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PERFORMANCE MODELING OF A SOLAR THERMAL SYSTEM FOR COOLING AND HEATING IN CARNEGIE MELLON UNIVERSITY'S INTELLIGENT WORKPLACE

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ABSTRACT

The Robert L. Preger Intelligent Workplace (IW) is a 650 m^2 living laboratory of office space at Carnegie Mellon University (Pittsburgh, PA). The IW has received the first commercially available solar absorption system for air-conditioning with integrated controls as a donation from BROAD in August 2006. The IW is now testing this solar thermal system.

A TRNSYS model has been developed and used to assist the design of the system, evaluate its performance throughout an entire year, and optimize its initial configuration. The components of the system are a 52 m^2 parabolic trough high temperature solar array, a 16 kW hot water and gas fired absorption chiller, and an overall control system. This model predicts the energy required to cool and heat the south part of the IW (around 10 MWh in winter, 15 MWh in summer) and the fraction of that energy that can be provided by solar energy. The effects of significant system parameters – orientation of the receivers, volume of hot/chilled water thermal storage and insulation thicknesses on the piping and tank – on the fraction of solar provided energy have been calculated by the model.

This study emphasizes on two significant aspects:
- the impact of system integration during the preliminary building design on the energy performance
- the importance of the energy modeling to assist and optimize the design of the system and its operation but also to reduce the investment and operation costs.

1. INTRODUCTION

The world demand of energy for air conditioning is continually increasing. As traditional cooling devices are electrically powered, demand for electrical power in summer keeps increasing and reaches the capacity limit in some countries. Because most of the electrical power stems from fossil fired power plants this trend also increases the emission of CO_2. A more innovative approach to provide cooling is to use solar energy in a heat driven active absorption cycle for air conditioning. The high correlation between the availability of solar energy and the need for cooling in a building provides an advantage to solar driven cooling. In addition, absorption based systems have the advantage of using reject heat from power generation as well as solar heat. A cooling system for building through absorption refrigeration makes direct and efficient use of solar heat, replacing the use of natural gas or electrical energy for vapor compression refrigeration. Approximately 50 to 60 % of the radiant energy impinging on the receivers is passed to the heat transfer medium for use. The coefficient of performance of absorption chiller, the fraction of heat removed in cooling to the heat supplied to the system is 1.1 to 1.2 for a two stage chiller. The performance of a solar driven absorption cooling system was studied and modeled in TRNSYS for an office space in Pittsburgh, PA, the Intelligent Workplace. The location of the IW is not an ideal location for solar application due to its latitude and frequently cloudy weather. Moreover the small scale of the solar driven cooling system militates against an economic application of the technology. Nonetheless, the TRNSYS model and the simulation evaluation can explore how solar energy through high temperature solar receivers and heat storage might be integrated into efficient energy supply system for a building, even in a place like Pittsburgh (latitude 40.3°N, longitude 79.6°W).

1.1 Building description

The IW is a 650 m^2 living laboratory of office space at Carnegie Mellon University. The IW south zone's net floor area is about 245 m^2. The average height is about 3.1 m, including the raised floor and average height of roof. The open space is subdivided by partition walls and furniture in 10 office or conference spaces. The building has horizontal shadings on the east and west facades. The IW$_s$ floor plan is shown in Fig.1.

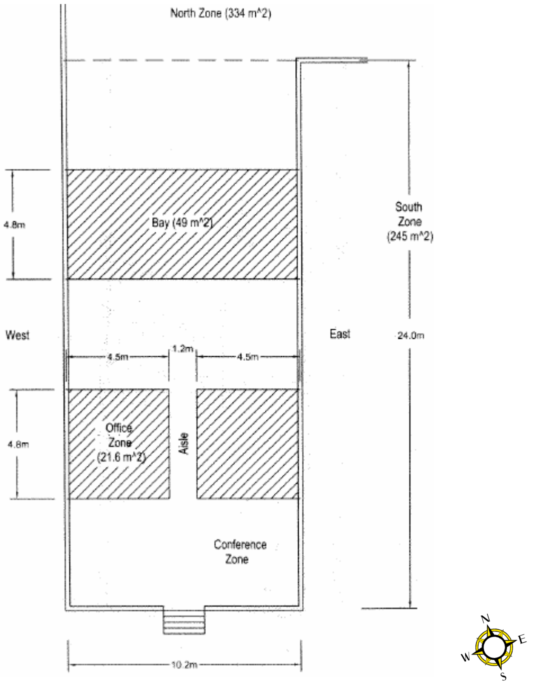

Figure 1. IW south Floor Plan

1.2 Internal Loads

The IW_s is occupied throughout the by faculty and students. The internal loads in the IW_s including lighting, plug loads such as computers, and occupants contribute to the overall cooling requirements. The maximum occupancy is 30 people. Most of the occupants arrive between 9AM and 10AM and leave the building between 5PM and 8PM. The equipment heat gain is 100 W per computer (one per person) and 50 W for one printer. The total heat gain of the artificial lighting is 17 W/m^2. The equipment heat gain is based on the occupancy schedule and the lighting heat gain is based on solar radiation available. The lights are seldom turned on due to the architectural integration of day lighting features (skylight, windows) of the space.

1.3 HVAC System

Ventilation and air conditioning are split to reduce the amount of air circulated: ventilation handles the latent and sensible loads of the outside air supply whereas air conditioning handles the sensible load of the space.

1.3.1 Ventilation. Fresh air is supplied to the IW_s by a desiccant wheel heat pump based ventilation unit supplied by SEMCO via diffusers in the floor. The outside air volume rate is about 34 m^3/hr per person based on the ASHRAE standards. The outside air is supplied during the whole year with -3°C to -6°C below the set room temperature at a humidity that maintains comfortable room conditions.

1.3.2 Air Conditioning. System design and modeling were performed before the procurement of the equipment (solar troughs, hot water and natural gas driven two stage absorption chiller, heat exchanger and storage tank). In a solar thermal system studied previously, solar radiation was captured by evacuated tubes solar receivers mounted on the IW roof. This thermal energy was transferred to a heat transfer medium, Syltherm 800, flowing to a steam generator through an auxiliary natural gas fired heater or alternatively to a hot fluid storage tank. The steam was utilized in a two stage 16 kW absorption chiller to provide chilled water to the cooling coils. This study shows that further effort is needed to improve the performance of this solar thermal system. The life cycle cost of the system can be increased by:

- operating the system all year long for space heating and cooling without critical additional investment cost
- decreasing the heat losses in the system by increasing insulation thickness and converting cold storage to hot storage
- collecting more thermal energy by the use of solar tracking devices and of a water mixture as the heat transfer fluid

In the new proposed system, solar radiation is captured by high temperature solar receivers (solar trough with one tracking axis) mounted on the IW roof. Then:

- *in cooling mode*: this thermal energy is transferred to heat transfer medium (propylene glycol/water mixture). The fluid medium flows to the two stage 16kW absorption chiller to provide chilled water to the fan coils. The IW_s solar driven cooling system is shown in Fig.2.

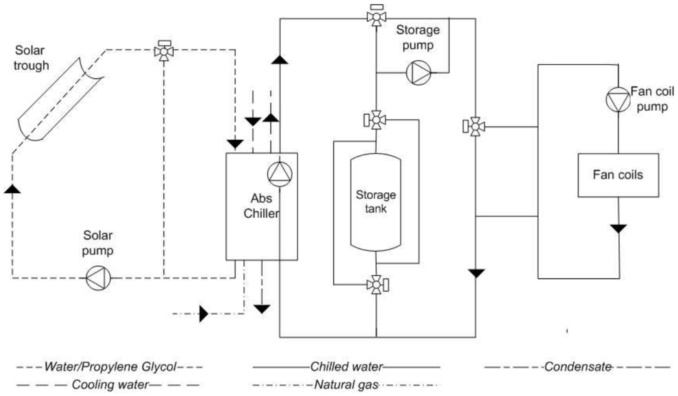

Figure 2. IW solar driven absorption system (cooling system)

- *in heating mode*: the solar thermal heating can be achieved by two alternative system configurations.

When the fluid temperature at the outlet of the solar troughs is lower than 120°C, the fluid medium from the solar trough flows through a heat exchanger. The heat collected by the solar receiver is directly exchanged to the water contained in the load loop.

When the fluid temperature at the outlet of the solar troughs meets the chiller operating temperature (higher than 120°C), the fluid medium from the solar trough flows through the chiller. The energy transferred heats the lithium bromide solution. The water vapor produced by the solution heats the hot water in chiller evaporation tubes, while condensate returns to the solution to be heated. The heat collected by the solar receiver is then exchanged to the water contained in the load loop.

Auxiliary heating can be provided by firing the chiller with natural gas.

The hot water is utilized in either of these ways to meet the heating load. The IW_s solar driven heating system is shown in Fig.3.

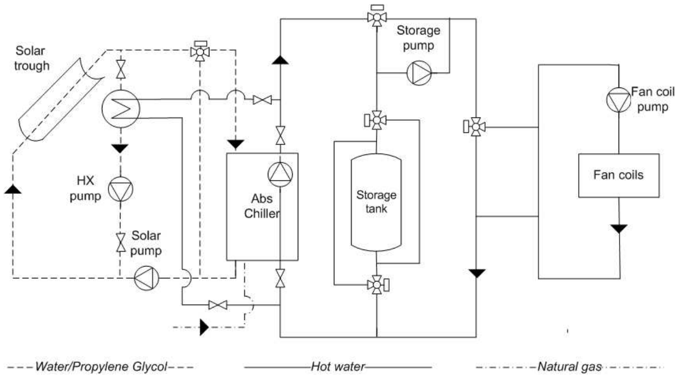

Figure 3. IW solar driven absorption system (heating system)

If the available solar energy is insufficient to cover the energy demand, the chiller is fired with gas and runs at full capacity to produce either heating or cooling. If a storage tank is added to the system, additional energy can be supplied by the tank.

2. TRNSYS MODEL

2.1 Model approach

The software program selected to model the IWs and its solar thermal system is TRNSYS [4]. This transient systems simulation program is developed by the Solar Energy Laboratory at the University of Wisconsin. This software supports detailed simulations of multi zone buildings and their energy supply equipment. The TRNSYS equipment library includes: sophisticated building models; many of the equipment components commonly found in building thermal energy systems; components that facilitate input of weather data and of occupancy, equipment, and set point schedules; and components that support output of simulation results. Exercise of the TRNSYS simulation tool enables the search for an optimal system configuration, equipment design and operational mode. To simulate solar driven cooling system, two TRNSYS simulations are performed: the building and the energy supply system simulations.

2.1.1 Building simulation. The purposes of the building simulation are to:

- simulate the IW_s zone: its geometry and materials for windows, walls, and floors; shading; ventilation supply from the ventilation unit.
- calculate the IW_s cooling and heating loads based on the supply of conditioned fresh air from the ventilation unit; the IW operating schedules for occupancy, lighting, equipment, and set points; and the Pittsburgh weather. The calculated loads are shown in Table 1.

Table 1. Heating and cooling loads of the IW_s

Heating season	Energy consumption	Peak load
	9,737 kWh	20.4 kW
Cooling season	Energy consumption	Peak load
	14,787 kWh	15.8 kW

The cooling peak load is 15.8 kW which means 64 W/m^2 (sensible load). The 16 kW absorption chiller is then adequate to meet the IW south cooling requirements. The heating peak load is 20.4 kW which means 83 W/m^2 (sensible load).

2.1.2 Energy supply system simulation. The purposes of the energy system simulation are to:

- simulate the solar loop (solar receivers, absorption chiller, heat exchanger), the storage loop (storage tank), the grid loop (campus grid), the load loop (fan coils)
- to assist the system design by:
  - evaluating the adequacy of the solar receiver area, the tank capacity, and the chiller capacity to meet the IW loads throughout the year
  - evaluating the system operating rules and feed forward control to adjust properly the system depending on the weather conditions, the solar energy stored in the tank, and the building loads
  - calculating the solar energy inputs to the solar system and any required hot/chilled water input from the grid required to meet the loads calculated by the building simulation
- optimize the system performance by performing a sensitivity analysis.

The TRNSYS simulations are carried out for the entire year. The simulation time step is set to 15 min. This small value is chosen based on the time step of the system controller.

2.2 Model assumptions

2.2.1 Weather. To simulate the solar thermal system, a climatic data base (TMY2 file) is used to get the direct normal solar radiation, the dry bulb temperature and the relative humidity of the outside air in Pittsburgh (latitude 40.3°N, longitude 79.6°W). Figures 4 and 5 show the typical outside conditions in Pittsburgh. The maximal beam solar radiation on a horizontal surface is between 500 and 900 W/m^2.

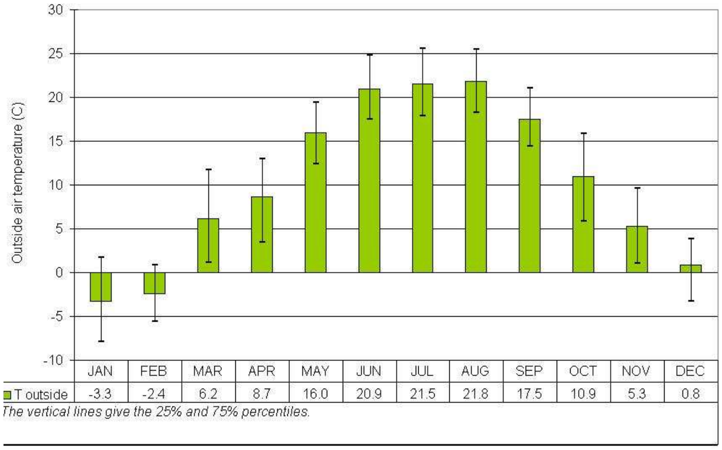

Figure 4. Monthly average outside air temperature (˚C) and percentiles in Pittsburgh

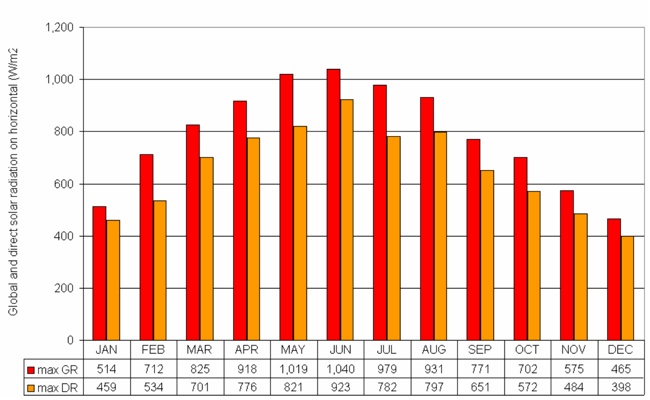

Figure 5. Maximum global and direct solar radiations (on a horizontal surface) in Pittsburgh

2.2.2 System modeling. Testing is currently underway to characterize the performance of the dual source chiller for different settings and operation modes. A data look up table will be created to properly model the chiller in TRNSYS for more detailed study. In this study, the natural gas is not being used to fire the chiller and provide auxiliary heat in cooling and heating seasons. The auxiliary energy is supplied by the chilled/hot water grid.

The solar system modeled in TRNSYS is shown in Fig. 6.

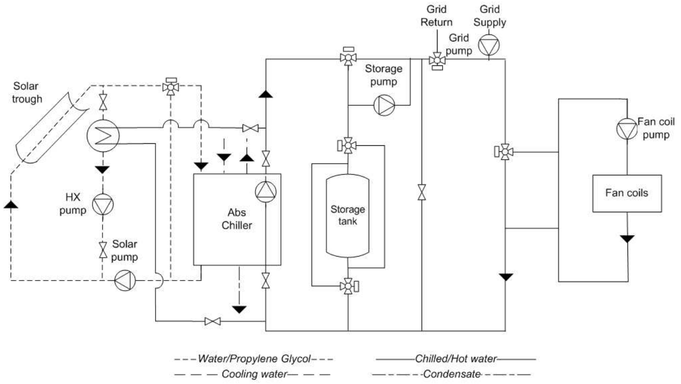

Figure 6. Modeled IW solar driven absorption system

The fan coils are 4 pipe fan coils. To simplify the graph, the chilled and hot water loop are the same.

2.2.3 Solar collection loop (SCL). The following section describes the different devices and specifications of the SCL.

Fluid medium. The heat transfer fluid used in the SCL is a mixture of water and propylene glycol. The percentage of glycol in the solution depends on:

- the typical year minimum outside air temperature in order to provide adequate freeze protection and pumpability
- the maximum operation temperature of the system to withstand high temperature and prevent fluid damage.

The temperature range of the process based on the ambient conditions and the operating temperature is -30°C-200°C. The fluid medium in the SCL is a 50/50 propylene glycol and water mixture.

Few data about the use of propylene glycol at the high pressure and temperatures of solar thermal system are available. Figure 7 presents the total pressure over aqueous propylene glycol solutions versus temperature.

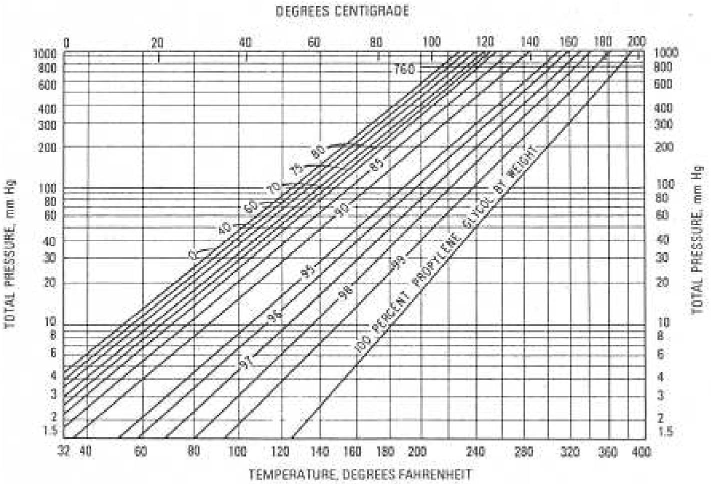

Figure 7. Total pressure over aqueous propylene glycol solutions versus temperature

The normal maximum operating temperature of a water/propylene glycol mixture is from 110°C to 200°C (for a percentage from 10 to 100%) for a non pressurized system. The heat capacity of propylene glycol is higher than traditional high temperature fluid medium such as Syltherm 800. Moreover its viscosity and its cost are significantly lower. Using 100% propylene glycol would eliminate freezing at low temperatures, would greatly decrease the pressure at high temperatures and would also greatly decrease corrosion. However, its viscosity is extremely high at low temperature. The thermal properties of the fluid medium (50/50) in the solar collection loop during the summer and winter are shown in Table 2 [8].

Table 2. Characteristics of water and propylene glycol mixture (50/50) in the SCL

Season	Cooling	Heating
Propylene glycol percentage	50%	
Average Temperature (˚C)	150	75
Pressure (bar)	Max 10 bar	1 atm
Freezing temperature (˚C)	-34°C	
Specific Heat (kJ/kg.K)	3.9	3.75
Density (kg/m^3)	1000	995
Thermal Conductivity (kJ/hr.m.K)	1.40	1.35
Dynamic Viscosity (kg/m.hr)	1.332	4.14

Piping and insulation. 1 ¼ inch schedule 40 (standard) pipe in carbon steel can withstand operating temperature and pressure of the system, and this pipe size is appropriate based on the different connections between devices. To prevent glycol from corroding the piping in steel, special inhibitors are added in the SCL. Two insulation materials are suitable: fiberglass and cellular glass. Fiberglass is chosen due to its lower thermal conductivity. The values of the fiberglass thermal conductivity for winter and summer are respectively 0.035 W/m.K (0.1260 kJ/hr.m.K) and 0.041 W/m.K (0.1476 kJ/hr.m.K).

Solar troughs and solar pump. There are many types of solar collectors that are used in air-conditioning applications such as flat plate, evacuated tube or parabolic collectors. In this study, the solar collectors are parabolic troughs. Solar troughs can deliver heat at high temperatures (ranging from 40 to 400°C) for applications such as hot water, space heating, air-conditioning, steam generation, industrial process heating, desalination and power generation.

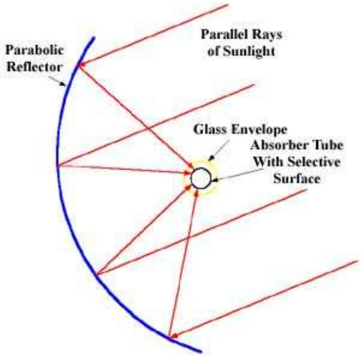

Figure 8. Parabolic trough

A parabolic trough (see Fig.8) is a one-dimensional parabola that focuses solar energy onto a line. This line is a pipe with a flowing liquid inside that absorbs the heat transmitted through the pipe wall and delivers it to the thermal load. A trough captures sunlight over a large aperture area and concentrates this energy onto a much small receiver area, multiplying the intensity of the sun by a concentration fraction. It is the process of concentration that allows troughs to delivery high temperature thermal energy. However, to achieve such concentration, a trough tracks the sun in one axis continually throughout the day. To avoid overheating and balance the energy in the system, the solar troughs can defocus. The specifications of the solar troughs are given in Table 3:

Table 3. Specifications of the solar troughs

Number of collectors in series	4
Number of collectors in parallel	1
Aperture area per module	13.11m^2
Concentfractionn fraction	19.266
Intercept efficiency a0 *Efficiency slope a1*	0.587 0.0637 kJ/hr. m^2.K
$\eta = a_0 - a_1 \frac{\Delta T}{SR}$ *ΔT: Average of temperature above ambient, °C* *SR: Instantaneous solar radiation, kJ/hr. m^2*	
IAM	One axis tracking
Flow rate	1,300 kg/hr (constant speed pump)
Maximum outlet temperature	Heating: 95˚C/ Cooling:175°C

Heat exchanger. This exchanger unit is a counter current heat exchanger used in the heating season and also during testing.

Absorption chiller. The chiller is a two stage, LiBr based, hot water and natural gas fired absorption chiller with an associated cooling tower. The rated conditions, for cooling operation, are:

- cooling capacity: 16 kW
- chilled water temperature: supply 7°C and return 14˚C
- chilled water flow rate: 2,044 kg/hr
- cooling water temperature: supply 30˚C
- cooling water flow rate: 4,088 kg/hr
- rated COP: 1.2

SCL controller. The SCL controller operates the solar pump, the three way valve and the absorption chiller. The solar pump and the chiller operate based on the value of the global solar radiation on the horizontal, IT. If IT<100 W/m^2, the SCL is OFF. If IT>50 W/m^2, the SCL is ON. The three-way valve allows the SCL to provide the energy needed to meet the loads when the temperature of the water/propylene glycol mixture is proper.

2.2.4 Water loops. The following section describes the different devices and specifications of the water loops (WL): the storage and the load loops.

Fluid medium. The thermal properties of the water in the storage and load loops during the cooling and heating seasons are shown in Table 4.

Table 4. Fluid characteristics of the storage and load loops

Season	Cooling	Heating
Fluid	Water	
Average Temperature (˚C)	15	30
Pressure (bar)	System not pressurized	
Specific Heat (kJ/kg.K)	4.184	4.183
Density (kg/m^3)	999.1	995.7
Thermal Conductivity (kJ/hr.m.K)	2.0772	2.1708
Dynamic Viscosity (kg/m.hr)	4.0968	2.8718

Storage tank and pump. The storage tank is needed to store chilled or heated water from the heat exchanger/absorption chiller in order to increase the efficiency of the system. The system can operate when there is no sunshine but energy is available in the storage tank. The main advantages of a cold side storage tank over a hot side storage tank are the following:

- the system does not have to be pressurized and the fluid medium is water (low cost of storage),
- the heat losses are reduced (due to the low temperature in the tank),
- the early morning load can be met by the system when the conditions are not proper to run the chiller. Indeed, the temperature in the tank can drop rapidly overnight in a hot storage tank and not be sufficient to operate the chiller and provide heating or cooling.

The insulation material of the tank is fiberglass. The loss coefficient of the storage tank is function of the tank dimensions, the insulation thickness and properties.

Water grid. The campus grid supplies chilled water at 7°C and heated water at 40°C. The flow rate of the grid is controlled by the WL controller to meet the temperature requirements at the inlet of the heating/cooling coils.

Fan coils. The neutral bridge enables to get the proper constant temperature at the inlet of the coils. The water flow rate in the fan coils is determined based on the building loads and water temperature. Table 5 summarizes the fan coils operating conditions.

Table 5. Fan coil characteristics

Inlet temperature	Heating:35°C/ Cooling:16°C
Outlet temperature to maintain	Heating:25°C / Cooling:23°C
Specific heat transfer of the fluid	Water characteristics
Maximum flow rate	2,000 kg/hr

WL controller. The WL controller determines the operation of the different pumps, valves and devices in the WL based on:

- the building loads,
- the energy transferred from the solar collection loop to the water supply loop,
- the temperature requirements of the fan coils,
- the temperature of the campus grid
- and, if the system has a storage tank, the water temperature in the tank

2.3 Analysis approach

2.3.1 Sensitivity Analysis. The TRNSYS model has been used to assist and optimize the system design by performing a sensitivity analysis to assess the impact of the following parameters on the system performance:

- the insulation thickness of the piping in the SCL
- the orientation of the solar troughs
- the volume of the storage tank
- the insulation thickness of the storage tank

2.3.2 Analysis indicators. The performance of the solar system is characterized by the following energy indicators:

- the solar fraction. The fraction of sensible load covered by the solar system is given by Eq.1:

$$Solarfraction = \frac{Qload - Qaux}{Qload} \qquad (1)$$

with Q_{aux} *Auxiliary energy and* Q_{load} *Cooling/Heating energy*
The power consumption of circulating pumps and controller is excluded.

- the energy savings

The previous study [5] has investigated the economic issue for such a solar system. This study will not define the life cycle cost for each system configuration.

3. SYSTEM DESIGN

The TRNSYS model has been used to evaluate a base case configuration for the solar thermal system.

3.1 Insulation of the piping in the SCL

The piping in the SCL is insulated in order to save energy because of the high temperature of the heat transfer fluid. There are instances when adding insulation actually increases heat loss. The thickness at which insulation begins to decrease heat loss is described as the critical thickness. Since the critical thickness is almost always a few millimeters, it is seldom an issue for piping. Critical thickness is a concern however in insulating wires. In this study, the critical thickness is between 1.5 and 2 mm based on the season: heating (winter) or cooling (summer). Increasing insulation thickness leads to a decrease in heat transfer as shown in Fig.9.

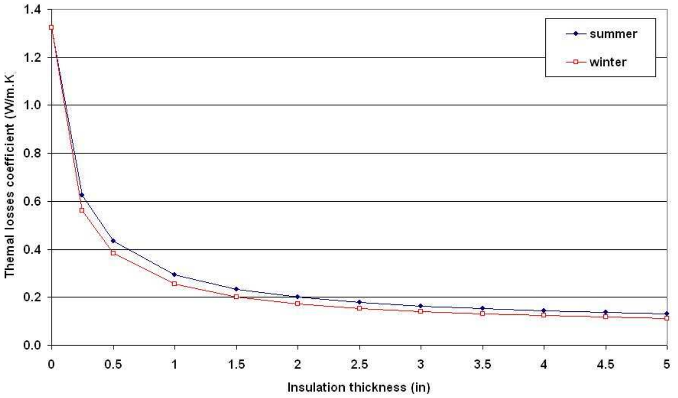

Figure 9. Thermal losses coefficients of the pipe for different insulation thicknesses

The TRNSYS model is used to determine the impact of this thickness on the system performance. The results are shown in Table 6 and Fig.10.

Table 6. Results of the sensitivity analysis on the insulation thickness of the piping in the SCL

Case	A
Orientation	EW axis
Insulation thickness of the piping in the SCL	From 0 to 5”
Volume of the storage tank	-
Insulation thickness of the storage tank	-
Solar fraction (cooling season) (%)	30.6-39.5
Energy savings (cooling season) (MWh)	4.5-5.9
Solar fraction (heating season) (%)	7.2-8.6
Energy savings (heating season) (MWh)	0.70-0.84

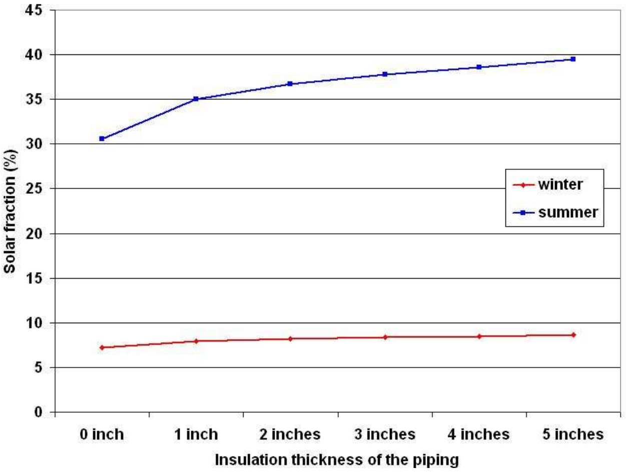

Figure 10. Solar fraction for different insulation thickness of the piping in the SCL

Increasing the insulation thickness of the piping (from 0 to 5 inches) leads to an increase of the solar fraction (from 30.6 to 39.5% in summer; from 7.2 to 8.6% in winter), which means a decrease in the heat losses in the SCL. The impact of the insulation thickness on the energy savings is more important in summer than in winter because temperature differentials for the cooling are much greater than for heating in the SCL (respectively 150°C and 90°C). Based on ASTM standards, the minimum insulation recommended for this type of high temperature and high pressure system is 3 inches. This study shows that the first inches of the insulation are very important to improve the system performance (from 30.6 to 36.5 % in summer).But the additional cost and space required by 4 inch insulation are not justified. The chosen thickness is 3 inches.

3.2 Orientation of the solar troughs

The solar trough can be oriented in two ways either with an east-west axis (north-south tracking) or a north-south axis (east-west tracking) as shown in Fig. 11.

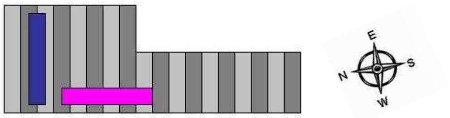

Figure 11. Possible orientations of the troughs on the IW roof

Figure 12 shows the daily profile of the direct solar radiation of the aperture of the solar collector for winter and summer (Clear days: May 10th/November 4th) and the two solar trough orientations.

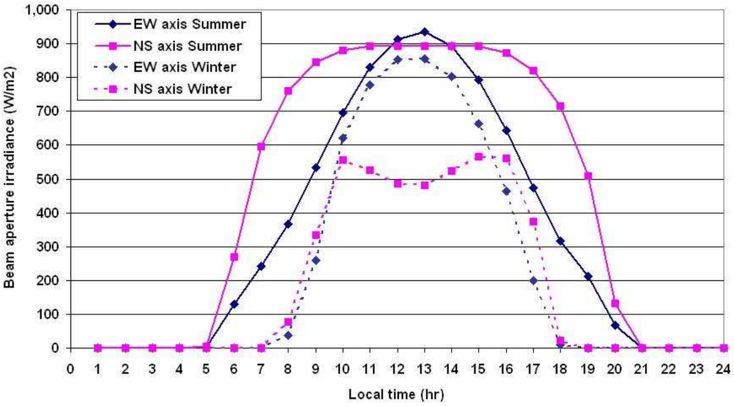

Figure 12. Clear-day aperture irradiance for different tracking aperture configurations for Pittsburgh

For the east-west axis system, the only time the reflector aperture points toward the sun is at noon. As the sun rises and sets, the cosine effect significantly reduces the rate of energy incident upon the aperture. For the north-south axis system, the aperture points toward the sun during a longer period. For a clear day in summer, the aperture for the north-south axis solar trough receives daily more direct solar radiation (10.9 kWh/m^2) than the aperture for east-west axis solar trough (8.0 kWh/m^2). Whereas for a clear day in winter, the aperture for east-west axis solar trough receives daily more direct solar radiation (5.5 kWh/m^2) than the aperture for north-south axis solar trough (4.5 kWh/m^2). Table 7 shows the seasonal beam solar radiation on the aperture of the solar troughs for these two orientations.

Table 7. Seasonal beam solar radiation on the aperture of the solar troughs

Period	Aperture irradiation (kWh/m^2)		Relative difference (%)
	EW axis	NS axis	(NS-EW)/EW
Cooling	583	726	25
Heating	304	273	-11
YEAR	887	999	13

The east-west axis system should be preferred to a north-south axis system if the system is operating only in winter. On the contrary, a north-south axis system should be preferred to an east-west axis system if the system is operating only in summer. The purpose of the studied system is to provide both heating and cooling (the IW has higher sensible cooling loads (15 MWh) than heating loads (10 MWh)). The optimum orientation for an annual use is north-south. Detailed study on the impact of the solar orientation on the system performance has been performed by exercising the TRNSYS model. Table 8 shows the solar fraction in winter and summer of the solar thermal system (without storage tank) for the two orientations.

Table 8. Solar fraction of the system for different trough orientations

Case	B	C
Orientation	EW axis	NS axis
Insulation thickness of the piping in the solar collection loop	3”	3”
Volume of the storage tank	-	-
Insulation thickness of the storage tank	-	-
Solar fraction (cooling season) (%)	37.8	61.4
Energy savings (cooling season) (MWh)	5.6	9.1
Solar fraction (heating season) (%)	8.4	7.5
Energy savings (heating season) (MWh)	0.82	0.73

3.2.1. Cooling season.

The higher amount of solar energy collected by the north-south axis east-west tracking solar trough leads to a higher fluid temperature in the SCL. The operating period of the system is defined by the ability of the absorption chiller to provide chilled water: it is the time period when the fluid temperature at the inlet of the absorption chiller is higher than 155°C. Figure 13 shows that the operating period of the east-west axis system is 6.75 hr (from 9:45AM to 4:30PM) whereas the operating period of the north-south axis system is 9.5 hr (from 8:45AM to 6:15PM).

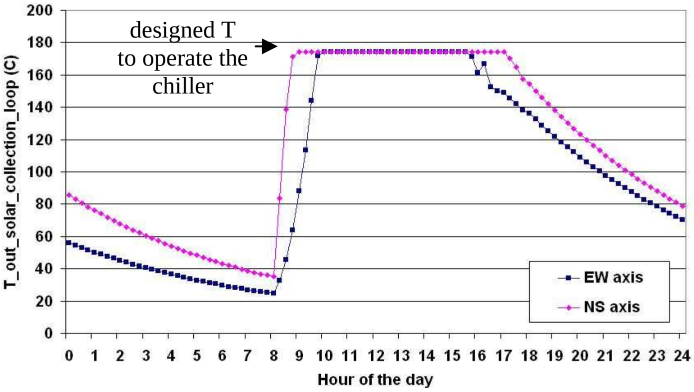

Figure 13. Evolution of the fluid temperature at the inlet of the absorption chiller for the two different solar trough orientations (cooling season)

For the north-south axis system, the fluid from the solar trough can be used directly to run the chiller due to its proper temperature (from 8:45AM to 6:15PM) instead of being bypassed to reach the required temperature. The average COP of the chiller is higher (1.18) in the north-south axis system than in the base case system (1.10) due to the longer period the fluid temperature at the inlet of the absorption chiller is at its designed value. The higher solar energy available, the longer operating period and the higher COP of the north-south axis east-west tracking solar system explain why this system is 62% more efficient than the east-west axis north-south tracking solar system (in summer).

3.2.2 Heating season. The solar fraction of the north-south axis system is slightly lower than the solar fraction of the east-west axis system. This difference can be explained by the lower amount of direct solar radiation on the solar trough reflector aperture, as shown previously in Table 7.

The optimum orientation of the solar troughs axis is definitely north-south. Despite the results, the solar troughs have been installed on the IW with an east-west orientation in the roof valleys (as shown in Fig. 14) to match the roof geometry, to minimize the wind loads, the structure complexity and cost. The roof was initially designed to install flat plate or evacuated tube collectors. The south slope has been calculated to optimize the amount of global radiation available on such collectors.

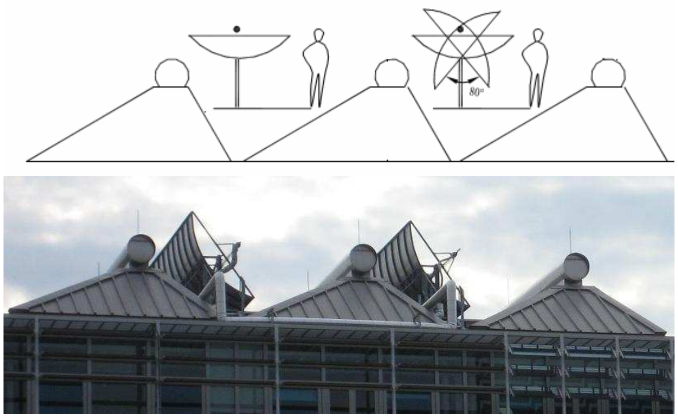

Figure 14. West elevation of the IW roof

3.3 Base case

The base case configuration is defined based on the previous results: solar troughs with an east-west axis and 3” fiberglass insulation on the SCL piping. Figure 15 shows the monthly solar fraction of the base case system.

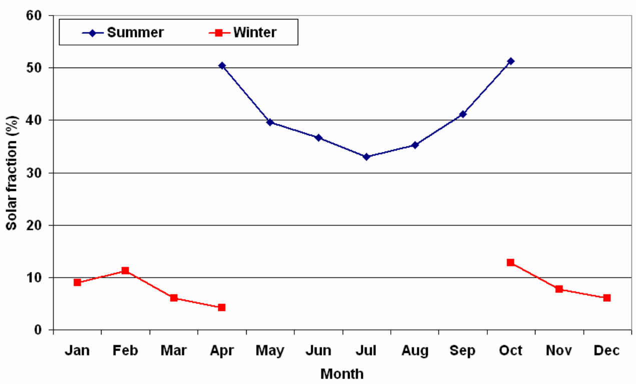

Figure 15. Monthly solar fraction of the base case system

The solar fraction is function of the solar energy available and the building load. For example, the monthly solar energy on the aperture of the trough is maximum in July for the base case configuration but the monthly building load is the largest in summer. The system performance of the base case (solar fraction) is 37.8 % in summer and 8.4 % in winter.

The solar fraction of the base case system is low in the heating season. Indeed, the building load is out of phase with the solar energy availability in winter: the heating demand is generally high during the night. On the contrary, the cooling demand is high at noon time when the solar radiation is maximum. The solar fractions of the base case can be increased by adding a storage tank to the system.

4. SYSTEM OPTIMIZATION

A sensitivity analysis on design parameters has been performed to improve the base case. TRNSYS simulations were performed for different volumes and insulation thicknesses of the storage tank.

4.1 Volume of the storage tank

Table 9 summarizes the results obtained from the sensitivity analysis on the storage tank volume.

Table 9. Results of the sensitivity analysis on tank volume

Case	BASE CASE	D
Orientation	EW axis	EW axis
Insulation thickness of the piping in the solar collection loop	3”	3”
Volume of the storage tank	-	1 - 5m^3
Insulation thickness of the storage tank	-	-
Solar fraction (cooling season) (%)	37.8	40.0-47.6
Energy savings (cooling season) (MWh)	5.6	5.9-7.1
Solar fraction (heating season) (%)	8.4	18.6-20.9
Energy savings (heating season) (MWh)	0.82	1.8-2.1

Figures 16 and 17 show the influence of the volume of the storage tank on the cooling and heating system performance. The inclusion of the storage tank has greater impact on the performance of the solar heating system than on the performance of the solar cooling system. The storage tank is especially useful to cope with the low correlation between the availability of solar energy and the need for heating.

4.1.1 Cooling season. By adding a storage tank (without insulation) to the base case cooling system, the solar fraction of the system increase between 38 % to 47 %.

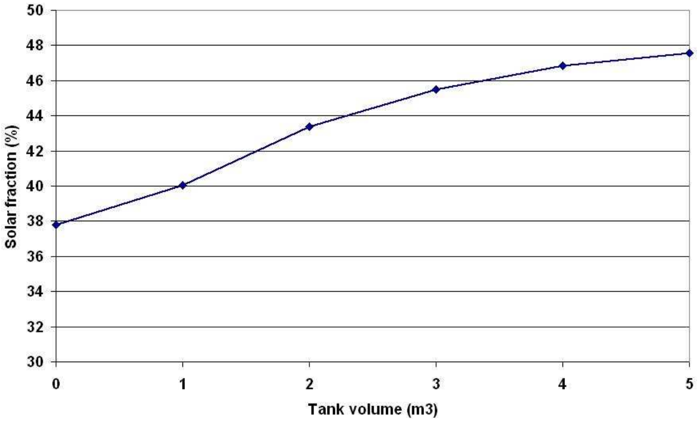

Figure 16. Performance of the solar cooling system for different volumes of storage tank

The larger the tank is, the higher is the solar fraction. This effect is due to the high amount of solar energy available in summer.

4.1.2 Heating season. By adding a storage tank (without insulation) to the base case heating system, the solar fraction of the system increase from 8 to 21 %.

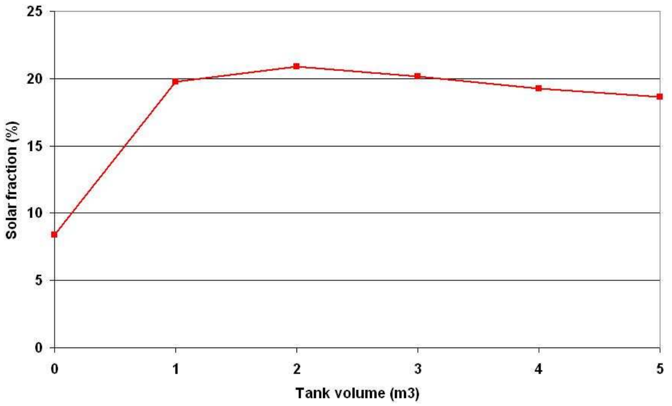

Figure 17. Performance of the solar heating system for different volumes of storage tank

Figure 17 shows that adding a small storage tank is critical for the performance of the solar heating system. The optimum size of the storage tank for a non insulated configuration in winter is 2 m^3 (height-to-diameter fraction as 2:1; height: 2.17 m, diameter: 1.08 m). Increasing the size of the storage tank increases the heat losses. The solar energy available in winter is limited; increasing the tank size beyond the optimum is not useful.

4.2 Insulation thickness of the storage tank

Table 10 summarizes the results obtained for the sensitivity analysis on the insulation thickness of the storage tank.

Table 10. Results of the sensitivity analysis on tank insulation

Case	BASE CASE	E
Orientation	EW axis	EW axis
Insulation thickness of the piping in the solar collection loop	3”	3”
Volume of the storage tank	-	From 1 to 5 m^3
Insulation thickness of the storage tank	-	From 0 to 4”
Solar fraction in summer (%)	37.8	40.0-49.2
Energy savings (cooling season) (MWh)	5.6	5.9-7.3
Solar fraction in winter (%)	8.4	18.6-27.0
Energy savings (heating season) (MWh)	0.82	1.8-2.6

Figures 18 and 19 show the variation of the solar cooling and heating system performance for different tank volumes and insulation thicknesses. Increasing the insulation thickness of the storage tank has more impact on the performance of the solar heating system than on the performance of the solar cooling system due to the fluid temperature in the storage, respectively 50°C and 10°C.

4.2.1 Cooling season. Increasing the insulation thickness of the storage tank tends to reduce the convection and radiation with the surroundings and improves the system performance, as shown in Fig.18. For solar cooling system with small storage tank, 0-2 m^3, the insulation thickness of the tank should be small, 1 inch. The energy stored in the tank is utilized rapidly. Whereas for solar cooling system with higher storage capacities, higher than 2m^3, the storage tank needs more insulation to reduce heat losses especially overnight.

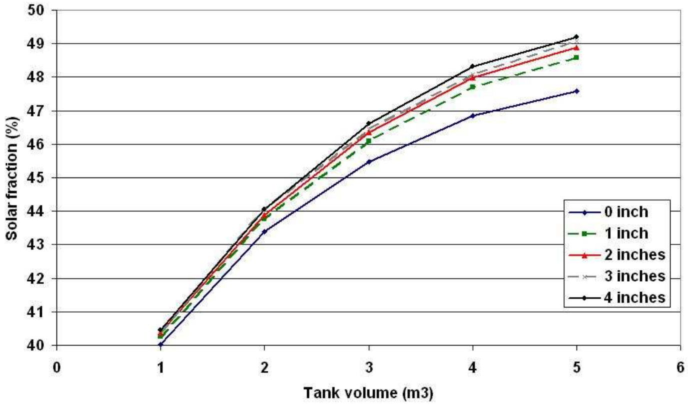

Figure 18. Performance of the solar cooling system for different tank volumes and insulation thicknesses

4.2.2 Heating season. Figure 19 shows that for an insulation thickness between 0 and 2 inches, the optimal system performance in winter is obtained with a 2 m^3 tank.

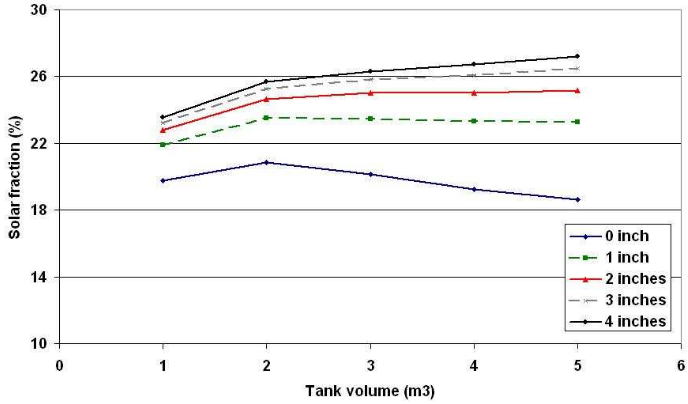

Figure 19. Performance of the solar heating system for different tank volumes and insulation thicknesses

The curves shows that increasing the volume of the insulated tank with less than 3 inch insulation above 2 m^3 does not appreciably affect the solar fraction in winter.

In an optimal system, the same storage tank will be used both in cooling and heating seasons. This storage tank based on the annual solar fraction or more precisely on the life cycle cost) will be between 2 and 3 m^3 in volume with a 3 inch insulation thickness.

The storage tank has not been included yet in the IW system due to:

- lack of space on the deck and weight load issues
- problems in modifying the existing control of the solar collection loop

5. CONCLUSION

The TRNSYS model has provided performance information that has proved useful in implementing and optimizing the design for this solar thermal driven heating and cooling system.

The building simulation indicates that the 16 kW absorption chiller is adequate to meet the IW south cooling requirements (sensible loads).

The energy supply system simulations indicate that:

- the solar collector array can provide energy supply rates up to 30 kW in summer and in winter (the mean values are 20 kW for summer and 17 kW for winter).
- the base case system is able to provide 37.8 % of the cooling loads and 8.4 % of the heating loads from the solar energy collected by the solar trough.
- estimated heat losses from the system can reach 20-35% of the total heat collected by the solar receiver.
- adding a storage tank (without insulation) to the base case system, the system solar fraction can increase from 37.8 to 40 - 47.6 % in summer and from 8.4 to 18.6-20.9 % in winter, for tank volumes from 1 to 5 m^3,
- the solar cooling system can attain a solar fraction of 49.2% and the solar heating system a solar fraction of 27% with a 5 m^3 storage tank having 5 inch insulation.

Even after being optimized, the performance of the designed system (based on the site configuration) is still lower than the performance of the same system without storage with an optimum orientation. This study shows the difference between efficiency and efficacy. Contrary to efficiency, the focus of efficacy is the achievement as such, not the resources spent in achieving the desired effect (larger storage tank, larger insulation thickness…).

Innovative technologies should be implemented at a very early stage in the design process. Projects such as active solar system should be held in building that creates opportunities for interaction with the natural environment and minimize demolition and construction wastes.

It is very important to employ building simulation at a very early stage in the design process, when decision about building shape, number of stories and orientation are being made. Available simulation tools allow the integration of active and passive building systems and can easily examine the interplay and trade-offs among HVAC systems, materials choices, shading, lighting… The energy simulation provides useful quantitative information to guide design teams and building owners in making the most appropriate design and investment decisions.

The work of the Center for Building Performance and Diagnostics is:

- to perform this kind of energy simulations but also validate them with commissioning, measurement and verification.
- and to promote the integration of advanced systems, such as in the proposed building BAPP, Building As Power Plant [9]. Building on the experience of the Robert L. Preger Intelligent Workplace, the CBPD is committed to realize the BAPP project on the Carnegie Mellon campus. The BAPP will be a living laboratory for research, demonstration and teaching of high performance workplaces. The BAPP initiative seeks to integrate advanced energy-efficient building technologies with innovative distributed energy generation systems, therefore becoming a producer of energy instead of an energy consumer. Most or all of the building's energy needs for heating, cooling, ventilating and lighting are met on-site, maximizing the use of renewable energies.

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REFERENCES

[1] ASHRAE, Applications of solar energy for heating and cooling of buildings, 1977.

[2] ASHRAE, Applications Handbook, Solar energy use, Chapter 33, 2003.

[3] ASHRAE, HVAC Systems and equipment, Solar energy equipment, Chapter 33, 2000.

[4] TRNSYS 16, a transient system simulation program, Solar Energy Laboratory, University Wisconsin Madison.

[5] Sophie V. Masson, Ming Qu, David H. Archer, Performance modeling of a solar driven absorption cooling system for Carnegie Mellon University's Intelligent Workplace, ICEBO, 2006.

[6] Duffie J.A., Beckman W.A., Solar Engineering of Thermal Processes, Second edition, John Wiley and Sons, 1991.

[7] Charles J.Kilbert, Sustainable construction, green building design and delivery, John Wiley and Sons, 2005.

[8] Houghton Chemical Corporation, SAFE-T-THERM Engineering Manual, Propylene Glycol Heat Transfer Fluid, 23 p.

[9] V. Hartkopf, D. Archer, and V. Loftness, Building as Power Plant, Smart and Sustainable Built Environments, Black publishing, Ltd. pp. 55-74, 2005.