An Advanced Economizer Controller for Dual Duct Air Handling Systems -with a Case Application

Mingsheng Liu and David Claridge
Energy Systems Laboratory
Texas A&M University

ABSTRACT

Heating penalty is expected when economizers are applied to dual-duct air handling systems. The heating penalty can even be higher than the cooling savings when the hot air flow is higher than the cold air flow. To avoid the excessive heating penalty, advanced economizers are developed in this paper. The application of the advanced economizer has resulted in $7,000/yr savings in one 95,000 ft^2 school building since 1993. The impacts of cold and hot deck settings on the energy consumption are also discussed.

INTRODUCTION

The economizer cycle is currently one of the most popular energy conservation measures for air handling units (AHU) in buildings. There are two types of economizers, the temperature economizer and the enthalpy economizer [1]. The temperature economizer maintains the mixed air temperature at the cold deck discharge air temperature when the outside air temperature is lower than the cold deck discharge air temperature. Consequently, the need for mechanical cooling is eliminated. When the outside air temperature is higher than the cold deck discharge air temperature, but lower than a change point temperature which is generally a few degrees lower than the return air temperature, the temperature economizer uses maximum outside air to minimize the mechanical cooling [2]. When the outside air temperature is higher than the change point temperature, the economizer uses minimum outside air to keep cooling energy consumption at the lowest level. If the outside air intake is determined by using air enthalpy, the economizer is called an enthalpy economizer. The enthalpy economizer generally saves more energy than the temperature economizer. However, an enthalpy economizer requires additional sensors to measure dew point temperature or the relative humidity. The economizers described above are called the normal economizers to distinguish with the advanced economizer developed in this paper.

Economizers can save a significant amount of cooling energy with little or no heating energy penalty for a single duct system. When Parken, Kao and Kelley [3] simulated the potential economizer energy savings for a small office building in seven climates (Washington, D. C.; Nashville, TN; Madison, WI; Seattle, WA; Dodge City, KS; Lake Charles, LA; and Santa Maria, CA), they found that cooling energy savings varied from 1% to 77% depending on climatic conditions.

When economizers are applied to dual duct systems, a wide range of heating energy penalties are expected. Kao, Parken and Pierce [4] simulated the potential economizer savings for a large retail store in the same seven representative U. S. A. climates. The heating penalty varied from a low of 6% in Lake Charles to a high of 30% in Madison. In all cases, the potential cooling energy savings are larger than the heating penalty regardless of the climates.

From the results of the 1982 study, Park, Kelly and Kao [3] realized that there were always heating penalties when economizers were applied to dual-duct systems. Therefore, they modified the normal economizer by introducing an energy cost ratio: the total AHU energy consumption if the minimum outside air is used to that if the maximum outside air is used. In regions I and II (See Figure 1), if this ratio is less than one, the minimum outside air intake should be used, otherwise, the maximum outside air should be used. In region III, the outside air intake is regulated to maintain the mixed air temperature at the cold deck discharge air temperature. In region IV, the minimum outside air is used. This algorithm improves the normal economizer algorithm in regions I and II if the hot air flow rate is higher than the cold air flow rate. However, no improvement was suggested in region III.

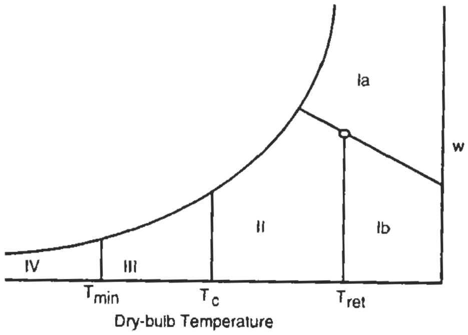


Figure 1: Schematic of Economizer Control Zones

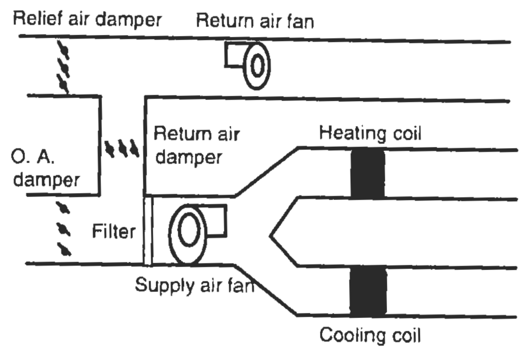


Figure 2: Systematic Diagram of Dual Duct Systems

Liu et al [5] identified excessive heating energy penalty in region III in one LoanSTAR building. In 1991, temperature economizers were installed in two dual-duct AHUs as part of the energy conservation retrofit in the case building. The measured heating penalty (1.2 MMBtu/hr or 352 kW) was 400% of the cooling energy reduction (0.3 MMBtu/hr or 88 kW). The fan power penalty was 100% (increased from 40 kW to 80 kW). Moreover, the room temperature could not be maintained at 72°F (22°C).

In this paper, advanced economizers are developed for dual-duct systems to eliminate the risk of the energy waste and to prevent the potential indoor thermal environment and mechanical problems in all operation conditions. The significance of the advanced economizers is demonstrated by the measured results. A theoretical analysis is also performed to compare the normal and the advanced economizer in different operation conditions.

AN ADVANCED ECONOMIZER FOR DUAL-DUCT SYSTEMS

A typical dual-duct system is shown in Figure 2. The heating deck generally discharges air at temperatures ranging from 80°F (27°C) to 120°F (49°C) according to the weather conditions. The cooling deck generally discharges air at temperatures ranging from 50°F (10°C) to 57°F (14°C). The economizer adjusts the mixing air condition by regulating the relief air damper, the O. A. damper and the return air damper.

The hot and cold air flow rates are determined by the heating and cooling loads, and the hot and cold deck settings if the system is under ideal condition.

The heating penalty occurs whenever the cooling savings are achieved by adjusting the mixed air temperature. If the mixed air temperature was changed from T_{m1} to T_{m2} by using the economizer, the changes of the cooling energy and heating energy consumption can be expressed by Equations (1) and (2), respectively.

$$E_{c,s} = \dot{m}_c c_p (T_{m,1} - T_{m,2}) \qquad (1)$$

and

$$E_{h,p} = \dot{m}_h c_p (T_{m,1} - T_{m,2}) \qquad (2)$$

When the hot air flow is higher than the cold air flow rate, the heating penalty will be higher than the cooling energy savings. Therefore, the normal economizer could waste energy when the cold air flow is lower than the hot air flow rate.

Note that the hot air flow rate may never exceed the cold air flow rate for commercial buildings when the ambient temperature is higher than 70°F (21°C) when the latent load becomes important. Therefore, Equation (1) can be used to calculate the change of cooling energy consumption.

Figure 3a shows the algorithm of the advanced temperature economizer. The heating and cooling energy prices (p_h, and p_c), the change point temperature (T_{cc}, the economizer is disabled when the outside air temperature is higher than this value), and the minimum outside air intake fraction (β_{min}) are pre-determined. The cold and hot air flow rates ($\dot{m}_c$, $\dot{m}_h$) and the cold deck, the outside air, and the return air temperatures (T_c, T_a, and T_{ret}) need to be measured. Then, a potential savings ratio (α) of heating to cooling is calculated. The measured outside air temperature is first compared with the change point temperature. If the outside air temperature is higher than the change point temperature, the dampers are regulated to give the minimum outside air intake. If the cost ratio is higher than one (when the hot air cost flow is higher than the cold air cost flow), then the minimum outside air intake should be used. If the cost ratio is lower than one (when the hot air cost flow is lower than the cold air cost flow), a normal economizer cycle should be applied.

The advanced enthalpy economizer is shown in Figure 3b. Both the economizers have exactly the same flow chart while the temperatures were replaced by the enthalpies in the advanced enthalpy economizer.

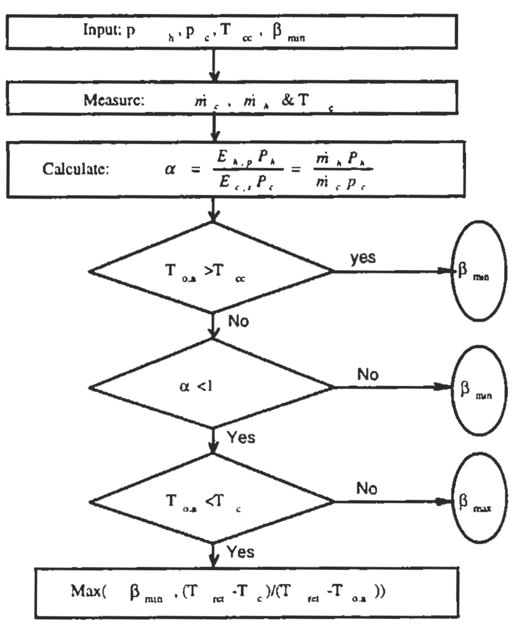
The advanced economizer can eliminate the excessive heating penalty of the normal economizer by introducing the cost ratio. The advanced economizer may work exactly the same way of the normal economizer when the cold air flow rate is larger than the hot air flow rate. However, when the cold air flow rate is smaller than the hot air flow rate, this economizer can avoid significant energy waste compared to the normal economizer cycle.

AN ECONOMIZER APPLICATION EXAMPLE-MEASURED RESULTS

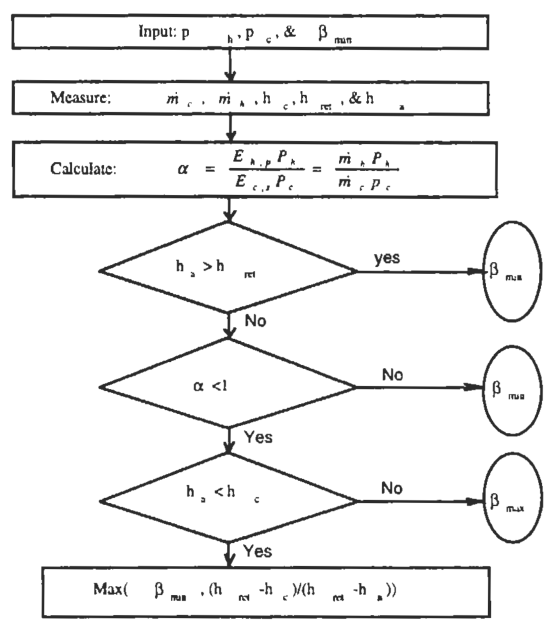
Two economizers were installed in a five-story school building at University of Texas at Austin when the constant volume AHUs (2-100 hp) were converted to VAV systems in April, 1991. The new HVAC systems use variable frequency drives for both supply air fans and chilled water pumps. The building was built in 1974 with a gross area of approximately 95,000 ft^2 (8800 m^2). The building houses nursing classrooms and lecture halls, workshops, lounges, and faculty offices. Electricity, chilled water, and steam are supplied by the main physical plant. The hourly chilled water, steam, and whole building electricity, as well as the supply air fan electricity consumption are monitored by the LoanSTAR program.

Figures 4a, 4b & 4c show the daily average electricity, steam, and chilled water consumption data from October 1991 to January 1994.

As shown in Figure 4a, the electricity consumption of the two air handlers is steady at about 20 to 25 kWh/hr before September 18, 1991. However, a sharp increase in the electricity consumption is first noted on September 19, 1991 and again on October 29, 1991. The 100 kW increase corresponded to the outside air temperatures falling below 55°F (13°C). Meanwhile the air handling units could not maintain the room temperature at 72°F (22°C) and occupants complained that the room temperature was too low. Consequently, the AHUs were forced to operate 24 hours a day in winter.



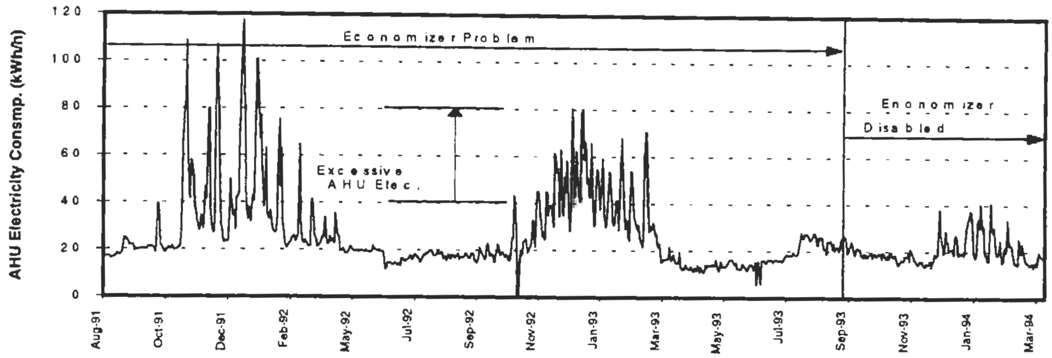
3a



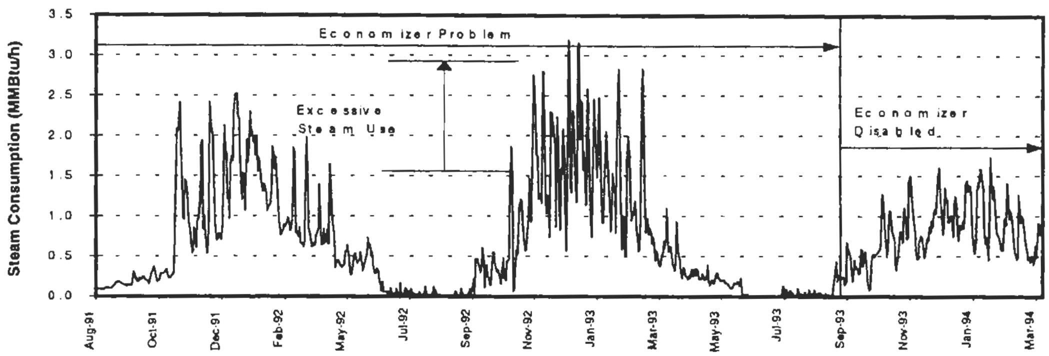
3b

Figure 3: Systematic Diagram of the Advanced Economizer Controller

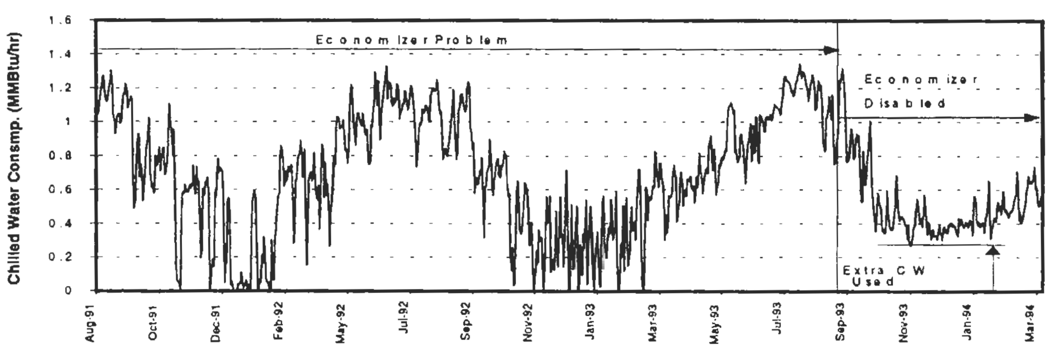
The steam pressure to the heating coils was increased from 5 psi (34 kPa) to 15 psi (103 kPa) and the size of the pressure regulating valve was increased from 1/2" (1 cm) to 2" (5 cm) in September 1992. In October 1992, when the temperature went below 55°F (13°C) and the economizer cycle started operating, some decrease in the AHU electricity and chilled water consumption was measured compared to Fall 1991. Unfortunately, a bigger increase in steam consumption was measured compared to Fall, 1991. The economizer cycle caused air handler electricity use and chilled water use to decline and generated positive savings of approximately $4,000/yr when compared to 1991. The steam usage during 1992, on the other hand, increased and generated negative savings of $6,000/yr, thus giving an overall cost increase of about $2,000/yr over 1991.



(4a)



(4b)



(4c)

Figure 4: The Measured Electricity, Steam, and Chilled Water Consumption in the Case Building

Analysis of data prior to the winter of 1993 revealed problems with the economizer cycle. Since this building has a primary width of 60 feet (18 m), the hot air flow rate is much higher than the cold air flow rate when the ambient temperature is lower than 70°F (21°C). When the economizer tried to maintain the mixed air temperature at the cold deck discharge air temperature, the hot deck lacked the capacity to heat air. Consequently, the supply air fan was speeded up on the request of room thermostats. This made the hot deck problem worse. Clearly, the normal economizer caused an excessive heating penalty and fan operating and room thermal environment problems.

Since the hot air flow rate is much higher than the cold air flow rate when the ambient temperature is lower than 70°F (21°C), the minimum outside air intake should be used according to the advanced temperature economizer principle. Consequently, it was suggested that the economizers be disabled.

In September 1993, the economizer cycle was disabled. Sharp drops in electricity and steam consumption were noticed from October 1993 to February 1994. A slight increase in chilled water consumption due to the use of a fixed fraction of the outside air intake was also noticed. The room temperature was maintained at comfort levels and no further complaints were received.

Drops in steam and AHU electricity consumption and an increase in chilled water use were noticed after October 1993. Daily data from October 1992 through January 1994 were used to calculate savings. The annual cost savings were determined as $7,000.

ENGINEERING MODELING ANALYSIS

The energy impacts of the economizer were complicated for dual duct systems since the cold and hot air flow rates changed significantly due to the different hot and cold deck settings. Therefore, a calibrated engineering model was developed for the case building to investigate the impact of the economizer under different operation and system conditions.

The simplified engineering models were developed by following procedures suggested by Liu and Claridge [6]. The models were calibrated against measured hourly steam consumption during March 1991 since the measured chilled water consumption data was not available. The simulated monthly total steam consumption is 3% higher than the measured value. The maximum hourly prediction error is 0.412 MMBtu/hr (121 kW). The mean root square error is 0.7%. Figure 5 presents both the measured and simulated hourly steam consumption in a time series format for March 1991. Figure 6 presents the same data in a scatter plot. Note that the data from the shutdown period (1 a. m. to 7 a.m) were removed.

Calibration processes allow us to identify the building thermal parameters, such as the heat transfer coefficient and the internal heat gain value, as well as to identify the system operation conditions, such as the control valve problems and the terminal box leak problems. The energy impacts of the economizer cycle are, then, investigated with this calibrated engineering model.

A total of 12 simulations were performed to investigate the impacts of the advanced temperature economizers in both constant and variable volume systems, and under two hot deck operation schedules. The impact of the advanced economizer was investigated by comparing the annual energy consumption to the base annual energy consumption (without the economizer).

The bin method was used for the simulation. The bin data were developed using the LoanSTAR measured hourly dry bulb and relative humidity at Austin in 1993. Table 1 summarizes the simulation results.

If the hot deck schedule 1 is used in the constant volume system, both economizers will save 5% of the total thermal energy cost (case CV1, CV2 and CV3). The advanced economizer works the same way the normal economizer does because the cold air flow rate is always higher than the hot air flow rate (see Figure 7a).

If the hot deck schedule 2 is used in the constant volume system, the normal economizer will increase the thermal energy costs by 30% (CA4, CA5, and CV6). In this case, the hot air flow rate is much higher than the cold air flow rate when the ambient temperature is lower than 75°F (24°C) (see Figure 7b). Consequently, the heating penalty (4,965 MMBtu/yr or 5,239 GJ/yr) is 3.8 times higher than the cooling energy savings (1,294 MMBtu/yr or 1,365 GJ/yr). However, the advanced economizer will use the minimum outside air intake so that the minimum energy is consumed

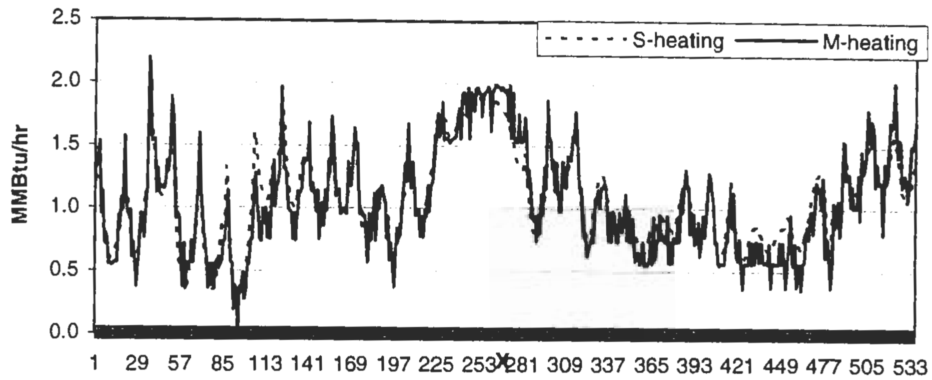


Figure 5: Comparison of Measured and Predicted Hourly Heating Energy Consumption in Time Series for the Case Building During March 1991 (Data are deleted for the nighttime shutdown period)

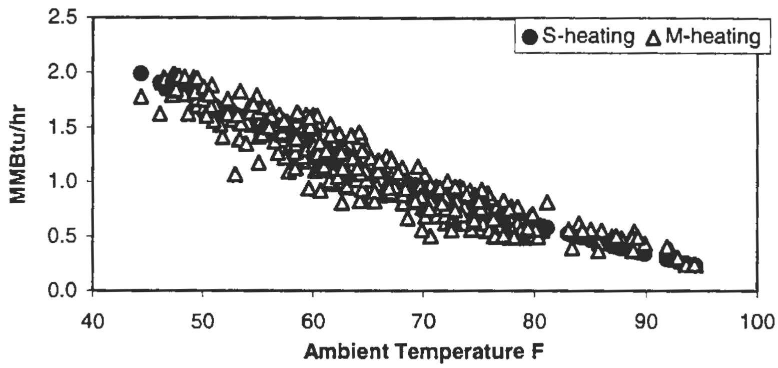


Figure 6: Comparison of Measured and Predicted Hourly Heating Energy Consumption for the Case Building During March 1991 (Data are deleted for the nighttime shutdown period)

Table 1: Summary of Simulation Results

Name	Hot Deck Settings	Economizer	Heating MMBtu/yr	Cooling MMBtu/yr	Total MMBtu/yr	Cost $/yr	Comparison
CV1	Schedule 1	No	9,370	13,460	22,830	$158,000	100%
CV2	Schedule 1	Economizer	12,060	10,040	22,100	$149,300	95%
CV3	Schedule 1	Economizer+	12,060	10,040	22,100	$149,300	95%
CV4	Schedule 2	No	3,170	6,810	9,990	$70,300	100%
CV5	Schedule 2	Economizer	8,140	5,520	13,660	$91,400	130%
CV6	Schedule 2	Economizer+	3,170	6,810	9,990	$70,300	100%
VAV1	Schedule 1	No	3,440	7,500	10,940	$77,000	100%
VAV2	Schedule 1	Economizer	4,900	6,310	11,210	$78,200	100%
VAV3	Schedule 1	Economizer+	4,340	6,600	10,940	$75,900	99%
VAV4	Schedule 2	No	1,700	5,580	7,290	$52,000	100%
VAV5	Schedule 2	Economizer	5,080	5,010	10,080	$68,600	132%
VAV6	Schedule 2	Economizer+	1,700	5,590	7,290	$52,000	100%

Note: 1. Cold deck was set at 55°F (13°C) for all cases.

2. Hot deck schedule 1: Min(125, 125-25/55(Tdry-20)) °F or Min(52, 52-25/55(Tdry+7)) °C.

3. Hot deck schedule 2: Min(100, 100-25/55(Tdry-20)) °F or Min(38, 38-25/55(Tdry+7)) °C.

4. Economizer refers to a normal temperature economizer.

5. Economizer+ refers to the advanced economizer.

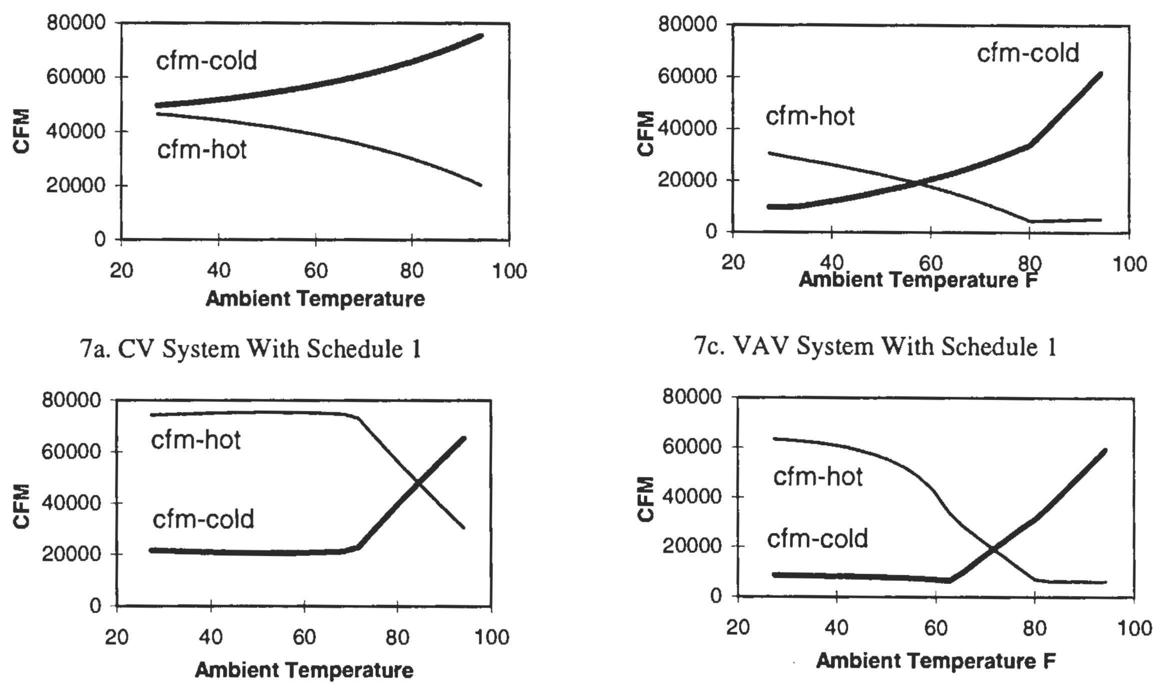
6. Chilled water price is $7.30/MMBtu ($7.70/GJ), and steam price is $6.20/MMBtu ($6.54/GJ).

If the hot deck schedule 1 is used in the variable volume system, the advanced economizer does not change the total thermal energy use, but it reduces the energy costs by 1% (case VAV1, VAV2, and VAV3). The normal economizer reduces the cooling energy consumption by 1,190 MMBtu (1,255 GJ), but increases the heating consumption by 1,460 MMBtu (1,540 GJ). The total energy consumption is 2.5% higher than the base energy consumption, and the energy cost increases about 1%. Under the hot deck schedule 1, the hot air flow rate is slightly higher than the cold air flow rate when the outside air temperature is lower than 55°F (13°C) (see Figure 7c). The heating penalty is very close to the cooling savings for the normal economizer.

If the hot deck schedule 2 is used in the variable volume system, the normal economizer increases the thermal energy cost by 32% ($16,600/yr) (case VAV4, VAV5, and VAV6) while the thermal energy consumption remains minimized if the advanced economizer is used. In this case, the hot air flow rate is about 5 to 6 times higher than the cold air flow rate when the outside air temperature is lower than 65°F (18° C) (see Figure 7d). Consequently, the heating penalty (3,380 MMBtu/yr or 3,566 GJ) is about 6 times higher than the cooling energy savings (570 MMBtu/yr or 601 GJ) for the normal economizer.

The cold air flow rates can be substantially smaller than the hot air flow rates due to a number of reasons: relatively large building envelope load (such as the example building), relatively low hot deck set point due to high total air flow rate, and relatively high cold deck set point. Under these conditions, the normal economizer can increase the energy costs substantially and also cause operation problems. However, the advanced economizer can always overcome the mechanical operation problem and maintain the minimum energy consumption.

It is also important to point out that both heating and cooling energy consumption are very sensitive to the cold and hot deck settings. The thermal energy cost can be reduced from $158,000/yr to $70,300/yr for constant volume systems, and from $77,000/yr to $52,000/yr for VAV systems just by reducing the hot deck set point by 25°F (14°C). Therefore, to optimize the cold and hot deck setting is one of the most important energy conservation measures for commercial buildings.



7a. CV System With Schedule 1

7c. VAV System With Schedule 1

7b. CV System With Schedule 2

7d. VAV System With Schedule 2

Figure 7: Hot and Cold Air Flow Rates Versus Ambient Temperature Under Different Systems and Operation Schedules

CONCLUSIONS

The energy impact of the economizer is complicated for the dual-duct system application. The normal economizer can cause excessive heating penalty as well as indoor thermal environment and operation problems. The advanced economizer, developed in this paper, can eliminate the excessive heating penalty of the normal economizer and eliminate the operation and indoor thermal environment problems.

To optimize the cold and hot deck settings is one of the most important energy conservation measures for commercial buildings. The thermal energy cost of the LoanSTAR building discussed above, for example, can be reduced from $158,000/yr to $70,300/yr for constant volume systems, and from $77,000/yr to $52,000/yr for VAV systems just by reducing the hot deck set point by 25°F (14°C).

ACKNOWLEDGMENTS

This paper is prepared with financial support from the State Energy Conservation Office of Texas. Mr. Aamer Athar calculated the measured savings and contributed the case building charts. Mr. Weida Chen collected case building information. Special thanks for editing are extended to Ms. Susan Swanson.

NOMENCLATURE

c_p specific heat of air (Btu/lb °F or J/kg °F)

$E_{c,s}$ cooling energy savings due to the economizer (Btu/hr or W)

$E_{h,p}$ heating penalty due to the economizer (Btu/hr or W)

h_a specific enthalpy of outside air (Btu/lb or J/kg)

h_c specific enthalpy of cold deck supply air (Btu/lb or J/kg)

h_{ret} specific enthalpy of return air (Btu/lb or J/kg)

$\dot{m}_c$ cold air mass flow rate (lb/hr or kg/s)

$\dot{m}_h$ hot air mass flow rate (lb/hr or kg/s)

p_h heating energy price ($/MMBtu or $/kJ)

p_c cooling energy price ($/MMBtu or $/kJ)

$T_{o,a}$ outside air temperature (°F or °C)

T_c cold deck discharge air temperature (°F or °C)

T_{cc} change point temperature (°F or °C)

T_{ret} return air temperature (°F or °C)

α potential savings ratio

β_{min} minimum outside air intake fraction

β_{max} maximum outside air intake fraction

REFERENCES

1. J. I. Levenhagen and D. H. Spethmann, HVAC Controls and Systems, McGraw-Hill, Inc (1993)
2. J. Y. Kao, W. H. Parken, and E. T. Pierce, Strategies for Energy Conservation for a Large Retail Store, *National Bureau of Standards*, NBSIR 82-2580 (1982).
3. W. H. Parken, J. Y. Kao, and G. E. Kelly, Strategies for Energy Conservation in Small Office Buildings, *National Bureau of Standards*, NBSIR 82-2489 (1982)
4. C. K. Park, G. E. Kelly and J. Y. Kao, Economizer Algorithms for Energy Management and Control Systems, *National Bureau of Standards*, NBSIR 84-2832 (1984)
5. M. Liu, J. Houcek, A. Athar, A. Reddy, D. E. Claridge, and J. Haberl, Identifying and Implementing Improved Operation and Maintenance measures in Texas LoanSTAR Buildings, *Proceedings of Commissioning, Operation and Maintenance, ACEEE 1994 Summer Study on Energy Efficiency in Buildings*, American Council for an Energy-Efficient Economy (1994).
6. M. Liu and D. E. Claridge, Application of Calibrated HVAC System Models to Identify Component Malfunctions and to Optimize the Operation and Control Schedules, Proceeding of Solar Energy 1995 (1995).