STRATEGIES FOR CONTROLLING RESIDENTIAL COMBINED COOLING, HEATING AND POWER SYSTEMS

Alex Ferguson
CANMET Energy Technology Centre, Natural Resources Canada, Ottawa
alex.ferguson@nrcan.gc.ca

ABSTRACT

Cogeneration technologies have received increasing attention in recent years as a viable alternative for meeting the electrical and space heating requirements of residential buildings. If coupled to thermally activated cooling equipment, such as an absorption chiller, the thermal output from the cogeneration system can also be exploited during the summer months. In a combined cooling, heating and power (CCHP) plant, the cogeneration system must be operated to simultaneously satisfy the seasonal heating and cooling loads, and year-round electrical and domestic hot water loads. In this study, strategies for meeting simultaneous cooling, heating and electrical loads in a residential building were proposed, and these strategies were implemented a control model compatible with the ESP-r/HOT3000 simulation environment. The behavior of the controller was also assessed by coupling it to a residential CCHP plant comprised of a fuel cell system and a small-scale thermally activated cooling device, and the results of this study are presented in this paper.

INTRODUCTION

Recently, combined cooling, heating, and power (CCHP) plants have been deployed in commercial buildings and in the food industry (Maidment & Tozer 2002, Bassols, Kuncklkorn, Schneider & Veelken 2002). This innovative technology, which is capable of simultaneously satisfying seasonal space heating and cooling loads, and year-round domestic hot water and electrical loads using a single fuel source, offers reduced energy costs and produces fewer environmentally harmful emissions in these applications.

Residential cogeneration applications are also excellent candidates for CCHP technology. In a preliminary modelling study, Beausoleil-Morrison, Cuthbert, Deuchars & McAlary (2002) demonstrated that the thermal output delivered by a residential fuel cell system can be significantly larger than a house's heating requirements during the summer months. Stirling engine and internal combustion technologies, which deliver lower electrical efficiencies than fuel cell systems, will likely produce even more surplus heat. If this excess heat can be exploited to deliver useful cooling to the dwelling using CCHP technology, the overall efficiency of a cogeneration plant can be increased, potentially making it more environmentally and economically attractive.

Researchers at the CANMET Energy Technology Centre (CETC) are investigating the technical and economic feasibility of CCHP technology in the residential sector (Beausoleil-Morrison, Mottillo, Brandon, Sears & Ferguson 2004). Over the course of this project, a model of a thermally-activated cooling (TAC) unit was developed and integrated into the ESP-r/HOT3000 residential simulation engine. The TAC unit model was coupled to a previously developed fuel cell model (Beausoleil-Morrison et al. 2002) in a residential HVAC network.

In this paper, the characteristics of the CCHP plant are briefly described, and control strategies suitable for meeting simultaneous cooling, heating and electrical loads are proposed. The integration of these control strategies into a CCHP system controller model is discussed, and the response of the controller to a set of arbitrary loads is illustrated using simulation results. Finally, recommendations are made for future research with the TAC unit and CCHP controller models.

The fuel cell, TAC unit and CCHP controller models used in this work were designed for use in the explicit HVAC modelling domain of the ESP-r/HOT3000 simulation engine. This simulator is based on the comprehensive and extensively validated ESP-r program developed at the University of Strathclyde, with algorithmic additions by CETC to support the modelling of Canadian and international housing. Clarke (2001) provides a thorough discussion of ESP-r's simulation methodologies, and Hensen (1991) describes the ESP-r explicit HVAC simulation domain in detail.

HVAC CONFIGURATION

The mechanical plant configuration investigated in this study is depicted in Figure 1. A cogeneration fuel cell system is used as the primary energy conversion device in the plant, producing both electricity and heat from a natural gas fuel supply. A description of the cogeneration fuel cell model used in this study is available in Beausoleil-Morrison et al. (2002). The fuel cell model is

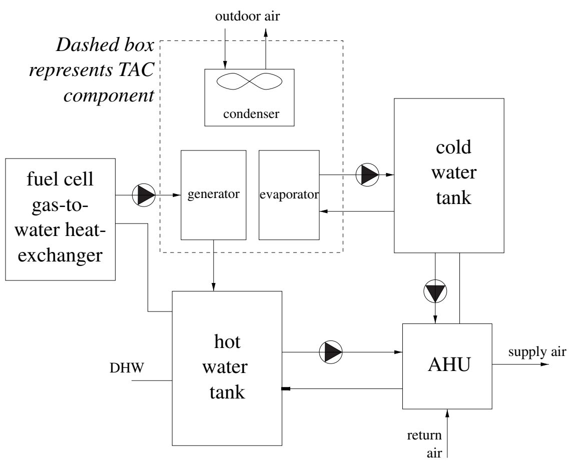

Figure 1: Schematic of residential CCHP plant.

quasi-steady state, and the unit's transient characteristics are not considered[1].

The TAC unit uses the high-grade surplus heat produced by the fuel cell to deliver useful cooling. The unit has three modes of operation:

1. *Cooling:* When the TAC unit runs in cooling mode, the majority of the surplus heat recovered from the fuel cell is used to deliver cooling to the cold storage tank. The TAC unit extracts high-grade waste heat from the hot water flowing through its generator, and this energy is used to extract low-grade heat from cold water circulating through the unit's evaporator. All of the heat extracted by the TAC unit is rejected in the condenser.

2. *Heat-dump:* In heat dump mode, the TAC unit is used as a heat rejection device to cool the hot storage tank[2]. Heat is extracted from the hot water flowing through the generator and is rejected in the unit's condenser, while no heat transfer occurs in the unit's evaporator. The heat-dump mode is used to prevent the fuel cell from overheating the hot storage tank during periods of low heating demand, and the TAC unit cannot deliver cooling to the cold storage tank when operating in this mode.

3. *Inactive:* When turned off, no heat transfer occurs in the unit's generator, evaporator or condenser. The TAC unit does not deliver any cooling to the cold storage tank, and all of the surplus heat recovered from the fuel cell is delivered to the hot water tank.

[1] The electrical and thermal capacitance of high-temperature fuel cell systems are not insignificant, and the assumption of steady-state behavior may be unreliable when short time steps of five-minutes or less are used to simulate controls in the HVAC plant. The authors intend to revisit fuel cell model when more information describing the transient behavior of these systems is available

[2] It is assumed that the TAC unit can operate as a heat rejection device, but the operational characteristics of the TAC unit are presently unknown. Future experiments will investigate the feasibility of this mode of operation.

A comprehensive discussion of the operation of the TAC unit and the methodology used to model this technology is available in Beausoleil-Morrison et al. (2004) Briefly, a coefficient of performance (COP) is used to relate the heat transfer occurring in the evaporator ($\dot{Q}_{evap.}$) to that in the generator ($\dot{Q}_{gen.}$):

$$\dot{Q}_{evap.} = COP \cdot \dot{Q}_{gen.} \tag{1}$$

The model uses an empirical equation correlating the coefficient of performance to the temperatures of water entering the evaporator and generator, and the temperature of air entering the condenser.

The fuel cell's high temperature exhaust flows through a heat exchanger, where heat is transfered to water from the hot storage tank. The resulting high-temperature water is passed through the TAC unit's generator before it is returned to the tank. The second tank is used to store the cold water produced by the TAC unit. Water is extracted from this tank and circulated through the TAC unit's evaporator, where it is cooled before being returned to the cold storage tank.

Water from the hot and cold storage tanks is circulated through a coil in an air handler unit (AHU) as necessary to meet the space heating and cooling requirements of the dwelling. The hot storage tank is also used to meet the occupants' domestic hot water needs. An auxiliary, gas-fired burner coupled to the hot water tank is used to ensure the dwelling's heating and domestic hot water requirements will always be met, but there is no auxiliary cooling system in the mechanical plant.

Since operation of the TAC unit in cooling mode substantially reduces the amount of heat delivered to the hot storage tank and the TAC unit cannot deliver any cooling to the cold storage tank when inactive or in heat dump mode, the hot and cold storage tanks are necessary to ensure that heating loads and cooling loads can be satisfied simultaneously. Additionally, the storage tanks permit the CCHP plant to meet intermittent heating and cooling loads that are substantially larger than the thermal output of the fuel cell and TAC units.

In the present study, the effects of electric storage were not considered. Instead it was assumed that all electricity by the fuel cell system can be used within the dwelling, or exported to the grid[3]. Electric storage systems may be a viable option in some residential cogeneration/CCHP configurations, and the use of these systems will undoubtedly effect the performance and control of CCHP technology. The control of CCHP plants with integrated electric storage and photovoltaics will be explored in future work.

OPERATION OF THE HVAC NETWORK

Preliminary study of the behavior of the residential CCHP plant demonstrated that the use of separate, decoupled controls to regulate the operation of the TAC unit may result in less than optimal use of the surplus heat produced by the fuel cell (Beausoleil-Morrison et al. 2004). In this study, the TAC system was controlled using two independent loops. The first control activated the TAC unit in cooling mode when the temperature of the cold storage tank rose above 10 °C and deactivated the unit when the temperature dropped below 5 °C. The second control activated the TAC unit in heat dump mode when the temperature in the hot storage tank rose above 80 °C, and deactivated the TAC unit when the temperature dropped below 70 °C. The heat dump control supplanted the cooling control under all circumstances.

Figure 2 shows the hot and cold storage tank temperatures plotted for an arbitrary summer day, on which the fuel cell was configured to deliver a constant 3 kW of electricity. Initially, no loads are placed on the storage tanks, and the CCHP plant operates in cooling mode to cool the cold storage tank down to its lower set point (5 °C). Shortly after 09:00, the cold storage tank reaches its lower set point, and the TAC unit is shut off. When the TAC unit is inactive, all of the surplus heat produced by the fuel cell is delivered to the hot storage tank, and the temperature of the tank rises quickly as a result. At approximately 11:00, the temperature of the hot storage tank reaches 80 °C, and the TAC unit is switched into heat dump mode to prevent the temperature from rising further. The unit remains in heat dump mode until 20:00, when the hot water tank has cooled to 70 °C.

At 14:00, a space cooling load is placed on the cold storage tank. Since the TAC unit is operating in heat dump mode, it cannot deliver any cooling to the tank and the temperature in the tank rises quickly. By 17:00 the temperature inside the tank has reached 15 °C, and effective space cooling is no longer possible. The plant controller then deactivates the pump providing the AHU with cold water to prevent the cold storage tank temperature from rising further, and the dwelling's space cooling requirements are unsatisfied.

[3]The feasibility and economics of dispatching power to the utility grid are not well understood, and warrant further research.

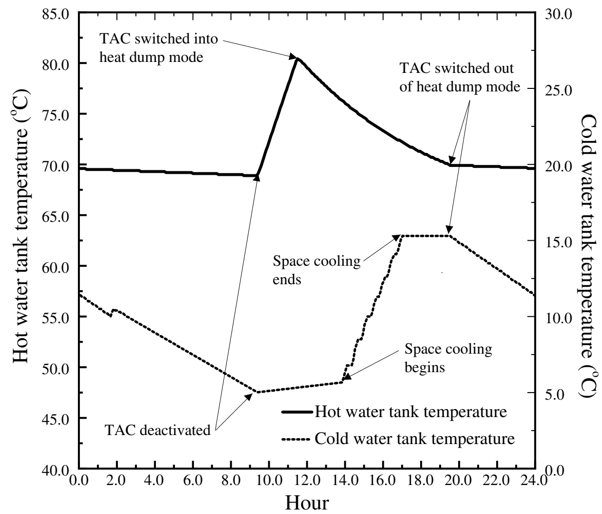

Figure 2: Hot and cold storage tank temperatures on an arbitrary summer day (June 1st).

In this example, operation of the TAC unit in heat dump mode prevented the CCHP plant from meeting cooling loads in the dwelling. However, when the performance of the plant between 00:00 and 09:00 is reviewed, it is clear the temperatures of both the hot and cold storages tanks decrease. When operating in cooling mode, the amount of heat transfer at the TAC unit's generator may exceed the amount of heat recovered from the fuel cell, and as a result the TAC unit delivers cooling to both tanks. Had the TAC unit been switched into cooling mode when the load was placed on the cold water tank at 14:00, the plant's heat-rejection and cooling needs would have been met simultaneously, and the dwelling's space cooling requirements would have been satisfied.

Clearly, control of the CCHP plant is non-trivial, and the performance of the plant can be improved if the heating, cooling and heat rejection requirements are considered when the operating modes of the fuel cell and TAC unit are determined. Therefore, a controller capable of determining the optimal CCHP plant operating point that satisfies all of these requirements is needed. Such a controller should be able to meet electrical, heating and cooling demands simultaneously, and make optimal use of the surplus heat produced in the plant.

THERMAL LOAD FOLLOWING CONTROL

Since the hot and cold storage tanks are used to meet the dwelling's thermal loads, the thermal load following control algorithm is designed to maintain the thermal storage tanks at temperatures suitable for space-heating, space-cooling and domestic hot water needs. This range is defined for each tank by upper and lower set point temperatures (T_{su} and T_{sl}).

For the hot storage tank, the upper set point describes the maximum permissible temperature inside the tank, above which heat rejection is required to prevent damage to the equipment. The lower set point describes the lowest temperature at which the plant can accomplish effective space heating. For the cold storage tank, the upper set point describes the highest temperature at which the plant can accomplish space cooling, while the lower set point describes the minimum permissible suitable for maintaining occupant comfort in the dwelling.

The thermal load following control algorithm attempts to maintain each storage tank at a target temperature $T_{tar.}$ between the set point temperatures:

$$T_{tar.} = T_{sl} + a \cdot (T_{su} - T_{sl}) \quad (2)$$

The coefficient a may be set to a value between zero and one. For the cold storage tank, a small value of a ensures that the target temperature will be close to the lower set point and the tank will require significant heating before its temperature rises above the useful range. For the hot storage tank, a large value of a ensures that the target temperature will be close to the upper set point and the tank will require significant cooling before its temperature drops below the useful range.

The controller evaluates the storage tank heating and cooling requirements by calculating an error coefficient e that describes the difference between the target temperature of the storage tank, and its actual temperature T:

$$e = \begin{cases} \frac{T - T_{tar.}}{T_{su} - T_{tar.}} & \text{for cold storage tank} \\ \\ \frac{T_{tar.} - T}{T_{tar.} - T_{sl}} & \text{for hot storage tank} \end{cases} \quad (3)$$

The fuel cell system's operating point is determined using a coefficient U, which is calculated by the controller:

$$\dot{W}_T = \begin{cases} 0 & \text{if } U \cdot \dot{W}_{max.} < \dot{W}_{min.} \\ U \cdot \dot{W}_{max.} & \text{if } U \cdot \dot{W}_{max.} \geq \dot{W}_{min.} \end{cases} \quad (4)$$

where $\dot{W}_T$ is the target system electrical production calculated by the controller, $\dot{W}_{max.}$ is the maximum electrical output of the fuel cell, and $\dot{W}_{min.}$ is the minimum electrical output of the cogeneration system.

The control signal U is calculated by applying PID control to the error coefficient e:

$$U = k_p e + k_i \int_0^t e \partial t + k_d \frac{\partial}{\partial t} e \quad (5)$$

where: t is the present time, and k_p, k_i and k_d are the control proportional, integral and derivative gains.

The terms on the right hand side of Equation 5 may sum to more than one, or to less than zero. Under these circumstances, U is set to one or zero to ensure that the cogeneration system's operating range is respected.

There are some practical difficulties with the implementation of Equation 5:

- Depending on the duration of the simulation, the absolute value of the integral term (the second term on the right hand side of Equation 5) may grow quite large relative to the proportional and derivative terms. This phenomenon results in controller saturation over extended periods. Therefore, it is more useful to evaluate the integral over the finite period $t - t'$.
- While the control signal U is constrained between zero and one, the error coefficient e calculated using Equation 3 may be negative if the storage tank has been heated or cooled beyond its target temperature. Since the storage tank will not return to the target temperature until a load has been placed the tank, this condition may persist for an extended period, resulting in the integral term growing large and negative. When a load is placed on the storage tank, the integral term will introduce substantial lag into the controller's response. Therefore, the performance of the controller can be improved if the integral term is included in Equation 5 only when it is greater than zero.
- Some events in the mechanical plant, such as burner operation and domestic hot water draw, may cause high rates of change in storage tank temperatures over very short periods. Controlling the cogeneration and TAC systems to respond to these changes is not feasible, and the derivative control term is instead evaluated over a longer period $t - t''$.

Equation 5 can be rewritten to reflect these changes:

$$U = \begin{cases} k_p e + k_d \frac{e_t - e_{t''}}{t - t''} & \text{if } \int_{t'}^{t} e \partial t < 0 \\ k_p e + k_i \int_{t'}^{t} e \partial t + k_d \frac{e_t - e_{t''}}{t - t''} & \text{if } \int_{t'}^{t} e \partial t \geq 0 \end{cases} \quad (6)$$

The selection of the controller parameters is an inexact science, and some trial-and-error may be necessary to obtain the desired performance. Increasing the proportional and derivative gains (k_p and k_d) will increase the responsiveness of the controller, but may make the system less stable. Conversely, increasing the integral gain (k_i) and the integral and derivative periods ($t - t'$ and $t - t''$) will improve the system's stability, but may slow the controller's response.

Table 1: Configuration of PID algorithm for heating load following control

Parameter		Value	
Lower set point	(T_{sl})	75.0	$^\circ$C
Upper set point	(T_{su})	80.0	$^\circ$C
Target coefficient	(a)	1.0	
Proportional gain	(k_p)	1.4	
Integral gain	(k_i)	0.0002	
Derivative gain	(k_i)	3000.0	
Integral period	$(t - t')$	2.0	hours
Derivative period	$(t - t'')$	0.5	hours

Table 2: Configuration of PID algorithm for cooling load following control

Parameter		Value	
Lower set point	(T_{sl})	5.0	$^\circ$C
Upper set point	(T_{su})	10.0	$^\circ$C
Target coefficient	(a)	0.2	
Proportional gain	(k_p)	4.5	
Integral gain	(k_i)	0.0003	
Derivative gain	(k_i)	1000.0	
Integral period	$(t - t')$	2.0	hours
Derivative period	$(t - t'')$	0.5	hours

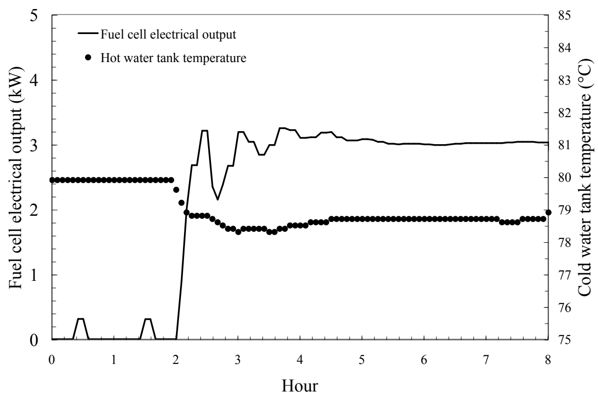

Figure 3: PID load following response to 2000 W step load on hot storage tank

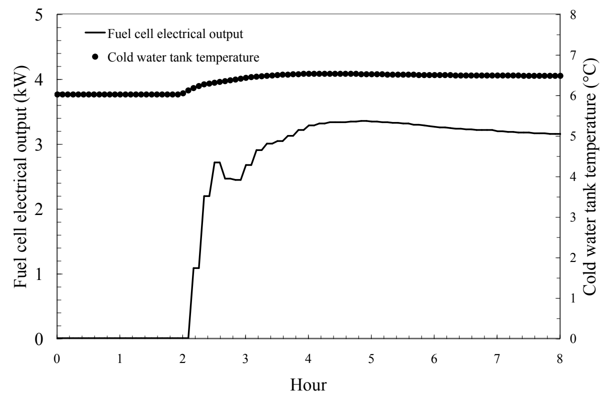

Figure 4: PID thermal load following response to 600 W step load on cold storage tank

To evaluate the effectiveness of the thermal PID control algorithm, the controller was coupled to a CCHP plant with hot and cold storage tanks that could be subjected to step loads, and simulations were conducted using a five-minute time step. Discussion of the algorithm's response to these loads follows.

Heating thermal load following

The PID controller was configured using the data presented in Table 1. The lower set point, upper set point, and target coefficient a were selected to provide a target temperature of 80 $^\circ$C. Figure 3 shows the controller's response when a constant, 2000 W thermal load is placed on the hot storage tank. The controller increases the cogeneration system's output quickly, and only requires 0.41 hours to meet the load.

The temperature of the hot storage tank stabilizes at 1.3 $^\circ$C below the target temperature, and does not return to the target while the thermal load remains on the tank. This steady-state error results from the use of the finite period to calculate the integral control term in Equation 6. Increasing the integral gain or integral period would reduce this steady state error, but would also introduce additional lag into the controller's transient response.

Cooling thermal load following

The PID load following controller was configured using the data presented in Table 2. The lower set point, upper set point, and target coefficient a were selected to provide a target temperature of 6 $^\circ$C. Figure 4 shows the controller's response when a constant, 600 W thermal load is placed on the cold storage tank. In this configuration, the temperature in the tank stabilizes after rising 0.4 $^\circ$C above the target. Again, the steady state error results from the finite period used to calculate the integral control term in Equation 6.

CCHP SYSTEM CONTROLLER

The CCHP system controller is comprised of a set of control schemes used to determine the appropriate operating point for the CCHP plant based on the temperatures of the hot and cold thermal storage systems, and the electrical demands of the building. These schemes permit the controller to determine optimal electrical output from the cogeneration system and the appropriate operational mode for the TAC unit to best use the surplus heat produced in the CCHP plant.

TAC operating mode

Indiscriminate operation of the CCHP plant may result in boiling the water in the hot storage tank, or freezing the water in the cold storage tank. In the event that one or both of the storage tanks is over-charged[4], the CCHP controller adjusts the TAC unit's operating mode to prevent damage to the mechanical plant:

- If the cold storage tank is over-charged, the TAC unit will remain inactive unless the hot water tank becomes over-charged. Under these circumstances, the TAC unit will be activated in heat dump mode.
- In the event that the hot storage tank is over-charged, operation of the TAC unit in cooling mode will cool the hot water tank if the amount of heat recovered from the fuel cell is less than that transferred at the TAC unit's generator. Therefore, the CCHP controller first attempts to cool the hot storage tank by running the TAC system in cooling mode, since the TAC system also delivers useful cooling to the cold storage tank in this configuration. If (a) the hot storage tank over-charge state persists for more than 25 minutes, or (b) the cold storage tank becomes over-charged, the CCHP controller switches the TAC system into heat dump mode.
- When the TAC unit is in heat dump mode, the CCHP controller will switch it out of heat dump mode if (a) the temperature of the hot storage tank is below its target, (b) or the temperature of the cold storage tank is above its target, which indicates that there is an opportunity to deliver cooling to the cold storage tank. In the latter case, the TAC system is switched into cooling mode.

If the storage tanks are not over-charged, the TAC unit will be turned on when cooling is required, and off when heating is required. Since the heating and cooling requirements are coincident during the summer months and the cold storage tank does not have an auxiliary cooling system, the controller designates the cold storage tank as the *primary* storage tank, and the hot storage tank as the *auxiliary* storage tank. If the loads on the tanks are too large to be satisfied simultaneously, the controller will operate the CCHP system to meet the cooling load first, and the auxiliary gas burner on the hot storage tank will be used to meet the heating load.

When determining if the plant should meet the heating or cooling requirement, the CCHP controller considers the error coefficients from both the cold (e_{cold}) and hot (e_{hot}) storage tanks. The system operating plant is determined by comparing the error coefficients to a defined *priority switching error threshold*, $e_{swi.}$. If $e_{cold} < e_{swi.}$ and $e_{cold} < e_{hot}$, the error in the hot storage tank is larger than than in the cold storage tank, and the error in the cold storage tank has not yet reached the priority switching threshold. Under these circumstances, the CCHP plant will be operated in heating mode, to meet the loads on the hot storage tank. However, if $e_{cold} > e_{swi.}$ or $e_{cold} > e_{hot}$, the CCHP system will be switched into cooling mode and the load on the cold storage tank will be met.

[4] The hot storage tank is assumed to be over-charged if its temperature exceeds its upper set point T_{su}, and the cold storage tank is assumed to be over-charged if its temperature is below its lower set point T_{sl}.

Selection of control scheme

The CCHP controller uses a set of control schemes to determine the operating point of the cogeneration system. Presently, constant electrical output, electric load following, thermal load following, and thermal load priority control schemes are supported:

- *Constant electrical output:* In the constant electrical output control scheme, the fuel cell is maintained at a constant electrical output.
- *Electric load following:* In the electrical load following control scheme, the cogeneration system's output is matched to the building's electric loads.
- *Thermal load following:* In the thermal load following control scheme, the cogeneration system is operated to meet the building thermal requirements. The CCHP controller applies PID control to the error coefficient of the hot or cold thermal storage tank, depending if the plant is operating in cooling or heating mode.
- *Combined electric and thermal load following:* In the thermal and electric load following control scheme, the CCHP controller attempts to meet both the electrical and thermal loads in the building. The CCHP controller applies PID control to the error coefficient of the hot or cold thermal storage tank, depending if the plant is operating in cooling or heating mode. If the optimal electrical output of the cogeneration system calculated by the PID thermal load following algorithm is larger than the building's electric loads, the cogeneration system is operated to meet the thermal load. Otherwise, the cogeneration system output is matched to the building electrical load.

CCHP CONTROLLER BEHAVIOR

To demonstrate the behavior of the CCHP controller, it was integrated into a plant network similar to that depicted in Figure 1. The fuel cell was configured to deliver a maximum of 4000 W of electricity, and when operating at full power in this arrangement, the CCHP plant

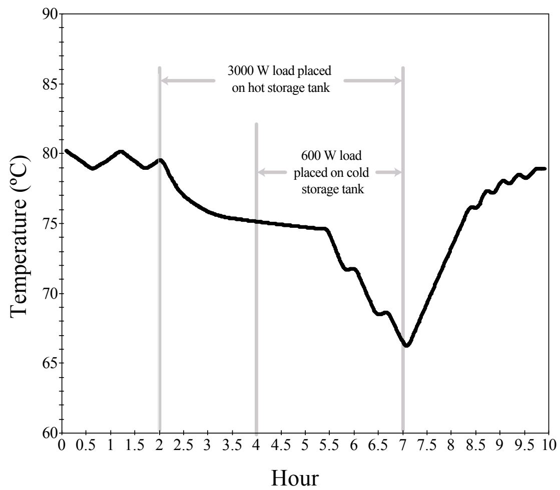

Figure 5: Hot storage tank temperature

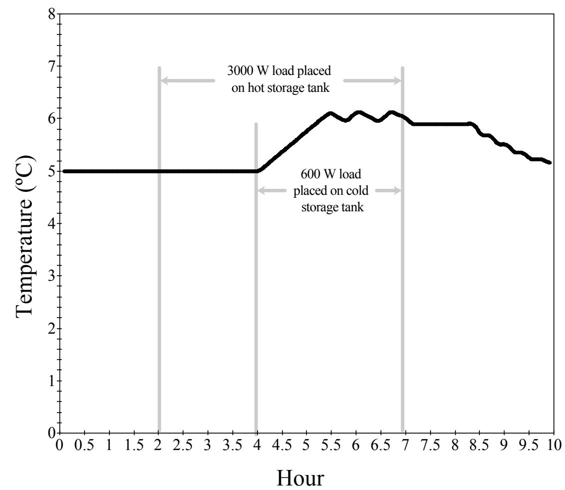

Figure 6: Cold storage tank temperature

can recover approximately 2800 W of the surplus heat produced by the fuel cell.

The TAC unit model was configured using an arbitrary, constant COP value of 0.3[5]. In this configuration, the magnitude of the cooling delivered to the cold storage tank is equal to 30% of the heat transferred at the generator. Therefore, the TAC unit can deliver approximately 840 W of cooling when the fuel cell system operates at maximum power.

The CCHP controller model was configured to use the electrical and thermal load following control scheme, and the priority error switching threshold ($e_{swi.}$) was set to 0.2. The heating and cooling PID control algorithms were configured using the data in Tables 1 and 2.

The hot and cold water tanks were connected to fixed temperature sources that permitted step loads to be applied to each tank. The plant network was configured to deliver a 3000 W load to the hot storage tank commencing on the second hour of the simulation and ending on the seventh hour, and a 600 W load to the cold storage tank commencing on the fourth hour and ending on the seventh hour.

The storage tank temperatures are plotted over a ten-hour period, in Figures 5 and 6. The storage tank coefficients are plotted in Figure 7, and the fuel cell's electrical output is plotted along with the building's electrical requirements in Figure 8. At the start of the ten-hour period, there are no loads on the storage tanks and the fuel cell is operated to meet the building's electrical load. The hot and cold storage tanks are in a quasi steady-state condition at their respective target temperatures[6].

The hot storage tank temperature begins to drop from 80 °C at the start of the second hour, when the 3000 W heating load is placed on the hot water tank. Shortly after the load is placed on the tank, the CCHP controller begins to increase the electrical power produced by the fuel cell, and by the start of the fourth hour the fuel cell is operating at its maximum output (4000 W). In this configuration the fuel cell system only delivers 2800 W of heat at its maximum operating point, which is less than the 3000 W load placed on the tank. As a result, the temperature of the hot storage tank continues to slowly drop.

The temperature of the cold storage tank remains at its specified target until the start of the fourth hour, when the 600 W cooling load is placed on the tank. The CCHP controller continues to deliver heat to the hot storage tank and does not activate the TAC unit until the cold storage tank error coefficient rises above the priority switching error threshold (0.2) in the fifth hour. At this point, the CCHP controller switches the plant into cooling mode to meet the load on the cold storage tank. Over the next hour, the CCHP controller switches the plant system between

[5] At present, the performance of residential TAC technology is not known. It is anticipated that upcoming experiments at CETC will characterize these systems, and these data will enable detailed technical assessments in the future.

[6] At the start of the ten-hour period, the fuel cell's output is determined by the building electrical loads, and the system continues to deliver heat to the hot storage tank even though the temperature of the tank is near its upper set point (80 °C). As a result, the CCHP controller must continuously switch the TAC system in and out of heat-dump mode to ensure that the hot storage tank does not overheat, and the temperature of the tank oscillates slightly.

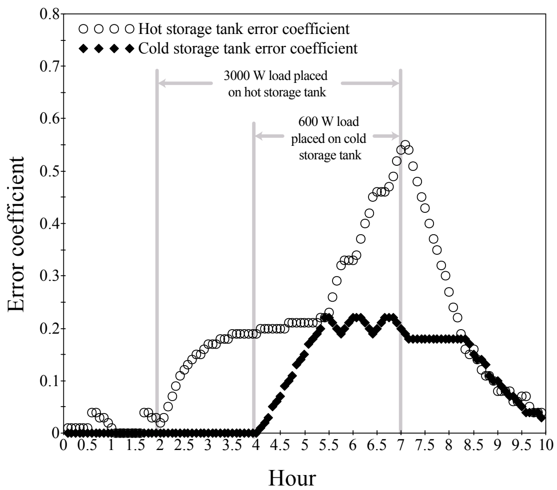

Figure 7: Hot and cold storage tank error coefficients.

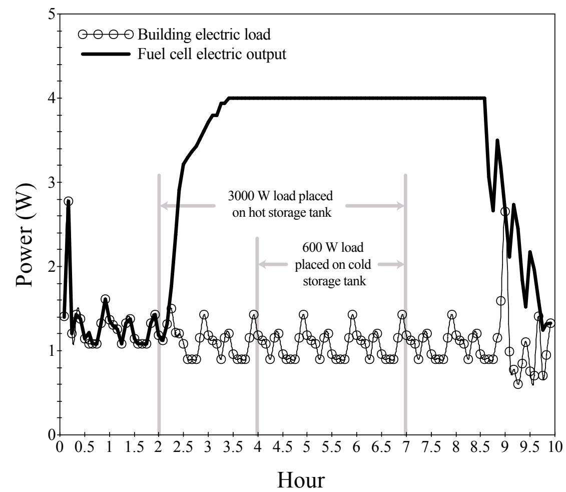

Figure 8: Building and HVAC electric loads, and fuel cell electrical production.

heating and cooling modes to keep the cold storage tank temperature near the priority switching error threshold.

Since the heating and cooling loads are coincident, operation of the TAC system also prevents the CCHP system from meeting the load on the hot storage tank. Thus, the temperature of the hot water tank drops by nearly 10 °C over the next hour, and reaches a minimum of 66 °C.

Once the loads are removed from the storage tanks, The CCHP controller alternates between delivering heating and cooling until the storage tanks have been returned to their target temperatures. Only at this point does it return to electric load following mode.

CONCLUSIONS

In this study, the interactions between cogeneration systems and thermally activated cooling (TAC) equipment were considered, and strategies to manage a CCHP system to meet simultaneous heating, cooling and electrical loads have been proposed. These strategies were implemented in a CCHP system controller model. The behavior of the CCHP model has been demonstrated under a set of arbitrary conditions, and the author anticipates that the model will enable detailed study of different operating strategies in residential CCHP plants when performance data for residential TAC technology is available.

The fuel cell model used in this study is a quasi-steady-state model, and ignores the transient characteristics of this technology. The CCHP controller model will be compatible with improved, dynamic fuel-cell models, although the parameters used to configure the controller and the results obtained with it will differ.

The controller model has been designed for use in CCHP systems with hot and cold storage tanks. Future work will extend its capabilities to permit use in plants with electrical storage systems and on-site renewable technologies such as photovoltaics. Support for control schemes based on economic or environmental criteria would also be a welcome addition to the model.

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