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### **Basic Air Conditioner Diagnostics Using a Simple Digital Thermostat**

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#### **ABSTRACT**

Unitary air conditioning equipment often receives poor maintenance because there are no diagnostic sensors and the equipment owners have no real understanding of how the system operates. Maintenance is often called for only when the capacity is no longer adequate, which is usually at the time of the greatest need for the system and the busiest service time. Using a simple model of constant heating/cooling capacity during an individual on-off cycle, a first order equation of run-time versus percent on-time was developed. The theoretical curve can be easily applied to an installed unit to determine the best fit coefficient for a particular application that provides a good prediction of cycling characteristics over its entire operating range. The best fit coefficient is specific to the performance of the particular unit, so a change in the unit capacity would cause the cycling characteristic to change. The only measurements that are needed for this cycling characteristic are the system on-time and off-time at various conditions. Digital thermostats could be programmed to "learn" the system cycling characteristic within a short period of operation. If future cycling patterns deviated from this initial learned cycling characteristic by more than a prescribed amount, a signal could alert the owner to the likely need for service. This concept is demonstrated using data from a residential heat pump unit with cycling data taken over a 10-year period. The best fit cycling coefficient was determined before and after a change of compressors, as well as before and after sealing the ductwork, to demonstrate the ability to detect small changes in system performance using this simple cycle timing system.

#### 1. INTRODUCTION

Large capacity cooling equipment used in commercial applications accounts for a significant part of the total installed air conditioner capacity. However, as developing countries embrace comfort cooling as part of a desirable and affordable lifestyle, unitary residential systems are beginning to account for an increasing percentage of all installed capacity. In terms of actual numbers of installed systems, unitary products outnumber the large systems by perhaps two orders of magnitude.

As with any mechanical system, the performance of an air conditioning system will depend on periodic maintenance to ensure that air flows are within normal specifications, the refrigerant charge has been maintained, and the compressor is performing as it should. Largely due to cost factors, there are typically no sensors installed with most unitary equipment which can be used for monitoring system performance by the owner. Even if there were sensors installed, the diagnostics would have to be very simplified since the majority of homeowners have no concept of how a vapor compression system works. Most service on unitary products is performed on an as-needed basis when the owner observes that the system is no longer able to meet the load requirements. Such service calls often occur on high load days causing service technicians to be overloaded on a relatively few days of the heating or cooling season. While some service requirements are the result of a sudden failure of a component, many are the result of gradual wear or a gradual loss of refrigerant. These service needs could be addressed at any time once they have a measurable impact on system performance. Since inadequate capacity is the only indicator that the homeowner has to indicate performance degradation, they usually discover the need for service only when the system's full rated capacity is needed on a peak load day.

While the homeowner may experience uncomfortable conditions at peak cooling loads when the system capacity is inadequate, more severe problems may occur with performance degradation of a heat pump in heating mode. Most heat pumps have electric auxiliary heaters that can adequately heat the space in the event of a major component failure, such as a compressor failure or complete loss of refrigerant. Most homeowners are unaware of the symptoms of the system operating on auxiliary heat, only to discover a utility bill several weeks later that is double

their normal electric bill. By the time they realize the problem and have gotten a service technician to fix their heat pump, they may have been operating on the much more expensive auxiliary heaters for up to two months.

There have been a number of efforts to develop system diagnostics to detect performance degradation. These generally fit in two categories: 1) simple cycling diagnostics, and, 2) smart models with system state point measurement inputs.

An example of a system that uses cycling diagnostics can be found in Parkinson et. al. (1986). This system uses a thermostat that monitors compressor run time and outdoor air temperature. It requires as input the building load characteristic versus temperature and the rated capacity of the unit. Easy to implement and with modest costs, this system has not gained acceptance due to the difficulty of obtaining the required inputs specific to the unit and the building. A variation of  $\pm$ 0% from a calculated load would be common due to variations in building tightness or internal loads that are associated with occupancy patterns and preferences. In addition, the capacity of the installed system may vary by 10% or more from its rated value if its installation is not typical.

The smart diagnostic models require certain measured inputs so the model can determine the nature of the operating fault. Rossi (1995), Chen and Braun (2000), and Dexter and Ngo (2001) report on variations of this type of system. The capabilities of this type of system can be impressive, and would include an indicator to the service technician of the probable cause of the fault. These systems can reduce service time as well as provide early fault detection for timely service but are not used in the residential market due to the first cost of the measurement instrumentation.

The diagnostic system described in this paper is a type more closely related to the simple cycling diagnostics described by Parkinson, et al. (1986). Rather than requiring calculated system or building inputs, the thermostat would have the capability to monitor system cycling performance to establish a baseline cycling characteristic curve. This baseline cycling characteristic requires as input only the compressor cycling times and does not require measurements of outdoor conditions or system state conditions. As cycling conditions deviate from the baseline characteristic beyond some acceptable tolerance, an appropriate diagnostic warning can be issued via the thermostat.

#### 2. SYSTEM CYCLING CHARACTERISTICS

The expected trend for the cycling relationship of a fixed capacity heating or cooling system can be illustrated using a simple thermal mass system with constant internal heat generation as shown in Figure 1. Consider the temperature of a simple mass contained in an insulated container that has supply and return air from a heating or cooling system that operates in an on/off mode. The analogy would apply the same for either heating or cooling, so cooling will be assumed in this example. A simple energy balance on the mass gives:

$$Q_{Net} = Mc \frac{dT}{dt}$$
 (1)

where M is the mass, c is the material specific heat, and  $Q_{\text{Net}}$  is the net cooling rate. The time derivative of temperature accounts for the energy buildup during the cooling off-cycle or released from the mass during the cooling process.

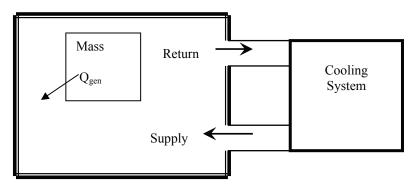


Figure 1. Simple analogy used for cycling characteristic development.

As with typical comfort cooling systems, the cooling capacity of the system is greater than the heat generation rate, so the cooling system is cycled on and off to maintain some desirable average temperature of the mass. Neglecting startup transients and issues associated with leaking ductwork and building pressurization effects, the energy flow in this simple model will be as shown in Figure 2.

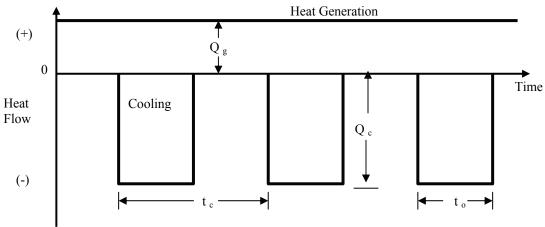


Figure 2. Simple cooling of a mass with heat generation using a constant capacity cooling system.

The constant heat generation produces a uniform load profile while the cooling system will cycle off and on at a certain rate in order to maintain a certain average temperature. The actual cycling rate will be determined by the range of the temperature fluctuation. For instance, if the temperature fluctuation range  $(T_{High} - T_{Low})$  were to double, the on-time and the off time must both double as well.

The cooling produced during the on-time, t<sub>o</sub>, must be equal in magnitude to the heat generated during the entire cycle time, t<sub>c</sub>. Using magnitudes without sign conventions for heat loss or generation yields:

$$Q_{c}(t_{o}) = Q_{a}(t_{c}) \tag{2}$$

Integration of Equation (1) from compressor startup to shutdown (from t=0 to t=t<sub>o</sub>) yields the relationship:

$$Mc(T_{High} - T_{Low}) = Q_c t_o - Q_g t_o$$
(3)

Solving Equation (3) for on-time t<sub>o</sub> and substituting the relationship between  $Q_c$  and  $Q_g$  from Equation (1) yields:

$$t_{o} = \frac{Mc(T_{High} - T_{Low})}{Q_{c} - Q_{g}} = \frac{Mc(T_{High} - T_{Low})}{Q_{c}(1 - \frac{t_{o}}{t_{c}})}$$
(4)

Solving for the on-time fraction from Equation (4) gives the simple relationship:

$$\frac{t_o}{t_c} = 1 - \frac{Mc(T_{High} - T_{Low})}{Q_c t_o}$$
 (5)

It may appear that it would take quite a leap of one's imagination to go from this simple model to something representative of the complexity of a building structure being heated or cooled by a system whose capacity varies with outdoor temperature. However, the deadband of a thermostat would be nearly constant from cycle to cycle. In addition, the energy transfer into or out of the structural and interior mass of the building (numerator of Equation (4)) would also vary little from cycle to cycle. The capacity of the heating or cooling system would vary significantly at extreme conditions, but the majority of the operating conditions would experience little more than a 10% deviation from a capacity at an average outdoor heating or cooling temperature. Duct losses, pressure-induced

infiltration, and other real world operating system effects simply reduce the value of  $Q_c$  from its factory rating to an as-installed de-rated value.

For a particular application (a given house with a given heating or cooling system) Equation (5) can be simplified to a single coefficient form:

$$\frac{t_o}{t_c} = 1 - \frac{t_{o,min}}{t_o} \tag{6}$$

where  $t_{o,min}$  is the point at which an extrapolation of  $t_o/t_c$  versus  $t_o$  would cross the  $t_o$  line, as shown in Figure 3. The data from Figure 3 were taken from Murphy (1977) as part of a study to model air conditioner cycling in mobile home applications and were measured by manual timing of air conditioner start and stop times. The parameter  $t_{o,min}$  can be viewed as the on-time when the off-time becomes very large. In practice, A/C units will not run that short of a time, so the value of  $t_{o,min}$  is a mathematical extrapolation of the trendline and can be easily determined from a least-squares analysis of the data using the form of Equation (6):

$$t_{o,min} = \frac{N - \sum_{i=1}^{N} \left(\frac{t_{o}}{t_{c}}\right)_{i}}{\sum_{i=1}^{N} \left(\frac{1}{t_{o}}\right)_{i}}$$
(7)

where N is the number of cycles for which on-time and cycle times are measured.

The data shown in Figure 3 were taken from three different days. Taken together, they yield a curve with a standard deviation about the curve fit line of 0.016. Given the simple model used to generate the form of the curve fit, such a good least squares fit would be considered very satisfactory. Similar experiments by Hart (1978) using the same mobile home but with a heat pump in heating mode yielded equally good correlations.

Using the data from Figure 3, one can examine the expected deviations for computed values of on-time,  $t_o$ , based on given values of the on-time fractions. This analysis is shown in Figure 4. While there is a tendency for a slightly higher percent error at short on-times, it cannot be determined from the data that such a trend is based on actual physical phenomena or simply due to a comparable deviation but with a smaller value in the denominator. Except for two outlier points, all the data fall within a  $\pm$ - 5% range. There is an approximate equal distribution of points above and below the zero line as you would expect from a least squares relationship. Given the variations one might expect from a real heating/cooling system, results within  $\pm$ - 5% should be considered very good.

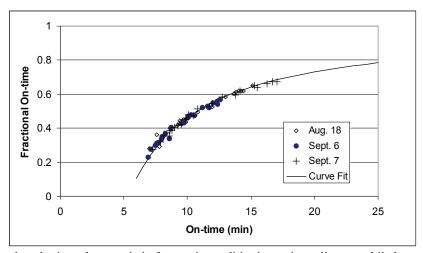


Figure 3. Measured cycle time characteristic for an air conditioning unit cooling a mobile home (Murphy, 1977).

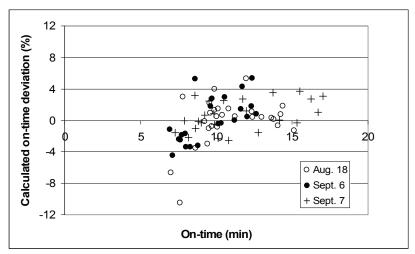


Figure 4. Deviations of calculated on-times from measured values for a mobile home and air conditioning system.

To examine how good the form of Equation (6) would be for a different application, cycling time measurements were taken for an air source heat pump unit heating a 2-story, 200 m² home. These results are shown in Figure 5. Heating mode permits longer on-times during outdoor temperatures just above the balance point, and also produces larger variations in system capacity due to temperature variations. Cycling data were collected over several weeks in two different years, January 1987 and December 1993 and January 1994. The January 1994 period was much colder than normal, with many days more than 10°C below average, and included an all-time record low temperature for that location. The data were obtained by manually recording the times that the heat pump came on or shut down. Defrost operation could not always be readily detected by the cycling pattern of the system. Not every defrost cycle was likely detected so the cycle data could be discarded. Some of the outlier points may have been influenced by the system's defrost mode operation.

The important aspect of Figure 5 is that the cycling characteristic,  $t_{o, min}$ , was very similar over the 7-year period from 1987 to 1994. The value of ,  $t_{o, min}$  from the 1987 data was 4.116 minutes, while it was 4.160 minutes for the 1994 data. While the room thermostat was set to approximately the same value each heating season, there was no way to ensure that the system controls were set identically each year. Figure 6 shows the pattern of deviation between the data and the least squares curve fit. For data from the two years, it can be seen that the 1994 data were scattered much more than the 1987 data. The standard deviation  $S_{yx}$  for the 1987 data is 0.017, while it is 0.021 for the 1994 data. This greater scatter was very likely due to the greater occurrence of more extreme weather conditions during the measurement periods in 1994. The combined value of  $t_{o, min}$  was 4.139 minutes, and  $S_{yx}$  for all points was 0.020. The majority of the 1987 deviation results for the on-time are within the range of +/- 6%.

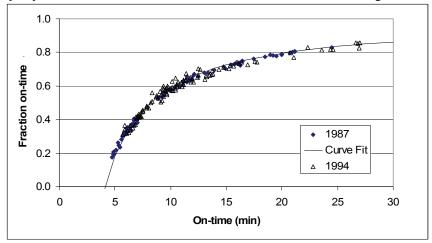


Figure 5. Cycling characteristic for a 2-story house heated by an air source heat pump.

The consistency of this procedure can be tested further from cycling data taken in 1995. The heat pump compressor failed in the summer of 1994 and it was replaced with a like model, which should have brought the unit back to its same original capacity. The capacity of the unit was never field tested before or after the compressor change-out, so any resulting difference is subject to speculation.

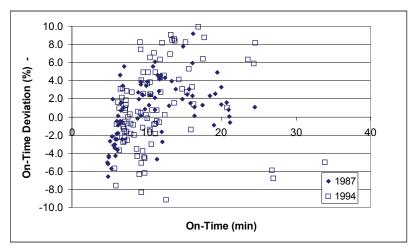


Figure 6. Deviations of calculated on-times for a 2-story home heated with an air source heat pump.

Figure 7 shows the cycling characteristic curve for measurements made during the period January 3 to February 9, 1995. The cycling curve is characterized by the value of  $t_{o,min}$ . For the 1995 data, the  $t_{o,min}$  value is 4.163 minutes, compared to the values of 4.116 minutes for 1987 and 4.160 minutes for the 1994 data. If this  $t_{o,min}$  value does characterize the ratio of the thermal storage to the heating or cooling rate, as suggested by Equations (5) and (6), then if the structure did not change, it could be inferred that:

$$\frac{Q_{c,2}}{Q_{c,1}} = \frac{t_{o,min,1}}{t_{o,min,2}}$$
 (8)

Recognizing that the heating or cooling rate is not constant, this result would suggest that the heating/cooling curve versus temperature would be shifted up or down over the entire operating range by this relative amount. Since the ratio of  $t_{o,min}$  was virtually identical for all three years, this would suggest that the heating capacity was also virtually the same after the compressor change-out. The standard deviation of the data about the curve fit line for 1995 was 0.014, also very similar to the 0.017 and 0.021 for 1987 and 1994, respectively.

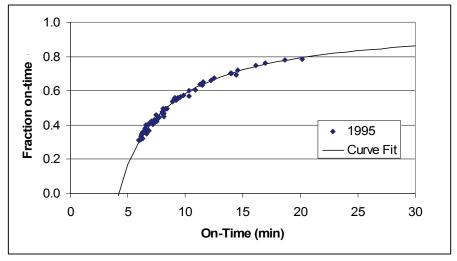


Figure 7. Cycling characteristic curve for 1995 after compressor change.

One additional field experiment with cycling data was also conducted to determine the sensitivity of cycling measurements. The ductwork in this 2-story house was standard galvanized metal duct with the ductwork serving the second floor located in the attic overhead. In the fall of 1996, the supply ductwork in the attic was sealed with mastic to reduce supply air leaks. While the ducts were generally properly installed and the straight connections were already taped, the metal elbows were not sealed and not all the taped joints were tight. The larger plenum slip joints had not been taped earlier, and they were also sealed with mastic. Cycling data measured during the following heating season are shown in Figure 8, with the 1995 data from Figure 7 shown for comparison.

Following the logic of Equation (8), the ratio of the  $t_{o,min}$  values should indicate the relative change in the delivered capacity of the heat pump system. In this case, it is not due to changes in actual capacity provided by the unit, but the delivered capacity to the heated space after incurring losses due to air leakage in the attic. Despite the different mechanism, the end result seen by the home is essentially the same as if the capacity of the unit itself was increased. The 1997 cycling data yield a value of  $t_{o,min}$  of 3.949 minutes with a standard deviation about the curve fit equation of 0.0106. The  $t_{o,min}$  value suggests that the delivered capacity was increased by about 5.4% due to sealing the attic ducts. Since many reports on duct leakage suggest common leakage rates of 20 to 40% for galvanized duct systems, an improvement of 5% would seem reasonable. As before, trying to perform field measurements of such a relatively small change would be quite challenging. Given the nearly identical values of  $t_{o,min}$  from the prior years' measurements, these results suggest that a meaningful change in the system performance has obviously occurred.

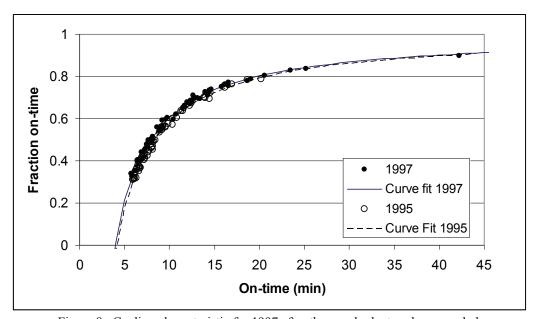


Figure 8. Cycling characteristic for 1997 after the supply ductwork was sealed.

#### 3. IMPLICATIONS FOR DIAGNOSTIC APPLICATIONS

While a cycling analysis obviously is not perfect, the data presented here suggest that consistent results can be obtained with a typical single family dwelling. How can the cycling relationship for a particular heating or cooling system with a given dwelling be used for system diagnostic purposes? The measurement of cycling characteristics requires only a simple timer mechanism that is already included in every digital thermostat. The thermostat would need the capability to be programmed to "learn" the cycling characteristic of the given unit and dwelling, then to compare future cycling results against this learned characteristic for deviations. Some details of what should trigger a warning and the number of levels of warnings would need to be determined from more detailed tests with specific thermostats. A heat pump will require a slightly different algorithm since defrost cycles must be accounted for and taken out of the cycle calculation sequences. Other things that the thermostat should probably account for could include setpoint resets and initial and final cycles of a sequence. An example of a suggested sequence of operations for such a controller is shown in Figure 9.

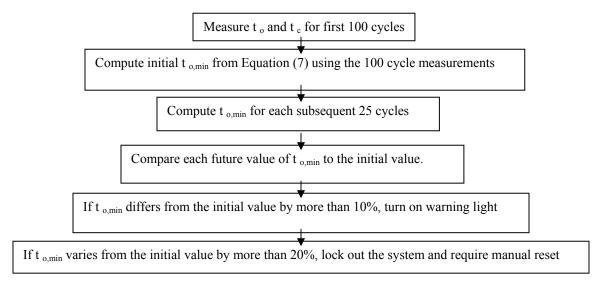


Figure 9. Sample algorithm for simple performance diagnostics using system cycling measurements and analysis

#### 4. CONCLUSIONS

An air conditioner or heat pump that uses an on/off control when heating or cooling a dwelling will exhibit a regular cycling characteristic. This characteristic can be easily determined and can potentially be programmed into a digital thermostat as an early warning for system performance degradation. Cycling measurements taken in a mobile home and in a 2-story frame house indicated that this cycling characteristic will typically represent all normal cycling measurements within a 10% range. These measurements were taken over a period of 10 years, and were able to measure the difference in system performance when the duct system was sealed. Some additional testing would be needed to determine when the diagnostic device should ignore a cycle in its ongoing cycling data collection and evaluation processes.

#### **NOMENCLATURE**

c	specific heat	kJ/kg-K	$t_{o}$	compressor on-time	S
M	mass	kg	t <sub>c</sub>	cycle time	S
N	number of cycles	C	$t_{o,min}$	minimum on-time	S
$Q_c$	cooling rate	W	$T_{high}$	upper deadband temperature	K
$O_{\sigma}$	heat generation rate	W	Tlow	lower deadband temperature	K

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