IMPROVING WATER LOOP HEAT PUMP PERFORMANCE BY USING LOW TEMPERATURE GEOTHERMAL FLUID

LI XINGUO

Tianjin Geothermal Research and Training Center, University of Tianjin. Tianjin, P.R. China

SUMMARY

Water-loop heat pump (WLHP) systems are an important option for space conditioning of commercial buildings. They provide the opportunity of saving energy through heat recovery and thermal balancing when heating and cooling occur simultaneously. WLHP systems typically operate with loop water temperature between 16°C and 32°C. When cooling loads dominate, loop water temperatures are maintained below 32°C by rejecting excess heat with a cooling tower. When heating dominates, loop water temperatures are maintained above 16°C by a heater input. The capacity and efficiency of water-source heat pumps (WSHP) in both operating modes are strong functions of the inlet water temperature.

The emphasis of this paper is on the analysis of system performances, energy savings of the mixed cooling and heating mode of the WLHP systems for it is a unique operating mode in the air-conditioning and space heating systems. The energy saving effect by using low temperature geothermal as the heat input for WLHP systems was examined.

Key words: Water-loop heat pump systems, Low temperature geothermal, Cooling, Heating, Energy saving, System performance.

1. WATER-LOOP HEAT PUMP SYSTEMS

Figure 1 is a diagram of the typical WLHP systems. A WLHP system consists of individual water-source heat pumps (WSHP) located in each zone. The heat pumps are linked with a common circulating water loop that serves as a heat sink when cooling and a heat source when heating. The system is capable of operating in three modes.

Cooling Only: In cooling--load--dominate, heat is being added to the loop by the heat pumps, and the temperature of the water in the loop increases. A cooling tower is used to maintain loop water temperatures below a maximum level, usually about 32°C.

Heating only: In heating—load—dominate, heat is being removed from the loop by the heat pumps, and the temperature of the water in the loop decreases. A heater is used to maintain loop water temperature above a minimum level, usually about 16°C.

Mixed cooling and heating: In this mode, some of the heat pumps operate in cooling mode and others in heating mode. Heat that is rejected to the loop by the heat pumps in cooling mode can serve as a heat source for those heat pumps in heating mode. If the amount of heat added to the loop by the units in cooling mode exceeds the amount of heat removed from the loop by the heat pumps in heating mode, then the excess heat is

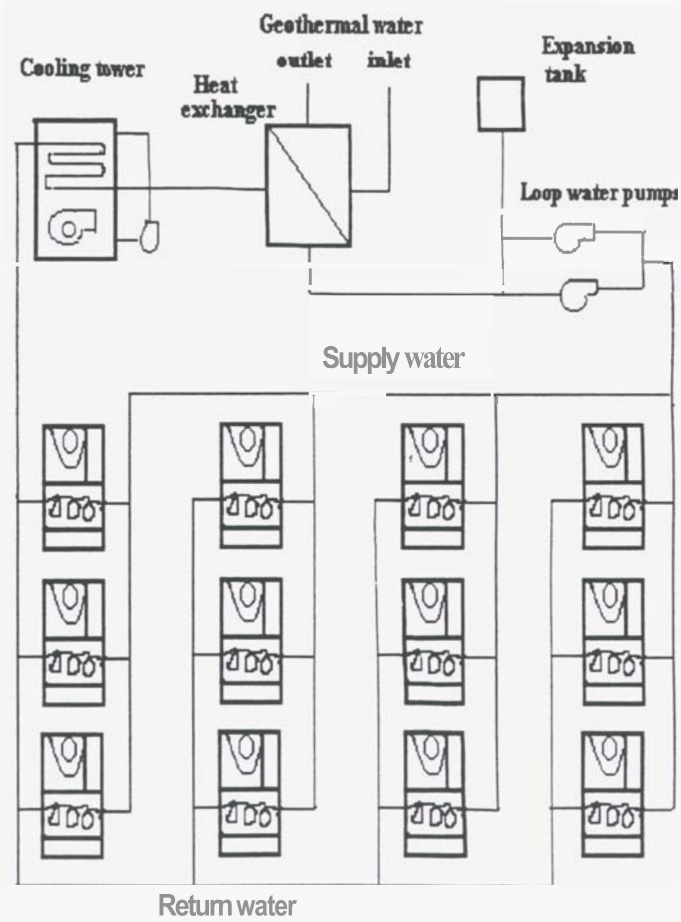

Figure 1 Water-loop heat pump systems

rejected to the ambient by the cooling tower. If the amount of heat rejected to the loop by the units in cooling mode is less than the amount of heat removed from the loop by the heat pumps in heating mode, heat is added to the loop by a heater input. The heater can be a gas or oil--fired boiler, or electric heater, or ground--source energy, e.g. the low temperature geothermal shown in Figure 1.

These features make WLHP systems attractive for many commercial and public buildings for the energy saving by transferring or balancing heat from building areas requiring cooling (typically, the core) to areas requiring heating simultaneously (i.e. perimeter zones).

In the three operating modes: cooling only, mixed cooling and heating, and heating only, the mode of mixed cooling and heating is a unique operating mode in the air-conditioning and space heating systems, and its system performance and energy saving is characteristic differently from the conventional systems. The emphasis will be on the analysis of load features, operating characteristics, energy saving and system performance of the mixed cooling and heating mode for WLHP systems. The conditions of heating only and cooling only for WLHP systems are similar to the conventional air-conditioning and heating systems, and the discussions on them will not be taken in this paper.

The climatic conditions will be the base of the performances for the WLHP systems. Tianjin, for example, is in the North of China. The four seasons vary clearly. The average outdoor temperature of a year is 11.0~13.3°C. The minimum temperature is -18.3°C, and the maximum temperature is 39.9°C in a year. The main meteorological parameters in heating season are shown below.

Item	Value
Indoor calculation temp.	18 °C
Outdoor calculation temp.	-9 °C
Average outdoor temp. during a heating season	0.3 "C
Start and end outdoor temp. during a heating season	≤+8 °C
Duration of a heating season	147 Days/y
Heating degree-days of a heating season	2014°C.day

2. WSHP PERFORMANCE AS A FUNCTION OF LOOP TEMPERATURE

In WLHP systems, the loop water temperature is designed to operate between 16°C and 32°C by the cooling tower and the heater. The capacity and efficiency of WSHPs in every operating mode are strong functions of the inlet water temperature, which is the loop water temperature of the WLHP system. Table 1 shows the average relative performance values for WSHPs in accordance with Air-Conditioning and Refrigeration Institute (ARI) Standard 320 at the following inlet water temperature: for cooling performance ratings--85°F (29.4°C), and for heating performance ratings--70°F (21.1°C).

During the cooling--dominated periods, the loop operators at the upper extremes of the temperature ranger, where the COPc is as much as 6% below the ARI rating and the COPh is as much as 8% above the ARI rating. During the heating--dominated periods, the loop operators at the lower extremes of the temperature ranger, where the COPh is as much as 4% below the ARI rating, but the COPc is as much as 30% above the ARI rating[1].

Table 1 Performance of WSHPs at Various Loop Temperatures

Loop Temp. °F (°C)	ARI Rating	Relative Cooling Capacity Qc^R	Relative Cooling $COPc^R$	Relative Heating Capacity Qh^R *	Relative Heating $COPh^R$
90(32.2)		0.98	0.94	1.50	1.08
85(29.4)	Cooling	1.00	1.00	1.45	1.06
80(26.7)		1.02	1.06	1.40	1.04
75(23.9)		1.04	1.12	1.35	1.02
70(21.1)	Heating	1.06	1.18	1.30	1.00
65(18.3)		1.08	1.24	1.25	0.98
60(15.6)		1.10	1.30	1.20	0.96

*Heating capacity/ARI-rated cooling capacity

These performances of WSHPs trends as a function of loop water temperature, shown in Table 1, can be represented by the following linear equations:

$$COPc = COPc^R \quad COPc^{ARI} = (1.64-0.0216T_L) \; COPc^{ARI} \qquad (1)$$

$$COPh = COPh^R \cdot COPh^{ARI} = (0.85+0.0072\,T_L) \; COPh^{ARI} \qquad (2)$$

T_L ---- The loop water temperature °C.

$COPc^{ARI}$, $COPh^{ARI}$ ---- The coefficients of performance of heat pumps in cooling and heating respectively at ARI Standard for cooling 85°F (29.4°C) and heating 70°F (21.1°C). In this paper, the $COPc^{ARI}$, $COPh^{ARI}$ were assumed:

$$COPc^{ARI} = 3.2, \; COPh^{ARI} = 4.0$$

3. LOAD FEATURES OF MIXED COOLING AND HEATING

To simplify the presentation, a specific combined cooling and heating load of the buildings, is assumed. This load is shown in Figure 2 and can be represented by the equations.

Most core zones can be manageable, and the core cooling load (Qc) is constant 90% of the time.

$$Qc = \text{A relative value of } 1.0 \quad (3)$$

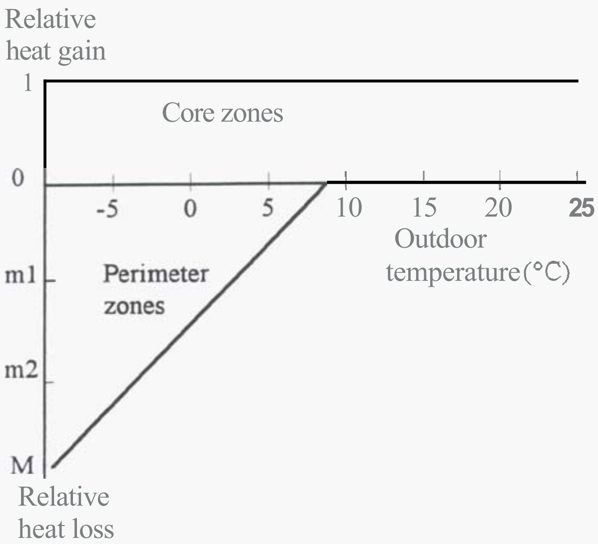

Figure 2 Relative cooling and heating loads
*M — The relative heat loss at outdoor temperature -9°C, referenced to a core cooling load Qc, with a relative value of 1.0.

Perimeter of the buildings is the most critical and variable, being constantly affected by outdoor temperatures changed, wind, rain etc. The perimeter heating load (Qh) is strong function of the size, structure of the building at a certain outdoor temperature. For simplification, the Qh is assumed as a linear equation with the outdoor temperature (T_A) referenced to a core cooling load Qc, with a relative value of 1.0.

$$Qh = Qc \cdot (8 - T_A) \cdot M/17 \quad (4)$$

The rate of heat addition to the loop by the core heat pumps operating in the cooling mode can be expressed as:

$$Qa = Qc \cdot (1 + 1/COPc) \quad (5)$$

The rate of heat removal from the loop by the perimeter heat pumps operating in the heating mode is:

$$Qr = Qh \cdot (1 - 1/COPh) = Qc \cdot (8 - T_A) \cdot M/17 \cdot (1 - 1/COPh) \quad (6)$$

When Qr is more than Qa, the loop heater comes into use to maintain the loop water temperature above 16°C. The heat output to the loop by the heater is the difference of Qr and Qa, which can be delivered as follow

$$W_L = Qr - Qa = Qc \cdot [(8 - T_A) \cdot M/17 \cdot (1 - 1/COPh) - (1 + 1/COPc)] \quad (7)$$

The power input to the heat pumps in cooling and heating mode can be expressed as follows respectively:

$$Wc = Qc/COPc \quad (8)$$

$$Wh = Qh/COPh = Qc \cdot (8 - T_A) \cdot M/17 / COPh \quad (9)$$

In the operting mode of mixed cooling and heating, the power input to the heat pumps is the sum of the power supplied to the units operating in the cooling mode plus the power supplied to the units in the heating mode. Which can be expressed as:

$$Whp = Wc + Wh \quad (10)$$

4. BALANCE OUTDOOR TEMPERATURE

A balance point of the loop can be delivered from equation (7). That is, at an outdoor temperature (T_A^b), the amount of heat added Qa by the heat pumps that are cooling equals the amount of heat removed Qr by the heat pumps that are heating At T_A^b, the cooling tower and a heater is keeping off. Above T_A^b, the cooling tower is on to reject excess heat with a 32°C leaving water temperature. Below T_A^b, a heater comes into use, and the loop water temperature moves to 16°C. From equation (7), T_A^b can be obtained:

$$T_A^b = 8 - 29.48/M \quad (11)$$

In this discussion, the M is assumed to be 6.0, and the T_A^b can be obtained as 3.09°C.

T_A^b is variable, and critical function of the relative heat loss in the perimeter zones. Which is shown in Figure 3. It shows that T_A^b increases with the increase of relative heat loss (M). If M is large enough referenced to Qc, or Qc is small enough referenced to M, the T_A^b approaches the Starting temperature of heating, which is 8°C. It means that the heating load dominates, and operating mode of heat pumps tends to the heating only.

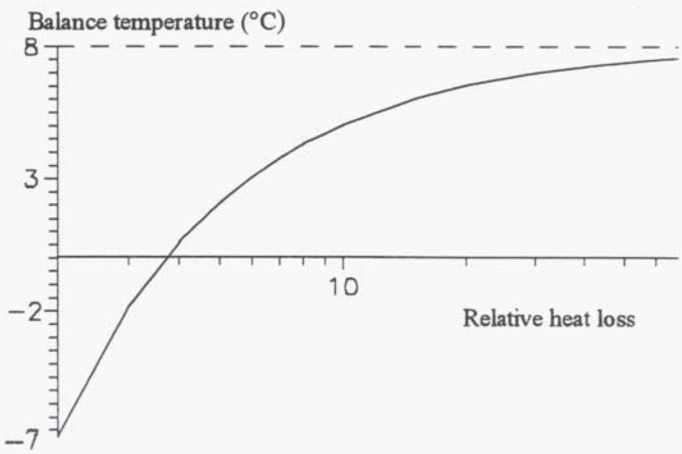

Figure 3 The variation of balance temperature with the relative heat loss

5. OPTIMUM LOOP WATER TEMPERATURE

Both COPc and COPh are the function of loop temperature, there may be other loop operating temperature that would result in lower energy consumption. To determine the optimum loop temperature for a particular condition, the power input was expressed as a function of loop temperature, differentiated to obtain the slope, and the derivative was set equal to zero; this yielded the loop temperature at which lowest power input occurs.
Using equation (1) and (2), equation (10) can be expanded to:

$$Whp = Qc/[(1.64-0.0216 \cdot T_L) \cdot COPc^{ARI}] + QW/[(0.85+0.0072 \cdot T_L) \cdot COPh^{ARI}] \qquad (12)$$

Differentiating this expression with respect to T_L, setting the derivative equal to zero, and solving for the optimum T, which yields a minimum power input, the following is obtained:

$$T_{L(opt)} = \frac{1.64(1/3 \times COPc^{ARI}/COPh^{ARI} \times Qh/Qc)^{0.5} - 0.85}{0.0216(1/3 \times COPc^{ARI}/COPh^{ARI} \times Qh/Qc)^{0.5} + 0.0072}$$

Figure 4 shows that the higher the heating to cooling load ratio (Qh/Qc), the higher the optimum loop temperature. At the lower or higher Qh/Qc, the values indicate very low and high optimum loop temperature respectively, which are definitely not practical for they beyond the normal operating range of 7°C to 32°C. It just suggests that the loop temperature should be kept as low or high as possible for best overall efficiency. The reasonable loop operating temperature should be kept within the range of 7°C to 32°C outlined in the Figure 4.

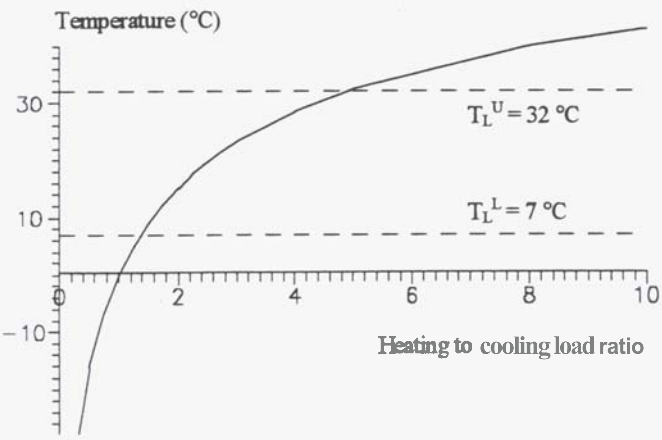

Figure 4 The variation of optimum loop temperature with the heating to cooling load ratio

6. POWER USE BY HEAT PUMPS AND LOOP HEATER

The power consumption of the WLHP systems is the sum of the power supplied to the heat pumps plus the energy supplied to the loop heater and the cooling tower. To simplify the presentation, the energy input to the cooling tower is not included for it can be negligible at these winter outdoor temperatures.

For non-optimum loop temperature conditions, the heat pumps operate at the loop water temperature 32°C and 16°C respectively with the outdoor temperature above and below the balance temperature T_A^b. In these conditions, the power input to the heat pumps in cooling and heating mode can be expressed as follows fiom equations (1) (2) (8) (9).

$Wc = 0.33 \quad (8°C \sim T_A^b)$
$Wc = 0.24 \quad (T_A^b \sim -9°C)$

$Wh = (8-T_A^b) \cdot M/73.44 \quad (8°C \sim T_A^b)$
$Wh = (8-T_A^b) \cdot M165.62 \quad (T_A^b \sim -9°C)$

The total power input to heat pumps is:

$Whp = Wc + Wh$

Below the balance temperature T_A^b, the loop heater comes into use. The heat output to the loop by the heater can be expressed as follow by equation (7):

$Wl = (8-T_A^b) . M/22.94 - 1.24$

The results of this analysis for non-optimum conditions are shown in Table 2 and Figure 5 with solid lines. The total power input to heat pumps Whp is increased linearly with the outdoor temperature T_A. T_A^b is a slight discontinuity, as a result, there are two straight liners above and below T_A^b respectively. The increase of Whp with T_A is correspondent to the increase of relative heat loss M with T_A.

Below T_A^b, the loop heater comes into use, and the increase rate of energy use (i.e. the linear slope) by heater is larger than that of Whp. Below -2.5°C, the heater output is higher than Whp.

Similar to the analysis of non-optimum conditions, the calculations of optimum conchtion for the same loads are shown in Table 3 and Figure 5 with the dashed lines. Significant reductions in average power to heat pumps are indicated when the loop is operated at these optimum temperature levels. Energy savings by heat pumps operating at optimum loop temperatures would be at 5% to 10% level. The loop heater output is increased at the same operating conditions. It's found that the amount of energy increased by the heater output equals the amount of power reductions by heat pumps, and the total power use by the heat pumps and loop heater is the Same for the non-optimum and optimum conditions. It's demonstrated that the conservation of energy of the WLHP system is indicated for it's a close energy system.

Accumulated energy use during a heating season is an important parameter, which can directly indicate the amount of energy consumption and energy saving effect for WLHP systems during the operating season. Accumulated energy use during a heating season can be calculated by use of the heating degree-days. In the paper, the relative values W_R^{Total} are used, which W_R^{Total} is the ratio of accumulated energy use during a heating season for power input to heat pumps, loop heater output and the total power use to the value of Qc^{Total} as the accumulated energy use during the heating season for core cooling load Qc, which is a relative value of 1.0.

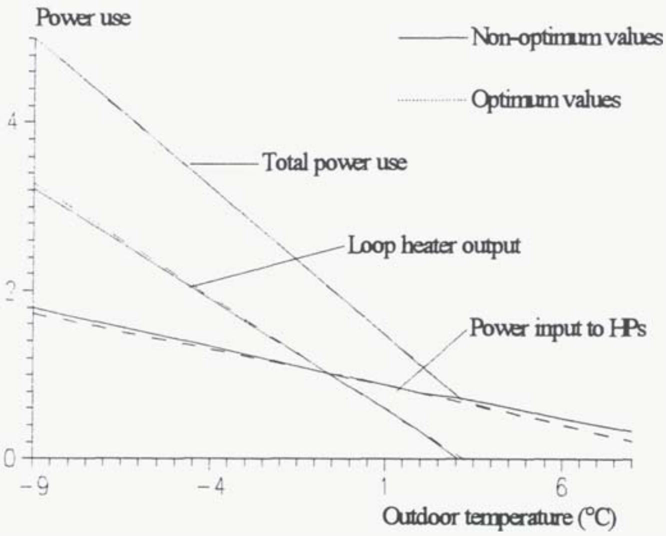

Figure 5 The variation of power use by heater and heat pumps with outdoor temperature

Table 2 Power input to the loop and heat pumps

Outdoor temp. °C	Heating load Qh	Loop temp. °C	Power input to heat pumps Cool	Heat	Total	Loop Heater output	Total Power use
8	0.00	32	0.33	0.00	0.33	0.00	0.33
6	0.71	32	0.33	0.16	0.49	0.00	0.49
4	1.41	32	0.33	0.33	0.66	0.00	0.66
3.09	1.73	32	0.33	0.40	0.73	0.00	0.73
2	2.12	16	0.24	0.55	0.79	0.33	1.12
0	2.82	16	0.24	0.73	0.97	0.85	1.82
-2	3.53	16	0.24	0.91	1.15	1.38	2.53
-4	4.23	16	0.24	1.10	1.34	1.90	3.24
-6	4.94	16	0.24	1.28	1.52	2.42	3.94
-8	5.65	16	0.24	1.46	1.70	2.94	4.65
-9	6.00	16	0.24	1.55	1.79	3.21	5.00
*W_R^{Total}			0.26	0.81	1.07	1.22	2.29

All heating load, power input to HPs, and heater putput are referenced to a core cooling load Qc, with a relative value of 1.0.

* W_R^{Total} is the relative accumulated energy use during a heating season referenced to the value of Qc^{Total} as the accumulated energy use during the heating season for core cooling load Qc, with a relative value of 1.0

Table 3 Power input to the loop and heat pumps at optimum loop temperature

Outdoor temp. °C	Heating load Qh	Loop temp. °C	Power input to heat pumps Cool	Heat	Total	Loop Heater output	Total Power use
8	0.00	7.00	0.21	0.00	0.21	0.00	0.21
6	0.71	7.00	0.21	0.20	0.41	0.00	0.41
4	1.41	7.64	0.21	0.39	0.60	0.00	0.60
3.26	1.73	11.25	0.22	0.45	0.67	0.00	0.67
2	2.12	16.32	0.24	0.55	0.79	0.33	1.12
0	2.82	22.10	0.27	0.70	0.97	0.86	1.82
-2	3.53	26.32	0.29	0.85	1.14	1.39	2.53
-4	4.23	29.61	0.31	1.00	1.31	1.93	3.24
-6	4.94	32.00	0.33	1.14	1.47	2.47	3:94
-8	5.65	32.00	0.33	1.31	1.64	3.01	4.65
-9	6.00	32.00	0.33	1.39	1.72	3.28	5.00
*W_R^{Total}			0.28	0.76	1.04	1.24	2.28

All heating load, power input to HPs, and heater output are referenced to a core cooling load Qc, with a relative value of 1.0.

* W_R^{Total} is the relative accumulated energy use during a heating season referenced to the value of Qc^{Total} as the accumulated energy use during the heating season for core cooling load Qc, with a relative value of 1.0.

The calculations of W_R^{Total} for non-optimum and optimum conditions are shown in the last row of Table 2 and Table 3. It's shown that the W_R^{Total} of power input to heat pumps for optimum condition is lower than that of non-optimum condition, but the W_R^{Total} of loop heater output for optimum condition is higher than that of non-optimum condition, and the W_R^{Total} of total power use for optimum and non-optimum condition is the same. The conclusions of this analysis are the same as above.

Figure 6 shows the variation of relative accumulated energy use during a heating season W_R^{Total} with the relative heat loss M. The results indicate the same conclusions for the values W_R^{Total} of power input to heat pumps, loop heater output and the total power use.

7. ENERGY SAVING EFFECT FOR WLHP SYSTEMS BY USING LOW TEMPERATURE GEOTHERMAL,

A heater is used for the loop of *WLHP* systems to maintain loop water temperature above a minimum level, usually about 16°C. The heater can be a gas or oil–fired boiler, or electric heater, or ground--source energy, e.g. the low temperature geothermal shown in Figure 1.

The results of the analysis on the power use by heat pumps and loop heater above show that the loop heater output is the large amount of energy consumption in the WLHP systems. From the calculations, a point of intersection can be obtained. Figure 6 shows that, above this point, the W_R^{Total} of loop heater output is higher than the W_R^{Total} of power input to heat pumps. Below

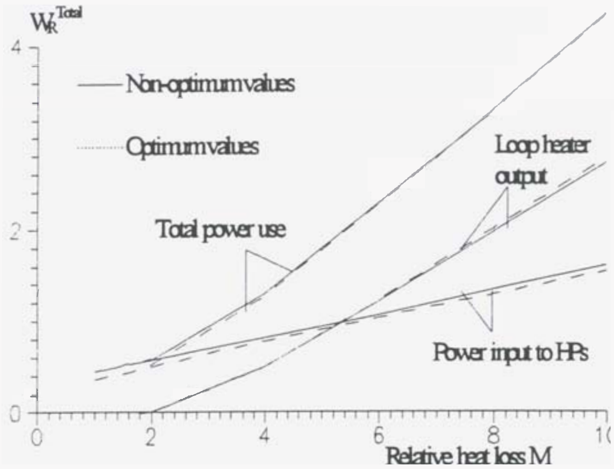

Figure 6 The variation of relative accumulated energy use W_R^{Total} with relative heat loss M

this point, the W_R^{Total} of loop heater output is lower than the W_R^{Total} of power input to heat pumps. For example, in non-optimum conditions, this point is 5.38 for relative heat loss M.

As a result, the energy consumption by loop heater is quite large in the energy use of *WLHP* systems, so the energy saving on loop heater is considerably valuable and effective.

It's quite common that the discharged water temperature of most geothermal space heating systems is higher than 45°C, some even reaching 60°C in China. If this kind of abandon energy can be used to the WLHP systems as the loop heat input, the energy saving is not only gained effectively, but also the energy waste and pollution by the geothermal water discharged at high temperature would be prevented or avoided.

From the calculations above, the energy saving effect of 53.3% for non-optimum conditions and 54.4% for optimum conditions can be obtained by using the discharged geothermal water or low temperature geothermal to replace the boiler, which the boiler's thermal efficiencies are not counted in.

8. CONCLUSIONS

Water-loop heat pump systems are an important option for space conditioning of commercial and public buildings. The energy is saved by transferring or balancing heat from building areas requiring cooling (typically, the core) to areas requiring heating simultaneously (i.e. perimeter zones).

The mixed cooling and heating mode of the WLHP systems is a unique operating mode in the air-conditioning and space heating systems.

The energy saving effect of 53.3% for non-optimum conditions and 54.4% for optimum conditions can be obtained by using the low temperature geothermal to replace the boiler.

REFERENCES

Kush, E.A. and Brunner, C A. **(1992).** Optimizing water-loop heat pump design and performance. *ASHRAE Journal,* No.2.

Lienau, P.J. **(1995).** Geothermal heat pumps performance and utility programs in the United States. ***Proceeding of the World Geothermal Congress 1995,*** Italy, May.

Pietsch, J.A. **(1991).** Optimization of loop temperatures in water-loop heat pumps systems. *ASHRAE* ***Transactions,*** Vol. **97, Part 1**.

Xinguo, L. **(1994).** Analysis on technique and economics of geothermal heat pump-air conditioning systems. ***5th College and University's Engineering Thermophysics Conference,*** **China, Oct**

Xinguo, L. **(1995).** Analysis on technique and economics of low temperature geothermal space heating by heat pumps. ***Proceeding of the World Geothermal Congress 1995,*** Italy, May.