SIMULATION OF THE PERFORMANCE OF A BIPV/T SYSTEM COUPLED TO A HEAT PUMP IN A RESIDENTIAL HEATING APPLICATION

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Abstract: Building-Integrated Photovoltaic/Thermal (BIPV/T) systems consist of photovoltaic arrays incorporated seamlessly as a functional part of the building envelope; while generating electricity, they also make use of a circulating fluid (often air) for recovery of useful heat from the incident solar radiation. This has the additional benefit of cooling the photovoltaic panels, consequently improving their efficiency. For open loop BIPV/T air systems, although the air is considerably heated, its temperature often remains too low for direct use in building space heating applications. However, it is usually adequate to serve as the source of a heat pump. This paper presents the results of a simulation used as a decision-making tool in the system configuration design and the selection of the heat pump model to be coupled to the BIPV/T roof of a net-zero energy house. The simulation took into account the performance of several key elements of the house (BIPV/T, air-to-water heat exchanger, heat pump, storage tank) and manufacturer's data. Recommendations of desirable features in a heat pump operating with a BIPV/T system are presented.

Key Words: ***BIPV/T*, *heat pump, sustainable building, solar energy***

1 INTRODUCTION

In 2006 the Canada Mortgage and Housing Corporation (CMHC), a governmental institution, organised the *EQuilibrium Housing* initiative, a nation-wide house design competition. This program had the goal of promoting an innovative approach to the design, construction and operation of houses. At the core of this approach is the exploration of inherent possibilities and advantages of currently available technologies and design techniques for the development of houses with new standards in energy efficiency, environmental impact, comfort and health for their occupants. Nearly 70 projects were presented in the first phase of the competition. Several criteria were taken into account in the assessment of the proposals: energy-efficiency, health and comfort, environmental impact, repeatability and affordability. In early 2007, twelve projects were chosen from across Canada by CMHC to receive a grant to contribute to carry the project through completion. Several members of the Concordia University Solar Laboratory (Chen et al. 2007; Candanedo et al. 2007) participated in the design of two of the winning projects: Maison ÉcoTerra Alouette (located in Eastman, Québec) and Alstonvale Net Zero House (located in Hudson, a town in the vicinity of Montréal).

Both the ÉcoTerra and the ANZH projects have a Building Integrated Photovoltaic/Thermal (BIPV/T) roof as a fundamental component. BIPV/T systems use a circulating fluid (usually exterior air) to recover useful heat from photovoltaic (PV) panels integrated on the envelope of the house, which makes them particularly practical for cold climate conditions. Recovering heat from the PV panels also improves their electrical efficiency by lowering their temperature. The air coming from the BIPV/T roof will sometimes be hot enough to allow direct heat recovery. Although air temperatures will often be too low for this use, they will be within the optimum range to serve as the source of a heat pump.

A feature that makes the ANZH unique among the *EQuilibrium* demonstration projects is its application of a heat pump to recover energy from the BIPV/T roof hot air, making it the main source of heat for space heating needs. This is accomplished by passing hot air through an air-to-water heat exchanger, acting as the heat source for a heat pump. The heat will finally be stored in a large water reservoir. Occasionally, the temperature of the air will be high enough to avoid the use of the heat pump altogether, and the heat exchange can take place directly between the air and the water of the reservoir. To further boost the temperature of the air, a glazing section will be located above the 7 kW PV array. Similar (but not identical) systems have been previously used (Puren 2007).

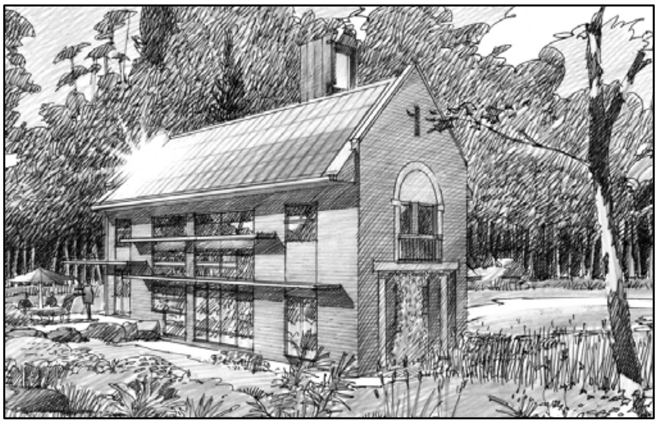

Figure 1. Alstonvale Net Zero House.

2 DEVELOPMENT OF THE BIPV/T – HEAT PUMP CONFIGURATION

Figure 2 depicts conceptually some of the features of the original design of the ANZH. Apart from the BIPV/T system, the house included —and still does— a solar collector connected to a domestic hot water (DHW) tank and a wood pellet stove as the final backup system. For simplicity, the piping system between these systems is not shown. However, heat exchange between them is possible, as indicated by the arrows in the diagram.

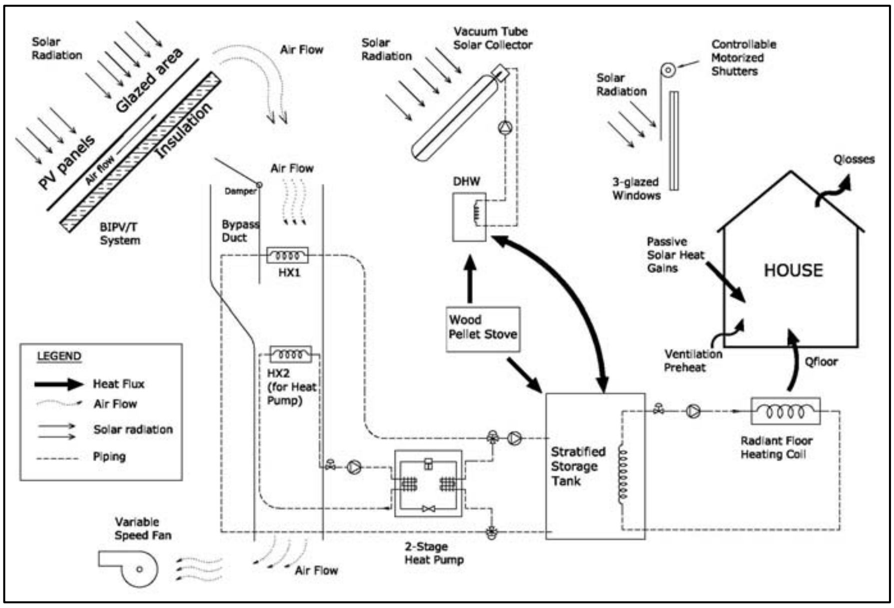

Figure 2. Schematic of the main features of the original Alstonvale House design. Note the BIPV/T–heat pump configuration.

The original plan included two heat exchangers: one for direct connection with the water reservoir and one for the heat pump. This configuration offered the advantage that under optimal conditions (i.e. very hot air) both heat exchangers could work in series removing heat successively. If the air temperature were not high enough for direct heat extraction, the first heat exchanger could be bypassed to reduce the pressure drop and consequently the energy consumption. With this configuration, a single air-to-water heat pump could replace the group formed by the second heat exchanger plus the water-to-water heat pump. However, the BIPV/T design in Figure 2 underwent several modifications before reaching its final form. Some of the reasons for these changes are explained below.

3 SELECTION OF THE HEAT PUMP: FIRST STEPS

3.1 Deciding between an air-to-water HEAT PUMP or a water-to-water HEAT PUMP

An appropriate air-to-water heat pump with proper characteristics proved difficult to find. At least one model was seriously considered (Climate Master Tranquility 27™) but the uncertainty about its connection to the chosen control system was a strong factor against its selection. Another disadvantage of the air-to-water heat pump was that the occasions allowing both direct heat recovery (HX1) and heat pump usage (HX2) would be rather atypical, making the configuration in Figure 2 unnecessary. These factors, along with space, cost of the overall installation and other practical considerations, finally imposed the use of only one heat exchanger (air-to-water) together with at least one water-to-water heat pump, preferably with several stages. The modified configuration is shown in Figure 3. This configuration had the additional advantage of simplified ducting and piping systems.

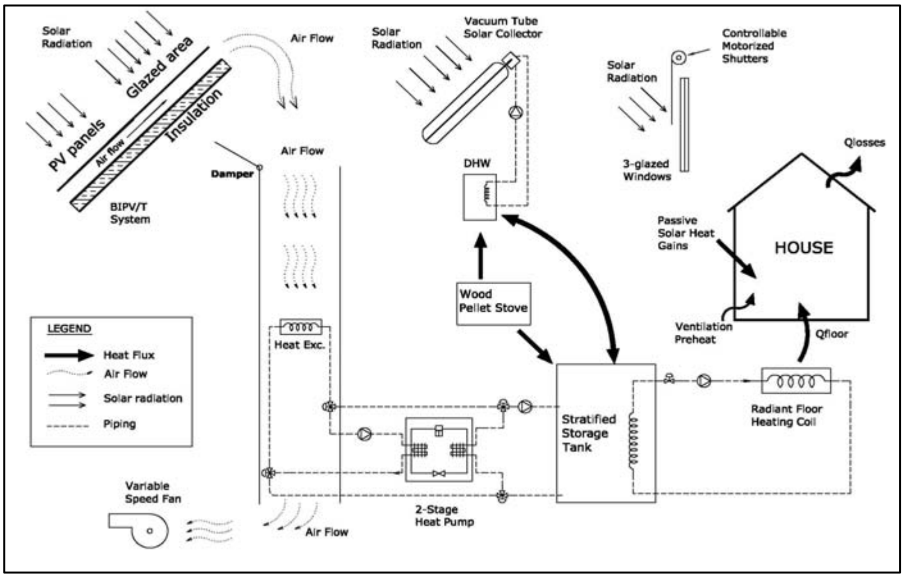

Figure 3. Configuration with a single heat exchanger and a 2-stage heat pump.

3.2 Requirements of the Heat Pump for the BIPV/T System

The most relevant attributes considered in selecting the heat pump are summarised below:

- The ability to make use of relatively cold temperatures at the source side, thus extending the availability of useful heat for days even with moderate solar radiation figures.
- Temperatures as high as possible on the sink side (or load side), to increase the heat storage capacity of the tank.

- Nominal capacity close to the estimated peak load (12-13 kW).
- Two or more stages were highly desirable as a BIPV/T system is highly dependent on variable weather conditions; capacity of working at part load was needed.
- Related to the point above, flexibility to work under rapidly varying conditions was also required.
- Availability of equipment and service in local markets.
- A reasonably high coefficient of performance (COP) under any circumstances (higher than 3.5).
- Ease of control.

3.3 One large Heat Pump vs. two small Heat Pumps in Parallel

None of the available models were optimal. In particular, a suitable two stage heat pump was especially difficult to find. Two options were considered, both using Genesis™ Water-to-Water heat pumps (Climatemaster®), shown in Figure 4 and Figure 5: this document must not be considered an endorsement for this or any other product mentioned herein.

a) A single heat pump with a nominal capacity higher than desired (17.6 kW = 5 Ton).

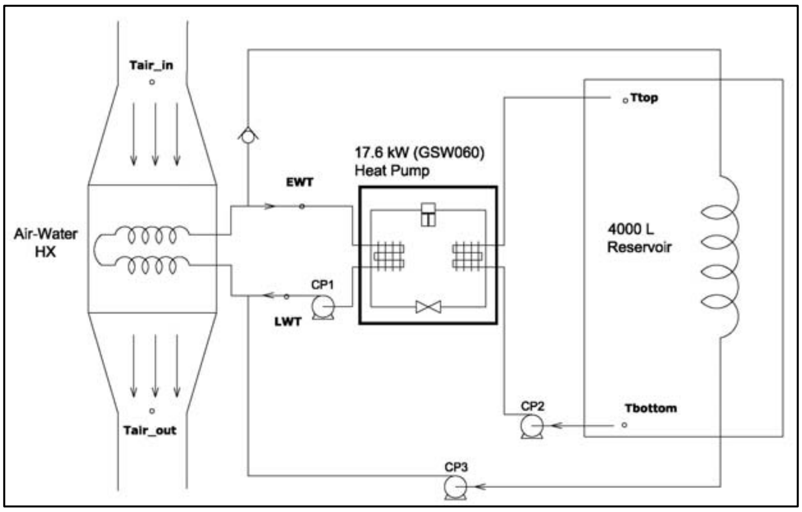

Figure 4. Option 1, with a single water-to-water heat pump.

b) Two smaller heat pumps in parallel (10.6 kW = 3 Ton each, or 21.2 kW in total).

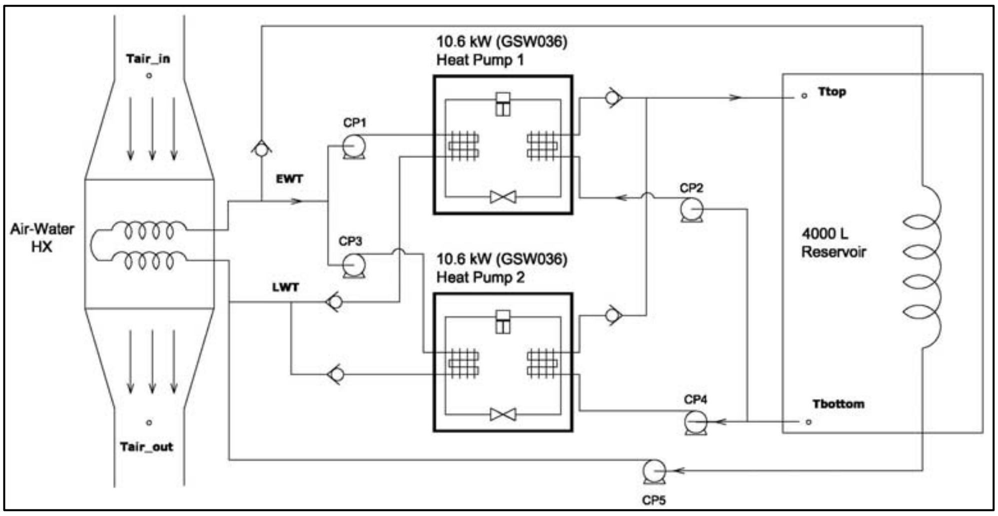

Figure 5. Option 2, with two smaller water-to-water heat pumps.

It soon became apparent that simulations would be useful in making the decision between both systems.

4 SIMULATIONS

In the following discussion, the word "source" refers to the water/glycol mixture exchanging heat with the BIPV/T air, and "sink" refers to the side exchanging heat with the storage tank. The manufacturer's tables used for the simulation were: (a) heat removed and (b) electrical power consumption. Both variables were tabulated for 6 temperatures on the source side, and 4 temperatures on the sink side (in total, 24 elements per table), for a 15% glycol mixture on both sides. The tables were available for three flow rates on the source side, and three flow rates on the sink side. In total, nine tables were shown within the same specifications sheet. However, in a conservative approach, only the tables corresponding to the lowest flow rate on the sink side were used (see Table 1 and Table 2).

Table 1. Heat extraction rate (kW) for the 10.6 kW heat pump (GSW036). The flow rate at the sink side is 0.315 L/s.

Source side flow rate = 0.315 L/s				
Source Temperature	Sink Temperature 15.6 °C	26.7 °C	37.8 °C	48.9 °C
-6.1 °C	N/A	N/A	N/A	N/A
-1.1 °C	6.01	5.48	4.81	3.99
4.4 °C	6.80	6.39	5.69	4.87
10.0 °C	7.88	7.27	6.51	5.57
15.6 °C	8.91	8.47	7.74	6.86
21.1 °C	10.26	9.64	8.82	N/A

Source side flow rate = 0.378 L/s				
Source Temperature	Sink Temperature 15.6 °C	26.7 °C	37.8 °C	48.9 °C
-6.1 °C	N/A	N/A	N/A	N/A
-1.1 °C	6.54	5.98	5.30	4.48
4.4 °C	7.39	6.98	6.24	5.42
10.0 °C	8.56	7.94	7.12	6.18
15.6 °C	9.64	9.20	8.44	7.53
21.1 °C	11.11	10.46	9.64	N/A

Source side flow rate = 0.567 L/s				
Source Temperature	Sink Temperature 15.6 °C	26.7 °C	37.8 °C	48.9 °C
-6.1 °C	N/A	N/A	N/A	N/A
-1.1 °C	6.68	6.13	5.42	4.60
4.4 °C	7.53	7.09	6.39	5.54
10.0 °C	8.73	8.09	7.30	6.33
15.6 °C	9.85	9.38	8.62	7.71
21.1 °C	11.31	10.67	9.82	N/A

Table 2. Heat extraction rate (kW) for the 17.6 kW heat pump (GSW060). The flow rate at the sink side is 0.4725 L/s.

Source side flow rate = 0.4725 L/s				
Source Temperature	Sink Temperature 15.6 °C	26.7 °C	37.8 °C	48.9 °C
-6.1 °C	N/A	N/A	N/A	N/A
-1.1 °C	8.65	7.44	6.27	5.13
4.4 °C	10.29	9.32	8.06	6.51
10.0 °C	11.99	10.96	9.64	8.03
15.6 °C	13.57	12.49	11.11	9.41
21.1 °C	14.71	13.69	12.46	N/A

Source side flow rate = 0.712 L/s				
Source Temperature	Sink Temperature 15.6 °C	26.7 °C	37.8 °C	48.9 °C
-6.1 °C	N/A	N/A	N/A	N/A
-1.1 °C	9.29	8.06	6.86	5.69
4.4 °C	11.05	10.02	8.73	7.18
10.0 °C	12.84	11.78	10.43	8.76
15.6 °C	14.51	13.39	11.96	10.23
21.1 °C	15.74	14.65	13.42	N/A

Source side flow rate = 0.945 L/s				
Source Temperature	Sink Temperature 15.6 °C	26.7 °C	37.8 °C	48.9 °C
-6.1 °C	N/A	N/A	N/A	N/A
-1.1 °C	9.82	8.56	7.33	6.15
4.4 °C	11.64	10.61	9.29	7.71
10.0 °C	13.51	12.46	11.05	9.38
15.6 °C	15.27	14.13	12.69	10.93
21.1 °C	16.56	15.47	14.21	N/A

These tables were used to calculate the approximate heat removal corresponding to a given combination of source and sink temperatures. For instance, if the fluid at the source side enters at 5 °C (with a flow rate of 0.567 L/s) and the fluid at the sink side enters at 35 °C (flow rate of 0.315 L/s), the heat removed by one GSW036 heat pump is calculated (after interpolating twice) as 6.658 kW. Electrical consumption tables were used in a similar way to estimate the electrical consumption of the heat pump(s).

Naturally, the temperature of the water on both sides also depends on the heat exchanger and the reservoir. Especially in the case of the source side, the temperature of the water leaving the heat exchanger (and entering the heat pump) depends on the air and temperature of the BIPV/T air. Both heat pump models are designed to operate in dynamically changing conditions. The heat pump will adjust itself to operate at a point where the heat removed is equal to the heat extracted from the air by the heat exchanger.

The maximum possible temperature of the storage tank is about 55-58 °C (maximum exit temperature of the water on the sink side). If the temperature of the top of tank can oscillate between 55 °C and 25 °C (still a useful temperature), then a 4000 L tank can store about 504 MJ (140 kW-hr) of useful heat. For a 6 kW heating load, this represents nearly one day of heating.

Mathcad 2001i was the tool chosen for the simulations. This general mathematical calculation tool was previously used for calculating the overall energy performance of the house and the exit temperatures of the BIPV/T system (details of this simulation are discussed in Candanedo et al., 2007). The results of this simulation for 4 days of a typical February in Montréal are shown in Figure 6; relatively high temperatures (above 20 °C) could be obtained on clear sunny days even if the exterior temperature is below -10°C and the flow rates are relatively high (nearly 1000 L/s). Higher temperatures (about 40 °C) can be obtained by reducing the flow rate, but this action also decreases the available amount of heat. On cloudy days, the exit temperature of the BIPV/T air is only slightly above the exterior temperature. Obviously, this is also the case during the night. Therefore, being able to use air at relatively cold temperatures would enhance the applicability of the heat pump configuration. The BIPV/T simulations provided an estimate of the temperature and air flow ranges at which the system would be operating under normal conditions.

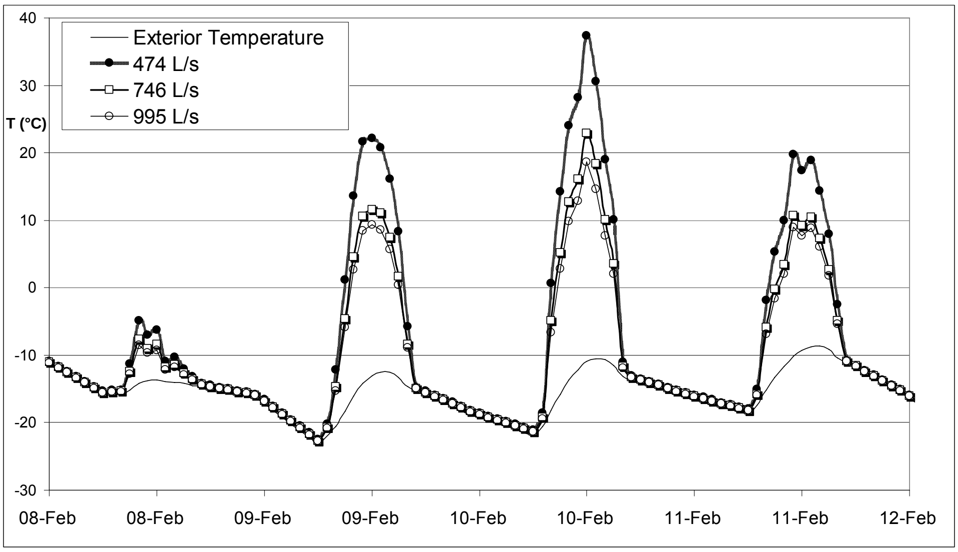

Figure 6. Exterior temperature and BIPV/T exit air temperature at different flow rates.

According to the manufacturer of the heat exchanger, its effectiveness will always be above 0.7 and will not vary significantly within this specified range, but no curve was provided. The effectiveness of the heat exchanger was estimated by using the following equation:

$$\varepsilon_{hx} = 1 - e^{\left[\frac{NTU^{0.22}}{Cr}\left(e^{-Cr(NTU)^{0.78}} - 1\right)\right]} \quad (1)$$

This equation corresponds to a single pass cross-flow heat exchanger with both fluids unmixed (Incropera and DeWitt 2002). In this equation, ε_{hx} is the effectiveness of the heat exchanger; Cr is the ratio C_{air}/C_{water} (see next paragraph); NTU is the number of heat transfer units (obtained from assumptions on the characteristics of the heat exchanger). NTU is a function of the air flow rate. Although this configuration is not identical to the heat exchanger used in the ANZH, it provides an approximate description of the variation of the effectiveness with other parameters. A system of three equations can then be solved numerically:

$$Q_{\text{extracted}} = C_{\text{air}}\varepsilon_{\text{hx}}\left(T_{\text{air\_in}} - LWT\right) \tag{2}$$

$$EWT = LWT + \frac{0.95 \cdot Q_{\text{extracted}}}{C_{\text{water}}} \tag{3}$$

$$0.95 \cdot Q_{\text{extracted}} = f\left(EWT, T_{\text{bot\_tank}}\right) \tag{4}$$

where $Q_{extracted}$ is the heat removed by the heat pump; C_{air} is the heat capacity rate of the air flow (mass flow rate times specific heat); T_{air_in} is the temperature of the air entering the heat exchanger; LWT is the temperature of the water leaving the heat pump on the source side (and thus entering the heat exchanger); EWT is the temperature of the water entering the heat pump at the source side; C_{water} is the heat capacity rate of water; T_{bot_tank} is the temperature of the bottom of the large reservoir. For these purposes, this temperature was considered quasi-static. It is also assumed that about 5% of the heat is lost between the heat exchanger and the heat pump.

Equation 4 represents the functional dependence of the heat extracted on the temperatures of the source and the sink. The information used was taken from Tables 1 and 2. A numerical function was defined based on a numerical double interpolation of the tables. When solving the system of equations for the case of the two heat pumps working in parallel, a factor of 2 was introduced into equation 4.

5 RESULTS

In order to explore the performance of the mechanical system under different conditions, the system of equations described above was solved numerically for an array of inlet BIPV/T air temperatures and flow rates, for a fixed, typical temperature (33 °C) at the sink side (i.e., bottom of the large storage tank). For the GSW060 heat pump, the water/glycol flow rate on the source side was 0.945 L/s and the water flow rate on the sink side was 0.4725 L/s. For both GSW036 heat pumps, the water/glycol flow rate on the source side was 1.14 L/s and the water flow rate on the sink side was 0.631 L/s. The upper and lower limits of the air flow rate were 853 L/s (1800 ft^3/min) and 474 L/s (1000 ft^3/min) respectively. The air temperature range chosen for the simulation was between 10 and 40 °C. These conditions guarantee the operation of the heat exchanger-heat pump combination. However, with higher flow rates (1042 L/s or more) it is possible to operate the heat pump(s) with lower temperatures (the limit is somewhere about -4°C for one GSW036 heat pump, and -2 °C for one GSW060 heat pump). Conversely, it is possible to operate the system with lower flow rates and higher temperatures. For example, at 40 °C, even an air flow rate of 300 L/s could supply some useful heat.

Figures 7, 8 and 9 show respectively the heat extracted from the air, the heat delivered to the storage tank and the resulting COP for a single GSW060 heat pump. Figures 10, 11 and 12 show the same information for two GSW036 heat pumps operating in parallel. It has been found that the performance of the system for both cases is a stronger function of the air temperature than of the flow rate. This result seems to favour the use of lower air flow rates, provided that high temperatures are obtained. In general, more heat can be obtained with the operation of two GSW036 in parallel than with a GSW060, and with a better COP.

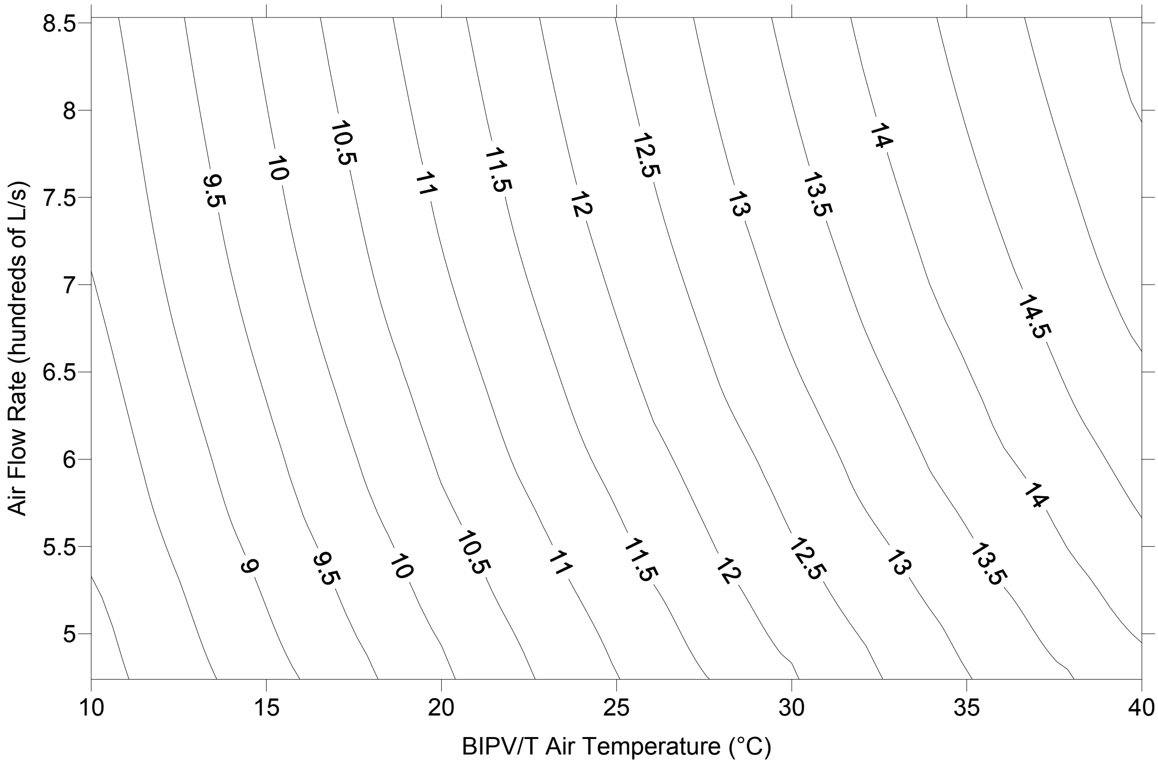

Figure 7. Heat extracted (kW) as a function of air flow rate and air temperature – one GSW060 heat pump.

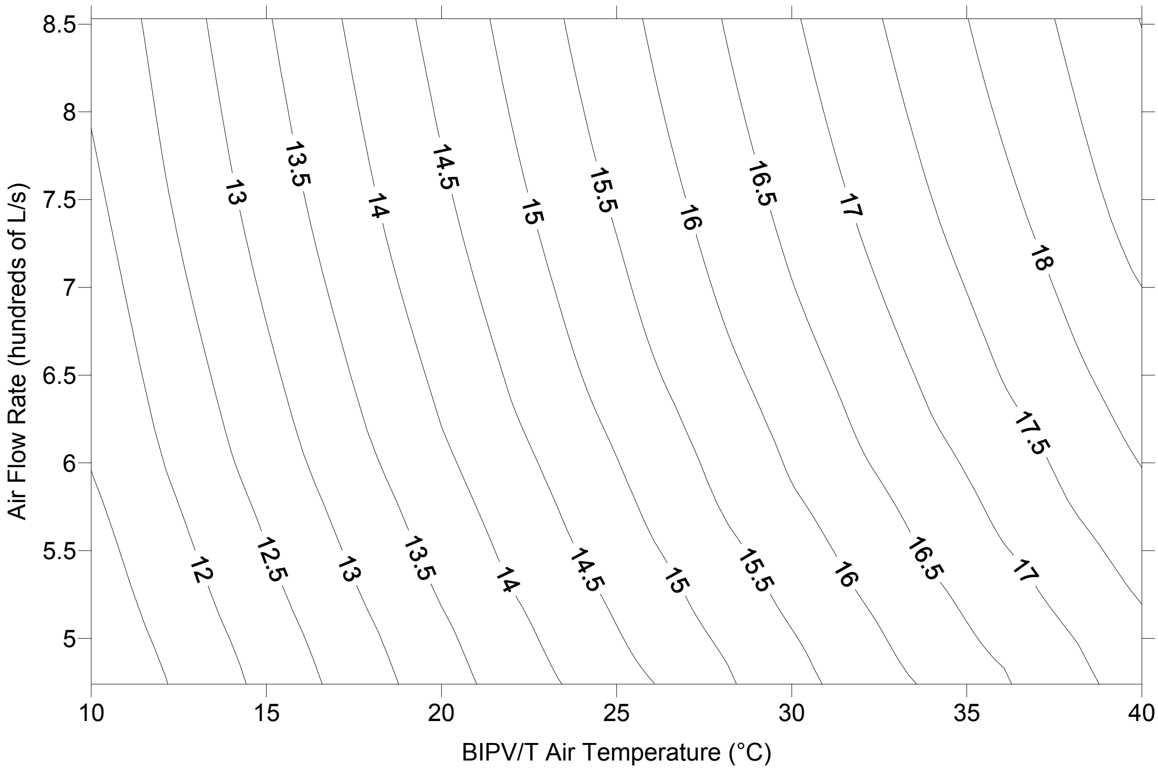

Figure 8. Heat delivered (kW) as a function of air flow rate and air temperature – one GSW060 heat pump.

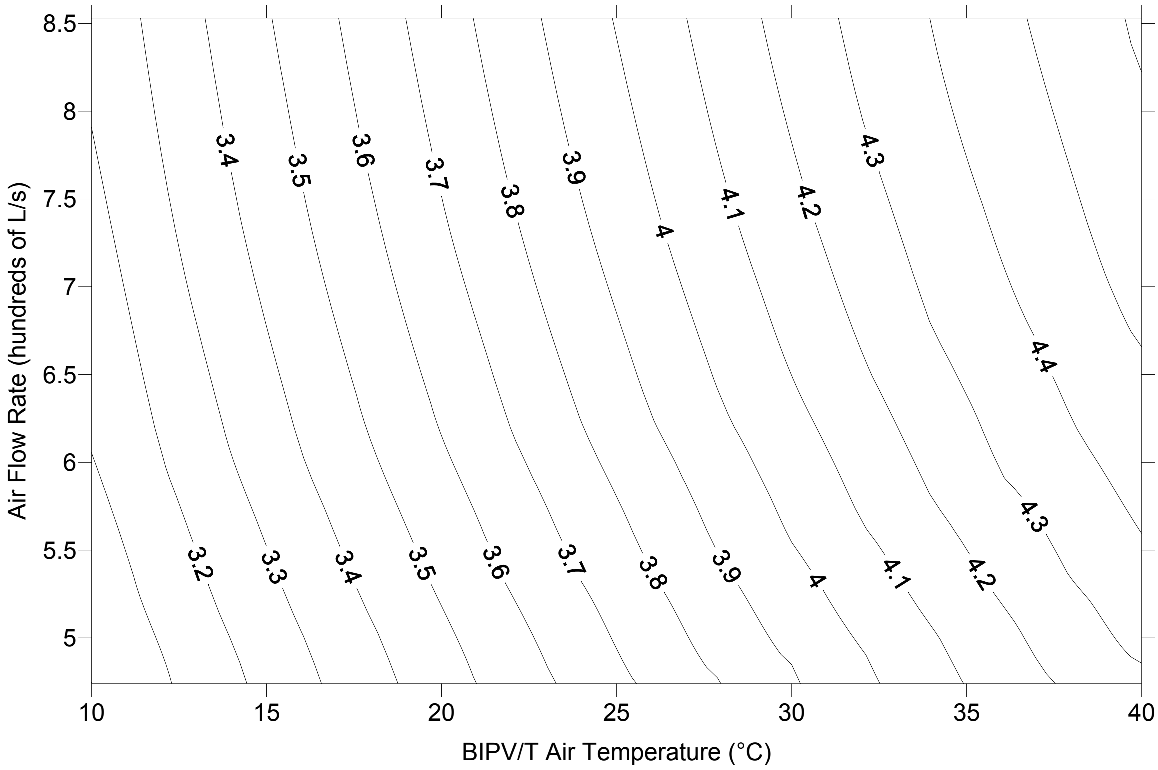

Figure 9. COP as a function of air flow rate and air temperature – one GSW060 heat pump.

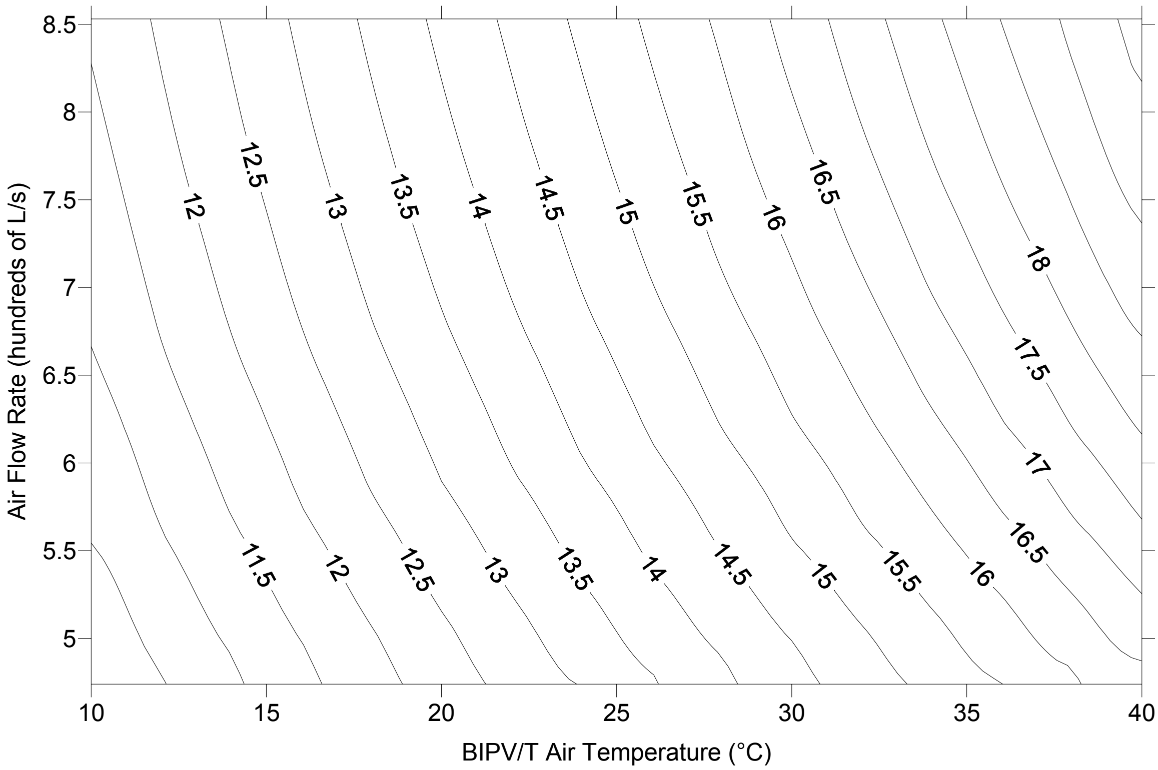

Figure 10. Heat extracted (kW) as a function of air flow rate and air temperature - 2 GSW036 heat pumps.

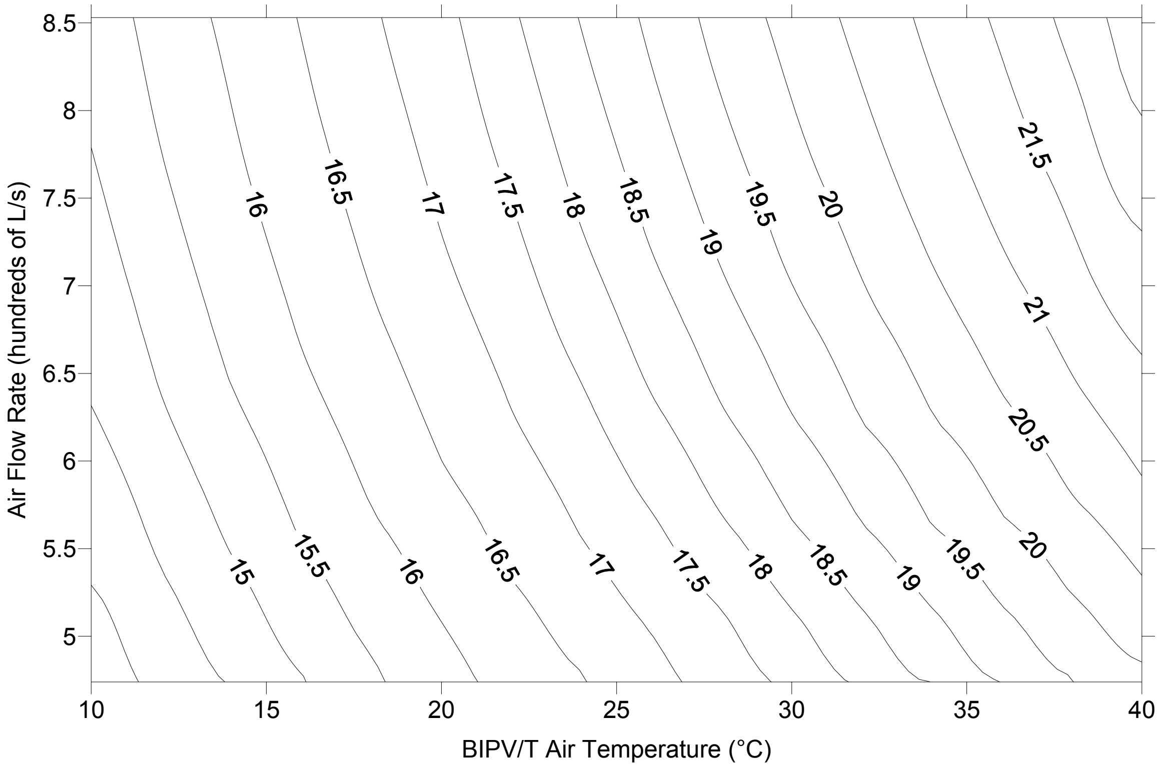

Figure 11. Heat delivered (kW) as a function of air flow rate and air temperature - 2 GSW036 heat pumps.

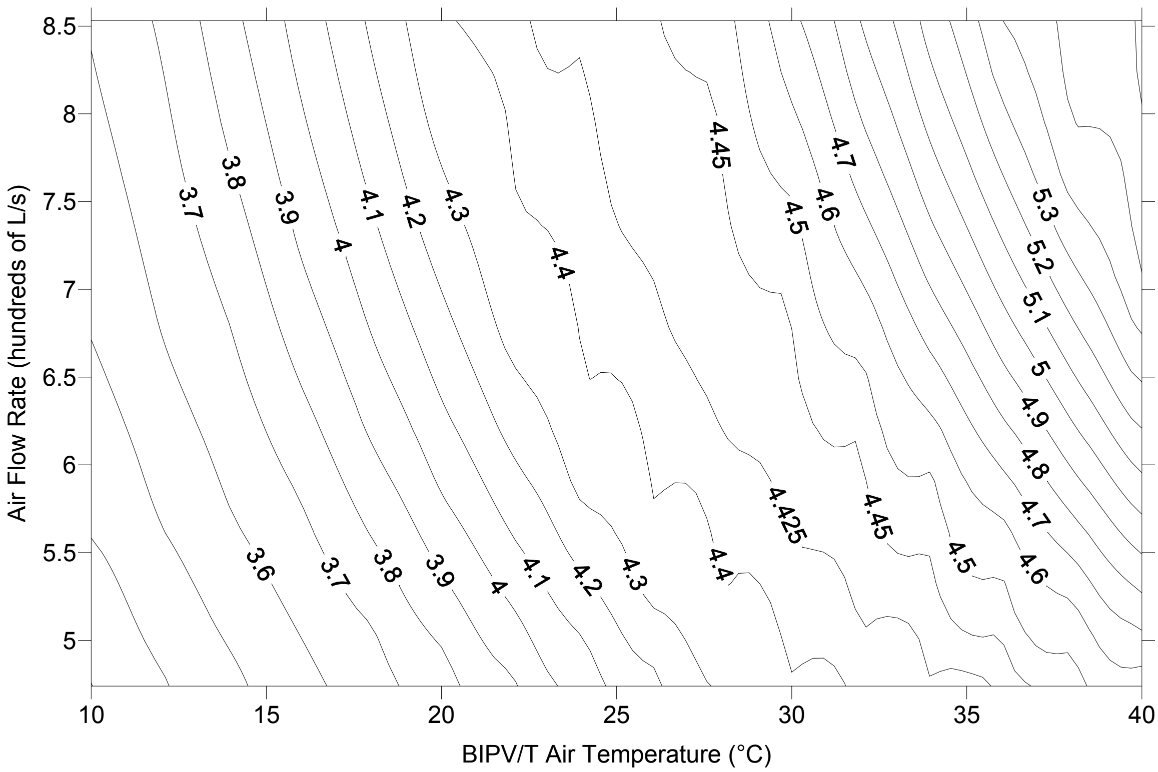

Figure 12. COP of the two as a function of air flow rate and air temperature - 2 GSW036 heat pumps.

6 DISCUSSION AND CONCLUSION

The configuration with two heat pumps in parallel, as shown in Figure 5, has been chosen for the ANZH. The curves obtained by the simulations indicate that this 2-GSW036 heat pump configuration outperforms a single GSW060 heat pump configuration, in heat delivery and COP, under the same conditions of air flow rate and temperature. Two GSW036 can supply more than 22.5 kW of heat to the large reservoir tank. The COP of this configuration is also higher, and can be above 5.5 with high flow rates and high temperatures. Using two heat pumps has other advantages: by turning off one of the heat pumps, it is possible to work at even lower flow rates. Two heat pumps offer some desirable redundancy for the system.

The main limitation for heat pumps is the exterior air temperature, which precludes their use when the temperature is too low (below -5°C). Another limitation is the maximum temperature at the top of the storage tank. This temperature is determined by the maximum operating temperature of the sink side (in this case it is about 55°C at the top and 49 °C at the bottom of the tank). The storage tank and the massive structure of the building can be used for storing about 2 days' worth of heating, but this may not be enough. A backup system is still necessary for prolonged cloudy periods, which will inevitably occur. At the time of writing, a ground loop as a secondary source for the heat pump group is under study to replace the wood pellet boiler as the backup system.

After completion (planned for 2008) and commissioning, the ANZH house will undergo a period of monitoring by several parties: CMHC, Hydro-Québec (the electrical utility of Québec) and Concordia University. The performance of the BIPV/T-heat pump system will be closely followed.

The solution found by this simulation is satisfactory, but not optimal. A heat pump product specially conceived for BIPV/T applications is needed. Air source heat pumps especially designed for BIPV/T systems are also needed. Devices using CO_2 as their working refrigerant are a very promising technology, since they can operate at very low exterior temperatures, down to -20 °C (Sanyo). Also, cold water at the load side can reach very high temperatures. The line of products Eco Cute in Japan, which has been used for domestic hot water heating (Hashimoto 2006), has been suggested for radiant floor heating systems (Kansai). CO_2 heat pumps have been considered for combined domestic hot water and space heating (Stene 2005). A house in Montréal using a BIPV/T system linked to a CO_2 heat pump might not need additional heat sources and achieve net-zero energy performance.

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