OPTIMIZATION OF HEAT SAVING IN BUILDINGS USING UNSTEADY HEAT TRANSFER MODEL

by

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Reducing the energy consumption growth rate is increasingly becoming one of the main challenges for ensuring sustainable development, particularly in the buildings as the largest end-use sector in many countries. Along this line, the aim of this paper is to analyse the possibilities for energy savings in the construction of new buildings and reconstruction of the existing ones developing a tool that, in terms of the available heating technologies and insulation, provides answer to the problem of optimal cost effective energy consumption. The tool is composed of an unsteady heat transfer model which is incorporated into a cost-effective energy saving optimization. The unsteady heat transfer model uses annual hourly meteorological data, chosen as typical for the last ten-year period, as well as thermo-physical features of the layers of the building walls. The model is tested for the typical conditions in the city of Skopje, Macedonia. The results show that the most cost effective heating technology for the given conditions is the wood fired stove, followed by the inverter air-conditioner. The centralized district heating and the pellet fired stoves are the next options. The least cost effective option is the panel that uses electricity. In this paper, the optimal insulation thickness is presented for each type of heating technology.

Key words: *optimal insulation thickness, unsteady heat transfer model, cost effective energy consumption, heating technologies, energy savings*

Introduction

Energy consumption growth has led to higher waste of resources and higher greenhouse emissions. Reducing the energy consumption growth rate is increasingly becoming one of the main challenges for ensuring sustainable development.

Buildings consume 41% of total final energy consumption in Europe in 2010, and it is the largest end-use sector [1]. Residential buildings represent around 76% of the total building floor area. Also, energy consumption in households in Macedonia is quite high when expressed per unit of GDP, and in 2009, this number is four times higher than the average in developed European countries and two times higher than in non-OECD Europe [2]. This suggests that despite relatively low *per capita* consumption, greater attention should be paid to energy efficiency

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measures in households or to reduce energy consumption in households relative to the economic power.

Therefore, one of the biggest opportunities for energy savings is in public and private buildings. In Macedonia special attention should be paid to the public buildings which are large consumers of energy, and they should be an example for energy saving that will be followed by others.

The problem of energy saving by providing optimum insulation thickness on buildings has devoted much attention in the literature. For example, in [3] calculations of optimum insulation thickness are carried out on a prototype building in Bursa in Turkey. The optimum insulation thickness, energy saving and payback period are calculated for a typical wall structure based on both cooling and heating loads for a Tunisian buildings in [4]. In [5] the optimum thickness of thermal insulation is investigated for different insulation materials for the city of Elazig, Turkey, using transient model. The author has also used this model in [6] for finding the optimum insulation thickness including the analyses of the effect of wall orientation. The authors in [7] present a study on the effects of external wall insulation thickness on annual cooling and heating energy uses under different Chinese climates. Investigation on the impact of the thermal wall insulation for residential villas in Dubai is made in [8]. In [9] the optimal location, number (one, two, or three layers) and thickness of the insulation layers is analyzed in order to improve the thermal performance of a building. The aim of [10] is to improve the insulation performance by configuring wall layers with fixed volumes of insulation and thermal mass, varying the layer distribution. The aim of [11] is to stipulate the internal temperatures of the building located in Ghardaia region, Algeria, in case with and without insulation and at the same time the authors investigate the influence of the buildings orientation on the internal temperature. In [12] it is examined whether the heavy mass materials used in building structures can reduce the heating and cooling energy requirements in the region of Belgrade, Serbia. How energy efficiency of industrially made buildings in Novi Sad, Serbia, is influenced by the thermal properties of façades is analyzed in [13].

The aim of this paper is to analyze the possibilities for energy savings in the construction of new buildings and reconstruction of existing ones. A model that provides answer to the problem of optimal cost effective energy consumption in terms of available heating technologies and insulation is developed in this paper. This goal is achieved by developing unsteady heat transfer model incorporated into cost-effective energy saving optimization. The unsteady heat transfer model includes 4,392 hourly meteorological data (the heating season starts on 15th of October and ends on 16th of April or the heating period lasts 183 days) as well as thermo physical features of the layers of the walls for the city of Skopje, Macedonia. The meteorological data are chosen as typical for the last ten years period.

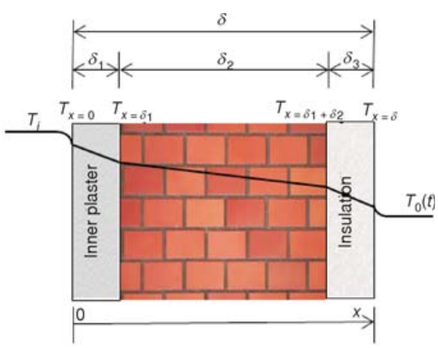

Figure 1. Three layer wall structure

Physical model, mathematical formulation, and numerical solution

The physical problem involves a multilayer wall consisting of N parallel layers. On fig. 1 an example of three layer wall structure is presented. Each layer has a thickness of δ_i, and the overall thickness of the wall is δ.

For the calculation of the heat energy losses it is assumed that the external walls are made of inner plaster with thickness of 2 cm, brick with thickness of 20 cm and external insulation whose thickness varies from 1 to 16 cm. For each of these materials the parameters are given in tab. 1.

The analyses made in this paper consider an apartment of 66 m^2 located in Skopje, Macedonia, in a building with five floors. Each floor has two flats. The apartment is located on the third floor, and consequently has neighboring apartments on three sides, one on the same floor, one above and one below it. It is assumed that the temperature in the neighboring apartments is not changing, so the heat loss through the neighboring apartments is calculated using the steady-state model. The size of the internal wall bordering the neighboring apartment on the same floor is 32 m^2.

Table 1. Characteristics of building materials [6, 14]

Material	δ [cm]	λ [Wm^{-1}K^{-1}]	ρ [kgm^{-3}]	c [Jkg^{-1}K^{-1}]
Plaster	2	0.720	1865	840
Brick	20	0.620	1800	840
XPS	1-16	0.029	35	1,213
Wood*	3	0.100		
Concrete*	15	1.500		

* Used only for steady model

Assuming that the outside temperature is changing more frequently, the heat loss through the outside wall is calculated using the transient model. The outside wall of the analyzed apartment consists of three parts that span on three different orientations. The largest part which is 24 m^2 (not including the windows) is located on the north side. All of the windows of the apartment are situated on this part of the outside wall. The windows occupy a total of 8.5 m^2, the heat conductivity parameter is 1.1 W/m^{2}K and the solar factor is 61.3% [15]. Each of the other two parts of the outside wall has an area of 15 m^2. One of them is located on east, and the other on west.

Transient model

In the case of an infinite flat plate, the transient heat conduction equation for a wall constructed of N layers is given by the following partial differential equation:

$$\frac{\partial T}{\partial t} = a_j \frac{\partial^2 T}{\partial x^2} \quad \text{for} \quad j = [1, N] \tag{1}$$

Here, T, t, and x are the temperature, time, and the co-ordinate direction normal to the wall, respectively. The parameter a_j represents the thermal diffuzivity of the j-th layer and:

$$a_j = \frac{\lambda_j}{\rho_j c_j} \quad \text{for} \quad j = [1, N] \tag{2}$$

where λ_j, ρ_j, and c_j are the thermal conductivity, density, and the specific heat, respectively, of the j-th layer. The boundary conditions are given by the following equations:

$$\alpha_1 (T_i - T_{x=0}) = -\lambda_1 \left(\frac{\partial T}{\partial x} \right)_{x=0} \tag{3}$$

$$-\lambda_1 \left(\frac{\partial T}{\partial x} \right)_{x=\delta_1} = -\lambda_2 \left(\frac{\partial T}{\partial x} \right)_{x=\delta_1} \tag{4}$$

$$-\lambda_2\left(\frac{\partial T}{\partial x}\right)_{x=\delta_1+\delta_2} = -\lambda_3\left(\frac{\partial T}{\partial x}\right)_{x=\delta_1+\delta_2} \tag{5}$$

$$-\lambda_3\left(\frac{\partial T}{\partial x}\right)_{x=\delta} = \alpha_2 (T_{x=\delta} - T_\mathrm{o}) \tag{6}$$

Here α_1 and α_2 are the heat-transfer coefficients at the indoor and the outdoor surface of the wall, and T_i and T_o are the indoor and the outdoor air temperatures, respectively. The initial condition is:

$$T_{x,t=0} - \frac{T_i T_{\mathrm{o},t=0}}{2} \quad \text{for} \quad x = [0, \delta] \tag{7}$$

The heat flux q_j is calculated in the middle of each hour j.The final useful energy consumption for the whole heating season is determined by:

$$E = \sum_{j=0}^{4391} q_j AB \tag{8}$$

where A and B represent the width and the length of the surface, respectively.

Steady-state model

For each layer i the heat resistance can be calculated according to the following equation [14]:

$$R_i = \frac{\delta_i}{\lambda_i} \tag{9}$$

where δ_i represents the thickness of the material i and λ_i represents the thermal conductivity, which has characteristic value for each type of material.

The total heat resistance is calculated using the sum of the separate resistances for each material. The overall equation for the total heat resistance is defined by:

$$R = \frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \sum R_i \tag{10}$$

The thermal conductivity k for more than one layer is defined by:

$$k = \frac{1}{R} \tag{11}$$

Using this heat transmission coefficient k, the heat flux q can be calculated according to the following equation:

$$q = k(T_i - T_\mathrm{o}) \tag{12}$$

The total heat transfer rate is then calculated by the equation:

$$Q = qAB \tag{13}$$

where A and B are the width and length of the analyzed surface. The final useful energy consumption for the whole heating season can be calculated by multiplying the heat transfer rate by the number of hours in the heating season, which is presented by the equation:

$$E = Q \cdot 4.392 \tag{14}$$

Solar radiation model

In this paper, Collares-Pereira and Rabl model was used for calculation of hourly solar radiation [16]. The model is expressed by the equation:

$$\overline{H}_{\mathrm{h}} = \overline{H}_{\mathrm{day}} \frac{\pi}{24}(b + d\cos\omega)\frac{\cos\omega - \cos\omega_{\mathrm{s}}}{\sin\omega_{\mathrm{s}} - \dfrac{2\pi\omega_{\mathrm{s}}}{360}\cos\omega_{\mathrm{s}}} \tag{15}$$

where coefficients b and d are calculated using the equations:

$$b = 0.409 + 0.5016\sin(\omega_{\mathrm{s}} - 60°), \quad d = 0.6609 - 0.4767\sin(\omega_{\mathrm{s}} - 60°) \tag{16}$$

$\overline{H}_{\mathrm{day}}$ is the daily solar radiation, ω – the hour angle of the Sun for the mid-hour for which hour radiation is computed, and ω_{s} – the sunset hour angle, calculated by the following equation:

$$\omega_{\mathrm{s}} = \cos^{-1}(\mathrm{tg}\varphi\,\mathrm{tg}\theta) \tag{17}$$

where φ is the latitude of the considered place and θ is the solar declination angle calculated for a representative day of the month.

Using Liu-Jordan, Klein model [17] solar radiation (I) for vertical walls is calculated as:

$$I = I_{\mathrm{b}} + I_{\mathrm{d}} + I_{\mathrm{r}} \tag{18}$$

where I_{b} is the beam radiation, I_{d} – the diffuse radiation and I_{r} – the reflected (hemispherical) radiation:

$$I_{\mathrm{b}} = \overline{H}_{\mathrm{h}}(1 - \overline{K}_{\mathrm{d}})R_{\mathrm{b}} \tag{19}$$

$$I_{\mathrm{d}} = \overline{H}_{\mathrm{h}}\overline{K}_{\mathrm{d}}\frac{1 + \cos\beta}{2} \tag{20}$$

$$I_{\mathrm{r}} = \overline{H}_{\mathrm{h}}\rho_{\mathrm{a}}\frac{1 - \cos\beta}{2} \tag{21}$$

where $\overline{K}_{\mathrm{d}}$ and $\overline{R}_{\mathrm{d}}$ are given by:

$$\overline{K}_{\mathrm{d}} = 1.05 - 1.125K_{\mathrm{T}} \tag{22}$$

$$\overline{R}_{\mathrm{b}} = \frac{\cos(\varphi - \beta)\cos\theta\sin\omega_{\mathrm{s}} + \dfrac{\pi}{180}\omega_{\mathrm{s}}\sin(\varphi - \beta)\sin\theta}{\cos\varphi\cos\theta\sin\omega_{\mathrm{s}} + \dfrac{\pi}{180}\omega_{\mathrm{s}}\sin\varphi\sin\theta} \tag{23}$$

and $\overline{K}_{\mathrm{T}}$ is the insolation clearness index, φ – the latitude, β – the surface azimuth angle, and ρ_{a} – the ground albedo.

The effect of solar radiation of the external walls is expressed using the equation [18]:

$$T_{\mathrm{oe}} = T_{\mathrm{o}} + \frac{\alpha_{\mathrm{s}}I}{\alpha_2} \tag{24}$$

where α_{s} is the solar absorptivity of the external wall surface.

On the other hand, the effect of solar radiation of the windows is expressed by the equation:

$$W_{\mathrm{in}} = IW_{\mathrm{SF}}W_{\mathrm{Area}} \tag{25}$$

where W_{SF} is the window solar factor and W_{Area} – the window surface area.

Calculation procedure and numerical solution

The goal of this paper is to find the optimum between the insulation thickness and heating technology. In order to achieve this, the calculations for total heat losses through the walls of the analyzed apartment are made varying the insulation thickness by 1 cm in the range from 1 cm to 16 cm. Using the information from the total heat losses, the associated costs for each technology are calculated for each thickness of the insulation.

The process starts by initializing the insulation thickness to 1 cm. For each insulation thickness, one heating season is analyzed, so that firstly the total heat loss through the outside walls is calculated using the transient model and then the total heat loss through the inside walls, the floor and the ceiling is calculated using the steady state model. The heat loss for the outside walls (including windows) is determined for each hour, taking into account the outside temperature. The sun radiation is also included in the outside temperature as stated by eq. (24). The outside wall can have different orientations and for each side the total heat loss is calculated. The temperatures of the outside walls along the x axis are calculated according eqs. (1)-(7), for each layer, using smaller time intervals $\Delta\tau$ (which is equal to 16.3 s). Consequently, the total heat loss q for that hour is determined. This process is repeated until 4,392 hours are reached, then, the sum of the total heat losses through the external walls for all hours is calculated in order to get the total heat loss through the external walls in the analysed heating season, eq. (8). The radiation through the windows is included using eq. (25). Also, using a steady-state model, heat losses through internal walls, floor and ceiling are calculated. In the next step, the maximum heat transfer rate (in kW) of all hours, through all walls is calculated in order to determine the needed heating capacity for each thickness of the insulation. Furthermore, the appropriate heating technologies are applied. This whole process is repeated until the thickness of the insulation reaches 16 cm.

Equation (1) with the initial (7) and the boundary conditions (3)-(6) is solved numerically. In order to approximate the solution an explicit procedure is used. The derivative with respect to time is represented using forward differencing and the space derivative is approximated using central differencing.

The numerical solution of the model is implemented in MATLAB.

Applied heating technologies

In this paper, we are analyzing investment in five technologies that are used for heating: wood fired stoves, pellet stoves, air-conditioner (inverter), electric heating panels and district heating.

In order to calculate the total investment in a new technology, the maximum power needed for a certain thickness of insulation is estimated. For each technology except for the district heating an average investment in denars per kW is calculated, as shown in tab. 2. An average price for buying wood fired stove is 2,635 den/kW, for pellet stoves is 7,181 den/kW, for electric heating panels is 2,769 den/kW and for air-conditioner is 13,612 den/kW. Multiplying the maximum power needed by the average investment in denars per kW, the total investment in buying new technology is calculated, which includes investment in new stove, panels or air-conditioner. The price for installation and connection to the district heating is varying from 1,845 to 2,460 den/m^2. The investment in buying new technology is discounted according to the life time of the technology. It is assumed that the lifetime of all technologies is 20 year, except for the district heating for which it is 40 years, and the air-conditioner for which it is 13 years.

An average efficiency is calculated for the five technologies. As shown in tab. 2 an average efficiency of a wood fired stove is 80%, of a pellet stove is 92%, of electric heating panels is 100%, of an inverter air-conditioner is 300% and of the district heating is 100%.

Taking into account the efficiency of each technology, the power needed in kWh is estimated for each of the four technologies (wood fired stoves, pellet stoves, electric heating panels, and air-conditioner), for the analyzed period. The price for the fuel for each of the four technologies is also calculated in den/kWh. The product of these two numbers gives the price of fuel for the analyzed period. For electricity, the engaged power and the value added tax are also added. The total cost of the heat energy using district heating in Skopje, Macedonia, is calculated using the equation [32]:

$$\cos t = \left(FC_1 U_c \frac{M_D}{H_P} + PE_{DH} \right) VAT \quad (26)$$

Table 2. Average efficiency and average prices of installed capacity of the technologies [19-31]

Technology	Average efficiency [%]	Average price of installed capacity [den/kW]
Woodfired stoves	80	2,635
Pellets stoves	92	7,181
Electric heating panels	100	2,769
Air-conditioner (inverter)	300	13,612
District heating	100	

where F is a fix cost, C_1 – the engaged power, U_c – the participation in fix costs, P – the price of heat energy per kWh, E_{DH} – the consumed energy, H_P – the heating period, M_D represents days in a month, and VAT isthe value added tax.

The total cost of a new technology is the sum of the cost of investment in buying the technology and the cost of fuel in the analyzed period.

For pellet and wood fired stoves the price for storage of wood and pellets is also included, as a product of the cubic meters needed for one heating season and an average price of a basement in denars/m^3.

The total investment for each of the technologies is discounted in order to calculate the price in 2012 denars, or in denars of the first analyzed year.

Results and discussion

Input data

In this paper, a period of 13 years, from 2013 to 2025 is analyzed.

One of the most important parameter in this model besides the efficiency of the technologies, investment and their lifetime, are the prices of the fuels. For this purpose, tab. 3 provides the prices of fuels for the considered period and it is assumed that they are going to approach the fuel prices in Europe.

Table 3. Energy Price Trajectory Assumptions (denars/kWh)

	2013*	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Electricity	3.25	3.40	3.56	3.71	3.86	4.02	4.17	4.32	4.47	4.63	4.78	4.93	5.09
Heat (DH**)	3.38	3.26	3.14	3.03	2.91	2.79	2.68	2.56	2.44	2.33	2.21	2.09	1.97
Wood	0.79	0.83	0.86	0.89	0.93	0.96	1.00	1.03	1.06	1.10	1.13	1.17	1.20
Pellet	2.20	2.29	2.38	2.48	2.57	2.66	2.75	2.84	2.93	3.03	3.12	3.21	3.30

* The values are used from [33-36]; ** District heating

In this paper the net calorific value for wood is considered to be 10.902 TJ/10^3 m^3 [37] and the calorific value for pellets is 18 MJ/kg [36].

The discount rate is assumed to be 6%.

The inside temperature in the analyzed apartment is considered to be 23 °C. According to the analysis of the air temperatures in Skopje in the last ten years period, the average temperature in the heating seasons is 6 °C [38]. Thus, a heating season in which the average temperature is 6 °C is used in this paper. So, for the outside temperature, the meteorological data for the heating season 2008/2009 in Skopje is used.

Case studies

In this paper, two case studies are analyzed. In the first case study it is assumed that the neighboring apartments use some heating technology and the temperature is the same as the temperature of the analyzed apartment. On the other hand, in the second case the neighboring apartments do not use heating technology and their temperature is constant. The temperature of the neighbouring apartments, when none of the apartments in the building is heated except the analyzed one is calculated using the steady-state model and depending on the position of the apartment the temperature is in the range of 9 °C to 10 °C in the corresponding heating season. In both cases the analyzed apartment has no insulation.

For the first case study, the required installed capacity is presented in fig. 2 as a function of the insulation thickness. If the insulation thickness is 1 cm, the installed capacity in the analyzed apartment should be about 2.4 kW and if the insulation thickness is 16 cm the needed installed capacity will be reduced to about 0.6 kW.

An analysis of what is the optimal technology for heating and the optimum insulation thickness is made. Five technologies are considered: wood fired stoves, pellet stoves, inverter air-conditioner, electric heating panels and district heating.

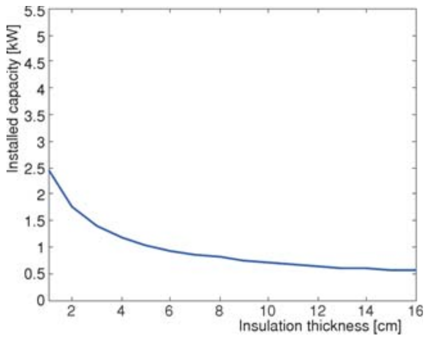

Figure 2. Required installed capacity depending on insulation thickness if the neighboring apartments have the same temperature as the analyzed apartment

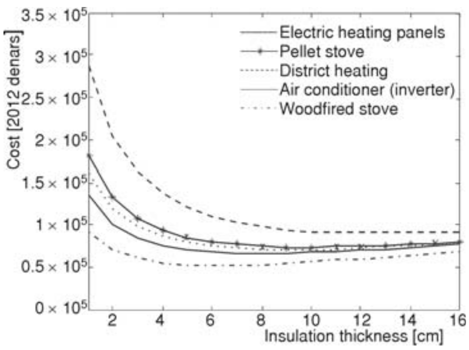

Figure 3. Total cost for each technology including the cost of insulation for the next 13 years if the neighboring apartments have the same temperature as the analyzed apartment

To evaluate the optimum between each of the technologies and investment in insulation, the investment in insulation is added to the total cost of each of the technologies. The total cost of each technology includes the cost of buying new technology plus the cost of the appropriate fuel of each technology for the analyzed period. Figure 3 shows the total cost for each technology including the cost of insulation. Clearly, it can be seen that the lower the thickness of the insulation is, the difference in the price between the different technologies is greater. By increasing the thickness of the insulation, the price difference between the technologies is reduced. Also, it can be noticed that at first, by increasing the thickness of the insulation, the total cost of the system (investment in new technology for heating, fuel prices and investment in insulation) for each of the technologies is reduced because the benefits of energy savings are increasing as compared to the total cost, until the optimum in terms of cost and thickness of the insulation is reached. After the optimum, there is slight increase of the cost because the benefits of energy savings are becoming smaller in relation to the total cost.

As shown in fig. 4, it is obvious that the most cost-effective option is the wood fired stove. It should be considered that this option requires constant engagement of a human to supplement the stove. The optimum insulation thickness is 6 cm (as shown in tab. 4), and the total price for 13 years period is 52,560 (2012) denars. Second cost-effective option is the inverter air-conditioner. According to the current price of electricity and the assumed price increase, it is very worthwhile option. Minimum total cost for 13 years is 66,390 (2012) denars (fig. 4), for optimum insulation of 8 cm, as shown in tab 4. Next option is the district heating. The optimal insulation thickness is 9 cm (tab. 4), for total minimum cost for 13 years of 71,385 (2012) denars (fig. 4). The pellet stove heating technology is about as worthwhile as the district heating. The lowest total price is 73,806 (2012) denars (fig. 4), for an insulation thickness of 10 cm (tab. 4). The least profitable option are the electric heating panels. The minimal price of the total investment for the analyzed period is 90,326 (2012) denars (fig. 4), with optimum insulation thickness of 13 cm (tab. 4), which is the highest insulation thickness of all the technologies.

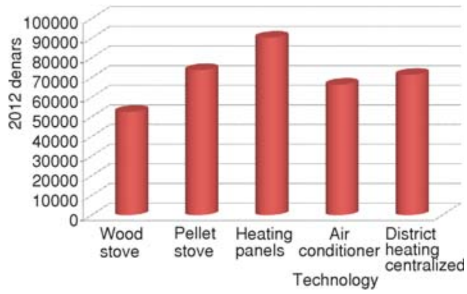

Figure 4. Minimal total cost of each of the technologies for the analyzed period if the neighboring apartments have the same temperature as the analyzed apartment

Table 4. Optimal insulation thickness for each heating technology

Technology	Fuel	Optimal thickness of the insulation [cm]
Wood fired stove	Wood	6
Pellet stove	Pellets	10
Electric heating panels	Electricity	13
Air conditioner	Electricity	8
District heating – centralized	Natural gas	9

The second case study is made for an apartment whose neighboring apartments do not use any heating technology. On fig. 5 the required installed capacity is presented as a function of the insulation thickness. If the insulation thickness is 1 cm, the installed capacity in the analyzed apartment should be about 4.5 kW which is about 2 times more than in the first case study and if the insulation thickness is 16 cm the needed installed capacity will be reduced to about 2.7 kW which is about 4.5 times more than in the first case study.

For the second case study the total cost for each technology including the cost of insulation for the next 13 years is presented on fig. 6.

It is interesting that the optimal insulation for each of the heating technologies for the second case study is the same as the optimal insulation in the first case study, so the data from tab. 4 also refer to the case if the neighbouring apartments do not use any heating technology. This is because in both cases, the heat losses through the outside walls depend on the thickness of the insulation, while losses through the neighbouring apartments are compensated with the necessary power of the heating technology. So, the difference between the

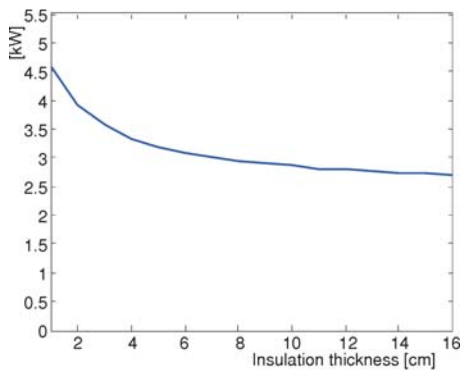

Figure 5. Required installed capacity depending on insulation thickness if the neighboring apartments do not use any heating technology

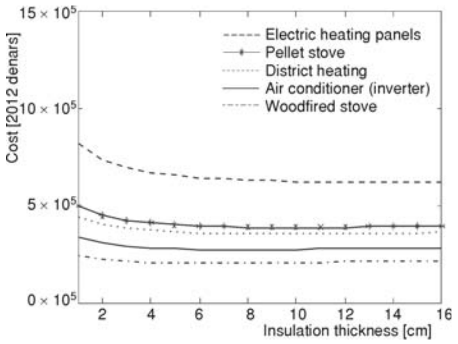

Figure 6. Total cost for each technology including the cost of insulation for the next 13 years if the neighboring apartments do not use any heating technology

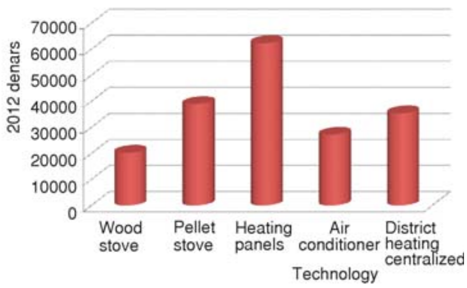

Figure 7. Minimal total cost of each of the technologies for the analyzed period

two analyzed case studies is in the minimal total cost for each of the technologies for the analyzed period, as presented on fig. 7. Again, the most cost effective option is the wood fired stove with minimum total cost of 202,030 (2012) denars. The second cost effective option is the inverter air-conditioner with 271,580 (2012) denars, followed by the district heating with 353,720 (2012) denars and the pellet stove with total cost of 389,270 (2012) denars. As in the first case study, the least profitable option are the electric heating panels with total price of 623,130 (2012) denars.

Conclusions

In this paper, an investigation of the optimal insulation thickness and heating technology for a typical apartment in Skopje was analysed. An unsteady heat transfer model was used for the external walls and a steady-state model was used for the internal walls. Two case studies were carried out. In the first case study it is assumed that the neighbouring apartments and the analysed apartment have the same temperature and in the second case study the neighbouring apartments do not use any heating technology. There is a big difference between the two cases, in the amount of installed capacity needed, and thus the total cost of investment for each of the technologies. However, the results show that the optimum insulation thickness should be calculated regardless of the temperature in the neighbouring apartments. In both cases the most cost effective technology is the wood fired stove, with 7 cm insulation and the least cost effective technology are the electric heating panels with 14 cm insulation thickness.

Nomenclature

A	– width of the surface, [m]
a	– thermal diffuzivity, [$m^{-2}s^{-1}$]
B	– length of the surface, [m]
c	– specific heat, [$Jkg^{-1}K^{-1}$]
C_1	– engaged power, [kW]
den	– Macedonian denars – (1 Euro = 61.5 denars)
E	– useful energy consumption, [Wh]
E_{DH}	– consumed energy for DH [Wh]
F	– fix cost, [den kW^{-1}]
H_{day}	– daily solar radiation, [Whm^{-2}]
H_P	– heating period, [days]
H_h	– hourly solar radiation, [Wm^{-2}]
I	– solar radiation, [Wm^{-2}]
I_b	– beam irradiation, [Wm^{-2}]
I_d	– diffuse irradiation, [Wm^{-2}]
I_r	– hemispherical irradiation, [$Wm^{-2}K^{-1}$]
k	– thermal conductivity, [Wm^{-2}]
K_T	– insolation clearness index
M_D	– days in a month, [days]
N	– number of layers of composite wall
P	– price of heat energy total heat transfer rate for an analyzed surface, [den kWh^{-1}]
Q	– surface [W]
q	– heat flux, [Wm^{-2}]
R	– heat resistance, [m^2KW^{-1}]
T	– temperature, [K]
T_i	– indoor air temperature, [K]
T_o	– outdoor air temperature, [K]
t	– time, [s]
U_c	– participation in the fix cost
VAT	– value added tax (18%)

x – co-ordinate direction normal to wall, [m]
W_{Area} – window surface area, [m^2]
W_{in} – effect of solar radiation, [W]
W_{SG} – window solar factor

Greek symbols

α_1 – heat-transfer coefficient at the indoor surface of the wall, [Wm^{-2}K^{-1}]
α_2 – heat-transfer coefficient at the outdoor surface of the wall, [Wm^{-2}K^{-1}]
α_s – solar absorptivity
β – surface azimuth angle
δ – thickness of the wall
δ_i – thickness of different layer of the wall, [m]
θ – solar declination angle, [rad]
λ – thermal conductivity, [Wm^{-1}K^{-1}]
ρ – density, [kgm^{-2}]
ρ_a – ground albedo
φ – latitude, [rad]
ω – hour angle of the Sun for the mid-hour, [rad]
ω_s – sunset hour angle, [rad]

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