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Painting Green: Design and Analysis of an Environmentally and Energetically Conscious Paint Booth HVAC Control System

E. Sadeghipour, E. R. Westervelt, and S. Bhattacharya

Abstract— **Paint booths in the automotive industry require conditioned air to achieve desired product finish quality. The large amount of conditioned air required to operate a paint booth results in large amounts of energy consumption. This paper presents an analysis of the energy consumption of a paint booth and gives a means of reducing this consumption by designing and implementing a novel control strategy. This proposed strategy is expected to decrease the plant's HVAC utility costs by more than a fifth, and reduce its annual carbon dioxide emissions from natural gas combustion by roughly a quarter.**

Nomenclature

Symbol	Meaning	Units
t_{db}	dry bulb temperature	°F or °R
ω	humidity ratio	-
ω_{s}	humidity ratio at water vapor saturation	-
ϕ	relative humidity	%
h	specific enthalpy	Btu/lbda
p	atmospheric pressure	psi
p_{ws}	partial pressure of saturated water vapor	psi
lbda	pound mass of dry air	-

I. INTRODUCTION

Two of today's important topics are the depletion of the world's fossil fuel resources and concerns over man-made contributions to global warming. The large heating, ventilation, and air conditioning (HVAC) systems used for paint booths in automotive plants across the world condition large volumes of fresh air, which means they consume an enormous amount of energy. For example, up to a fifth of the energy consumed by a typical automotive plant is consumed by the plant's paint booth HVAC systems. Therefore, improving the efficiency of paint booth HVAC systems can not only save energy and reduce the negative environmental impact of these plants, but also decrease the financial costs associated with large amounts of energy consumption.

HVAC systems are used in paint booth systems to bring the temperature and humidity of the air inside the paint booth to specified values required for a high-quality paint finish. Poorly conditioned air can cause paint finish defects such as drips, sags, mottling, etc. In these cases, the products must be repaired, which increases operational costs.

This paper demonstrates a new control strategy that improves the thermodynamic efficiency of a paint booth HVAC system. The analysis makes use of the tolerance in paint booth air conditions (ranges in dry bulb temperature and relative humidity) allowed by the paint manufacturers and proposes an operating target window as opposed to an operating target point. Additionally, the analysis considers the costs associated with different processes within the HVAC system, and proposes the use of these processes in a way to minimize the costs of bringing the state of the air to a state in the target window. The proposed strategy makes use of the following observation: the system will consume less energy when operating at a setpoint on the lower end of the temperature and relative humidity boundaries on a cold and dry day, or, similarly, when operating at a setpoint on the higher end of the temperature and relative humidity boundaries on a warm and humid day.

The paper is organized as follows: Section II gives an overview of psychrometrics. Section III explains the setup of the paint booth that was analyzed. Section IV-A explains the methods used to find the optimal partitioning of the psychrometric chart and the final partitions. Section IV-B explains the control algorithms used to implement the partitioning system and gives an example of the differences between the current control system and the proposed control system. The results of this study are presented in Section V. Conclusions are drawn in Section VI.

II. HVAC BASICS

The psychrometric chart[1] is one of the primary tools used for analyzing moist air and is used extensively in the analysis of HVAC systems; see Fig. 1. The horizontal axis of the psychrometric chart is dry bulb temperature, denoted by t_{db}. Dry bulb temperature is simply the temperature of the air-vapor mixture. The vertical axis of the graph is humidity ratio, denoted by ω. Humidity ratio is the mass of water per mass of air of the air-vapor mixture. The curved lines on the graph are constant relative humidity lines, denoted by ϕ and usually measured in percentage. The upper-most curve is termed the saturation line. Relative humidity is the partial pressure of water vapor in an air-vapor mixture divided by

E. Sadeghipour is a third-year undergraduate student of Mechanical Engineering at The Ohio State University, Columbus, Ohio 43210, USA; E. R. Westervelt is with the General Electric Global Research Center, Niskayuna, NY; S. Bhattacharya is with the Honda of America Manufacturing, Marysville, Ohio; Sadeghipour.2@osu.edu, Eric.Westervelt@ge.com, Shubho_Bhattacharya@ham.honda.com.

[1] Since English units are the HVAC industry's standard system of measurement, all charts, equations, and data presented in this paper are given in these units instead of their SI counterparts.

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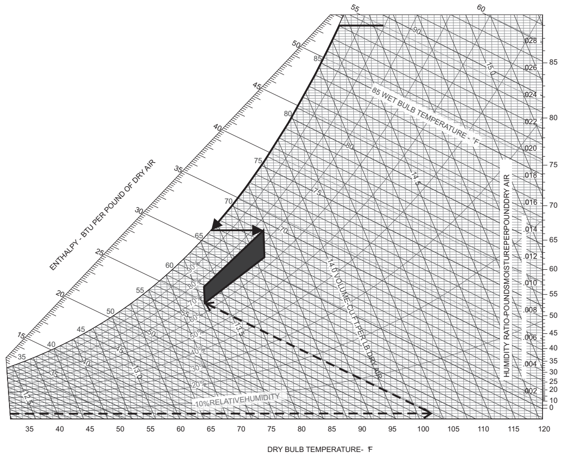


Fig. 1. A psychrometric chart for sea-level atmospheric pressure with possible incoming air states and the corresponding conditioning requirements. The solid lines represent the summer trajectory, and the dashed lines represent the winter trajectory. Figure courtesy of Heatcraft.

the partial pressure that it would have at that temperature if its state was on the saturation line.

Wet-bulb temperature is the temperature that a thermometer would show if its bulb was covered by a wet cloth. Therefore, wet-bulb temperature is different than dry bulb temperature as it is dependant on air humidity. Drier weather leads to cooling through evaporation, which results in a lower wet-bulb temperature. Similarly, more humid weather leads to less evaporation through cooling, which results in a higher wet-bulb temperature. Constant wet-bulb temperature lines are straight lines from the upper left side of the chart to the lower right side. Specific enthalpy, denoted by h, is the sum of the internal and flow energies of an air-vapor mixture. Specific enthalpy has units of energy per mass of dry air[2]. Constant specific enthalpy lines are almost parallel with constant wet-bulb temperature lines; therefore, these lines are often used interchangeably when delineating partitions of the psychrometric chart.

Sensible cooling corresponds to moving to the left on the psychrometric chart; sensible heating corresponds to moving to the right; and evaporative cooling corresponds to moving to the upper left along constant wet-bulb temperature lines. Evaporative cooling through a wet wall is the type of humidification that was used in the HVAC system that was studied. Steam humidification is another common method used in other HVAC systems. Steam humidification corresponds to the state of the air-vapor mixture moving up almost vertically on the psychrometric chart, with a limited amount of moving right due to sensible heating. For example, for a mass flow rate of 2,900 lbda per minute, adding 32.2 pound mass of steam per minute will cause roughly 3°F of sensible heating. If an air-vapor mixture is cooled to 100% relative humidity, dehumidification will occur, and its state will move down along the 100% relative humidity curve.

[2]Many thermodynamic quantities are given in units that are defined in terms of per unit mass of the flowing fluid, which in psychrometrics is often per pound mass of dry air (lbda).

For example, suppose the outside air conditions are those of a hot and humid day: 95°F and 80% relative humidity. To reach a point on the outer boundary of the target region, the incoming air must be cooled to the 100% relative humidity line, dehumidified to the same humidity ratio as the top of the target window, and then heated to reach that point (see Fig. 1). As another example, suppose the outside air conditions are those of a cold and dry day: 32°F and 10% relative humidity. To reach a point on the outer boundary of the target region, the incoming air must be heated to the same wet-bulb temperature as the bottom of the target window, and then humidification through evaporative cooling will bring the state of the air-vapor mixture to the state of that point (see Fig. 1).

Depending on the specifications of an HVAC system, measurements of values such as specific enthalpy h and humidity ratio ω may be unavailable or difficult to obtain; therefore, one can use curve-fit equations offered in [2, Chp. 6] to calculate these variables from simpler measurements such as dry bulb temperature t_{db}, relative humidity ϕ, and pressure. The following equations were instrumental in implementing the analysis presented in this paper:[3] The partial pressure of saturated water vapor may be calculated as a function of dry bulb temperature t_{db} by

$$p_{\mathrm{ws}}(t_{\mathrm{db}}) = \exp\left(\frac{C_1}{t_{\mathrm{db}}} + C_2 + C_3 t_{\mathrm{db}} + C_4 t_{\mathrm{db}}^2 \right. \\ \left. + C_5 t_{\mathrm{db}}^3 + C_6 t_{\mathrm{db}}^4 + C_7 \ln t_{\mathrm{db}}\right) \quad (1)$$

where coefficients C_1 to C_7 may be found [2]. The humidity ratio at water vapor saturation may be calculated as a function of dry bulb temperature t_{db} and relative humidity ϕ as

$$\omega_{\mathrm{s}}(t_{\mathrm{db}}, \phi) = \frac{0.62198\, \phi\, p_{\mathrm{ws}}(t_{\mathrm{db}})}{p - \phi\, p_{\mathrm{ws}}(t_{\mathrm{db}})} \quad (2)$$

where p is the atmospheric pressure. The product of humidity ratio at saturation ω_{s} and relative humidity ϕ yields the actual humidity ratio ω. Specific enthalpy as a function of dry bulb t_{db} and relative humidity ϕ is given by

$$h(t_{\mathrm{db}}, \phi) = 0.240\, t_{\mathrm{db}} + \omega(t_{\mathrm{db}}, \phi)(1061 + 0.444\, t_{\mathrm{db}}). \quad (3)$$

III. Configuration of the Paint Booth System

Although the control principles suggested in this paper may be applied to a variety of HVAC systems, it is instructive to consider the specific attributes of the HVAC system that was studied. A schematic of the paint booth of the plant that was studied is provided in Fig. 2 and details of the HVAC system's conditioning units are given in Fig. 3. The system operates as follows: Outside air is conditioned in Unit 1. This unit conditions the outside air to a desired state using its four conditioning devices: a preheat gas burner, cooling coils, a wet wall, and a reheat gas burner. After the air passes through Painting Area 1 it is scrubbed, conditioned in Unit 2, and then used in Painting Area 2. After passing

[3]Dry bulb temperature t_{db} is measured here in degrees Rankine.

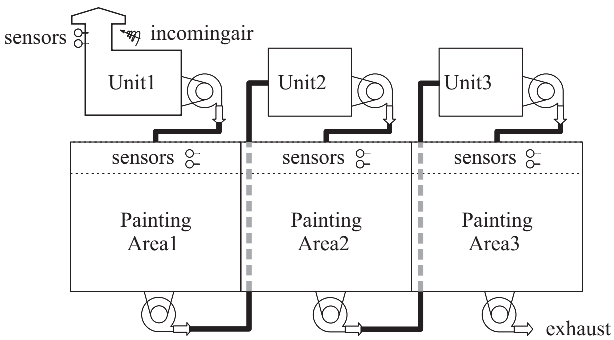
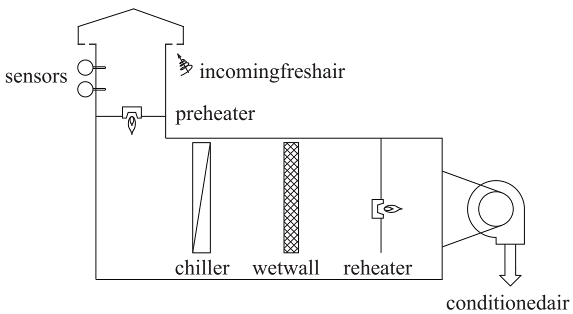
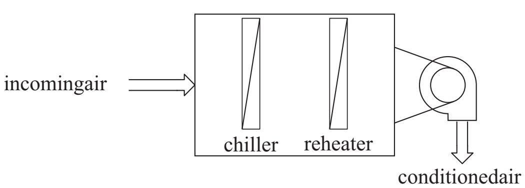


Fig. 2. Architecture of the automotive plant paint booth HVAC system under study. The paint booth is divided into three painting areas. The incoming air is conditioned by Unit 1 and recycled twice before being exhausted. Units 1 and 2 recondition the air before recycling. Sensors are installed to measure dry bulb temperature and relative humidity of the incoming fresh air stream and in the booth plenums. Details of Units 1, 2, and 3 are given in Fig. 3.



(a) Unit 1



(b) Units 2 and 3

Fig. 3. Details of the automotive plant paint booth supply air house HVAC system under study. The energy required by the reheaters of Units 2 and 3 is supplied via hot water.

through Painting Area 2 it is scrubbed again, conditioned in Unit 3, used in Painting Area 3, and finally pumped out of the plant as exhaust. Scrubbing refers to the process of removing overspray residue from the air. Scrubbing is usually performed by flooding the sub-floor of the booth with water.

Units 2 and 3 condition air that has been recycled from either of the first two painting areas of the paint booth using heating coils and cooling coils. Since these units do not contain devices that can add water vapor, the units can only bring the state of the air to the desired state through sensible heating, sensible cooling, or dehumidification, and not through humidification. Additionally, since the air has already been conditioned in Unit 1, most of the change in the state of the air between consecutive painting areas is caused by the process of scrubbing. Considering that the air is cleaned using running water, the psychrometric effect of scrubbing is much like the effect of a wet wall, as the air is humidified along lines of constant wet bulb temperature. Most of the energy costs of the system are incurred in bringing the state of the outside air to a state in the target window; therefore, almost all of the savings take place in Unit 1, and the analysis is focused in that area.

It is important to note that the conditioning devices of an HVAC system are sized for the given local geographic climatic conditions and desired air conditions of the system's output. Since using conditioning devices with excess capacity results in higher initial HVAC system cost and potentially higher operating costs, the conditioning devices are often sized to have only enough capacity to be able to condition the air for typical incoming air condition extremes. Therefore, when designing a cost-minimization strategy that changes the setpoint of an HVAC system, the capacities of the conditioning devices must be considered—when choosing the conditioning processes of a system, the designer should consider capacity limits and ensure that the corresponding trajectories are realizable.

IV. Control for Cost Minimization

Just as the target window corresponds to a region on the psychrometric chart, control strategies for different air conditions also correspond to different regions on this chart. These regions may be delineated by psychrometric quantities such as temperature, relative humidity, and humidity ratio.

A. Calculating Optimal Partitioning

Most existing paint booth HVAC controls, including the original controls for this system, operate with a fixed setpoint for the state of the conditioned air [3], [4, Chp. 5]. The strategy proposed in this work makes the setpoint a function of the state of the incoming air. The setpoint is varied to minimize the energetic and financial costs of conditioning the air while meeting the air conditions required by the paint manufacturer.

1) Partitioning for Unit 1: After defining the target window of the HVAC system, the next step is to determine for each possible state of the incoming air the least fiscally (or energetically) expensive combination of conditioning processes that will bring the state of the air to a point on the target window. For example, if the state of the incoming air is at a point to the lower right hand side of the target window, its state can reach the target window through humidification, sensible cooling, or a combination of the two.

When determining the least expensive strategy, the unit price of each process is required. At the time that this work was completed, the cost per Btu of heating was approximately three times more expensive than that of cooling. The cost of humidification using a wet wall was negligible, which meant that humidification was the conditioning process of choice wherever it could be used.

To calculate the optimal partitioning, the psychrometric chart was divided into a fine grid. Using an understanding of the plant's HVAC system, as well as comparing the costs of different conditioning processes, the least costly conditioning

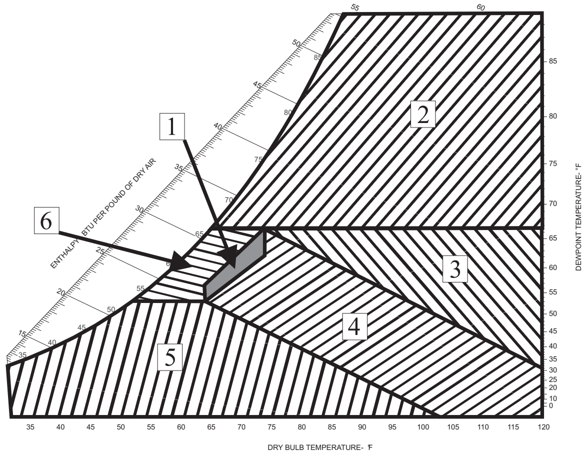


Fig. 4. Partitioning for the control strategy of Unit 1

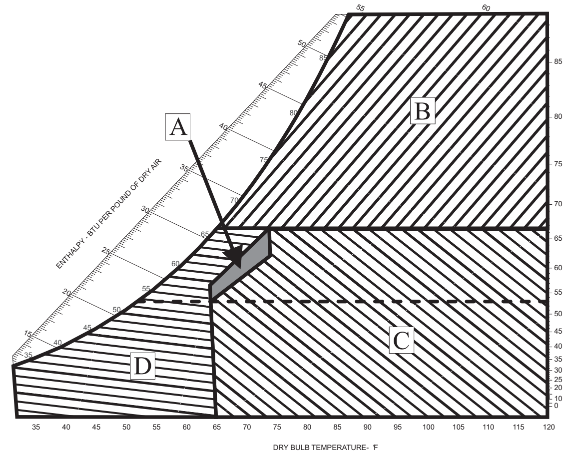


Fig. 5. Partitioning for the control strategy of Units 2 and 3

strategy was determined for each point on the grid. After performing the analysis, the points on the psychrometric chart with the same conditioning strategy were grouped into six distinct areas; see Fig. 4. The points in region 1 fall in the target window, where no conditioning is required. The points in region 2 need to be cooled and dehumidified to reach the humidity ratio of the top of the window, and then the air must be reheated to reach the temperature of the top of the target window. The points in region 3 must be cooled to the same wet-bulb temperature as the top of the target window, and then evaporative cooling must take place to bring the state of the air to the top of the target window along the lines of constant wet-bulb temperature. The points in region 4 must be humidified using evaporative cooling to bring their state to a point on the right or lower right side of the target window. The points in region 5 must be preheated to the same wet-bulb temperature as the bottom point on the target window, and then evaporative cooling must take place to bring their state to the bottom point of the target window. Finally, the points in region 6 must be preheated or reheated to bring their state to a point on the left or upper left side of the target window.

2) Partitioning for Units 2 and 3: Units 2 and 3 condition to the same target window as Unit 1. However, as previously mentioned, the conditioning devices in Units 2 and 3 are different than the devices in Unit 1; therefore, the strategies developed for these units are also different (see Fig. 5).

If the state of the unit's incoming air falls in region A, then no conditioning is required. If the state falls in region B, then cooling, dehumidification, and reheating are required to reach the top of the target window. For states that fall in region C, sensible cooling is required to reach the boundary of the target window. For region D, sensible heating is required. It is important to note that because of the units' lack of humidification devices, if the humidity ratio of the incoming air is less than the humidity ratio of the bottom of the target window, the target window cannot be reached. For the HVAC system under study, it was chosen to use sensible heating or cooling in these cases to bring the temperature of the air to the temperature of the bottom point of the target window. However, these cases are unlikely because of the humidification that occurs during scrubbing.

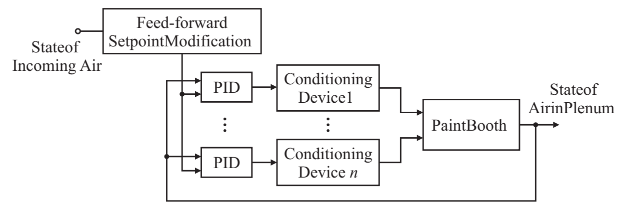


Fig. 6. Block diagram of proposed control strategy

B. Controlling the HVAC System

The developed control algorithm adaptively changes the setpoints of the units based on the state of the outside air to minimize cost; see Fig. 6. As is the case with most HVAC systems, PID controllers are used to regulate the individual conditioning devices. The PID controllers are tuned to act primarily as integral controllers since the state of the outside air is slowly varying; that is, the system's conditioning processes operate at quasi-steady state.

Implementation of the strategy proposed here can be cumbersome on a system controlled by a programable logic controller (PLC), like the system under study. The ladder logic used to program PLCs is not amenable to implementing complex calculations such as those required by this strategy to convert between psychrometric quantities. Conversion between psychrometric quantities is required because most HVAC systems, including the one under study, measure only two psychrometric quantities, such as temperature and relative humidity, yet the six psychrometric regions of the strategy are delineated by four quantities: dry bulb temperature, relative humidity, wet-bulb temperature and humidity ratio. Relations such as equations (1), (2), and (3) may be used to convert between these quantities. However, most of the relations are nonlinear and several involve curve-fits to empirically-measured quantities. Moreover, calculating wet-bulb temperature given any other pair of psychrometric quantities is especially difficult since it requires root finding.

TABLE I
UNIT 1 DEVICE CONTROLS

	First Device		Second Device		Third Device	
	Action	Setpoint	Action	Setpoint	Action	Setpoint
Region 1	-	-	-	-	-	-
Region 2	Chill	ω	Reheat	$t_{\rm db}$	-	-
Region 3	Chill	$t_{\rm db}$	Humidify	h	-	-
Region 4	Chill	$t_{\rm db}/\omega$	Humidify	$t_{\rm db}/\phi$	Reheat	$t_{\rm db}$
Region 5	Preheat	h	Humidify	ω	Reheat	$t_{\rm db}$
Region 6	Chill	ω	Reheat	$t_{\rm db}/\phi$	-	-

TABLE II
UNITS 2 AND 3 DEVICE CONTROLS

	First Device		Second Device	
	Action	Setpoint	Action	Setpoint
Region A	-	-	-	-
Region B	Chill	ω	Heat	$t_{\rm db}$
Region C	Chill	$t_{\rm db}/\phi$	-	-
Region D	Heat	$t_{\rm db}/\phi$	-	-

TABLE III
CURRENT WARM AND HUMID CONDITION TRAJECTORY

	Dry Bulb T (°F)	Relative Humidity (%)	Specific Enthalpy (Btu/lbda)	Energy Change (Btu/lbda)
State 1	95.00	80.00	54.71	
State 2	59.83	100.00	26.29	28.41
State 3	70.00	70.00	28.76	2.47
			Total energy expended	**30.88**

The difficulty of programming these relations in ladder logic makes implementation of the algorithm cumbersome.

Since lines of constant enthalpy and constant wet-bulb temperature are nearly parallel on the psychrometric chart, enthalpy was used in place of wet-bulb temperature as it is easier to calculate. As demonstrated in (3), enthalpy may be calculated as a function of dry-bulb temperature $t_{\rm db}$ and relative humidity ϕ. In this case, the humidity ratio at water vapor saturation $\omega_{\rm s}$ function was implemented as a look-up table, instead of using (2). Humidity ratio was also used to delineate the horizontal lines of the conditioning strategies graphs (see Figs. 4 and 5).

Tables I and II present the devices and types of setpoints needed to implement the proposed strategies for each psychrometric region. For the Unit 1 strategy, no conditioning is required in region 1. In region 2, the chiller uses humidity ratio as its setpoint, and the reheater uses dry bulb temperature. In region 3, the chiller uses drybulb temperature as its setpoint, and the humidifier uses enthalpy. In region 4, the chiller uses dry bulb temperature or humidity ratio as its setpoint, the humidifier uses dry bulb temperature or relative humidity, and the reheater uses drybulb temperature. In region 5, the preheater uses enthalpy as its setpoint, the humidifier uses humidity ratio, and the reheater uses drybulb temperature. In region 6, the chiller uses humidity ratio as its set point, and the reheater uses dry bulb temperature or relative humidity. In each case, the devices that have not been mentioned are turned off.

For the strategies of Units 2 and 3, no conditioning is required in region A. In region B, the chiller uses humidity ratio as its setpoint, and the heater uses dry bulb temperature. In region C, the chiller uses dry bulb temperature or relative humidity as its setpoint. In region D, the heater uses dry bulb temperature or relative humidity as its setpoint. As before, the devices that have not been mentioned are turned off.

There is also certainly a danger in creating such a stringent set of conditioning policies for each area on the psychrometric chart, since there is only a fine line between implementing two completely different conditioning strategies. For example, regions 2 and 6 are separated only based on whether or not the humidity ratio of the incoming air exceeds the humidity ratio of the top point of the target window. If its humidity ratio exceeds this value, the air must be cooled, whereas if it does not exceed this value, the air must be heated. Therefore, another important aspect of the development of the improved algorithm is to use hysteresis or a timer delay when switching between regions. Using hysteresis or a timer delay means that the various conditioning systems within the HVAC of the paint booth will not continuously toggle between on and off because of fluctuations of the state of the incoming air on the border of two different regions. Although such a capability may not necessarily add to the efficiency of the system, it will nevertheless save money by avoiding the unnecessary wearing of the conditioning devices.

Additionally, some of the processes involved in the strategy have been added to increase the robustness of the system. For example, although as mentioned earlier the main conditioning process for incoming air in region 6 is heating, the chiller is also turned on in that region. However, the setpoint of the chiller is set so that it does not condition the air unless the humidity ratio in the plenum exceeds the humidity ratio of the top of the target window. In such a case, even with an incoming air state in region 6, the chiller will dehumidify the air to bring its plenum state back to the target window. Processes for other regions have also been added to increase the robustness of the system.

C. Estimated Energy Savings

Before implementing the proposed control strategy, the psychrometric relations of [2, Chp. 6] may be used to estimate the energy savings that will result from applying the strategy. Consider again a warm and humid day at 95°F and 80% relative humidity, and a cold and dry day at 32°F and 10% relative humidity. Based on the proposed partitioning of the psychrometric chart, the setpoint on the warm and humid day will be 75°F and 75% relative humidity instead of the standard 70°F and 70% relative humidity. Similarly,

TABLE IV

PROPOSED WARM AND HUMID CONDITION TRAJECTORY (REGION 2)

	Dry Bulb T (°F)	Relative Humidity (%)	Specific Enthalpy (Btu/lbda)	Energy Change (Btu/lbda)
State 1	95.00	80.00	54.71	
State 2	66.58	100.00	31.22	23.49
State 3	75.00	75.00	33.27	2.05
			Total energy expended	**25.54**

TABLE V

CURRENT COLD AND DRY CONDITION TRAJECTORY

	Dry Bulb T (°F)	Relative Humidity (%)	Specific Enthalpy (Btu/lbda)	Energy Change (Btu/lbda)
State 1	32.00	10.00	8.08	
State 2	116.08	0.01	28.43	20.34
State 3	70.00	70.00	28.76	0.33
			Total energy expended	**20.68**

during the cold and dry day the setpoint will be 65°F and 65% relative humidity instead of the aforementioned standard setpoint.

Significant savings are observed when comparing Table III with Table IV, as well as Table V with Table VI. These savings become even more pronounced when keeping in mind the enormous mass of air that circulates through the system almost continuously throughout the year. For a summer month with an average of 95°F and 80% relative humidity, at a mass flow rate of 2,900 lbda per minute, this difference in strategy translates into an energy savings of 40.9×10^7 Btu. For a winter month with an average of 32°F and 10% relative humidity, at the same mass flow rate, the difference in strategy produces an energy savings of 29.6×10^7 Btu. To put these energy savings into perspective, based on a report by the Energy Information Administration, the total monthly electrical energy consumption of an average American household is 31.3×10^5 Btu [1]. Therefore, the energy savings in Unit 1 alone are equivalent to the total electrical energy use of hundreds of households.

TABLE VI

PROPOSED COLD AND DRY CONDITION TRAJECTORY (REGION 5)

	Dry Bulb T (°F)	Relative Humidity (%)	Specific Enthalpy (Btu/lbda)	Energy Change (Btu/lbda)
State 1	32.00	10.00	8.08	
State 2	100.48	0.01	24.69	16.60
State 3	65.00	65.00	24.89	0.21
			Total energy expended	**16.81**

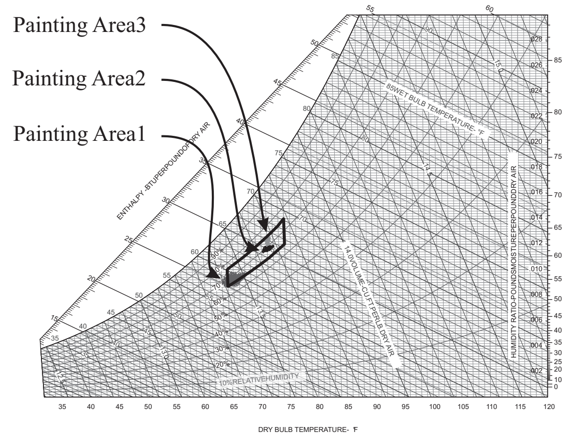


Fig. 7. State of air from painting areas operating for 48 hours with the proposed strategy.

V. RESULTS

This proposed control system is currently being implemented at a Honda of America Manufacturing (HAM) automotive plant. Results for 48 hours of operation for painting areas 1, 2, and 3 are presented in Fig. 7. The plot shows the state of the air in each plenum. In the figure, some data points appear inside the target window as opposed to the edges of that window. This occurrence is due to the decision of Honda engineers to begin implementation of the new algorithm with a smaller target window and to gradually increase that size.

The estimated savings are a decrease of 22% in annual HVAC utility costs, and a 24% annual reduction in carbon dioxide emissions from natural gas combustion.

VI. CONCLUSIONS

Two of the pressing challenges of the new millennium are the depletion of the world's natural resources and the adverse effects of man-made contributions to global warming. This study makes use of the temperature and relative humidity tolerances provided by paint manufacturers to condition paint booth air to a target window as opposed to a setpoint. The control strategy developed automatically uses the least expensive set of conditioning devices and set points given the current outside air conditions. The result is a closed-loop paint booth system that uses less energy, has decreased carbon dioxide emissions, and lower operating costs.

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