

SIMULATION RESULTS{ TC "SIMULATION RESULTS" \\1 1 }

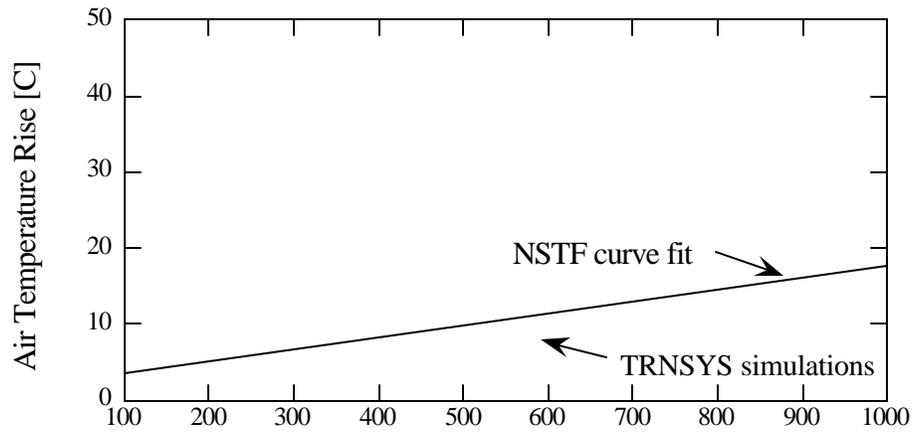
The TRNSYS model is validated with data from laboratory experiments and monitored installations. The model is then used to explore the effects of climate, summer bypass set temperature, automatic night bypass, and wall absorptivity on the UTC system performance.

4.1 Model Validation{ TC "4.1 Model Validation" \\1 2 }

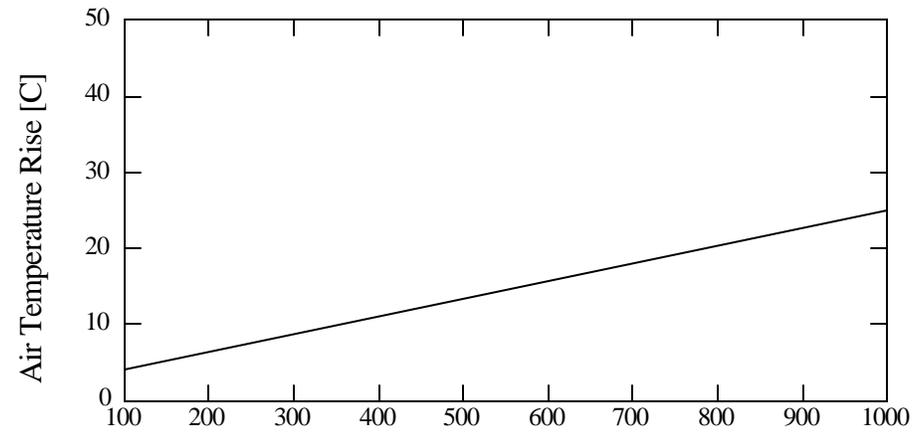
Experiments on UTC performance have been done at the National Solar Test Facility (NSTF) near Toronto, Ontario, Canada. Curve fits of the data are presented by Hollick [1994]. These curve fits of air temperature rise as a function of solar radiation are plotted as solid lines in Figure 4.1.1 for three flow rates. The UTC plates used in these experiments have the parameters in Table 4.1.1 [Giesberger, 1995]. A UTC plate with 1.0% porosity is used for $V = 0.035$ m/s and 0.020 m/s (Fig. 4.1.1a-b), and one with 0.5% porosity is used for $V = 0.005$ m/s (Fig. 4.1.1c). The NSTF experiments were performed indoors at room temperature.

To validate the accuracy of the UTC plate model, TRNSYS simulations of the NSTF collector are performed. Actual weather data from Madison, WI are used for the simulations. The air temperature rise ($T_{plen} - T_{amb}$) is plotted for every hour of the year for which the ambient temperature is between 20 and 25 C. Variations in the conditions (e.g. sky temperature) cause the scatter in the results. In Figure 4.1.1, it is important to note that the experimental curve fits are the lines, and the simulation results are the data points.

(a)



(b)



(c)

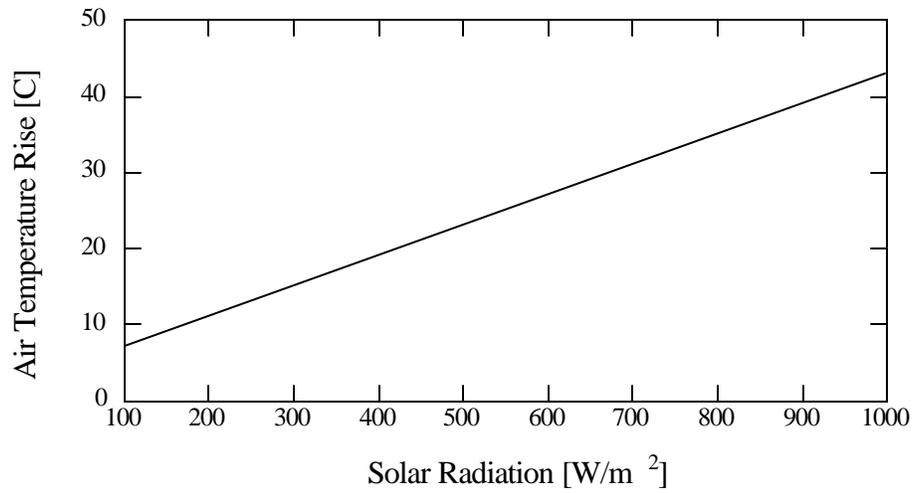


Figure 4.1.1. Air temperature rise vs. Solar radiation. { TC "Figure

4.1.1. Air temperature rise vs. Solar radiation." \l 5 }

(a) V = 0.035 m/s; (b) V = 0.020 m/s; (c) V = 0.005 m/s.

Table 4.1.1. NSTF UTC plate parameters. { TC "Table 4.1.1. NSTF UTC plate parameters." \l 7 }

Parameter	Value
collector height, ht	2.44 m
collector length	1.83 m
collector area, A	4.465 m ²
plenum depth	0.0762 m
hole diameter, D	0.00159 m
porosity, σ	0.5% (low flow) 1.0% (high flow)
hole pitch, P	0.0214 m (low flow) 0.0151 m (high flow)

At an approach velocity of 0.035 m/s, the empirical curve fit is slightly higher than the simulation results (Fig. 4.1.1a). At low solar radiation, the experimental temperature rise is twice as large as the simulation temperature rise. An energy balance on the collector yields Equation 4.1.1.

$$\rho V c_p (T_{plen} - T_{amb}) = \eta_{sol} I_T \quad (4.1.1)$$

At room temperature, $\rho = 1.2 \text{ kg/m}^3$ and $c_p = 1007 \text{ J/kg-C}$. The maximum possible temperature rise occurs when all of the energy incident on the collector heats the air (i.e. $\eta_{sol} = 1.0$). For $I_T = 100 \text{ W/m}^2$ and $V = 0.035 \text{ m/s}$, Equation 4.1.1 yields a maximum temperature rise of 2.36 C, but the experimental temperature rise is about 3.0 C from Figure 4.1.1a. The simulation results are

reasonable at low solar radiation.

In the three plots in Figure 4.1.1, the simulation data intersect the origin when extrapolated, as expected. However, the empirical curve fits do not intersect the origin when extrapolated. This suggests, along with the previous energy balance calculation, that the empirical curve fits are too high at low solar radiation.

At an approach velocity of 0.035 m/s (Fig. 4.1.1a) the model slightly under predicts the air temperature rise at high solar radiation. For an approach velocity of 0.02 m/s (Fig. 4.1.1b), the UTC plate model agrees with the empirical results at high solar radiation. At lower approach velocities, the UTC model substantially over predicts the performance of the collector (Fig. 4.1.1c). Below $V = 0.02$ m/s, convection loss from the collector to the surroundings is no longer negligible [Kutscher, 1992]; however they are still assumed to be zero in the UTC model. Assuming no convection loss is the reason for the over estimation of the UTC performance at low approach velocities.

To further verify the UTC system model, simulation results are compared with data from an operating UTC system at the General Motors (GM) battery production facility in Oshawa, Ontario [Enermodal, 1994]. The data from this UTC system are the most complete and reliable information currently available from any UTC installation. TMY weather data for Toronto is generated for this simulation using the TRNSYS weather generator. The UTC system at the monitored GM facility operates at night, so the UTC system is operated at night in the simulation as well (i.e. no automatic night bypass; see Section 4.5).

The solar efficiency is the ratio of the active solar gain of the UTC system to the solar energy incident on the collector. Enermodal [1994] calculated the active solar gain as $Q_{\text{conv,col-air}}$ during the day only. Figure 4.1.2 shows how well TRNSYS predicts the monitored solar efficiency of the GM facility [Enermodal, 1994]. Conserval has developed a simulation program, called SIMAIR, which was used to predict the performance of the GM facility by Enermodal [1994]. The SIMAIR predictions are included in Figure 4.1.2 to compare with the TRNSYS

predictions.

The GM TRNSYS model has an outdoor air flow rate from 35,000 to 70,000 m³/h and a UTC plate area of 365 m² [Enermodal, 1994]. Therefore, the approach velocity varies from 0.027 to 0.053 m/s. The NSTF results, in Figure 4.1.1, suggest that the active solar gain is slightly under estimated for approach velocities this high. As seen from the active solar efficiencies in Figure 4.1.2, active solar gain is indeed slightly under estimated by the UTC model. The under estimation is greater during warm months than during cold months due to increased average approach velocities.

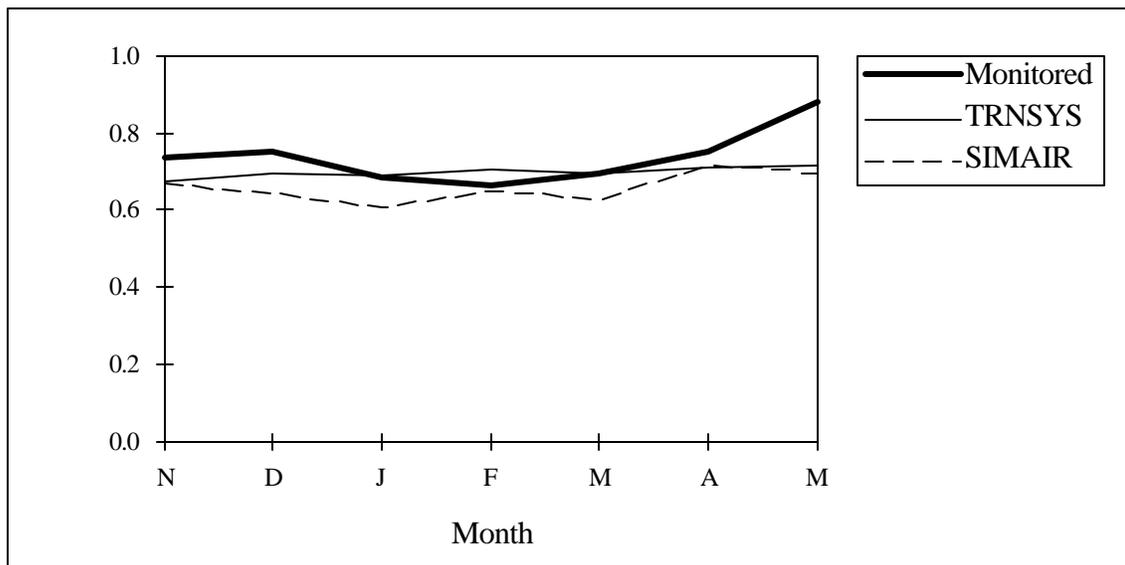


Figure 4.1.2. Active solar efficiency, GM facility. { TC "Figure 4.1.2. Active solar efficiency, GM facility." \l 5 }

The total recaptured wall loss is given for both the simulation and the monitored facility in Table 4.1.2. Enermodal [1994] calculates the recaptured wall loss during the day as the difference between the total useful energy from the UTC system and the active solar gain. This value is simply $Q_{conv,wall-air}$. However during the night, the recaptured wall loss is the total useful energy from the UTC system since there is no solar gain [Enermodal, 1994]. This value

includes both $Q_{\text{conv,wall-air}}$ and $Q_{\text{conv,col-air}}$. Since the collector is often colder than the ambient air at nighttime, $Q_{\text{conv,col-air}}$ is usually negative. The simulation recaptured wall loss is the sum of $Q_{\text{conv,wall-air}} = 0.34 \text{ kWh/m}^2\text{-day}$ during both the day and night, and $Q_{\text{conv,col-air}} = -0.20 \text{ kWh/m}^2\text{-day}$ during the night. As discussed in Section 2.2, experimental work is necessary to obtain an accurate heat transfer correlation for convection from the wall to the air. The correlation used in the UTC model under estimates the monitored recaptured wall loss. The monitored value may also be inaccurate since it is the result of subtracting two large numbers.

The simulation values in Table 4.1.2 are sensitive to the R-value of the wall that is used in the simulation. For the simulated recaptured and reduced wall losses shown, a wall R-value of $0.72 \text{ m}^2\text{-C/W}$ is used. This is within the range of $0.3 - 0.9 \text{ m}^2\text{-C/W}$ measured at the GM facility [Enermodal, 1994].

Table 4.1.2. Recaptured and reduced wall loss. { TC "Table 4.1.2. Recaptured and reduced wall loss." \l 7 }

GM facility	Recaptured wall loss [kWh/m ² -day]	Reduced wall loss [kWh/m ² -day]
Simulated	0.14	0.18
Monitored	0.66	0.13

For both the simulated and monitored results, the active solar gain is on the order of $2.0 \text{ kWh/m}^2\text{-day}$. The difference in the reduced wall loss of $0.05 \text{ kWh/m}^2\text{-day}$ is insignificant. The UTC system model predicts the performance of the GM facility well except for the recaptured wall loss.

4.2 Sensitivity Analysis{ TC "4.2 Sensitivity Analysis" \l 2 }

A sensitivity analysis is done for some of the parameters, inputs, and calculated values of the UTC system model. The total energy saved is obtained for a base case simulation and compared to energy saved from simulations in which one property is changed. Table 4.2.1 summarizes the results from this sensitivity analysis.

The two properties that are the most sensitive are the collector absorptivity and area. For both, a drop of about 10% reduces the energy saved by about 10%, as expected for the two parameters that are directly related to the amount of solar energy absorbed by the collector. There are three other properties that are slightly sensitive to changes: T_{sky} , ϵ_{col} , and $h_{conv,col-air}$. These are related to either the radiation loss from the collector to the surroundings or the convection from the collector to the air. Therefore, they affect the active solar gain, which is the largest part of the energy savings. The other parameters, inputs, and calculated values are not sensitive to changes.

Table 4.2.1. Results of sensitivity analysis. { TC "Table 4.2.1. Results of sensitivity analysis." \l 7 }
}

Property	Base value	New value	Q save [kW]	Change	
				Value	Q save
Base case	--	--	398	--	--
α_{col}	0.9	0.8	345	-0.1	-13.3%
A [m ²]	1240	1116	355	-10.0%	-10.7%
T _{sky} [C]	-5.0	-15.0	378	-10.0 C	-4.9%
ϵ_{col}	0.9	1.0	389	+0.1	-2.1%
h _{conv,col-air} [W/m ² -C]	51.2	41.2	390	-10.0 W/m ² -C	-2.0%
h _{conv,wall-air} [W/m ² -C]	7.8	6.8	398	-1.0 W/m ² -C	-0.1%
plenum depth [m]	0.08	0.10	398	+0.2 m	-0.1%
wall R-value [m ² -C/W]	1.76	1.86	398	+0.1 m ² -C/W	-0.1%
ϵ_{wall}	0.9	0.8	398	-0.1	<0.1%
ht [m]	12.8	11.8	398	-1.0 m	<0.1%
UA of building [W/C]	8066	7966	398	-100.0 W/C	0.0%

4.3 Climate { TC "4.3 Climate" \l 2 }

Unglazed transpired collector (UTC) systems are modelled on the same building in five different climates. The results, shown in Table 4.3.1, suggest that there are three climate variables which affect the thermal performance of UTC systems: the average solar radiation during operation, the amount of time the system operates annually (determined by the number of hours that the ambient temperature is below the bypass set temperature), and the average ambient temperature during operation.

Table 4.3.1. UTC system performance in different climates. { TC "Table 4.3.1. UTC system performance in different climates." \l 7 }

City	Q _{save} [GJ/yr]	Operating time [hr/yr]	Q _{save} [MJ/hr]
Bismarck, ND	2050	2870	710
Buffalo, NY	1170	2450	480
Denver, CO	2340	2610	900
Madison, WI	1900	2450	770
Washington, DC	1430	2090	680

City	T _{amb} [C]	I _T [W/m ²]	Solar Efficiency
Bismarck, ND	0.4	230	0.68
Buffalo, NY	3.7	150	0.68
Denver, CO	5.4	350	0.67
Madison, WI	2.1	250	0.69
Washington, DC	5.7	240	0.67

The most important factor is the average solar radiation incident upon the collector surface during operation (I_T). There is a direct relation between the solar radiation and the hourly energy savings. Out of the five cities in Table 4.3.1, Denver has the most solar radiation, and Buffalo has the least. The hourly savings of the UTC system shows that a UTC system saves the most energy in Denver and the least energy in Buffalo. The other three cities have about the same amount of solar radiation, and therefore save about the same amount of energy each hour of operation.

When comparing the annual energy savings for these five cities, Denver has the most and Buffalo has the least due to the hourly energy savings. The other three cities have different annual

energy savings due to the fact the UTC systems in these three climates operate for different amounts of time each year. The operating time, and therefore the annual energy savings, is highest in Bismarck, followed by Madison and then Washington.

The average ambient temperature during operation does not make a noticeable difference in the hourly energy savings of the UTC system. Although the average ambient temperature during operation varies between the five cities in Table 4.3.1, there is no significant correlation with the hourly energy savings. Bismarck, which has the median hourly energy savings, has the coldest ambient temperature. Buffalo, which has the lowest hourly energy savings, has the median ambient temperature. If there is any correlation between average ambient temperature and hourly energy savings, it is insignificant compared to the correlation between average solar radiation and hourly energy savings.

There is some correlation between the average ambient temperature during operation and the operating time. The UTC system operates the most hours per year in Bismarck, where it is the coldest. And it is the warmest in Washington, where the UTC system operates the least. However, Denver is the second-warmest city, and the operating time is the second-highest. The operating time is determined by the amount of time that the ambient temperature is below the bypass set temperature. Since the operating time is an important factor in the annual energy savings, it is important to distinguish it from the average ambient temperature during operation, which is not important.

The solar efficiency of the UTC systems is the same for all five simulations, regardless of ambient temperature or solar radiation. But predicting the solar efficiency of a UTC system is not useful for predicting the energy savings because the energy savings may be less than the active solar gains, as discussed in Section 2.5.

4.4 Summer Bypass Set Temperature { TC "4.4 Summer Bypass Set Temperature" \l 2 }

In a UTC system, the summer bypass temperature can be set to any temperature, independent of the other parameters in the system. UTC systems on buildings with different bypass temperatures operate for different amounts of time during the year. A UTC system with a low bypass temperature does not operate as often, and therefore does not save as much energy and is not as good of an investment, as a UTC system with a high bypass temperature. Both the climate and bypass temperature affect the annual operating time of the UTC system.

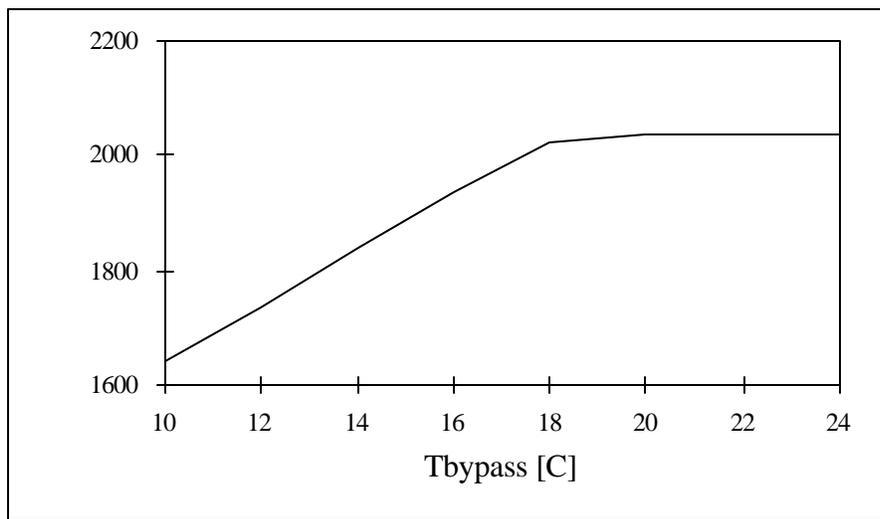


Figure 4.4.1. Annual energy savings as a function of bypass temperature. { TC "Figure 4.4.1. Annual energy savings as a function of bypass temperature." \l 5 }

As shown in Figure 4.4.1 for a building in Madison, WI, decreasing the summer bypass set temperature lowers the annual energy savings substantially. Q_{save} does not increase when the bypass set temperature is above the building balance temperature of 20 C. Q_{save} is calculated so that it never exceeds the heating requirements of a building with a traditional heating system (see Section 2.5). When the ambient temperature is above the building balance temperature, there is no heating load on a traditional heating system, and there can be no energy savings from a UTC system.

However, if the summer bypass set temperature is high, the UTC system overheats the

building more often than if the bypass temperature is low, as seen in Figure 4.4.2. The overheating is also more severe at high bypass temperatures. In other words, the mixed air temperature can exceed the desired supply air temperature by a greater amount when the bypass temperature is high. The TRNSYS subroutine outputs a warning when overheating occurs, as discussed in Section 3.4.

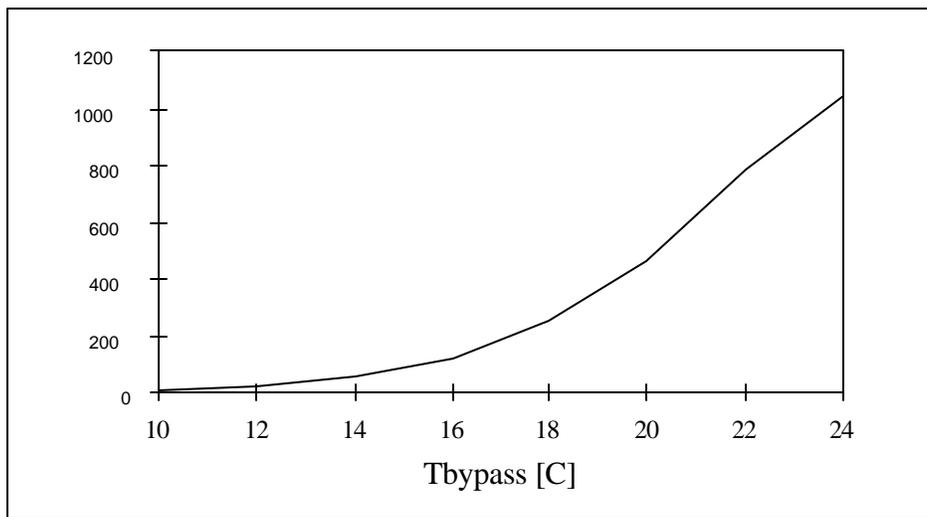


Figure 4.4.2. Annual hours of overheating as a function of bypass temperature. { TC "Figure 4.4.2. Annual hours of overheating as a function of bypass temperature." \l 5 }

Therefore, when choosing a summer bypass set temperature, the potential for overheating the building needs to be weighed against the desire to maximize the energy savings.

4.5 Automatic Nighttime Bypass { TC "4.5 Automatic Nighttime Bypass" \l 2 }

The summer may not be the only time when the bypass damper should be opened. It may be advantageous to open the bypass at night because the UTC system may lose energy on cold and clear nights. Since the radiative sky temperature is lower than the ambient temperature, the collector may be colder than the ambient air. The air flowing through the collector loses energy to the collector surface, but it gains energy from the outside wall surface. Therefore, opening the

bypass damper during nighttime operation may or may not save energy.

Annual TRNSYS simulations are performed with various R-values for the south wall behind the collector. A parameter in the TRNSYS deck allows the bypass damper to be automatically opened at night. By performing two annual simulations, one with automatic night bypass and one without, the best operating strategy can be determined.

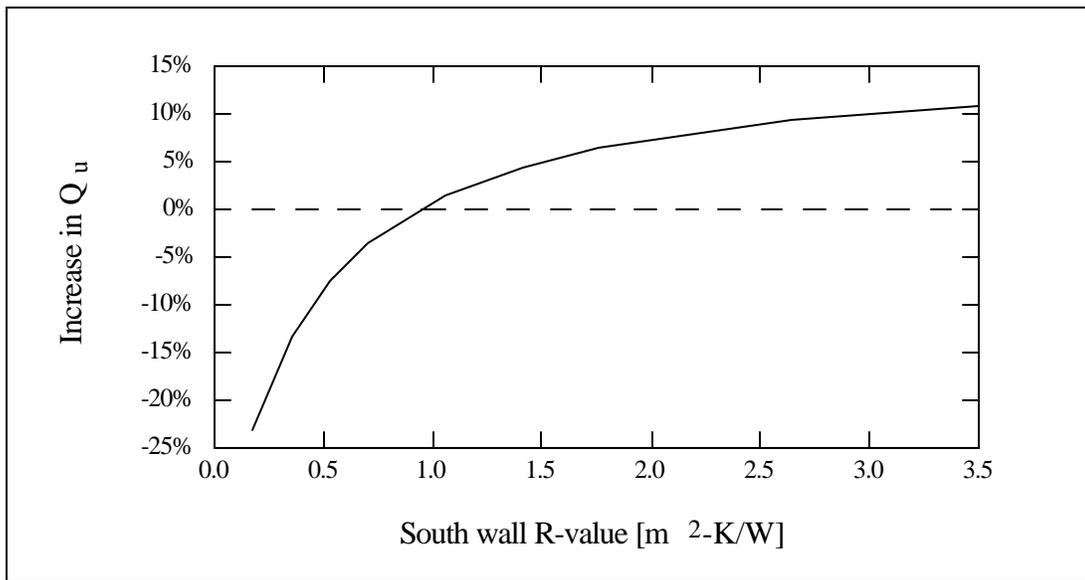


Figure 4.5.1. Increase in Q_u by automatically opening bypass damper at night. { TC "Figure 4.5.1. Increase in Q_u by automatically opening bypass damper at night." \ 5 }

In Figure 4.5.1, the base simulation is for a UTC system operating at night. The percent increase in the annual useful energy gained by automatically opening the bypass damper at night is plotted as a function of the wall R-value. UTC systems on well-insulated walls should have the bypass damper opened at night. There is not enough recaptured wall loss from a well-insulated wall to offset the energy lost to the cold collector.

For most simulations in this thesis, the south wall R-value is $1.76 \text{ m}^2\text{-C/W}$ (R-10). Automatically opening the bypass damper at night increases the annual performance of the UTC system by about 7% for this R-value. The simulations in this thesis are performed with the

automatic night bypass turned on, unless otherwise noted.

4.6 Reduced Wall Loss{ TC "4.6 Reduced Wall Loss" \l 2 }

The reduced wall loss is given by Equation 2.4.4.

$$\begin{aligned} Q_{\text{red,wall}} &= U_{\text{cond,wall}} A (T_{\text{plen}} - T_{\text{solair}}) \\ &= U_{\text{cond,wall}} A (T_{\text{plen}} - T_{\text{amb}} - \alpha_{\text{wall}} I_T / h_{\text{film}}) \end{aligned} \quad (4.6.1)$$

For dark walls (i.e. high α_{wall}), the reduced wall loss is smaller than for light walls. If the wall is dark enough, it is possible that the UTC plate may actually increase the wall loss. The wall loss increases when the sol-air temperature is higher than the plenum air temperature. In effect, the UTC plate is increasing the conduction through the wall by shading the wall.

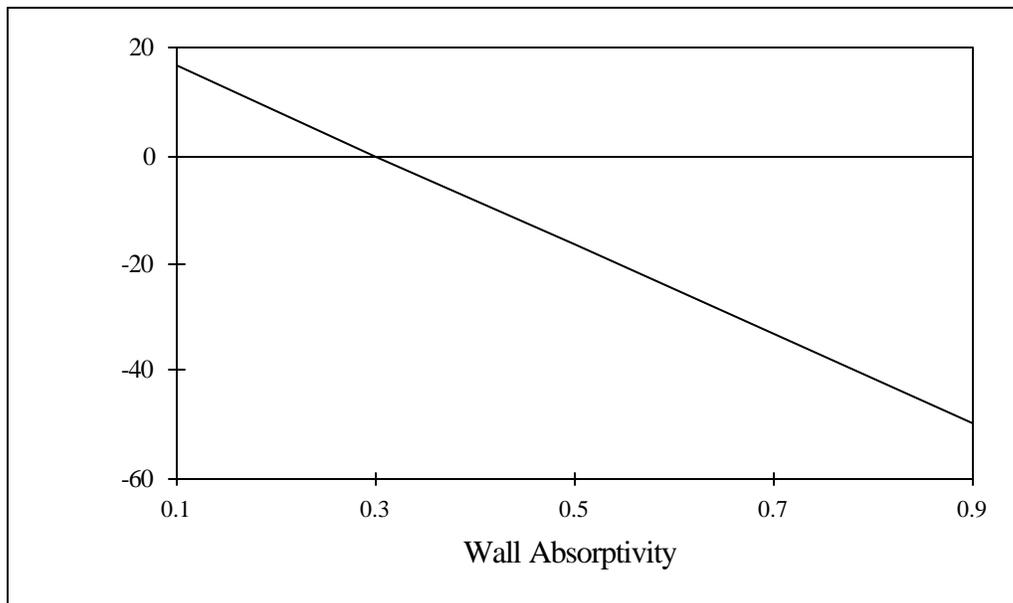


Figure 4.6.1. Reduced wall loss as a function of wall absorptivity.{ TC "Figure 4.6.1. Reduced wall loss as a function of wall absorptivity." \l 5 }

Annual TRNSYS simulations are performed to calculate the reduced wall loss for several wall absorptivities. As shown in Figure 4.6.1, the wall loss actually increases for most values of

α_{wall} . These simulations are performed with the automatic night bypass turned on. At night, $I_T = 0$, and the reduced wall loss is given by Equation 4.6.2.

$$Q_{\text{red}} = U_{\text{cond,wall}} A (T_{\text{plen}} - T_{\text{amb}}) \quad (4.6.2)$$

The collector is usually colder than the ambient air at night, therefore the plenum air is usually colder than the ambient air as well. So the wall loss is slightly increased if the UTC system is operated at night.

The UTC system that is installed at the General Motors facility in Oshawa, Ontario (see Section 4.1) is on a white wall with an absorptivity of 0.2 [Enermodal, 1994]. So, the wall loss is reduced by the UTC system for this facility. For most buildings, the wall loss increases due to the UTC system. However, the magnitude of the reduced or increased wall loss is small in comparison to the total energy savings of the UTC system. In a near-worst case, for $\alpha_{\text{wall}} = 0.9$ and $U_{\text{cond,wall}} = 1.4 \text{ W/m}^2\text{-C}$ (i.e. an R-4 wall), the increased wall loss only reaches 7% of the total energy savings.