Applied Energy 87 (2010) 599–607

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A case study for influence of building thermal insulation on cooling load and air-conditioning system in the hot and humid regions

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ARTICLE INFO

Article history:
Received 20 February 2009
Received in revised form 8 April 2009
Accepted 6 May 2009
Available online 26 May 2009

Keywords:
Thermal insulation
Reducing cooling load
Saving energy
Building energy performance

ABSTRACT

Ensuring the effective thermal insulation in regions, where the cooling requirement of building with respect to heating requirement is dominant, is very important from the aspect of energy economy. In this study, the influence of thermal insulation on the building cooling load and the cooling system in case of air-conditioning by an all-air central air-conditioning system was evaluated for a sample building located in Adana, based on the results of three different types of insulation (A, B and C-type buildings) according to the energy efficiency index defined in the Thermal Insulation Regulation used in Turkey. The operating costs of the air-conditioning system were calculated using cooling bin numbers. Life-cycle cost analysis was carried out utilizing the present-worth cost method. Results showed that both the initial and the operating costs of the air-conditioning system were reduced considerably for all three insulation thicknesses. However, the optimum results in view of economic measurements were obtained for a C-type building. The thickness of thermal insulation for the buildings in the southern Turkey should be determined according to the guidelines for a C-type building.

1. Introduction

Air-conditioning system (ACS) is responsible for a significant part of total energy consumption in building. Capacity of ACS is determined according to total cooling load of building. Building cooling loads consist of heat gains through opaque external surfaces and fenestration areas of the building and internal heat gains. Architectural and physical properties of building, such as thermal mass, structural material and its shape, are the most important parameters, which influence the space-cooling load. Another parameter is local climate. As reported in literature, different effective techniques such as free cooling, natural ventilation, thermal mass and night cooling can used in order to reduce the cooling load. Therefore, a significant energy saving (more than 50% as compared to an existing building) can be achieved [1–7]. On the other hand, thermal insulation is applied for reducing of heat loss or/and gain in buildings through the envelope. Yearly building cooling load and the peak cooling demand of building can be reduced significantly in the thermally insulated buildings located in hot dry and hot humid regions [7–13]. Therefore, reducing energy use for space cooling in buildings is a key measure to energy conservation and environmental protection. The main objective of this study is to reveal the influence of the building thermal insulation on the annual energy consumption of the cooling system in hot and humid regions, especially in the southern Turkey.

2. Application of thermal insulation in building

In Turkey, the thickness of thermal insulation material that should be applied to buildings is determined according to Turkish Standard 825 (TS 825) "thermal insulation in building" [14]. TS 825 is an application of "ISO 9164-Thermal insulation calculation of space heating requirements for residential buildings" in every respect and basically similar to EN 832-Thermal performance of buildings calculation of energy use for heating residential buildings. It is adapted to climatic conditions of Turkey [14,15]. In TS 825, the thickness of thermal insulation material can be determined according to the annual requirement of heating energy of the building which based on heat losses calculation. Turkey is classified into four climatic zones considering only heating energy requirement by using degree-day concept in TS 825. However, in the standard, cooling load of the building is not taken into consideration and the heat storage capacity of the building envelope is neglected. While heating is required in a region, cooling is needed in another region of Turkey. Because Turkey has a wide geographical area and different climatic regions. Bulut [16] showed that Turkey should be divided into five different heating degree-day and three different cooling degree-day regions. Aktacir and Büyükalaca [17] emphasized in result of study that the cooling-degree days for the main provinces Şanlıurfa (South-eastern Anatolia Region), Antalya (Mediterranean

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0306-2619/$ - see front matter
doi:10.1016/j.apenergy.2009.05.008

Nomenclature

ACS	air-conditioning system
AHU	air-handling unit
CAV	constant-air-volume system
COP_{full}	coefficient of performance of the chiller at full load
COP_{part}	coefficient of performance of the chiller at part load
E_{part}	total energy consumption of the compressor in the chiller unit and the fans under real operating conditions
L	thermal insulation thickness (m)
M_{fan_full}	design (maximum) capacity of the fan (m^3/h)
M_{fan_part}	quantity of the mixing air supplied to room (m^3/h)
N_{bin}	bin number
O_{cost}	energy cost of air-conditioning system ($/year)
PLR_{chil}	part load ratio of the chiller unit
PLR_{fan}	part load ratio of the fan
PWC	present-worth cost method
Q	annual energy requirement of building (in TS 825) (kW h/m^2)
Q_l	maximum allowed annual energy requirement of building (in TS 825) (kW h/m^2)
Q_{coil_full}	full load of the chiller unit (kW)
Q_{coil_part}	instantaneous load of the chiller unit (kW)
RTS	radiant time series cooling load calculation method
SHR	sensible heat ratio
T	price of electricity ($/kW h)
T_{out}	outdoor air temperature (°C)
U	overall heat transfer coefficient (W/m^2 K)
VAV	variable-air-volume system
VRF	variable refrigerant flow air-conditioner
VSD	variable-speed drive
W_{chil_part}	power consumption of the compressor in the chiller unit for part load (kW)
W_{fan_full}	power consumption of the fan at full load (kW)
W_{fan_part}	power consumption of the fan under the real operating conditions (kW)

Region), Istanbul (Marmara Region) and Zonguldak (Black Sea Region) at 22 °C base temperature are 933 h, 550 h, 104 h and 6 h, respectively, although all these cities are listed in the second region in TS 825. But, these provinces were positioned into the different regions according to their cooling-degree day values by Bulut [16]. Similarly, Yılmaz [7] investigated thermal performance of the same typical residential building in Istanbul and Mardin. Istanbul and Mardin are considered in the second region in TS 825, however those are in temperate-humid and hot-dry climatic zones, respectively. The study showed that cooling load in the same building in Mardin is bigger than that of Istanbul.

It is stated in TS825 that insulation should be applied according to PrEN ISO 13791 "Thermal performance of buildings – Internal temperatures in summer of a room without mechanical cooling – General criteria and calculation procedures" for cooling if necessary. However, this approach is not followed in Turkey even in the buildings for which cooling is more important than heating. Bolattürk [18] studied the optimum insulation thicknesses for external walls of buildings using cooling and heating degree-hours in the warmest regions of Turkey. Results of his study showed that use of cooling degree-hours is more suitable in these regions.

Ensuring the effective thermal insulation in regions, where the cooling requirement of building with respect to heating requirement is dominant, is very important from the aspect of energy economy. In some provinces of Turkey, such as the South-eastern Anatolia Region and in the coastal provinces located in the Mediterranean and Aegean Regions, which have a hot dry or hot humid climate and a longer cooling season (about 7 month) than heating season [17,19], the thermal insulation applied considering only heating energy consumption using degree-day concept may be insufficient during summer. Parallel to the economic growth of the country, package air-conditioners are used more and more frequently for thermal comfort in these regions. This can be seen clearly from Table 1 that shows the number of the split type and variable refrigerant flow (VRF) type package air-conditioners sold in Turkey during 1998–2006 [20].

In some countries, special procedures are followed for the regions having hot and longer summers and warm winters. The local energy conservation design standards used for residential buildings in Shanqai of China and the Single Family Housing Programs used in Colorado only at locations exceeding 600 cooling degree-day at 18.3 °C base temperature may be given as examples [21,22] to these procedures. Furthermore, AS2627.1–1993, "Thermal insulation of roof/ceilings and walls in dwellings" is uniquely and specifically Australian in that it deals with heating and cooling aspects with equal emphasis. It nominates the optimum amount of thermal resistance for 760 climate locations throughout Australia [23].

Table 1
Number of split and VRF air-conditioning systems manufactured and sold in Turkey [20].

Year	Production (unit)	Import (unit)	Sold (unit)	Export (unit)
1998	14,112	69,666	83,938	2193
1999	31	113,348	109,673	69
2000	21,488	122,847	140,056	538
2001	105,970	53,142	128,057	8872
2002	214,282	100,653	233,610	68,932
2003	392,360	206,317	378,658	225,445
2004	743,478	357,570	759,778	255,098
2005	963,725	557,879	1,117,613	376,186
2006	1,025,960	647,705	1,314,217	347,232

3. Sample building and thermal insulation

3.1. Building characteristics

In this study, an office center with three floors and 27 offices located in Adana, Turkey (36° 59′ latitude, 35° 18′ longitude and 20 m altitude; in Mediterranean region) was considered. Adana has hot and humid summer and warm winter, and is in the first degree-day region according to TS 825. To benefit from solar energy and light, typical window areas of building in Mediterranean region are generally designed larger than that of the standard. Total gross area of the building is 1628 m^2 and total fenestration area and external wall surface area are 299 m^2 and 668 m^2, respectively. Therefore, in this study, fenestration area is 45% of the external surface area of the building. Two people in each office and three laborers in each floor of the office center work between 09:00 and 20:00 h.

The height of each floor of the office center is 3 m. Fig. 1 shows the architectural plan of the ground floor of the sample building. Features of the opaque construction materials of the sample building are given in detail in Table 2.

3.2. Calculation of insulation thickness

In this study, it was assumed that thermal insulation with three different thicknesses is applied to opaque external components of

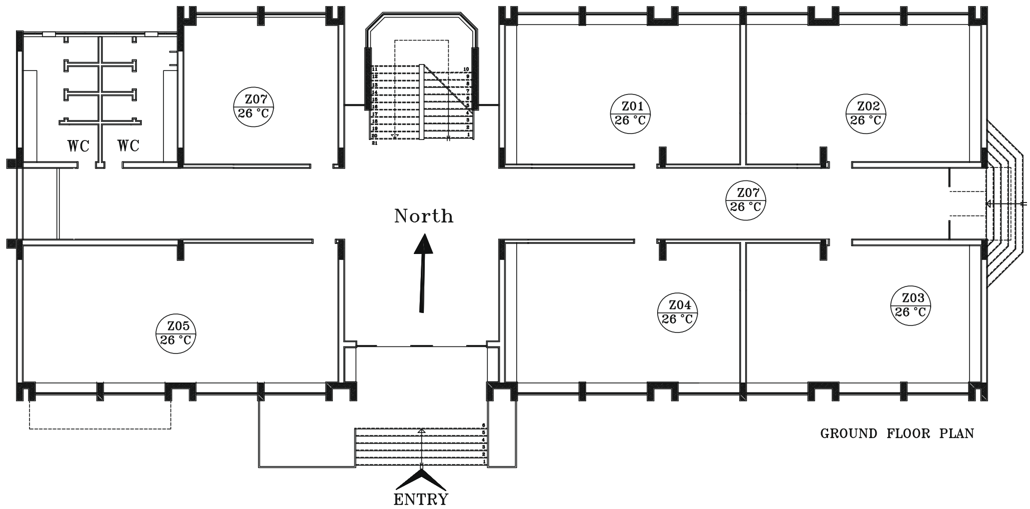

Fig. 1. Architectural plan of the sample building for the ground floor.

Table 2
Details of building construction materials.

Building construction	Details (thickness–thermal conductivity)
Exterior wall	Internal plaster (2 cm–0.87 W/m K), brick (20 cm–0.6 W/m K), thermal insulation (extruded polystyrene foam 0.031 W/m K), external plaster (2 cm–1.4 W/m K)
Floor	Mosaic tile (3 cm–1.05 W/m K), lightweight concrete (2 cm–1.4 W/m K), water insulation (2 mm–0.19 W/m K), thermal insulation (extruded polystyrene foam 0.031 W/m K), heavyweight concrete (12 cm–2.1 W/m K), lightweight concrete (10 cm–1.28 W/m K), blockage (10 cm–1.96 W/m K)
Roof	Internal plaster (2 cm–0.87 W/m K), heavyweight concrete (12 cm–2.1 W/m K), lightweight concrete (2 cm–1.4 W/m K), thermal insulation (extruded polystyrene foam 0.031 W/m K), lightweight concrete (2 cm–1.4 W/m K)

the sample building (Building A, Building B and Building C). Thickness of the thermal insulation for each building was determined so that Buildings A, B and C are, respectively type A, B and C buildings according to the building classes defined in thermal insulation regulation [24]. In the regulation, the buildings are classified as "A-type", "B-type" or "C-type" according to the ratio of the annual energy requirement of building Q (kW h/m^2) to the maximum allowed annual energy requirement of building Q_l (kW h/m^2). Table 3 presents classification of the energy efficiency index of the buildings according to the regulation. If Q/Q_l is higher than 0.99, insulation should be applied to reduce annual energy required for building.

The thermal insulation thickness (L) and the overall heat transfer coefficient (U) of opaque constructions of the sample building given in Table 4 were obtained by equalizing Q/Q_l to 0.79, 0.89 and 0.99 for Buildings A, B and C, respectively. The overall heat transfer coefficient of fenestration for all cases was 3 W/m^2 K.

Table 3
Classification of buildings according to the thermal insulation regulation effective in Turkey [24].

Type	Q/Q_l	Energy efficiency
A	$\leqslant$0.80	Very good
B	$\leqslant$0.90	Good
C	$\leqslant$0.99	Normal

In this study, architectural and physical properties of building are the same for all calculations, but not insulation thickness as given above.

3.3. Thermal insulation cost

The extruded polystyrene foam with thermal conductivity of 0.031 W/m K was used as thermal insulation material. The amount and cost of the thermal insulation material required for the building components for all three types of buildings considered in this study are given in Table 5.

4. Air-conditioning system

4.1. System design

All-air systems have been widely used in air-conditioning applications. The sample building is conditioned by an all-air central air handling unit (AHU) as shown in Fig. 2. As can be seen from the figure, the air-conditioning system consists of AHU, duct, air-cooled chiller system and control units. The indoor air conditions are 26 °C dry bulb temperature and 50% relative humidity. In the system, air is supplied to the air-conditioned volumes by mixing the minimum amount of the outdoor air (fresh) required for ventilation with the return air. Two main air distribution systems associated with all-air air-conditioning systems are constant-air-volume (CAV) and variable-air-volume systems (VAV). CAV systems have been used since the introduction of air-conditioning while VAV systems have been utilized since the 1960s. Energy saving is one of primary reasons that VAV systems are very popular design choices today for some commercial buildings and many industrial applications.

In this study, both CAV and VAV air distribution systems were investigated. In the VAV system, the mixing air supplied to conditioned space is constant at a temperature of 15 °C, but the mixing air flow rate is varied by the combined action of the closing of the zonal VAV box dampers and the fan speed controller to meet the building cooling load. In the CAV system, supply air flow rate is constant, but supply air temperature (minimum 15 °C) is varied to remove the heat gain from inside of conditioned space. Outdoor air requirement of the sample building was obtained to be 1596 m^3/h for minimum ventilation level in accordance with ASHRAE Standard 62 ventilation rate procedure [25].

Table 4
Overall heat transfer coefficients (U) and thickness of the insulation material (L).

Type	Wall		Roof		Floor	
	L (m)	U (W/m^2 K)	L (m)	U (W/m^2 K)	L (m)	U (W/m^2 K)
Building A	0.06	0.403	0.08	0.349	0.07	0.374
Building B	0.04	0.546	0.06	0.451	0.04	0.588
Building C	0.03	0.662	0.04	0.637	0.03	0.725
No insulation building	0	1.849	0	3.588	0	2.440

Table 5
Amount and cost of thermal insulation material.

Type	Required insulation (m^3)				Insulation cost ($)
	Walls	Roof	Floors	Total	
Building A	40.06	47.40	41.48	128.93	15,278
Building B	26.70	35.55	23.70	85.95	10,186
Building C	20.03	23.70	17.78	61.50	7,288

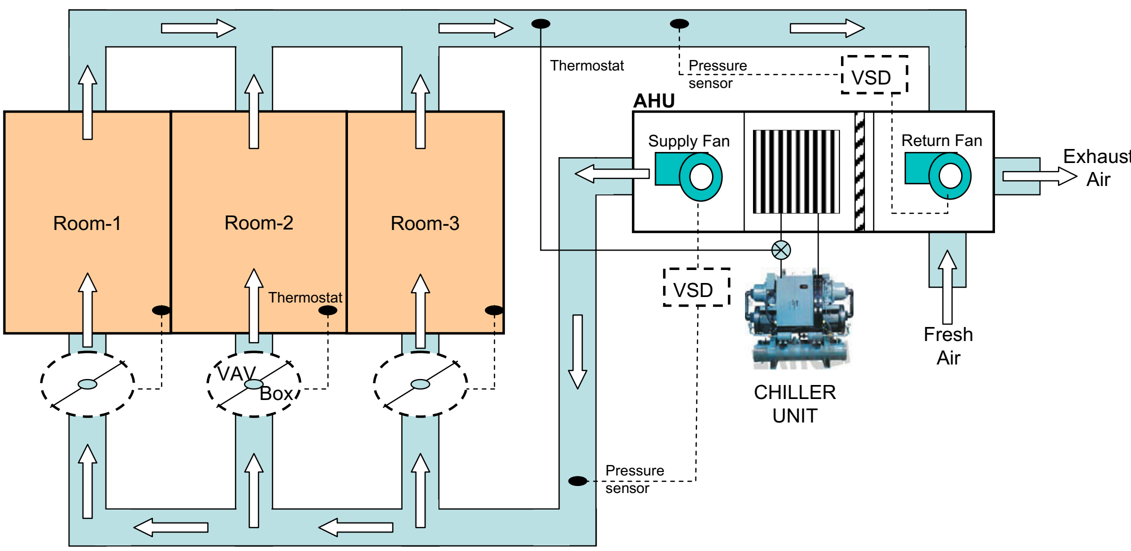

Fig. 2. A general view of all-air air-conditioning system (for VAV, additional units are shown with dashed line).

Building cooling load was calculated according to the Radiant Time Series (RTS) method suggested by ASHRAE [26,27]. Hourly distribution of the design-cooling load calculated for all types of buildings considered are shown in Fig. 3. In the calculation, outdoor design conditions for Adana were taken to be 38 °C dry bulb temperature and 26 °C wet bulb temperature. As shown in Fig. 3, design-cooling load of the no insulation building is 145.14 kW

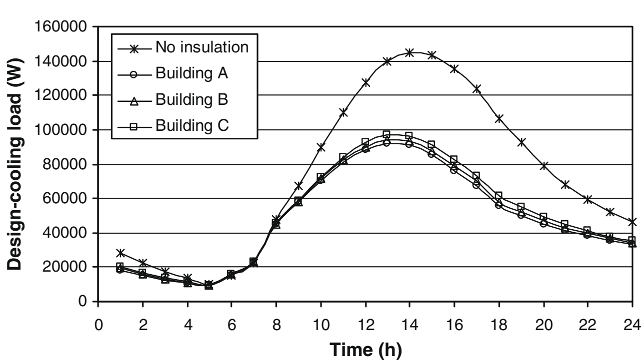

Fig. 3. Variation of Hourly cooling load of sample building.

and sensible heat ratio (SHR) is 0.98. Design cooling loads of Buildings A, B and C are 92.15 kW, 94.19 kW and 97.11 kW, respectively, and their SHRs are all 0.97. Design cooling load of the sample building is decreased maximum 33% due to thermal insulation. Increase of the thickness of the insulation material does not reduce significantly cooling load of the building. Design cooling load of Building A, which has the best insulation, is only 2% and 5% less than that of Building B and Building C, respectively. Hourly distributions of parts of the design-cooling load for building without insulation are presented in Fig. 4. As it can be seen in Fig. 4, the cooling load due to opaque external components (external wall, roof, and floor) surface areas of the building without insulation is about 40% of the maximum total cooling load. For this reason, thermal insulation was applied to the building's opaque surfaces for reducing of heat gain in buildings through the envelope. Moreover, space-cooling load can be reduced because of the low solar heat gains, when fenestration surface area (openings) is decreased. Similarly, cooling load is influenced by thermal mass of opaque elements [1,2,7]. In this study, the ratio of the building's openings to the opaque areas is 0.45. Construction materials of sample building were the same for all calculations.

Variation of the ratio of cooling load due to insulation applied opaque external components to the total cooling load of the build-

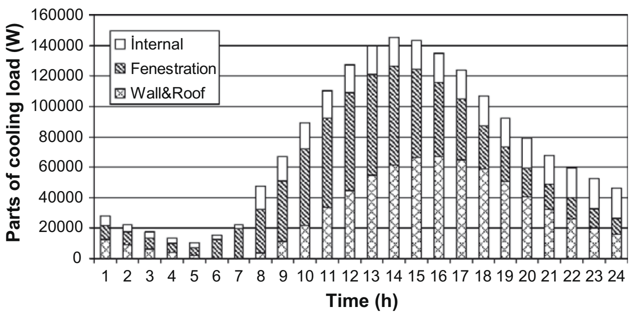

Fig. 4. Hourly distribution of design-cooling load for building without insulation.

ing during occupation period is shown in Fig. 5. The ratio obtained for the no insulation building is also shown in the figure. As can be seen from the figure, the opaque external components of the no insulation building constitute approximately 50% of the total load, while this percentage is between 2% and 20% for the insulated buildings (Buildings A, B and C).

Using the design conditions given above (design-cooling load, sensible heat ratio, minimum fresh air ventilation requirement and supply air temperature), the maximum (design) cooling coil capacity and the maximum (design) total mass flow rates of supply and return fans were determined with an iterative approach (Table 6). Therefore, a computer program was written for the calculations. Capacities of the supply and return fans for CAV and VAV systems are the same.

Equipment of the air-conditioning system was selected from a local supplier (Alarko-Carrier). Net cooling capacity and electricity consumption of the chiller unit selected are 111 kW and 47.4 kW for Buildings A, B and C, 152 kW and 67 kW for the no insulation building under nominal operating conditions (38 °C condenser temperature, 12 °C evaporator inlet and 7 °C outlet water temperature), respectively. Total mass flow rates of the supply and return fans in AHU for the no insulation building is 45,438 m^3/h. The supply and return fans have 22 kW and 18.5 kW power consumptions, respectively. Total mass flow rates and power consumptions of the supply and return fans for Buildings A, B and C are 30,000 m^3/h, 15 kW and 11 kW, respectively.

4.2. Initial cost

Total initial costs of the air-conditioning system including the chiller unit, AHU, duct and automation equipment costs are given in Table 7. When building envelopes were insulated (Buildings A, B and C), the initial cost of ACS for CAV and VAV systems were about 22% less than those of buildings without insulation.

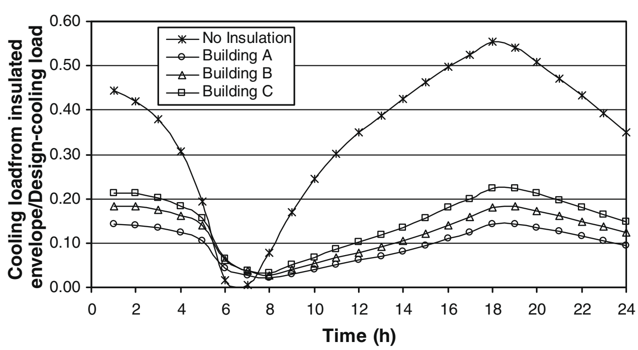

Fig. 5. Ratio of thermal insulation dependent loads to the total cooling load.

4.3. Operating cost

The Bin method was used for calculation of energy consumption of the chiller unit. This method is based on the calculation of the energy consumption for different values of the outdoor temperature (T_{out}) and multiplying it by the corresponding number of hours (N_{bin}) in the temperature bin centered on that temperature [27]. The bin method, which has different forms today, has been developed from the various degree-day methods available. For many applications, the degree-day method should not be used, even with the variable-base method, because the heat loss coefficient, the efficiency of the HVAC system, or the balance point temperature may not be sufficiently constant. The efficiency of the HVAC equipment, for example, varies strongly with outdoor temperature. In such cases, a steady-state calculation can yield good results for the annual energy consumption if different temperature intervals and time periods are evaluated separately [27].

Monthly bin data with 3 °C increments in 4-h periods between 9:00–20:00 h during cooling season for Adana are given in Table 8 [28]. The cooling period for Adana, which has a hot and humid climate during summers, covers 184 days between May and October [7].

Operating costs of the air-conditioning systems during cooling season for 9:00–12:00 h, 13:00–16:00 h and 17:00–20:00 h were obtained using bin number. The minimum reducing ratio of the variable-speed drive (VSD) used in VAV system in order to adjust the operating speed of the fan was taken to be 30%.

Free cooling systems use outdoor air to reduce the cooling requirement when outdoor air is cool enough to be used as a cooling medium. In this study, the sample building is conditioned by free cooling (outdoor air is directly supplied to the air-conditioned space) when outdoor air temperature is least 8 °C lower than indoor temperature ($T_{out} \leqslant 18$ °C) [29]. By doing this, operating hours of the chiller unit in ACS is reduced. Therefore, both electricity consumption and environmental impact are reduced as well.

Total operating hours of the mechanic and free cooling systems during cooling season for Adana are presented in Table 9. Free cooling is possible only in May and October with the conditions $T_{out} \leqslant 18$. As shown in Table 9, the potential of free cooling is not enough for the occupation period considered in this study (9:00–20:00). However, an increase in the potential of free cooling for Adana is noticeably observed in night time (20:00–08:00).

The main electricity-consuming units in the air-conditioning systems are the fans and the chiller unit. In this study, the energy consumption of the ACS was determined by the following procedure. Firstly, part load ratio of the chiller unit (PLR_{chil}) was found using:

$$PLR_{chil} = Q_{coil\_part}/Q_{coil\_full} \tag{1}$$

where Q_{coil_full} indicates the full load of the chiller unit and is obtained from the manufacturer's data for all bin data (time shift and interval temperature). Q_{coil_part} indicates the instantaneous load removed by the ACS from interior of building. It was obtained using psychometric analysis for all bin data. Q_{coil_part} is the sum of the cooling load of the building and the fresh air load due to the mixing air supplied to room.

Secondly, coefficient of performance at part load (COP_{part}) was calculated by the following equation [30]:

$$COP_{part} = (COP_{full} \cdot PLR_{chil})/(0.16 + 0.32PLR_{chil} + 0.52PLR_{chil}^2) \tag{2}$$

in which, COP_{full} indicates the coefficient of performance of the chiller at full load. It was obtained from the manufacturer's data for all bin data.

Thirdly, the power consumption of the compressor in the chiller unit for part load (W_{chil_part}) was determined using:

Table 6
Capacities of air-conditioning equipments.

	No insulation building	Building A	Building B	Building C
Nominal cooling capacity of the chiller unit (kW)	152	111	111	111
Power consumption of chiller unit (kW)	67	47.4	47.4	47.4
Total mass flow rate for AHU (m^3/h)	45,438	28,560	29,191	30,097
Total fan motor capacities (kW)	40.5 (18.5 + 22)	26 (11 + 15)	26 (11 + 15)	26 (11 + 15)

Table 7
Initial cost of air-conditioning system.

Equipments of the air-conditioning system	No insulation building		Buildings with insulation	
	CAV ($)	VAV ($)	CAV ($)	VAV ($)
AHU	33,040		21,240	
Duct	27,000		20,000	
Chiller	31,860		27,140	
Automation	6854	15,617	5895	11,737
Variable speed drive	–	7469	–	5610
VAV box	–	9305	–	8893
Total	98,754	124,291	74,275	94,620

Table 8
Monthly bin values (N_{bin}) for Adana during cooling season [28].

Temp. bin (°C)	May			June			July		
	9:00–12:00 (h)	13:00–16:00 (h)	17:00–20:00 (h)	9:00–12:00 (h)	13:00–16:00 (h)	17:00–20:00 (h)	9:00–12:00 (h)	13:00–16:00 (h)	17:00–20:00 (h)
39/42	0	1	0	0	0	0	0	1	0
36/39	1	3	1	1	3	1	2	7	1
33/36	4	10	2	4	14	2	12	44	7
30/33	8	16	6	21	49	14	58	65	43
27/30	18	29	15	52	41	42	48	6	61
24/27	35	34	28	36	10	45	4	1	11
21/24	34	18	36	6	2	14	0	0	1
18/21	17	9	25	0	1	2	0	0	0
15/18	6	3	9	0	0	0	0	0	0
12/15	1	1	2	0	0	0	0	0	0
	August			September			October		
39/42	0	2	0	0	1	0	0	0	0
36/39	2	9	2	1	9	1	1	5	0
33/36	18	63	9	8	32	4	4	12	1
30/33	62	47	44	39	59	19	10	26	4
27/30	40	3	58	48	15	46	23	33	13
24/27	2	0	11	20	2	43	31	25	32
21/24	0	0	0	4	1	5	28	14	37
18/21	0	0	0	0	1	2	20	7	24
15/18	0	0	0	0	0	0	6	2	11
12/15	0	0	0	0	0	0	1	0	2

Table 9
Operating hours of the mechanical and free cooling during cooling season.

Month	9:00–12:00		13:00–16:00		17:00–20:00	
	Mechanical cooling (h)	Free cooling (h)	Mechanical cooling (h)	Free cooling (h)	Mechanical cooling (h)	Free cooling (h)
May	117	7	120	4	113	11
June	120	0	120	0	120	0
July	124	0	124	0	124	0
August	124	0	124	0	124	0
September	120	0	120	0	120	0
October	117	7	122	2	111	13
Total	722	14	736	6	712	24

$$W_{chil\_part} = Q_{coil\_part}/COP_{part} \quad (3)$$

For determining the power consumption of the fan, the part load ratio of the fan (PLR_{fan}) was found by the following equation:

$$PLR_{fan} = M_{fan\_part}/M_{fan\_full} \quad (4)$$

where M_{fan_full} represents the design (maximum) capacity of the fan. M_{fan_part} indicates the quantity of the mixing air supplied to

Table 10
Seasonal operating cost of air-conditioning system.

Air distribution system	Unit	No insulation building ($/year)	Building A ($/year)	Building B ($/year)	Building C ($/year)
VAV	Fan	1590	1326	1299	1272
	Chiller	5377	3914	3959	4031
	Total	6967	5240	5258	5303
CAV	Fan	8938	5738	5738	5738
	Chiller	5377	3914	3959	4031
	Total	14,315	9652	9697	9769

Table 11
Insulation cost of the building, the initial and operating costs of air-conditioning system.

Cost type	Air distribution system	No insulation building ($)	Building A ($)	Building B ($)	Building C ($)
Building insulation cost	VAV and CAV	–	15,278	10,196	7288
Initial cost of the ACS	VAV	124,291		94,620	
	CAV	98,754		74,275	
Operating cost of the ACS	VAV	6967	5240	5258	5303
	CAV	14,315	9652	9697	9769

room. For the CAV system, mass-flow rate is constant through the operation of the system; therefore even for the part-load conditions the fans consume the maximum power. Under peak-cooling conditions, the VAV system operates identically to a CAV system with AHU operating at maximum flow (M_{fan_full}) and maximum cooling coil capacity (Q_{coil_full}). However, at reduced cooling load, the airflow is reduced by the combined action of the closing of the zonal VAV box dampers and the fan speed controller. The power consumption of the fan under the real operating conditions (W_{fan_part}) was calculated by the following equation [19]:

$$W_{fan\_part} = W_{fan\_full}\mathrm{PLR}^3_{fan} \quad (5)$$

in which, W_{fan_full} indicates the power consumption of the fan at full load.

Finally, total energy consumption of the compressor in the chiller unit and the fans under real operating conditions (E_{part}) was obtained multiplying BIN data (N_{bin}) with the power consumption of the chiller unit and the fans:

$$E_{part} = N_{bin}(W_{chil\_part} + W_{fan\_part}) \quad (6)$$

Energy cost of the system (O_{cost}), can be determined using the energy consumption of the system (E_{part}) and price of electricity (T), which is currently about 0.11 $/kW h in Turkey:

$$O_{cost} = E_{part}T \quad (7)$$

Using the procedure given above, operating costs of the chiller, the fans and the total operating cost were calculated and the results are given in Table 10 for a cooling season.

Seasonal operating cost of the ACS with VAV was determined to be $6967 for the no insulation building. In the case of Buildings A, B and C, seasonal operating cost is about 25% less than that of the no insulation building. Similar results were obtained with CAV air distribution system. In this case, seasonal operating cost for Buildings A, B and C is about 33% less than that of the no insulation building.

5. Economic analyses

An economic analysis was carried out in order to determine influence of the thermal insulation on the initial and operating costs of the ACS. Present-worth cost (PWC) method, which is one of the analyses methods of the life-cycle cost, was used for evaluating the ACS in case of different thermal insulations [19,27,31,32]. Results of the LCC analysis are directly affected by the economic measures. Therefore, in the analyses, an annual interest rate of 14% and inflation rate of 8% were selected considering the present economic conditions of Turkey. The system life of the ACS was taken as 15 years. Total initial cost consists of the initial cost of the ACS and the cost of the building insulation.

The initial and operating costs of the ACS and the insulation cost of the building are given in Table 11 for all building types considered in this study.

Results of the economic analyses are given in Table 12. From the table it is seen that at the end of the lifetime (15 years), the present-worth cost of the no insulation building is $302,873 for the CAV air distribution system. There is almost no difference between the insulated buildings (<2.8%). The present-worth cost for the insulated buildings is approximately 26% smaller than that for the no insulation building.

In the case of the VAV air distribution system, the trend is similar to that for the CAV. While the present-worth cost of the no insulation building at the end of the lifetime is $223,634, its value for Buildings A, B and C are, respectively, 17.5%, 19.6% and 20.6% less than for the no insulation building.

Annual variation of the overall present-worth cost of the ACS for all building types are presented in Figs. 6 and 7 for VAV and CAV systems, respectively. From the figures it is seen that the present-worth cost of the no insulation building is always higher than that of Buildings A, B and C even from the initial installation of the system. The difference between the no insulation building and the insulated buildings continually increases during lifetime. These results show that the insulation applied to the building envelope for all thicknesses considered in this study is feasible.

In this study, Building C, which has the least thermal insulation among the insulated building types, was compared with Buildings

Table 12
Results of economic analyses.

System	Building	PWC at the end of lifetime ($)	Saving ($)	Saving (%)
CAV	No insulation	302,873	–	–
	A	227,182	75,691	25.0
	B	222,741	80,131	26.5
	C	220,860	82,013	27.1
VAV	No insulation	223,634	–	–
	A	184,616	39,018	17.5
	B	179,790	43,844	19.6
	C	177,524	46,110	20.6

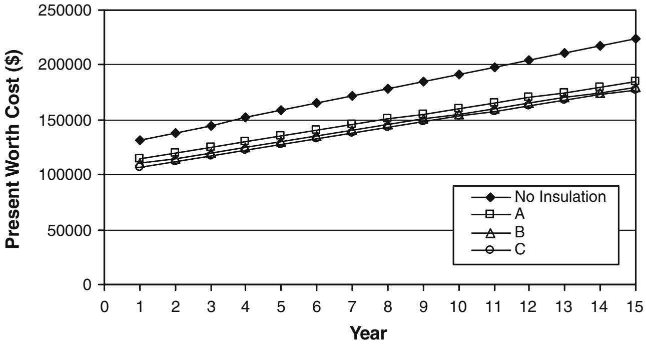

Fig. 6. Annual variation of overall present-worth cost of the ACS with VAV.

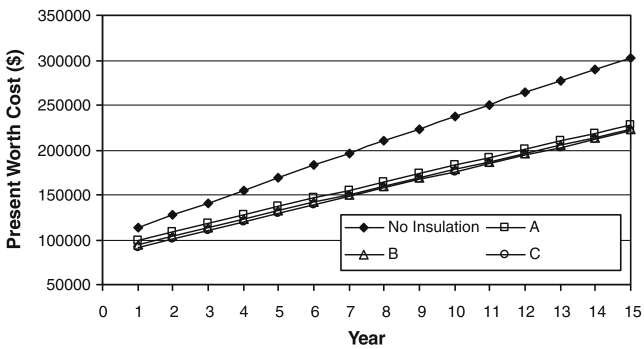

Fig. 7. Annual variation of overall present-worth cost of the ACS with CAV.

Table 13
Yearly saving and payback time for extra investment of Buildings A and B with respect to Building C.

		Building A	Building B
Yearly saving ($)	CAV	63	45
	VAV	117	72
Payback time (year)	CAV	125	65
	VAV	68	40

A and B to determine the optimum thermal insulation thickness from economy point of view. Extra investment needed for Buildings A and B with respect to Building C is $7990 and $2908, respectively. Compared with these extra investments needed, the savings due to thicker insulations (Buildings A and B) are not significant. Yearly savings in operating cost of ACS with VAV for Buildings A and B were found to be, respectively, $117 and $72 with respect to Building C (Table 13). In the case of the CAV system, the savings are even smaller ($63 for Building A and $45 for Building B).

Payback times of applying extra insulation with respect to Building C vary between 40 and 125 years. These results clearly show that the insulation thickness applied to Building C is enough. Thicker insulations do not offer extra savings.

6. Conclusions

In this study, a sample building located in Adana in Mediterranean Region (hot and humid summer and warm winter) was considered for studying the influence of different thicknesses of insulation applied to the opaque external components on cooling load and energy consumption of air-conditioning system. Energy performance of the building for cooling period was investigated with life-cycle cost analysis. The thicknesses of the insulation material were determined according to A, B and C-type buildings defined in the "energy efficiency index" in TS 825.

Design cooling load of the sample building decreased maximum 33% due to thermal insulation. The capacities of the equipment used in the air-conditioning system for the insulated buildings were lower than that of the no insulation building. Therefore, both the initial and the operating costs of the ACS were reduced considerably. For Buildings A, B and C;

- initial cost of the ACS for CAV and VAV systems are about 22% less,
- operating cost of the ACS is 25% less for VAV and 33% less for CAV,

with respect to the no insulation building.

Results of economic analyses show that the insulation investments for Buildings A, B and C are feasible due to reduced operating and initial costs of the ACS. However, when the different insulation thicknesses considered in this study are compared with each other, it is clearly seen that C-type insulation applied to buildings is satisfactory from economic aspect. Therefore, if a building located in hot regions of Turkey is constructed according to C-type building in "energy efficiency index" both the operating and initial costs of the ACS are significantly reduced.

As a result, it is suggested that the thickness of thermal insulation material for buildings in the coastal provinces located in the Mediterranean countries (such as Turkey, Italy, Spain and Greece), which have hot and longer summers and warm winters, should be determined according to the cooling-degree day. Otherwise, the thermal insulation applied considering only heating degree-day concept may be insufficient during cooling period.

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