EVALUATION OF A LIQUID DESICCANT AIR CONDITIONING SYSTEM WITH SOLAR THERMAL REGENERATION

Lisa Crofoot[1] and Stephen Harrison[2]

[1,2]Solar Calorimetry Laboratory, Dept. Of Mechanical and Materials Engineering, Queen's University, Kingston, Ontario (Canada)

Abstract

To investigate the feasibility of solar thermal air-conditioning systems in Canada, a 95m^2 vacuum tube solar array was installed and instrumented to drive a liquid-desiccant (LD) dehumidifier. The novel low-flow LD unit was configured to operate as a dedicated outdoor air system. Phase I of the demonstration project focused on characterizing and modelling the LDAC using a gas fired boiler to simulate the solar heat input. As part of phase II, currently in progress, the TRNSYS simulation environment was used to model the performance of the system when driven by solar energy. Simulations were used as a design tool for the solar array which is currently being commissioned. The installed system was simulated for the months of July and August using Toronto, Canada weather data and the system was predicted to have an average solar fraction of 65% and average collector efficiency of 64% (based on absorber area). Latent cooling power was predicted to be between 13 and 23 kW (3.8-6.6 tons). Experimental operating results will be used to validate simulations and identify practical considerations not currently represented by system models. Performance of the system is predicted to improve with upgrades including variable speed pump control and the installation of desiccant storage.

1. Introduction

Air conditioning systems consume a significant amount of energy and contribute to peak electrical loads. Due to the high peak power consumption of common vapour compression (VC) air conditioners, Ontario's electricity demand has shifted from a winter to summer peak (Ontario Power Authority, 2009). Thermally driven air-conditioning systems using solar energy are an attractive alternative to traditional systems since the air conditioning load is matched closely with the overall solar availability. In temperate climates, such as Canada and Northern Europe, solar space cooling systems can be combined with combi-systems that provide space heating and domestic hot water to allow for year round utilization of solar collectors, resulting in improved economic performance.

While the majority of installed solar cooling demonstrations use absorption chillers, this project focuses on liquid desiccant dehumidification technology as it requires lower temperature heat (60-90ºC) that can be provided by flat plate or evacuated tube solar collectors. A 95m^2 evacuated tube solar array was installed and instrumented as part of the second phase of a solar liquid desiccant demonstration project in Kingston, Ontario, Canada. Characterization of the solar driven desiccant system under different operating conditions will allow for optimization of control strategies and storage configurations to increase performance of both the air conditioner and the collector array.

Building Ventilation and Latent Cooling Loads

Mechanical building ventilation is critical in maintaining acceptable Indoor Air Quality (IAQ) as well as occupant comfort. As building envelopes have become tighter, required ventilation rates have increased resulting in higher space cooling loads (ASHRAE, 2010). In the majority of Canadian cities, and in many cities worldwide, cooling loads are dominated by dehumidification, or latent cooling. The Ventilation Load Index (VLI) defines the sensible and latent portions of the cooling load and is a measure of the annual energy required to bring a unit volume of ventilation air down to space neutral conditions (24ºC and 50% relative humidity). Figure 1 shows the VLI for several world cities.

Traditional vapour compression (VC) and fan coil systems are not ideally suited to handle latent cooling.

Inadequate dehumidification can result in occupant discomfort, as well as mold, mildew, and other microbial growth. Dehumidification with VC air conditioners is accomplished by cooling air below its dew point to remove humidity, and then reheating air to the desired delivery conditions. As well, conventional air conditioning systems are controlled through the use of thermostats, which only control the dry bulb temperature of the delivery air.

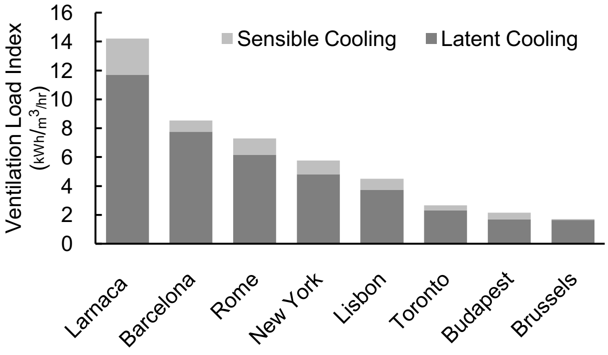

Fig. 1: Ventilation Load Index (VLI) for various world cities

Dedicated Outdoor Air Systems (DOAS) aim to mitigate the inefficiencies of conventional systems by decoupling the latent and sensible cooling loads. Typically, the DOAS dehumidifies outdoor air while a downstream evaporative cooler or smaller VC system is used to meet the sensible cooling load. This strategy eliminates the overcool-reheat cycle and ensures adequate dehumidification since each system is designed to meet its particular load.

Liquid Desiccant Air Conditioning

Liquid desiccant air conditioning systems (LDAC) utilize the hygroscopic properties of a salt solution to dehumidify air. These systems operate on an open absorption cycle, ie, ventilation air is brought into contact with the concentrated desiccant solution in the conditioner where water vapour is absorbed. Diluted desiccant is then regenerated using low grade heat. The driving force behind the transfer of moisture is the difference in the vapour pressure between the desiccant and the air (Mesquita, 2007). Since effective dehumidification occurs only when the desiccant is at a low temperature and high concentration, the latent heat of condensation must be removed to maintain conditioner effectiveness.

Liquid desiccant technology is ideal for use in solar cooling applications as it requires low temperature heat (60-90°C) and provides the potential for high density (1000 MJ/m^3), loss-less energy storage in the form of cooling potential (Burch et al., 2009, Shi et al., 2007). The ability to store concentrated liquid desiccant solution for use at times when solar energy is inadequate or unavailable is an important advantage of liquid desiccant systems when compared to solid desiccant or enthalpy wheel dehumidifiers.

2. System Description

Low-flow Liquid Desiccant System

A novel low-flow LDAC system, shown in Fig. 2, has been designed for use in building air conditioning systems (Lowenstein, 2007). The conditioner and regenerator are parallel plate heat and mass exchangers which are internally cooled and heated. Desiccant flows in a thin wick over the outside of the plates while air is blown horizontally between the plates to allow for absorption and desorption of water vapour. The desiccant system, shown in Fig. 2 and Fig. 3, is configured as an air handling unit containing the regenerator, conditioner, pumps, blowers, a desiccant sump and all required data acquisition and control equipment.

The low flow configuration eliminates carryover of the desiccant into the air stream. Carryover is a common problem in industrial packed bed structures. Additionally, lower desiccant flow rates provide a higher air to desiccant mass flow ratio, improving the desiccant storage capacity (Kessling et al, 1998).

As part of an ongoing investigation of this technology, a prototype commercially available liquid desiccant system was installed at Queen's University in Kingston Ontario. Previous studies (Phase I) evaluated the performance of the system using a gas-fired boiler as a heat source (Jones 2008, Mesquita 2007,).

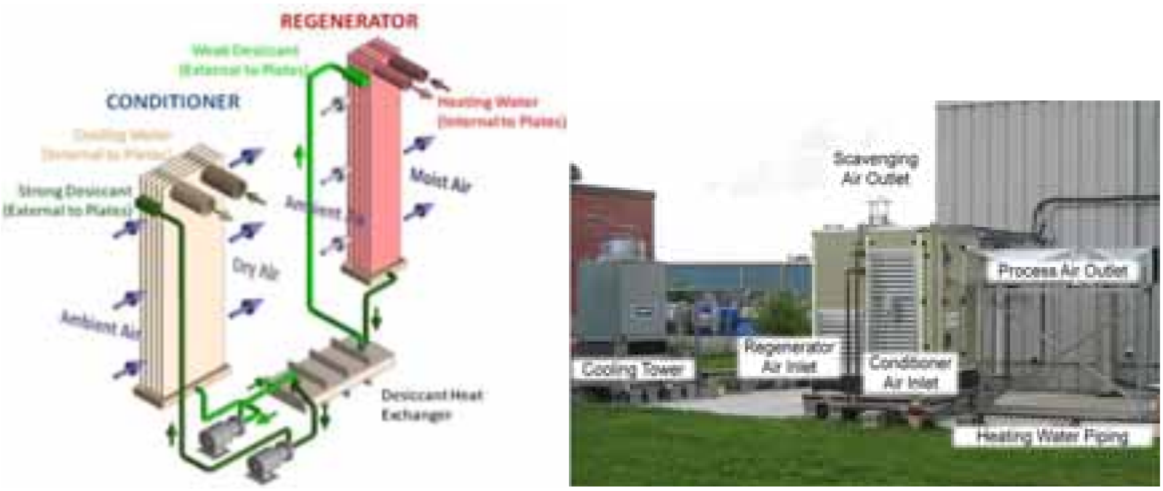

Fig. 2: Left: Low-flow liquid-desiccant system (Adapted from Miller & Lowenstein, 2008), Right: Liquid desiccant DOAS installed at Queen's University in Kingston, Canada.

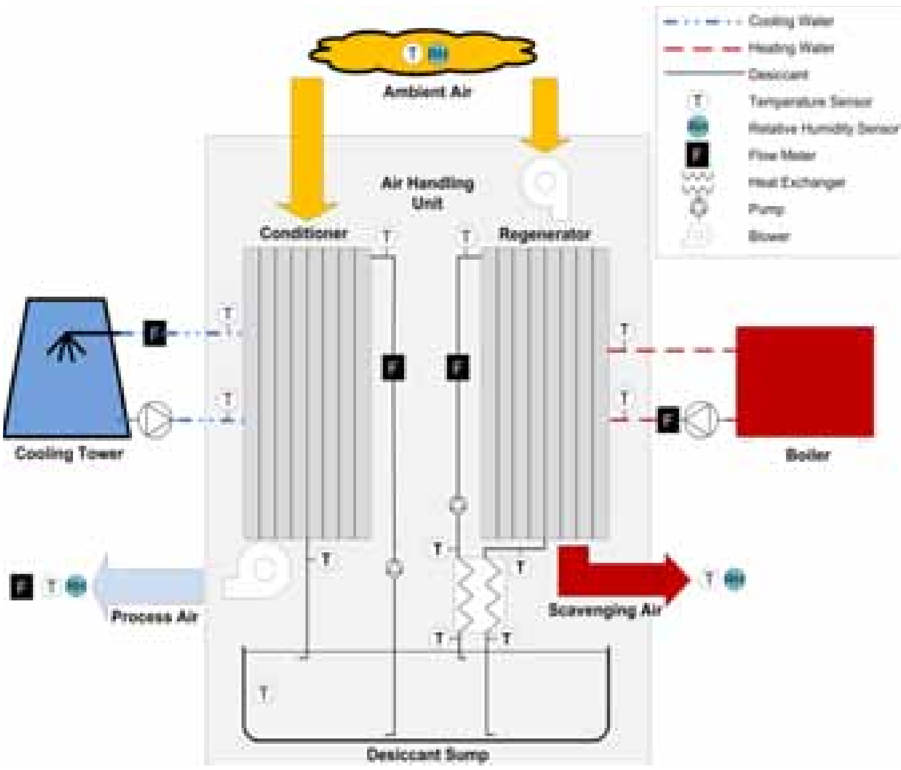

Fig. 3: Desiccant system schematic for Phase I testing (Andrusiak and Harrison, 2009)

Phase I testing of the system used a 90kW natural gas fired boiler as a heat source for the regenerator where regeneration temperatures were varied from 50^{0}C to 90^{0}C, similar to temperatures produced by flat plat and evacuated tube solar collectors. A 65kW cooling tower was used for heat rejection. The system, as shown in Fig. 3, was operated for 23 days in 2008 and 51 days in 2009 and performance was characterized using experimental results. Table 1 summarizes the Phase I results from two summers of system operation.

Tab. 1: LDAC Experimental Operating Results from Phase I Testing

System Parameter	Results
Process Air Flow	1200 L/s
Hot Water Flow	90 L/min
Cold Water Flow	130 L/min
Desiccant Concentration	25.64-42.73 wt%
Conditioner Desiccant Flow	5.3 L/min
Regenerator Desiccant Flow	6.5 L/min
Regeneration Thermal COP	0.419 – 0.761
Heating Water Temperature	50 - 90°C
Measured Latent Cooling Capacity	4.5 – 23.3 kW (1.3 – 6.6 tons)
Measured Total Cooling Capacity	4.8 – 18.1 kW(1.4 – 5.1 tons)

Based on experimental results, models were developed for the conditioner and regenerator. It was found that higher heating water temperatures increased the system capacity and coefficient of performance. As a result, the solar array was designed using evacuated tube solar collectors (Jones 2008).

Solar Array Installation

Phase II of the project, currently in progress, involves connecting the previously studied liquid desiccant air conditioner to an evacuated tube solar collector array. Based on previous system performance and simulation results (Andrusiak et al., 2010, Andrusiak and Harrison, 2009), the solar array was designed and installed in the summer of 2011. Initial simulations indicated system configurations and control strategies can have a significant impact on performance, therefore the system was designed and installed to have variable configurations. Figure 4 shows a simplified schematic of the solar driven desiccant system.

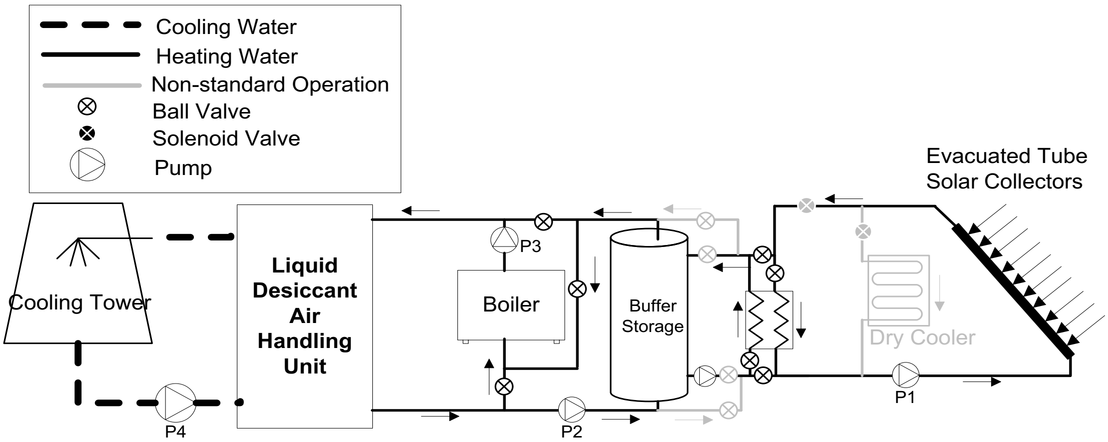

Fig. 4: Simplified solar driven liquid desiccant system schematic

The system can be operated as a direct or indirect solar thermal system with, or without two buffer hot water storage tanks. For initial cooling studies the array will be operated with water in a direct solar mode. For for future heating studies a heat exchanger will be installed and the system will be operated as an indirect solar system with glycol as a heat transfer fluid.

The boiler, used for auxiliary heat, can be run in parallel or series with the collector loop. Additionally, both heat sources (boiler and collectors) can be isolated and operated with the desiccant air handling unit independently. The ability to study different configurations and apply different control schemes in a full-scale demonstration will reveal operational features not currently represented by simulations to evaluate the suitability of current modeling and simulation methods.

The ground mount solar array consists of 24 evacuated tube solar collectors which provide 61m^2 of absorber area and cover a gross area of 95m^2. The collectors were arranged in five parallel banks of 120 tubes (12m^2 absorber area). Figure 5 shows the layout of the collector array. Hydraulic balancing valves were installed to ensure balanced flow between collector banks. Collectors were oriented at an incidence angle of 45 degrees and azimuth angle of 15 degrees due to space constraints. The collector circulator (P1), and the pump between the storage and regenerator (P2), are high efficiency variable speed pumps which provide additional testing and control configurations. System design parameters are summarized Tab. 2.

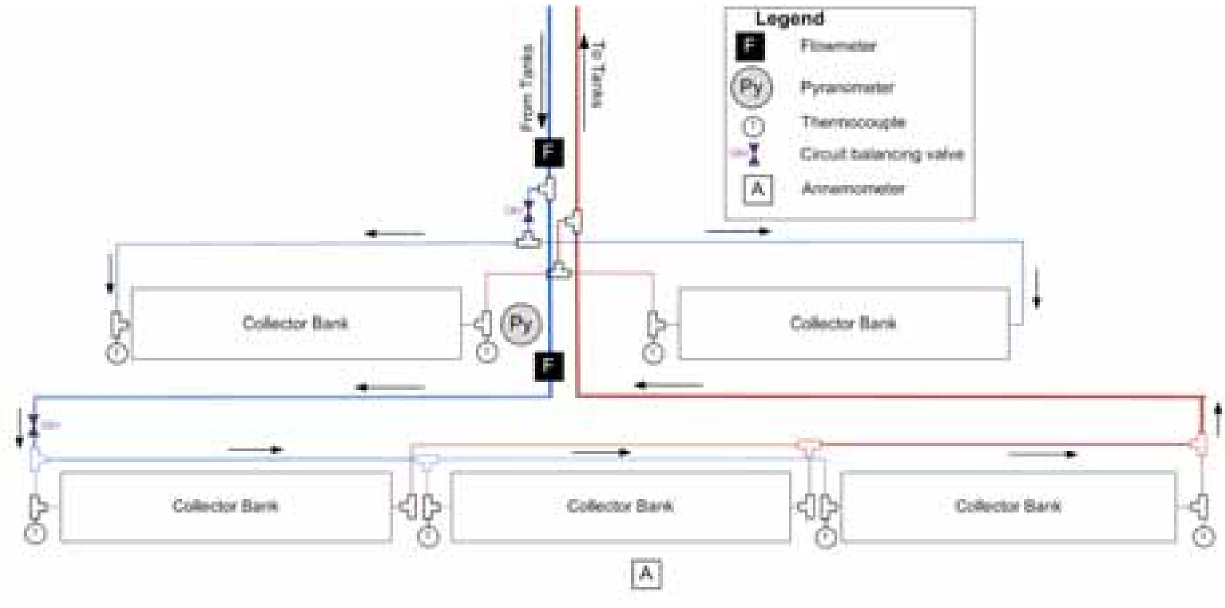

Fig. 5: Solar array layout and instrumentation (plumbing details such as ball valves, pressure relief valves, air vents, and drain valves not shown).

Tab. 2: Solar Array Design Parameters

Parameter	Design Value
Design Temperature Rise	10°C
Total Collector flow rate	40-50 L/min
Collector Absorber Area	61m^2
Buffer Storage Size	870L
Pumping Power (collector circulator)	25-450W
Dry Cooler Rated Capacity (used for stagnation heat rejection)	56.5kW

The buffer storage is not intended to be a full scale thermal store for the system, and is instead meant to provide a capacitance between the collector and air conditioner loop to allow for varying flow rates. Two storage tanks, shown in Fig. 6, were installed in parallel and together provide 870L of storage capacity.

A 56.5kW dry cooler was installed for stagnation heat rejection, preventing collectors from overheating and damaging sensors and other equipment. Thermostatically controlled solenoid valves will divert the flow to the dry cooler when the tanks are charged and regenerator load is met. An 8kW natural gas powered generator was installed to provide backup power to the pumps and dry cooler in case of a power outage.

The array is fully instrumented to experimentally assess the performance of the solar-thermally driven system. Installed sensors, shown in Fig. 5 and Fig. 6 will be used to quantify total collected energy, collector efficiency, heat losses, ambient weather conditions and parasitic power. A datalogger, installed on site, continually monitors the array and transmits data to the Internet.

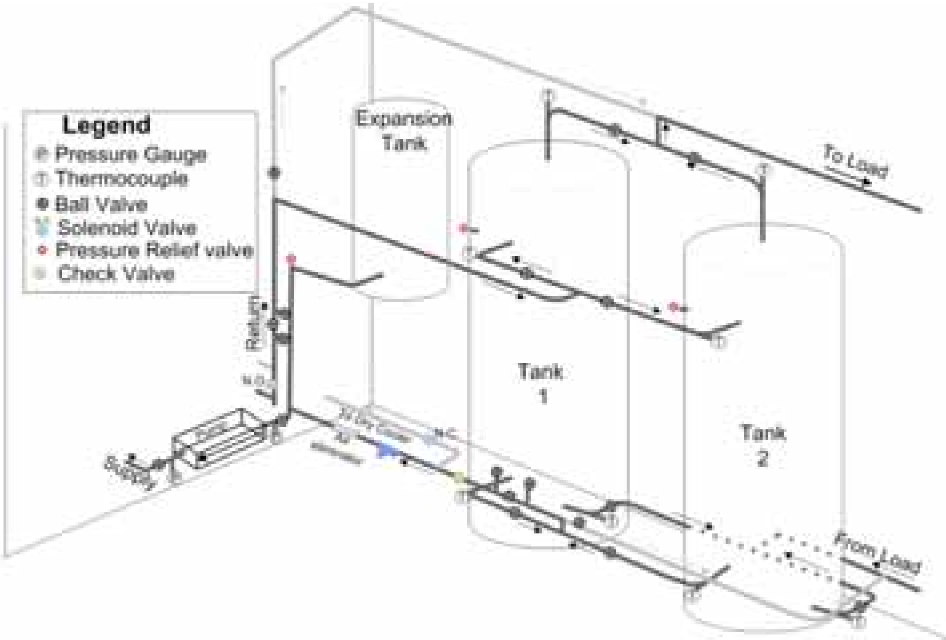

Fig. 6: Tank room layout and instrumentation (heat exchanger not shown, will be located under expansion tank)

3. System Performance, Characterization, and Modelling

TRNSYS, a transient simulation software package, was used to model the liquid desiccant air conditioning system. While TRNSYS types are available for solar array components, new types were created for the desiccant conditioner, regenerator, and desiccant sump.

As mentioned, in Phase I of this study, the LDAC system was tested using a gas fired boiler to simulate the solar thermal energy input. The system was then characterized using the experimental data and modeled by adapting the effectiveness method, which is commonly used with packed bed and spray tower systems (Gandhidasan 2004, Liu et al., 2009). Details pertaining to the characterization and modelling of these components were outlined by Andrusiak and Harrison (2010).

Cooling systems are commonly compared using coefficient of performance (COP), which represents the ratio of cooling power to required input power. For thermally driven systems the thermal COP (TCOP) compares cooling power to input heat, and the electrical COP (ECOP) compares cooling power to the electrical power required to drive the pumps and fans. For desiccant systems, the regenerator COP can also be defined, comparing the desorption power to the input heat energy. Solar collector efficiency and total solar fraction are also important performance measures for the system when driven by solar energy.

4. Simulation and Expected Results

At the time of this publication, final installation and commissioning of the solar array was ongoing and experimental results were not yet available, therefore only predicted results are presented. TRNSYS was used to model the solar driven liquid desiccant air conditioner and simulations were used as a design tool to help size the solar array and storage tank components.

The system was modeled as a direct solar system with either a series or parallel boiler configuration (shown in Fig. 4). In both cases the tanks (Type4) were used as a buffer between the collector loop and the desiccant loop due to differing flow rates. Performance specifications from the manufacturers were used for the boiler (Type26), cooling tower (Type51a), pumps (Type3d), and evacuated tube solar collectors (Type71).

The conditioner and regenerator were operated on a daily 6am to 6pm schedule. The collector loop was controlled by a “delta T” controller (Type21), which compared the temperatures of the collector outlet to the bottom of the storage tank using a 12°C upper deadband and 0°C lower deadband.

System Sizing and Design

Initial simulations using weather data from Toronto, Ontario were used to size the array. As shown in Fig. 7, increasing collector area also increases solar fraction, however if the collector array is too large, utilization of the collectors begins to decrease. Sizing collectors for a very large solar fraction leads to increased costs, prolonged periods of stagnation, and higher pumping power (Lowenstein 2003, Carrillo et al., 2010). Use of desiccant storage should decrease the required array size while simultaneously increasing utilization and will be studied in the future.

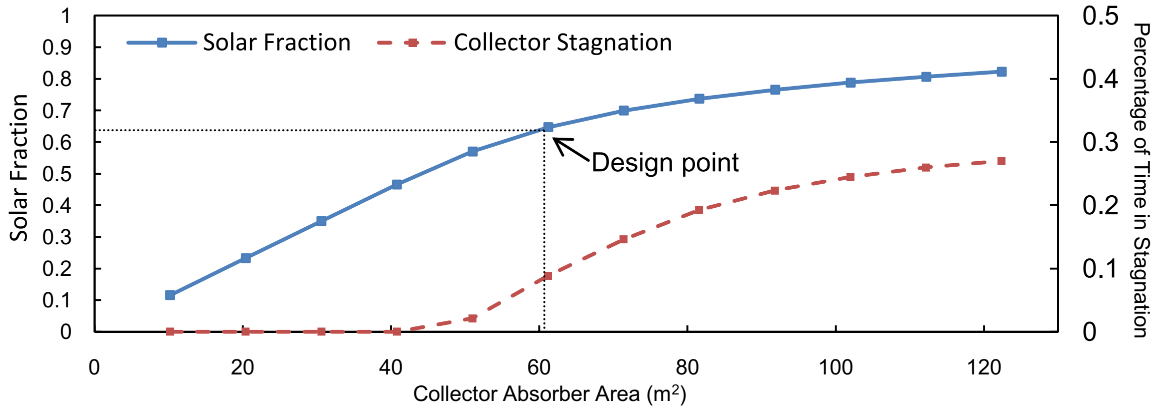

Fig. 7: TRNSYS simulation results for solar LDAC performance as a function of collector area

The solar array was sized to provide approximately 65% of the required heat to mitigate the problems associated with prolonged periods of stagnation and allow for future installation of desiccant storage.

Predicted System Performance

The system as installed was simulated in TRNSYS using parallel and series boiler configurations. Performance was averaged daily and is shown in Fig. 8 and Fig. 9 for a heating water setpoint of 80°C.

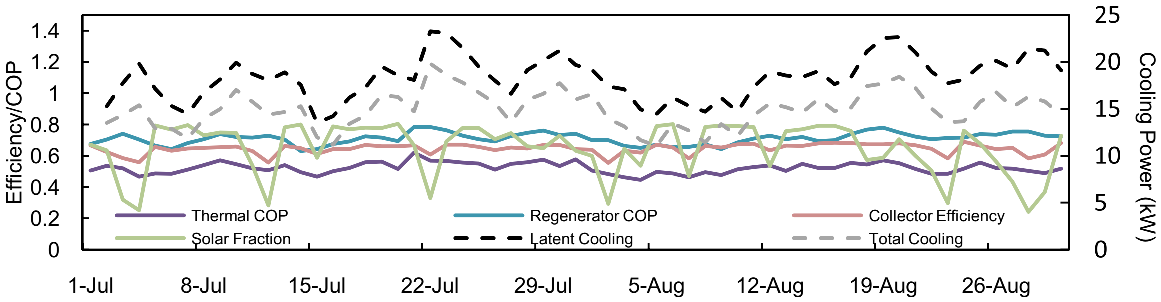

Fig. 8: Daily average solar LDAC performance for series configuration

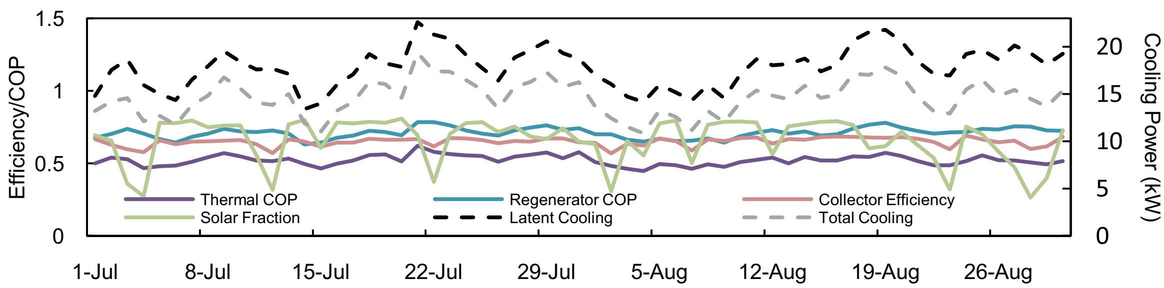

Fig. 9: Daily average solar LDAC performance for parallel configuration

Table 3 summarizes the average, maximum and minimum predicted results.

Tab. 3: Daily average performance for the solar LDAC using typical meteorological year data from Toronto, Canada

Parameter	Series Average	Parallel Average	Maximum	Minimum
Latent Cooling Power, kW (tons)	18.3 (5.1)	17.8 (5.1)	23.3 (6.6)	13.4 (3.8)
Total Cooling Power, kW (tons)	14.9 (4.2)	14.6 (4.2)	19.8 (5.6)	10.9 (3.1)
Process Air Humidity Ratio, g/kg	5.55	5.68	9.61	3.19
Electrical Coefficient of Performance (ECOP)*	2.97	2.91	3.94	2.17
Thermal Coefficient of Performance (TCOP)	0.52	0.52	0.62	0.44
Absorption Rate, kg/hr	26.0	25.3	32.8	19.0
Collector Efficiency based on absorber area	64.5%	64.9%	69.1%	55.5%
Collector Efficiency based on gross area	41.4%	41.6%	44.4%	35.7%
Solar Fraction	64.7%	66.0%	80.8%	24.1%

The ECOP is directly proportional to the total cooling power and low in this case due to the high electricity requirements of fan components, particularly in the cooling tower. Future system upgrades will greatly improve the ECOP by replacing inefficient fan motors and pumps to reduce the parasitic power.

Previous work by Jones indicated that increasing heating water temperature resulted in higher LDAC cooling power and ECOP (Jones, 2008). Since collector efficiency decreases with increasing temperature, the boiler setpoint temperature is an important parameter for overall system performance. This design tradeoff was investigated in TRNSYS and Fig. 10 plots the results for the parallel and series boiler arrangements.

It is important to note that Fig. 10 does not show the performance as a function of heating water supply temperature since at times the collectors provide water at a higher temperature than the boiler setpoint. Relationships for LDAC performance as a function of supply temperature were determined by Jones (2008). Figure 10 is instead meant to show the effect of boiler setpoint temperature in actual system operation.

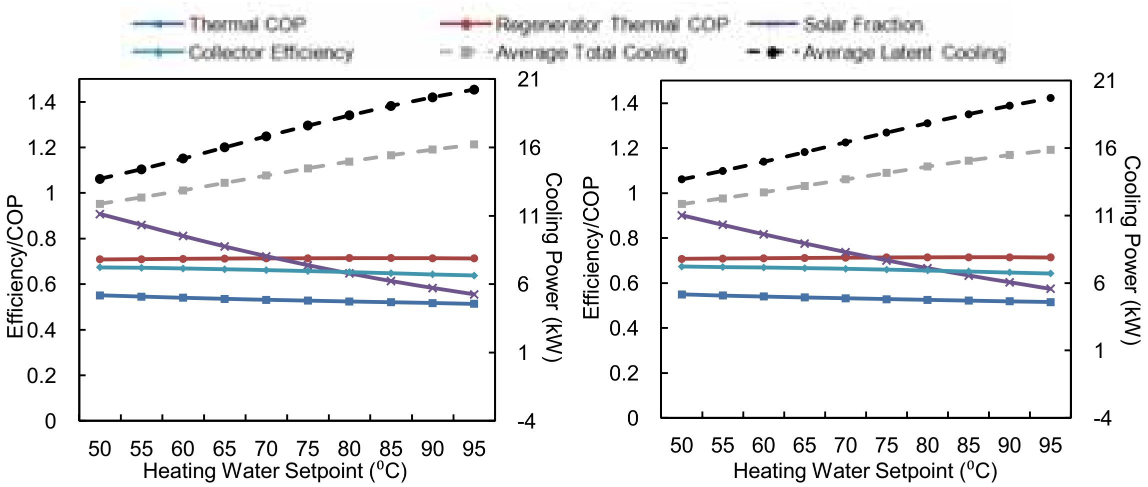

Fig. 10: Effects of heating water setpoint temperature on solar LDAC system performance for series (left) and parallel (right) configurations

Figures 8, 9 and 10 predict similar performance for the series and parallel configurations. It is, however, expected that when implemented, the non-ideal boiler control will cause experimental results to show distinct differences between the two configurations. In particular, the boiler may cause the delivery temperature to exceed the setpoint temperature in the series configuration, reducing the solar performance. Additionally, solar array and LDAC performance is predicted to improve with the implementation of desiccant storage.

5. Conclusions

A novel low flow liquid desiccant dehumidification system was tested with a gas fired boiler for two summers as part of Phase I of a solar cooling demonstration project. The experimental results were used to characterize and model the system in the TRNSYS simulation environment. Phase II of the study, currently in progress, involves running the LDAC unit on solar energy provided by a $95m^2$ vacuum tube solar array. While experimental operating results are not yet available, simulations predicted the solar array will provide 65% of the thermal energy while operating with an average solar collector efficiency of 65% (based on absorber area). The desiccant unit was predicted to have an average thermal COP of 0.52 and latent cooling power between 13 and 23 kW (3.8-6.6 tons).

6. Future Work

Operating data from the solar LDAC for August and September 2011 will be analyzed and compared with TRNSYS results to validate system simulations. The system will be improved and expanded by implementing the variable speed pumping capabilities of the collector circulator pump and installing a heat exchanger between the collectors and storage tanks. Inefficient fans and pumps will also be replaced to reduce the parasitic power and increase the ECOP.

The project will then focus on two main objectives. First, simulations will be used to investigate desiccant storage configurations, culminating in the installation of storage within the current demonstration project. Second, the array will be monitored during the winter of 2011 to determine its capacity for space heating and evaluate the potential of a solar combi-system. By providing solar space heating and cooling to a laboratory space this project aims to demonstrate the technical and economic benefits of solar heating and cooling combination systems.

7. Acknowledgements

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