ENERGY EFFICIENT OPERATION OF THE OPEN LOOP HEAT PUMP SYSTEMS

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Abstract: *Even if heat pump systems tend to be considered an efficient issue from the energy point of view, when considering the annual COP the building heat losses due to the envelope insulation is determinant for its capacity choice. As the flow rate of the groundwater influences the performance of the system, an analysis is presented to emphasise the importance of the energy consumption of circulatory pumps for the system energy efficiency. An optimum specific groundwater flow rate results together with a building loop return temperature. Variable frequency drive will assure the necessary flow rate for different heating/cooling conditions.*

Key words: *heat pump, open loop system, efficiency.*

1. Introduction

The primary justification for an open loop heat pump system consists in the improvement of the heating efficiencies followed by a decrease of the total building energy and cost savings respectively. An open well earth coupling can be the lowest cost and the highest efficiency method. Figure 1 presents the schematic of an open loop heat pump system used for the heating and the cooling of a building.

Some specific features of the heat pump system must be taken into consideration in the design phase i.e. before the execution and the operation of an open loop system. First, the envelope of the building must be a good insulated one, meaning low energy consumption. Then the appropriate capacity of the heat pump must be correlated with the energy use of the building. The third feature consists in the energy savings resulting from an efficient operation of the groundwater flow. The sizing criterion for a groundwater system is the groundwater flow. Also the heating/ cooling distribution system has to be designed in accordance with the comfort requirements and the economic efficiency of the system.

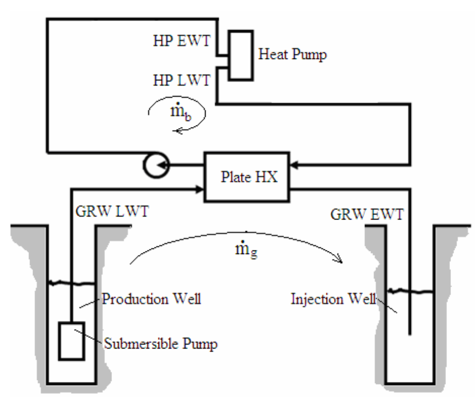

Fig. 1. *Principal elements of an open-loop heat pump system*

Most building codes require two layers of separation between the oil and refrigerant in a heat pump condenser and any potable water supply. This is the role of the

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intermediate heat exchanger (HX) incorporated between the earth connected loop and the heat pump: to isolate the building loop fluid from the groundwater. In this way scaling and corrosion of the heat pump caused by the groundwater chemistry is prevented too. The incremented capital cost of installing the heat exchanger is only small percentage of the total cost. The additional heat transfer loss will slightly reduce the heat pump COP.

2. Heat Pump Capacity and the Annual COP

The bin method has been used for the evaluation of the heat pump performance in the case of a given building characteristic i.e. its heat loss rate [6]. The practical possibility to adapt the energy produced by the heat pump to the building energy use is the cycling operation. In this way the heat pump is working only part-load. The part-load operation of the heat pump reduces its integrated capacity given in the manufacturer's documentation and resulted from the test procedures carried out on stand at constant parameters. This is called the adjusted capacity.

The adjusted capacity of the heat pump leads to losses as shown in Figure 2.

In the actual example a heat pump of 34 kW capacities (given for a standard ambient temperature of 10 °C) will provide a reduced (adjusted) power compared with its integrated capacity (the upper curve in Figure 2). As can be noticed that the heat pump energy losses depend on the building characteristic which is determined by the envelope insulation and by the internal heat gains. The analysis will be carried out on a building having the following features:

- basement 100 m², height 2.80 m, ambient temperature 10 °C,
- first floor 130 m², height 2.80 m, ambient temperature 20 °C,
- masonry wall, 30 cm thick without insulation,
- concrete floors no insulation under the first floor nor upon the last,
- single glazed windows, no insulation, no tight fitting,
- wind speed, 4 m/s (the building is inside the town),
- internal heat gains, 500 W (occupants, lights, appliances, solar),
- exterior/interior heating design temperature −21 °C/+20 °C,
- heat loss rate 26.988 W (heating load),
- building overall loss coefficient,

$$UA = 658 \text{ W/K},$$

- balance temperature, 19.2 °C.

The balance temperature corresponds to the intersection of the heating load characteristic with the abscissa, i.e. no heating is required. The temperature at which the heating load of the building equals the heat pump capacity is called balance-point temperature. For values higher than this balance-point temperature the cycling operation starts and the adjusted capacity is more and more visible.

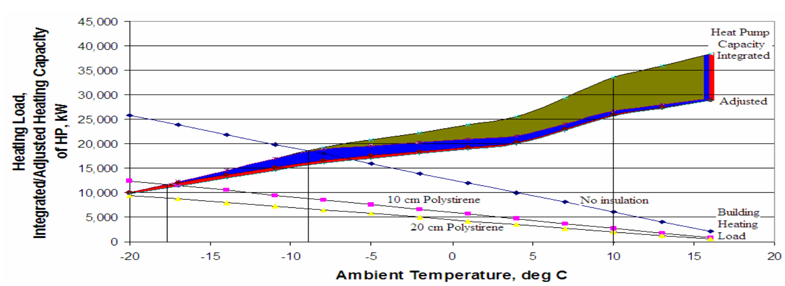

Fig. 2. *The balance point for three different building loads*

Improvements of the envelope thermal insulation (by using expanded polystyrene for the outside surface of the walls and mineral wool over the upper side of the floor, double/triple glazed thermo pane windows), and reducing the air leaks (tight-fitting windows and doors) result in a smaller load, and in a diminished building overall loss coefficient. A lowering of the balance temperature T_b can be noticed, as presented in Table 1. The most significant effect results by insulating with 10 cm of polystyrene: the heating load and the building overall loss coefficient are half the initial values. A double thickness of insulation will affect considerable less the thermal loss and the overall loss coefficient. Further improvement can be realized only by recovering the heat from the ventilated air.

Effects of Insulation Table 1

Improvements		Load	UA	T_b
Poly-styrene, mineral wool	40% heat recovery ventil. air	kW	$\frac{W}{K}$	°C
No	No	26.9	658	19.2
10 cm	No	13.2	323	18.5
20 cm	No	10.3	250	18.0
	Yes	7.9	193	17.4

The better the building insulation the lower the heating load and the lower the adjusted capacity of the heat pump.

As can be seen from Figure 3 this reducing of the integrated capacity leads to losses: for the insulated envelope with 20 cm of polystyrene the balance-point temperature is about −21 °C and it needs no supplemental (back-up) heating system. These losses due to cycling appear just from this balance-point temperature and are proportional with the surface limited by the upper and the lowest curve. The same heat pump is better used in the case of a similar building but only 10 cm of polystyrene insulated. In this case the balance-point temperature is −18 °C and losses due to the heat pump cycling are a little bit smaller as in the previous case.

Even smaller are the cycling losses for the building with no insulation: the balance-point temperature is increasing to −9 °C. In conclusion, by insulating a building envelope the corresponding balance-point temperature will diminish, and so the supplemental heating required. A reduced heat pump capacity can be selected by improving the insulation level of the building envelope. This results in a smaller capital costs and in smaller energy consumption during the system operation.

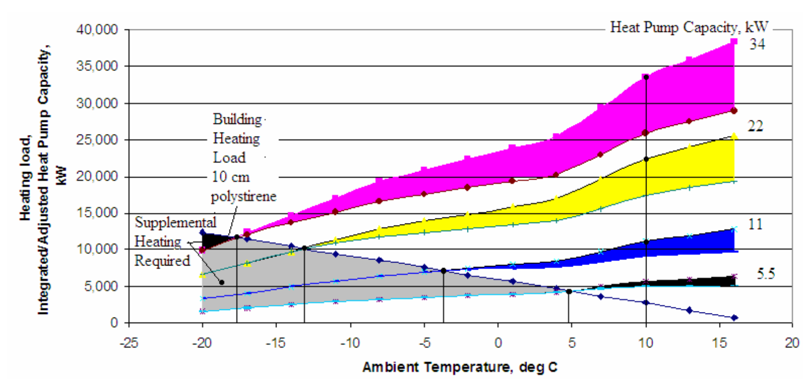

Fig. 3. *The influence of the heat pump capacity on the energy losses and on the supplemental heating required*

As can be seen from Figure 3 the smaller the capacity of the heat pump the smaller the losses (shaded surfaces over the balance point). But in the same time the supplemental heating required is increased when smaller capacity heat pump are selected.

All the above mentioned losses have as a result a decreasing of the coefficient of performance (COP) calculated on an annual basis. The COP of the system is decreasing compared with the COP of the heat pump when considering the losses together with the supplemental heating required, as shown in Figure 4.

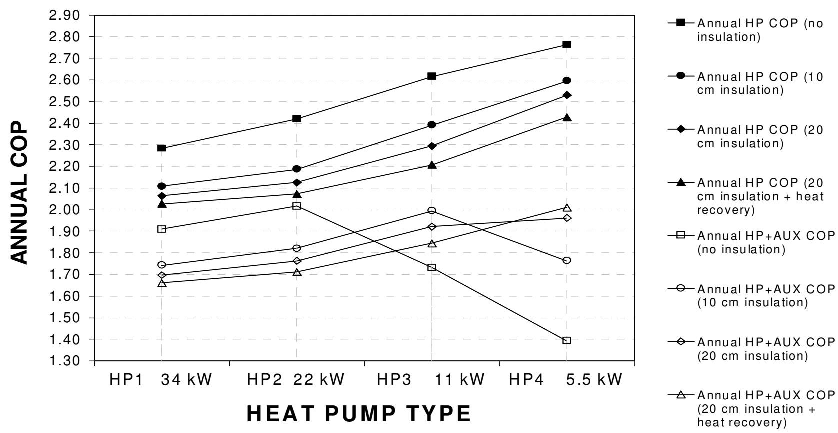

Fig. 4. *The maximum COP corresponding to the considered building and to the capacity of the heat pump*

In this way the optimum capacity for the heat pump in a given situation can be selected.

The heat pump COP is also influenced by the entering water temperature (HP EWT) in both the heating and in the cooling mode. The groundwater temperature (GW LWT), Figure 1 will affect the heat pump entering water temperature (HP EWT) and through this the heat extracted (HE):

$$HE = \dot{m}_g \, c\,(GW\ LWT - GW\ EWT)\,, \quad (1)$$

where $\dot{m}_g$ is the flow rate of the ground water extracted and c is its thermal capacity.

In the case of the cooling mode the same GW LWT will affect the heat rejected HR:

$$HR = \dot{m}_g c(GW\ EWT - GW\ LWT)\,. \quad (2)$$

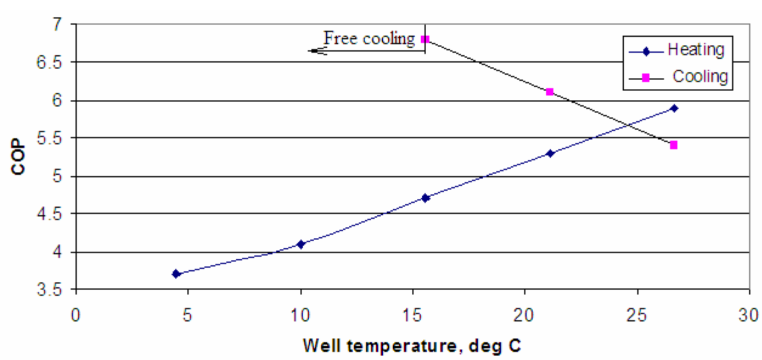

Fig. 5. *Geothermal operating efficiency for the heating/cooling mode*

Figure 5 presents the Geo-H/C operating efficiency correlated with the well temperature [1].

When the groundwater temperature (GR LWT) is becoming warmer the COP for the heating mode is improved, and for the cooling mode is falling down.

As a result the price of the thermal energy provided by the heat pump is changing. Considering also the cost of the electricity used to drive the heat pump (0.0781 €/kWh in August 2007 compared to 0.0875 €/kWh in April 2009, in Romania) a correlation of the thermal energy price with the ground-water temperature can be put in evidence as shown in Figure 6.

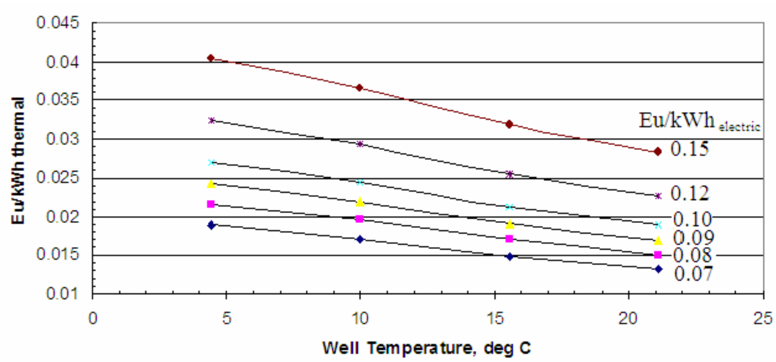

Fig. 6. *The cost of the energy provided by the heat pump for different temperatures of the well water and for some usual prices of electricity*

The cost per kWh mentioned before does not include the energy required by pumps or fans used for the operation of the heat pump. Changing in groundwater flow also has an impact on the HP EWT.

If the groundwater flow is increased the heat transfer inside the heat exchanger develops lowering the entering water temperature in the heat pump in the case of cooling mode and vice versa in the case of heating mode, as shown in Figure 7. In both cases an improvement of the COP is possible but limited.

For a more accurate analysis of the system

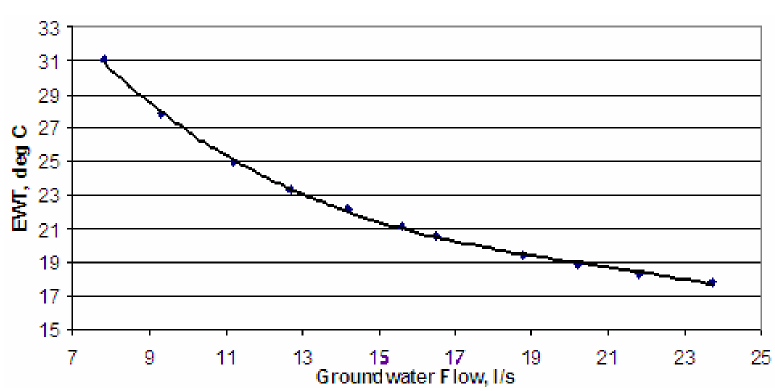

Fig. 7. *Entering water temperature as a function of the groundwater flow in case of the cooling mode*

the energy used to drive the pumps for the groundwater and for the building loop must be taken into account. In this case the COP of the system will be reduced compared with the COP of the heat pump and its payback period will be longer.

The motor efficiency of high water pump capacity is usually over 85%, but in the case of small water pump (50 to 100 W) the efficiency is much more less and the annual system COP is affected by this loss.

3. Optimum Groundwater Flow

Small groundwater systems have frequently been identified with excessive well pump energy consumption. Circulatory pumps may represent a significant portion of the total energy consumption of the ground coupled heat pump systems.

The well pump power is obtained as work required to rise the water over a height Δh from the drawdawn level DD plus static water level SWL called lift as shown in Figure 8.

This is the largest component of total well pump head in most applications. A constant additional height C_{st} (6 to 15 m) account for the remainder of the ground loop losses [8]:

$$P_{wp} = \frac{\rho \cdot g \cdot \dot{V}_g (\Delta h + C_{st})}{\eta_{pump} \cdot \eta_{motor}}, \tag{3}$$

where ρ is the density of the groundwater; *g* the acceleration of the gravity (9.81 m/s^2) and η is the efficiency.

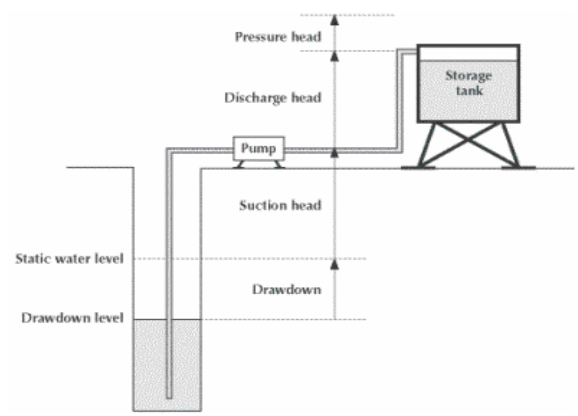

Fig. 8. *Well pump power constituents*

The wire-to-water efficiency for small circulating pumps (< 375 W), the so-called circulators, is usually less than half of the theoretical pumping power. Different practical surveys resulted in the following correlation of the theoretical power P_{th} with the circulators efficiency η_c [4]:

$$\eta_c = 0.06066 \cdot P_{th}^{0.3543}. \tag{4}$$

The recommended (electrical) power for the circulating pumps is 2.9 to 3.8 kW for 100 kW of refrigeration (air conditioning). Even if well pump power is less than 5% of the heat pump capacity the annual pumping energy may represent a significant portion of the total energy consumption of a heat pump system, i.e. 15 to 48% (in some cases even more than 100%). From the building loop performance perspective higher groundwater flows are always preferable but large values of the flow in the groundwater loop may entail high values of pumping energy. For this reason it is useful to rate the flow to the heat pump capacity (L/(s.kW) the specific flow resulting in this way. Many systems have been designed with groundwater specific flows in the range 0.036 to 0.054 L/(s.kW) but typical values are 0.018 to 0.031 L/(s.kW).

For the building loop the flow is usually 0.045 to 0.054 L/(s.kW). The building loop pumping power is assumed to be 17 W per kW of installed cooling capacity [7].

To arrive at system performance (COP), different from heat pump performance, the well pump power must be added with the building loop component power. As shown in Figure 9 higher flow rates increase system COP [2].

But at some point additional increase in groundwater flow results in a greater increase in well-pump power that the resulting decreases in heat pump power. The conclusion is that every particular application has an optimum peak groundwater flow for the heating and for cooling mode respectively and any flow in excess of this would result in greater cost, lower efficiency, and maintenance costs for the owner. An optimum flow exists for both of the two modes (heating/cooling). The sizing of the system including well, pump, heat exchanger, and piping will be based on the larger of these optimum flow. The operation of the system at the lower flow is possible by means of a variable speed or by cycling avoiding in this way the constant flow. Using a variable frequency drive (VFD) will bring benefits to the cost of energy. Supplementary cost and efficiency of the VFD together with the decreasing efficiency of the electric motor at part-load operation have to be taken into consideration.

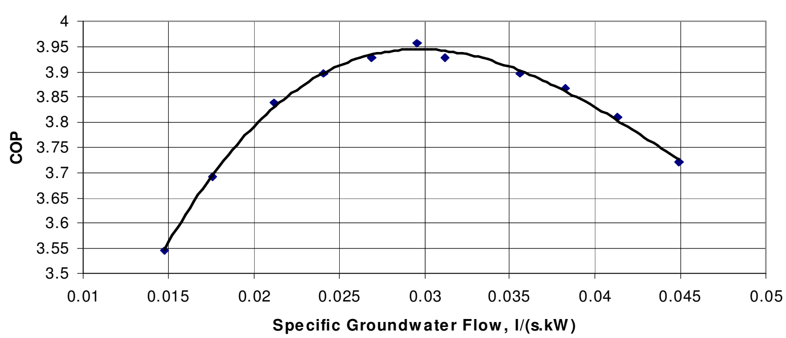

Fig. 9. *The system COP correlation with the specific groundwater flow*

To control the well pump cycling, i.e. to keep the specific flow around the optimum value corresponding to a maximum COP a temperature range between pump-on and pump-off temperatures has to be established. This depends on the optimum system building loop return temperature LWT (corresponding to the maximum COP value), but also it depends on the building loop water volume as a thermal capacity of the system.

Figure 10 shows the COP of the system consisting of the heat pump and the circulating pumps correlated with the building loop return temperature LWT. The COP of the system is kept at their peak values if the start and stop temperatures of the well pump are 27±2 ^{o}C (in this case 8.6 L/kW water volume of the building loop system) [7]. Starting the groundwater loop pump at LWT of 25 ^{o}C building loop return temperature and cutting it off at 29 ^{o}C the COP will be kept at higher values, in the above example over 3.78.

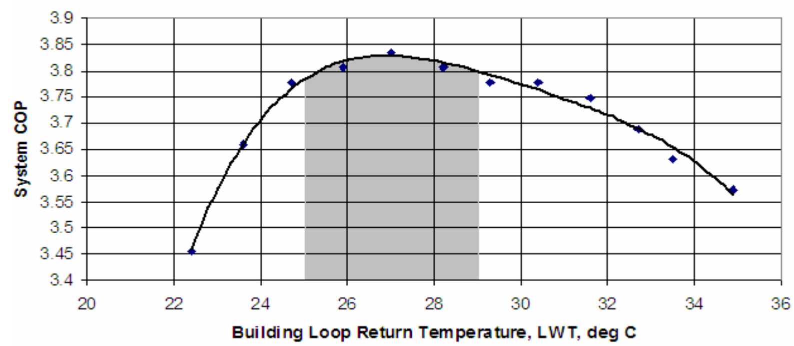

Fig. 10. *Peak system COP and start/stop temperatures from the building loop control the excessive well pump cycling*

4. Radiant Floor Heating

Efficient operation of the heat pump system is directly connected with the low temperature distribution of the heat: as shown in Figure 11 the COP of a heat pump decreases significantly as the hot water supply temperature increases.

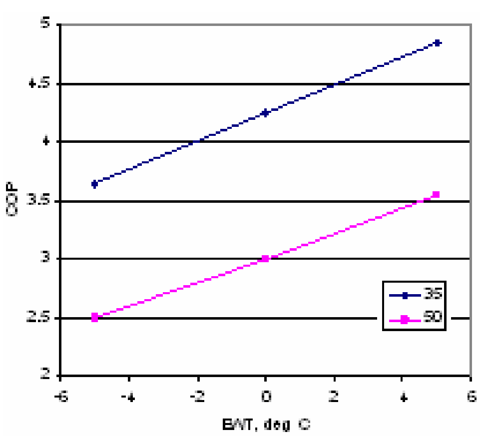

Fig. 11. *COP as a function of entering water temperature EWT for an output water temperature of 35 °C and 50 °C*

Manufacturers have developed tubing designed for installation in concrete floors and built-up wood floors, the so called radiant floor heating having several benefits in residential, commercial and industrial heating applications. In residential applications, occupants in a space feel comfortable with lower air temperatures if their feet are warm. Typically the space will feel comfortable with air temperatures as low as 18 °C.

Since the heat loss of a building is directly related to the temperature difference between the inside and outside, a lower temperature difference means the heat loss is lower.

Air temperatures in a room with floor heating tend to be warmer at the floor than the ceiling, helping cut down on infiltration in the building. The energy savings in a building with floor heating can range from 20-40% over traditional forced air systems, Figure 12.

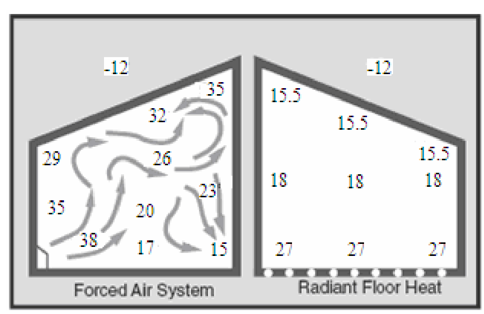

Fig. 12. *Heat distribution in the case of the radiant floor heating compared to the forced air system*

Temperatures in a forced air system tend to be more uneven than in a radiant floor heating system.

5. Conclusions

Designing an efficient open loop heat pump system needs to follow good design criteria as follows:

• An accurate heat loss and heat gain calculation must be done to size the system to operate efficiently. Solar radiation entering the room through the windows can be several hundreds watts, which is often even much more than the heat demand. The heat of the sun combined with the internal gains creates a need for cooling during the heating season. Shading windows from the direct sun radiation is highly recommended.

• The system must meet the application requirements. In other words, the design of the system must take into consideration the type of distribution system and the needs of the customer. The floor heating system is often designed with a tube spacing of 150 mm or more but for cooling mode it may be necessary a smaller spacing. Because of the condensation risk excessively low supply temperatures must be avoided and the system should be designed with a 3 to 5 ^{o}C temperature difference between supply and return water. This will result in higher water flow rate and a higher pressure drop in the tubes.

• The components of the system must be designed to work together. The loop must be designed to work with the heat pumps, the pumping system must work efficiently with the water-well and the heat distribution, and the distribution system must be chosen to work efficiently with the water temperatures available from the equipment.

• The system must be controlled to operate as efficiently as possible. It is important to operate the system to take variations in the building loads into account. For example, the heat loss of the building is reduced hence the outdoor temperature climbs, and the temperature of the water circulated through the distribution system can be lowered, allowing the heat pumps to operate more efficiently.

• Modulating the various components of a system to meet the varying requirements of a building can significantly improve the efficiency of a system. Variable-speed pumps, for example, can greatly increase the overall efficiency of a system. Most of the variable refrigerant flow systems currently available on the market dispose of linear inverter driven compressors which have a variable proportional integral control system utilizing refrigerant pressure sensors to refine the compressor control steps into even smaller units, resulting in more precise control over air conditioned areas. Energy efficiency increases dramatically during part load operation, during which less capacity is required. The compressor therefore, rotates more slowly and the coil becomes virtually oversized [5].

• The cost-effectiveness of the system must be considered. Regardless of the application, the design must take into account operating costs, installation costs and future repair/maintenance.

The minimum value of seasonal coefficient of performance should be greater than 2.875 [3]. Water-to-water heat pumps have a COP of 3.50 or higher, while a typical hot water boiler has a COP of 0.85.

It is true that replacing a fossil fuel boiler with an electric drive heat pump causes the building electrical consumption to increase and this will increase CO_2 emissions at the utility power plant. However, this is more than offset by the significant reduction in CO_2 emissions by not burning as much fossil fuel to heat the building.

Available standard heat pump systems will only be economically feasible in buildings with centralized heating systems that are well insulated, have double glazing or better, have an air-tight envelope and use a low temperature heat distribution system.

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