2 Methodology

2.1 AHU Performance Assessment Rules (APAR)

The basis for the air handling unit fault detection methodology is a set of expert rules used to assess the performance of the AHU. The tool developed from these rules is APAR (AHU Performance Assessment Rules). A brief overview of APAR is presented here; a detailed description is available elsewhere [5].

APAR is applicable to single duct VAV and constant volume AHUs with airside economizers. The operation of this type of AHU during occupied periods can be classified into a number of modes, depending on the heating/cooling load and outdoor air conditions. Each mode of operation can be characterized by a different range of values for each of three control signals: the heating coil valve, cooling coil valve, and mixing box dampers. For convenience, the operating modes are summarized below:

- Mode 1: heating
- Mode 2: cooling with outdoor air
- Mode 3: mechanical cooling with 100 % outdoor air
- Mode 4: mechanical cooling with minimum outdoor air
- Mode 5: unknown

Once the mode of operation has been established, rules based on conservation of mass and energy can be evaluated using the sensor and control signal information that is typically available from AHUs. APAR has a total of 28 rules (see Table 2.1). Each rule is expressed as a logical statement that, if true, indicates the presence of a fault. Because the mass and energy balances are different for each mode of operation, a different subset of the rules applies to each mode. There are also some rules that are independent of the operating mode and are always evaluated. A list of possible causes is associated with each rule (see Table 2.2).

Several modifications to the basic APAR algorithm were made to enhance usability and reduce nuisance alarms. Each rule can be individually disabled by the user in order to eliminate nuisance alarms caused by fault conditions that are known to the maintenance staff, but will not be repaired immediately. Since the rules are based on steady state assumptions, there are several delays, during which the rules are not evaluated, to ensure that quasi-steady state conditions exist. There is a delay at the beginning of occupancy and another delay after each mode switch. A third delay establishes the length of time a rule must be satisfied before an alarm is reported. Furthermore, the rules are evaluated using exponentially weighted moving averages of the raw data rather than the current values [5].

The rules in Table 2.1 are generic, not tightly linked to a specific sequence of operations. The rule set was developed for AHUs with hydronic heating and cooling coils and relative enthalpy-based economizers, however, it can easily be adapted for different types of AHUs. For example, Rules 9 and 15 will change based on the type of economizer, whether it is temperature- or enthalpy-based, and whether it compares outdoor conditions to return or to a fixed changeover condition, or some combination thereof. If the cooling coil uses direct expansion instead of chilled water, Rules 13, 14, 19, and 20 do not apply. Also, the causes in Table 2.2 related to the cooling coil valve (valve stuck or leaking) or the chilled water system (chilled water supply temperature too high, problem with chilled water circulating pump, chilled water not available) are interpreted as problems with the mechanical refrigeration system. If some form of staged heating (electric or combustion) is used instead of hydronic heating, Rules 3 and 4 do not apply. Also, the causes in Table 2.2 related to the heating coil valve (valve stuck or leaking) or the hot water system (hot water supply temperature too low, problem with hot water circulating pump) are interpreted as problems with the staged heating system. For single zone or other AHUs with no supply air temperature setpoint, Rules 5, 8, 13, 19, and 25 do not apply. If there is no mixed air temperature sensor, delete Rules 1, 2, 7, 10, 11, 16, 18, 26, and 27 cannot be evaluated and therefore do not apply.

Table 2.1: APAR Rule Set

Mode	Rule #	**Rule Expression** (true implies existence of a fault)
Heating (Mode 1)	1	$T_{sa} < T_{ma} + \Delta T_{sf} - \varepsilon_t$
	2	For $\|T_{ra} - T_{oa}\| \geq \Delta T_{min}$: $\|Q_{oa}/Q_{sa} - (Q_{oa}/Q_{sa})_{min}\| > \varepsilon_f$
	3	$\|u_{hc} - 1\| \leq \varepsilon_{hc}$ and $T_{sa,s} - T_{sa} \geq \varepsilon_t$
	4	$\|u_{hc} - 1\| \leq \varepsilon_{hc}$
Cooling with Outdoor Air (Mode 2)	5	$T_{oa} > T_{sa,s} - \Delta T_{sf} + \varepsilon_t$
	6	$T_{sa} > T_{ra} - \Delta T_{rf} + \varepsilon_t$
	7	$\|T_{sa} - \Delta T_{sf} - T_{ma}\| > \varepsilon_t$
Mechanical Cooling with 100% Outdoor Air (Mode 3)	8	$T_{oa} < T_{sa,s} - \Delta T_{sf} - \varepsilon_t$
	9	$T_{oa} > T_{co} + \varepsilon_t$
	10	$\|T_{oa} - T_{ma}\| > \varepsilon_t$
	11	$T_{sa} > T_{ma} + \Delta T_{sf} + \varepsilon_t$
	12	$T_{sa} > T_{ra} - \Delta T_{rf} + \varepsilon_t$
	13	$\|u_{cc} - 1\| \leq \varepsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \varepsilon_t$
	14	$\|u_{cc} - 1\| \leq \varepsilon_{cc}$
Mechanical Cooling with Minimum Outdoor Air (Mode 4)	15	$T_{oa} < T_{co} - \varepsilon_t$
	16	$T_{sa} > T_{ma} + \Delta T_{sf} + \varepsilon_t$
	17	$T_{sa} > T_{ra} - \Delta T_{rf} + \varepsilon_t$
	18	For $\|T_{ra} - T_{oa}\| \geq \Delta T_{min}$: $\|Q_{oa}/Q_{sa} - (Q_{oa}/Q_{sa})_{min}\| > \varepsilon_f$
	19	$\|u_{cc} - 1\| \leq \varepsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \varepsilon_t$
	20	$\|u_{cc} - 1\| \leq \varepsilon_{cc}$
Unknown Occupied Modes (Mode 5)	21	$u_{cc} > \varepsilon_{cc}$ and $u_{hc} > \varepsilon_{hc}$ and $\varepsilon_d < u_d < 1 - \varepsilon_d$
	22	$u_{hc} > \varepsilon_{hc}$ and $u_{cc} > \varepsilon_{cc}$
	23	$u_{hc} > \varepsilon_{hc}$ and $u_d > \varepsilon_d$
	24	$\varepsilon_d < u_d < 1 - \varepsilon_d$ and $u_{cc} > \varepsilon_{cc}$
All Occupied Modes (Mode 1, 2, 3, 4, or 5)	25	$\| T_{sa} - T_{sa,s} \| > \varepsilon_t$
	26	$T_{ma} < min(T_{ra}, T_{oa}) - \varepsilon_t$
	27	$T_{ma} > max(T_{ra}, T_{oa}) + \varepsilon_t$
	28	Number of mode transitions per hour $> MT_{max}$

Where

MT_{max}	=	maximum number of mode changes per hour
T_{sa}	=	supply air temperature
T_{ma}	=	mixed air temperature
T_{ra}	=	return air temperature
T_{oa}	=	outdoor air temperature
T_{co}	=	changeover air temperature for switching between Modes 3 and 4
$T_{sa,s}$	=	supply air temperature set point
ΔT_{sf}	=	temperature rise across the supply fan
ΔT_{rf}	=	temperature rise across the return fan
ΔT_{min}	=	threshold on the minimum temperature difference between the return and outdoor air
Q_{oa}/Q_{sa}	=	outdoor air fraction = $(T_{ma} - T_{ra})/(T_{oa} - T_{ra})$
$(Q_{oa}/Q_{sa})_{min}$	=	threshold on the minimum outdoor air fraction
u_{hc}	=	normalized heating coil valve control signal [0,1] where $u_{hc} = 0$ indicates the valve is closed and $u_{hc} = 1$ indicates it is 100 % open
u_{cc}	=	normalized cooling coil valve control signal [0,1] where $u_{cc} = 0$ indicates the valve is closed and $u_{cc} = 1$ indicates it is 100 % open
u_d	=	normalized mixing box damper control signal [0,1] where $u_d = 0$ indicates the outdoor air damper is closed and $u_d = 1$ indicates it is 100 % open
ε_t	=	threshold for errors in temperature measurements
ε_f	=	threshold parameter accounting for errors related to airflows (function of uncertainties in temperature measurements)
ε_{hc}	=	threshold parameter for the heating coil valve control signal
ε_{cc}	=	threshold parameter for the cooling coil valve control signal
ε_d	=	threshold parameter for the mixing box damper control signal

Table 2.2: APAR Diagnoses

Rule #	Alarm Description	Supply Air Temperature Sensor Error	Return Air Temperature Sensor Error	Mixed Air Temperature Sensor Error	Outdoor Air Temperature Sensor Error	Leaking Cooling Coil Valve	Stuck Cooling Coil Valve	Undersized Cooling Coil	Fouled Cooling Coil	Chilled Water Supply Temperature Too High	Problem with Chilled Water Circulating Pump	Chilled Water not Available to Season	Leaking Heating Coil Valve	Stuck Heating Coil Valve	Undersized Heating Coil	Fouled Heating Coil	Hot Water Supply Temperature Too Low	Problem with Hot Water Circulating Pump	Leaking Mixing Box Damper	Stuck Mixing Box Damper
		Possible Diagnoses																		
1	In heating mode, supply air temp should be greater than mixed air temp.	X		X		X	X							X	X	X	X	X		
2	Outdoor air fraction (percentage of outdoor air) is too low or too high.		X	X	X														X	X
3	Heating coil valve command is fully open and supply air temp error exists.	X				X	X							X	X	X	X	X		
4	Heating coil valve command is fully open. If heating load increases, supply air temp will drift from setpoint.	X				X	X							X	X	X	X	X		
5	Outdoor air temp is too warm for cooling with outdoor air.	X			X															
6	Supply air temp should be less than return air temp.	X	X										X	X						
7	Supply and mixed air temp should be nearly the same.	X		X		X	X						X	X						
8	Outdoor air temperature is too cool for mechanical cooling with 100% outdoor air.	X			X								X	X					X	X
9	Outdoor air enthalpy is too great for mechanical cooling with 100% outdoor air.																			
10	Outdoor and mixed air temp should be nearly the same.			X	X														X	X
11	Supply air temp should be less than mixed air temp.	X		X			X	X	X	X	X	X	X	X						
12	Supply air temp should be less than return air temp.	X	X				X	X	X	X	X	X	X	X						
13	Cooling coil valve command is fully open and supply air temp error exists.	X					X	X	X	X	X	X	X	X						
14	Cooling coil valve command is fully open. If cooling load increases, supply air temp will drift from setpoint.	X					X	X	X	X	X	X	X	X						
15	Outdoor air enthalpy is too low for mechanical cooling with minimum outdoor air.																			
16	Supply air temp should be less than mixed air temp.	X		X			X	X	X	X	X	X	X	X						
17	Supply air temp should be less than return air temp.	X	X				X	X	X	X	X	X	X	X						
18	Outdoor air fraction (percentage of outdoor air) is too low or too high.		X	X	X														X	X
19	Cooling coil valve command is fully open and supply air temp error exists.	X					X	X	X	X	X	X	X	X						
20	Cooling coil valve command is fully open. If cooling load increases, supply air temp will drift from setpoint.	X					X	X	X	X	X	X	X	X						
21	Heating coil valve, cooling coil valve, and mixing box dampers are all modulating simultaneously.																			
22	Heating coil valve and cooling coil valve are both modulating simultaneously.																			
23	Heating coil valve and mixing box dampers are both modulating simultaneously.																			
24	Cooling coil valve and mixing box dampers are both modulating simultaneously.																			
25	Persistent supply air temp error exists.																			
26	Mixed air temp should be between return and outdoor air temp (mixed air temp too great).		X	X	X															
27	Mixed air temp should be between return and outdoor air temp (mixed air temp too low).		X	X	X															
28	Too many mode switches per hour.																			

2.2 VAV Box Performance Assessment Control Charts - VPACC

The challenges presented in detecting and diagnosing faults in VAV boxes are similar to those encountered with other pieces of HVAC equipment. Generally there are very few sensors, making it difficult to determine what is happening in the device. Limitations associated with controller memory and communication capabilities further complicate the task. The number of different types of VAV boxes and lack of standardized control sequences add a final level of complexity to the challenge. These needs and constraints led to the development of VAV Box Performance Assessment Control Charts (VPACC), a fault detection tool that uses a small number of control charts to assess the performance of VAV boxes. A brief overview of VPACC is presented here; a detailed description is available elsewhere [6].

VPACC implements an algorithm known as a CUSUM (cumulative sum) chart [7]. The basic concept behind CUSUM charts is to accumulate the error between a process output and the expected value of the output. Large values of the accumulated error indicate an out of control process. Mathematically, the technique can be expressed as:

$$z_i = (x_i - x_{exp}) / \sigma_{exp}$$

where z_i is the normalized error at time i, x_i is the error at time i, x_{exp} is the expected value of the error, and σ_{exp} is the expected variation of the error. Separate positive (S) and negative (T) sums are then accumulated. The slack parameter, k, is defined as the amount of variation that is considered normal, and therefore ignored. The cumulative positive and negative sums are calculated by:

$$S_i = max[0, z_i - k + S_{i-1}]$$

$$T_i = max[0, -z_i - k + T_{i-1}]$$

The final step is to compare S and T to the alarm limit, h, to determine whether the process is out of control.

In order to make VPACC independent of the control strategy used in a particular controller/VAV box application, four generic errors were identified: the airflow rate error, the absolute value of the airflow rate error, the temperature error, and the discharge air temperature error. As long as the VAV box controller has an airflow setpoint, as well as heating and cooling temperature setpoints, VPACC will function independently of the specific control strategy used. Common mechanical and control faults will result in a positive or negative deviation of one or more of these errors from its value during normal operation, which can be detected by a CUSUM chart. A list of possible causes is associated with each alarm (see Table 2.3).

The airflow rate error, Q_{error}, is defined as the difference between the measured airflow rate and the airflow rate set point. The absolute value of the airflow rate error, $|Q_{error}|$, is defined simply as the absolute value of the difference between the measured airflow rate and the airflow rate set point. Only one CUSUM value is defined for this error since it is never negative.

The zone temperature error, T_{error}, is defined as

$$T_{error} = T_{zone} - CSP \quad : \text{ If } T_{zone} > CSP$$
$$T_{error} = 0 \quad : \text{ If } HSP \le T_{zone} \le CSP$$
$$T_{error} = T_{zone} - HSP \quad : \text{ If } T_{zone} < HSP$$

where

T_{zone} = zone temperature
CSP = cooling set point
HSP = heating set point.

The discharge air temperature error, DAT_{error}, is only applied to VAV boxes with hydronic reheat. The DAT_{error} is calculated only when the reheat coil valve is fully closed, otherwise it is set equal to zero. It is defined as the difference between the VAV box discharge air temperature and the entering air temperature. The supply air temperature from the AHU serving the VAV box can be used as a surrogate for the entering air temperature. This value is generally obtained via the building control network.

The errors and CUSUMs are only calculated during occupied periods. During unoccupied periods, the errors are not computed and the CUSUMs are reset to zero. There is a delay at the onset of the occupied period to allow quasi-steady state conditions to develop. Also, the CUSUMs are periodically reset to zero to prevent alarms from being reported due to small steady state errors. Each alarm can be individually disabled by the user in order to eliminate nuisance alarms caused by fault conditions that are known to the maintenance staff, but will not be repaired immediately.

VPACC was developed for pressure independent VAV boxes with hydronic reheat coils, however, it can easily be adapted for different types of VAV boxes. For cooling only VAV boxes or boxes that do not have discharge air temperature sensors, the discharge air temperature error (ΔT_{error}) does not apply. For dual duct boxes, two airflow errors ($Q_{error,hot}$ and $Q_{error,cold}$) and two absolute value airflow errors ($|Q_{error,\ hot}|$ and $|Q_{error,\ cold}|$) are needed, and the discharge air temperature error (ΔT_{error}) does not apply. Although VPACC was originally tested using VAV boxes without fans [1, 2, 3, 5], the algorithm is independent of fan configuration and can be applied to boxes with series or parallel fans without modification.

Table 2.3. VPACC Diagnoses.

Alarm Description	Possible Diagnoses																			
	Zone temperature sensor drift/failure	Airflow (DP) sensor drift/failure	Discharge temperature sensor drift/failure	Damper stuck or failed	Damper actuator stuck or failed	Reheat coil valve stuck or failed	Reheat coil valve actuator stuck or failed	AHU Supply air too warm	AHU Supply air too cool	Supply air static pressure too low	Scheduling conflict with AHU	Undersized VAV box	Tuning problem with airflow feedback control loop	Tuning problem with zone temperature feedback control loop	Inappropriate zone temperature setpoint	Minimum airflow setpoint too low	Minimum airflow setpoint too high	Maximum airflow setpoint too low	Maximum airflow setpoint too high	Sequencing logic error
High zone temperature alarm	X	X				X	X	X			X	X	X	X	X			X		X
Low zone temperature alarm	X	X				X	X		X		X	X	X	X	X		X			X
High airflow alarm		X		X	X						X		X							X
Low airflow alarm		X		X	X					X	X	X	X						X	X
Unstable airflow alarm		X		X	X					X	X	X	X			X				X
High discharge temperature alarm			X			X	X													
Low discharge temperature alarm			X			X	X													