Energy simulation of rooms with Controlled Active Mass

Master of Science thesis

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Building Physics
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

In this thesis work different aspects of using Controlled Active Mass (CAM) have been studied using numerical analysis. The CAM is an extra thermal mass which is placed inside the building to decrease energy demand for cooling and heating. Different kinds of CAM has been modeled in a type of room based on International Energy Agency Building Energy Simulation Test (BESTEST). Two kinds of walls, light weight and heavy weight, have been used for modeling the room. The indoor climate of the room has been studied when CAMs with different sizes and materials were placed at different locations of the room.
The CAM and the room have been modeled and simulated using the Simulink toolbox of Matlab and IBPT (International Building Physics Toolbox). The simulation has been done for the weather data of a whole year.

The simulation results show that using a CAM can decrease energy demand in the building specially for cooling. The best performance of a CAM strongly depends on its location inside a room. Selecting an optimum CAM in a room depends on the size, material and location of the CAM and also the time duration. A good choice can decrease the energy demand considerably.

Key words: CAM, energy simulation, heat storage, SIMULINK, building physics

Contents

1. Introduction

Lots of energy is consumed in buildings to prepare a suitable indoor climate. Nowadays using advanced insulation methods and also improved materials in constructions has decreased energy demand specially in the case of heating demands. Reaching to this level of advanced *permanent* constructions asks for new methods in indoor climate conditioning.

Using *Controlled Active Mass (CAM)* is a recommended new way in this field. CAM is an extra mass which affects the heat transfer and energy storage and consumption inside a room. It can have different shapes, materials and locations and of course it is removable. CAM affects both the heating and cooling demands of a room. But it is more effective in decreasing cooling demands.

In this thesis work different effects of using a CAM on indoor temperature of a room and energy consumption for heating and cooling has been studied. Two different rooms have been modeled. The difference is in using light weight and heavy weight materials in the wall construction. In some steps to simulate more practical cases some additional heat loads has been added to the room instead of room stuffs like furniture. The indoor climate of the room has been simulated when different kinds of CAM are placed in different locations of the room. The room is in contact with the outside air and is located on the ground. Weather data for whole year in Göteborg has been used. The simulation has been done using the Simulink toolbox of Matlab and IBPT (International Building Physics Toolbox).

2. Case of study

A model of a room based on BESTEST standard has been used in this work. Figure 1 shows a schematic drawing of the room with a CAM inside. A CAM is shown in figure 2. Some of the geometrical properties are listed below:

Room

Length	8 m
Width	6 m
Height	2.7 m

Window

Width	3 m
Height	2 m

Window is located on the south wall of the room
Distance of window from floor is 0.2 m

CAM

Thickness	0.1 m-0.2 m-0.3 m-0.4 m
Width	2 m
Height	1 m-2 m

CAM has the same distance from east and west walls and it moves in the direction of the room length. The longitudinal place of a CAM inside the room is measured as the distance between north face of the CAM and north wall of the room.

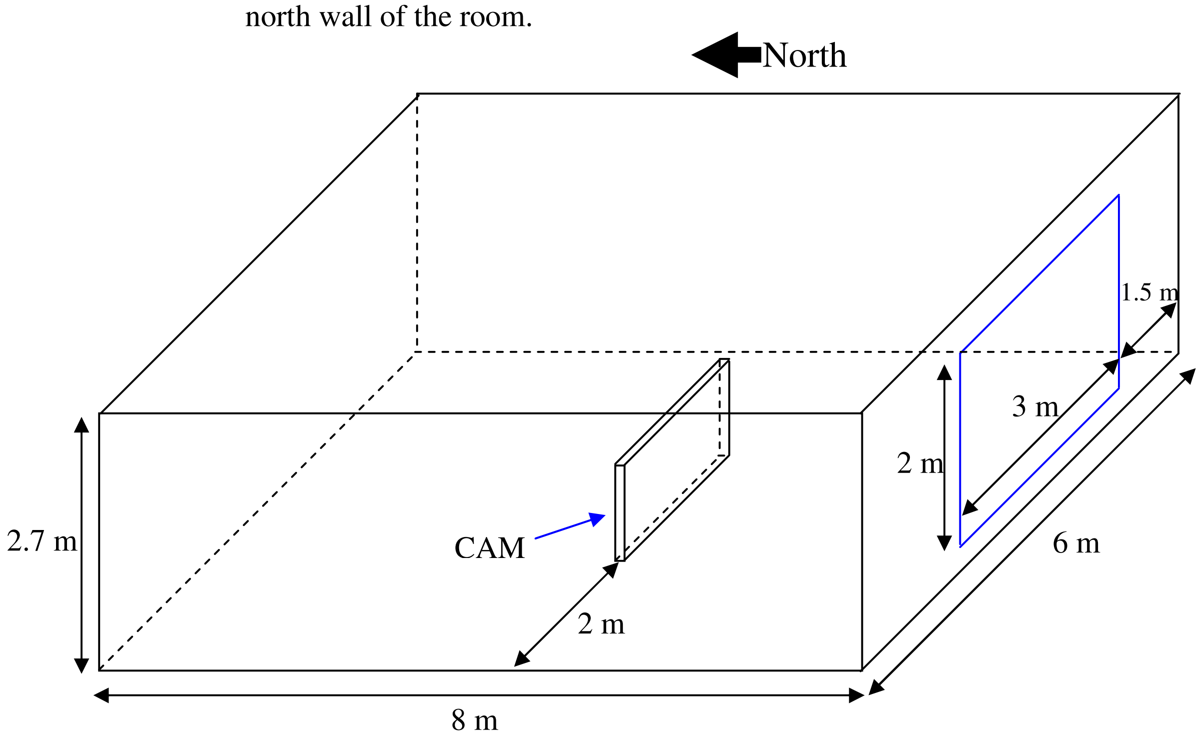


Figure 1. Room with a CAM inside

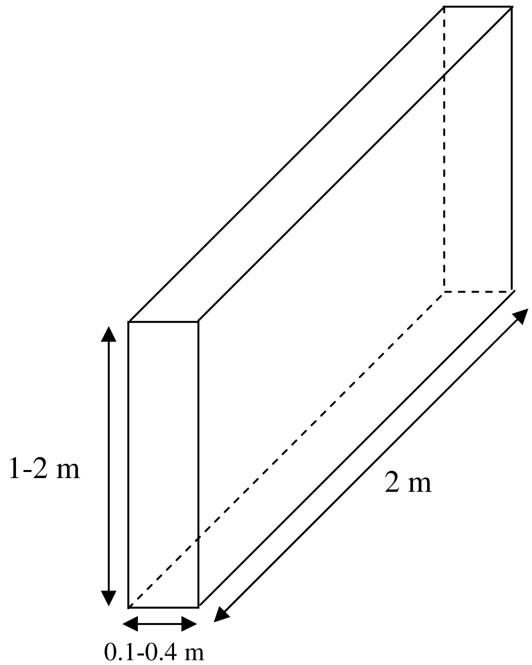


Figure 2. Schematic drawing of CAM

2.1. Construction parts

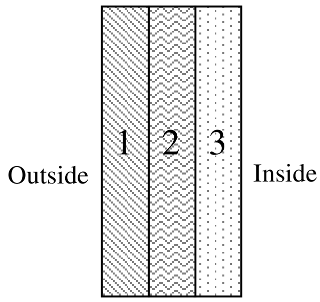
The room has different parts which are modeled based on IBPT. The CAM is inside the room and is modeled as a wall. The physical properties of materials are listed in table 1.

Wall

Each wall is made of two or three layers with different materials and thicknesses.

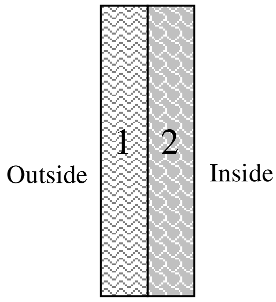
Light weight construction

Layer	Material	Thickness (mm)
1	Wood	20
2	Insulation	130
3	Gypsum	9



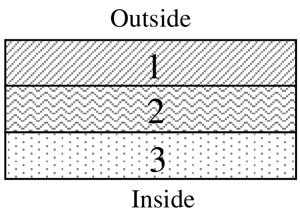
Heavy weight construction

Layer	Material	Thickness (mm)
1	Insulation	130
2	lw con. 2	20



Roof

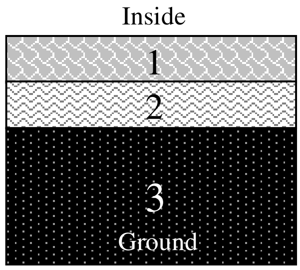
Layer	Material	Thickness (mm)
1	Wood	20
2	Insulation	130
3	Gypsum	9



Floor

The floor has two layers with two different materials and thicknesses. It is located on the ground which is simulated as an extra layer with the thickness of 1 m.

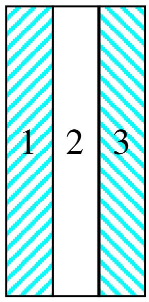
Layer	Material	Thickness (mm)
1	Concrete	200
2	Insulation	200
3	Soil-Clay	1000



Window

The window has two panes of glass. The space between the panes is filled with air.

Layer	Material	Thickness (mm)
1	Glass	3.175
2	Air	12
3	Glass	3.175

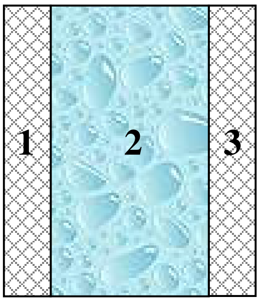


CAM

The CAM has a shell with different materials (layers 1 & 3) which stores water (layer 2) inside.

Type 1

Layer	Material	Thickness (mm)
1	Al_1	10
2	Water	80, 180, 280, 380
3	Al_1	10



Type 2

Layer	Material	Thickness (mm)
1	Al_2	10
2	Water	80, 180, 280, 380
3	Al_2	10

Type 3

Layer	Material	Thickness (mm)
1	soil-clay	10
2	Water	80, 180, 280, 380
3	soil-clay	10

Material	air	Al_1	Al_2	concrete	lw con.* 2	lw con. 4	glass	gypsum	insulation	soil-clay	water	wood
dry Density (ρ) [$\frac{kg}{m^3}$]	1.2	2702	2702	2300	1400	1000	2500	900	100	2000	1000	500
Thermal conductivity (λ) [$\frac{W}{m\,K}$]	0.025	237	237	1.7	0.65	0.42	0.7	0.22	0.04	1.5	0.6	0.14
Specific heat (C_p) [$\frac{J}{kg\,K}$]	1000	900	900	900	1000	1000	840	800	1000	1500	4181.3	1500
Absorptivity (α)	-	0.6	0.8	0.6	0.6	0.6	0.1	0.6	0.9	0.9	-	0.6
Emissivity (ε)	-	0.09	0.09	0.92	0.7	0.7	0.8	0.9	0.9	0.9	0.95	0.9
Transmittance (τ)	-	0	0	0	0	0	0.75	0	0	0	-	0

* lw con.: light weight concrete

Table 1. Material properties

2.2. Mechanical devices

The room has a ventilation system, cooling and heating systems to get a suitable indoor climate conditions for occupants.

In most of the cases the ventilation system has a constant air exchange rate of 0.5 h^{-1} m^3/s. The volume of the room is 130 m^3. Driving pressure of ventilation system is 1 Pa. In some cases a ventilation system with variable air exchange rate has been used. More information about these cases is found in the result section.

Heating and cooling systems start working when the indoor temperature is outside the comfort limit which is between 20^{o}C and 24^{o}C. When temperature decreases below 20^{o}C the heating system turns on and when it increases above 24^{o}C the cooling system starts working. Our reference in measuring the energy consumption in the building is amount of consumed energy for cooling and heating.

2.3. Boundary and initial conditions

The room outside is in contact with the outdoor weather. The weather data of Göteborg for a year has been used. The convective heat transfer coefficient for the outside surface of the room is 20 W/m^2K. For inside surfaces it is equal to 3W/m^2K.

The initial temperature of the room and the CAM is 20^{o}C. It means that the results for the first few days of the simulation should be neglected. In this work whenever the results for a certain time period are considered, the simulation has been begun at least 7 days before that time to eliminate effects of initial conditions on the results.

3. Numerical model

Effects of using CAM on indoor climate have been studied by simulating the study cases using Simulink toolbox of Matlab and International Building Physics Toolbox (IBPT).
The model is a room with four walls, one window and a ceiling which are in contact with outdoor weather. The floor is on the ground and there is a CAM which can be moved inside the room. This room has a ventilation system and cooling and heating systems.
It is assumed that the CAM divides the room into two zones, *south* and *north*. CAM is modeled as a wall between these two zones. Each zone has six surfaces. That side of the CAM which faces the window works as a north wall in the south zone. The other side of the CAM is the south wall in the north zone. South wall of the room is the south wall of south zone and north wall of the room is the north wall of the north zone. Ceiling, floor, west and east walls are divided between two zones according to the longitudinal location of a CAM in the room. In this kind of simulation, modeling a CAM as a wall makes us to neglect heat transfer from side surfaces of the CAM.

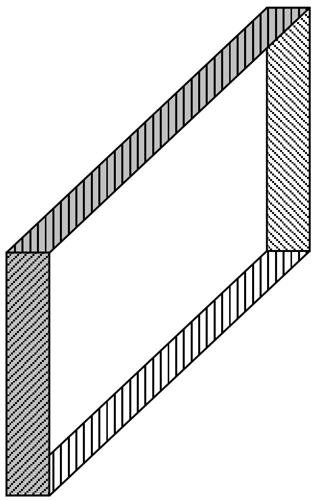


Figure 3. Side surfaces of a CAM

In most of the cases the ventilation system and the heating and cooling systems (which are named as *Gains*) are in the south zone. Two air exchangers with high rate of 100×130/3600 m^3/s are used for exchanging air between two zones and making a uniform indoor climate.

Window transmits light into the south zone, which is between the CAM and the south wall of the room, according to its transmittance; τ. Each surface in two zones receives a portion of this solar radiation. These portions are named as *solar fractions*. Solar fractions have been found for each location and size of a CAM in each hour of the year. Finding window transmittance and solar fractions are discussed more in section 4 of this report. The weather data is available for each hour of the year for the city of Göteborg in Sweden with geographic latitude of 57° 42´ N, geographic longitude of 11° 58´ E and altitude of 31 m. This weather data includes different kinds of information such as sun angle, air pressure, wind speed and air temperature. Window transmittance, solar fractions and weather data are used as data series during simulation.

Figure 4 shows a schematic drawing of the model in Simulink toolbox of Matlab. Different parts of each zone are connected to the corresponding zone. Zones are connected to each other through two air exchangers with high exchanging rate and a CAM. These two air exchangers do not affect the indoor climate. They are added to the model to reach the real condition of the room and have the same climate conditions in both zones of the model.

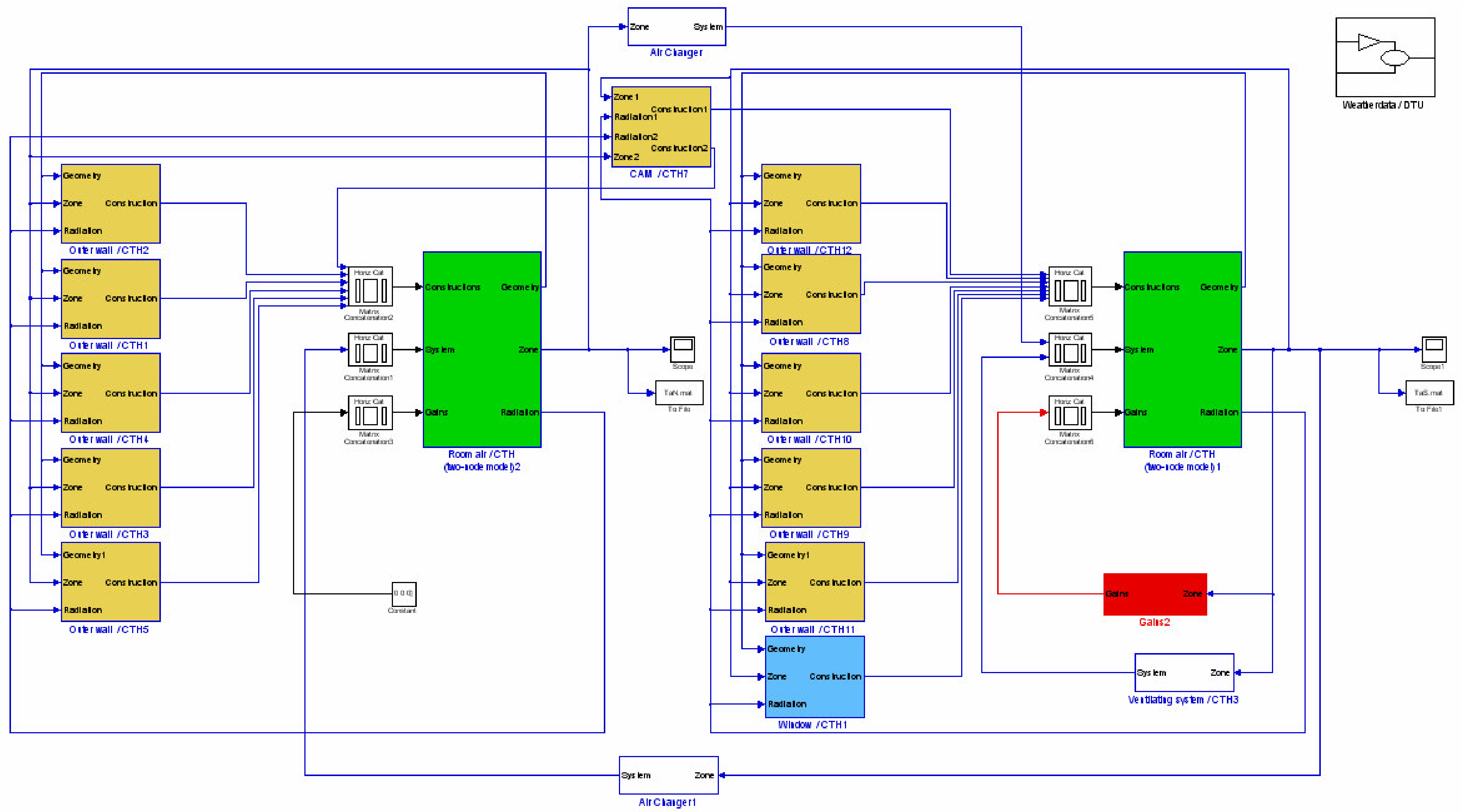


Figure 4. Schematic of a room model in the Simulink toolbox of Matlab

4. Distribution of solar radiation within a room

CAM is used inside a room to use free solar energy optimally. Size, location and surface properties of a CAM affect the amount of solar radiation usage. Solar energy is transferred to the room through radiation. Radiative energy is absorbed, transmitted or reflected by surfaces. It affects the temperature of the surfaces and materials which also causes variations in the rates of convective and conductive heat transfer. It is obvious that finding a reliable amount of solar radiation which hits each surface is very important for different situations of a CAM. Numerical calculations have been done for finding solar fractions for surfaces in each hour of the year and for different positions and types of a CAM. View factors and solar fractions have been calculated assuming diffusive propagation of radiations.

4.1. View factors

For simple geometries like two perpendicular or parallel surfaces there are well known relations and graphs for finding the view factors. These view factors can be applied in the case of an empty room. But they are not suitable for this case of study which is a cubic room with an extra cubic mass inside it. When a room is empty each surface can see other surfaces. But when an extra mass is inside the room, it acts as an obstacle between surfaces and makes some parts blind to each other and decreases view factor of the corresponding surfaces. So at the first stage sighted and unsighted (blind) parts of each two surfaces respect to each other has been found when there is a CAM inside room. To do this a Cartesian coordinate system has been adjusted to the room. Figure 5 shows that. Length of the room is adjusted to the X axis, width to the Y axis and height to the Z axis. Length, width and height of the room are divided into ni, nj and nk pieces. A grid is made and each surface divides into several cells. For example south wall divides to nj×nk cells with the area of (6/nj) × (2.7/nk) m2. A 40×40×40 grid has been used. The middle point of each cell, a node, is found. The radiations propagate diffusively inside the room. So each node on a wall can see nodes on other walls more or less when there is no obstacle inside the room. When there is a CAM inside the room, to find out which nodes cannot see each other the line equation between each two nodes is found. The intersection point of the line with the CAM surfaces is found. If it is located in or on the CAM then the corresponding nodes of that line cannot see each other and their sight factor is equal to zero. Otherwise the sight factor is one. This process is done for all of the surfaces when the line is between a node on a surface and any other node on other surfaces. For example if we choose the first point of the line a node on the south wall, the second point is a node on any other surfaces. If there are *n1* nodes on south wall and *n2* nodes on each of the other five surfaces, then there will be $n1 \times (n2)^5$ sight factors for the south wall. The result is a number of 4 dimensional tensors with the values of 1 or 0 which dedicates to two nodes on different surfaces. Each value tells us about two cells on two different surfaces. 1 means that two cells see each other (sight factor = 1) and 0 means they cannot see each other (sight factor = 0).

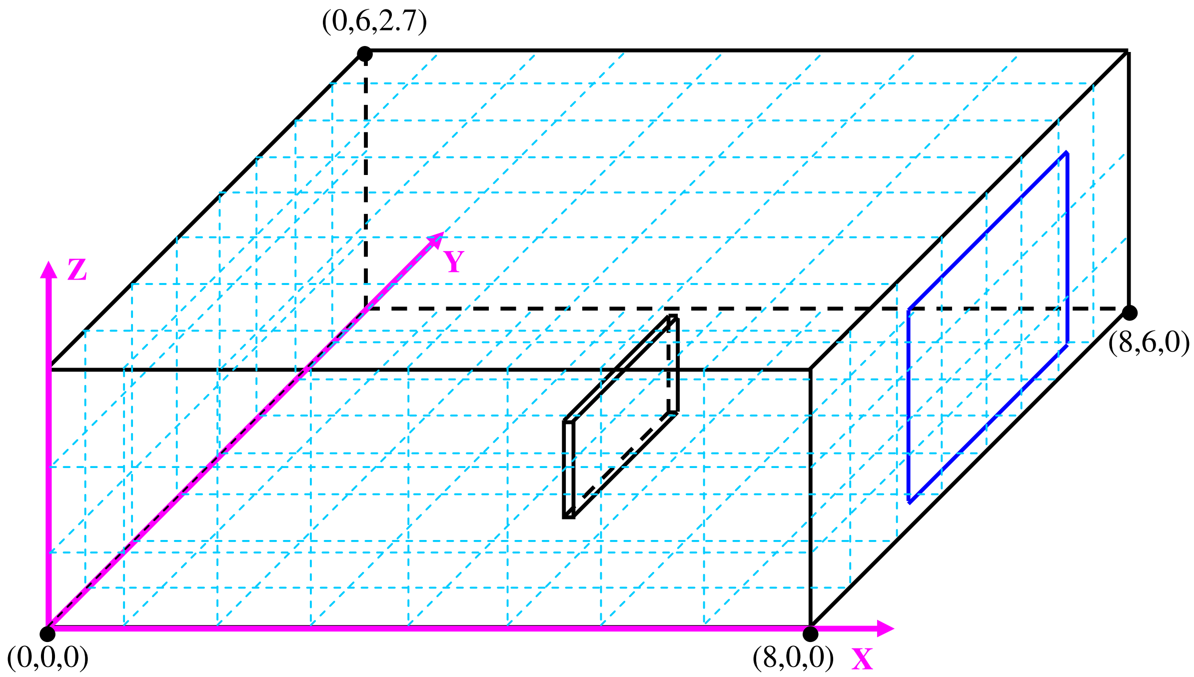


Figure 5. A Cartesian coordinate system is adjusted to the room. Room is divided into different cells

The sight factors are used in finding view factors which are calculated numerically based on relation (1) which calculates view factor of surface 1 to surface 2. [6]

$$F_{1-2} = \frac{1}{A_1} \int_{A1} \int_{A2} \frac{\cos\beta_1 \cos\beta_2}{\pi s^2} dA_1 \, dA_2 \qquad (1)$$

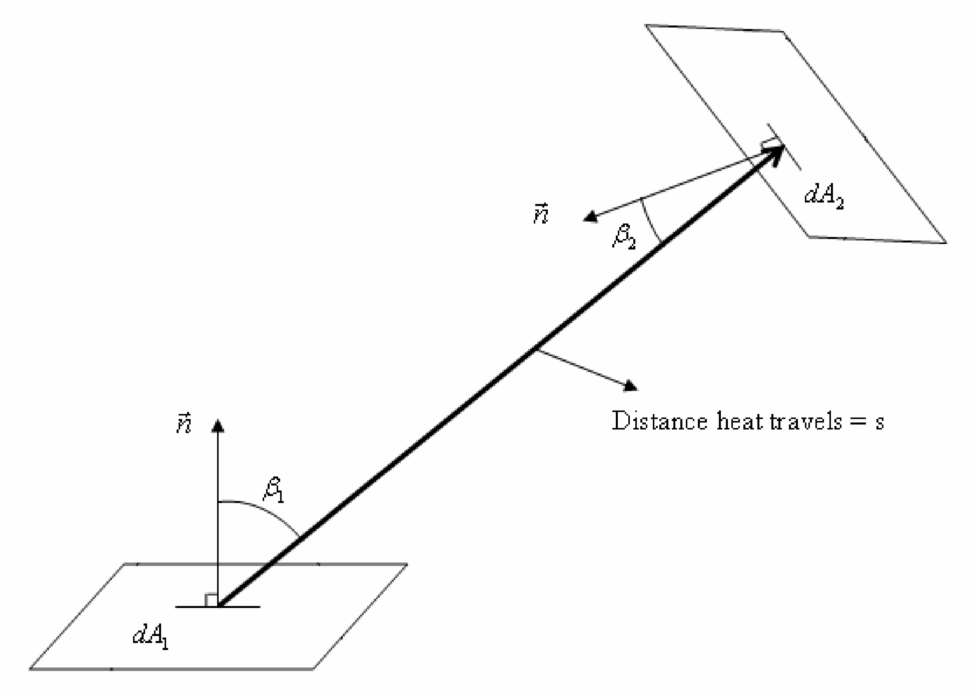


Figure 6. Radiant exchange between two elements which are parts of bodies 1 and 2

View factors of that cells which their corresponding sight factor is 1 has been found by calculating the surface integral of relation (1) on the surfaces of each two cells. Sight factors refers back to the nodes of the cells, but view factors refers back to the cell itself and it depends of the surface area of that cell. The view factor of a surface to another surface is found by integrating the view factors of those surface cells to the cells of another surface. Using these discrete cells also helps in finding view factors for parts of the surfaces respect to each other. Like window which is a part of the south wall.

4.2. Window transmittance

The window transmits solar radiation inside the room. The percentage of transmitted light depends on the transmittance of the window, τ, which depends on several factors like type of the window, material of the glass, number of panes and the incidence angle of the window and light. It is obvious that τ varies during time because of the relative motion of the sun in the sky which causes variations in the incidence angle. The τ value has been found according to appendix A for each hour of the year. These values have been used in finding solar fractions and also as a data source in simulation of the model.

4.3. Solar fractions

For simulating the room with a CAM inside, it has been divided into two zones; north and south. The CAM is between these two zones, so it is modelled as a north wall in the south zone and a south wall in the north zone. Window is located on the south wall of the south zone. If we run this model as an ordinary model then there will be no solar radiation in the north zone because it does not have any window. For making a logical simulation solar fractions should be calculated. Solar fraction of each surface shows how much of the total incoming solar radiation hits that surface in percentage. Solar fractions has been found based on the relations in BESTEST [1]. In BESTEST the assumption is that all of the incoming solar radiation hits the floor initially. Some of that is absorbed to the floor and the remaining part is propagating to other surfaces. In this thesis work the assumption is that the incoming shortwave solar radiation initially hits the floor and the CAM. It is the first bounce. The portions that the floor and the CAM receive depend on the incidence angle of the solar radiation, size of the CAM and its location inside the room. The summation of these two portions is always equal to 100% of the incoming light. It means that if *a* percent of the incoming radiation hits the floor then *100-a* percent hits the CAM. The second bounce is the diffusive reflection of shortwave radiations by the floor and the CAM which is distributed over other surfaces in portions which are dependent on view factor and absorptance of the surfaces. The third bounce is the remaining non-absorbed shortwave radiation which is distributed over each surface in proportion to its area-absorptance product. Also distribution of all the remaining bounces based on distribution fractions from calculations for the third bounces is found. Summation of this last term and all the previous bounces for each surface is the solar fraction of that surface. These solar fractions have been obtained for different locations and sizes of the CAM for each hour of a year. The azimuth angle of the sun has been neglected and only its height comes into effect. Finding solar fractions is explained in more detail in appendix B.

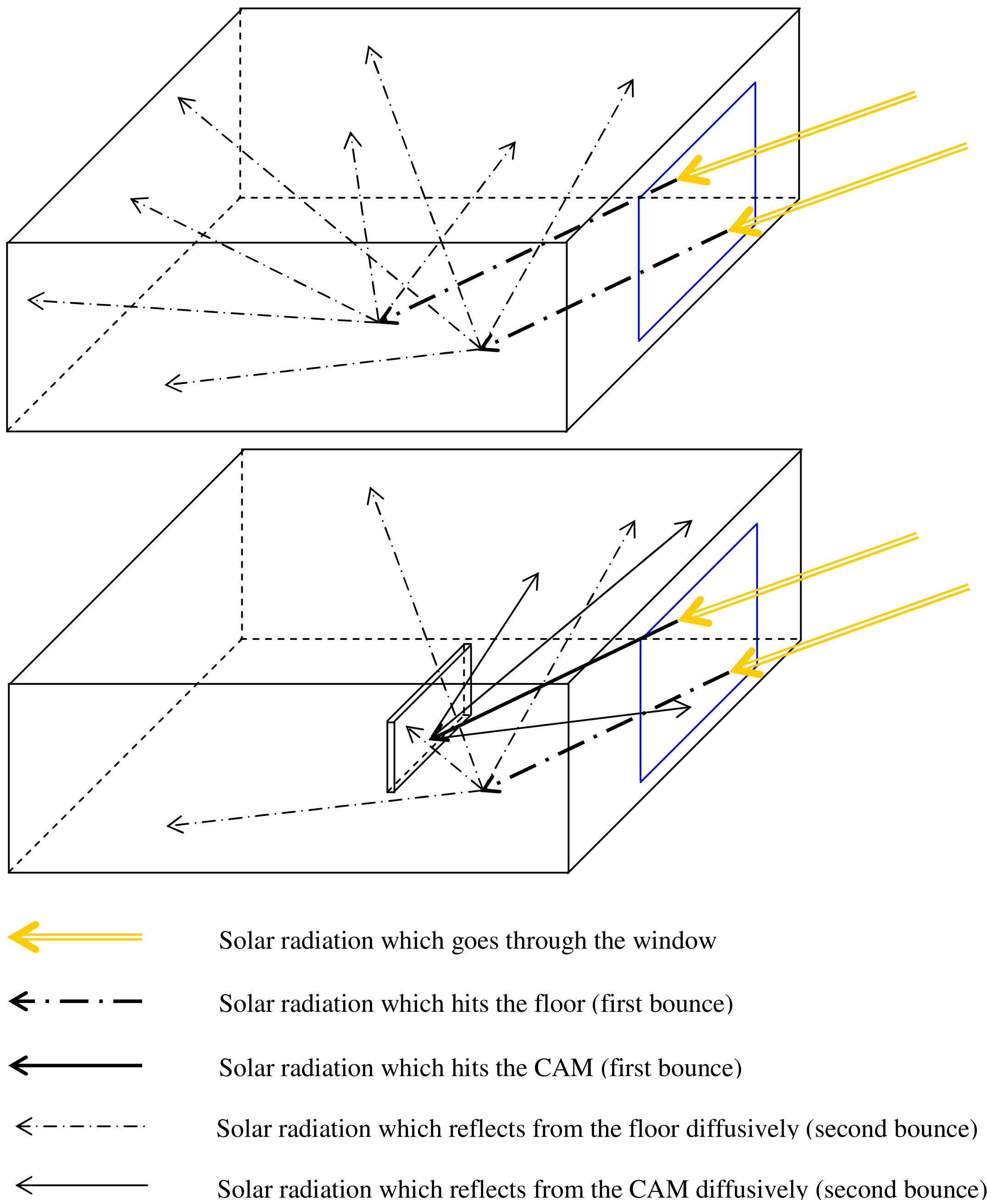


Figure 7. Solar radiation treatment inside a room with and without a CAM

Taking the azimuth angle of the sun into account makes finding the solar fractions very time consuming and difficult. In finding solar fractions when the azimuth angle is neglected, the incoming solar radiation hits the CAM and the floor. But when it is not neglected, in some hours of a day lots of incoming solar radiation hits the west or east wall instead of the CAM or the floor and it is necessary to find that part. Finding that sighted area on the east or west wall is very time consuming and case dependent.
Figure 7 shows how putting a CAM inside a room influences the propagation of the radiations inside the room. The upper figure is an empty room and the below one has a CAM inside. The figure shows that some parts of the incoming solar radiation hits the CAM instead of the floor (first bounce). The reflected radiation propagates diffusively to other surfaces. For finding the amount of this second bounce view factors of the surfaces are needed. It is obvious that view factors are changed when there is a CAM inside the room. The written Matlab code has the ability to find the view factors and solar fractions when a CAM (or any other obstacle) is located at any place of a room.

Figures 8 and 9 show the solar fractions of a CAM surface which faces the window (south surface of the CAM) when it is located 3 m and 7 m far from the north wall. Height, width and thickness of the CAM are 1 m, 2 m and 0.1 m respectively. Surface absorptance of the CAM is equal to 0.6. When the CAM is far from the window, figure 8, the south face of the CAM receives considerable amount of solar radiation in winter. But during warmer periods of a year its solar fractions are very low. In this period the sun is higher in the sky comparing with winter. It means that solar radiations go through the window with higher angle of incidence and consequently they cannot reach the surfaces far from the window and hit the floor. Moving the CAM closer to the window increases its solar fractions in the warmer periods of a year. Figure 9 shows that in summer considerable amount of the solar radiations hit the CAM when it is at X=7 m, just 1 m far from the window. Also the amount of solar fractions in winter increases to higher values in this case.

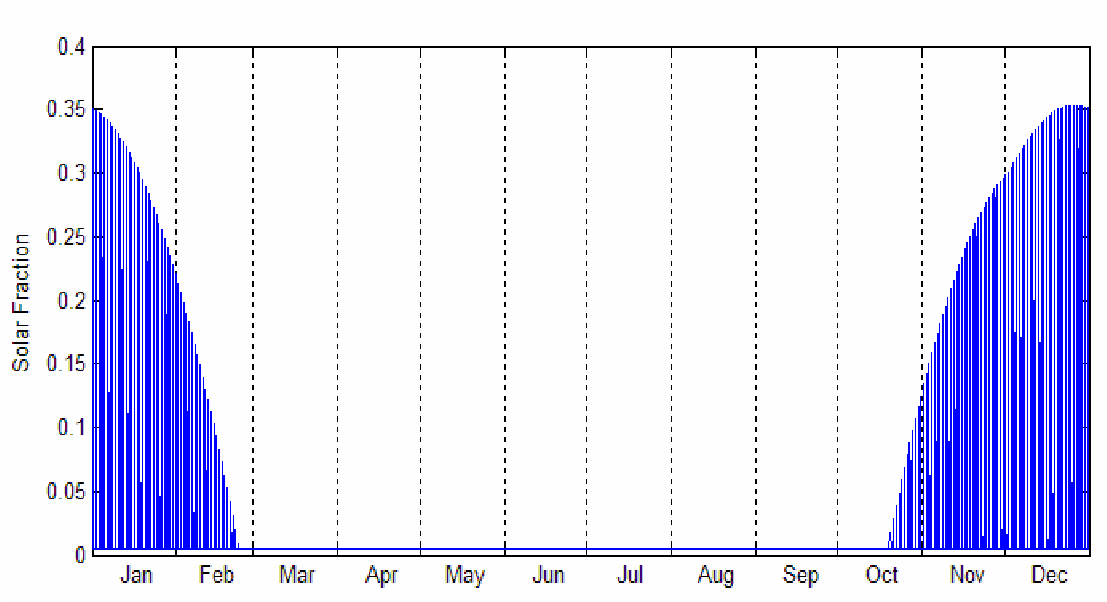


Figure 8. Solar fractions of the south face of the CAM when X_{CAM}=3 m

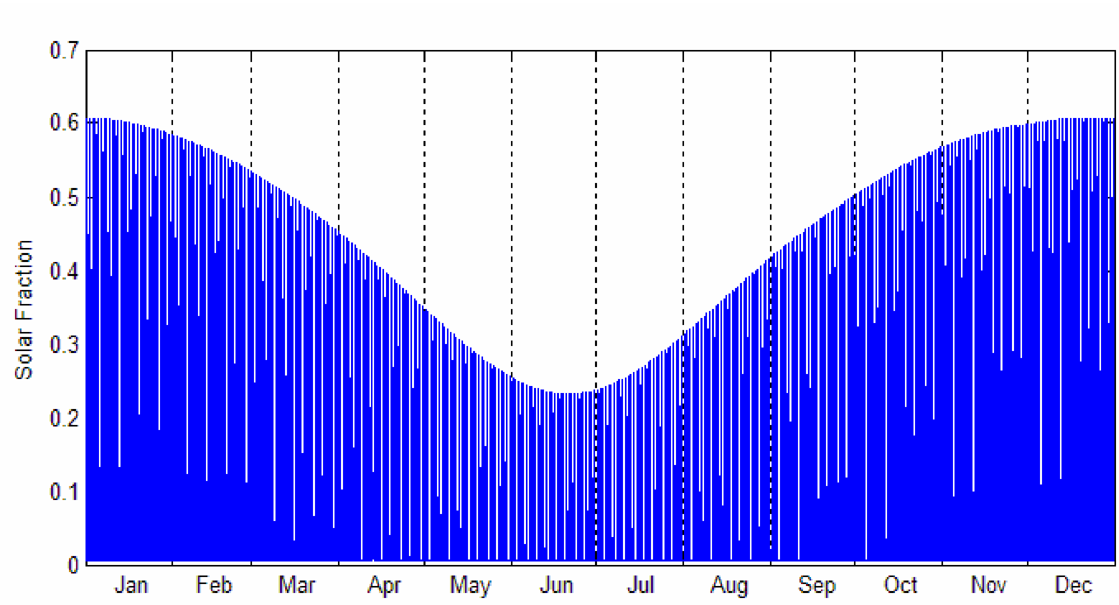


Figure 9. Solar fractions of the south surface of the CAM when X_{CAM}=7 m

4.4. The importance of finding proper solar fraction

It is interesting to find out how much is really important to calculate the true (close to real) value of the solar fractions. To answer this question the room with a CAM when it is 50 cm close to the window has been simulated two times. First when the solar fractions are the proper ones which have been calculated using the code. Next time the same model has been used but with the unfit solar fraction. It means that the only difference is using solar fractions which correspond to the room when it is empty. But the position and properties of the CAM and every other things of the room are the same as the first case. Height, width and thickness of the CAM in two cases are respectively 2 m, 2 m and 0.1 m. The CAM is of type 2 which its α is equal to 0.8.

Figure 10 compares the heating demand of these two cases. The heating demand for the case with proper solar fractions is 4550 kWh in whole year and for the case with unfit solar fractions it is 4750 kWh.

In figure 11 cooling demand is considered. For the case with proper solar fractions the cooling demand is 804 kWh in whole year and for the case with unfit solar fractions it is 495 kWh. In both figures it is obvious that the difference between two cases is considerable in the warm or sunny months of the year.

These two figures show us the importance of using proper solar fractions. It is necessary to note that these two cases almost have the extreme possible difference which is caused by using unfit solar fractions. Because the CAM is very close to the window and also it has a large surface area. It means that in cases where the CAM is far from the window and it has a small surface area comparing to other surfaces of the room or solar radiation hits small area of the CAM surfaces, it is reasonable to neglect finding the true solar fractions. Actually using or not using the proper solar fractions and its effect on the results depend on the case of study. In this thesis work the proper solar fractions has been calculated and used in each case.

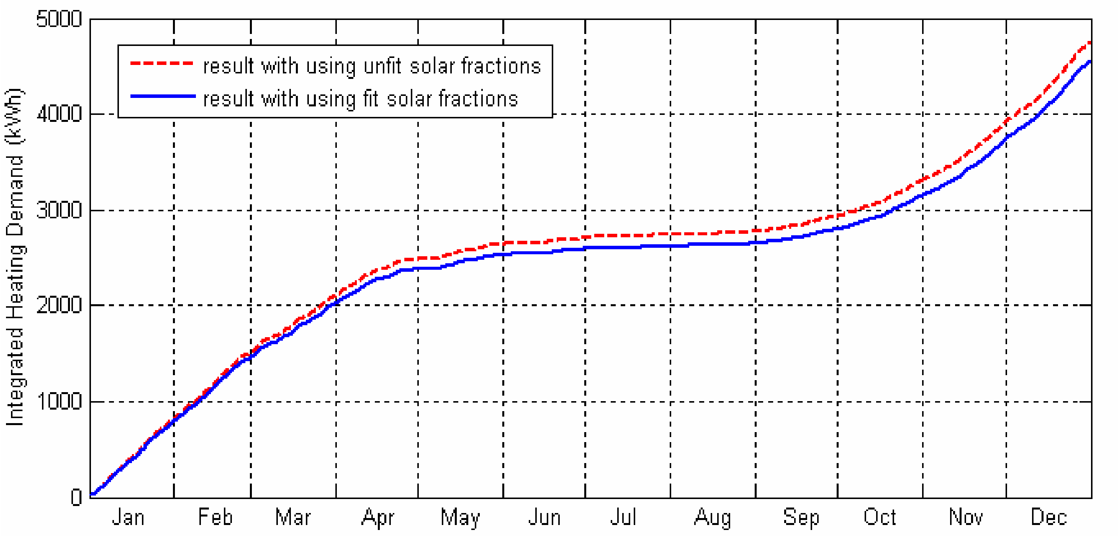


Figure 10. Heating demand in whole year using fit and unfit solar fractions

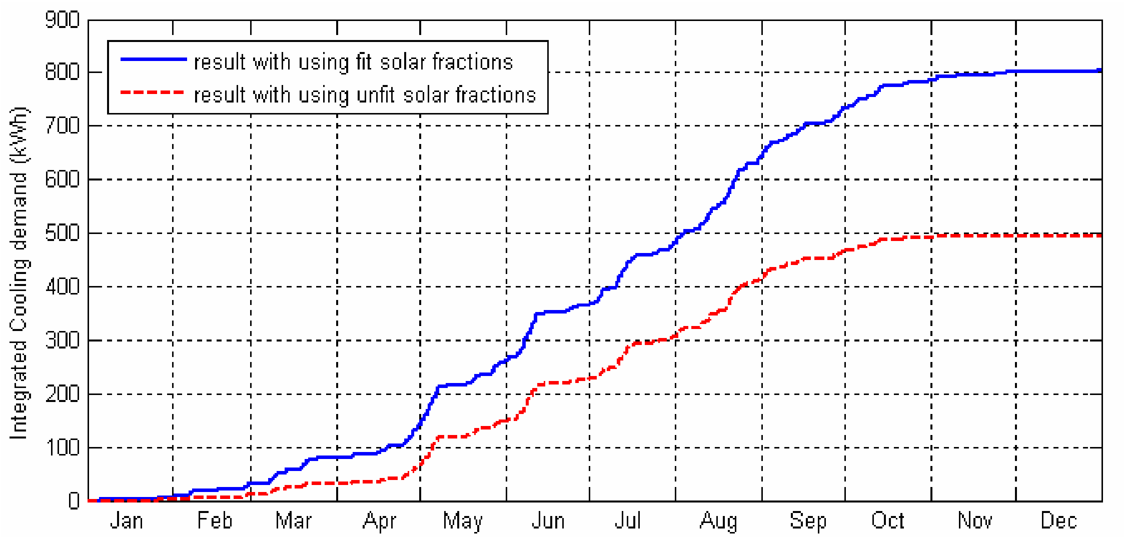


Figure 11. Cooling demand in whole year using fit and unfit solar fractions

5. Results and discussion

In this section results of the simulation of different models are considered using graphs. These results are found in numbers in the tables of appendix C.

In sections 5.1 to 5.5 results are corresponding to the room with light weight wall construction and in section 5.6 the heavy weight room is studied. In section 5.7 refilling effects of the CAM have been considered for the light weight room. In sections 5.5 and 5.7 to simulate more practical cases some additional heat loads has been added in the room instead of room stuffs like furniture.

The bar graphs tell us how much using a CAM affects a parameter. For example when a bar value is 5 it means that parameter has been increased for 5% comparing the same case without CAM. Consequently minus value tells about decrement of that parameter in percentage comparing with the same case without CAM.

Some results are considered in warm and cold periods in the year. The cold week is from 21st January to 27th January. The warm week starts at 7th June and ends at 13th June. The selected cold day is 21st January and the warm day is 7th June.

5.1. Effects of CAM on the indoor temperature

In-span effect of a CAM

Effects of CAM on the indoor climate have been studied. One of the most important properties in this field is the inside temperature of the room. The comfort temperature for human is between 20°C and 24°C. Studying the indoor temperature of the room shows that using a CAM increases or decreases the number of instances with comfort temperature. In this report this effect is called as *In-span effect* of the CAM. In-span effect of a CAM on the indoor temperature is found in this way:

$$\text{In-span effect (\%)} \equiv \frac{\sum t1 - \sum t2}{t_{total}} \qquad (2)$$

$t1$: the instance which the temperature is in the comfort span with the CAM inside

$t2$: the instance which the temperature is in the comfort span without the CAM

t_{tootal}: total time of simulation which is the same for all cases and is equal to one year

The indoor temperature of the room without cooling and heating systems for different locations and properties of a CAM has been compared in this statistical approach.

Figure 12 shows the temperature during a specific time for a room with and without a CAM. The comfort span is marked with two horizontal dashed lines. In this case when there is a CAM inside the room in more time instances temperature is in the comfort span.

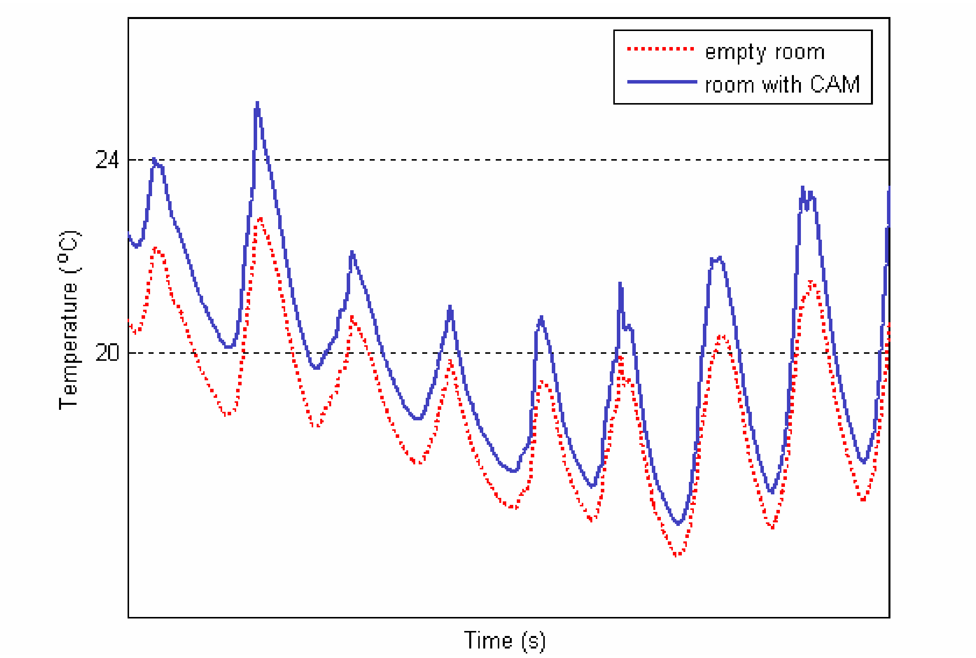


Figure 12. In-span effect of a CAM on the inside temperature

5.1.1. CAM with different surface absorbtances

<u>CAM Properties</u>

Height: 1 m Width: 2 m Thickness: 0.1 m Type: 1 & 2

Figure 13 shows the results for the CAM with the height of 1 m. Horizontal axis shows different locations of the CAM in respect to the north wall. At each location of the CAM there are two values corresponding to α=0.6 and α=0.8. Vertical axis shows the difference of the number of instances that the indoor temperature is in the comfort limit for the room with and without the CAM in percentage.

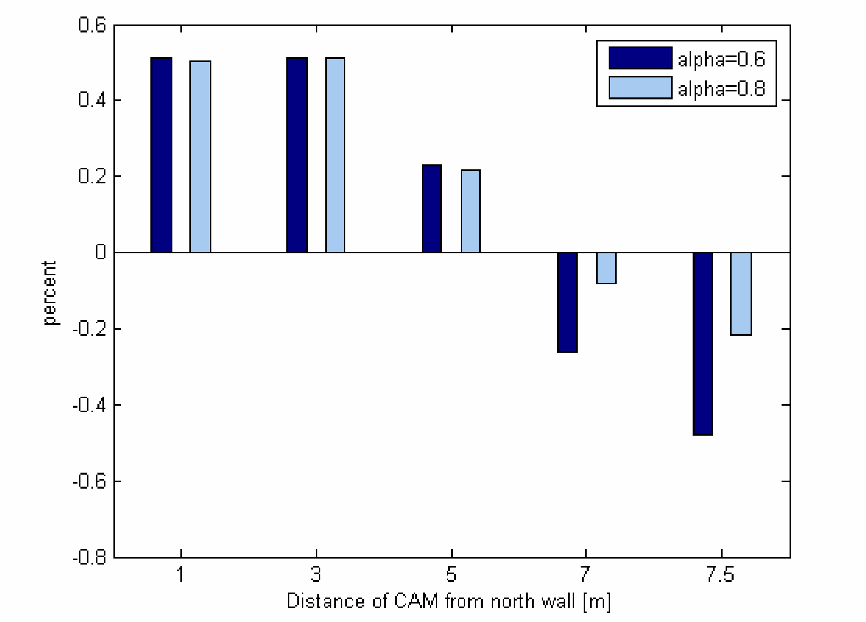


Figure 13. In-span effect of the CAM (compared with the empty room) for different surface absorptances of the CAM

There is not much difference between two CAMs at each location except near the window. At this location the CAM with α=0.6 decreases the room temperature a little more than the CAM with α=0.8. When the CAM is closer to the window its In-span effect decreases. Close to the window the CAM responses faster to the outdoor temperature variations. Also it works like a shield and reflects some part of solar radiation. The CAM with α=0.6 absorbs less solar radiation and reflects more. Comparing the results in appendix C shows that when the CAM is 1 m and 3 m far from the north wall the inside temperature increases. For the next three locations of the CAM the inside temperature decreases a little.

Figure 14 shows variations of the indoor temperature in the cold week with and without the CAM. Figure 15 shows the same data in the warm week. The surface absorptance of the CAM is 0.6, the same as the room surfaces.

In the cold days, when there is no sun in the sky, placing the CAM close to the window (X_{CAM}=7 & 7.5 m) decreases the room temperature more than the other places of the CAM. In the sunny hours the room has the maximum temperature for these two locations of the CAM. In the dark hours of the warm days the CAM place affects the indoor temperature in the same way during the dark hours of the cold days. In sunny hours of the warm days the minimum temperature is reached at X_{CAM}=7 m, where the maximum shielding effect of the CAM is used. Figures 14 and 16 show that the CAM location affects the indoor temperature more in the sunny hours. For example on 26th January T_3-T_4 is almost 2.5°C but T_1-T_2 is less than 0.25°C. In the warm days it is vice versa; T_1-T_2 > T_3-T_4. For example on 10th June T_1-T_2 is almost 1.1°C and T_3-T_4 is 0.7°C. Number of the sunny hours during the cold days is less than the number of dark hours, contrary to warm days. It means that when the whole system has enough time, it responses to the outside conditions more continuously. In the cold days with short sunny hours when the CAM is close to the window it responses faster and increases the room temperature more. There is not enough time for the system to be stabilized much and the effects of the CAM place on the room temperature are more noticeable. But in the hours without solar radiation, which are more in cold days, the system has enough time to be more stabilized and the CAM place does not show that much effect on the inside temperature. The same logic rules the warm days with longer sunny hours. In warm days there are more sunny hours and the whole system has more time to absorb energy.

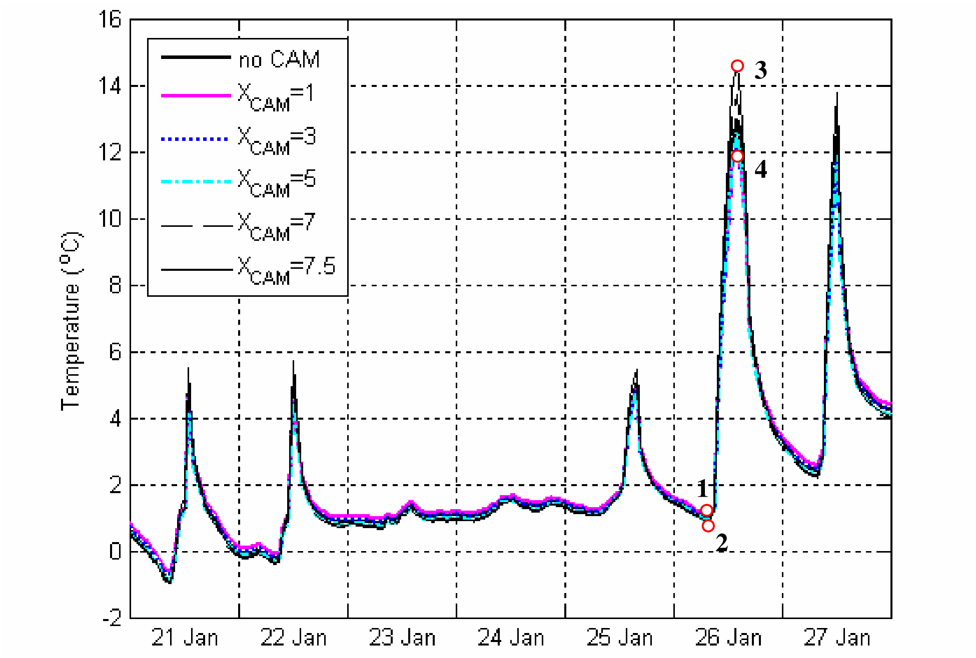


Figure 14. Variations of the indoor temperature in the cold week (α_{CAM}=0.6)

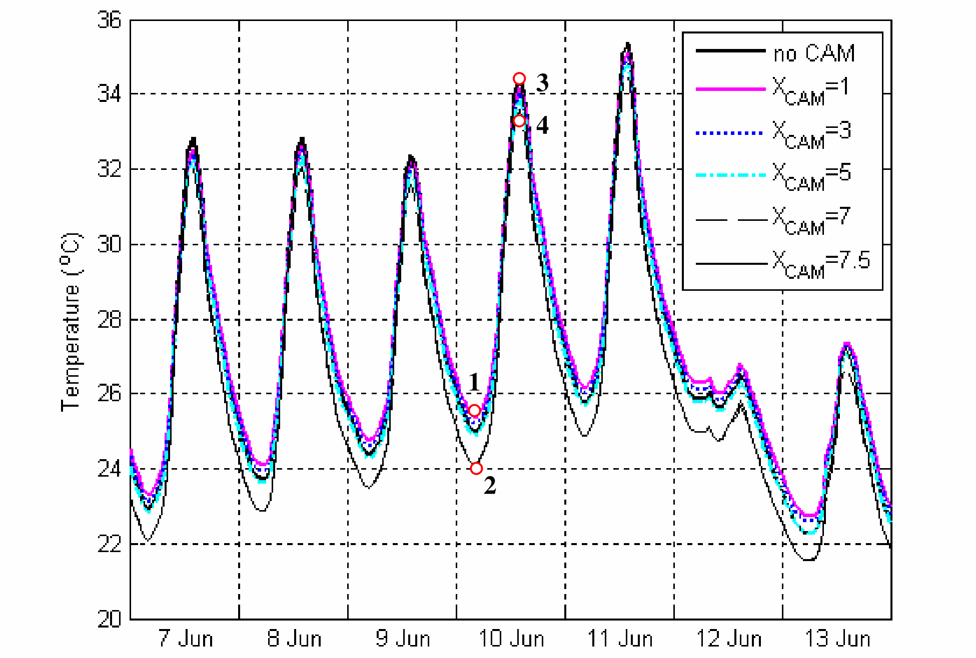


Figure 15. Variations of the indoor temperature in the warm week (α_{CAM}=0.6)

Figure 16 shows the temperature variations in a cold day when α_{CAM} is equal to 0.6. Figure 17 shows the same data in a warm day. The cold day is 21^{st} of January and warm day is 7^{th} of June. Both figures show that in the periods without sun in the sky or without solar radiation to the window, the longer distance of the CAM to the window the higher temperature of the room. It means that in the periods that the CAM does not absorb solar radiation, placing it far from the window prevents losing heat to the outside through the window and heats up the indoor more. So it is better to place the CAM far from the window to save more energy in theses hours.

When the sun is in the sky and there is some solar radiations in the room, the inside temperature increases and it reaches to its maximum. In figure 16 it can be seen that in these hours the location of the CAM affects the indoor temperature in a different way. The first three locations of the CAM, X_{CAM}=1, 3 and 5 m, affects the temperature almost the same. But when the CAM gets closer to the window it increases the inside temperature more. At X_{CAM}=7 & 7.5 m in sunny hours the CAM absorbs solar radiations and heats up the room. When the CAM is at X=7 m, in most of the sunny hours there is a shaded area behind the CAM which is not receiving the solar radiation. This shade cools down the CAM. The shaded area is smaller when the CAM is at X=7.5 m and in some hours there is some sunshine behind the CAM. So the CAM is heated up a lot and warms up the room inside. It means that in using a CAM it is important to take care about the time period in the year and sunny hours of a day and also presence or absence of the cooling or heating systems. For example in winter, when there is no heating system, it is better to locate the CAM far from the window when there is no solar radiation inside the room and put it close to the window in sunny hours. In summer the CAM can be close to the window all the time, but in a certain distance from the window.

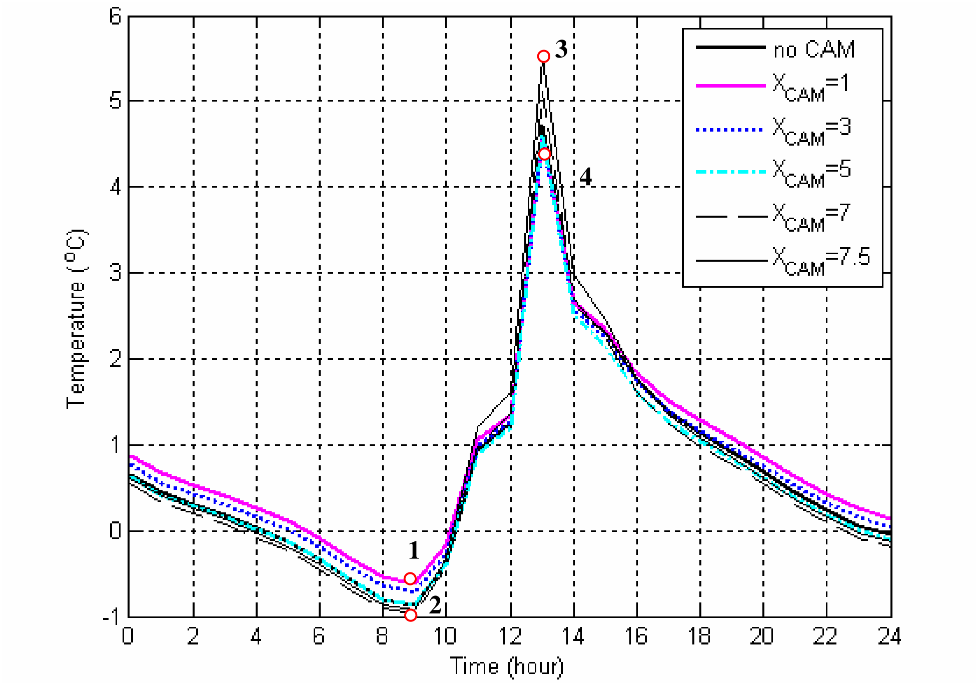


Figure 16. Variations of the indoor temperature on 21st January (α_{CAM}=0.6)

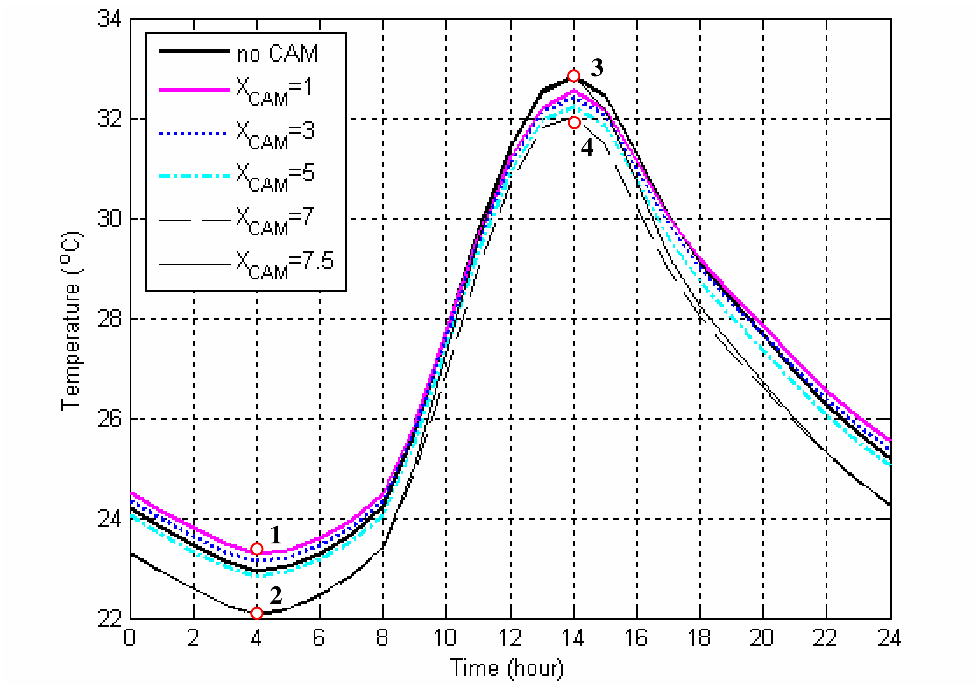


Figure 17. Variations of the indoor temperature on 7th June (α_{CAM}=0.6)

Figures 18 and 19 are again the temperature variations in the cold and warm day, but when the surface absorbtance of the CAM is 0.8. They are almost the same as figures 16 and 17 but the maximum temperature has been increased a little when the CAM is close to the window at X_{CAM}=7 & 7.5 m. Also the total temperature for these cases, specially for X_{CAM}=7.5 m, has been increased in the cold day. It is the effect of absorbing more solar radiation in sunny hours which affects the next hours consequently.

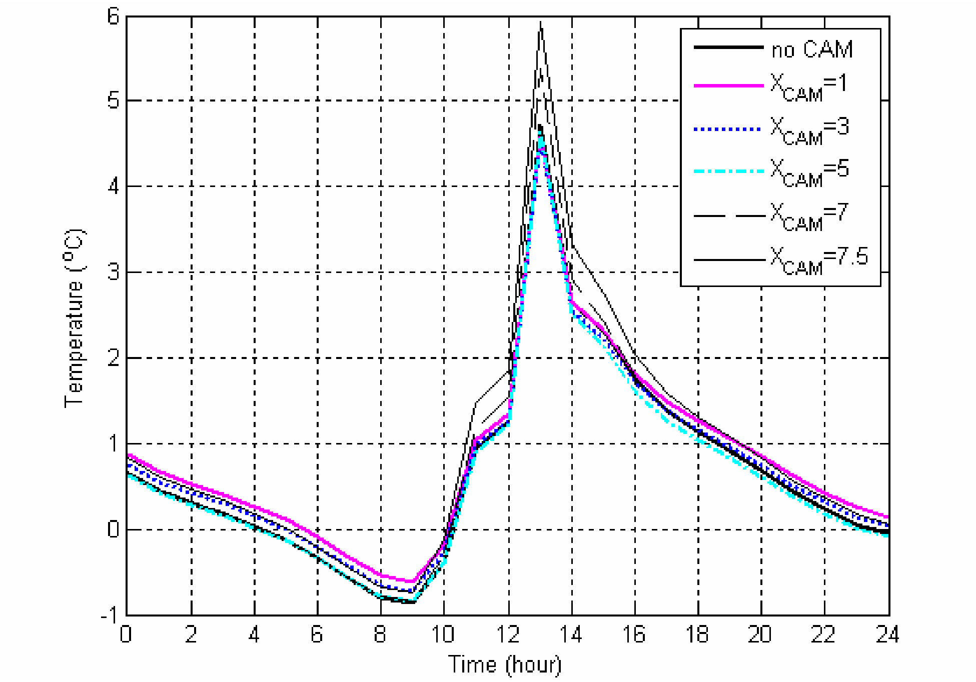


Figure 18. Variations of the indoor temperature on 21st January (α_{CAM}=0.8)

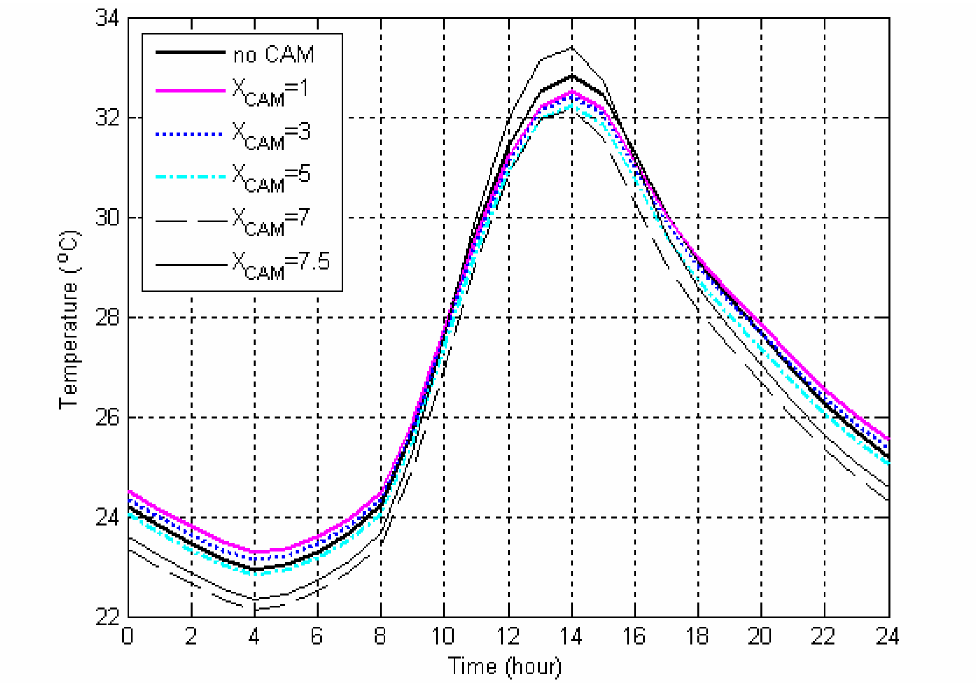


Figure 19. Variations of the indoor temperature in 7th June (α_{CAM}=0.8)

5.1.2. CAM with different heights

CAM properties:

Height: 1 m & 2 m Width: 2 m Thickness: 0.1 m Type: 1

Figure 20 shows the comparison of the In-span effect when there are two CAMs with different heights, 1 m and 2 m, and the same absorptances, α=0.6. The CAM with the height of 2 m affects the indoor temperature in the same manner as the CAM with 1 m height, but with some improvement. Making the CAM surface and consequently its amount of mass doubled by changing its height from 1 m to 2 m affects the In-span effect of the CAM. The area and mass amount has been increased about 100%. It is shown in appendix C that when the CAM is close to the window in more instances temperature is less than 20°C when CAM height is 1 m. The smaller area of the CAM absorbs solar energy less than the CAM with 2 m height. For X_{CAM}=1, 3 and 5 m in more instances temperature is more than 24°C for this height of the CAM. Smaller mass of the CAM reaches to higher temperatures with the same energy comparing with the larger CAM.

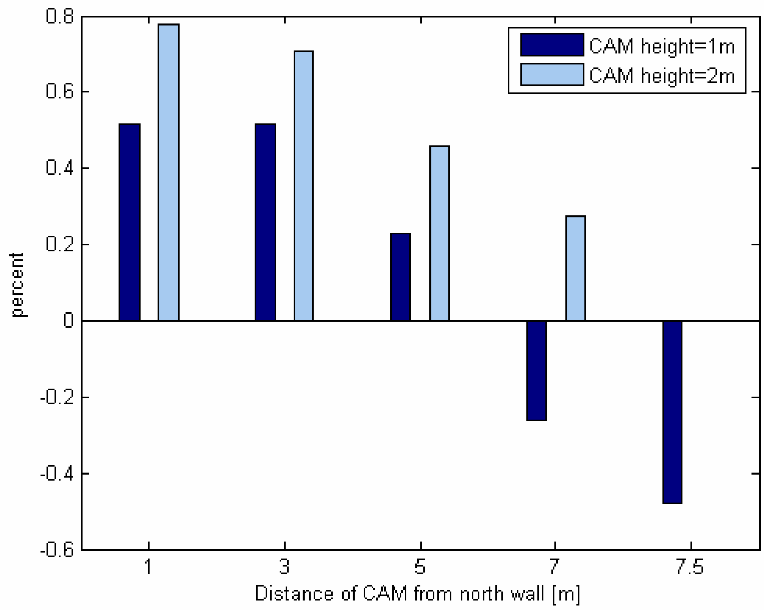


Figure 20. In-span effect of the CAM (compared with the empty room) for different heights of the CAM

Figures 21 and 22 show the temperature variations in the cold and warm days when the CAM height is 2 m. They are almost the same as figures 16 and 17 which are showing the same data for the CAM with the height of 1 m. But the minimum temperature in the cold day increases a little when the height of the CAM is 2 m. Also the maximum indoor temperature in the warm day decreases with the CAM with the height of 2 m.

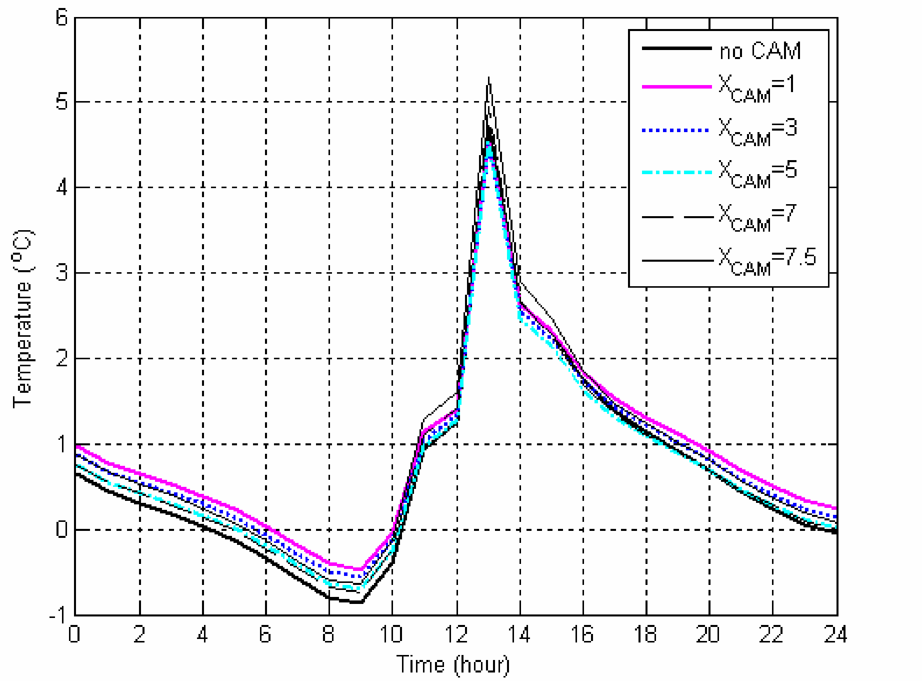


Figure 21. Variations of the indoor temperature on 21st January (H_{CAM} = 2 m)

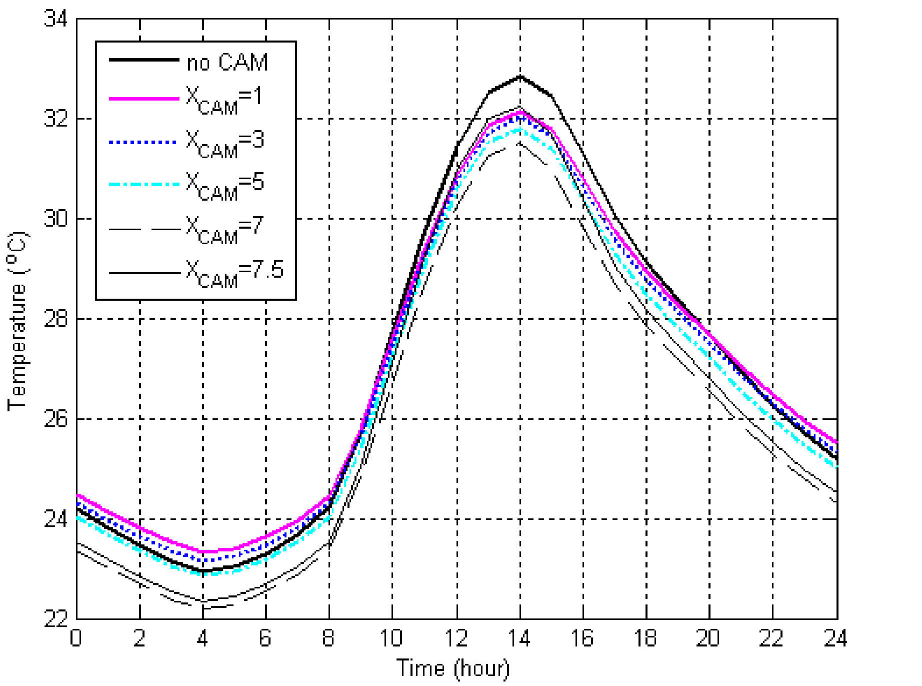


Figure 22. Variations of the indoor temperature on 7th June (H_{CAM} = 2 m)

These increment and decrement happens because of the mass amount increment of the CAM. It saves more energy and also balances the inside temperature more than the CAM with less mass amount. But this amount is not such a considerable amount in this case. Considering the minimum temperature in the cold day for different height of the CAM shows that the minimum temperature in the case of 2 m height has increased. Figure 23 shows the minimum temperature for the height of 1 m and figure 24 shows that for 2 m height. Another considerable thing in these two figures is variation in the CAM performance at X=7.5 m. For the case with 2 m height, the CAM increases the minimum temperature to a value higher than the time it is located at X=5 m. The larger area of the CAM absorbs more solar energy which compensates some part of lost energy and heats up the room more than X=5 m and X=7 m.

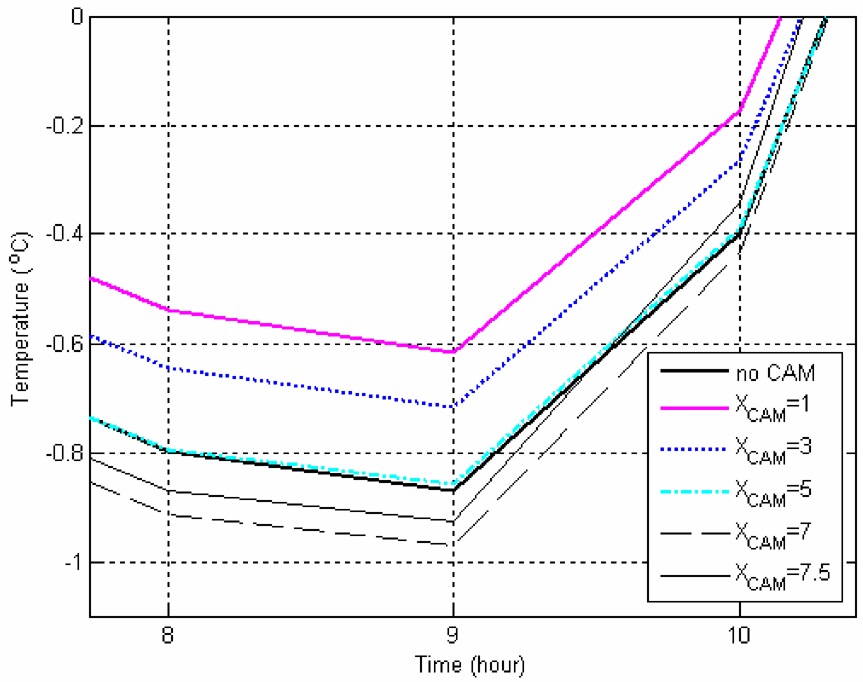


Figure 23. Minimum temperature on 21st January (H_{CAM} = 1 m)

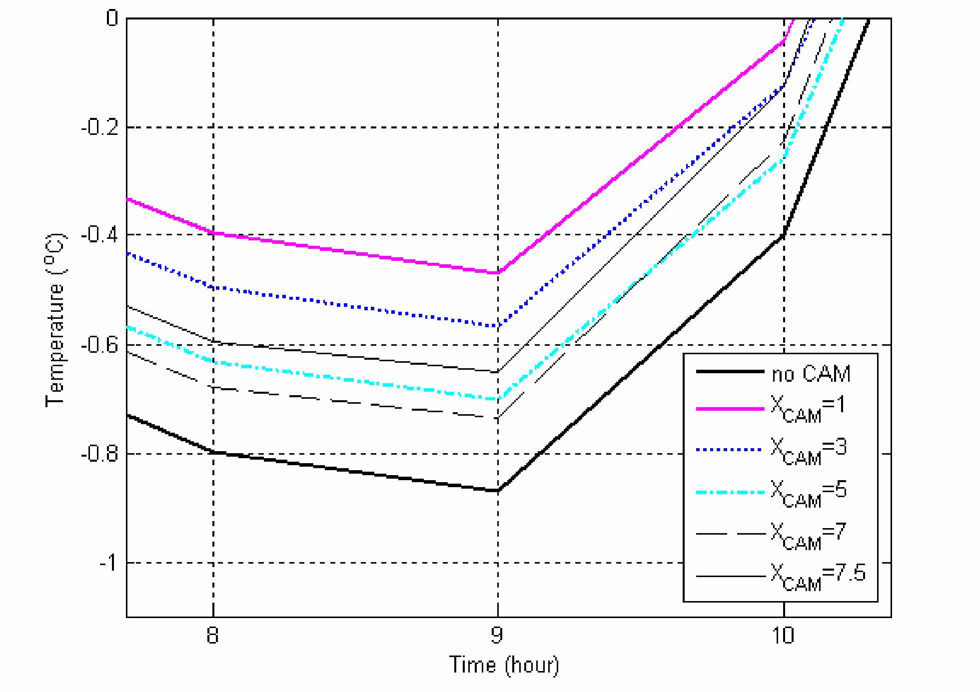


Figure 24. Minimum temperature on 21st January (H_{CAM} = 2 m)

5.1.3. CAM with different materials

<u>CAM properties:</u>

Height: 1 m Width: 2 m Thickness: 0.1 m Type: 2 & 3

Effects of changing the shell material of the CAM from aluminum to soil-clay on indoor temperature are studied here. The properties of these two materials are in table 1. Al_2, aluminum with the absorptivity of 0.8 has been used. The volumetric heat capacity ($\rho \cdot C_p$) of the aluminum is $2.43\times10^6\ J/m^3K$ and for soil-clay it is $3\times10^6\ J/m^3K$. It seems that the soil-clay should show a better In-span effect because of its higher heat capacity. But another important parameter in this field is the *thermal diffusivity* of the material which is defined as $a = \frac{\lambda}{\rho \cdot C_p}[\frac{m^2}{s}]$. It is the ratio of the thermal conductivity to the volumetric heat capacity of the material. Substances with high thermal diffusivity rapidly adjust their temperature to that of their surrounding, because they conduct heat quickly in comparison to their thermal bulk. The thermal diffusivity of the aluminum is

$9.75\times10^{-5}\,m^2s^{-1}$ and for soil-clay is equal to 5×10^{-7} m^2s^{-1}. Ratio of these two values is almost 195 which mean that it takes longer time for soil-clay to conduct heat through itself comparing with aluminum. This delaying effect of the material in heat conductance affects the performance of the CAM in the room.

Another important criterion in comparing conductional and convectional heat transfer of a body is the *Biot number* which is defined as:

$$Bi = \frac{h\,L_C}{\lambda}$$

h: convective heat transfer coefficient which is assumed to have the constant value of 3

L_C: characteristic length of the body, which is commonly defined as the volume of the body divided by the surface area of the body

λ: thermal conductivity of the body

The interesting point is that contrary to thermal diffusivity the Biot number also depends on geometrical properties of the substances.

In this case of study the characteristic length of the CAM is:

$$L_C = \frac{2\times1\times0.1}{0.1(1+2+1)+2\times2} \cong 0.045\,\text{m}$$

Biot number for the aluminum shell: $Bi = \frac{3\times0.045}{237} = 5.7\times10^{-4}$

Biot number for the soil-clay shell: $Bi = \frac{3\times0.045}{1.5} = 0.09$

When the CAM has the soil-clay shell the Biot number is almost 158 times more than the aluminum shell. The thermal resistance of the fluid is the same in two cases. The high thermal resistance of the soil-clay results in lower rate of heat transfer in respect to aluminum, causing the slower response of the CAM to the temperature variations of the surrounding air. But it is necessary to note that the shell is thin comparing with the water thickness inside the CAM.

Figure 25 compares the In-span effect of the CAM with aluminum and soil-clay shell. The higher heat capacity of the soil shell increases the In-span effect of the CAM.

When the mass amount of the shell is small and also when there is no cooling or heating system in the room, changing the shell material of the CAM does not affect its performance much. When there is no cooling or heating system, the time response of the shell is not very important and it does not affects the total effect of the CAM on the indoor temperature. The whole system (indoor and outdoor) works in its natural way with continuous responses in longer time periods comparing with the room with heating or cooling system.

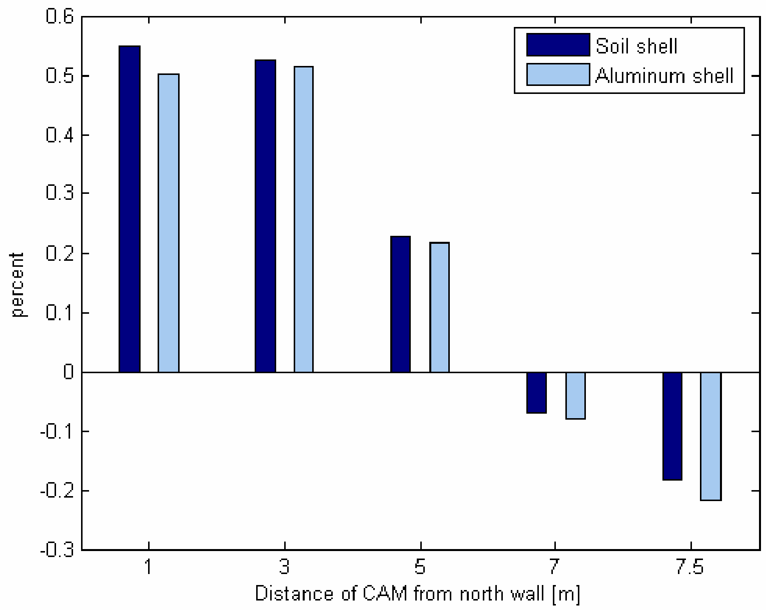


Figure 25. In-span effect of the CAM (compared with the empty room) for different materials of the CAM

Figures 26-29 show the variations of the indoor temperature in different time periods when the CAM with the soil-clay shell in inside the room. Comparing figures 28 and 29 with figures 18 and 19 shows that there is almost no difference in the temperature profiles in these two days.

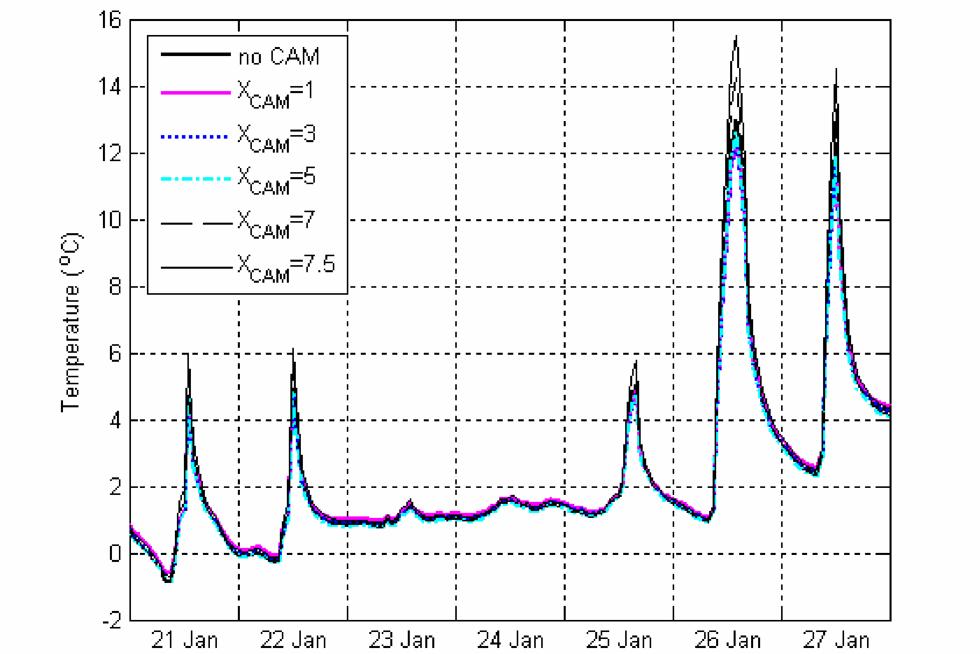


Figure 26. Variations of the indoor temperature in the cold week for the CAM with soil shell

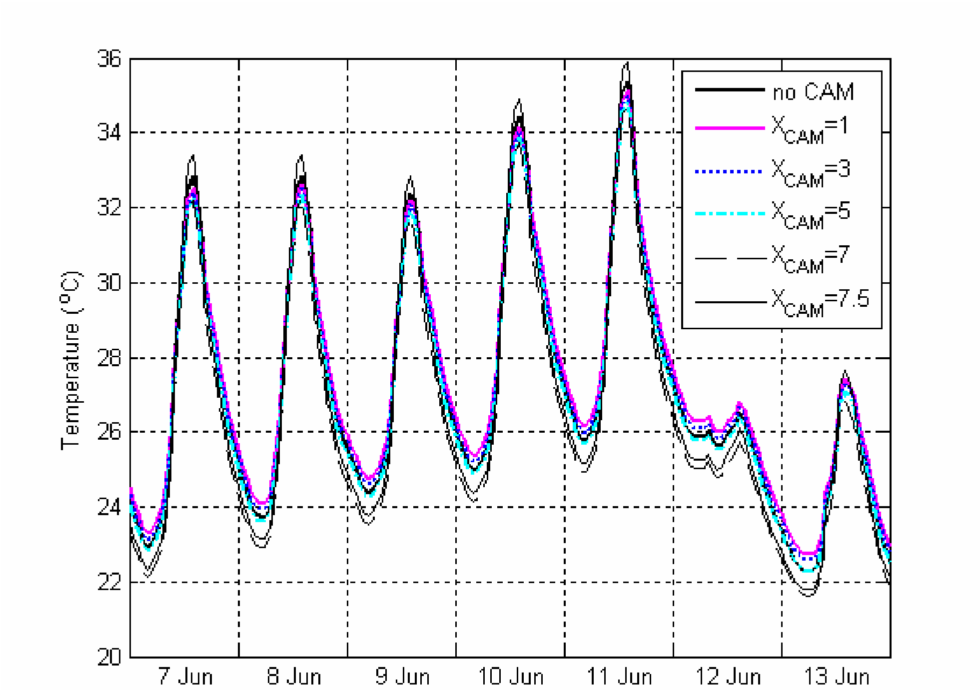


Figure 27. Variations of the indoor temperature in the warm week for the CAM with soil shell

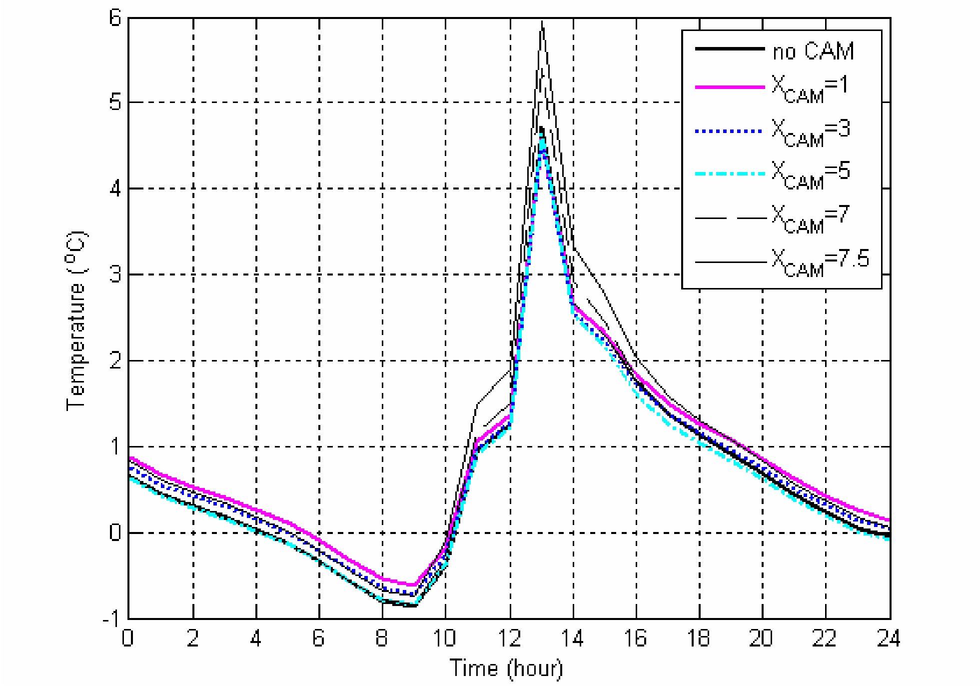


Figure 28. Variations of the indoor temperature on 21st January for the CAM with soil shell

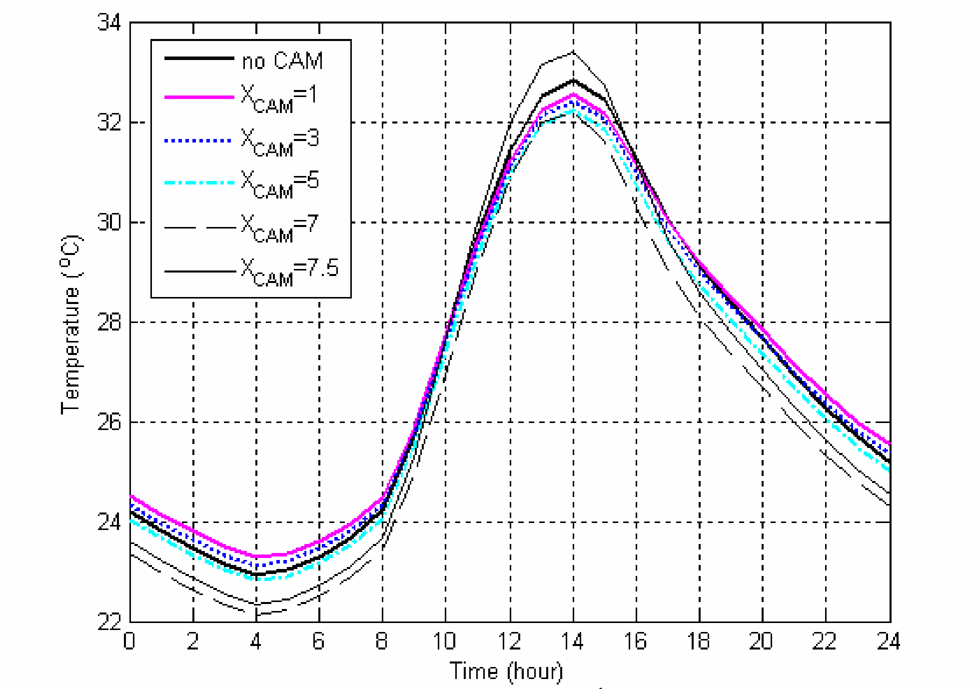


Figure 29. Variations of the indoor temperature on 7th June for the CAM with soil shell

5.1.4. CAM with different thicknesses

CAM properties:

Height: 1 m Width: 2 m Thickness: 0.1-0.4 m Type: 1 & 2

Temperature variations in whole year for different thicknesses of the CAM have been studied. By increasing the thickness of the inside layer of the CAM, which contains water in this work, the mass and area of the side surfaces increase while the CAM surface which faces the window (south face of the CAM) remains constant. Figure 30 shows results for four different thicknesses when the distance of the CAM to the window is 3 m (X_{CAM} = 5 m). Figure 31 is the same result when the CAM is 1 m close to the window (X_{CAM} = 7 m).

As it is cited on page 10, modeling the CAM as a wall neglects the heat transfer from the side surfaces of the CAM. It could be a source of inaccuracy which increases by thickness increment of the CAM.

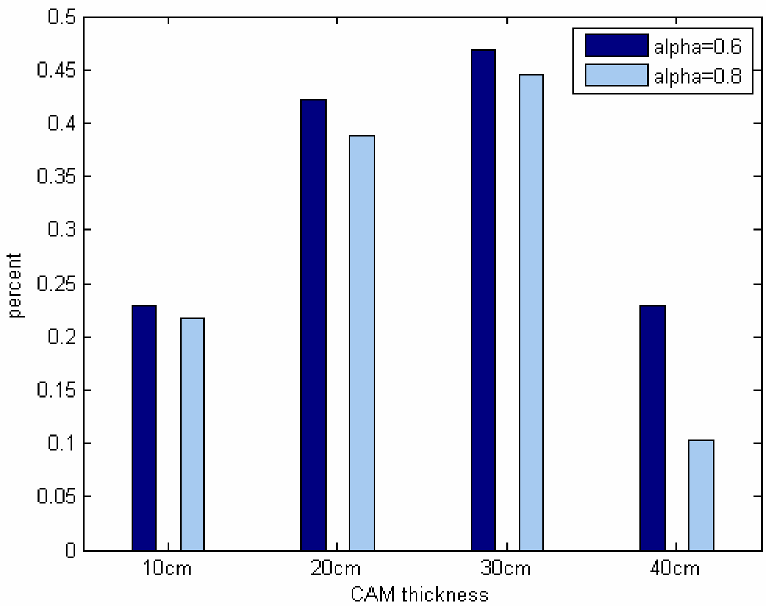


Figure 30. In-span effect of the CAM (compared with the empty room) with different thicknesses of the CAM (X_{CAM} = 5 m)

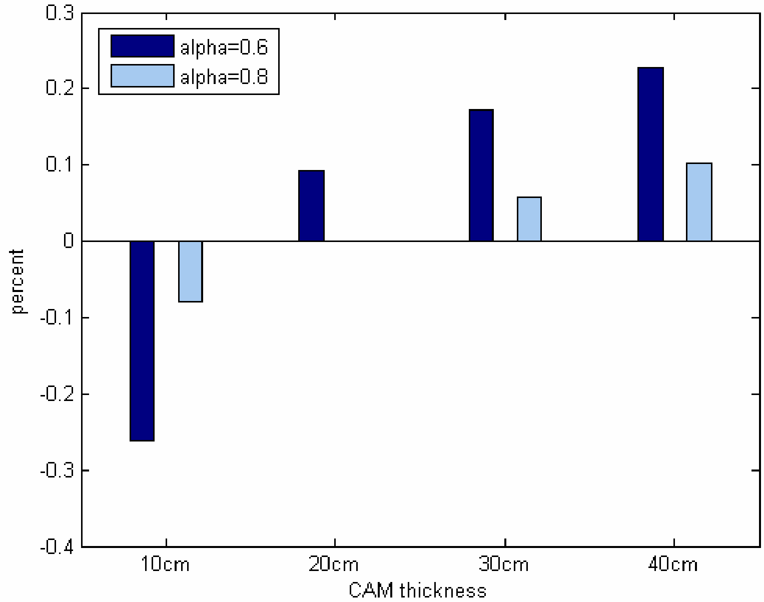


Figure 31. In-span effect of the CAM (compared with the empty room) with different thicknesses of the CAM ($X_{CAM} = 7$ m)

When the CAM thickness is 0.1 m, summation of the CAM surfaces which incoming solar radiation hits them is $2\times1+(1+2+1)0.1=2.4m^2$ (solar radiation does not hit the north face of the CAM). By increasing the thickness to 0.2 m this value increases for about 17%, for thickness of 0.3 m about 33% and for 0.4 m about 50%. The mass increment for thicknesses of 0.2 m, 0.3 m and 0.4 m is almost 100%, 200% and 300% respectively comparing with the thickness of 0.1 m. These values tell us that by increasing thickness of the CAM, its mass increases much more than its surface area. So we have more increased effects of thermal properties which are related to the amount of mass (like heat storage) not the surface area (like radiative and convective heat transfer). Figures 30 and 31 show that increasing the mass of the CAM increases its In-span effect but not very close to the window.

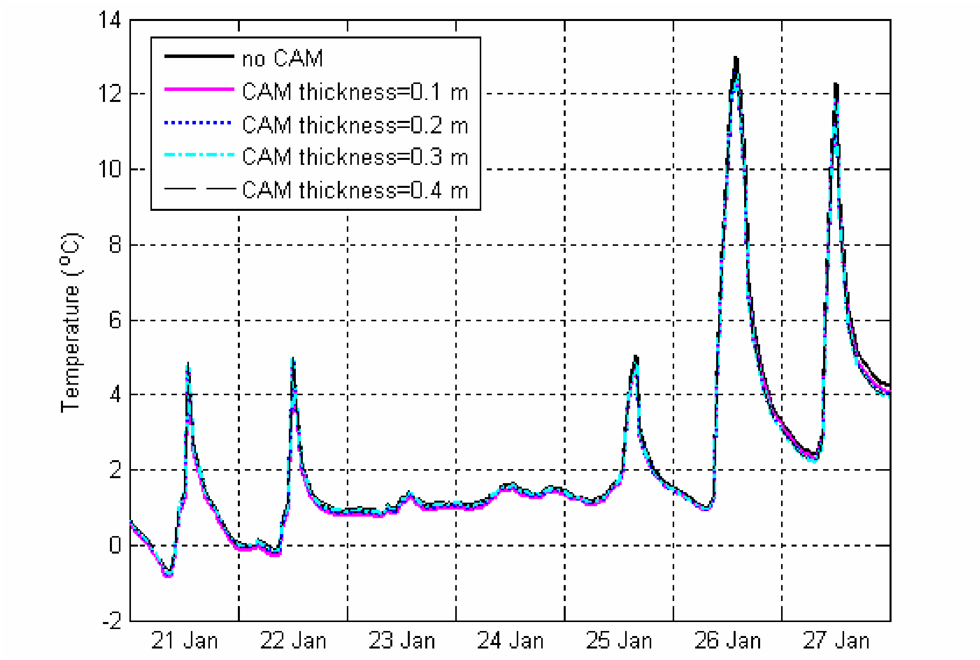


Figure 32. Variations of the indoor temperature in the cold week for the CAM with different thicknesses ($X_{CAM} = 5$ m)

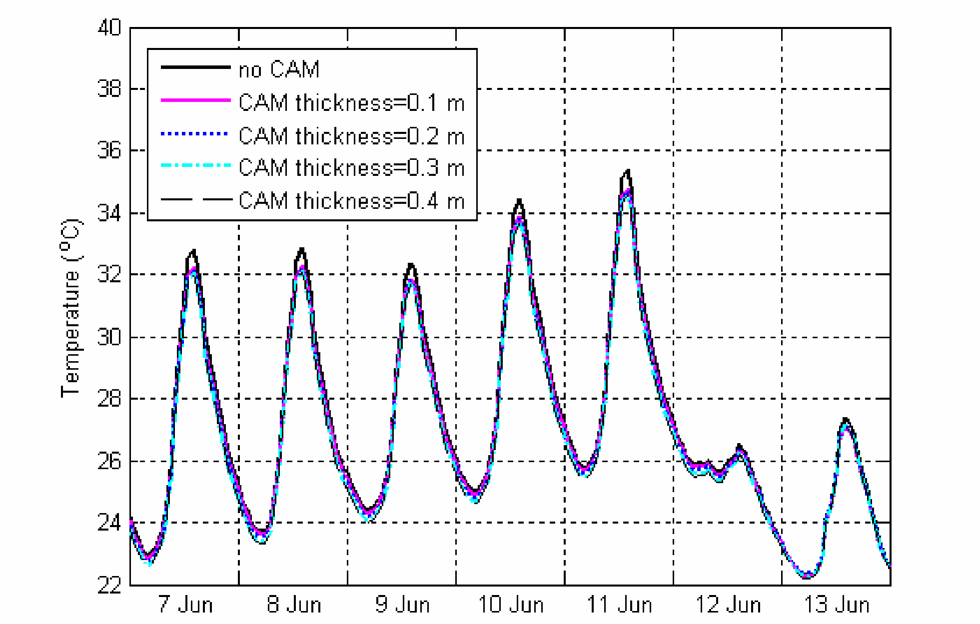


Figure 33. Variations of the indoor temperature in the warm week for the CAM with different thicknesses ($X_{CAM} = 5$ m)

Figures 32 and 33 show the temperature variations in the cold and warm week respectively. There is not much difference for different thicknesses of the CAM. Looking at figure 34, which is the temperature variations in the cold day, it is found that by increasing the thickness of the CAM, the indoor temperature increases a little. It is the good effect of the mass increment which saves more energy. Another benefit of the mass increment is apparent in figure 35 which shows the temperature variations in the warm day. By increasing the mass amount of the CAM, indoor temperature shows lower values. In the warm days of a year, a CAM with a larger mass absorbs more energy and warms up the room less than the CAM with smaller mass. But the important thing is finding the optimum format of a CAM. The results in this section tell that there is not much benefit in increasing the mass amount of the CAM.

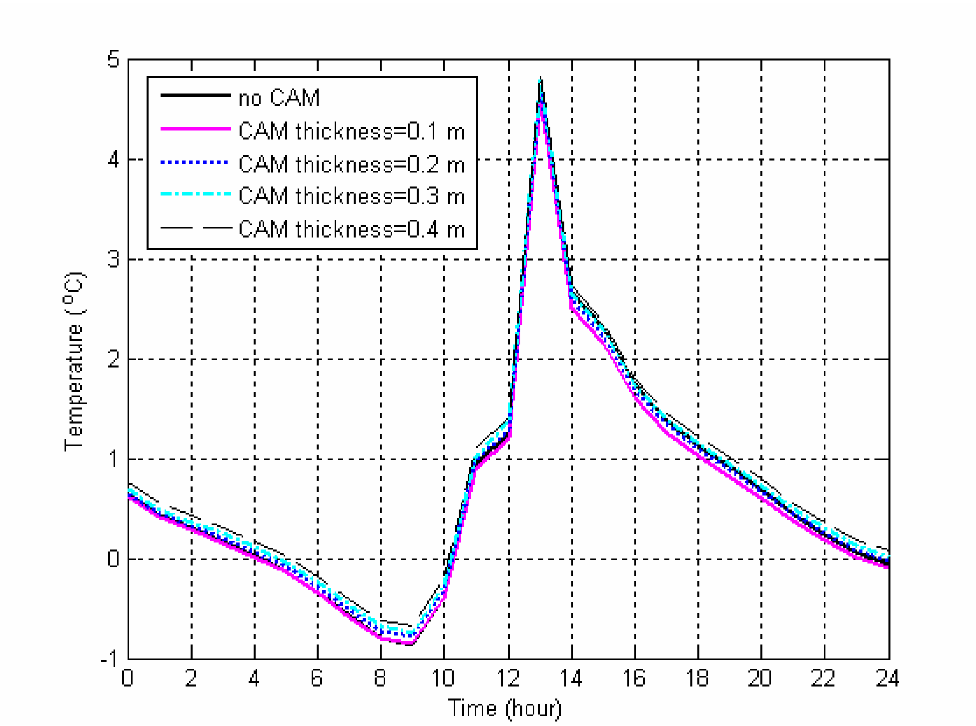


Figure 34. Variations of the indoor temperature on 21st January for the CAM with different thicknesses (X_{CAM} = 5 m)

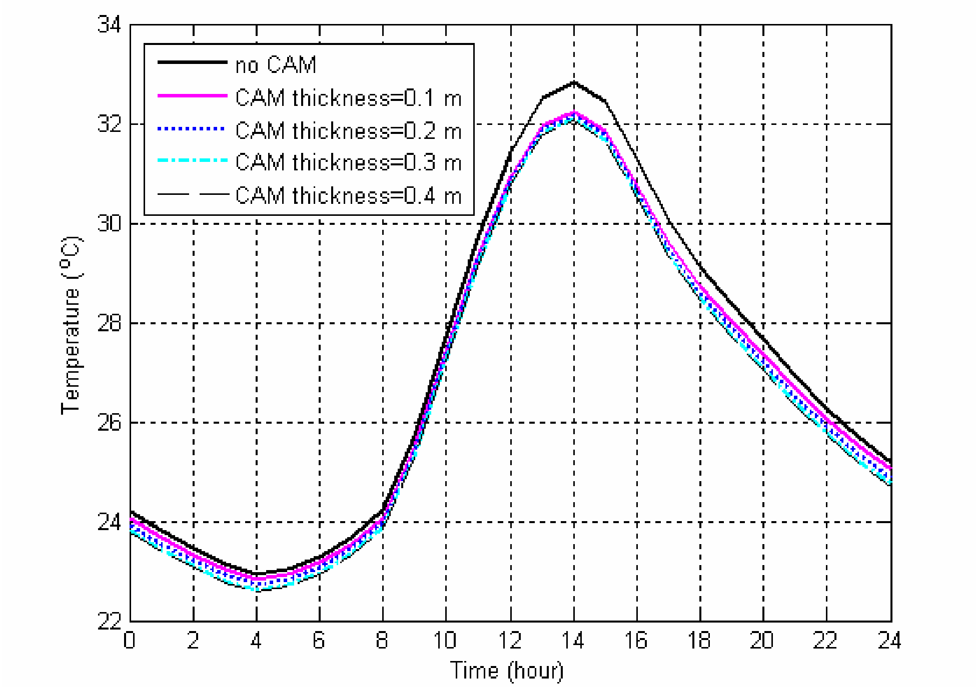


Figure 35. Variations of the indoor temperature on 7th June for the CAM with different thicknesses (X_{CAM} = 5 m)

5.2. Effects of CAM on cooling demand

Effects of a CAM on cooling demand of the room have been studied for the whole year and the 158th day of the year which is the 7th of June. In the warm days of summer the incidence angle of the solar radiation is high. Figure 36 shows the relative angle between sun and south wall of the room in 24 hours of the 158th day of year. [4]

In section 5.1 there was no heating or cooling system in the room. In this section and wherever the CAM effects on cooling or heating demand are considered, there is cooling and heating system in the room.

Figure 37 shows the integrated cooling demand in the warm day when the room is empty and when it has a CAM inside. The CAM type is 1 and its height is 2 m. It is located 1 m from the window. In this warm day the CAM has shown its best performance for α = 0.6 at this location.

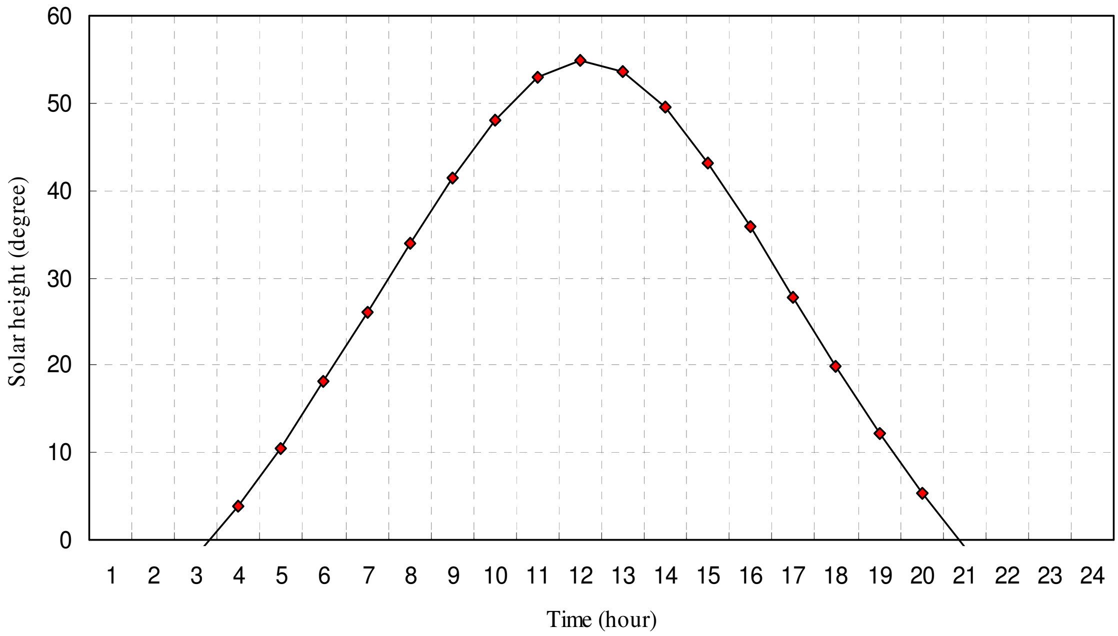


Figure 36. Angle between sun and south wall of the room during 7th of June

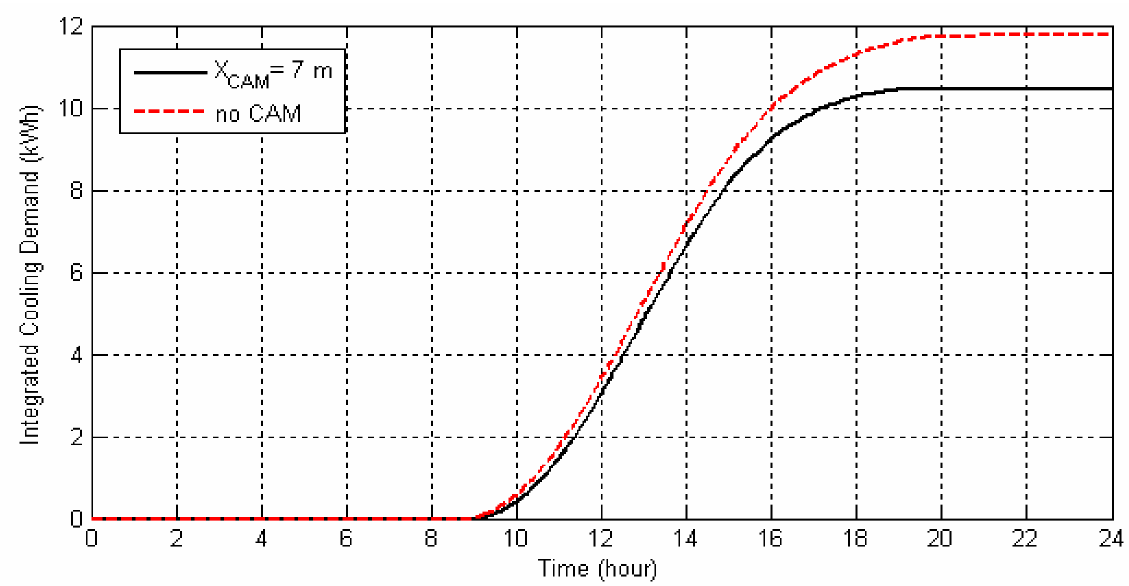


Figure 37. Integrated cooling demand in the warm day

In the warm days of June, the angle of incidence of the solar radiation to the window is high. The high angle of incidence causes the most part of the solar radiation to hit the near window area (see figures 8 & 9). When a CAM is far from the window the incoming solar radiation hits the floor and warms it up and consequently the indoor temperature increases. When the CAM is moved close to the window lots of solar radiation hits the CAM instead of the floor. A CAM prevents the indoor temperature increment in two ways; first it reflects some of the solar radiation to the window, so that part does not warm up the room. The second effect of the CAM is because of its high heat capacity (ρC_p). Having a high heat capacity means that the amount of energy for increasing temperature of the CAM for one degree is more than an equal mass with lower heat capacity. So the CAM has the potential to absorb lots of heat energy without rapid and high temperature variations.

Figure 38 compares the integrated cooling demand in whole year for the room when it is empty and when it has the CAM inside. Distance of the CAM to the window is 1 m (X_{CAM}=7) and 7 m (X_{CAM}=1).

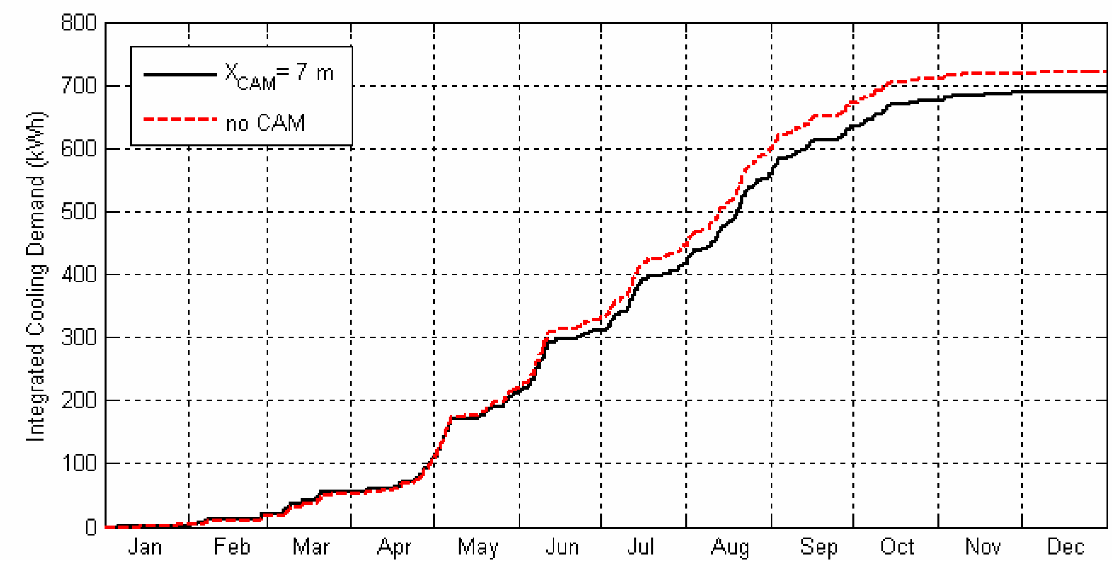


Figure 38. Integrated cooling demand in whole year

5.2.1. CAM with different surface absorbtances

CAM properties:

Height: 1 m   Width: 2 m   Thickness: 0.1 m   Type: 1 & 2

Figure 39 shows the cooling demand in the warm day. Negative values tell us how much using a CAM decreases cooling demand in percent comparing with the empty room. When the CAM is 1 m close to the window the maximum amount of energy is saved. When the CAM is far from the window it saves the incoming solar energy and works like an ordinary extra mass which increases cooling demand of the room. Moving the CAM closer to the window decreases cooling demand more and more up to the value at X_{CAM}=7 m which is the optimum place of the CAM.

When the distance between the CAM and window is 50 cm, more cooling demand is needed in the case of α=0.8. The CAM absorbs more solar energy comparing the case with α=0.6 and warms up the room. The amount of absorbed energy causes the CAM temperature to increase above the room temperature. Then it begins to warm up the room through convection and radiation.

In warm days with high angle of incidence of the solar radiation, when a CAM is far from the window it does not receive solar radiation directly from the window. It absorbs energy by receiving reflected short wave radiations or long wave radiations from other surfaces of the room and also convectional heat transfer through air inside the room.

Figure 40 tells us about the effects of the CAM on the cooling demand of the building in whole year. The CAM is fixed at its place in whole year. The results of the whole year help us to make a rough estimate about amount of energy that could be saved using a CAM. But of course more energy is saved when different kinds of CAM in different locations of room are used during a year.

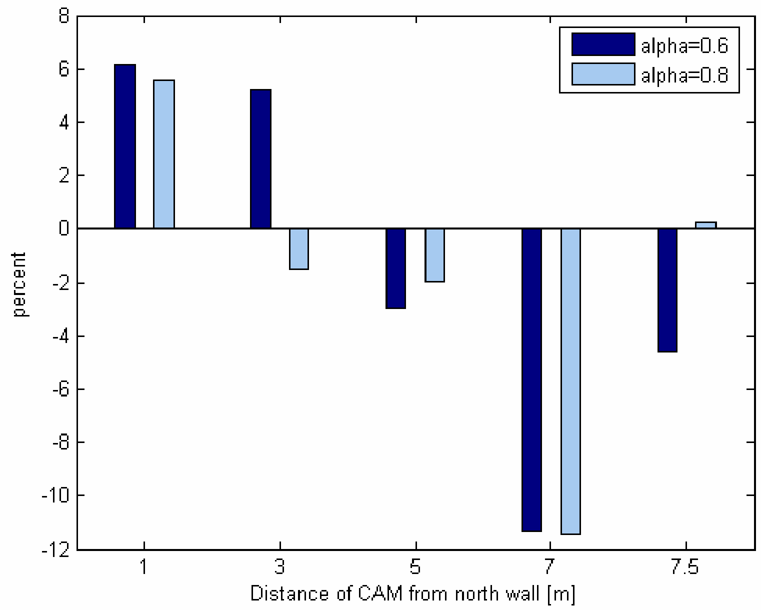


Figure 39. Cooling demand in the warm day (compared with the empty room) for different surface absorptances of the CAM

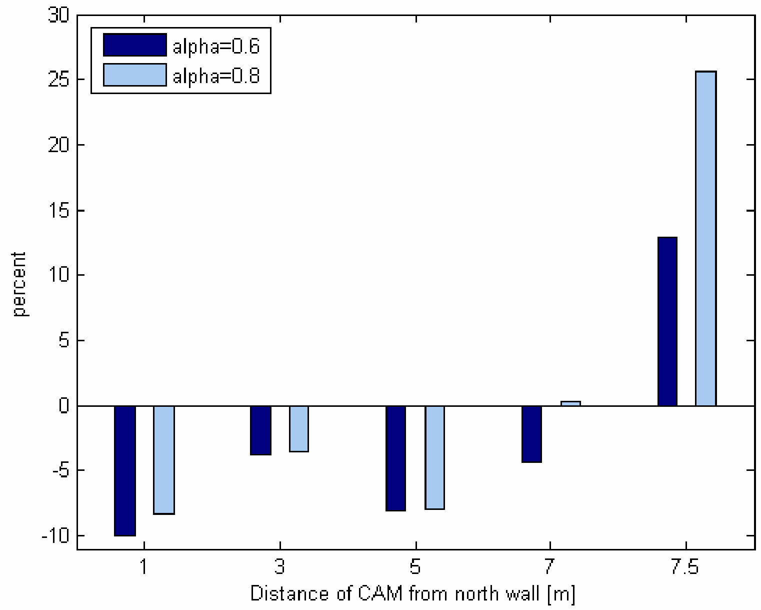


Figure 40. Cooling demand in whole year (compared with the empty room) for different surface absorptances of the CAM

5.2.2. CAM with different heights

CAM properties:

Height: 1 m & 2 m   Width: 2 m   Thickness: 0.1 m   Type: 1

Increasing height of the CAM to 2 m doubles mass and surface area of the CAM.
Figure 41 shows that when height of the CAM is 2 m it decreases the cooling demand more than the CAM with 1 m height except at X_{CAM}=7 m. The absorbed energy increases the temperature of the CAM to the values higher than the room temperature and the CAM works as a heat source in subsequent instances until its temperature equals the room temperature. Increasing mass amount of the CAM prevents its temperature increment to high values. At X_{CAM}=3 m, CAM height increment decreases the cooling demand more than other places.
The shielding effect of a CAM is used by placing it closer to the window. The best performance of the CAM is at X_{CAM} =7 m for both heights of it. There is not much difference in the CAM performance for both heights of it at this location. It is possible to reach a good performance of a CAM without increasing its mass or area by finding the optimum location of the CAM. Suitable location of a CAM, which is also dependent on its size, is very important in using the shielding effects of it. When the distance of the CAM from the north wall is 7 m, it prevents solar radiation to come inside the room by reflecting back the radiation to the window. Moving the CAM closer to the window (X_{CAM} =7.5 m) decreases the volume of the south zone, so less energy is absorbed by this part which is in contact with the window. Also more solar energy radiates directly to the north zone (note the high incidence angles of the warm days). North zone gets warmer and also makes the CAM warmer. Comparing with the place farther from the window (X_{CAM} =7 m), less amount of energy is transferred from south face of the CAM to the window. The result is saving more solar energy inside the room and increment of cooling demand comparing with the optimum place of the CAM (X_{CAM} =7 m). This effect is obvious in all the other figures which are about cooling demand in different places of a CAM.

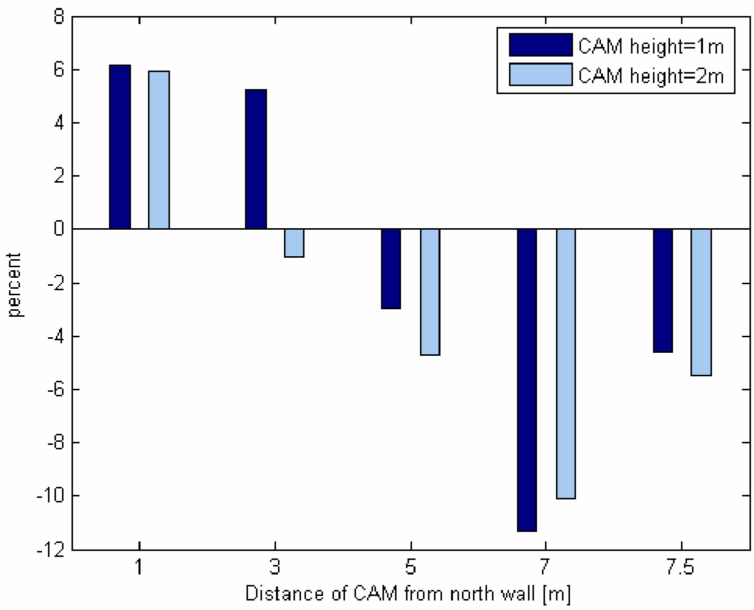


Figure 41. Cooling demand in the warm day (compared with the empty room) for different heights of the CAM (α_{CAM}=0.6)

Figure 42 compares the results of simulation the models with the CAM in whole year. It is obvious that the CAM with the height of 2 m decreases cooling demand more.

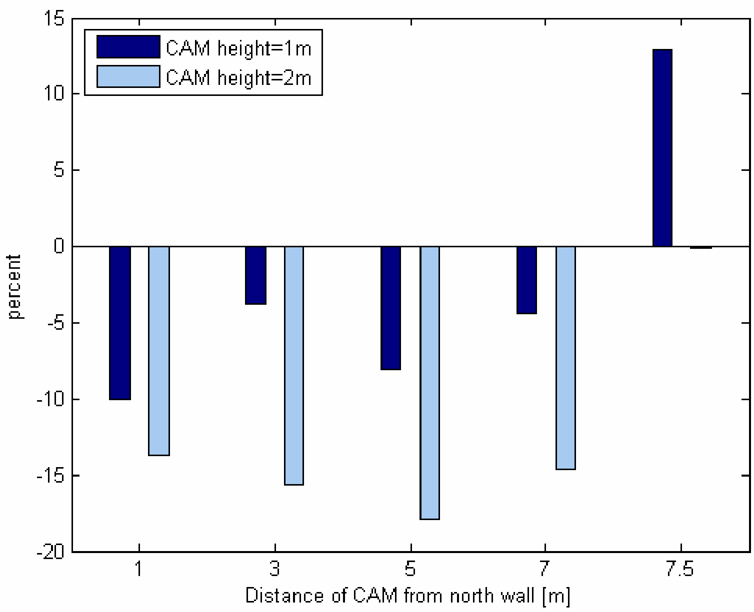


Figure 42. Cooling demand in whole year (compared with the empty room) for different heights of the CAM (α_{CAM}=0.6)

5.2.3. CAM with different materials

<u>CAM properties:</u>

Height: 1 m Width: 2 m Thickness: 0.1 m Type: 2 & 3

Figure 43 compares cooling demand in the warm day for the CAM with the soil-clay and aluminium shell. Absorptivity of both shells is 0.8. The Biot number and thermal diffusivity of the aluminium shell is more than the other one. So it transfers heat through convection better than a soil shell. The emissivity of soil-clay is higher than aluminium; it means that soil shell radiates long wave radiations to the surrounding with higher rates.

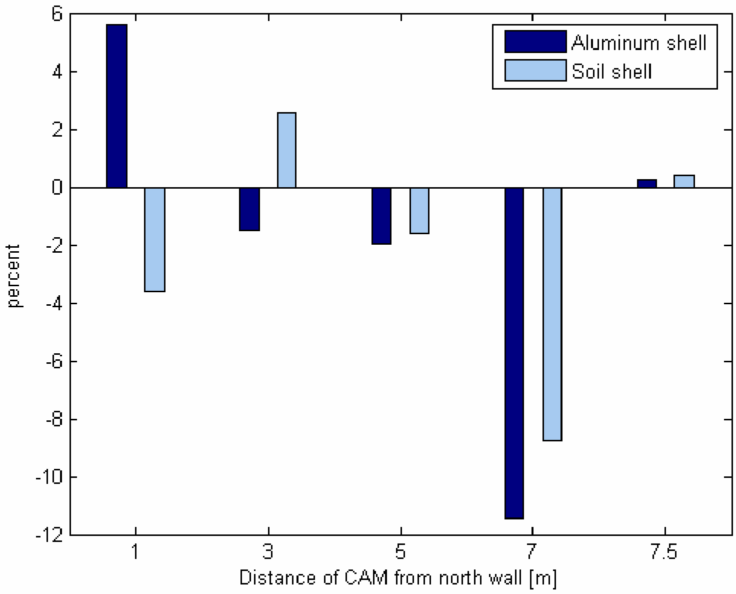


Figure 43. Cooling demand in the warm day (compared with the empty room) for different materials of the CAM

The energy is saved in or released from the CAM in different time periods. For example it saves energy when the room temperature is high and at the night when the temperature decreases it releases energy and increases the room temperature. Soil-clay shell retards heat transfer between the CAM and the room comparing with the aluminium shell. It responses to the temperature variations with longer delay which causes releasing energy at some undesirable moments and heating up the room. It is important to do not mix up the performance of a CAM when there is cooling or heating system in the room and when there is not (section 5.1). In the previous section the whole system responded to the temperature variations of the outside in its natural way. But when a cooling or heating system works, the responses of the system to the temperature variations varies. Now the inside temperature is controlled to be between 20^{o}C and 24^{o}C. The inside experiences heating or cooling loads in different and somehow quick time steps. In this case the speed that the CAM adjusts itself to the temperature variations is important and shell material plays an important role. When selecting the shape and the material of a CAM, their effects on heat transfer should be considered. The Biot number and thermal diffusivity are suitable criterions in this field.

The effects of using the CAM with different materials in whole year are shown in figure 44.

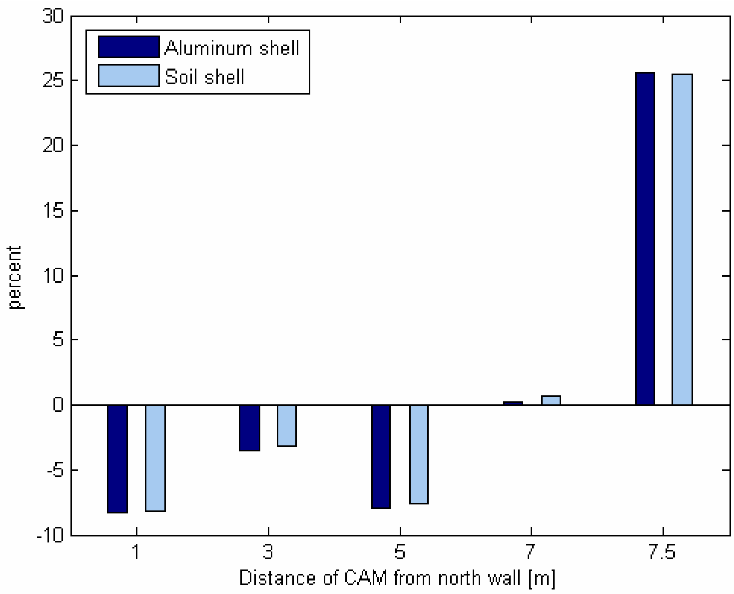


Figure 44. Cooling demand in whole year (compared with the empty room) for different materials of the CAM

5.2.4. CAM with different thicknesses

<u>CAM properties:</u>

Height: 1 m   Width: 2 m   Thickness: 0.1-0.4 m   Type: 1 & 2

Figure 45 shows results for four different thicknesses of the CAM when its distance to the window is 1 m. Increment of the CAM thickness and consequently its mass does not improve its performance much and somehow it shows weaker results.

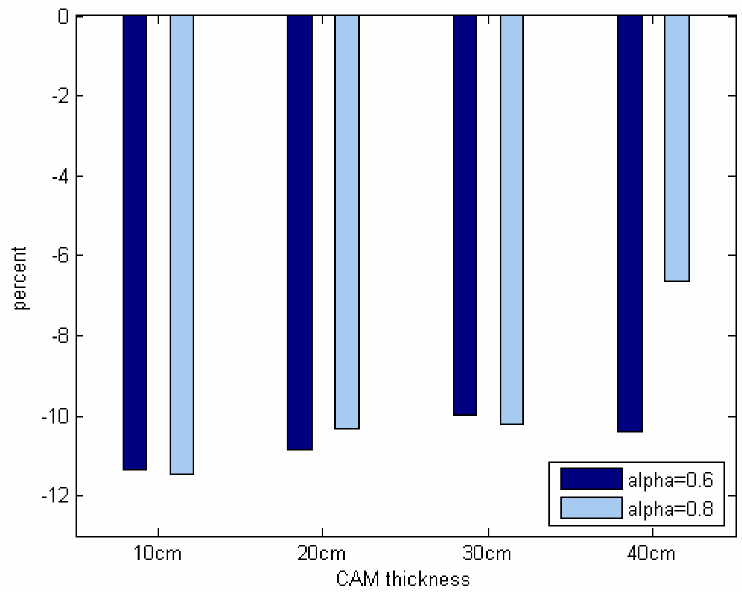


Figure 45. Cooling demand in the warm day (compared with the empty room) for different thicknesses of the CAM (X_{CAM}=7 m)

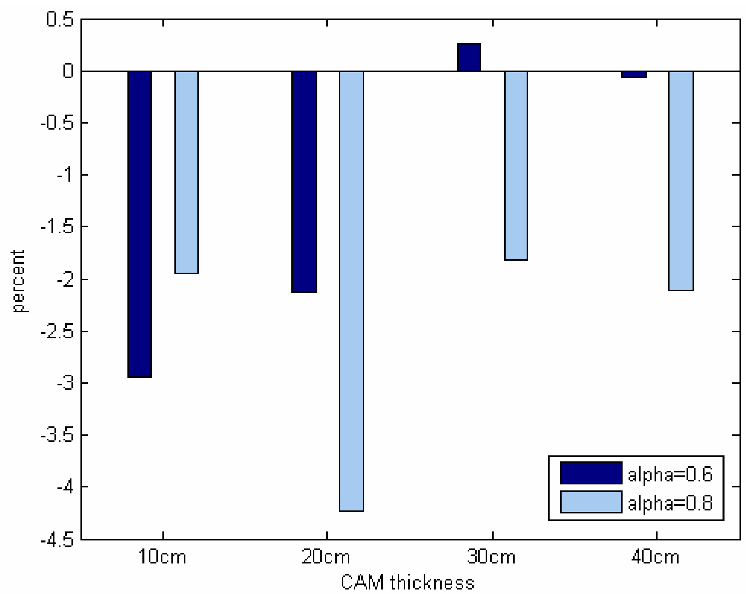


Figure 46. Cooling demand in the warm day (compared with the empty room) for different thicknesses of the CAM (X_{CAM}=5 m)

In this report increasing the thickness of the CAM just increases the mass amount of the CAM not the surface area of it, contrary to height increment of the CAM. It is important to find the optimum mass amount of the CAM.

Figure 46 shows the results for four different thicknesses when the CAM distance to the window is 3 m. At this location changing the CAM thickness works in a different way. Size, mass amount and location of the CAM depend on each other strongly.

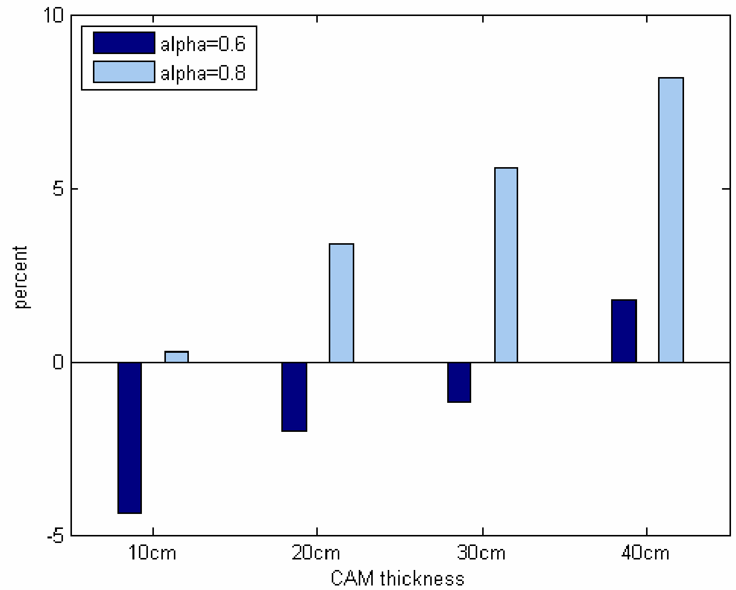


Figure 47. Cooling demand in whole year (compared with the empty room) for different thicknesses of the CAM (X_{CAM}=7 m)

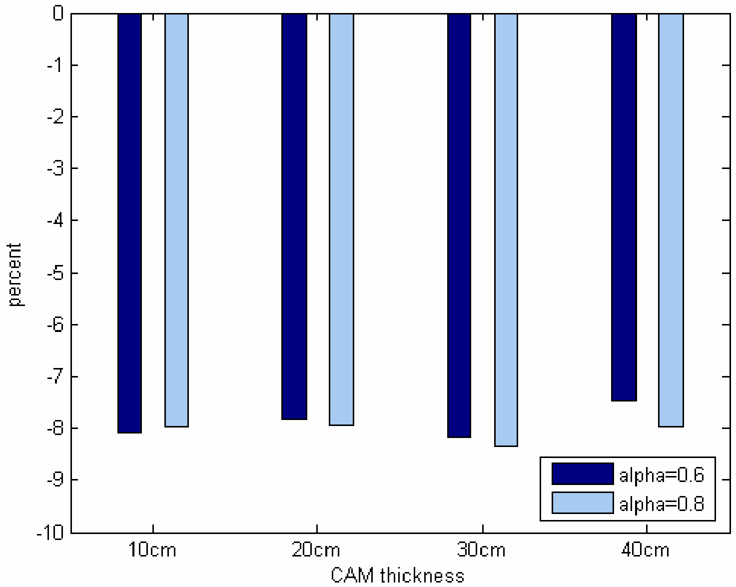


Figure 48. Cooling demand in whole year (compared with the empty room) for different thicknesses of the CAM (X_{CAM}=5 m)

Figures 47 and 48 show effects of increasing thickness of the CAM on cooling demand in whole year when the CAM is 1 m and 3 m far from the window respectively. Size effects are really dependent on the CAM location in the room. It is interesting to see opposed effects of the CAM just by changing its location in the room for 2 m.

5.3. Effects of CAM on heating demand

Effects of different kinds of CAM on heating demand of the room have been studied for the 21st day of the year and the whole year. In cold days of winter the incidence angle of the solar radiation decreases to lower values than warm days. The lower incidence angle, the further surfaces from window absorb more solar radiation. Figure 49 shows the relative angle between sun and north wall of the room in 24 hours of the 21st of January. [4]

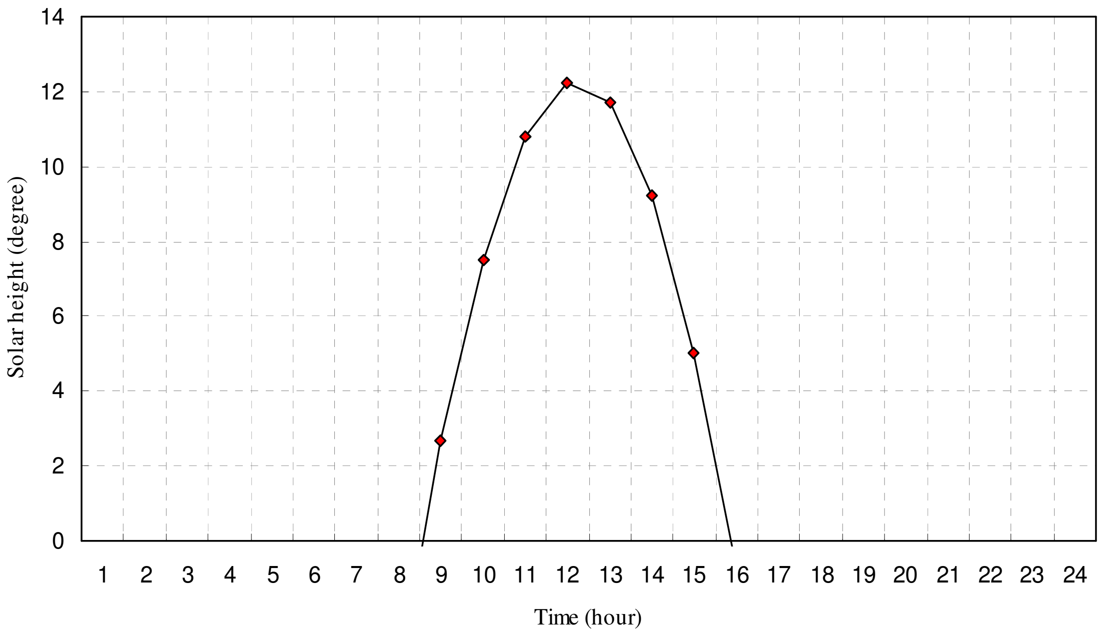


Figure 49. Angle between sun and south wall of the room during 21st of January

Figure 50 shows the integrated heating demand in the cold day for the room when it is empty and when there is a CAM inside it. The height of the CAM is 1 m and it is located 1 m far from the north wall. Figure 51 compares the heating demand for these two cases in whole year.

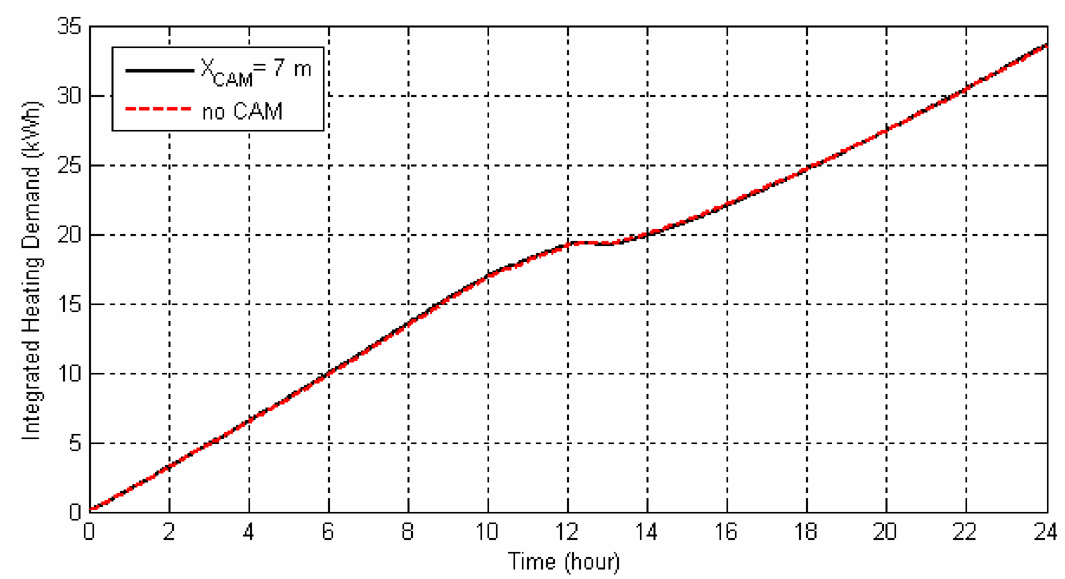


Figure 50. Integrated heating demand in the cold day

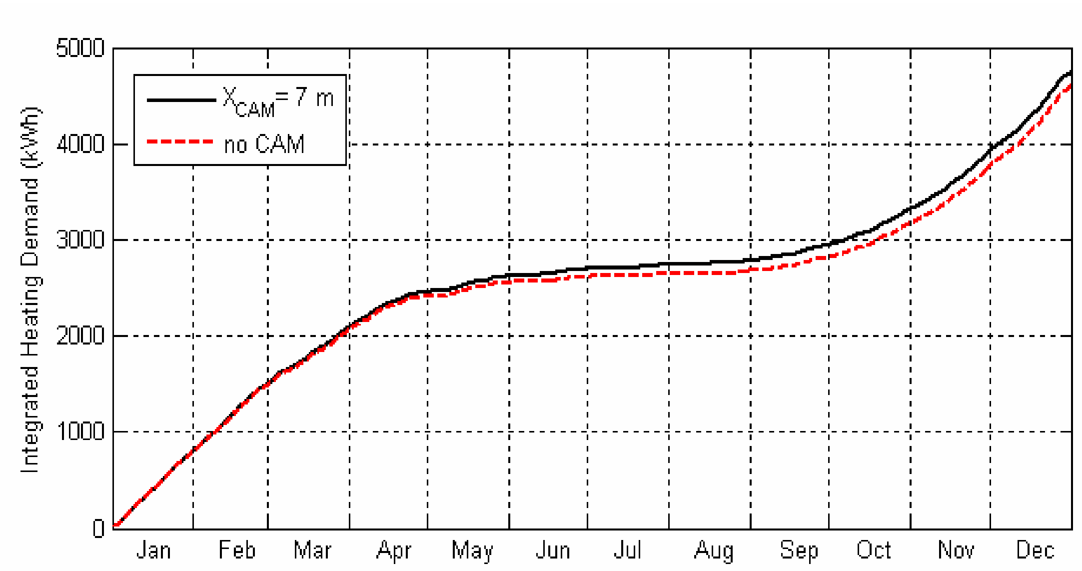


Figure 51. Integrated heating demand in whole year

5.3.1. CAM with different surface absorbtances

CAM properties:

Height: 1 m Width: 2 m Thickness: 0.1 m Type: 1 & 2

Figure 52 shows the comparison of the heating demand of the room with the CAM inside and the empty room. In the cold day the outside temperature is lower than the inside temperature of the room. When the CAM is far from the window (X_{CAM} =1 m) it absorbs some solar energy. The difference with the next two locations of the CAM (X_{CAM} =3 m & 5 m) is that it losses less energy through convection or radiation to the window. When the CAM gets closer to window shielding effects of the CAM comes to effect. The CAM prevents room to loose its energy to the outside through the window.

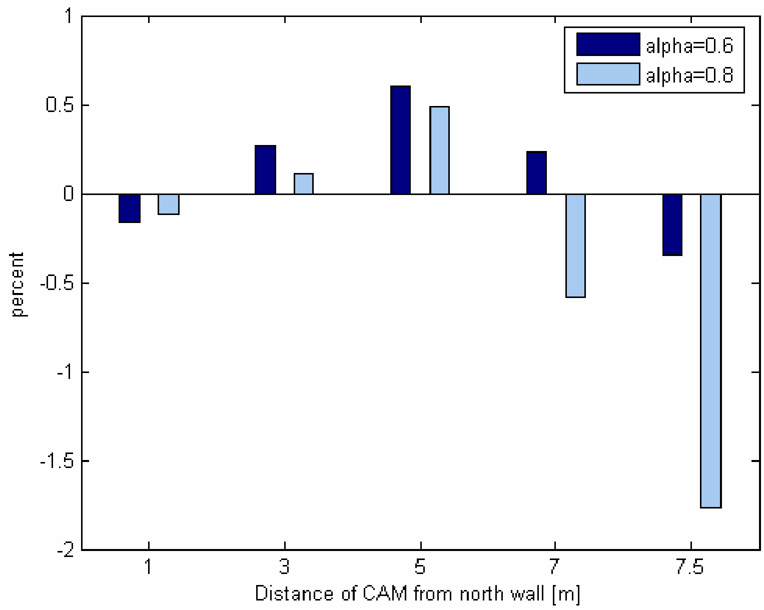


Figure 52. Heating demand in the cold day (compared with the empty room) for different absorptances of the CAM

In warm days there was an optimum region near the window for decreasing energy consumption, but in cold days it is better to put the CAM too far or very close to the window corresponding to the angle of the incoming solar radiation. In cold days solar radiation is welcomed to the room. A CAM with higher solar absorption works better near the window. The CAM absorbs solar radiation by its south face and transfers it to its north face. Heat is transferred to the north part of the room through convection and radiation from the CAM north face. By decreasing convection losses through the window and enhancing heat transfer to north zone of the room, CAM helps to save more solar energy and decrease the heating demand.

Figure 53 shows the heating demand in different locations of the room in whole year. The best performance of the CAM is when the CAM is far from the window. For decreasing the heating demand these two should be minimized; loosing energy through convective heat transfer between the CAM and window and undesired shielding effect of the CAM.

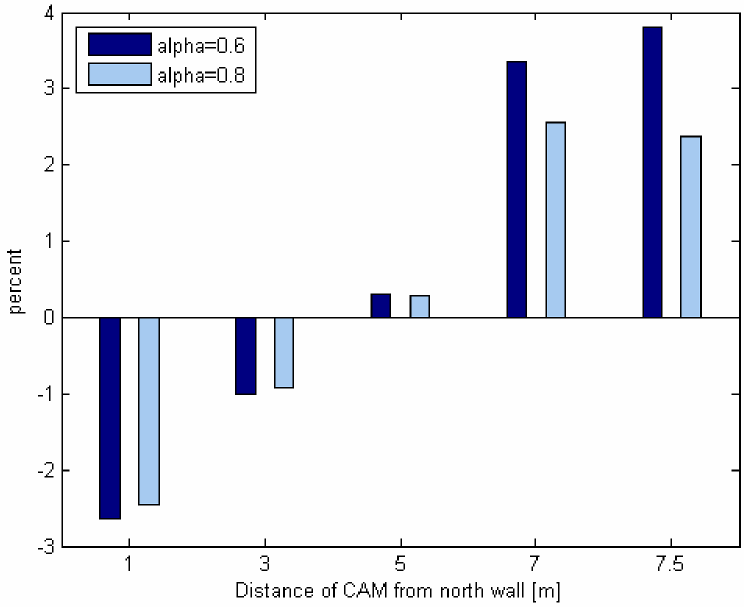


Figure 53. Heating demand in whole year (compared with the empty room) for different absobtances of the CAM

5.3.2. CAM with different heights

<u>CAM properties:</u>

Height: 1 m & 2 m   Width: 2 m   Thickness: 0.1 m   Type: 1

Effects of increasing volume and surface of the CAM are shown in figure 54. The absorptivity of the CAM surface is equal to 0.6. Close to the window, the shielding effect of the CAM increases by increasing the surface area. Consequently more energy is saved by decreasing convection heat transfer between inside air and the window. In the other locations of the CAM there is not much difference in the CAM height and also not much benefit in using the CAM. In the gray cold days a choice is using curtains instead of putting an extra mass inside the room.

Figure 55 shows the heating demand for two heights of the CAM in whole year. Again the best performance of the CAM in whole year for decreasing heating demand is when the CAM is far from the window. There, the CAM works like an extra mass which saves free energy from surroundings and releases it when there is a potential for heat transfer.

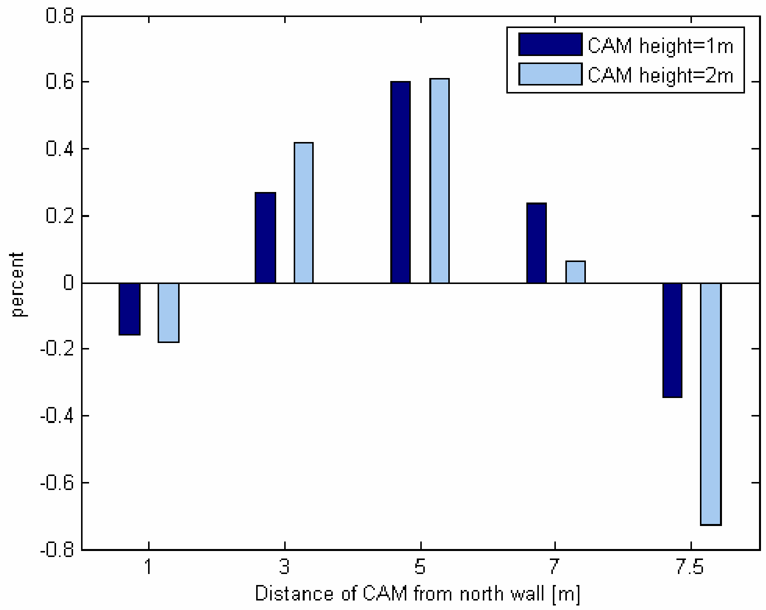


Figure 54. Heating demand in the cold day (compared with the empty room) for different heights of the CAM

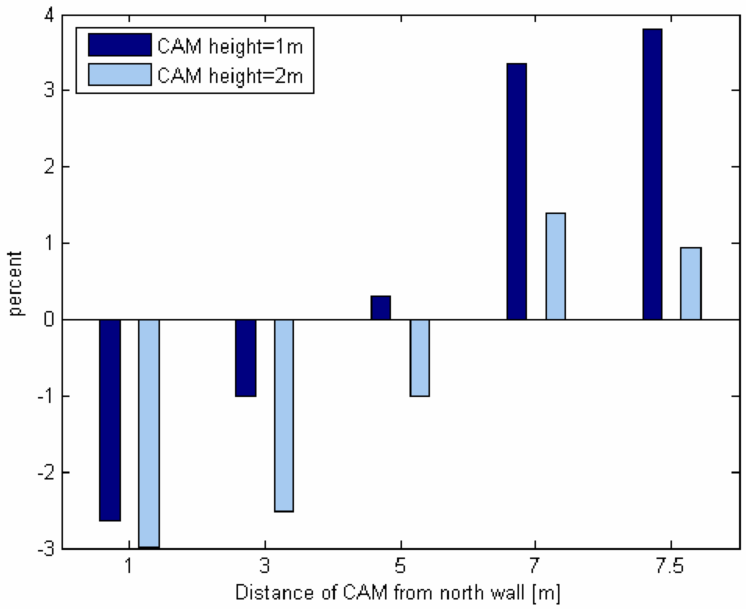


Figure 55. Heating demand in whole year (compared with the empty room) for different heights of the CAM

5.3.3. CAM with different materials

<u>CAM properties:</u>

Height: 1 m   Width: 2 m   Thickness: 0.1 m   Type: 2 & 3

Figure 56 shows the effects of using different materials as the CAM shell. There is not much difference in the CAM performance with aluminium and soil shell. When the CAM is close to the window its shielding effect decreases loosing energy through the window. The higher heat capacity of the soil shell decreases heating demand a little more than the aluminium shell.

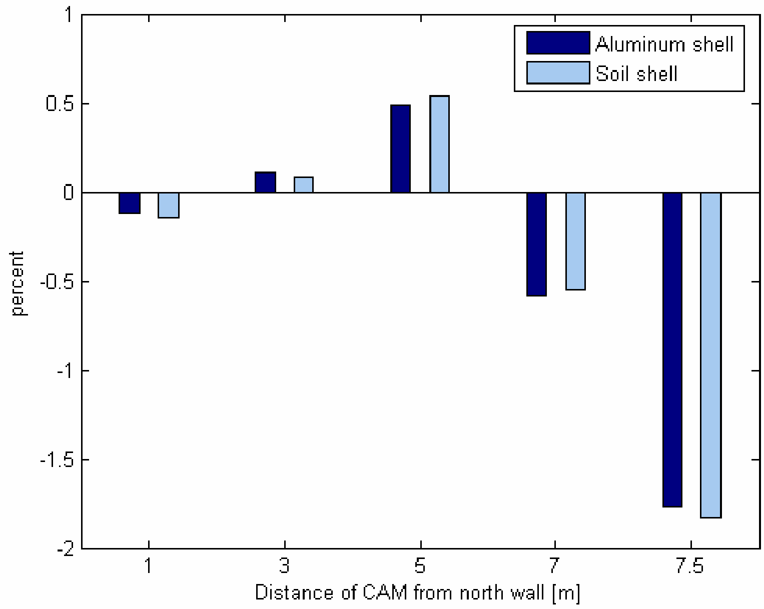


Figure 56. Heating demand in the cold day (compared with the empty room) for different materials of the CAM

Figure 57 shows the heating demand for two shells of the CAM in whole year. The best performance of the CAM is when the CAM is far from the window. There is no considerable difference between two shell materials. By increasing the distance between the CAM and window the difference decreases.

Generally the place, material and size of a CAM should be chosen based on its desired performance in each specific period of time.

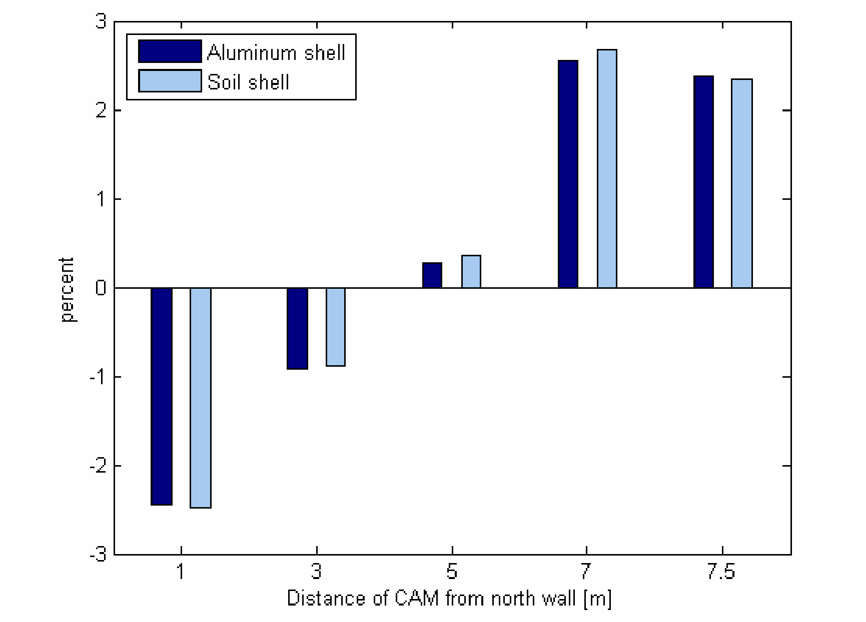


Figure 57. Heating demand in whole year (compared with the empty room) for different materials of the CAM

5.3.4. CAM with different thicknesses

<u>CAM properties:</u>

Height: 1 m Width: 2 m Thickness: 0.1-0.4 m Type: 1 & 2

Figures 57 and 58 show the effects of increasing thickness of the CAM on heating demand in the cold day when the CAM is 1 m and 3 m far from the window respectively. Amount of mass and size effects are dependent on location of the CAM.

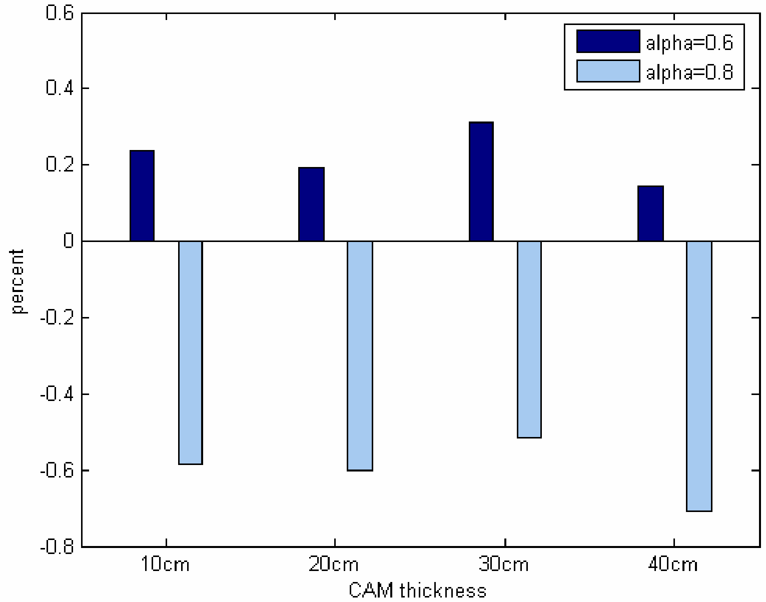


Figure 58. Heating demand in the cold day (compared with the empty room) for different thicknesses of the CAM (X_{CAM}=7 m)

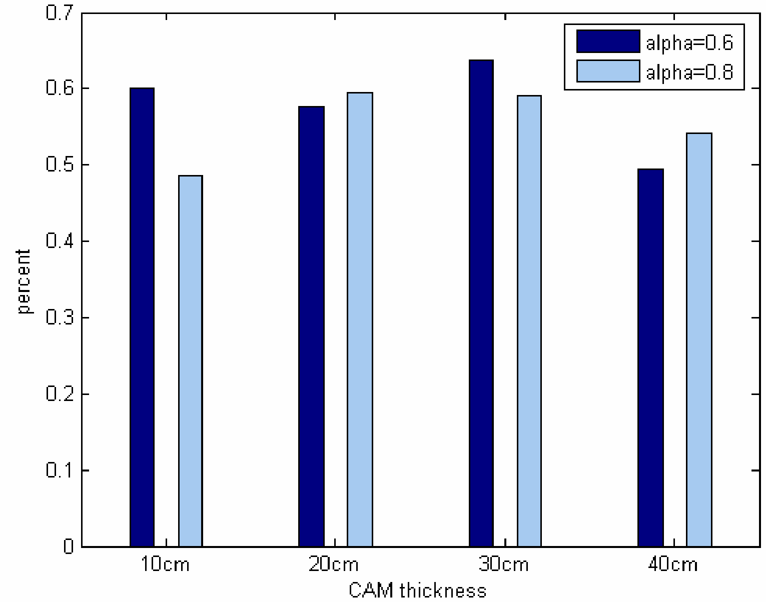


Figure 59. Heating demand in the cold day (compared with the empty room) for different thicknesses of the CAM (X_{CAM}=5 m)

Figures 60 and 61 show effects of increasing thickness of the CAM on heating demand in whole year.

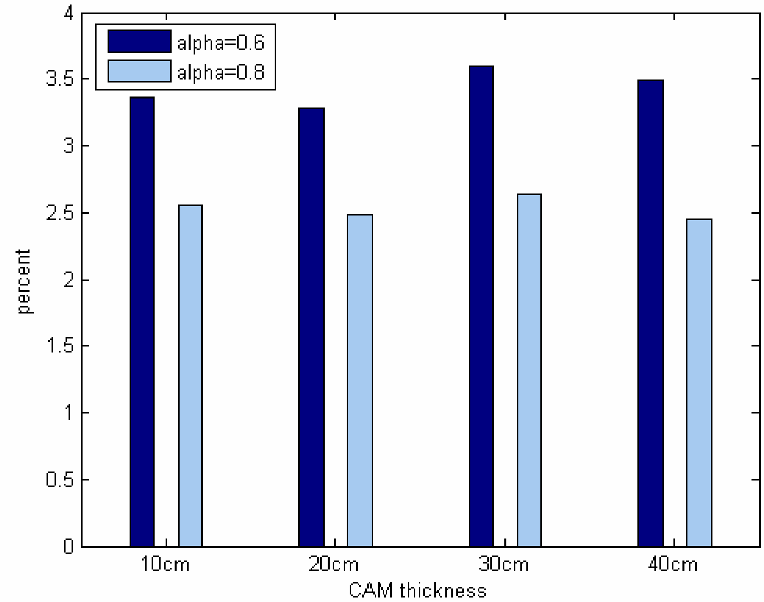


Figure 60. Heating demand in whole year (compared with the empty room) for different thicknesses of the CAM (X_{CAM}=7 m)

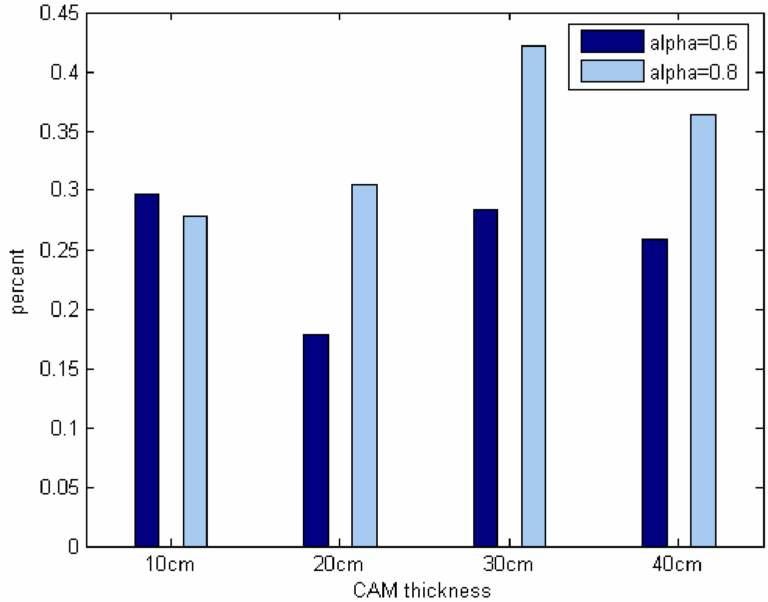


Figure 61. Heating demand in whole year (compared with the empty room) for different thicknesses of the CAM (X_{CAM}=5 m)

In most of the cases increasing the CAM thickness does not works very effectively.

Increasing just mass amount of the CAM does not improve energy saving much.

5.4. Effects of CAM on energy demand in whole year

In this section, effects of different CAMs on energy demand in whole year have been considered. Energy demand means the total energy which is used for cooling or heating the room. The total energy demand is the summation of the cooling and heating demand in each time step in whole year. The following diagrams show the comparison results between the empty room and the room with a CAM. The room has light weight walls.

5.4.1. CAM with different surface absorbtances

CAM properties:

Height: 2 m   Width: 2 m   Thickness: 0.1 m   Type: 1 & 2

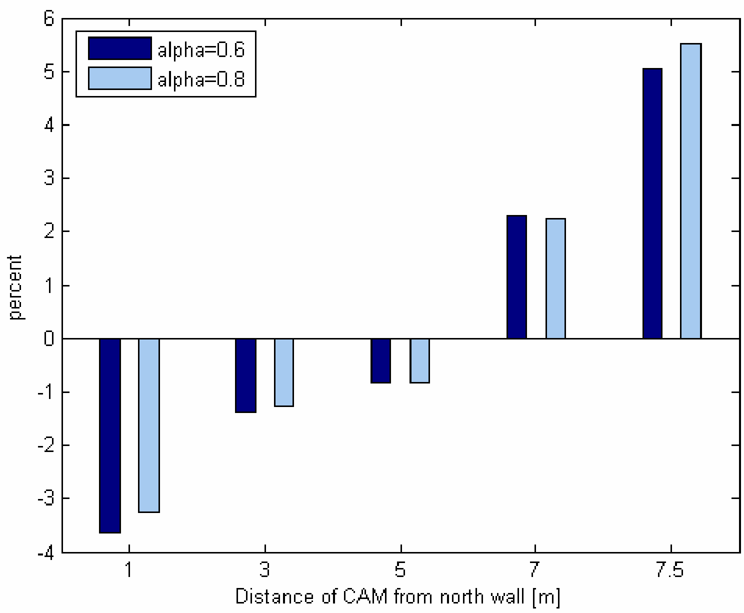


Figure 62. Energy demand in whole year (compared with the empty room) for different absorptances of the CAM

5.4.2. CAM with different heights

<u>CAM properties:</u>

Height: 1 m & 2 m Width: 2 m Thickness: 0.1 m Type: 1

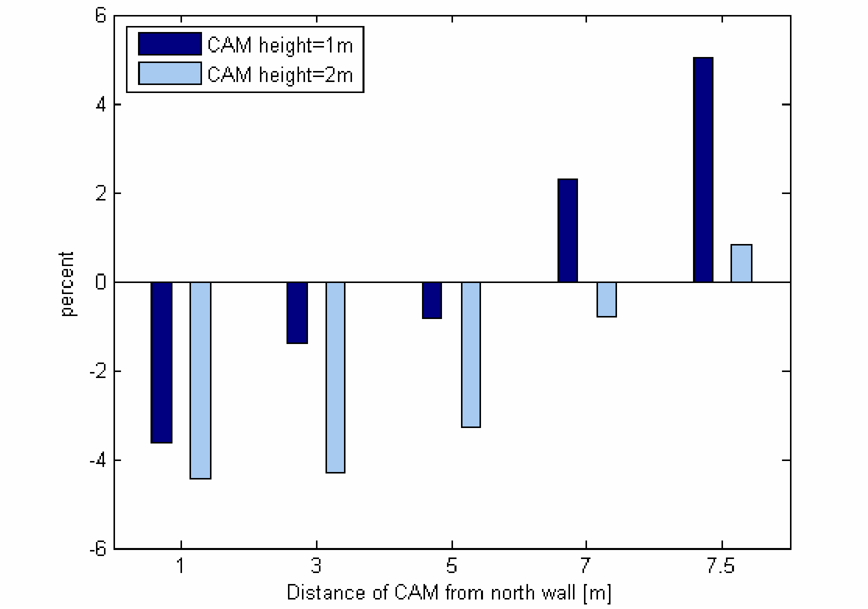


Figure 63. Energy demand in whole year (compared with the empty room) for different heights of the CAM

5.4.3. CAM with different materials

<u>CAM properties:</u>

Height: 1 m Width: 2 m Thickness: 0.1 m Type: 2 & 3

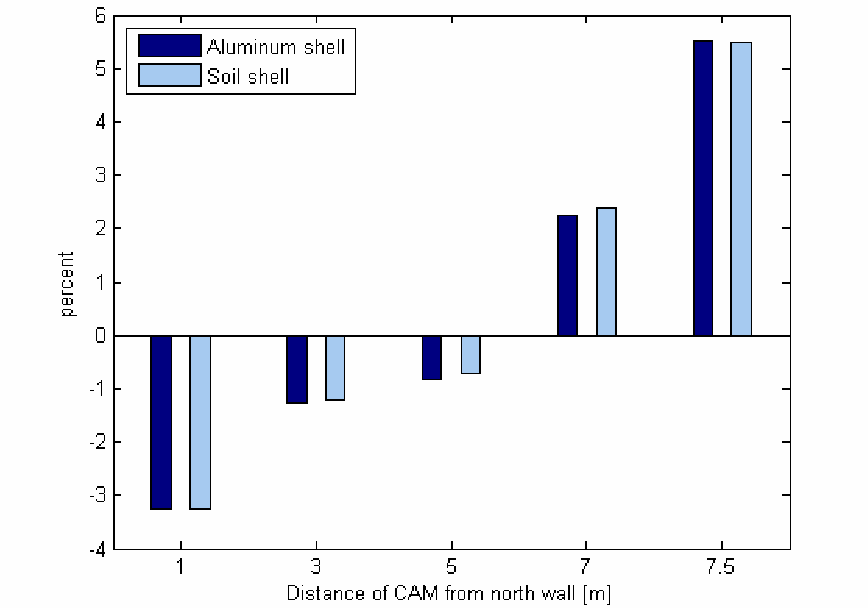


Figure 64. Energy demand in whole year (compared with the empty room) for different materials of the CAM

5.4.4. CAM with different thicknesses

CAM properties:

Height: 1 m   Width: 2 m   Thickness: 0.1-0.4 m   Type: 1 & 2

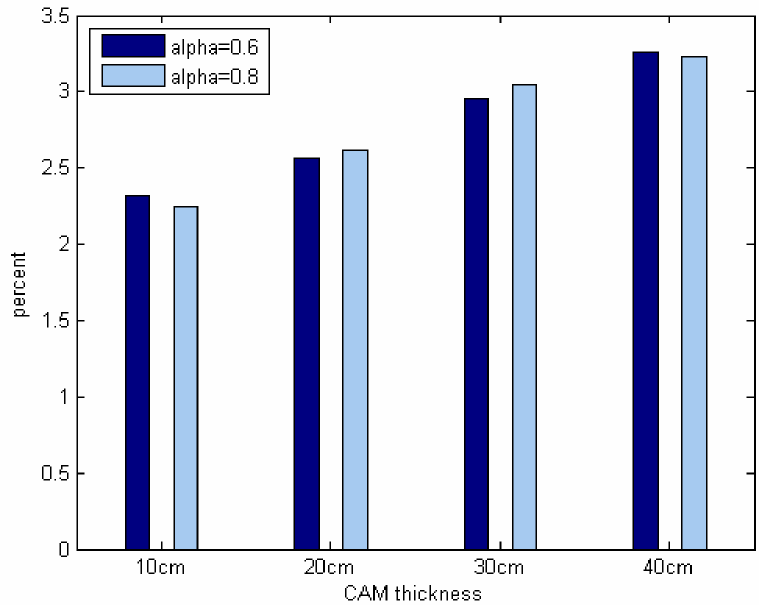


Figure 65. Energy demand in whole year (compared with the empty room) for different thicknesses of the CAM (X_{CAM}=7 m)

Results of the section 5.4 show that in the case of a fixed CAM in the light weight room, as much as the distance between the CAM and the window increases more energy is saved. But of course an important characteristic of a useful CAM is its mobility.

5.5. Internal Gains

At this stage the system has been simulated when there is some additional heat loads and mass in the room. The additional mass is in the room for the whole time, like furniture. In the simulation it is added as an additional volumetric heat capacity with the amount of 4×10^5 J/K to the both zones. So this amount is 8×10^5 J/K for the whole room. The heat loads come to effect from 09:00 to 17:00 in each day with the amplitude of 200 W. They represent the heat loads from persons, computers or any other stuff. These loads are named as *Internal Gains.* For this case a ventilation system with a variable air exchanging rate has been used. From 00:00 to 06:00 it works with the rate of 0.4 h^{-1} m^3/s. This value is doubled for the next 14 hours. Then it decreases to the first rate for the remaining 4 hours of day.

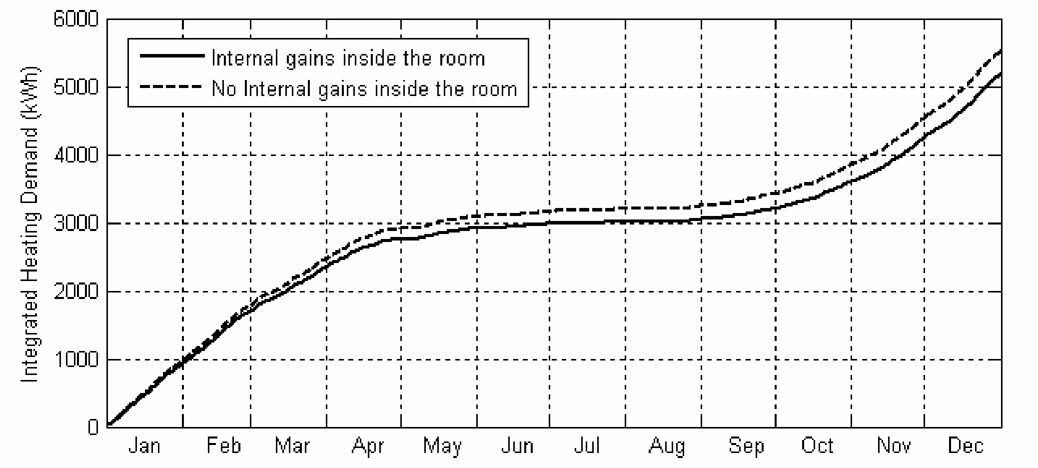


Figure 66. Integrated heating demand with and without internal gains

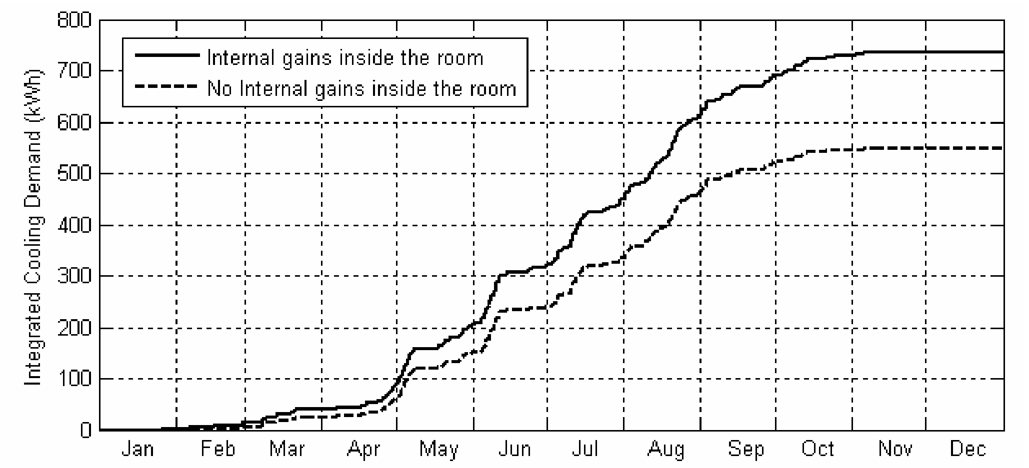


Figure 67. Integrated cooling demand with and without internal gains

With internal gains heating demand decreases and cooling demand increases. Figures 66 and 67 compare the energy consumption for heating and cooling the room with and without the internal gains. There is no CAM inside the room.

In the kind of simulation that has been done using IBPT toolbox the exact place of the additional heat sources could not be distinguished. These loads are just added to the heat loads of a zone. There are two zones in our model; 1- South zone, the room space between the CAM and window. 2- North zone, the room space between the CAM and north wall.

<u>CAM properties:</u>

Height: 1 m & 2 m   Width: 2 m   Thickness: 0.1 m   Type: 1

The following figures compare different aspects of using a CAM with aluminium shell when the source of the additional heat loads is in the south or north part of the room. It is convenient that distance increment of the CAM from north wall, increases the volume of the north zone while decreases the south's.

Figure 68 compares the cooling demand in the warm day. The first interesting point is that in the case of having internal gains, which is more practical comparing with the previous cases, using the CAM saves more energy. In the best case when the CAM is 1 m far from the window, the cooling demand decreases about 17% less than the empty room. When the CAM is located at X=1 m, we save more energy if internal heat loads are located between the CAM and the north wall. But this area is very small and in a real case the source of the heat load is not fixed. So the best place for the CAM in this warm day is where it shows a suitable performance when the heat source moves inside room. With due attention to this fact the best place of the CAM is in the region between X=5 m and X=7 m.

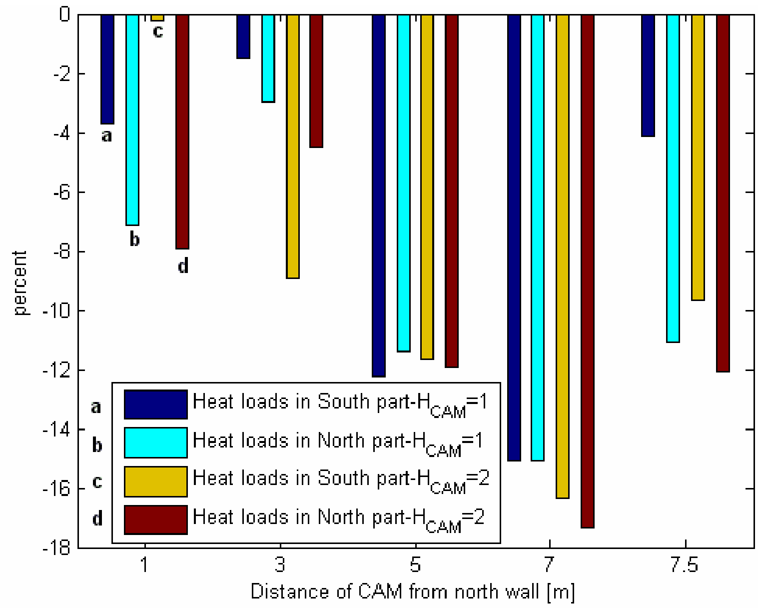


Figure 68. Cooling demand in the warm day (compared with the empty room) for the room with additional heat loads

Increasing the mass amount of a CAM does not always improve energy saving. Figure 69 shows that increasing mass amount of the CAM decreases its efficiency. The better performance of the CAM when it is located near the window is because of the shielding effects increment due to larger surface area. A good choice is the CAM with the height of 1 m when it is located 3 m far from the north wall and heat loads are in the south part of room.

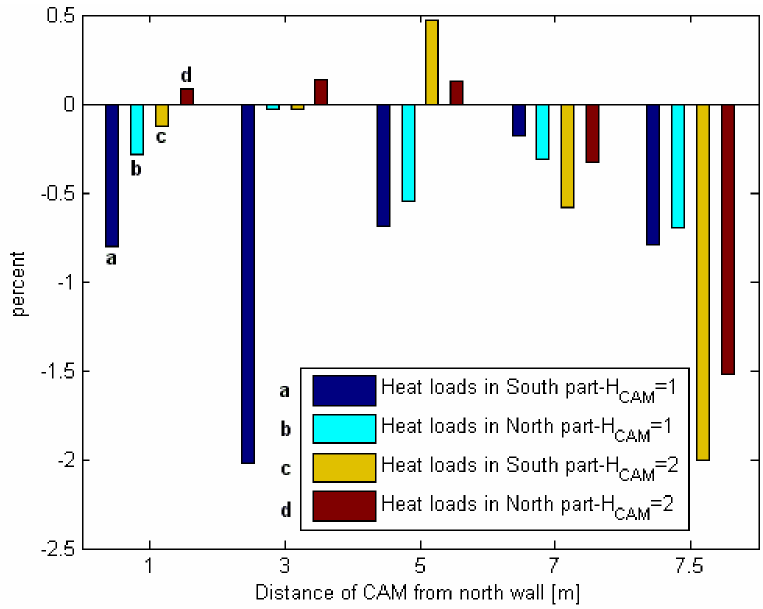


Figure 69. Heating demand in the cold day (compared with the empty room) for the room with additional heat loads

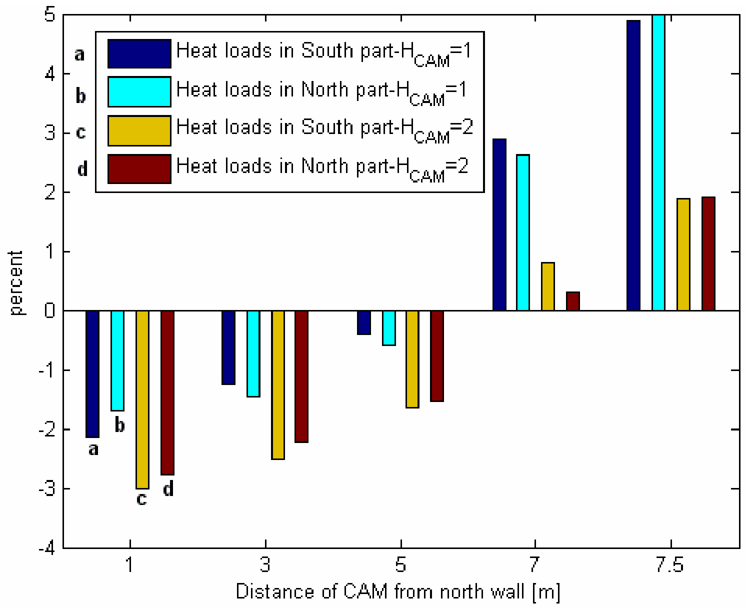


Figure 70. Cooling demand in whole year (compared with the empty room) for the room with additional heat loads

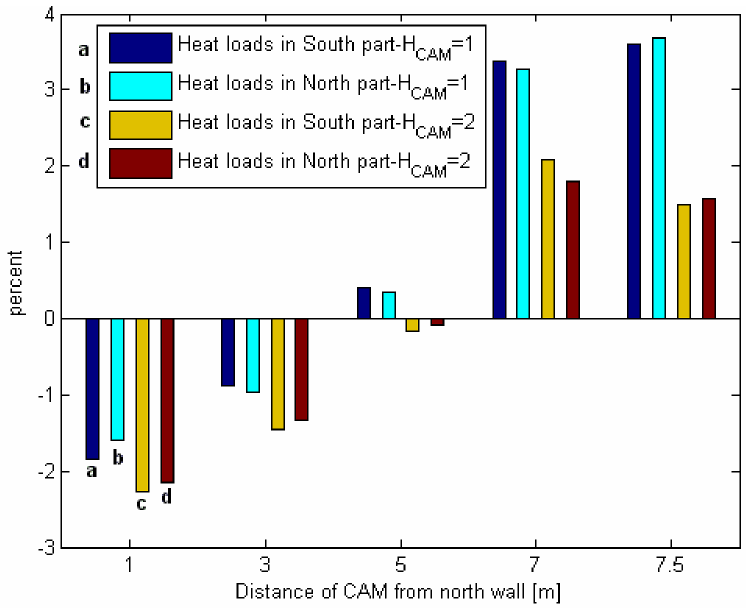


Figure 71. Heating demand in whole year (compared with the empty room) for the room with additional heat loads

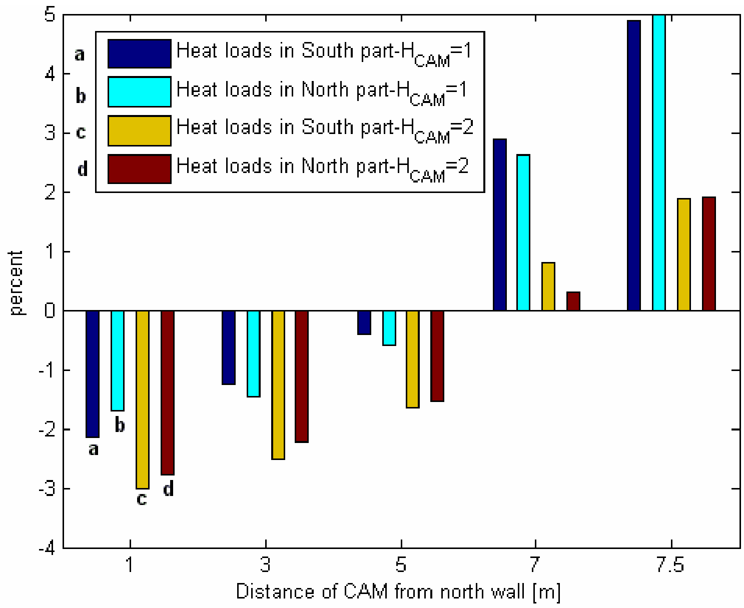


Figure 72. Energy demand in whole year (compared with the empty room) for the room with additional heat loads

5.6. Heavy weight construction

Effects of a CAM on indoor climate of the heavy weight construction room are studied. The walls of the light weight room have been replaced with the heavy weight walls which are described in section 2.1. Floor and roof of the room are the same in heavy weight and light weight constructions. The results of the simulation for heavy weight and light weight constructions in similar situations are compared. A CAM with aluminium shell with α=0.6 has been used. Height, width and thickness of the CAM are respectively 1 m, 2 m and 10 cm.

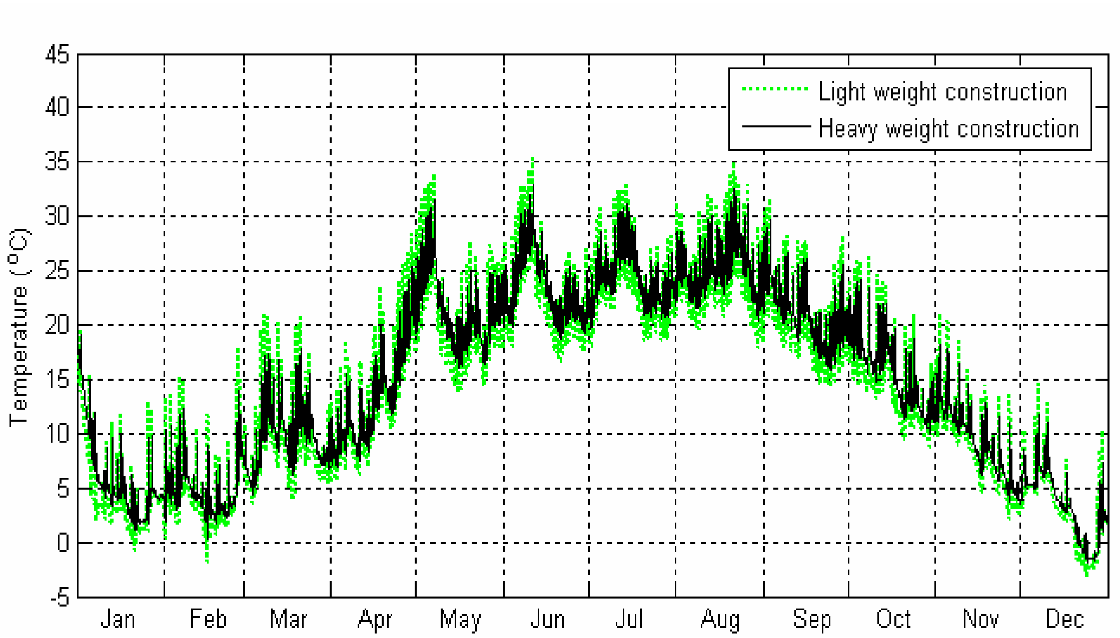


Figure 73. Indoor temperature of the empty room during a year for heavy weight and light weight constructions

Figure 73 shows the indoor temperature for the heavy weight and light weight constructions when there is no CAM inside the room. It shows that using the heavy weight wall construction increases the indoor temperature during the whole year comparing with the light weight construction.

5.6.1. Effects of CAM on indoor temperature

<u>CAM properties:</u>

Height: 1 m Width: 2 m Thickness: 0.1 m Type: 1

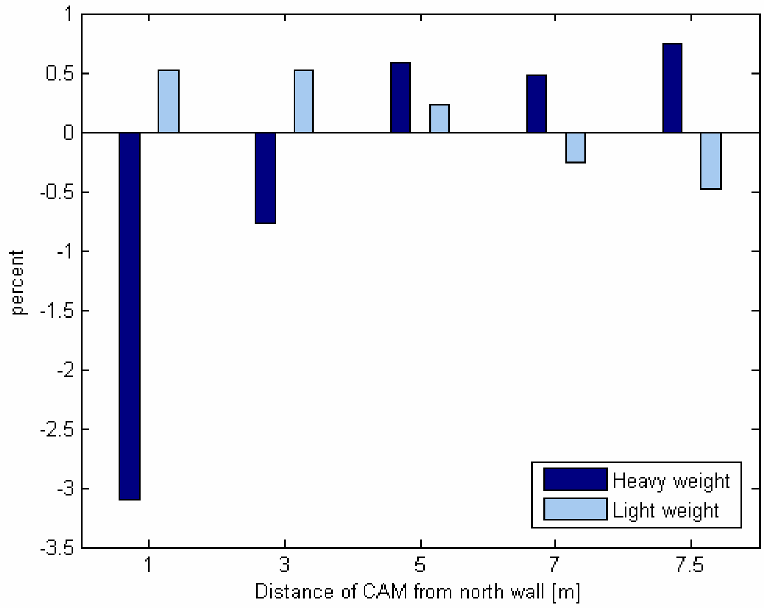


Figure 74. In-span effect of the CAM (compared with the empty room) for the rooms with heavy weight and light weight walls

Figure 74 shows that using the CAM in the heavy weight room affects the In-span effect almost opposite to the light weight room. In the empty room with heavy weight walls the temperature is between 20°C and 24°C in 20 % of the hours in whole year. It is 17 % in the room with light weight walls. In both kind of rooms when the CAM is far from the window (X_{CAM}=1 m & 3 m) the inside temperature increases. It causes increment of the In-span effect of the CAM in light weight construction but decrement in the heavy weight. In the heavy weight the number of instances with the temperature higher than 24°C increases. When the CAM is closer to the window, the room temperature decreases which decreases the In-span effect of the CAM in the light weight room and increases that in the heavy weight room.

The variations of the indoor temperature for the heavy weight construction room are shown in figure 75 for the cold week with and without CAM. Figure 76 shows the same data in the warm week. Heavy weight materials store lots of energy and adding a CAM to the system affects the indoor conditions somehow different comparing with the light weight room.

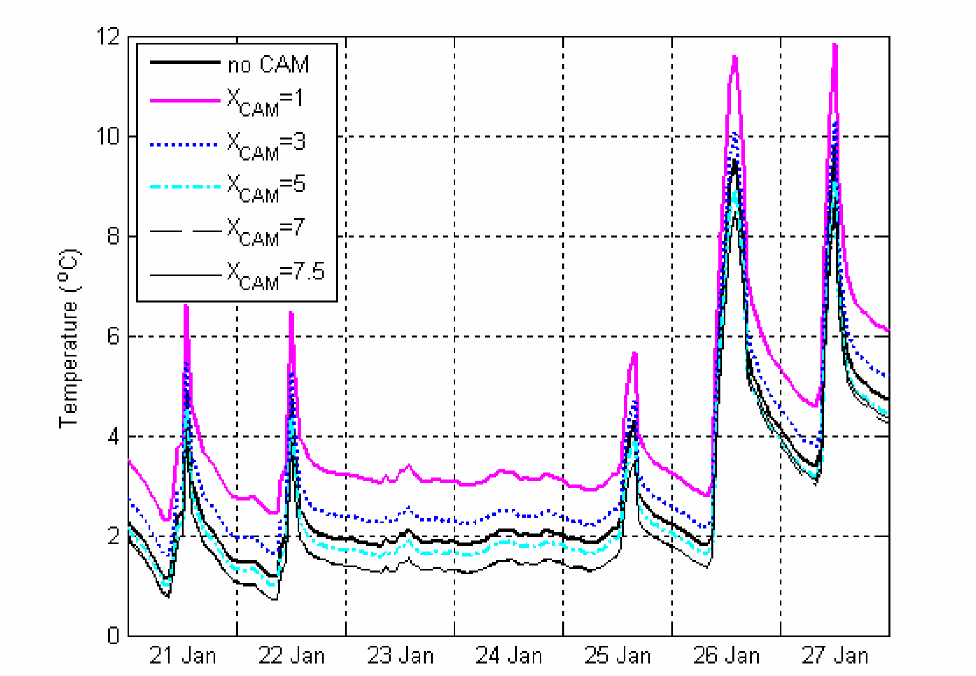


Figure 75. Variations of indoor temperature in the cold week

Comparing figures 75 and 76 with figures 14 and 15 shows another interesting difference between the CAM performance in two different kinds of constructions. In figures 14 and 15 the temperature profile of different locations of the CAM are very close to each other and in some instances, specially in the cold week, their difference is negligible. But it is not the same for the heavy weight room. The only exception is in figure 75, where temperature profile is almost the same for X_{CAM}=7 m and X_{CAM}=7.5 m. But for the other places of the CAM there is a clear difference between their temperature profiles. It could be explained in this way; the massive walls increase the effects of the CAM place in the room. Changing the CAM place causes changes in the view factors and solar fractions. It is followed by changes in radiative and convective heat transfer rates.

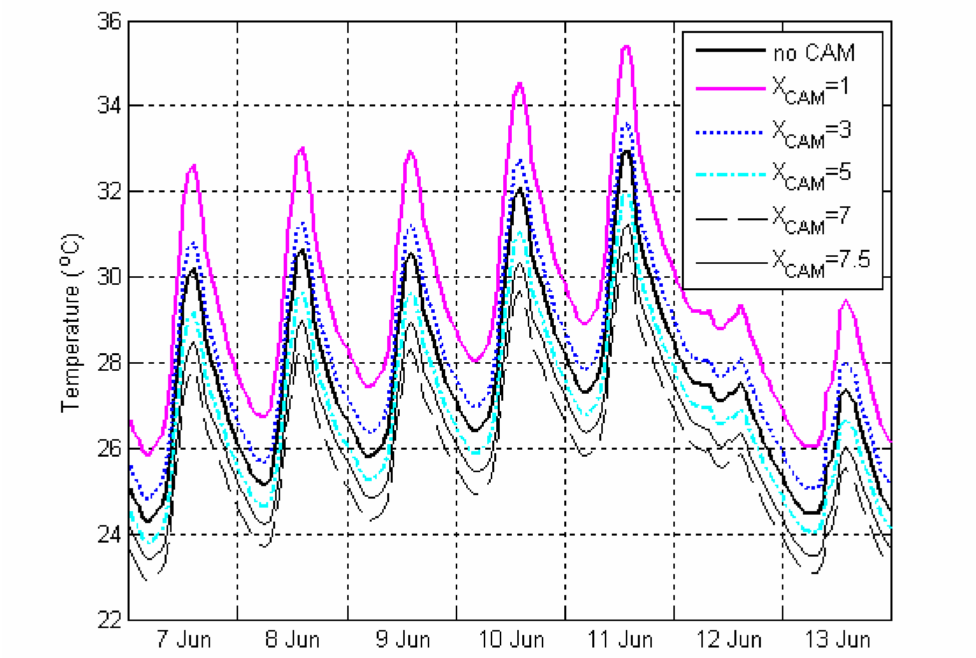


Figure 76. Variations of indoor temperature in the warm week

These changes in the room with the massive walls, which have the ability of saving lots of energy, effect the indoor temperature more than the light weight room.

Figures 77 and 78 show the temperature profile in the warm and cold day respectively.

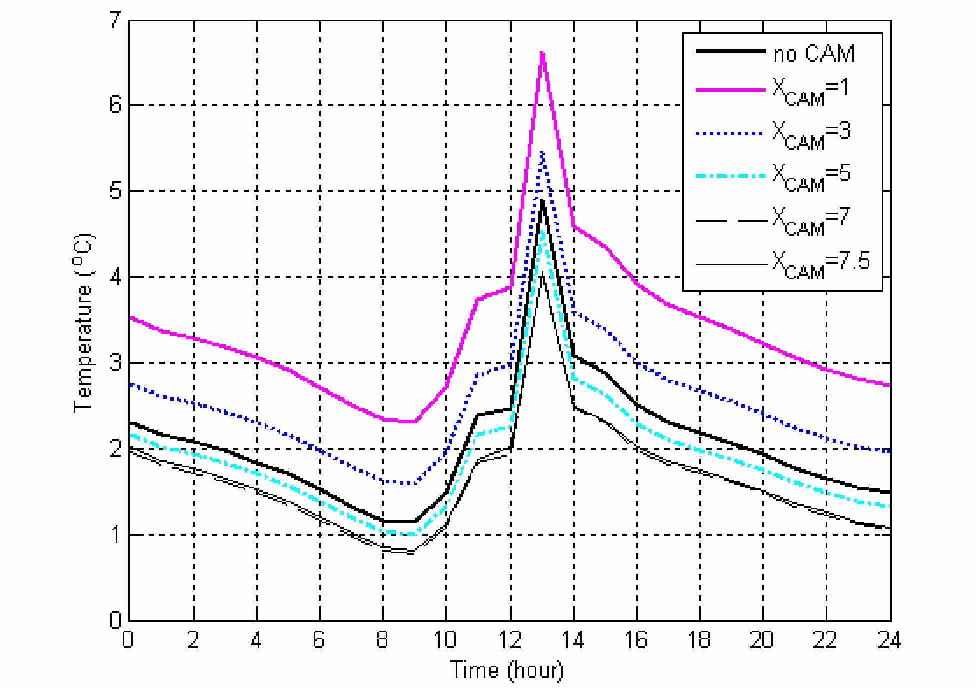


Figure 77. Variations of the indoor temperature on 21st January

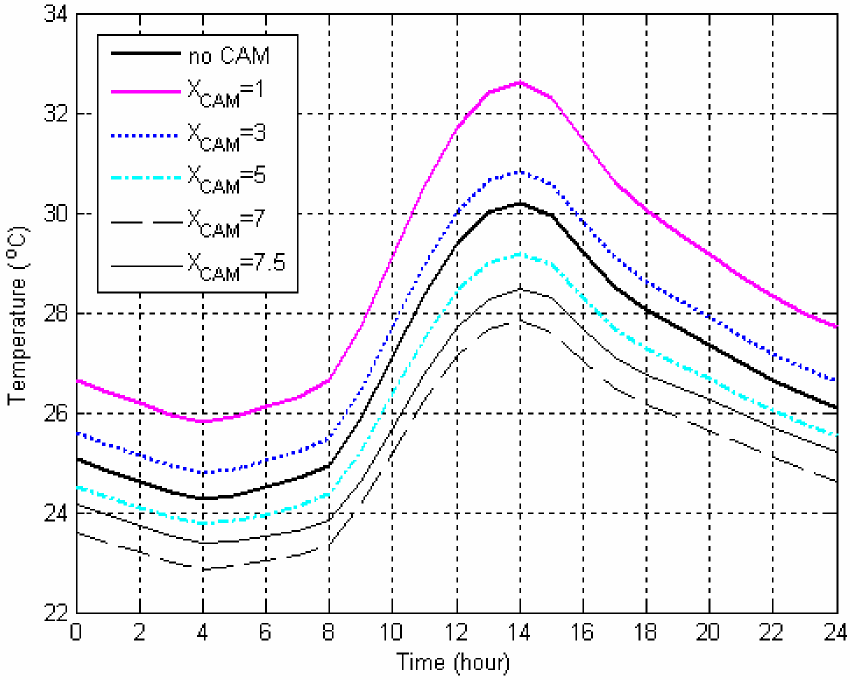


Figure 78. Variations of the indoor temperature on 7th June

5.6.2. Effects of CAM on cooling demand

<u>CAM properties:</u>

Height: 1 m Width: 2 m Thickness: 0.1 m Type: 1

Effects of the CAM on cooling demand of the heavy weight room is studied and compared with the light weight room. The integrated cooling demand of the empty room with both kinds of construction is shown in figure 79. The light weight room demands more energy for cooling. The heavy weight constructions save energy more than light weigh ones and stabilize the indoor climate more effectively. The high heat capacity of the constructions helps to save lots of solar energy per unit temperature increment comparing with the light weight rooms.

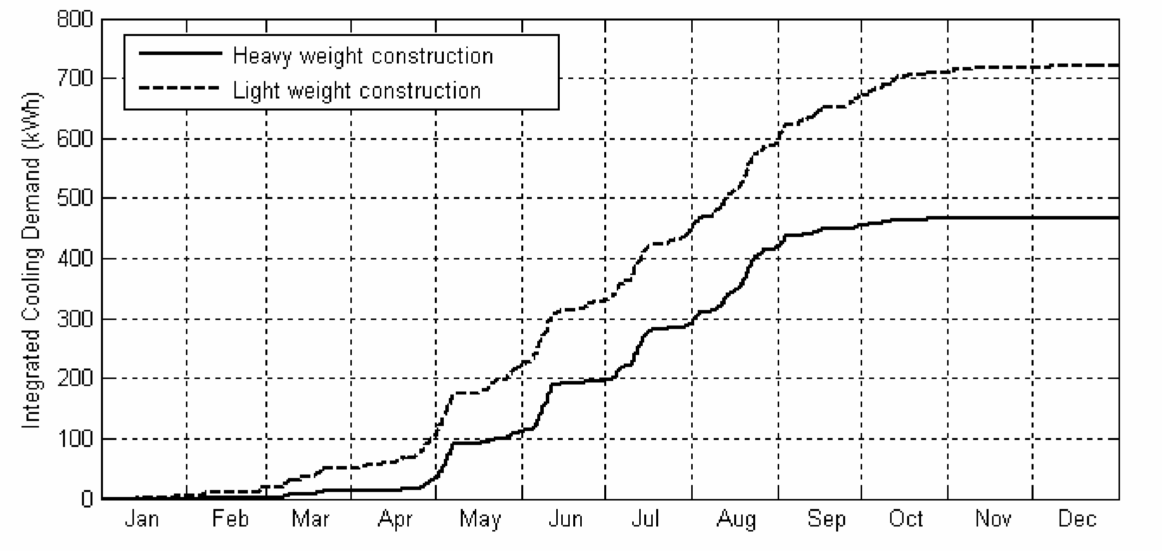


Figure 79. Integrated cooling demand in whole year for the empty room

Figure 80 compares cooling demand in the warm day. In warm days with high angle of incidence of the solar radiation, when a CAM is far from the window it does not receive solar radiation directly. It absorbs energy by receiving short wave and long wave radiations from other surfaces and also convectional heat transfer through air inside the room. Putting the CAM 1 m far from the north wall increases the cooling demand very much. Far from the window the absorbed energy of the CAM increases its temperature higher than the room temperature and the CAM works as a heat source. Far from the window, the CAM should have a large mass to decrease the cooling demand. In heavy weight rooms putting a CAM far from the window destabilizes the whole system. By placing the CAM closer to the window its shielding effects are used.

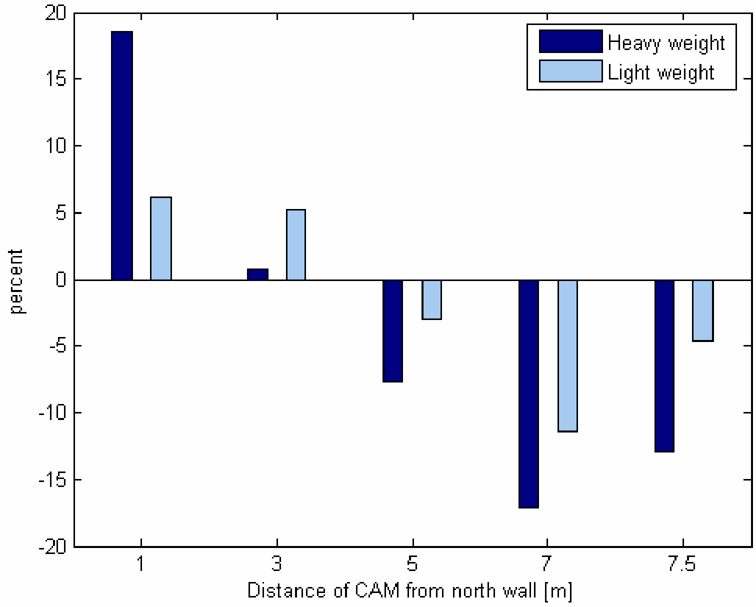


Figure 80. Cooling demand in the warm day (compared with the empty room) for the room with light and heavy weight walls.

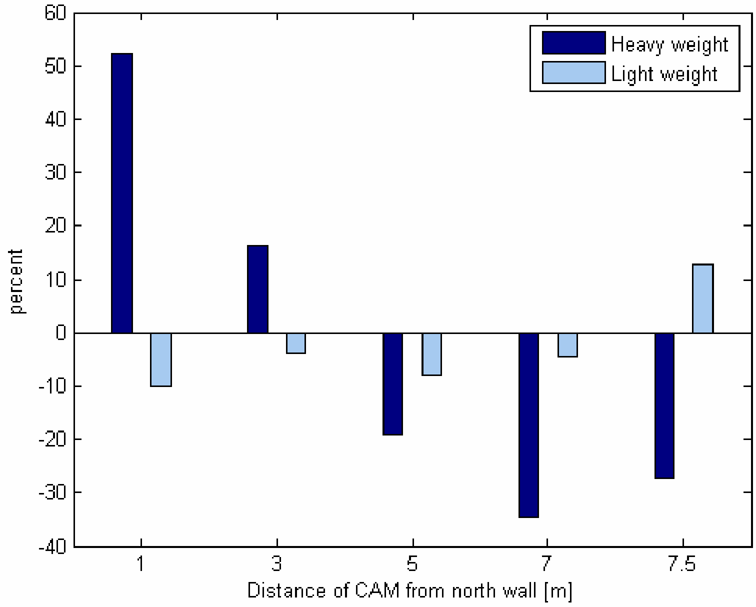


Figure 81. Cooling demand in whole year (compared with the empty room) for the room with light and heavy weight walls.

Figure 81 shows effects of the CAM on energy consumption for cooling the room in whole year. It is interesting to see that putting a CAM fixed 1 m from the north wall increases cooling demand to 1.5 times more than the empty room but putting it 1 m from the window decreases it to 30% less than the empty room.

5.6.3. Effects of CAM on heating demand

CAM properties:

Height: 1 m Width: 2 m Thickness: 0.1 m Type: 1

Effects of the CAM on heating demand of the heavy weight room is studied and compared with the light weight room. Figure 82 shows the integrated heating demand of the empty room with both kinds of construction. Heating demand of the light weight room is more than the heavy weight. The heavy weight constructions save more solar energy and also they release their inside energy later than light weight constructions. It is important to note that every surface of the room is in contact with the outside. It is possible for a heavy weight room in a building to use more energy for heating comparing with a light weight room in the same situation.

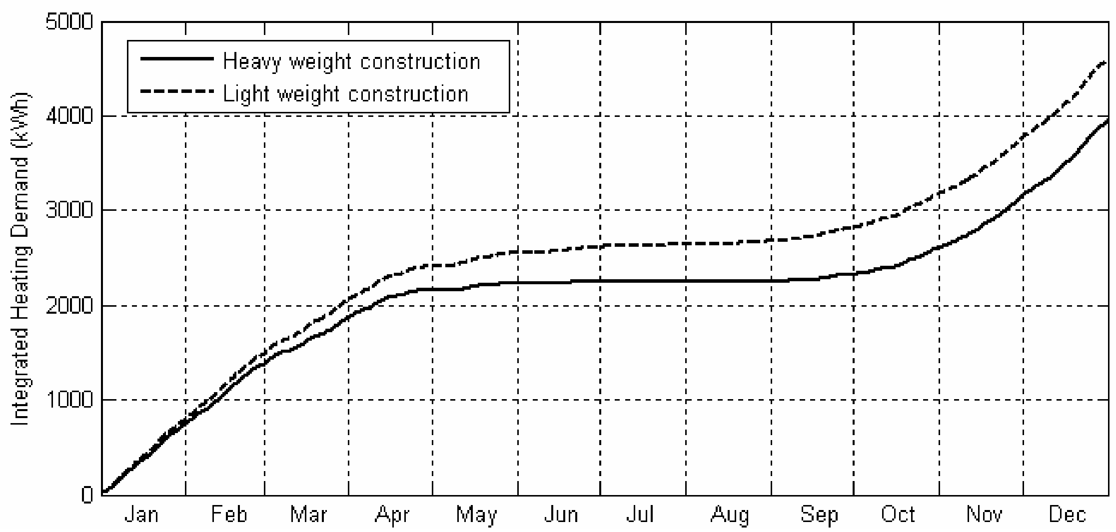


Figure 82. Integrated heating demand in whole year for the empty room

Figure 83 tells us in the heavy weight room the CAM works better when it is far from the window. There the CAM receives some solar radiations and also some radiations from other surfaces and stores energy. It works like an additive mass to the large mass amount of the room. But when it comes closer to the window its shielding effect causes less solar radiation hits the massive walls and the floor. The CAM itself does not save much energy comparing with the walls. Then less energy is saved in the room and heating demand increases comparing with the empty room and also comparing with the room made of light weight constructions. Also it receives some solar radiations and absorbs part of it and reflects the remaining part. When the CAM is far from the window it works like a mass which stores heat but when it comes close to window its shielding effects conquer its heat storage property and increases heating demand of the room.

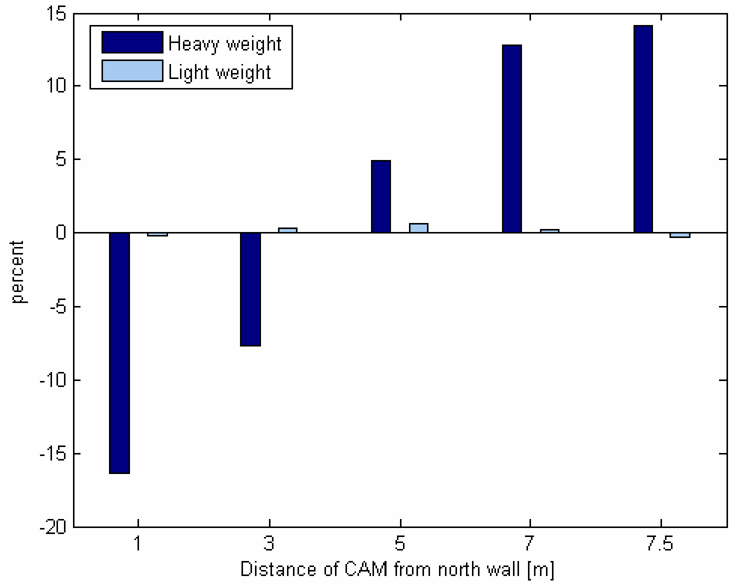


Figure 83. Heating demand in the cold day (compared with the empty room) for the room with light and heavy weight walls.

Figure 84 shows these effects of CAM on heating demand of the room in whole year.

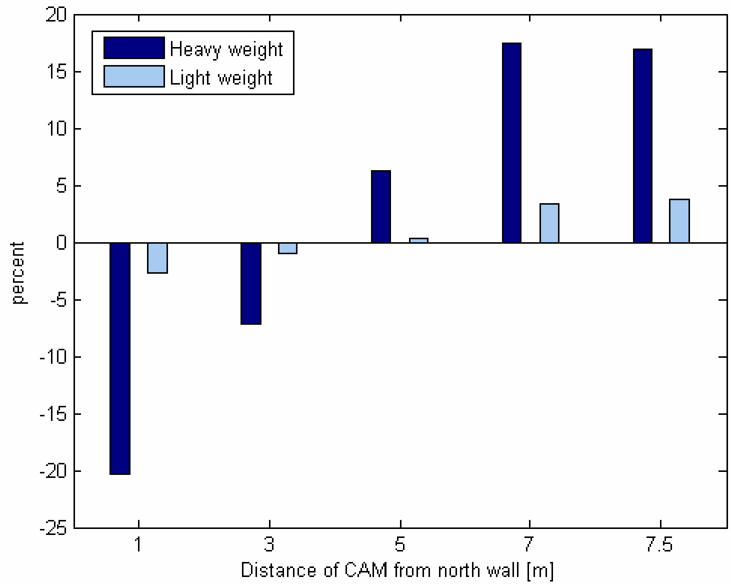


Figure 84. Heating demand in whole year (compared with the empty room) for the room with light and heavy weight walls.

5.6.4. Effects of CAM on energy consumption

CAM properties:

Height: 1 m   Width: 2 m   Thickness: 0.1 m   Type: 1

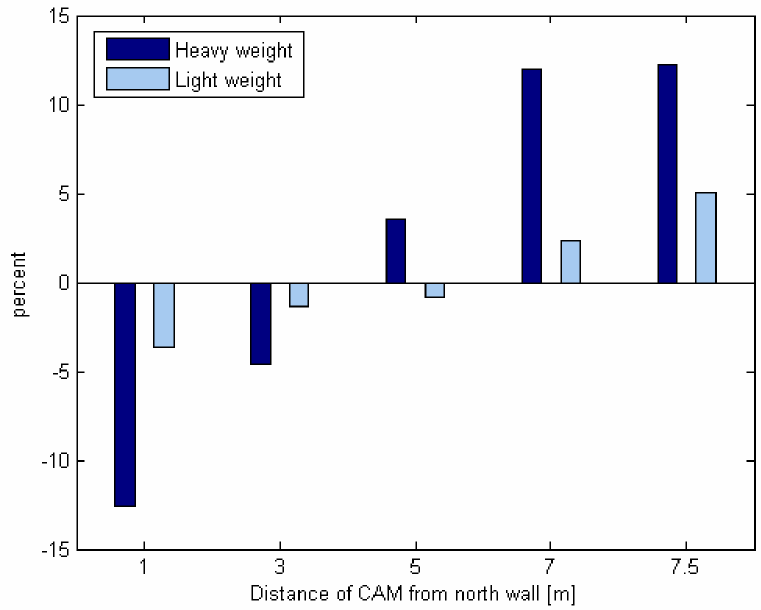


Figure 85. Energy demand in whole year (compared with the empty room) for the room with light and heavy weight walls.

5.7. Refilling the CAM

<u>CAM properties:</u>

Height: 2 m   Width: 2 m   Thickness: 0.1 m   Type: 1

In the present work the CAM is filled with water. In the previous results the initial temperature of the water was 20°C which is equal to the initial temperature of the room air and all of the constructions. It is possible to refill the CAM with fresh water. In this section effects of refilling the CAM with fresh water is studied. Here the light weight room has been simulated when there is some additional mass in the room, like furniture. In the simulation mass is added as an additional volumetric heat capacity with the amount of 4×10^5 J/K to the both zones. So this amount is 8×10^5 J/K for the whole room.

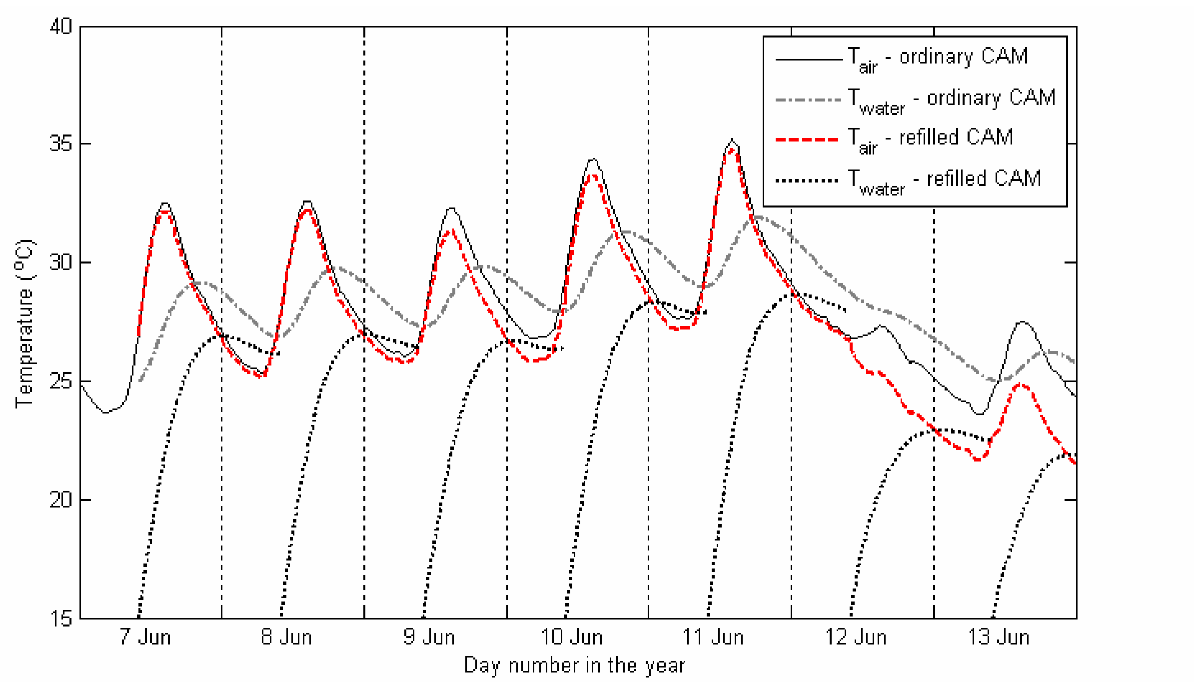


Figure 86. Variations of the indoor temperature in the warm week

The model has been studied in the warm week. The CAM has been refilled at 10:00 am of each morning with 15°C water. The temperature variations and energy consumption of the room has been studied and compared for different situations of the CAM for both of the refilled and ordinary (non-refilled) CAM.

Temperature profile of the room and the inside water of the CAM are plotted in figure 86. Figure 87 shows that the In-span effect of the CAM increases much when it is refilled.

Again note that no heating or cooling system works when the In-span effect of the CAM is considered. It seems useful to refill the CAM in warm days when no cooling system works. Looking more carefully at figure 86 we find that refilling the CAM start its effective performance from 12th June. In the previous days the refilled CAM does not decreases the indoor temperature considerably. But in the last two days of the week it works very effectively. These two days are themselves colder than previous days. It means that refilling a CAM in a room works well when the temperature is lower than a certain temperature. This temperature depends on the size and properties of the CAM and room. When the indoor temperature is high and the CAM is small comparing with the room volume, the fresh water inside the CAM absorbs heat and its temperature increases to the room temperature very soon. So before deciding about refilling the CAM it is important to care about the size and temperature proportions.

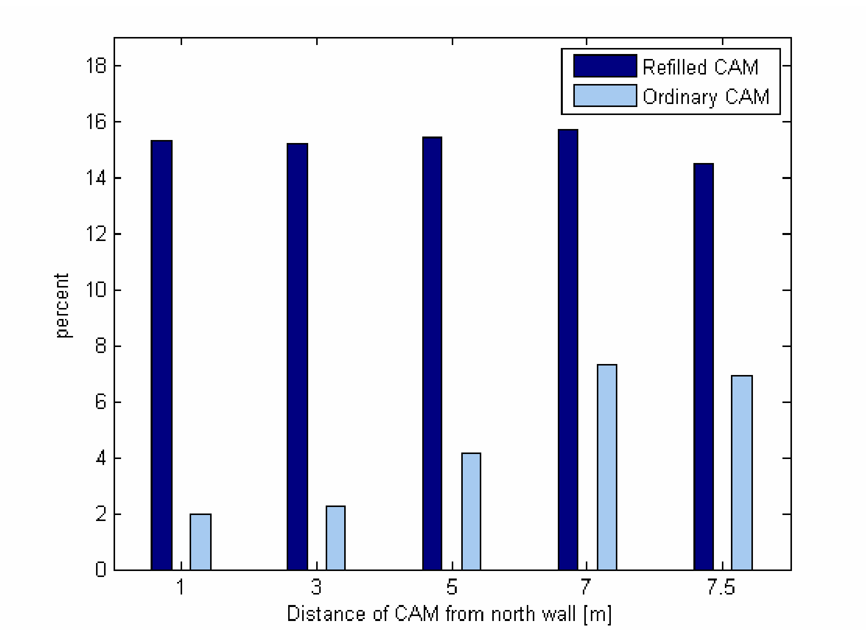


Figure 87. In-span effect of the refilled and ordinary CAM

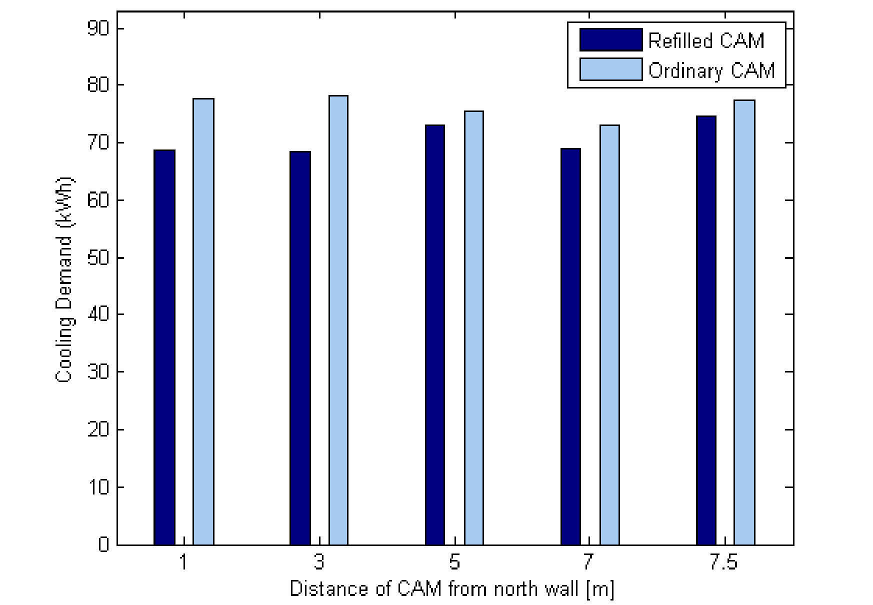


Figure 88. Cooling demand in the warm week for the room with the refilled or ordinary CAM

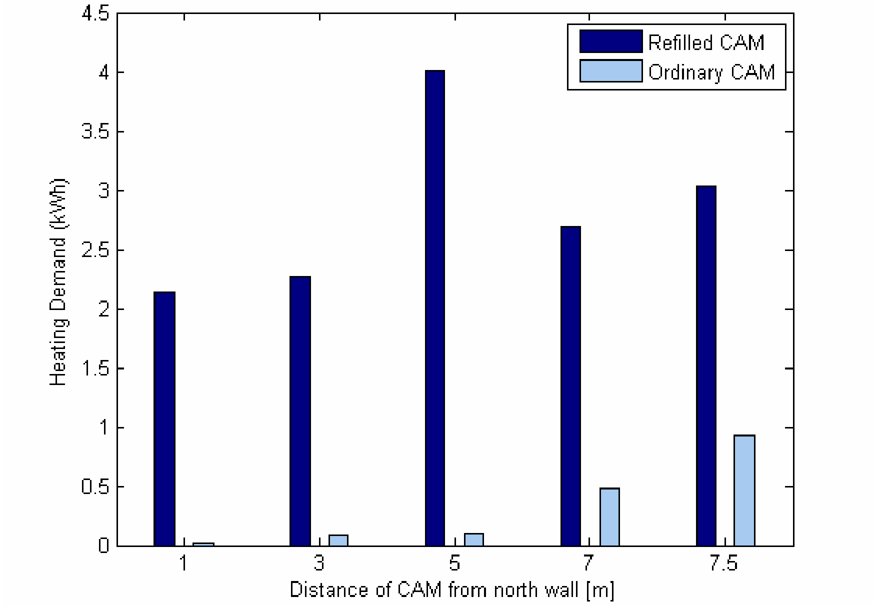


Figure 89. Heating demand in the warm week for the room with the refilled or ordinary CAM

Effects of refilling the CAM with fresh water when cooling and heating systems work in the room has been considered. Refilling the CAM with fresh water decreases the cooling demand of the room in all of the cases. But it increases the heating demand comparing with the ordinary CAM. Figure 90 shows the energy demand. At X=3 m energy demand decreases about 10% when the CAM is refilled. At X=5 m refilling of the CAM increases energy demand to an amount more than the ordinary CAM. It is necessary to note that these results are only for one warm week.

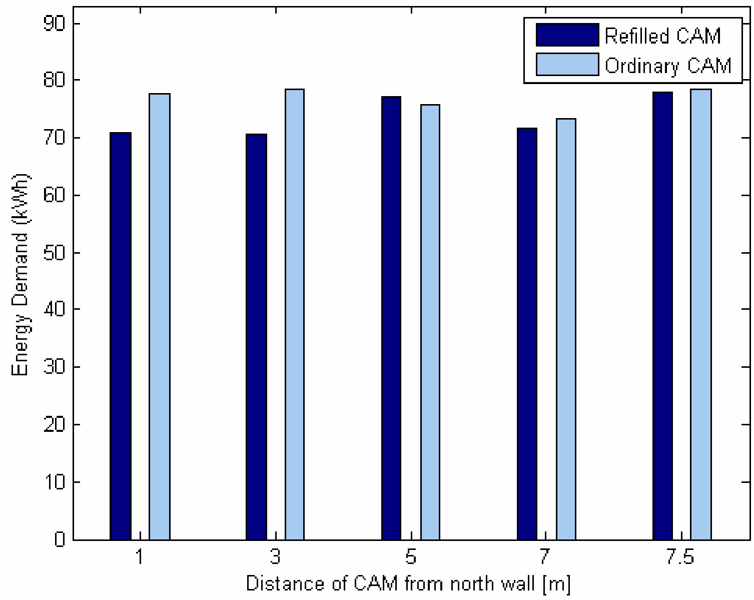


Figure 90. Energy demand in the warm week for the room with the refilled or ordinary CAM

The results of the refilled CAM simulation are presented in the section 5 of appendix C.

Conclusion

General

- Using or not using the proper solar fractions and its effect on the results depends on the case of study.
- It is important to do not mix up the performance of a CAM when there is cooling or heating system in the room and when there is not.
- For decreasing the heating demand these two should be minimized; loosing energy through convective heat transfer between the CAM and window and also undesired shielding effect of the CAM.
- Generally the place, material and size of a CAM should be chosen based on its desired performance in each specific time span.

Time

- In using a CAM it is important to take care about the time period in a year and sunny hours of a day. Also presence or absence of the cooling or heating systems should be considered.
- In the cold periods when no solar radiation hits the window, it is better to place the CAM far from the window to save more energy. In sunny hours it is better to put the CAM very far from or very close to the window corresponding to the angle of the incoming solar radiation.
- In cold days a CAM with higher solar absorption works better near the window.
- In warm days there is a region near the window for decreasing the energy consumption optimally.

The CAM shape

- Finding optimum formats for the shape, size, material and location of the CAM is the key for optimum energy saving.
- When the mass amount of the shell is not much and also when there is no cooling or heating system in the room, changing the shell material of the CAM does not affect its In-span effect much.

- There is not much benefit in just increasing the mass amount of the CAM by increasing its surface area or its thickness. Increasing the mass amount of the CAM does not always improves energy saving.
- Increasing mass amount of the CAM prevents its temperature increment to high values. When the CAM is far from the window, it should have a large mass with high heat capacity to decrease the cooling demand.
- In selecting shape, size and material of a CAM their effects on heat transfer should be considered. Biot number and thermal diffusivity are suitable criterions in this field.
- The shielding effect of a CAM is used by placing it closer to the window. It is possible to reach a good performance of a CAM without increasing its mass or area by finding the optimum location of the CAM. Suitable location of a CAM, which is also dependent on its size, is very important in using the shielding effects of it.
- When a cooling or heating system works in the room, the time response of the CAM to the temperature variations becomes more important and the shell material plays an important role.

Room construction

- In both kind of rooms when the CAM is far from the window the inside temperature increases. It causes increment of the In-span effect of the CAM in the light weight construction but decrement in the heavy weight.
- Massive walls of the heavy weight room increase the effect of the CAM location in the room.
- In light weight rooms when there are some additional heat loads in the room (internal gains), using a CAM saves energy more effectively. In this case it is important to find a practical optimum place for the CAM.
- Refilling a CAM in a light weight room works well when the temperature is lower than a certain temperature. This temperature depends on the size and properties of the CAM and room. Before deciding about refilling a CAM it is better to take care about the size and temperature proportions.

- In heavy weight rooms putting a CAM far from the window destabilizes the whole system.

Recommendations

- In finding solar fraction the computer was encountering with the lack of memory. It is better to use finer meshes, especially in the room length direction, for calculating the view factors and solar fractions.
- Adding the azimuth angle of the sun for finding the incidence angle and solar fractions inside the room.
- The convectional heat transfer inside the CAM has not been modeled in this work. Only the conductional heat transfer between the water inside the CAM and the CAM shell has been considered. It means that inaccuracy of the simulation grows by thickness increment of the CAM. It is possible to add a model for convective heat transfer inside the CAM.
- It is possible to write a program using optimization algorithms to find the suitable shape, size, material and location of the CAM in each time period for a room.

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Appendix A (Appendix E of [1])

Window Transmittance Equations

Snell's law, Fresnel equations and Bouger's law for transmittance of glass in air.

AOI Angle on incidence

AOR Angle of refraction

INDRA Index of refraction for ai1=1.0

INDRG Index of refraction for glass=1.526 (in our case)

RPERP Perpendicular reflectance (component of polarization)

RPAR Parallel reflectance (component of polarization)

R Reflectance – (RPERP + RPAR)/2

n Number of panes of glass (n=2 in our case)

τ_r Transmittance due to reflectance losses (transmittance if there were just reflectance losses and no absorptance losses)

τ_{abs} Transmittance due to absoptance losses (transmittance if there were just absorptance losses and no reflectance losses)

τ Total transmittance $\tau = \tau_r \times \tau_{abs}$

K Extinction coefficient = 0.0196/mm (in our case)

TH Thickness of glass = 3.175 mm (in our case)

L Path length = TH/(cos AOR)

Snell's law

INDRA / INDRG = sin AOR / sin AOI

AOR = arcsin[(sin AOI) / INDRG]

Fresnel equations (reflectance at 1 air to glass interface)

RPERP = $[\sin(AOR-AOI)]^2 / [\sin(AOR+AOI)]^2$

RPAR = $[\tan(AOR-AOI)]^2 / [\tan(AOR+AOI)]^2$

R = (RPERP + RPAR) / 2

Fresnel equations (transmittance due to reflectance with several panes)

$\tau_{r,n} = 0.5 \{[(1\text{-RPERP}) / (1 + (2n\text{-}1)\ \text{RPERP})] + [(1\text{-RPAR}) / (1 + (2n\text{-}1)\ \text{RPAR})]\}$

Bouger's law (transmittance due to absorptance)

$\tau_{abs} = e^{n(-KL)}$

$\tau = \tau_r \times \tau_{abs}$

Appendix B (Based on Appendix F of [1])

$$SF_n = B1_n + B2_n + B3_n + BR_n$$

n: particle surface

SF: total solar fraction

$B1$ describes the first bounce of incidence shortwave radiation assuming all of it initially hits the floor and CAM. Different portions of solar radiation hits the floor and CAM at each hour of a year so for each hour there is a $B1$ value for floor and CAM:

$$B1_{floor} = \alpha_{floor} \cdot floor\ portion$$

$$B1_{CAM} = \alpha_{CAM} \cdot CAM\ portion$$

$$B1_{other\,surfaces} = 0$$

α_{floor} and α_{CAM} are the absorptivity of floor and CAM surfaces. The absorptivity of the floor and other surfaces in the room (except CAM) is assumed to be equal to 0.6. CAM absorptance has two values, 0.6 and 0.8.

$B2$ describes the second bounce such that the shortwave radiation diffusively reflected by the floor and CAM is distributed over other surfaces in portions which depend on view factor and absorptance of the surfaces.

$$B2_{floor-floor} = 0$$

$$B2_{CAM-CAM} = 0$$

$$B2_{floor(CAM)-other\,opaque\ surfaces} = (1-\alpha)\alpha \cdot VF_i$$

$$B2_{floor(CAM)-window\ lost} = (1-\alpha)VF_i\left[1-\left(\rho_w + \alpha_w/2\right)\right]$$

$$B2_{floor(CAM)-window\ absorbed} = (1-\alpha)VF_i\left(\alpha_w/2\right)$$

VF is the view factor of the corresponding surfaces.

i: particular surface which the floor sees

α is the absorptivity of the surface we are interested to find its $B2$ value (floor or CAM).

$\rho_w = 1 - \tau_r$

$\alpha_w = 1 - \tau_{abs}$

Use of $(\alpha_w / 2)$ assumes half of the interior reflected radiation absorbed by the double-pane window is conducted back out to ambient; the other half remains as heat in the zone.

*B*3 describes the third bounce such that the remaining non-absorbed shortwave radiation is distributed over each surface in proportion to its area-absorptance product.

$$B3_{opaque-opaque} = \alpha\left[1 - \alpha - \sum(B2_n)\right](A_n / A_{total})$$

$$B3_{opaque-window\ lost} = \left[1 - \alpha - \sum(B2_n)\right](A_n / A_{total})\left[1 - (\rho_w + \alpha_w / 2)\right]$$

$$B3_{opaque-window\ absorbed} = \left[1 - \alpha - \sum(B2_n)\right](A_n / A_{total})(\alpha_w / 2)$$

BR describes the distribution of all remaining bounces based on distribution fractions from calculations for $B3_n$ above.

$$BR_n = \left[1 - \alpha - \sum(B2_n) - \sum(B3_n)\right]\left(B3_n / \sum(B3_n)\right)$$

Appendix C

The results of simulations are presented in the following tables.

C.1. Light weight wall construction – CAM with 0.1 m thickness

C.1.1. Empty room

Instances with the temperature lower than 20°C (%)	69.5
Instances with the temperature between 20°C and 24°C (%)	17.2
Instances with the temperature higher than 24°C (%)	13.3

Cooling demand in the warm day [kWh]	11.8
Heating demand in the cold day [kWh]	33.6
Cooling demand in whole year [kWh]	720
Heating demand in whole year [kWh]	4591

C.1.2

<u>CAM properties:</u>

Height: 2 m Width: 2 m Thickness: 0.1 m Type: 1

X_{CAM} [m]	1	3	5	7	7.5
Instances with the temperature lower than 20°C (%)	68.3	68.9	70	71.8	70.8
Instances with the temperature between 20°C and 24°C (%)	18	17.9	17.6	17.5	17.2
Instances with the temperature higher than 24°C (%)	13.7	13.2	12.4	10.7	12

X_{CAM} [m]	1	3	5	7	7.5
Cooling demand in the warm day [kWh]	12.5	11.6	11.2	10.6	11.1
Heating demand in the cold day [kWh]	33.5	33.7	33.8	33.6	33.3
Cooling demand in whole year [kWh]	622	608	592	615	720
Heating demand in whole year [kWh]	4454	4475	4545	4655	4635

C.1.3

CAM properties:

Height: 1 m Width: 2 m Thickness: 0.1 m Type: 2

X_{CAM} [m]	1	3	5	7	7.5
Instances with the temperature lower than 20°C (%)	68.4	68.9	70	71.5	70
Instances with the temperature between 20°C and 24°C (%)	17.7	17.7	17.4	17.1	17
Instances with the temperature higher than 24°C (%)	13.9	13.4	12.6	11.4	13

X_{CAM} [m]	1	3	5	7	7.5
Cooling demand in the warm day [kWh]	12.4	11.6	11.5	10.4	11.8
Heating demand in the cold day [kWh]	33.5	33.6	33.7	33.4	33
Cooling demand in whole year [kWh]	660	695	663	722	905
Heating demand in whole year [kWh]	4478	4549	4604	4708	4700

C.1.4

CAM properties:

Height: 1 m Width: 2 m Thickness: 0.1 m Type: 1

X_{CAM} [m]	1	3	5	7	7.5
Instances with the temperature lower than 20°C (%)	68.4	68.9	70	72.2	71.4
Instances with the temperature between 20°C and 24°C (%)	17.7	17.7	17.4	16.9	16.7
Instances with the temperature higher than 24°C (%)	13.9	13.4	12.6	10.9	11.9

X_{CAM} [m]	1	3	5	7	7.5
Cooling demand in the warm day [kWh]	12.5	12.4	11.4	10.4	11.2
Heating demand in the cold day [kWh]	33.5	33.6	33.8	33.6	33.4
Cooling demand in whole year [kWh]	649	693	662	689	813
Heating demand in whole year [kWh]	4469	4545	4604	4745	4766

C.1.5

CAM properties:

Height: 2 m Width: 2 m Thickness: 0.1 m Type: 3

X_{CAM} [m]	1	3	5	7	7.5
Instances with the temperature lower than 20°C (%)	68.4	68.9	70	71.5	70
Instances with the temperature between 20°C and 24°C (%)	17.7	17.7	17.4	17.1	17
Instances with the temperature higher than 24°C (%)	13.9	13.4	12.6	11.4	13

X_{CAM} [m]	1	3	5	7	7.5
Cooling demand in the warm day [kWh]	11.3	12.1	11.6	10.7	11.8
Heating demand in the cold day [kWh]	33.5	33.6	33.7	33.4	32.9
Cooling demand in whole year [kWh]	662	698	666	725	904
Heating demand in whole year [kWh]	4477	4550	4607	4714	4699

C.2. Light weight wall construction – CAM with different thicknesses

C.2.1. X_{CAM} = 5 m

CAM properties:

Height: 1 m Width: 2 m Thickness: 0.1-0.4 m Type: 1

CAM thickness [cm]	10	20	30	40
Instances with the temperature lower than 20°C (%)	70	69.9	70	71.5
Instances with the temperature between 20°C and 24°C (%)	17.4	17.6	17.6	17.4
Instances with the temperature higher than 24°C (%)	12.6	12.5	12.4	11.1

CAM thickness [cm]	10	20	30	40
Cooling demand in the warm day [kWh]	11.4	11.5	11.8	11.8
Heating demand in the cold day [kWh]	33.8	33.7	33.8	33.7
Cooling demand in whole year [kWh]	662	664	661	667
Heating demand in the whole year [kWh]	4605	4599	4604	4603

CAM properties:

Height: 1 m Width: 2 m Thickness: 0.1-0.4 m Type: 2

CAM thickness [cm]	10	20	30	40
Instances with the temperature lower than 20°C (%)	70	70	70.1	70.8
Instances with the temperature between 20°C and 24°C (%)	17.4	17.6	17.6	17.3
Instances with the temperature higher than 24°C (%)	12.6	12.4	12.3	11.9

CAM thickness [cm]	10	20	30	40
Cooling demand in the warm day [kWh]	11.5	11.3	11.6	11.5
Heating demand in the cold day [kWh]	33.7	33.8	33.7	33.7
Cooling demand in whole year [kWh]	663	663	660	663
Heating demand in the whole year [kWh]	4604	4605	4610	4608

C.2.2. X_{CAM} = 7 m

CAM properties:

Height: 1 m Width: 2 m Thickness: 0.1-0.4 m Type: 1

CAM thickness [cm]	10	20	30	40
Instances with the temperature lower than 20°C (%)	72.2	71.8	71.8	71.5
Instances with the temperature between 20°C and 24°C (%)	16.9	17.3	17.4	17.4
Instances with the temperature higher than 24°C (%)	10.9	10.9	10.8	11.1

CAM thickness [cm]	10	20	30	40
Cooling demand in the warm day [kWh]	10.4	10.5	10.6	10.5
Heating demand in the cold day [kWh]	33.6	33.6	33.7	33.6
Cooling demand in whole year [kWh]	689	705	712	733
Heating demand in the whole year [kWh]	4745	4742	4756	4751

CAM properties:

Height: 1 m Width: 2 m Thickness: 0.1-0.4 m Type: 2

CAM thickness [cm]	10	20	30	40
Instances with the temperature lower than 20°C (%)	71.5	71.3	71.2	70.8
Instances with the temperature between 20°C and 24°C (%)	17.1	17.2	17.2	17.3
Instances with the temperature higher than 24°C (%)	11.4	11.5	11.6	11.9

CAM thickness [cm]	10	20	30	40
Cooling demand in the warm day [kWh]	10.4	10.6	10.6	11
Heating demand in the cold day [kWh]	33.3	33.3	33.4	33.3
Cooling demand in whole year [kWh]	722	745	761	779
Heating demand in the whole year [kWh]	4708	4705	4712	4704

C.3. Light weight wall construction - Internal gains

C.3.1. Empty room

Cooling demand in the warm day [kWh]	11.5
Heating demand in the cold day [kWh]	33.6
Cooling demand in whole year [kWh]	685
Heating demand in whole year [kWh]	4565

C.3.2. Internal gains in the south zone

CAM properties:

Height: 1 m Width: 2 m Thickness: 0.1 m Type: 1

X_{CAM} [m]	1	3	5	7	7.5
Cooling demand in the warm day [kWh]	13.5	13.8	12.3	11.9	13.4
Heating demand in the cold day [kWh]	38.5	38	38.5	38.7	38.5
Cooling demand in whole year [kWh]	705	708	690	732	839
Heating demand in whole year [kWh]	5081	5130	5198	5350	5363

CAM properties:

Height: 2 m Width: 2 m Thickness: 0.1 m Type: 1

X_{CAM} [m]	1	3	5	7	7.5
Cooling demand in the warm day [kWh]	14	12.7	12.4	11.7	12.6
Heating demand in the cold day [kWh]	38.7	38.7	38.9	38.5	38
Cooling demand in whole year [kWh]	676	663	647	675	770
Heating demand in whole year [kWh]	5058	5100	5168	5284	5253

C.3.3. Internal gains inside the north zone

CAM properties:

Height: 1 m Width: 2 m Thickness: 0.1 m Type: 1

X_{CAM} [m]	1	3	5	7	7.5
Cooling demand in the warm day [kWh]	13	13.6	12	11.9	12.4
Heating demand in the cold day [kWh]	38.6	38.7	38.5	38.6	38.5
Cooling demand in whole year [kWh]	719	700	683	721	839
Heating demand in whole year [kWh]	5093	5126	5194	5345	5367

CAM properties:

Height: 1 m Width: 2 m Thickness: 0.1 m Type: 1

X_{CAM} [m]	1	3	5	7	7.5
Cooling demand in the warm day [kWh]	12.9	13.4	12.3	11.6	12.3
Heating demand in the cold day [kWh]	38.8	38.8	38.8	38.6	38.2
Cooling demand in whole year [kWh]	683	673	649	661	768
Heating demand in whole year [kWh]	5065	5107	5172	5270	5257

C.4. Heavy weight wall construction

C.4.1. Empty room

Instances with the temperature lower than 20°C (%)	63.676
Instances with the temperature between 20°C and 24°C (%)	20.103
Instances with the temperature higher than 24°C (%)	16.221

Cooling demand in the warm day [kWh]	11.7
Heating demand in the cold day [kWh]	31.4
Cooling demand in whole year [kWh]	466
Heating demand in whole year [kWh]	3937

C.4.2

CAM properties:

Height: 1 m Width: 2 m Thickness: 0.1 m Type: 1

X_{CAM} [m]	1	3	5	7	7.5
Instances with the temperature lower than 20°C (%)	58.1	61.7	66	70	67.7
Instances with the temperature between 20°C and 24°C (%)	17	19.3	20.7	20.6	20.8
Instances with the temperature higher than 24°C (%)	24.9	19	13.3	9.4	11.4

X_{CAM} [m]	1	3	5	7	7.5
Cooling demand in the warm day [kWh]	13.9	11.8	10.8	9.7	10.2
Heating demand in the cold day [kWh]	26.2	29	32.9	35.4	35.8
Cooling demand in whole year [kWh]	710	543	377	305	340
Heating demand in whole year [kWh]	3137	3656	4183	4623	4601

C.5. Light weight wall construction – Ordinary and Refilled CAM

C.5.1. Ordinary CAM

X_{CAM} [m]	1	3	5	7	7.5
In-span effect [%]	2	2.3	4.1	7.3	6.9
Cooling demand in the warm week [kWh]	77.5	78.2	75.6	72.9	77.5
Heating demand in the warm week [kWh]	0	0.1	0.1	0.5	0.9
Energy demand in the warm week [kWh]	77.6	78.3	75.7	73.4	78.4

C.5.2. Refilled CAM

X_{CAM} [m]	1	3	5	7	7.5
In-span effect [%]	15.3	15.2	15.4	15.7	14.4
Cooling demand in the warm week [kWh]	68.6	68.4	73	69	74.8
Heating demand in the warm week [kWh]	2.1	2.3	4	2.7	3
Energy demand in the warm week [kWh]	70.7	70.7	77.1	71.7	77.8