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HEATING WITH A HEAT PUMP

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ABSTRACT

Due to limited natural resources exploited for heating and in order to reduce the environmental impact people should strive to use renewable energy sources. Heat pumps allow the conversion of ambient heat, available in almost unlimited quantities, to heating energy. The paper describes an energy-saving house provided with good thermal insulation and heated by an air-to-water split type heat pump. The paper also presents the calculation of the heat pump thermal efficiency.

The condenser is located in the attic and evaporator in the boiler room of the house. The house heating up to the ambient temperature of 0ºC was provided by an air-to-water heat pump and a condensing oil heating furnace if the ambient temperature dropped to below 0ºC. The results of the nine-year testing showed that the heat pump was used during most of the heating season. The average coefficient of performance (COP) of the air-to-water heat pump in nine heating seasons was 3.16, indicating that over 68% of the heat was obtained from the ambient air. The comparison between COP of air-to-water heat pumps in energy-saving house and of water-to-water heat pumps fitted in houses dealt with under other projects indicates that water-to-water heat pumps have higher COPs. The heat pumps obtaining heat from groundwater, thus being capable of operating throughout the heating season, have the highest COP. The advantage of an air-to-water heat pump, however, lies in its simple design and a wide range of applications.

In comparison with the furnace the heat pump yielded considerable saving in fuel and money, which justifies its home heating application in the Central European climatic area.

INTRODUCTION

The paper describes the project and construction of an energy-saving house for the Slovene and Central European climatic area. The project was aimed at identifying the most efficient heating system of energy-saving single-family houses in terms of energy, consumption and price. The energy performance was tested over a nine-year period. Based upon the experience gained from the project we provided recommendations and advice on new residential house construction in Slovenia.

The reduction in energy consumption was achieved in two ways:

1. Through the installation of the latest construction materials, good thermal insulation, triple window glazing and good window and door sealing as well as adequate arrangement of rooms. Larger windows and entrances are located on the south side of the house. The single-family house (basement and first floor) has the heating surface of 136 sqm.
2. Through the use of a heat pump and a condensing light oil furnace for heating.

In view of a higher efficiency of energy consumption people should increase the use of renewable energy resources such as solar energy, wind energy and ambient energy. Ambient energy may be converted into heat used for heating with a heat pump, whose functioning has been known for a long time [1,2]. The heat pump produces heating energy from ambient heat and heating exergy, normally obtained in the form of electrical energy from the mains. Ambient energy can be obtained from earth, water or air. The heat pump can obtain heat from earth, using an evaporator with horizontally installed pipes 1 m to 1.5 m below ground. The evaporator pipes of various shapes can also be placed into vertical boreholes which can be up to 200 m deep. [3,4]. We can also use groundwater as a source of heat which has the temperature of 8º C to 10º C 10 m below ground [5,6,7]. High temperature of groundwater allows the heat pump to operate at a high coefficient of performance (COP) throughout the winter, regardless of the ambient air temperature [8,9].

The single-family detached house, constructed in 1988, is located in Maribor, which has the Central European climate.

The heating season usually lasts between six and seven months. The coldest month in the year is January, followed by December. Between 1988 and 1998, we measured energy consumption in the house and the ambient temperature at 7.00, 14.00 and 21.00.

The heat required for heating was provided by the air-to-water heat pump with the heating power of Q = 12 kW at the heating regime of 45ºC/35ºC and the ambient temperature of 7ºC. The coefficient of performance ε of the heat pump was 3.24. In terms of energy efficiency the heat pump is the best solution. The heat pump obtains the necessary heating anergy from the ambient air and the required heating exergy in the form of electrical energy from the mains. The house was heated using the heat pump up to the ambient air temperature of 0ºC. When the ambient air temperature dropped to below 0ºC the house was heated with a 25 kW condensing light heating oil furnace.

In the nine-year period of the central heating operation the light heating oil furnace was used 6 weeks on average in a single heating season, while during the remaining 6 to 7 months of the heating season the house was heated by the heat pump.

The analysis of the heat pump and furnace operation shows that the house was heated most of the time with the heat pump, which means that in terms of energy efficiency the air-to-water heat pump represents an optimum solution for the given climatic area.

The average COP of the heat pump over the period of nine years is 3.16

During the heating season the heat pump or the furnace also provided the necessary domestic hot water, whereas in the off-heating season this is ensured by the 3 kW air-to-water heat pump. The heat pump heats 300 l of water daily up to the temperature of 40ºC.

The house has no air-conditioning system installed as the highest temperatures in summer rarely exceed 30º C .

NOMENCLATURE

H_I	J/kgK	Heating value
h_{c_n}	W/m^2K	Heat transfer coefficient on the inner side of the wall
h_{c_z}	W/m^2K	Heat transfer coefficient on the outer side of the wall
k_I	W/mK	Thermal conductivity
m	kg	Heating oil mass
P_{el}	W, kW	Supply (electric) power
Q_0, Q_{sv}, Q_c	W, kW	Heating power
Q	W, kW	Heating power of heat pump
Q_H	kWh, J	Heat pump heating capacity
Q_F	kWh, J	Oil furnace heating capacity
T_0	°C, K	Ambient temperature
$\overline{T}$	°C, K	Average monthly ambient air temperature
T_i	°C, K	Ambient air temperature
U	W/m^2K	Overall heat transfer coefficient
W_{el}	kWh	Electricity consumption
ε		Coefficient of performance (COP)
$\overline{\varepsilon}$		Average annual heat pump coefficient of performance
δ	m, cm	Wall thickness
η		Oil furnace efficiency
ρ	kg/m^3, kg/l	Heating oil specific density

ENERGY-SAVING HOUSE

The first floor of the house has a surface of 125 sqm. The whole surface is heated and intended for the living zone, similarly as a hobby room and a workshop in the basement. These rooms along with the garage and toilets measure 82 sqm and can be heated, if necessary. The basement lies 1 m under the ground. All the entrances to the house and larger windows face south [10].

The wall insulation was installed to reduce the heat losses. The exterior wall is made of a 19 cm brick wall lined in 2 cm plaster. The exterior wall insulation is 9 cm thick, then follows a 2 cm air gap and a 12.5 cm silica brick wall with bottom and top openings allowing air flow in the air gap, thus preventing water condensation on the insulation [11].

The ceiling above the basement or the flooring on the first floor is made of a 19 cm brick, followed by the 8 cm insulation and 2 cm wood-chip board, onto which a 2.2 cm parquet is placed.

The overall heat transfer coefficient is calculated using the following equation:

$$\frac{1}{U}=\frac{1}{h_{c_n}}+\sum_i \frac{\delta_i}{k_i}+\frac{1}{h_{c_z}} \qquad 1$$

In the calculation of the overall heat transfer coefficient we took account of the fact that on the inner wall of the house the heat transfer coefficient was h_{c_n} =7.7 W/m^2K and on the exterior wall of the house h_{c_z} =25 W/m^2K. In the equation 1 d stands for wall thickness and k_i for thermal conductivity. In the latter, we took into consideration the 4 m/s wind velocity. The silica brick wall is excluded from the heat transfer coefficient calculation.

The calculated values of the heat transfer through the walls are indicated in Table 1 and are low for all the walls except the exterior basement walls, made of concrete blocks.

Walls in the house	Overall heat transfer coefficients U (W/m^2K)
Exterior wall on the first floor	0.3541
Ceiling on the first floor	0.277
Flooring on the first floor	0.3846
External wall in the basement	1.39

Table 1 Calculated overall heat transfer coefficients

Of the living zones only the hobby room is located in the basement. The hobby room is insulated in the inner side with a 9 cm insulation onto which 1 cm wooden veneered boards are placed. This improves heat transfer coefficient also in the basement room.

A special attention was paid to the triple-glazed windows with the heat transfer coefficient of $U=1.8\ W/m^2K$. The window sealing was improved through the utilization of appropriate sealing materials thus reducing to the minimum the losses due to window cracks.

The heat losses were calculated in accordance with the ÖNORM M 7500 standard, whereby we took account of the design requirements relevant to the Central European climate:

1. Wind velocity 4 m/s.
2. Ambient temperature T_0= - 18ºC.
3. Isolated site of the building.
4. Building height under 18 m.

The calculated heat losses for the heated surfaces of the house, considering the stated design requirements, are Q_0 = 15451 W. For domestic water heating we need additional heating power of Q_{sv} = 3000 W. The overall heating power to be supplied by the heating system is Q_c = 18451 W.

If necessary, the workshop and the garage may be heated for which additional heating power of 3 kW was envisaged. Thus, the required heating power of the heating system is
Q_c = 21451 W.

HEATING SYSTEM

We devoted special attention to the heating system. We chose a low temperature 45°C/35°C central heating allowing the use of heat pumps and condensing furnaces [12]. Low-temperature central heating also has low heat losses during the heat distribution.

Given the climatic area in which the house is located we decided to choose the air-to-water heat pump for the primary heating of the house. When the ambient air temperature falls below 0°C, the heating regulation turns off the heat pump and actuates the highly efficient oil furnace.

We used the heat pump split system. The heat pump evaporator was installed in the attic of the house and the condenser with other heat pump components in the central heating boiler room.

The evaporator was installed in the attic of the house, as the roofing was made of 1 mm corrugated aluminum sheet. On sunny days, the aluminum roofing ensures rapid additional heating of the air, from which the heat pump takes the necessary heating anergy. Thus, on sunny days the air in the attic was heated by 2°C to 3°C. The cooled air outlet from the heat pump evaporator was ensured through appropriate ducts, leading from the evaporator to the exterior of the house. The outlet ducts for the cooled-down air prevent any mixing of the cool air with the warm air in the attic of the house. The ambient air intake to the attic of the house is regulated in such a way that the air takes the longest possible way in the attic of the house before it enters the heat pump evaporator. This increases the inlet air temperature in the evaporator and consequently the heat pump coefficient of performance (COP).

Fig. 1 shows the coefficient of performance, heating power and supply (electric) power (heating exergy consumption) in relation to the inlet air temperature in the evaporator or the ambient air temperature. The curves are plotted for the water outlet temperature from the condenser 45°C and the inlet temperature of 35°C. The water exiting the condenser is used to heat the central heating radiators.

The lowest ambient air temperature at which the heat pump operates is 0°C. At this temperature the COP is $\varepsilon = 2.87$, supply power P_{el}=3.3 kW and heating power of the heat pump Q=9.5 kW. Fig. 1 also shows that the rise in the temperature of the ambient air from which the heating energy is obtained results in a higher coefficient of performance. The heating power Q_c, required for heating the house at 0°C and for heating the water for domestic use, is 9.1 kW, which is less than the heating power of the heat pump.

A 300 l boiler is installed to meet the domestic hot water requirements. Water for domestic use may be heated either with an electric heater, heat pump or oil furnace. The water in the boiler is heated to 45°C, which is a sufficiently high temperature for the household requirements. At this temperature no intense scale build-up occurs.

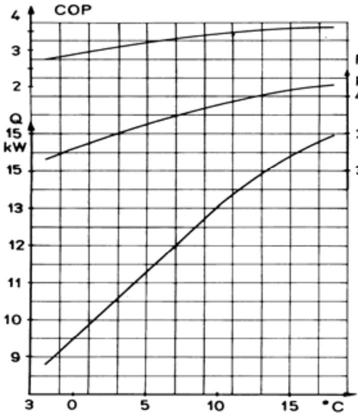

Figure 1 COP of heat pump

When the central heating is inoperative the domestic water is heated with the heat pump, whose supply power is P_{el} = 920 W and heating power Q = 2500 W at the ambient air temperature of 7 ºC. The heat pump is installed in the attic of the house, where in summer the temperature of the air, from which the heat pump obtains the heating anergy, may be as high as 40ºC. The heat pump operates at high COP, even up to 5, whereby its heating power increases up to 5 kW.

ANALYSIS OF RESULTS

This section of the paper presents the energy consumption for the domestic hot water heating and house heating in the period from September 1989 to September 1998.

Year	Heat pump heating %	Heating days per year		Energy consumption	
		Heat pump	Furnace	Heat pump kWh	Furnace litres
89/90	77	158	46	3300	826
90/91	72	143	55	3795	751
91/92	76	153	47	3613	777
92/93	88	174	22	4295	621
93/94	77	150	44	3817	777
94/95	80	163	40	3652	573
95/96	45	98	116	1809	1650
96/97	67	151	73	2854	1050
97/98	83	161	31	3949	500

Table 2 Heating days per year and energy consumption

Table 2 shows that in the above period the house was heated most of the time with the heat pump, namely from 67% of the time in the 96/97 heating season to 88% in the 92/93 heating season. The 95/96 heating season was an exception, as the house was heated for a longer period of time with the furnace than the heat pump (45%). According to meteorologists this was the longest winter in the previous century in the climatic area where the house is located. In January and partly in December, the heat pump was normally not used for heating, similarly as in February (except in the 95/96 season), when the temperature drops to below 0ºC. The COP of the heat pump are low in this period (Fig. 2). In view of the high portion of the heat pump use, over 72% in seven of the nine seasons, the air-to-water heat pump utilization is reasonable. This is clearly evident from the COP at which the heat pump operates. The diagram in Fig. 3 shows the COP at a specific ambient air temperature. Figure 2 shows COP for each month in relation to the mean monthly ambient air temperatures for the 1989/90 heating season.

The results in figure 2 indicate that the heat pump operated at the COP exceeding 3 in all the months except January. The average annual coefficient of performance was 3.2. The average annual COPs were all higher than 3 (Fig. 3), while the average COP for the nine-year operating period was 3.16. At the COP higher than 3, over 66% of the necessary heat is obtained from the exterior which, in terms of the energy efficiency, justifies the use of the air-to-water heat pumps for the house heating purposes. Figures 2 and 3 show that COP varies in relation to the ambient air temperature.

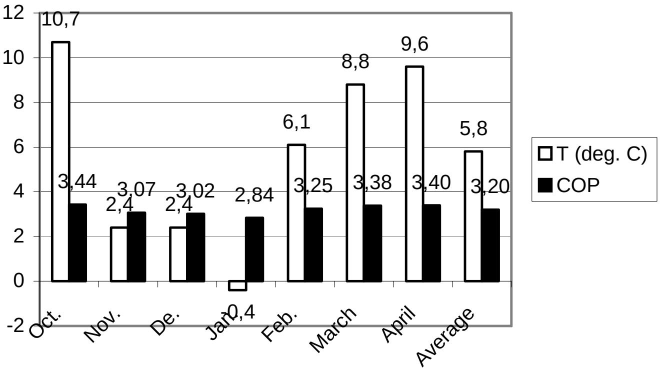

Figure 2 COP for the year 1989/90

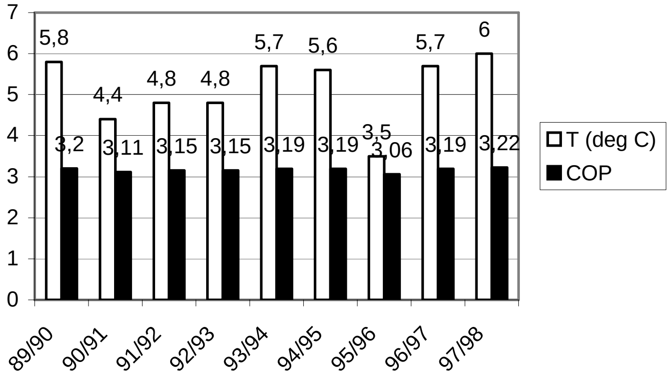

Figure 3 The average COP for the nine-year period

Figure 3 shows the average COP for the nine-year heat pump operating period.

The heat Q_H generated by the heat pump in one month is calculated using the equation

$$Q_H = W_{el}\varepsilon_i\,, \tag{2}$$

where W_{el} is the monthly electrical energy consumption.

The heat generated by the heat pump in one year is the sum of the monthly values.

The heat Q_F generated by the oil furnace is calculated using the equation

$$Q_F = mH_i\eta\frac{1}{3600}\,. \tag{3}$$

To facilitate the comparison of the heat Q_F with the heat pump heat Q_H, the heat Q_F is calculated in kWh. Figure 4 shows the consumption of electrical energy W_{el} and the generation of heat Q_H by the heat pump and the generation of the furnace heat Q_F in individual months of the 89/90 heating season. Figure 5 contains the same parameters for individual heating seasons in the period from 89/90 to 97/98. It is evident from both figures that the majority of the heat is generated by the heat pump. The 95/96 heating season was an exception, when the portion of the heat Q_F generated in the furnace was higher than the portion of the heat Q_H of the heat pump.

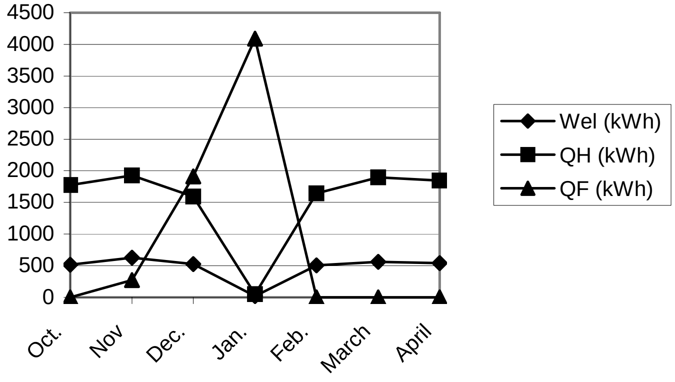

Figure 4 Monthly generation of heat in the 89/90 heating season

The nine-year analysis of the air-to-water heat pump operation demonstrates that in terms of energy efficiency the heat pump is the most appropriate for heating the energy-saving house. Its drawback, however, is that at low ambient air temperatures, the oil furnace must be used for the house heating, which means that two sources of heat need to be available, which increases the investment costs.

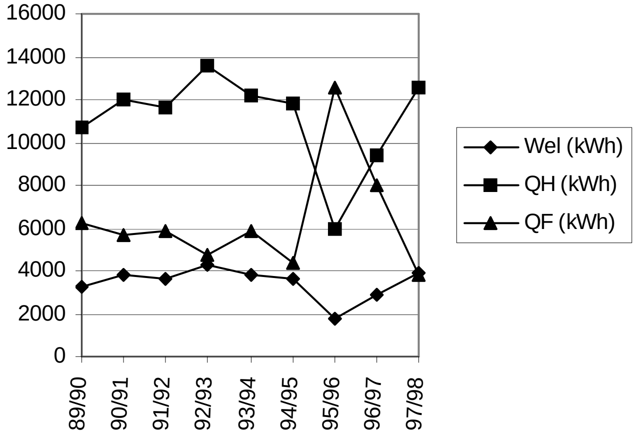

Figure 5 Generation of heat in the period from 89/90 to 97/98

HEATING COST ANALYSIS

The mean electricity price in Slovenia on 15 October 1998 was US$ 0.0495/kWh and US$ 0.064/kWh on 1 September 2001. Over the period of three years the electricity prices in Slovenia rose 29% compared to the year 1998.

The fuel oil price was US$ 0.19/l on 15 October 1998 and US$ 0.41/l on 1 September 2001. In three years, the fuel oil price in Slovenia increased 117% compared to the year 1998!

Considering the 1998 fuel oil price and the heating value H_i = 41200 kJ/kg =11.4 kWh/kg, the price of 1 kWh, generated from 1 l of fuel oil, is

$$\frac{0.19\ \text{US\$}}{H_i \eta \rho} = 0.025\ \text{US\$}/\text{kWh}\,.$$

The price of 1 kWh, generated from 1 l of fuel oil, at the 2001 fuel oil price, is US$ 0.054/kWh.

The price of 1 kWh of heat, generated by the heat pump, is $\frac{0.0495}{\varepsilon}\frac{\text{US\$}}{\text{kWh}} = 0.015\text{US\$}$ at the 1998 electricity price and $0.02\ US\$/kWh$ at the 2001 electricity price.

The COP ε was 3.16, representing the nine-year average value.

The ratio between the price of 1 kWh, generated by the oil furnace and the air-to-water heat pump at the 1998 electricity prices is $\frac{0.025}{0.015} = 1.66$ and at the 2001 prices is 2.7.

The calculation shows that the heat pump central heating system is by 66% cheaper than the fuel oil furnace heating system according to the 1998 electricity prices or even by 170% at the 2001 electricity prices. Moreover, the calculation showed that the air-to-water heat pump was economical primarily due to the world crude oil prices. The saving in terms of money amounted to US$ 960 over the nine-year period at the 1998 energy prices, when the fuel oil price was the lowest or US$ 3411 at the 2001 energy prices. Table 3 shows the cost savings in individual heating seasons and the total saving.

Year	Saving of fuel oil (litres)	Saving of money (Oil price in 1998)	Saving of money (Oil price in 2001)
89/90	1413	99	369
90/91	1580	113	406
91/92	1533	113	398
92/93	1787	128	459
93/94	1604	117	414
94/95	1555	116	405
95/96	784	60	206
96/97	1240	95	326
97/98	1656	119	428
Total	13252	960	3411

Table 3 The fuel oil and money saving in US$

SUMMARY

The paper presents the results of the nine-year testing conducted at the energy-saving house. The project was aimed at constructing a house with the lowest possible consumption of energy for heating the house and domestic hot water. The latest technology available in the 80s was used in the house construction. The single-story one family house was built with V-bricks, having low thermal conductivity and good heat accumulation properties. The windows were installed, if possible, on the south side and all had a three-layer glazing. The exterior wall insulation was 9 cm thick; then followed a 2 cm air gap and a 12 cm silica brick wall. All this resulted in reduced heat losses of the house.

The combined air-to-water heat pump and light fuel oil furnace central heating system was chosen for heating the house. The fuel oil heating was used when the temperature dropped to below 0ºC. The nine-year testing results show that in most of the heating season the house was heated with the heat pump, ranging from 67% (96/97 heating season) to 88% (92/93 heating season), which justifies the use of the heat pump.

The domestic hot water is heated either by the furnace or the heat pump during the heating season and by a small 2.7kW water-to-air heat pump, at the air temperature of 7ºC during the off-heating season. The pump is installed in the attic of the house where in summer the air temperature is as high as 40ºC. At this temperature, the heat pump operates at the COP of 4 or over.

The test results show that in terms of energy consumption and environmental pollution the heat pump has a huge advantage over the furnace. In the climatic area where the house is located the use of the air-to-water heat pump is fully justified.

If the furnace had been used for the heating instead of the heat pump 13252 l more heating oil would have been consumed in the nine-year period. The saving in terms of money amounted to US$ 960 over the nine-year period at the 1998 energy prices, when the fuel oil price was the lowest or US$ 3411 at the 2001 energy prices (Table 3).

The operating cost analysis suggests that the cost efficiency is dependent mainly on the world energy market prices while advanced technological level of heating systems has a much smaller impact on cost saving!

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