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Key words: environmental control, ship hull, painting, energy saving.

ABSTRACT

An integrated environment control system (IECS) is proposed to satisfy the requirements of IMO (International Maritime Organization) for ship hull painting. The IECS has four elements for environment control, namely, desiccant dehumidification, heating, cooling, and ventilation. Five operating modes are proposed, with each operating mode consists of one to more elements in the IECS system. Energy saving operating mode is selected based on the weather conditions and the conditions of painting work. Energy saving control strategy is applied to each operating mode. Theoretical energy models of the different operation modes are presented, along with the control schemes for the annual hourly operation. The calculation schemes presented include the energy performance for the elements of the integrated system, under different operating modes and operating conditions. The control strategy of the IECS system has been found to have the potential of 29.3% of energy saving against an actual painting plant that uses primarily desiccant dehumidifying system for environmental control.

I. INTRODUCTION

Ship hull is generally made of steel and has to be painted for protection against the electrochemical corrosion in sea. However the quality of painting especially the adherence of paint to the ship hull is affected greatly by the humidity of the ship hull painting environment. At higher humidity, dew can form at the work pieces of the ship hull and can have adverse effects on the painting quality. Therefore environmental control is necessary for high humid weather conditions to eliminate the possible dew formation at the surface of ship hull during the paint coating.

Due to the importance of the quality control for ship hull painting, the International Maritime Organization (IMO) announced in 2006 a performance standard for protective coatings [7]. In the mentioned standard, the operating environment of protective coating must be controlled to the following conditions:

(1) Relative humidity below 85%.
(2) The surface temperature of the work piece at least 3°C higher than the dew point of the surrounding air.

Combinations of refrigeration cooling, heating, ventilation and desiccant dehumidification are studied for satisfying the above requirements. Cooling by vapor compression refrigeration can remove water vapor through condensation. However vapor compression system is not effective in removing moisture when the air temperature is lower, especially during cooler seasons. This is due to the problem of operating with temperature near the freezing point. Therefore desiccant dehumidification is required for effective removal of water vapor for circumstances mentioned.

Often the combination of vapor compression cooling and desiccant dehumidification is advantageous to maintain a proper environment for paint coating. Literature can be found for the use of combined systems of vapor compression and desiccant dehumidification [1, 2, 10]. Some studies on the use of desiccant wheels can be found [3, 6, 8]. Also the performance of desiccant wheels is discussed by some researchers [4, 11, 12].

Energy consumption of desiccant dehumidification is an important concern in this study. Discussion on the energy consumption of desiccant dehumidification system can be found in some literatures [5, 9, 10]. However the energy saving control strategy of desiccant system in combination with vapor compression cooling has not attracted a broad interest. Therefore this study addresses the control strategy of applying

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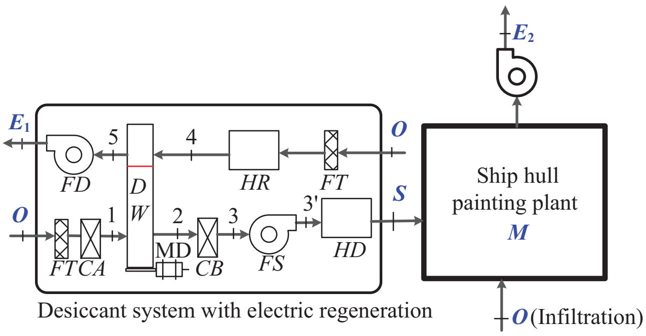

Fig. 1. The integrated environmental control system.

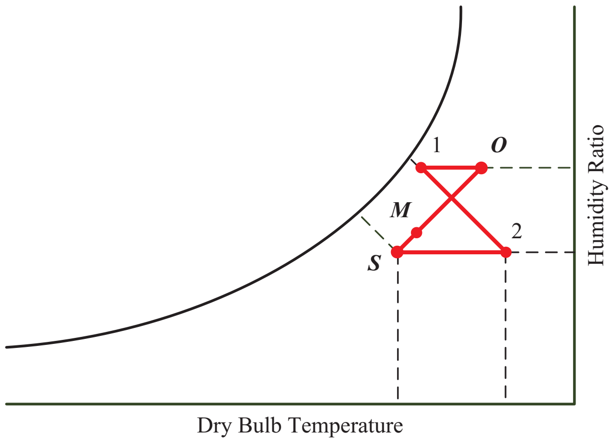

Fig. 2. The states of the process air.

desiccant systems in an integrated environmental control system (IECS) that consists of desiccant dehumidifying, vapor compression cooling, heating and ventilation, in different operating modes and control strategies.

A ship hull painting plant in northern part of Taiwan is used as a case study. The painting plant uses a desiccant system with electric heat regeneration. As much electric energy is used for long period of regeneration for the desiccant system, energy saving strategy is imperative. The total electricity consumption in 2008 is 4,680,476 kWh for the ship hull painting plant, including the power tools.

II. THE INTERATED SYSTEM FOR HULL PAINTING

The challenge for the ship hull painting plant is that due to the release of VOC gases from the coating, no recirculation of air is allowed. An integrated system is proposed and presented in Fig. 1. The outdoor air (***O***) enters and exhausts ($\boldsymbol{E_2}$) after used. In this application dryer air has to be supplied to the point of use where coating is being applied to the ship hull. In operation the exhaust volume ($\boldsymbol{E_2}$) is somewhat higher than the entering outdoor air (***O***), so to maintain a negative pressure in the painting plant (***M***).

It can be seen that the desiccant system is divided into the process and the regeneration sides. The process side of the desiccant wheel (*DW*) takes in outdoor air (***O***) through the filter (*FT*). A pre-cooling coil (*CA*) is put before the process side of the wheel. Pre-cooling may be advantageous to increase the capacity of dehumidification. The rotating wheel is driven by a motor (*MD*). A coiling coil (*CB*) is put after the desiccant wheel to cool down the air as adsorption heat is release during desiccant dehumidification. A supply fan (*FS*) is put before a heating element (*HD*). In the regeneration side a regeneration heater (*HR*) is used to raise the temperature of the regeneration air. The high temperature regeneration air would vaporize the adsorbed moisture in the desiccant wheel.

With the elements of the integrated system as described in Fig. 1, five modes of operations are possible as follows:

(1) Vapor compression cooling and desiccant dehumidification, used when the weather is hot and humid.
(2) Desiccant dehumidification, used when the weather is humid with moderate temperature.
(3) Ventilation, used when both the humidity and temperature of the outdoor air is low.
(4) Heating of air, used when the outdoor air temperature is low but with high humidity. In this mode heating the ventilation air is sufficient to lower the humidity for quality ship hull painting.
(5) Night operation with no paint job but to keep proper conditions so to avoid rusting spots on the ship hull pieces overnight.

For the process side, without the action of the heating element *HD*, the states of the process air can be represented by Fig. 2. The processes and the states can be described as follows:

(1) Air entering at state ***O*** undergoes pre-cooling (*CA*) to state 1. Lower the entering air temperature before the desiccant wheel would achieve higher dehumidification effects.
(2) The desiccant dehumidification process would release the heat of adsorption and hence cause a temperature increase of the air exiting the desiccant wheel, as the change in state from 1 to 2.
(3) When the weather is hot and humid, cooling after the desiccant wheel is needed so to maintain better comfortable working environment. The cooling would bring the state from 2 to S.
(4) The supply air would mix with the infiltration air and becomes state ***M***. State ***M*** has to satisfy the requirement of IMO [7].

III. THE PHYSICAL MODEL OF THE INTEGRATED SYSTEM

The physical model of the integrated system is represented by Fig. 3, composed of the elements as mentioned above.

Table 1. The operating strategy of the integration environmental control system.

The mode of operation	Process Side				Regeneration Side		
	Chiller A	Desiccant Wheel Motor	Chiller B	Supply Fan	Heater	Regeneration Heater	Regeneration Fan
	W_{CA}	W_{MD}	W_{CB}	W_{FS}	W_{HD}	W_{HR}	W_{FD}
Mode 1 Cooling and dehumidification	ON	ON	ON	ON		ON	ON
Mode 2 Dehumidification		ON		ON		ON	ON
Mode 3 Ventilation only				ON			
Mode 4 Heating only				ON	ON		
Mode 5 Night time dehumidification		ON		ON		ON	ON

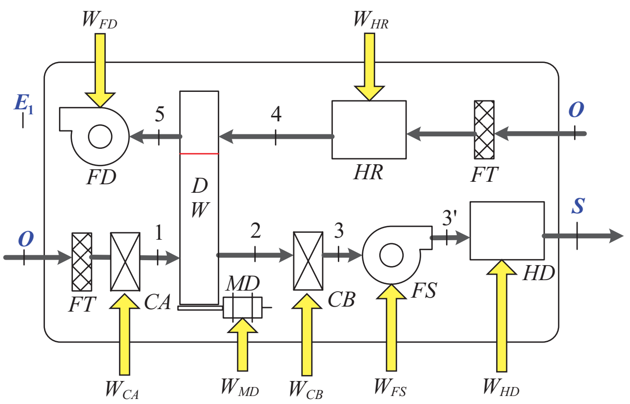

Fig. 3. The physical model of the integration dehumidification system.

The arrows shown represent the energy input into the elements: energy input to the fan (W_{FD}), energy input to the regeneration heater (W_{HR}), cooling input to the pre-cooling coil (W_{CA}), the desiccant wheel rotor (W_{MD}), cooling input to the cooling coil (W_{CB}), energy input to the fan (W_{FS}), and energy input to the heating element (W_{HD}).

1. Precooling Process

The precooling process has to consider the energy consumed by the refrigeration unit. The cooling input is determined by Eq. (1) with the energy input of the refrigeration unit determined by Eq. (2). Q_{CA} is the cooling capacity of *CA*, equal to the air flow rate multiplied by the enthalpy difference through the pre-cooling coil. The energy input to the refrigeration unit has to consider the coefficient of performance of the unit described in Eq. (2).

$$Q_{CA} = \dot{m}_{CA} \times (h_1 - h_0) \tag{1}$$

$$W_{CA} = \frac{Q_{CA}}{COP_{CA}} \tag{2}$$

2. The Dehumidifying Wheel

The energy input to the wheel is the regeneration heat, shown in Eq. (3). Outdoor air has to be heated to the regeneration temperature T_4.

$$Q_{HR} = \dot{m}_{HR} \times c_{HR} \times (T_4 - T_O) \tag{3}$$

Assume the efficiency of the heater is 1, the electricity input W_{HR} is equal to the heating capacity Q_{HR}, as shown in Eq. (4).

$$W_{HR} = Q_{HR} \tag{4}$$

For another cooling input for the cooling coil (*CB*), the energy input by the refrigeration unit are determined using Eqs. (5) and (6).

$$Q_{CB} = \dot{m}_{CB} \times (h_2 - h_3) \tag{5}$$

$$W_{CB} = \frac{Q_{CB}}{COP_{CB}} \tag{6}$$

Similarly for the heating element *HD*, the energy balance and the energy input are given by Eqs. (7) and (8).

$$Q_{HD} = \dot{m}_{HD} \times (h_S - h_3) \tag{7}$$

$$W_{HD} = Q_{HD} \tag{8}$$

The operating strategy is described in Table 1. The required energy inputs to the different elements under different operating modes are given in Table 1. The different modes of operation are represented by the on and off control of these elements as shown in Table 1.

The energy input of the each mode of operations is equal to the sum of that of the elements switched on, presented in Eqs. (9)-(12).

Table 2. Energy saving operation strategy for different weather conditions.

	Weather conditions	Control strategy	Mode and Functions
1	Outdoor air temperature exceeds 28°C	Set the painting plant at temperature 27°C and $\varphi = 75\%$.	Mode 1 Desiccant and refrigeration units both in operation, with both cooling coils in operation.
2	Outdoor air lie between 16°C and 28°C, with $\varphi > 80\%$	Painting plant controlled at relative humidity below 75%.	Mode 2 The dehumidifying rotor is used to maintain the φ.
3	Outdoor air lie between 16°C and 28°C, with $\varphi < 80\%$	Introduction of outdoor air is sufficient to maintain the painting at condition 3 of Fig. 5.	Mode 3 Only fan operation.
4	Outdoor air lie between 8°C and 16°C, with $\varphi > 80\%$	Heat the air to lower φ, and maintain φ below 75% in the painting plant.	Mode 4 Outdoor air heated by heater *HD* to at least 4°C above ambient.
5	When the outdoor air lie between 8°C and 16°C, with $\varphi < 80\%$	Maintain comfort condition in the painting plant.	Mode 4 Outdoor air heated by the heater *HD*.
6	Nocturnal or no painting work	No consideration for comfort but maintain the painting plant at 75%.	Mode 5 Dehumidification system turned on when necessary.

(1) Cooling and dehumidification:

$$W_1 = W_{CA} + W_{CB} + W_{MD} + W_{FS} + W_{HR} + W_{FD} \tag{9}$$

(2) Dehumidification:

$$W_2 = W_{MD} + W_{FS} + W_{HR} + W_{FD} \tag{10}$$

(3) Ventilation only:

$$W_3 = W_{FS} \tag{11}$$

(4) Heating only:

$$W_4 = W_{FS} + W_{HD} \tag{12}$$

(5) Night time dehumidification: same as dehumidification.

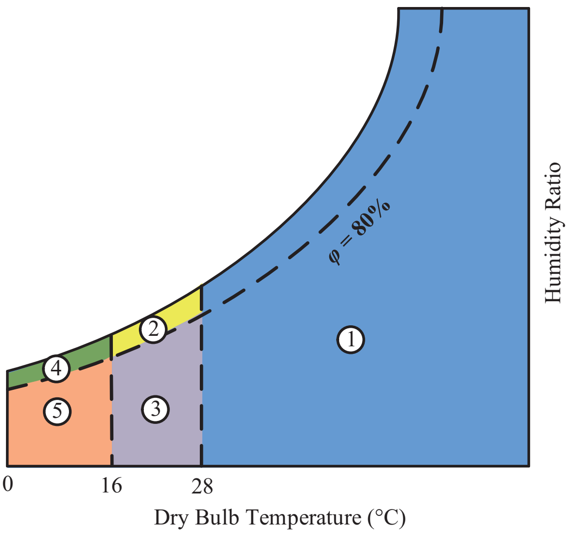

Fig. 4. The integrated system operates in five different weather zones.

3. Energy Saving Control Strategy

The control of the operating modes has to consider the outdoor air temperature and humidity so to conserve energy while satisfying the IMO [7] requirements. Although the relative humidity is required at 85%, the setting for the painting plant is 75% as an allowance for control range. When the relative humidity is above the setting point, dehumidification or cooling is needed to condition the air to the required conditions.

Other considerations are as follows:

(1) The summer air temperature in the painting plant is set at 28°C during work hours. This is not normally provided for such work environment but considered in this study. Therefore the refrigeration unit has to be turned on when the temperature exceeds 28°C.
(2) When the outdoor air temperature is between 16 to 28°C, and when the relative humidity is low enough, ventilation of outdoor air can maintain proper conditions in the painting plant.

During the cooler winter months in Taiwan, the lower temperature setting is 16°C. The heater *HD* is used to maintain the temperature above 16°C but below 20°C.

4. The Weather Zones and the Control Strategies

The integrated system operates in the weather zones represented by 1 to 5 in Fig. 4. Zone 1 represents weather conditions with higher temperature. Zone 2 represents relative humidity above 80% but at moderate temperature. Zone 3 has moderate temperature and humidity. Zone 4 represents weather conditions with lower temperature (<16°C) and relative humidity above 80%. Zone 5 represents weather conditions with low temperature (<16°C) and relative humidity below 80%. The operating strategies corresponding to the different weather conditions are described in Table 2.

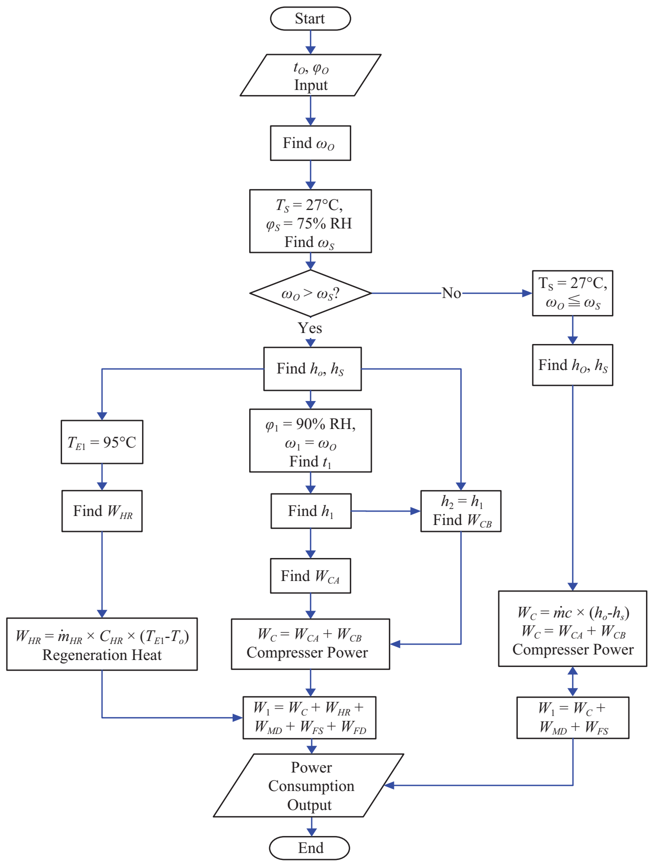

Fig. 5. The determination of dehumidification energy.

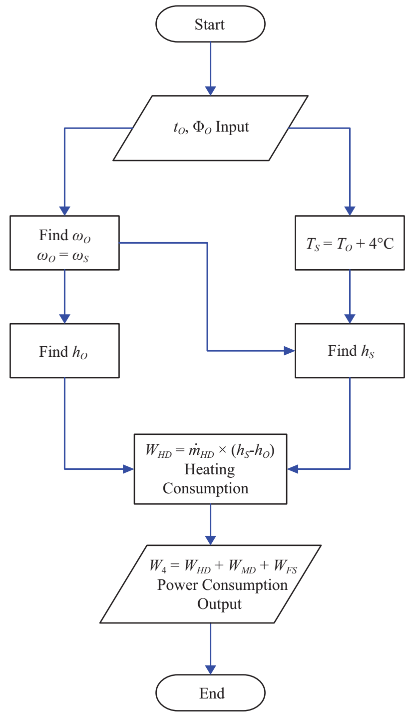

Fig. 6. The determination of heating energy.

5. The Analysis of Energy Conservation

The following steps are used to determine the energy consumption of the integration environmental control system, also presented in Fig. 5. The states of the air are referred to Fig. 3.

(1) The real time hourly outdoor air temperature t_o and relative humidity φ_o are used as the input, and for the computation of humidity ratio ω_O.
(2) For a setting of 27°C and 75% RH in the painting plant, compute the corresponding humidity ratio ω_S.
(3) Compare ω_O and ω_S to decide if dehumidification is required.
(4) In step 3, if $\omega_O > \omega_S$, then proceed to dehumidification and cooling processes.
(5) In step 3, if $\omega_O \leqq \omega_S$, then proceed to cooling process, the enthalpy of the supply air h_S and the enthalpy of the outdoor air h_O are then computed, and then determine the refrigeration energy to cool the supply air to 27°C.
(6) In step 3, when both dehumidification and cooling are needed, the energy consumption for both processes have to be separately calculated.
(7) The enthalpies of the supply air h_S and the outdoor air h_O computed in step 5 are used.
(8) The supply air from the cooling coil is set at RH 90% (sensible cooling) at state 1 ($\omega_1 = \omega_o$), compute the air enthalpy at the coil outlet, then from the enthalpy difference compute the corresponding compressor power.
(9) For the dehumidification process, use a regeneration temperature at 95°C for computing the regeneration heat.
(10) For the case with only cooling, the power consumption consists of the cooling unit and the fans.
(11) For the case with cooling and dehumidification, the power consumption is the sum of both systems.

6. The Dehumidifying Wheel

The hourly ambient temperature and humidity are required for the computation of regeneration heat required. It can be seen in the psychrometric chart (Fig. 4) that the temperature difference between the saturation curve and the 85% relative humidity line is about 3°C. Therefore relative humidity of 85% would approximately meet the requirement as stated by IMO that the hull surface temperature be 3°C higher than the dew point of the air in the painting site. For marginal control, it is proposed here that the relative humidity of the supply air be controlled at 75% as mentioned above. Heating is required when the temperature is low but with higher humidity. The heater (*HD*) after the cooling coil then has to increase the temperature of the supply air until the relative humidity can meet the required setting as mentioned above. The energy saving control scheme is shown in Fig. 6.

IV. ANNUAL ENERGY ANALYSIS FOR ENVIRONEMENTAL CONTROL

The weather year of 2008 is applied to a typical ship hull

Table 3. The number of hours per year for the five modes of operation.

Month	Work Hours (8:00~12:00, 13:00~17:00)				No Work Hours
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
	$t_o \geqq 28°C$	$16°C < t_o < 28°C$	$16°C < t_o < 28°C$	$t_o \leqq 16°C$	$t_o \leqq 16°C$
		$\varphi_o > 80\%$	$\varphi_o < 80\%$	$\varphi_o > 80\%$	$\varphi_o > 80\%$
Jan	0	62	90	127	295
Feb	0	25	120	116	333
Mar	1	44	231	3	295
Apr	21	66	176	7	26
May	104	31	144	0	0
Jun	193	29	48	0	0
Jul	259	20	0	0	0
Aug	275	2	2	0	0
Sep	183	56	31	0	0
Oct	25	82	172	0	0
Nov	12	82	176	0	24
Dec	0	37	227	15	120
Total hours	**1073**	**536**	**1417**	**268**	**1093**
Percent (%)	**24.5**	**12.2**	**32.3**	**6.1**	**24.9**

Table 4. The computed results of energy consumption.

The Mode of Operations	1	2	3	4	5	Energy Consumption (kWh)
	Cooling and Dehumidification	Dehumidification	Ventilation only	Heating only	Night time Dehumidification	
Outdoor Condition	$t_o \geqq 28°C$	$16°C < t_o < 28°C$ $\varphi_o > 80\%$	$16°C < t_o < 28°C$ $\varphi_o < 80\%$	$t_o \leqq 16°C$ $\varphi_o > 80\%$	$t_o \leqq 16°C$ $\varphi_o > 80\%$	
Jan	0	51,455	9,072	25,401	124136.0	210,064
Feb	0	20,942	12,096	23,252	140126.4	196,417
Mar	51	36,651	23,285	598	124136.0	184,722
Apr	4,286	53,752	17,741	1,397	10940.8	88,116
May	47,987	24,651	14,515	0	0.0	87,153
Jun	139,331	22,767	4,838	0	0.0	166,937
Jul	219,086	15,192	0	0	0.0	234,278
Aug	220,129	1,538	202	0	0.0	221,868
Sep	133,521	43,303	3,125	0	0.0	179,949
Oct	10,485	63,739	17,338	0	0.0	91,562
Nov	9,870	64,369	17,741	0	10099.2	102,079
Dec	0	30,588	22,882	2,994	50496.0	106,959
Amount	**784,747**	**428,948**	**142,834**	**53,643**	**459,934**	**1,870,105**
Percent (%)	**42.0**	**22.9**	**7.6**	**2.9**	**24.6**	**100.0**

painting in Taiwan. The hourly temperature and humidity data for the year are used in the analysis. The painting job is assumed to be done in work hours 8:00~12:00 am and 13:00~17:00 pm.

With the weather data known and the work hours set, number of hours per year for the five different modes of environment control can be calculated. The results are shown in Table 3.

With the results as presented in Table 3, the monthly energy consumption for the five different modes of operation of the integrated environment control system can be computed with the schemes as presented in Figs. 5 and 6. The computed results are shown in Table 4.

It can be seen that environmental control for non-work hours constitutes about 24.6% of the total energy, mostly from January to March. Dehumidification of the supply air for

Table 5. The total power use in the painting plant.

Equipment	Capacity (kW/set)	Quantity	Amount (kW)	Demand Factor (%)	Energy consumption Per hour (kWh)	Percent (%)
Air Compressor	262.5	2	525	60	315	15.1
Air Compressor	131.0	1	131	60	79	3.8
Cleaning Filtration System	187.5	2	375	60	225	10.8
Sand Blasting Equipment	112.5	2	225	60	135	6.5
Sand Blasting Equipment	75.0	2	150	60	90	4.3
dehumidification system 1, 2, 3	438.7	3	1316			37.9
dehumidification system 4	523.6	1	524			15.1
Exhaust Fan 1, 2	114.3	2	229	70	160	6.6
Amount			**3474**			**100.0**

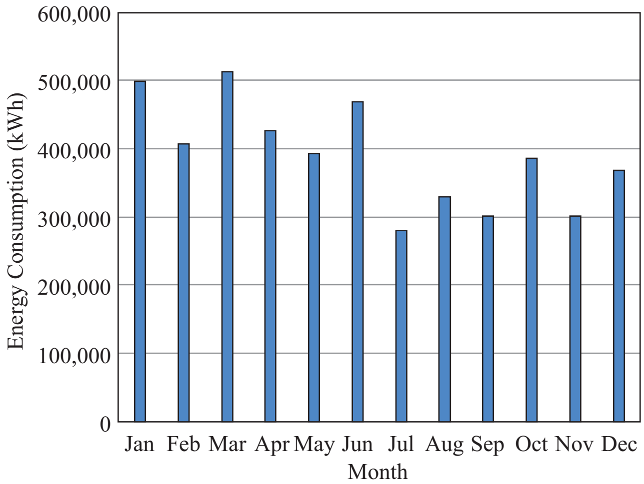

Fig. 7. The monthly energy use distribution for the painting plant.

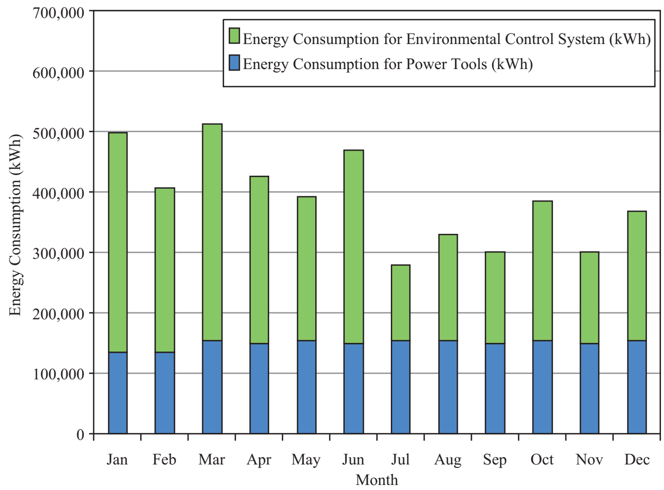

Fig. 8. The power use of the integrated dehumidification system.

work hours is also a major energy item; the percentage is about 22.9%. Both dehumidification and cooling are required to meet IMO requirement and to maintain comfort for warmer months between May and September. This would constitute about 42% of total energy. Heating and ventilation constitute the rest of the energy use. The month of August requires the least dehumidification as the relative humidity is lower.

1. A Case Study of Painting Plant

The example case of the painting plant consumed about 4,680,476 kWh of electric power in the year of 2008. The monthly energy distribution is shown in Fig. 7.

The total power use would include the power tools and the integrated environmental control system, as shown in Table 5. The power tools include the air compressors, dust filters, sand suction, and exhaust fans. The power tools operate constantly and not influenced by the ambient conditions. Therefore the power consumption of these power tools can be calculated and deducted from the total power so to obtain the power use of the integrated environmental control system. The calculated results of the total plant power and the power use of the integrated environmental control system are presented in Fig. 8. It can be seen that the power use of the integrated system varies with different months of the year.

2. The Evaluation of Energy Saving for the Integrated Environmental Control System

The comparison between the energy saving control strategy with the actual case is shown for each month in Table 6 and Fig. 9. It can be seen that for the months of January to June, the energy saving due to the energy saving control strategy ranges from 15.5% to 41.4%. For the months of October to December, the energy saving due to the energy saving control ranges from 12.2% to 32.3%. However for the months of July to September, the energy use exceeds the actual case by 44.1%, 18.4% and 13.1% respectively. This is due to air-conditioning provided to maintain the temperature below 28°C for comfort working environment. There is no air-conditioning provided for summer months for the actual case studied. This study includes the air-conditioning setting at 28°C in summer to enhance the comfort of the workers, therefore has additional energy use for air-conditioning.

The operating strategy as adopted by this study is found to save energy by the amount of 844,950 kWh annually or 18.1%

Table 6. The comparison between IECS with energy saving control to the actual case.

Month	Total Energy Consumption (kWh)	Power Tools Energy Consumption (kWh)	Dehumidification Energy for the Actual Case (kWh)	IECS with Energy Saving Strategy (kWh)	Energy Saving (kWh)	Energy Saving Ratio (%)
Jan	499,368	134,976	364,392	222,864	-141,528	-28
Feb	407,186	134,976	272,210	209,217	-62,993	-15
Mar	513,112	155,222	357,890	199,442	-158,448	-31
Apr	427,539	148,474	279,065	102,196	-176,869	-41
May	393,506	155,222	238,284	101,873	-136,410	-35
Jun	469,945	148,474	321,471	181,017	-140,455	-30
Jul	280,499	155,222	125,277	248,998	123,721	44
Aug	330,785	155,222	175,563	236,588	61,026	18
Sep	302,806	148,474	154,332	194,029	39,697	13
Oct	386,007	155,222	230,785	106,282	-124,503	-32
Nov	301,442	148,474	152,968	116,159	-36,809	-12
Dec	368,281	155,222	213,059	121,679	-91,379	-25
Amount	**4,680,476**	**1,795,181**	**2,885,295**	**2,040,345**	**-844,950**	**-18**

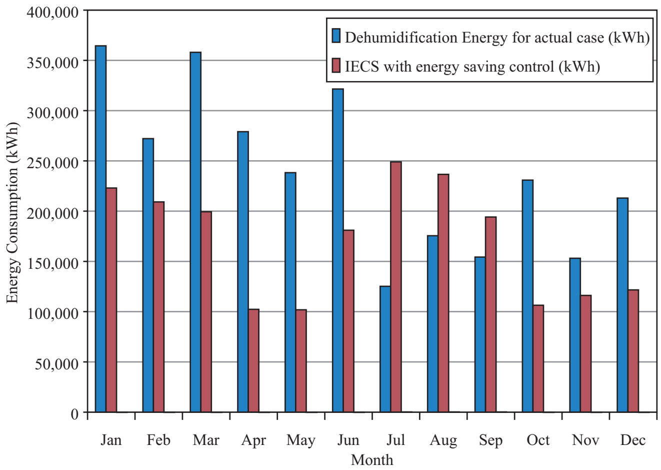

Fig. 9. The comparison between IECS with energy saving control to the actual case.

of the total plant use and with summer comfort cooling. In comparison to the actual case without summer cooling the energy saving is 29.28%.

V. CONCLUSION

The proposed integrated system has been found to have significant energy saving potential over the current desiccant dehumidification system for ship hull painting humidity control. The integrated environment control system as proposed has four elements that can be used alone or in combination so to minimize the energy use. Five different operating modes are proposed to respond to weather conditions and the painting works. It has been shown that minimum energy use control can be achieved with a marginal safety for humidity control. The energy saving is found to be 18.1% with summer comfort cooling against the actual case, and 29.3% without providing summer comfort cooling. Presently comfort conditions are not provided to the workers in the summer months. This effective control strategy can be applied in other manufacturing environments with similar humidity control requirements.

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