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Experimental Evaluation of Separate Sensible and Latent Cooling Air-Conditioning System Integrated with Desiccant Wheel

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ABSTRACT

A separate sensible and latent cooling (SSLC) air-conditioning system integrated with low regenerating temperature desiccant wheel was designed for 3.5 kW cooling capacity and experimentally evaluated. While the vapor compression cycle of the SSLC system was designed to meet the sensible cooling load only, the desiccant wheel was designed to meet the latent load. Two different refrigerants, R410A and CO_2, were tested and compared in the SSLC system. The waste heat from either the condenser or the gas cooler was used to regenerate the desiccant wheel. The SSLC system was tested under AHRI's summer test conditions for the air conditioners. Furthermore, the performance of the SSLC system was evaluated while the desiccant wheel was regenerated under various regeneration temperatures from 45°C to 55°C. For both refrigerants, the COPs of the SSLC systems were improved as compared to the respective baseline systems.

Key words: Separate sensible and latent cooling, Separated gas cooler, CO_2

1. INTRODUCTION

Although a natural refrigerant CO_2 has numbers of good properties like non-flammability, low toxicity and low GWP, it hasn't been widely used as refrigerant for air conditioners because the refrigeration cycle COP is lower than that of systems with HFCs for example R410A. Recently, a lot of low temperature regenerated desiccant materials are developed.

The COP of air conditioner has been raised by increasing evaporating temperature. However, increased evaporating temperature decreases dehumidification capacity and reduces comfort in conditioned space. A separate sensible and latent cooling (SSLC) air-conditioning system is one of the solutions for these problems. The SSLC separates the sensible load and the latent load by two different devices. The evaporator provides the sensible cooling capacity. The desiccant wheel removes the moisture from the conditioned air. The COP of the SSLC system is high because of its high evaporating temperature. It also provides enough dehumidification capacity to keep the conditioned space comfort condition without any additional heat source because the desiccant wheel is regenerated by rejected heat from the refrigeration cycle.

The SSLC system integrated with a desiccant wheel was tested under summer test condition for the air conditioners, and the performance was compared between the SSLC and baseline systems for CO_2 and R410A.

2. EXPERIMENTAL SETUP

The SSLC system performance test was carried out by building a wind tunnel with the refrigeration cycle and the desiccant wheel. Figure 1 and Figure 2 show schematic diagrams of the wind tunnel and the refrigeration circuit. The wind tunnel was placed in a climate control chamber so that constant outdoor air condition was provided for the wind tunnel.

The closed loop, located in the upper part of the wind tunnel, was the dehumidification process side of the desiccant wheel. The cooling capacity of the evaporator and the dehumidifying capacity were measured in this part. Because the heat and the moisture were removed by the evaporator and the desiccant wheel, an electric heater and a humidifier kept the constant condition of the conditioned space temperature and relative humidity (27°C, 50% RH). The conditioned air flew into the evaporator. Then a part of the cooled air went through the desiccant wheel and was dehumidified and sent back to conditioned space with the rest of the air flow.

The open duct, located in the lower part of the wind tunnel, was the regeneration process side of the desiccant wheel. The rejected heat and the moisture were measured. The air flow went through the condenser/gas cooler and increased its temperature. Then a part of the heated air went through and regenerated the desiccant wheel. Warm and moist exhaust was discharge to inside the climate chamber. The desiccant wheel, which was in honeycomb and cylindrical shape, continuously dehumidified the air flow while rotating slowly.

Nozzles and differential pressure transducers were used to measure the air flow rate in the wind tunnel. Temperature and relative humidity were measured with thermocouple grids and RH sensors. Then the cooling capacity and dehumidifying capacity were calculated from the measured data.

The refrigeration circuit consisted of a compressor, a condenser/gas cooler, an electronic expansion valve and an evaporator. An inverter drive controlled the compressor rotation speed and set the cooling capacity constant. The refrigerant temperature and the pressure were measured at the inlet and the outlet of each component and refrigerant mass flow rate before the expansion valve was measured. Compressor input was measured as the primary input of the inverter drive.

The heat exchangers in the refrigeration circuit were designed with the same circuitry for both of CO_2 and R410A and the same air side dimension was used to make it easy to compare the heat exchanger performance. Only the different tube wall thickness was used in order to account for different operating pressures of CO_2 and R410A. Also they were designed to meet the capacity requirement, air side and refrigerant side pressure drop limitation. The specification of the wind tunnel, components and measurement instruments are shown in Table 1.

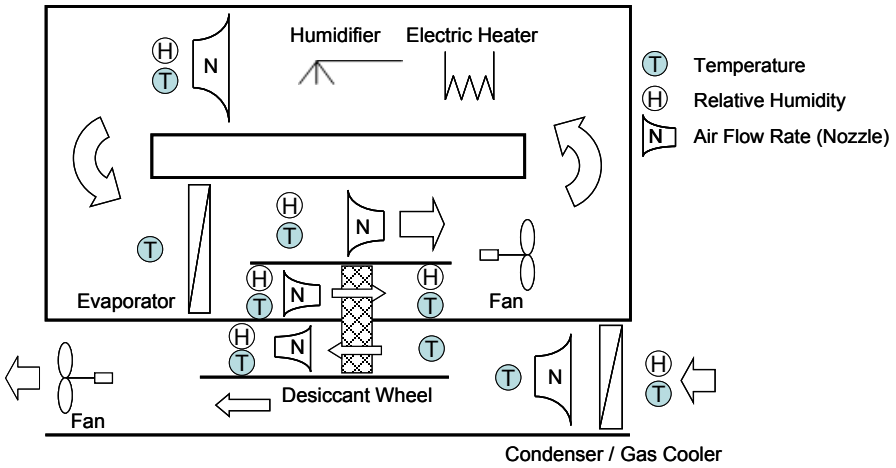

Figure 1: Wind Tunnel Setup and Measurement Points

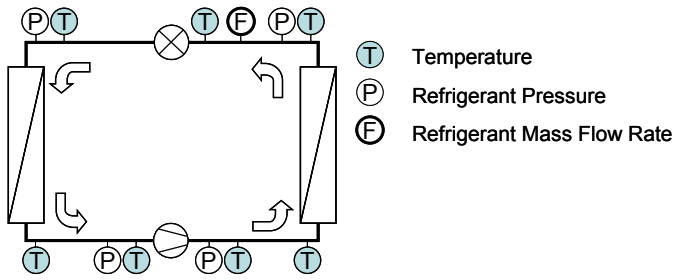

Figure 2: Measurement Points on Refrigeration Circuit

Table 1: Specification of the Wind Tunnel, Components and Measurement Instruments

Component / Instrument	Specification
Closed Loop Air Flow Range	Up to 2,100 kg/h, Inverter controlled
Open Duct Air Flow Range	Up to 1,000 kg/h, Inverter controlled
Desiccant Wheel	Diameter: 300 mm, Length: 100 mm Rotation Speed: 0,10-25 (Revolution/hour)
Compressor	(CO_2) Two Stage Rotary (R410A) Single Stage Rotary
Evaporator	Frontal Area: 704 mm (H) x 699 mm (W) 4 banks, 32 tubes/bank, 4 parallel circuitry Fin Pitch: 2.0 mm, Fin Thickness: 0.2mm (CO_2) Tube Diameter:7.94 mm, Wall thickness 0.80 mm, bare tube (R410A) Tube Diameter:7.94 mm, Wall thickness 0.31 mm, bare tube
Condenser/Gas Cooler	Frontal Area: 484 mm (H) x 622 mm (W) 4 banks, 22 tubes/bank, 2 parallel circuitry Fin Pitch: 2.0 mm, Fin Thickness: 0.2 mm (CO_2) Tube Diameter:7.94 mm, Wall thickness 0.80 mm, bare tube (R410A) Tube Diameter:7.94 mm, Wall thickness 0.31 mm, bare tube
Nozzle	Desiccant Wheel: 3 inches Diameter, 78-183 kg/s Condenser/Gas Cooler: 5 inches Diameter, 219-500 kg/s Evaporator: 7 inches Diameter, 417-1,000 kg/s
Relative Humidity Sensor	VAISARA, HMD60 (Error: 2% RH, Range: 0-100% RH)
Thermocouple	Type T
Pressure Transducer	Setra, Pressure Transducer 280E (0-6.89 MPa、0-13.79 MPa)
Differential Pressure Transducer	Setra, model264 (0-249 Pa, 0-1245Pa)
Refrigerant Mass Flow Meter	Micromotion, DS025S119SU (0-455g/s)
Power Transducer	OHIO SEMITRONICS, GH-020D

2.1 Experimental Condition

The temperature and humidity ratio conditions for the evaporator and the condenser/gas cooler were controlled at the cooling mode summer conditions. The cooling capacity, the dehumidifying capacity and the power consumption were measured. The air flow rate passing through the desiccant wheel was set at 300 kg/h and 350 kg/h. The desiccant wheel regeneration air temperature was varied from 45°C to 55°C. Refrigerant charge amount in the circuit was adjusted to maximize the COP at 50°C regeneration air temperature condition. The vapor compression cycle cooling capacity was set at 3.5 kW and the dehumidifying capacity was set at 0.7 kW.

The test condition and the test matrix are shown in Table 2 and Table 3. The SSLC system test was carried out at a limited number of conditions. The refrigeration cycle performance test (RC Test) was conducted while the desiccant wheel rotation was stopped. Therefore, the test condition for the RC test was exactly the same as one for the SSLC test.

Table 2: System Performance Test Condition

Parameter	Setting	Description
Cooling Capacity	3.5 kW	Cooling capacity of the evaporator
Latent Capacity	0.7 kW	SHF=0.8
Indoor Condition	27°C, 50% RH	Setting at the evaporator inlet
Evaporator Outlet Temperature	18°C, 20°C, 22°C	Desiccant wheel dehumidification side inlet temperature
Outdoor Condition	35°C, 44% RH	Setting at the condenser/gas cooler inlet
Condenser/Gas Cooler Outlet Temperature	45°C, 50°C, 55°C	Desiccant wheel regeneration air temperature
Air Flow Rate through the Desiccant Wheel	300 kg/h, 350 kg/h	Same air flow rate for both of dehumidification and regeneration
Desiccant Wheel Rotation Speed	0 rph, 10 rph – 25 rph	

Table 3: Test Matrix of Regeneration Air Temperature and Evaporator Outlet Air Temperature

		Evaporator Outlet Air Temperature		
		18°C	20°C	22°C
Regeneration Air Temperature	45°C	RC Test	RC Test (R410A)	RC Test
	50°C	No Test	SSLC Test	No Test
	55°C	RC Test	SSLC Test	RC Test

2.2 Error Analysis

The measurement errors were calculated based on the systematic errors of measurement instruments. Table 4 shows systematic errors of instruments and Table 5 shows typical errors calculated for the cooling and heating capacities of the refrigeration side and the air side.

Table 4: Systematic Error of Measurement Instruments

Sensor	Systematic Error
Differential Pressure	±1% Full Scale
Thermo Couple	±0.5 K
Relative Humidity	±2% RH
Refrigeration Mass Flow Rate	±0.05% Indicated Value
Refrigerant Pressure	±0.11% Full Scale
Power Transducer	±0.2% Full Scale

Table 5: Typical Number of Calculated Errors

Evaporator Capacity		Condenser/Gas Cooler	
Air Side	Refrigerant Side	Air Side	Refrigerant Side
±140 W	±30 W	±80 W	±30 W

3. TEST RESULT

The test results of the SSLC system performance are shown in Tables 6 and 7: CO_2 result in Table 6 and R410A result in Table 7. The system COP was calculated based on the air side cooling capacity and the inverter drive input. 3 or 4 tests were conducted for each condition and then the highest COP data was selected.
In Table 6 and Table 7, star means that the air flow rate exceeds the upper limit of measurement. In Figure 3, each line shows COP with different evaporator outlet air temperature.

Figure 3 shows the refrigeration cycle COP trend against the regeneration air temperature and the evaporator outlet air temperature. The COP was affected with both the regeneration air temperature and the evaporator outlet air temperature. Lower regeneration air temperature and higher evaporator outlet air temperature resulted in higher COP in the range of test condition. Although the COP of R410A system was higher than that of CO_2 system, the difference was slightly decreased at higher regeneration air temperature.

Table 6: Test Results of SSLC and RC Tests with CO_2

Refrigerant				Unit	SSLC Test		RC Test			
CO_2	Regeneration Air Temperature			[°C]	50.4	55.1	45.3	46.1	55.6	55.6
	Evaporator Outlet Air Temperature			[°C]	20.0	20.0	20.0	20.0	20.0	20.0
	Air Flow Rate through Desiccant Wheel			[kg/h]	350	350	-	-	-	-
	Desiccant Rotor Rotation Speed			[rph]	25	25	-	-	-	-
	Compressor	Discharge	Pressure	[MPa]	10.81	11.94	10.39	10.26	11.85	11.79
			Temperature	[°C]	78.3	88.8	80.1	73.6	88.5	84.5
		Suction	Pressure	[MPa]	5.35	5.30	5.07	5.47	5.18	5.51
			Temperature	[°C]	25.0	26.1	25.9	26.6	24.5	26.3
		Refrigerant Mass Flow Rate		[g/s]	32.12	30.51	25.91	27.96	31.80	31.13
		Inverter Drive Input		[kW]	1.209	1.396	1.036	0.924	1.480	1.285
	Evaporator	Cooling Capacity	Refrigerant	[kW]	3.981	3.904	3.709	3.653	3.992	3.706
			Air	[kW]	3.582	3.529	3.426	3.497	3.606	3.491
	Condenser	Heating Capacity	Refrigerant	[kW]	4.729	4.796	4.350	4.206	4.944	4.507
			Air	[kW]	4.579	4.579	*	*	4.732	4.338
	Refrigeration Cycle COP			[-]	2.964	2.528	3.308	3.783	2.437	2.716

Table 7: Test Results of SSLC and RC Tests with R410A

Refrigerant				Unit	SSLC Test		RC Test				
R410A	Regeneration Air Temperature			[°C]	50.3	55.6	45.3	45.3	45.3	55.9	55.8
	Evaporator Outlet Air Temperature			[°C]	19.7	19.8	18.0	20.1	21.2	17.7	20.8
	Air Flow Rate through Desiccant Wheel			[kg/h]	350	300	-	-	-	-	-
	Desiccant Rotor Rotation Speed			[rph]	25	15	-	-	-	-	-
	Compressor	Discharge	Pressure	[MPa]	3.41	3.86	3.06	3.05	3.04	3.85	3.85
			Temperature	[°C]	79.1	88.6	71.7	71.8	69.9	88.4	87.4
		Suction	Pressure	[MPa]	1.27	1.26	1.22	1.28	1.33	1.19	1.29
			Temperature	[°C]	26.6	27.4	23.8	27.2	27.6	23.7	27.7
		Refrigerant Mass Flow Rate		[g/s]	22.85	23.28	23.04	21.45	20.80	25.79	23.29
		Inverter Drive Input		[kW]	0.861	1.036	0.781	0.690	0.631	1.188	1.002
	Evaporator	Cooling Capacity	Refrigerant	[kW]	3.782	3.727	3.878	3.687	3.561	4.038	3.730
			Air	[kW]	3.541	3.543	3.531	3.527	3.505	3.571	3.607
	Condenser	Heating Capacity	Refrigerant	[kW]	4.317	4.382	4.395	4.113	3.935	4.842	4.356
			Air	[kW]	4.177	4.257	*	*	*	4.742	4.308
	Refrigeration Cycle COP			[-]	4.114	3.421	4.520	5.109	5.559	3.006	3.599

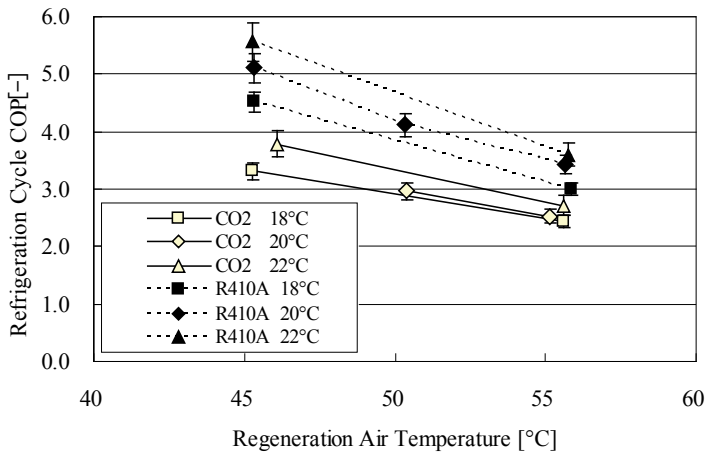

Figure 3: Refrigeration Cycle COP Trend to Regeneration Air Temperature

4. COMPARISON WITH BASELINE SYSTEM

A cycle simulation program was written using the parameters such as compressor efficiency, desiccant wheel dehumidification capacity, and heat exchanger UA value. Then the model was verified with the test result. Performance of the baseline system was calculated with a modified cycle simulation program based on the same UA value. The air flow rate through the evaporator and the evaporator outlet air temperature were determined to meet the sensible and the latent capacities of the evaporator with the SSLC system capacity.

The simulation results show that the lower limit of regeneration air temperature was 51°C to meet the latent capacity of the 300 mm diameter desiccant wheel with 0.7 kW latent capacity. Additionally, the system performance at 45°C regeneration air temperature was also calculated in case of a larger dehumidifying capacity wheel were available. Table 8 shows the calculation results of the SSLC and baseline system COPs with CO_2 and R410A. Operating condition assumption was as same as the SSLC test condition, 3.5 kW cooling capacity and 0.7 kW latent capacity. The COP of the SSLC system with star means that a cooling capacity loss from desiccant dehumidification, such as heat transfer from regeneration area to dehumidification area, was included.

As a result, the improvements from applying SSLC system were very close each other for CO_2 and R410A. The COP of the R410A system was higher than that of the CO_2 system.

Table 8: COP Comparison between Baseline and SSLC Systems

Refrigerant	System	Evaporating Temperature	High side Pressure	Regeneration air temperature	COP
CO_2	Baseline	13.9°C	10.37 MPa	47.3°C	2.58 (100%)
	SSLC	17.6°C	10.91 MPa	51.0°C	2.77* (107%)
		17.7°C	10.26 MPa	45.5°C	3.40* (132%)
R410A	Baseline	14.3°C	3.164 MPa	47.3°C	3.64 (100%)
	SSLC	18.3°C	3.415 MPa	50.7°C	3.91* (107%)
		18.5°C	3.033 MPa	45.7°C	4.89* (134%)

5. CONCLUSION

The SSLC system integrated with a desiccant wheel was tested under summer test condition for the air conditioners, and the performance was compared between the SSLC and baseline systems for CO_2 and R410A. In comparison with the baseline system simulation result, the SSLC system COP is 7% higher at 51°C regeneration air temperature, 32 to 34% higher at 45°C. The COP improvements from applying SSLC system were very close each other for CO_2 and R410A.

The COP was affected with the regeneration air temperature and the evaporator outlet air temperature. Lower regeneration air temperature and higher evaporator outlet air temperature resulted in higher COP. At the SSLC system test condition, the lower limit of regeneration air temperature was 51°C to meet the latent capacity with 300 mm diameter desiccant wheel. It is necessary to increase the wheel capacity to maximize the COP improvement.

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