption in high-rise buildings in hot and humid climate was previously investigated by several authors (Chau et al, 2000; Lam, 2000), but they did not address issue of their residential type as well as issue of envelope and partitions influence to their energy behavior. Also, envelope and partitions influence to energy behavior of buildings was previously addressed by several investigators (Bojic, Loveday, 1997; Bojic, Lukic, 2000) however they did not deal with buildings in hot and humid regions. However, this paper proposes that envelope and partitions properties such as proper thickness, composition, and location of walls essentially influence an energy behavior of high-rise residential buildings in Hong Kong. These issues are accessed by using a dynamic multi-zone building energy model called HTB2 (Alexander, 1996).

A study is carried out on cooling energy in high-rise residential buildings in Hong Kong when within an apartment envelope and partitions its walls and doors have different locations and properties. For thermally insulated apartments, the variations of three different parameters are studied: 1. povision of thermal insulation, 2. location of thermally insulated walls, 3. thickness of concrete in insulated walls. In addition, for thermally non-insulated apartments, variations of three different parameters are studied such as 1. thickness of concrete in envelope and partitions, 2. thickness of concrete in envelope, 3. uniformity of concrete distribution within envelope and partitions. Variations in cooling load are expected to exist because during cooling season 1) some apartment rooms are cooled as living rooms and bedrooms, and some apartment rooms are not cooled as bathrooms and kitchens. Furthermore, the living rooms and bedrooms possess different cooling schedule (Yik et al, 1999).

SIMULATION SOFTWARE HTB2

Computer model HTB2 is an example of a dynamic building energy model that takes to account hourly time varying conditions of climate and occupancy and predict heating and cooling loads and internal environmental conditions (Jones, Alexander, 1999). This model uses the finite difference fabric sub model and its ability to vary in time temperature profiles through the construction. The building energy model is developed at the Welsh School of Architecture and is able to access the influence of fabric, ventilation, solar gains, shading, thermal mass, control scenarios, and occupancy on the thermal and energy performance of a building. To gain the efficiency needed to allow hourly prediction for an annual simulation, there are necessary limitations imposed by assumptions and algorithm used. For instance, usual limitation in dynamic models is the assumption of uniform air temperature within each zone simulated. This software is validated for cold (Lomas, et al, 1997) and hot climate (Yik et al., 2000).

SIMULATION ARRANGEMENT

Two apartments denoted as an apartment set are studied; they face southeast direction (Fig. 1) and stay at 10th story of 30-story high-rise building in Hong Kong where every story contains four apartment sets. These apartments face environment with walls and windows, a lobby with walls and doors, and mutually with walls. The lobby is not cooled. The apartment 1 of the studied apartments set has two bedrooms, one living room, one kitchen, and one bathroom. The apartment 2 has three bedrooms, one living room, one kitchen, and two bathrooms.

Spaces in these apartments may be either cooled or non-cooled where cooled spaces experience different cooling schedule (Table 1). The cooled spaces are living rooms and bedrooms, while non-cooled spaces are bathrooms and kitchens that are naturally ventilated. During weekdays, the window air-conditioners in the living rooms operate from 6 pm to 10 pm, and the window air-conditioners in the bedrooms operate from 10pm to 8 am. During Saturday and Sunday, the window air-conditioners in the living rooms operate from 8 am to 10 pm, and the window air-conditioners in the bedrooms operate from 10pm to 8 am

Two types of apartment sets can be differentiated: the basic one and investigated ones. The basic one only contains the unmodified walls and doors, while investigated one contains unmodified and modified walls and doors. Unmodified walls and doors have parameters that are set before investigations and held constant during all investigations, while modified walls and doors have parameters that are varied during investigation. Unmodified walls and doors are thermally non-insulated and composed of three layers. The unmodified walls are composed of cement/sand plaster, 5 cm of concrete, and gypsum plaster. The unmodified doors are composed of wood, air cavity, and wood. Composition of these walls and doors is summarized in Table2. Modified walls and doors are made when thermal insulation and/or additional concrete are added to unmodified walls, so the modified walls and doors may be thermally insulated or thermally non-insulated. When thermal insulation is added, a thermal insulation layer is inserted in the wall next to

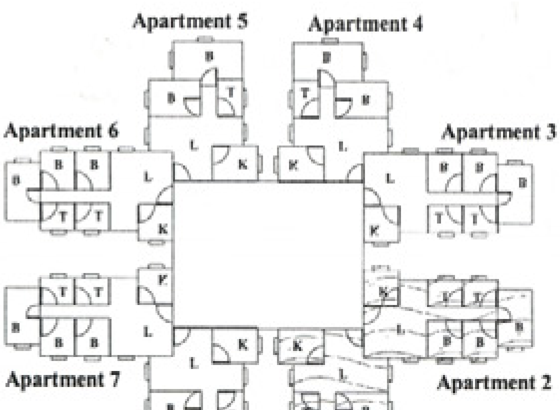

Fig.1 Plan of the floor of the building where filled apartments 1 and 2 present the investigated apartment set where B stands for bedroom, L for living and dining room, K for kitchen, and T for toilet.

concrete, and next to wood in unmodified door. In walls, this layer is placed on the concrete side that face outdoors. In doors, this layer is placed between two wood layers either next to wood that face outdoors. Composition of these walls and doors is summarized in Table3. The parameters of layers used in the envelope and partitions of these apartments are given in Table 4.

ENVELOPE AND PARTITIONS ARRANGEMENTS

Investigations are performed for eight arrangements of modified and unmodified walls and doors within apartments envelope and partitions; these arrangements are designated as F, W, L, B, E, A, T, and U (Fig. 2 and 3). Particular envelope and partitions arrangement is characterized by the part of envelope and partitions that consists of modified walls and doors. Then, other part of the envelope and partitions consists of unmodified walls and doors. The F arrangement means that the modified walls and doors of the both apartments face environment and lobby.

Table 1 Cooling of rooms and their cooling schedule

Type of room	Cooled / Not cooled	Cooling schedule
Living rooms	Cooled	6 pm –10 pm
Bedrooms	Cooled	10 pm- 8 am
Bathrooms	Not cooled.	-
Kitchens	Not cooled.	-

Table 2 Composition of the shell of the basic apartment set that is typical for Hong Kong

Envelope type	Layer 1	Layer 2	Layer 3
External wall	Cement/ sand plaster	Concrete of 0.1 m	Gypsum plaster
Partition wall	Gypsum plaster	Concrete of 0.1 m	Gypsum plaster
Door	Wood	Air cavity	Wood

Table 3 Composition of the insulated envelope for some investigated apartment set

Envelope type	Layer 1	Layer 2	Layer 3	Layer 4
External wall with poly-styrene	Cement / sand plaster	Poly-styrene	Concrete of variable thickness	Gypsum plaster
Partition wall with poly-styrene	Gyp-sum plaster	Poly-styrene	Concrete of variable thickness	Gypsum plaster
Door with poly-styrene	Wood	Poly-styrene	Air cavity	Wood

Layer 1 faces outside, and layer 2 faces inside

Table 4 Values of parameters of the layers used in simulation

	Con-crete	Cement / sand plaster	Gyp-sum plaster	Wood	Poly-styre-ne
Specific heat capacity (J/kg-K)	653	840.0	837	2093	1380
Density (kg/m^3)	2400	1860.0	1120	800.0	25.0
Thermal conductivity (W/K-m)	2.16	0.72	0.38	0.160	0.034

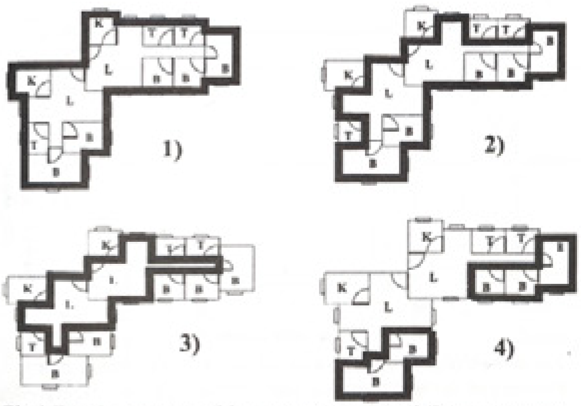

Fig.2 Envelope and partitions arrangements: 1) F arrangement, 2) W arrangement, 3) L arrangement, and 4) D arrangement where B stands for bedroom, L for living and dining room, K for kitchen, and T for toilet.

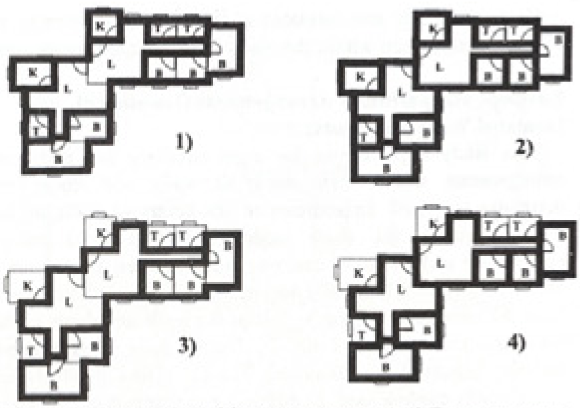

Fig.3 Envelope and partitions arrangements: 1) E arrangement, 2) A arrangement, 3) T arrangement, and 4) U arrangement where B stands for bedroom, L for living and dining room, K for kitchen, and T for toilet.

In this arrangement, the modified walls and doors are designated as F-walls and F-doors, and their location within this arrangement is designated as F-location; the unmodified walls and doors are designated here as non-F walls and non-F doors. This arrangement is widely used.

The W arrangement means that the doors and walls of the cooled spaces are modified; they face environment, lobby, and non-cooled spaces. In this arrangement, the modified walls and doors are designated as W-walls and W-doors, and their location within this arrangement is designated as W-location; the unmodified walls and doors are designated here as non-W walls and non-W doors. Cooled space consists of living rooms and bedrooms in both apartments that have joint walls and doors.

The L arrangement means that the doors and walls of the living spaces are modified; they face environment, bedrooms, and non-cooled spaces. In this arrangement, the modified walls and doors are designated as L-walls and L-doors, and their location within this arrangement is designated as L-location; the unmodified walls and doors are designated here as non-L walls and non-L doors. One living space is composed of several living rooms that have joint walls.

The B arrangement means that the doors and walls of the bedroom spaces are modified; they face environment, living rooms, and non-cooled rooms. In this arrangement, the modified walls and doors are designated as B-walls and B-doors, and their location within this arrangement is designated as B-location; the unmodified walls and doors are designated here as non-B walls and non-B doors. One bedroom space is composed of several bedrooms that have joint walls.

The E arrangement means that the doors and walls of apartment envelope, living spaces, bedrooms' spaces, and non-cooled spaces are modified. These walls and doors can be either common to two of spaces, or face outdoors, or face lobby. In this arrangement, the modified walls and doors are designated as E-walls and E-doors, and their location within this arrangement is designated as E-location; the unmodified walls and doors are designated here as non-E walls and non-E doors.

The A arrangement means that all doors and all walls are modified during investigations. In this arrangement, the modified walls and doors are designated as A-walls and A-doors, and their location within this arrangement is designated as A-location; the unmodified walls and doors are designated here as non-A walls and non-A doors.

The T arrangement means that the doors and walls of living spaces and bedroom spaces are modified during investigations. They can either be common to both spaces or face outdoors, or face lobby, or face non-cooled spaces. In this arangement, the modified walls and doors are designated as T-walls and T-doors, and their location within this arrangement is designated as T-location; the unmodified walls and doors are designated here as non-T walls and non-T doors.

The U arrangement means that all doors and all walls of living rooms and bedrooms are modified during investigations. These walls and doors can either be common to two rooms or face outdoors, or face lobby, or face non-cooled spaces. In this arrangement, the modified walls and doors are designated as U-walls and U-doors, and their location within this arrangement is designated as U-location; the unmodified walls and doors are designated here as non-U walls and non-U doors.

INVESTIGATED VARIABLES

For the purpose of later illustrations, two dependent variables are used:

a) Yearly cooling load, Q
b) Difference in percents in the yearly cooling loads of the investigated apartment set and basic apartment set

$$Dif=100(Q_b-Q_i)/Q_b \quad (1)$$

Where Q_i stands for the yearly cooling load of the investigated apartment set, and Q_b stands for the yearly cooling load of the basic apartment set. If this difference is positive, then the cooling load decrease is recorded, and if this difference is negative, then the cooling load increase is recorded compared to the basic case.

Particular simulation run is characterized by an insulation provision, location of modified and unmodified envelope and partitions, additional concrete provision.

RESULTS AND ANALYSES

For different apartments, this section shows results of the computation of influence on the yearly cooling load by 1. envelope and partitions arrangement in thermally insulated apartments, 2. thickness of concrete in apartments with thermally insulated F–walls, 3. provision of thermal insulation in apartments, 4. thickness of concrete in F-walls in thermally non-insulated apartments, 5. thickness of concrete in A(all)-

walls in thermally non-insulated apartments, 6. uniformity of concrete distribution within thermally non-insulated apartments

Envelope and partitions Arrangements (Location of Insulated Walls and Doors)

This study is performed for eight envelope and partitions arrangements where their modified walls and doors are thermally insulated. In addition to the layers of walls of the basic apartment set, these modified walls have 5 cm of polystyrene and 40 cm of concrete, and modified doors have 5 cm of polystyrene; thermally non-insulated walls and doors will have the same composition as that of the walls and doors of the basic apartment set (see Table 2). During these investigations, the four quantities are calculated. The calculated quantities are 1) the yearly cooling load, 2) difference in percents of the yearly cooling load compared to that of the B envelope and partitions arrangement, 3) difference in percents of the yearly cooling loads compared to that of the basic apartments set (without any thermal insulation and addition of concrete), and 4) difference in percents of the yearly cooling loads compared to that of the F envelope and partitions arrangement which is widely used as a envelope and partitions arrangement in practice. The calculation results are shown in Fig. 4 as a function of the envelope and partitions arrangements (the location of thermally insulated walls and doors) in the apartments sets. The calculation of the yearly cooling load shows that the lowest cooling load of 18.5 MWh/year is obtained for the L envelope and partitions arrangement. The relatively low cooling loads are recorded for the E, W, T, A, and U envelope and partitions arrangements. However, the highest cooling load of 19.8 MWh/year is obtained for the B envelope and partitions arrangement. The calculated percentage difference in yearly cooling load compared to that of the B envelope and partitions arrangement shows that for the L envelope and partitions arrangement the yearly cooling load decrease is 8.2%. The E, W, T, A, and U envelope and partitions arrangements give this decrease between 6 and 6.8%. The calculated percentage difference of the yearly cooling load compared to that of the basic apartment set for the L envelope and partitions arrangement shows the highest value of decrease of yearly cooling load of 7.6 %, while the E, W, T, A, and U envelope and partitions arrangements have this decrease between 4.8 and 5.8%. On the contrary, the B envelope and partitions arrangement has an increase in the yearly cooling load of 1.4%. The calculated percentage difference of the yearly cooling load compared to that of the apartment set with the F-envelope and partitions arrangement shows the highest decrease of 7.2 % for the L envelope and partitions arrangement, while the E, W, T, A, and U envelope and partitions arrangements give this decrease between 4.3 and 5.2%. On the contrary, the B envelope and partitions arrangement gives an increase in the yearly cooling load of 1.8%. These results drive to conclusion that optimal distribution of insulated walls exists and the apartment envelope and partitions should be designed accordingly. However, one should have in mind that there are unfavorable designs of the envelope and partitions that should be avoided.

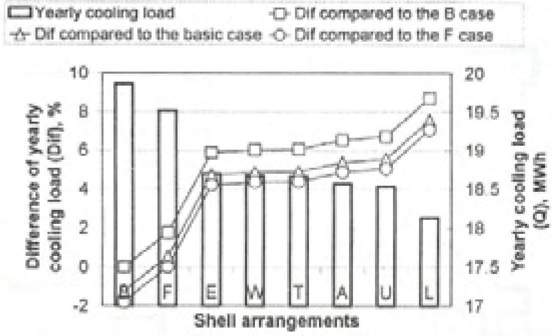

Fig. 4 Yearly cooling load and cooling load difference as a function of the envelope and partitions arrangement. Difference of cooling load is compared to that of 1) the B-case, 2) the basic case, and 3) the F-case. Here, modified walls have 5 cm of thermal insulation, and 40 cm of concrete.

Thickness of Concrete in Thermally Insulated F-Walls

This study of thermally insulated apartments sets is performed when thickness of concrete in the thermally insulated F walls is varied from 10 to 40 cm. Thickness of thermal insulation is held to be 5 cm. Other non-F walls are not thermally insulated and have 10 cm–thick concrete. During this study, three quantities are calculated as a function of the increase of the concrete thickness. The calculated quantities are 1) yearly cooling load of the apartment set, 2) difference of the yearly cooling loads compared to that of the apartments with the insulated F-walls with 10 cm of concrete, and 3) difference of yearly cooling loads compared to that of the basic apartment set (non-insulated apartments with 10 cm of concrete). The calculation results are given in Fig. 5. The calculation of the yearly cooling load shows a decrease from 19.63 MWh/year to 19.52 MWh/year for an increase of the concrete thickness for 30 cm. Then, the calculation of the difference of yearly cooling loads compared to that of the apartments with the insulated F-walls with 10 cm of concrete shows a decrease in cooling load of 0.6%. The difference of yearly cooling loads of investigated and basic apartment set (with 10 cm of concrete in all walls) reveals the cooling load increase of 0.45%. However, when in F location the 5 cm of polystyrene is added together with 30 cm of concrete, the 0.12% decrease of cooling load will be recorded. This results show that when F-walls are thermally insulated the provision of additional concrete in these walls will influence

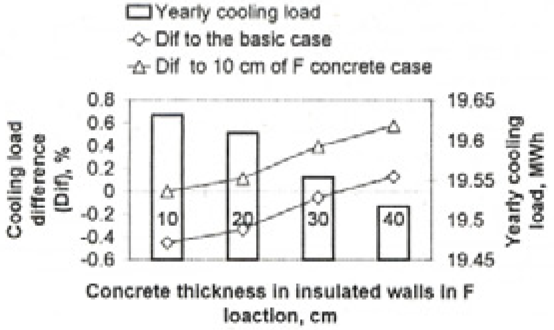

Fig.5. Cooling load and cooling load difference as functions of thickness of concrete in insulated F-walls. The difference is given for cooling loads compared to a) the basic case, and b) thermally insulated F case with 10 cm of concrete. Here, modified walls have 5 cm of thermal insulation.

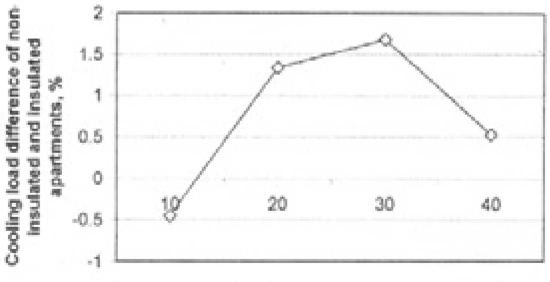

Fig.6. Difference of yearly cooling loads for thermally non-insulated and insulated apartments. This difference is given as a function of thickness of concrete in F-walls.

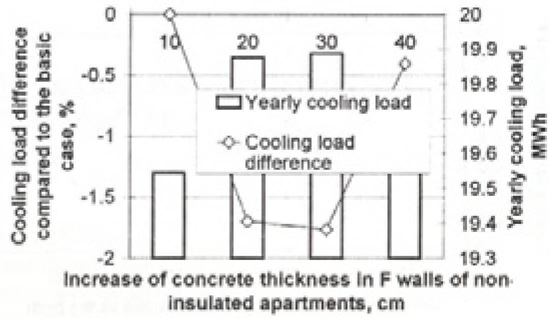

Fig.7 Cooling load and its difference as functions of thickness of concrete in thermally non-insulated F-walls. The difference is compared to the basic case.

favorable to decrease of the cooling load. When these F-walls are not insulated and have thin concrete layer than to get decrease in cooling load one have to provide to these walls simultaneously thermal insulation and additional concrete.

Thermally Insulated vs. Thermally Non-Insulated Apartment

During this study, cooling loads are compared for two apartment sets: one set that is thermally insulated, and one set that is thermally non-insulated. This comparison is performed as a function of thickness of added concrete in their F-walls, which is varied in the range from 10 to 40 cm. The thermally insulated apartment set has 5 cm of polystyrene additionally placed in its F-walls. The thickness of concrete in non- F walls of the both apartment sets was always held to be 10 cm. During this study, the difference in yearly cooling loads of these two apartment sets is calculated, and the calculated results are shown in Fig. 6. When concrete is not added, thermally insulated apartments have around 0.4% greater cooling load than that of thermally non-insulated apartments. However, when concrete is added thermally insulated apartments have lower cooling load than non insulated apartments, where this difference riches the maximum of 1.7 % for concrete thickness of 30 cm and then decreases when thickness of added concrete is further increased. These results show that a provision of the thermal insulation layer should be introduced when thickness of F-walls is seized around 25 cm, however when thickness of F walls is sized at 10 cm the provision of thermal insulation is not good strategy.

Thickness of Concrete in Thermally Non-Insulated F-Walls

This study of thermally non-insulated apartments is performed to examine how the thickness of concrete in their F-walls influences the yearly cooling load when this thickness is increased from 10 to 40 cm. At the same time, concrete thickness in their non-F-walls is held 10 cm what is the value of the concrete thickness in all walls of the basic apartment set. During this study two quantities are calculated 1) yearly cooling load and 2) percentage difference in cooling loads of investigated and basic apartment set. The calculation results are shown in Fig. 7 as a function of the concrete thickness. The calculation of the yearly cooling load shows that when no concrete is added (the basic apartment set), the cooling load is 19.54 MWh/year; when the concrete thickness increases, the cooling load increases where for the concrete thickness of 30 cm the yearly cooling load reaches its maximum of 19.89 MWh/year. When this thickness furthermore increases the cooling load decreases and for the concrete thickness of 40 cm, the cooling load will drop to 19.62 MWh/year which is still higher than 19.54 MWh/year (the cooling load for the basic case). The calculation of the difference in cooling load of the investigated and basic apartment set shows that for the concrete thickness of 30 cm, when the cooling load increases maximally, the difference is 1.75%; however, when 10 cm of concrete more is added, the cooling load difference drops to 0.4%. These results show that the increase of the concrete thickness of F-walls should be abandoned as a design strategy.

Thickness of Concrete in Thermally Non-Insulated A(All)-Walls

This study of thermally non-insulated apartments is performed to examine how the thickness of concrete in all walls influence the yearly cooling load when this thickness is varied from 10 to 40 cm. Note, that when the concrete thickness is 10 cm, this is the basic apartment set. During this study two quantities are calculated 1) the yearly cooling load, and 2) difference in percents of the yearly cooling load for investigated and basic apartment set. The calculation results are shown in Fig. 8 as a function of the thickness of concrete. The calculation of the yearly cooling load shows that higher concrete thickness yields higher cooling load which for 30 cm of concrete reaches its maximum of 19.68 MWh/year; then, higher concrete thickness yields decrease of cooling load and for 40 cm of concrete the yearly cooling load reaches the value of 19.49 MWh/year; this value is lower than that for the basic apartment set. The calculation of the difference in percents of the yearly cooling load for investigated and basic apartment set reveals that 20 cm of concrete yields the maximum increase of cooling load of 0.72%, however, 40 cm of concrete will yield the cooling

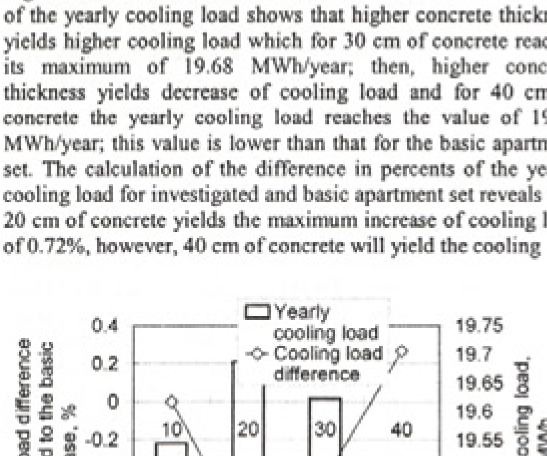

Fig.8. Cooling load and its difference as functions of thickness of concrete in thermally non-insulated A-walls. The difference is compared to the basic case.

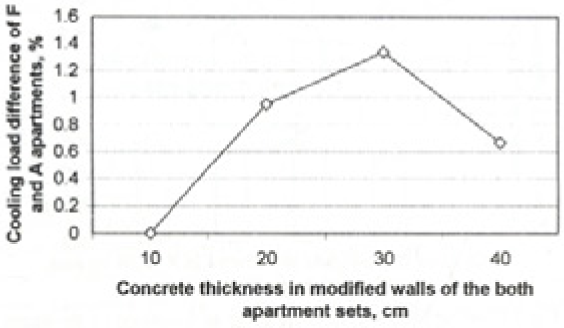

Fig. 9 Difference of cooling loads for the thermally non-insulated apartments with F and A-walls as given a function of thickness of modified concrete.

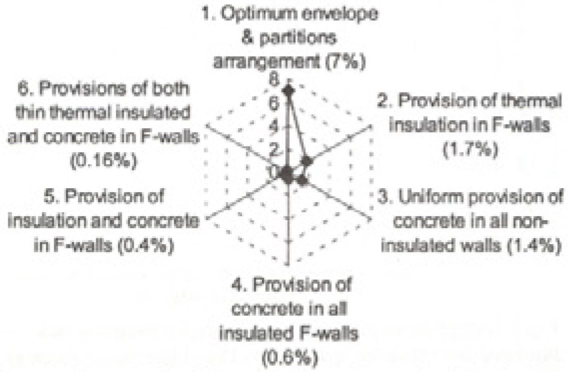

Fig. 10 The radar list of the minimum values of cooling load recorded in different investigations.

load decrease of 0.27%. So, when designing building envelope and partitions, concrete thickness around 20 cm should be avoided, while larger concrete thickness may be adopted.

Uniformity of Concrete Distribution within Thermally Non-Insulated Apartments

This study is performed to find the influence of uniformity of concrete distribution within apartment set to its yearly cooling load. During this study, the difference is calculated of cooling loads of two thermally non-insulated apartment sets: F-apartment set and A-apartment sets. The A-type apartment set has all walls modified by using concrete layers of the same thickness. The F-type apartment set has only F-walls modified by using concrete layers of the same thickness as that of concrete layers in the A-walls; its non-F-walls are not modified and have 10 cm-thick concrete layer. The concrete thickness of these modified walls varied from 10 to 40 cm. The investigation results are shown in Fig. 9 as a function of the thickness of concrete. The calculated differences show that they are always positive; that means that A apartment set has the lower cooling load than F apartment set. With increased concrete thickness, this difference increases, reaches its maximum of 1.35% (for the concrete thickness of 30 cm), and furthermore decreases. This means that for concrete thickness around 30 cm, the uniform concrete distribution may be one favorable strategy to decrease cooling load.

CONCLUSION

This paper describes the investigations that are performed on thermal behavior of residential apartments in Hong Kong for different characteristics of the apartments envelope and partitions. These investigations use the HTB2 software to calculate the yearly cooling load in these apartments. Obtained results serve for analyses of six different influences to the yearly cooling load of these apartments, i.e., that of 1. Envelope and partitions arrangement in thermally insulated apartments, 2. Provision of thermal insulation to apartments, 3. Concrete thickness in apartments with thermally insulated F-walls, 4. Concrete thickness in F-walls in thermally non-insulated apartments, 5. Concrete thickness in A(all)-walls in thermally non-insulated apartments, 6. Uniformity of concrete arrangement in envelope and partitions of thermally non-insulated apartments. These investigations yield the possible strategies to promote lower cooling load, and to avoid higher cooling loads.

The values of the maximum rise of cooling load reached for every of these investigations are presented in Fig. 10 in the radar form. The obtained values are (1) 7% for optimum envelope and partitions arrangement, (2) 1.7 % for a provision of thermal insulation in F-walls, (3) 1.3 % for optimum provision of concrete in all thermally non-insulated apartments, (4) 0.6 % for provision of concrete in the thermally insulated F-walls, (5) 0.4 % for provision of concrete to all walls in thermally non-insulated apartments, and (6) 0.16 % for provisions of both thin thermal insulation and concrete in F-walls.

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