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PERFORMANCE ANALYSIS OF INTEGRATED ACTIVE DESICCANT ROOFTOP AIR-CONDITIONING SYSTEM OPERATING IN HEATING MODE

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ABSTRACT
This investigation describes the performance study of a novel Integrated Active Desiccant-Vapor Compression Hybrid Rooftop (IADR) at Oak Ridge National Laboratory (ORNL) in heating mode. The tests were performed at two different ratios of outdoor/return air. Analysis of performance characteristics under each operating mode, including heating capacity and energy efficiency ratio, are given. Results of defrost cycle are also presented. Comparison between the experimental performance of IADR unit and the calculated performance of other commercially available heat pump systems at comparable operating conditions has been conducted.

INTRODUCTION
More than 95% of all commercial buildings in the United States (U.S.) are conditioned with some type of packaged equipment – mainly rooftop units. This equipment is compact and reliable, but it is often unable to accommodate the increased quantities of outdoor air, which must be continuously delivered to be in compliance with major building codes and the ASHRAE 62 Ventilation Standard [1]. Requirements put on U.S. equipment and appliance manufacturers to meet minimum efficiency standards for their products have been one of the most effective energy-saving policies instituted by Congress and the Department of Energy (DOE).

Based on the requirements mentioned above, there is a demand for compact, highly efficient, and cost competitive air conditioning units that can bring in varying amounts of outdoor air for cooling, heating, dehumidifying, and ventilation. The novel Integrated Active Desiccant-Vapor Compression Hybrid Rooftop (IADR) fully meets these requirements. The IADR technology combines the strengths of an advanced direct expansion (DX) cooling or heating cycle, utilizing variable speed compressors and optimal control strategies, with the unique dehumidification capability offered by an active desiccant wheel. It can be applied as a dedicated outdoor air system handling 100% outdoor air, or as total conditioning system, handling both outdoor air and space cooling or heating loads.

NOMENCLATURE
Abbreviations:

DX	= direct expansion
EER	= energy efficiency ratio
HVAC	= Heating, Ventilation, and Air Conditioning
IADR	= Integrated Active Desiccant-Vapor Compression Hybrid Rooftop
CHP	= Combined Cooling, Heating, and Power

Variables:

G	= volumetric air flow rate, scfm

h	= enthalpy, Btu/lb
Q	= heat input, heating output, Btu/h or kW
W	= electric power, kW
ρ	= density of air, lb/ft^3

EQUIPMENT

A general view and schematic of the IADR unit installed at ORNL site showing major components and flow diagram are given in Figures 1 and 2. The vapor compression cycle of the unit uses R-22 refrigerant. Fresh outdoor air enters the system at point "A", where it is mixed with return air from the laboratory building (point "B"), combining to produce the total air flow that enters the DX coil. The ratio of outdoor-to-total air flow is controlled by outdoor air and return air dampers. In the cooling mode of operation a portion of the cool saturated air leaving the DX coil passes through the active desiccant wheel where it is dried to a very low dewpoint, and warmed by the latent heat of vaporization from water adsorbed onto the desiccant wheel surface. The remaining portion of the air cooled by the DX coil is bypassed around the desiccant wheel through a bypass damper. Mixing of warm, very dry air after the wheel with the cool, moderately dry bypass air leaving the DX coil provides supply air at the temperature and humidity condition required by the space. The conditioned supply air is delivered to the laboratory building via perforated ducting systems (perforation only on one side, Figure 3).

Air required for desiccant regeneration is heated either by a modulating natural gas-fired burner or by hot water coil (point "C", Figure 2). Upon regeneration of the active desiccant wheel, the regeneration air is exhausted from the unit to the atmosphere.

The operation in the heating (heat pump) mode is similar to the cooling mode; the difference is in the desiccant wheel function. The desiccant feature of the unit with its provisions for thermal regeneration provides a means to resolve some primary weakness associated with heat pump technology. During extremely cold weather or during defrost cycles many heat pumps do not have the capacity or lose control to effectively warm the conditioned space. The traditional way to overcome this capacity loss is the use of electric resistance heaters. However the IADR unit can energize the regeneration burner and increase the rotational speed of the desiccant wheel, changing it from dehumidification device into a highly efficient heat exchanger. This provides additional effective heating of the supply air stream.

As mentioned previously, instead of the use of the natural gas burner, the regeneration stream of this IADR unit can be heated by optional hot water coil, i.e. this unit can be part of combined cooling, heating and power (CHP) system, using waste heat for heating and desiccant dehumidification purposes.

The unit at ORNL is fully instrumented in order to monitor and calculate various performance parameters. The data collection, analysis, and storage are performed with the

Figure 1. General View of the IADR Unit at ORNL Site.

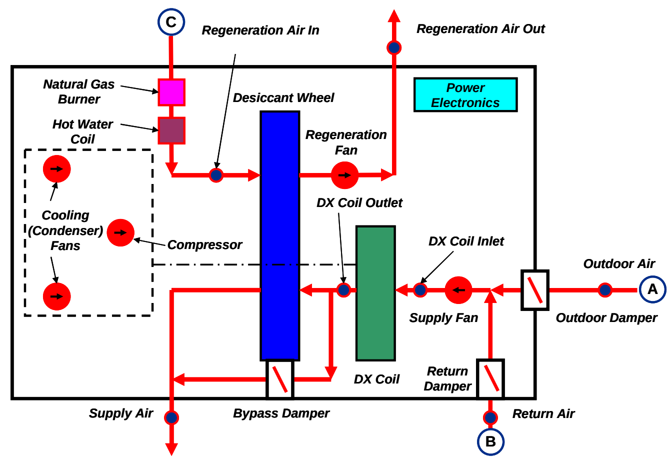

Figure 2. Schematic Diagram of the IADR Unit.

Figure 3. View of Air Supply Duct inside the Laboratory Building.

Internet-based Web Control system [2]. The major test instrumentation and sensor measurement accuracies used for this analysis are given in Table 1.

Table 1. The Major Test Instrumentation and Measurement Accuracies during IADR Testing

Measurement	Sensor	Range	Accuracy
Temperature	Thermistor	-67 to 302 °F	± 0.4 °F (32 to 158 °F)
Relative Humidity	Humidity sensor	10 to 90 % RH at 14 to 140 °F	± 3% RH
Air flow	Piezo ring pressure transducer	0 to 3,600 cfm	± 5%
Natural gas flow	High-precision Coriolis sensor	0 to 5 lb/h	±2.0%
Electric power	Watt transducer	0 to 20 kW	±0.5% of full scale

DISCUSSION OF TEST DATA

The IADR at ORNL works to maintain a building set-point temperature condition of 72°F over the wide range of outdoor temperatures (27-55°F) in the heat pumping mode. The conditions at these baseline tests were conducted at a supply air flowrate of 3,000 scfm and two outdoor air ratios: 50% and 0%. In addition, the IADR operation in a defrost mode was compared to normal operation at the same outdoor temperature at 50% outdoor air ratio. All the data points are averaged values over a 2-3 hour test run with minimum change in outdoor temperature. A large data collection and small sampling time intervals are especially needed in an analysis of defrost operation or during relatively high outdoor temperatures, when "on-off" cycling operation of natural gas burner or compressor occurs.

IADR Performance at 50% Outdoor Air, 50% Return Air

Figure 4 shows the dependence of outdoor temperature and the following temperatures: air entering the DX coil, supply air, and return air. The IADR unit was capable of maintaining the laboratory space set-point temperature of 72°F very well over the outdoor temperatures ranging from 27 to 55°F. All the temperature dependencies follow linear pattern, and the data scatter for both return and DX entering temperatures is much less than for the supply temperature. The reason for this is that, apart from the outdoor temperature, the entering temperature is mainly influenced by return temperature and percentage of outdoor air: both values are almost constant during these tests. In addition to the above-mentioned parameters, supply air temperature is influenced by the heating load needed to maintain the required laboratory space set-point temperature. Since the laboratory building is not an environmental chamber, different internal sensible and radiant loads occur during day and night. These variations in the building load result in compressor speed changes which, in turn, cause the supply temperature to fluctuate. For example, at the same outdoor temperature of 47°F, the supply temperature during night conditions was almost 4°F higher than during daytime conditions; coil entering temperature being almost the same in both cases. As a result, heating capacity produced by the heat pump in the first case is approximately 11 kBtu/h higher than the one achieved in the second case. This is why a better approach to do an analysis of the performance parameters is by a comparison to supply temperature, which is the method used in this study.

The dependence of supply heating capacity generated by the IADR unit in heating mode versus supply temperature is shown in Figure 5. Supply heating capacity was calculated by the following equation:

$$Q_{supply} = \rho \cdot G \cdot \left(h_{supply} - h_{entry} \right) \quad (1)$$

where ρ is the density of air at standard condition, G is the volumetric flow rate of supply air at standard condition, h_{supply} and h_{entry} are the supply air and DX entering air enthalpies, which are calculated from temperature and relative humidity data measured at corresponding air locations.

Supply capacity basically increases linearly with supply temperature. The maximum supply heating capacity at 50% outdoor air observed during these tests was approximately 100 kBtu/h. Figure 6 shows the dependence of total electric power consumed by IADR unit versus supply temperature: at the maximum supply temperature observed during these tests and 50% outdoor air it reached 8 kW. Increases in compressor operating frequency with supply temperature are shown in Figure 7. The maximum frequency observed during the heating mode with defrost is slightly below 50 Hz.

One of the major performance parameters of a heat pump unit, including IADR, is energy efficiency ratio (EER), which is the ratio of supply heating capacity to electrical and thermal power consumed by the unit. It is calculated with two options: using total power consumed by the IADR unit, and without the electric power consumption of the supply fan. The latter option, although does not give a complete picture of the relative use of power, can be useful while comparing the IADR performance with other conventional heat pump applications. The supply fan power is usually taken out of consideration, because of the variability of the static supply pressure. It should be noted that at elevated supply air flowrates, like in this particular case, the significant ductwork in the system results in much higher external static pressure than the 0.3"wc pressure specified by ARI ratings [3] used by most manufacturers.

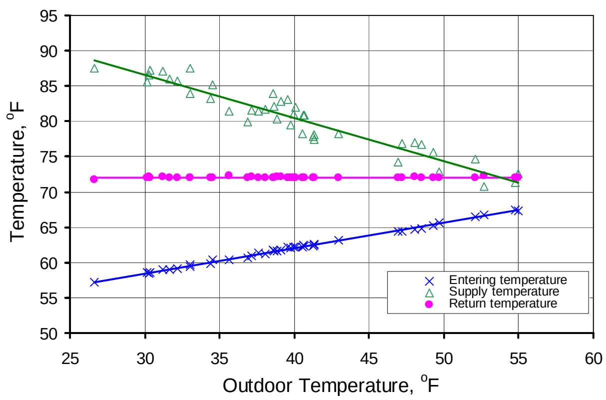

Figure 4. Effect of Outdoor Temperature on DX Coil Entering, Supply and Return Temperature at 50% Outdoor Air.

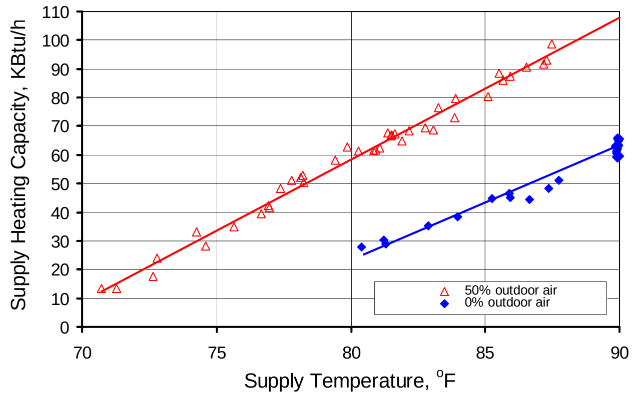

Figure 5. Effect of Supply Temperature on Heating Capacity at 50% and 0% of Outdoor Air

In both cases the variation of EER versus supply temperature is the same (Figure 8): it gradually increases and reaches maximum (14 and 17 Btu/W with and without accounting for the supply fan power) when supply temperature reaches around 82-83°F. That corresponds to an outdoor temperature of approximately 35-40°F. With further increases in supply temperature, EER values start to decrease. The difference between EER calculated with and without the supply fan power is greater at lower supply temperatures (or higher outdoor temperature), especially when power consumed by supply fan (constant value) becomes larger than power needed for refrigeration process (compressor power and condenser fan power).

Comparisons between normal heating and heating during defrost modes of the IADR operation were performed at similar outdoor temperature of 30.5°F. A picture of the frosted outdoor coil is shown in Figure 9. Some of the results of this analysis

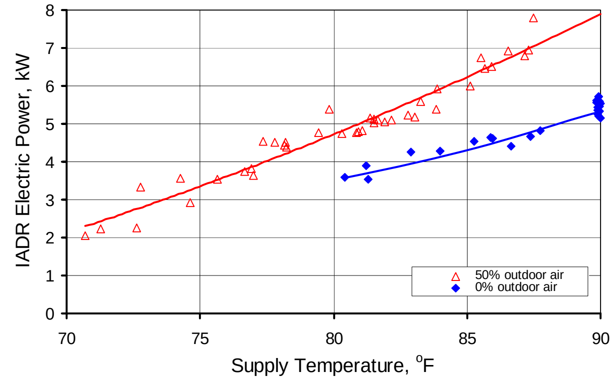

Figure 6. Effect of Supply Temperature on Electric Power Consumed by IADR at 50% and 0% Outdoor Air.

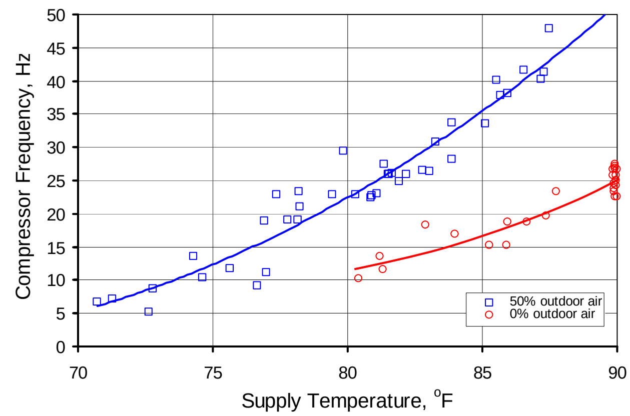

Figure 7. Effect of Supply Temperature on Compressor Speed at 50% and 0% Outdoor Air

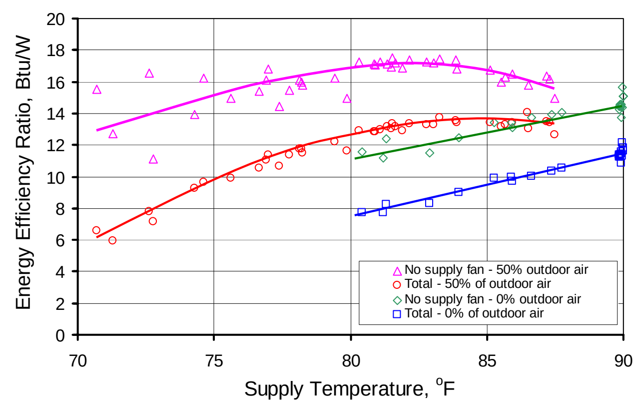

Figure 8. Effect of Supply Temperature on EER of IADR at 50% and 0% Outdoor Air.

are presented in Figures 10 and 11. The defrost operation of IADR was monitored for approximately three hours. During this period, the unit went into defrost for three minutes after operating for approximately 22-25 minutes. This operational mode called for activation of natural gas regeneration burner, regeneration fan, and desiccant wheel motor to operate at full speed to prevent dumping of cold air into the conditioned space during the defrost. This affected all the performance parameters of the IADR unit as compared to the "non-defrost" mode of operation: supply heating capacity decreased from 90 to 70 kBtu/h, supply temperature decreased from 87 to 80°F, EER fell from 13 to 8 Btu/W, total (electrical + thermal) power consumption increased from 7 to 9 kW. However, the most important factor is that during defrost mode, the unit was not able to hold the laboratory space set-point temperature of 72°F, - it dropped below 70°F (to a low of 68°F). Figure 12 shows real-time behavior of return air temperature during normal and defrost operation. The major reason for this temperature decrease is that the natural gas burner of the IADR unit at ORNL was sized primarily for desiccant wheel regeneration and the heating requirement needed to maintain the building set-point temperature was greater than the regeneration requirement. On the basis of this testing, the capacity of the regeneration burner was increased so that the delivered supply air temperature during defrost can be the same as that provided by the heat pump.

Figure 9. View of Frosted Outdoor Coil.

Use of this desiccant thermal reactivation system in this manner, to prevent "cold-blow" during defrost, suggests that it could also be used as a means to augment or replace the vapor compression heat pumping function of the unit on very cold (< 0°F) days when the efficiency of the reverse-Rankine cycle for heat pumping becomes ineffective and where inefficient electric resistance heating is commonly used to augment heat pumping performance.

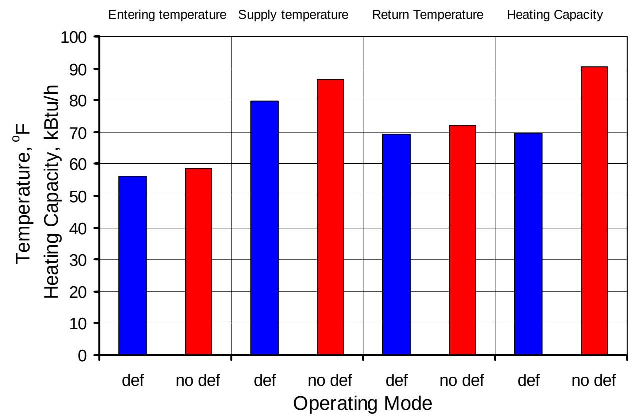

Figure 10. Effect of Defrost Mode on DX Coil Entering Temperature, Supply Temperature, Return Temperature, and Supply Heating Capacity at 50% Outdoor Air.

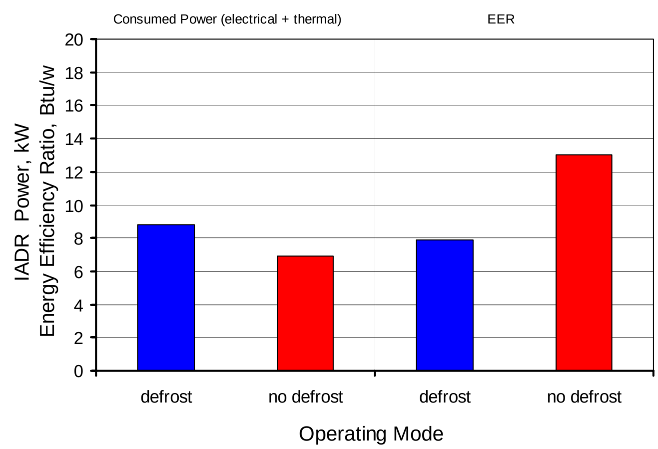

Figure 11. Effect of Defrost Mode on Power Consumption and EER of the IADR Unit at 50% Outdoor Air.

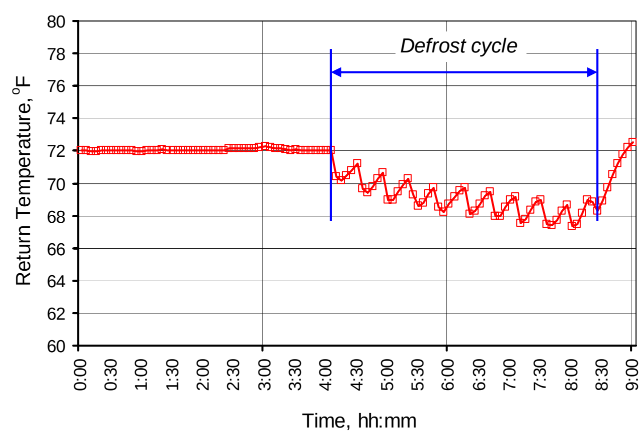

Figure 12. Real-Time Dependence of Return Temperature during Normal and Defrost Operation at 50% Outdoor Air.

Comparisons between experimentally determined EER values for the IADR and for different types of conventional heat pump equipment are shown in Table 2. The conventional equipment data are derived from manufacturer's datasheets by extrapolation to match IADR test conditions of outdoor and DX coil entering temperatures. IADR EER data are given without including the supply fan power consumption, since the EER evaluation of the conventional equipment usually does not include supply fan power. The data in this table show that over the range of outdoor temperatures studied, EER of IADR is significantly higher than those for conventional heat pump equipment. The highest EER improvement is observed at lower outdoor temperatures (7.1-7.8 Btu/W), and the lowest – at higher outdoor temperatures (2.5-3.4 Btu/W).

A consensus agreement has recently been worked out between U.S. air conditioning manufacturers represented by the Air-Conditioning and Refrigeration Institute (ARI) and energy efficiency advocates represented by the American Council for an Energy Efficient Economy that would raise EER of the most common air conditioning equipment from 8.9 to 11.2 Btu/W by 2010 [4]. The EERs for the IADR unit in Table 2 compare very favorably with these values.

IADR Performance at 0% Outdoor Air, 100% Return Air

This mode of IADR operation is similar to the way conventional residential heat pumps perform, when there is virtually no entry of outdoor air in the cycle. As a result, DX coil entering temperature is almost the same as return temperature (Figure 13). This coil entering temperature is much higher than in the case with 50% outdoor air. This, in theory, should be a beneficial factor in heating the conditioned space, provided that the building is properly sealed and there is no uncontrolled ingress of outdoor air. But in this specific laboratory building approximately 1,000 scfm of air was being exhausted via a laboratory fume hood, creating a negative building pressure and allowing for the same amount of unconditioned cold outdoor air to enter the building. This is why higher supply air temperatures are needed to maintain the set-point space temperature. But the supply air temperature of the IADR unit was limited to 90^{o}F in order to provide safe operation of the compressor in accordance with recommendations of compressor manufacturers [5]. As it can be seen from Figure 14, the maximum indoor coil condensing temperature of 95^{o}F (which corresponds to supply temperature of 90^{o}F) is based on the most extreme evaporating temperature of -10^{o}F, which is far less than the temperature observed during these tests (20-30^{o}F). As a result, at outdoor temperatures below 45^{o}F the lab space temperature went down to 70^{o}F (Figure 15) as a consequence of the depressurization of the building (0% outdoor air) and a constraint on the maximum indoor coil condensing temperature allowed by the IADR controller and control scheme.

The IADR unit under these 0% outdoor air conditions was unable to successfully maintain the required laboratory space set-point temperature, as it was in 50% outdoor air case. At 0% outdoor air, the compressor speed at maximum available load was only less than half of its rated frequency, i,e. 25-27 Hz (Figure 7). Therefore, the limiting indoor coil condensing temperature of the IADR unit should be modified to reflect the actual evaporating temperature. This can be easily implemented with this unit because all of its operating and control algorithms are performed with a direct digital control programmable logic board, which can be reprogrammed to accept and employ improved operating and control logic suited to the specific building application.

Table 2. EER Comparison: IADR vs Conventional Heat Pump Equipment at 50% Outdoor Air

Outdoor temp, ^{o}F	DX coil entering temp, ^{o}F	IADR EER, Btu/W	Conventional equipment EER, Btu/W				
			2,400 cfm 72 kBtu/h	2,400 cfm 72 kBtu/h	2,250 cfm 60 kBtu/h	5,000 cfm 150 kBtu/h	5,000 cfm 150 kBtu/h
26.7	57.2	15.0	9.7	9.6	9.3	9.3	9.1
34.4	59.8	17.5	10.4	10.3	9.8	9.9	9.7
36.9	60.7	15.9	10.6	10.5	9.9	10.1	9.8
40.0	62.2	16.8	10.8	10.7	10.1	10.3	10.0
43.0	63.2	15.8	11.2	11.1	10.4	10.6	10.4
47.2	64.4	16.1	12.1	12.0	11.5	11.1	11.4
49.3	65.3	14.9	12.2	12.1	11.7	11.2	11.5
52.1	66.4	16.3	12.4	12.3	11.8	11.4	11.6
55.0	67.7	16.5	12.6	12.5	12.0	11.5	11.8

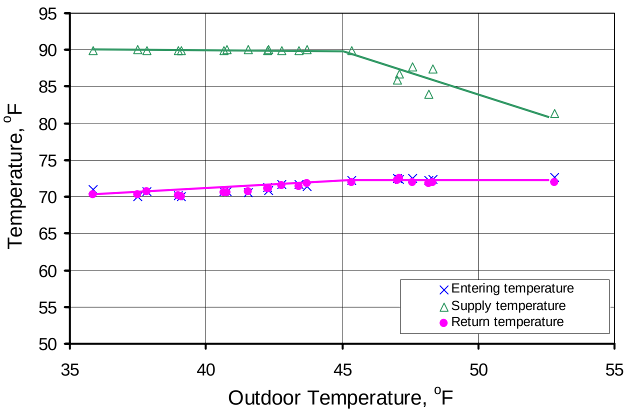

Figure 13. Effect of Outdoor Temperature on DX Coil Entering, Supply and Return Temperature at 0% Outdoor Air.

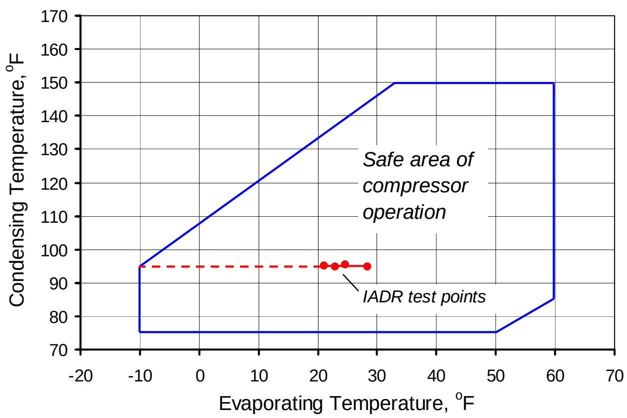

Figure 14. R-22 Operating Envelope [5].

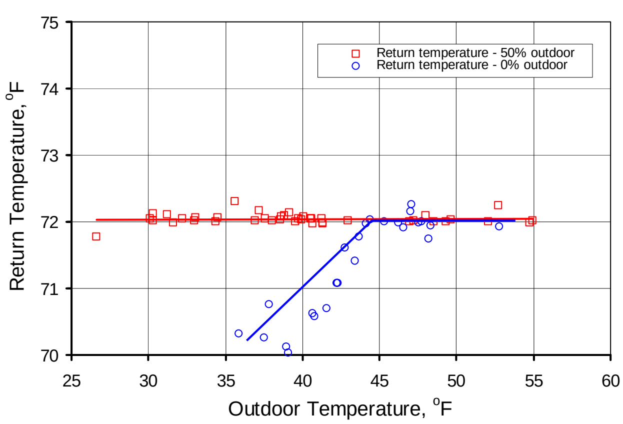

Figure 15. Effect of Outdoor Temperature on Return (Space) Temperature at 50 and 0% Outdoor Air.

The test results at the 0% outdoor air condition with the exhaust hood fan being in operation inside the building highlight a problem common in the HVAC industry. Many end-users close off outdoor air dampers in an attempt to improve heating and/or cooling/dehumidification control. If the exhaust air exiting the building is not effectively accommodated by the HVAC system (building pressurized), the unconditioned cold and/or hot and humid outdoor air would infiltrate the building through doors or cracks and degrade space comfort. Therefore, there is a need for outdoor air to pressurize space and for energy-efficient HVAC systems that can accommodate high outdoor air percentages.

The trend of the remaining major performance parameters of the IADR at 0% outdoor air plotted against supply temperature (supply heating capacity, electric power consumption, EER) is basically the same as those for 50% outdoor air (Figures 5, 6, and 8). The only exception is IADR efficiency: over the range of supply air temperatures studied (80-90°F), the IADR increased and reached maximum EER values at a maximum supply temperature of 90°F. There is no efficiency extremum, like in the 50% outdoor air case.

As in the previous case with 50% outdoor air, EER values for the IADR are higher than EER of conventional heat pump equipment (Table 3). Although at 0% outdoor air, this improvement is slightly less than that seen at 50% outdoor air (Table 2). But the 0% outdoor case is more typical for residential heat pump equipment. The EER improvement is also more noticeable at lower outdoor temperatures (4.7-5.5 Btu/W). At higher outdoor temperatures it decreases to 0.4-1.2 Btu/W.

CONCLUSIONS

A performance analysis of the novel Integrated Active Desiccant-Vapor Compression Hybrid Rooftop (IADR) at ORNL in a heat pump mode was performed at two outdoor/supply air ratios: 50 and 0%. The unit was able to perform successfully the heating function at outdoor temperatures down to 28 °F while delivering 50% outdoor air in the heat pump mode. The tests revealed clear advantage of variable speed compressors and blower motors over "on-off" cycling equipment. The EER of the IADR unit can be 7.1-7.8 Btu/W higher than that achieved by conventional heat pump equipment. The defrost cycle decreases EER and to some extent the ability to hold the set-point space temperature, but the use of desiccant regeneration system as a booster heater during defrost cycle prevents significant reduction of space temperature and the "dumping" of cold air on those occupying the space. Based on the results of these tests, the capacity of the gas burner used for desiccant regeneration was increased so that the supply air temperatures can be the same as that provided by the heat pump during normal operation. For this specific building application, slight building pressurization obtained by pulling in 50% outdoor air, resulted in better

Table 3. EER Comparison: IADR vs Conventional Heat Pump Equipment at 0% Outdoor Air

Outdoor temp, °F	DX coil entering temp, °F	IADR EER, Btu/W	Conventional equipment EER, Btu/W				
			2,400 scfm 72 kBtu/h	2,400 scfm 72 kBtu/h	2,250 scfm 60 kBtu/h	5,000 scfm 150 kBtu/h	5,000 scfm 150 kBtu/h
35.9	70.9	13.7	9.5	9.4	9.2	9.0	8.7
37.8	70.7	14.4	9.7	9.6	9.3	9.2	8.9
39.0	70.2	14.5	9.9	9.8	9.5	9.4	9.1
40.8	70.7	14.4	10.0	9.9	9.6	9.5	9.2
42.8	71.7	14.6	10.3	10.1	9.8	9.6	9.4
43.7	71.4	15.1	10.5	10.4	10.0	9.8	9.7
44.1	72.0	13.4	10.5	10.4	10.1	9.8	9.7
45.3	72.2	12.0	10.8	10.7	10.4	9.9	10.0
46.6	72.2	11.5	11.1	11.0	10.8	10.1	10.3
47.8	72.3	12.2	11.3	11.2	11.0	10.3	10.5
48.2	72.2	12.5	11.3	11.2	11.0	10.3	10.5
52.8	72.6	12.4	11.7	11.6	11.4	10.7	10.9

control of indoor set point at extreme ambient conditions. When outdoor air is brought through the IADR unit, as opposed to cracks and leaks in the building, better heating is provided, and better set-point control is obtained. Selection of the optimum heating mode should be based on both ambient and building conditions. If the building is slightly pressurized, there is no artificial extraction of air from the building, then the 0% outdoor air heating mode might be preferable.

The future study of the IADR unit will be focused on its performance in cooling and dehumidification modes, for both stand-alone and as part of ORNL CHP system.

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