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Theoretical Study on Separate Sensible and Latent Cooling Air-Conditioning System

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ABSTRACT

The advantage of separating sensible and latent cooling (SSLC) by using separate devices is to save energy by raising the evaporating temperature of the sensible cooling process. The latent cooling portion can be met either by vapor compression cycles or desiccant devices. The later can be achieved by using waste heat or other heat sources. The study presented here focuses on using two vapor compression cycles, one for sensible and one for latent cooling. Pertinent characteristics of the SSLC system are discussed, including (1) the coincident of the maximum energy savings and the highest air flow rate through the system, (2) energy savings potential under varying sensible cycle outlet air temperatures, and (3) energy savings potential under varying ambient conditions.

1. INTRODUCTION

Conventional air conditioners use evaporators to cool and to remove moisture from hot and humid indoor air. In order to remove the moisture, or meet the latent load, the air temperature has to be decreased below the dew point temperature. However, the dew point temperature is usually lower than that required by the supply air. Some kind of reheat is necessary to increase the air temperature, but the energy is wasted in reheating. In the separate sensible and latent cooling (SSLC), a small portion of an air can be dehumidified in different ways, i.e. using a desiccant or vapor compression cycle. The air temperature of the remaining air is reduced only enough to meet the sensible load. Therefore, the reheat process is not needed. This paper focuses on using two vapor compression cycles to realize the SSLC. Typical condensing and evaporating temperatures of the conventional vapor compression cycles are about 45°C and 7°C, respectively. In the SSLC, the latent cooling has essentially the same temperature level with the typical level; however, the sensible cooling can be accomplished with the higher evaporating temperature, resulting in enhanced cycle efficiency. The condensing pressure is expected to be lower than the typical pressure because of the enhanced isentropic efficiency of the compressor. Therefore, the sensible cooling cycle can achieve a much higher coefficient of performance (COP) than that of the conventional system. In overall, the whole SSLC system is expected to have a higher COP than the conventional system.

2. SSLC SYSTEM DESCRIPTION AND CHARACTERISTICS

2.1 SSLC System Description
SSLC systems use one vapor compression cycle to deal with sensible cooling load and a second to deal with latent cooling demand from indoor and outdoor air. A counter flow heat exchanger is also used in the system to utilize the cooling from the latent evaporator for pre-cooling of the incoming air. The configuration of an SSLC system is shown in Figure 1. In the configuration, the sensible and latent heat exchangers are arranged in sequence along the air processing flow direction. Return air from the space is mixed with outdoor fresh air before flowing into the sensible evaporator. After it passes through the sensible evaporator, air flow is divided into two streams. While one stream is sent to the reheat heat exchanger for pre-cooling, and processed through the latent evaporator, the other stream is bypassed. The air stream exiting the latent evaporator is then reheated through the reheat heat exchanger, and is mixed with the other stream bypassed. This mixed stream becomes the supply air and is sent to the space.
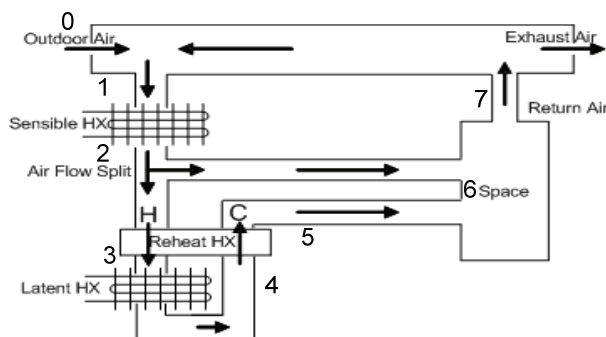
Figure 1: Schematic diagram of an SSLC system

3. MODELING RESULTS AND ANALYSIS

3.1 System Modeling Methods

Engineering Equation Solver (EES) was used to model the SSLC system. A conventional combined system was also simulated in the EES for comparison with the SSLC system. Assumptions used in the modeling are as follows:

- Air side:
  - Pressure drops and heat loss in the ducts and pipes are neglected.
  - Return air and outdoor fresh air are well mixed.
  - Air mixing process is adiabatic.
  - Temperature distribution and mass distribution in the space are uniform.
- Refrigerant side:
  - Refrigerant: R410A
  - Degree of subcooling: 5 K
  - Degree of superheating: 10 K
  - Isenthalpic expansion
  - Condenser pressure drop: 100 kPa
  - Evaporator pressure drop: 50 kPa
  - Isentropic efficiency is calculated as a function of the pressure ratio ($\eta_{iso} = 0.9 - 0.467 \times PR$).
  - Initial Conditions:
  - Outdoor air temperature is under ARI standard 210/240 (2006): 35°C, 44% relative humidity (RH)
  - Outdoor air mass flow rate is set to be 1 kg/s.
  - Space air condition is under ARI standard 210/240 (2006): 27°C, 50% RH
  - Space load is 100 kW.
  - Sensible heat factor (SHF) of the space is 0.7.
  - For the baseline system, the mass flow rate of air is set to be 5 m³/s based on cooling capacity 120 kW
- Range of conditions studied in the parametric study:
  - Outdoor temperature: 15°C ~ 37°C
  - Outdoor humidity ratio: 5.8 g/kg dryair (15°C, 55% RH) ~ 28 g/kg dryair (37°C, 70% RH)

3.2 Modeling Results

Figure 2 shows the air process by the SSLC system (solid line) and the conventional reheat system (dotted line) in the psychrometric chart. For the baseline system, in order to meet the cooling demand of the space, especially the dehumidification demand, which is 30 kW, air temperature exiting the evaporator is 12.8°C, which is much lower than the dew point temperature 16.7°C. Based on the size of the evaporator used in the model, the refrigerant temperature is 6.0°C. Decreasing the temperature of the return air below the dew point temperature consumes much power in the vapor compression cycle. The COP of the baseline is 3.9. For the SSLC system, the sensible heat load is removed separately at first. It can be simply achieved by decreasing the air temperature by 3°C and increasing the air flow rate to maintain the total sensible load. In order to do a fair comparison to the baseline system, the same air flow rate is used for the latent heat removal cycle. It is cooled down to approximately the same temperature as in the baseline system, which is 12.0°C. The power consumption of the SSLC system is 30% lower and the COP of the SSLC is 5.45.
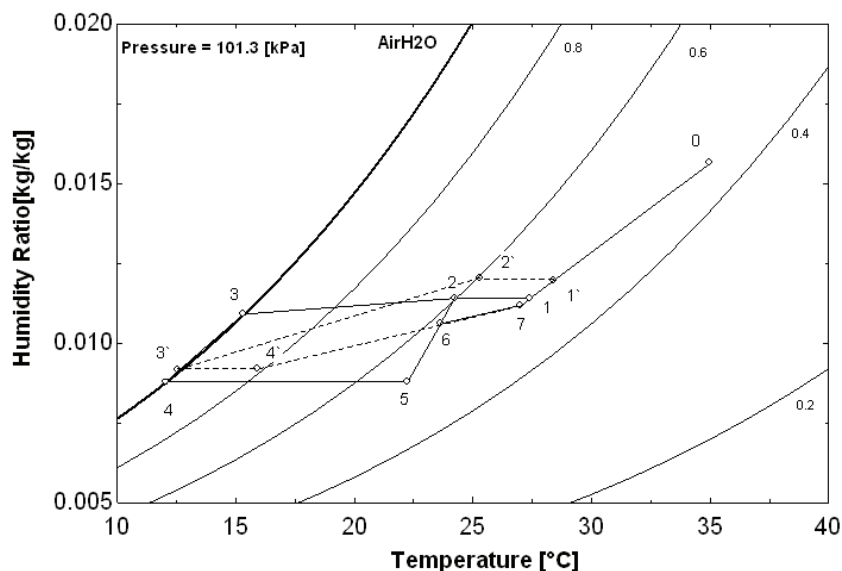
Figure 2: Comparison of SSLC system and baseline system in psychrometric chart
(SSLC: 0: outdoor condition, 7: indoor condition, 1: mixing point, 2: after sensible HX, 3: after pre-cooling, 4: after latent HX, 5: after reheat, 6: supply air; Baseline: 1`: mixing point, 2`: after pre-cooling, 3`: after evaporator, 4`: after reheat and supply air)

The reasons of energy savings are described as following. In the baseline system, the sensible cooling load is 78.3 kW, which accounts for about 64% of the total load. The vapor compression cycle consumes 20 kW, which is also 64% of the total power to meet the sensible cooling load. However, in the SSLC system, the refrigerant evaporating temperature of the sensible cycle is increased to 19.1°C due to the higher air temperature. The sensible cycle compressor pressure ratio is decreased from 2.93 (baseline system) to 2.00. The power consumption of the sensible cycle is reduced to 9.7 kW, which means 10.3 kW are saved as compared to the baseline system. For the latent cycle, both the baseline system and the SSLC system consume about the same power to remove the same amount of water vapor (16g/s) as expected.

In order to keep the size of heat exchangers (HX) (excluding the internal HX) the same as for the baseline system, the total UA values of evaporators and condensers are both set to be 50 kW/k in order to keep the same total cost. Since there are two evaporators in the SSLC system which account for higher UA value than the one in the baseline system, a higher condensing approach temperature is expected in the SSLC system, which slightly increases the power consumption for the latent cycle. However, the SSLC system still has a 8.6 kW lower power consumption than the baseline. There are also other benefits resulting from the SSLC system. In the sensible cycle, the higher isentropic efficiency is expected because of the reduced pressure ratio. In fact, the isentropic efficiency is increased from 0.76 to 0.81. Moreover, the total displacement volume of the two compressors in the SSLC system can be 25% smaller than that in the baseline system. It should be noted that the SSLC system requires a higher air flow rate. This is due to the smaller air enthalpy difference in the sensible cycle. More air is required to meet the sensible cooling load. This raises a question whether the increased power consumption of the fan will offset the power savings from compressors. Kopko (2002) presented a concept using an entire drop ceiling as the plenum to distribute a large flow rate of air. The air in the plenum is transported slowly so there is almost no pressure drop as compared to a duct. In light of this, a propeller fan, which produces high flow rates but low pressure head can be utilized. Since the blades of propeller fans rotate slowly, the power consumption is even lower than that of conventional blowers.

3.3 Parametric Studies
Parametric studies are conducted in order to obtain information on the SSLC system under different operating conditions. In Figure 3, the air temperature leaving the sensible evaportor changes from 19°C, which is close to dew point temperature, to 25.5°C. The COP of the SSLC system increases with the increase of the air temperature leaving sensible cycle. However, the trade off is the higher air mass flow rate. Figure 3 shows that the highest COP coincides with the highest air mass flow rate, which is almost 5 times as high as the baseline system. If both the COP benefit and the higher air mass flow rate disadvantage are considered, the temperature leaving the sensible

evaporator can be set between 22°C (70% RH) and 24°C (60% RH). Since the higher temperature condition (24°C, 60% RH) shows a higher COP, that condition is selected for the rest study. The SSLC system shows different power saving ability under different ambient conditions. Figure 4 demonstrates the SSLC system's power savings over the baseline under different ambient humilities. The ambient temperature is set to be 37°C, and the relative humidity ranges from 15% to 75%. The system demonstrates the feature of distributing the sensible and latent cooling load depending on the ambient condition. The sensible load of the system is kept constant at 66 kW, however, the latent load ranges from 38 kW to 88 kW. Therefore, the ratio of sensible load to latent load decreases with the increase of relative humidity, which is shown on the secondary y-axis. It is also observed that the power savings decrease when the relative humidity increases. This is because more power is required from the latent cycle and it makes the savings from the sensible cycle less significant. However, even under the highest relative humidity condition, the power savings over baseline are over 15%.
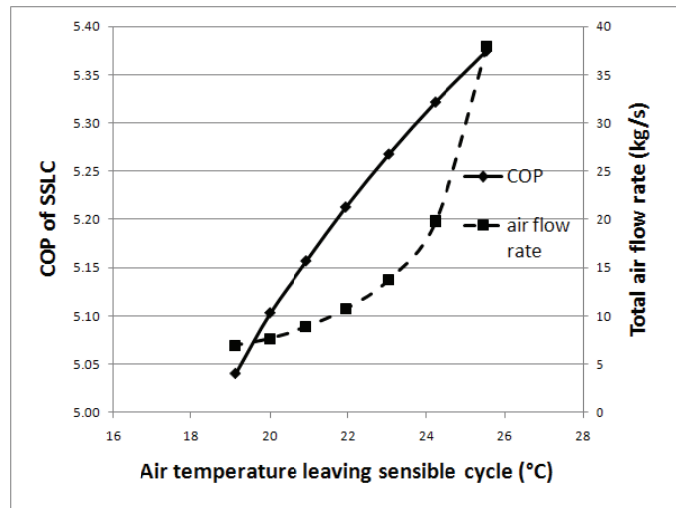

Figure 3: COP and total air flow rate under different air temperature leaving sensible evaportor
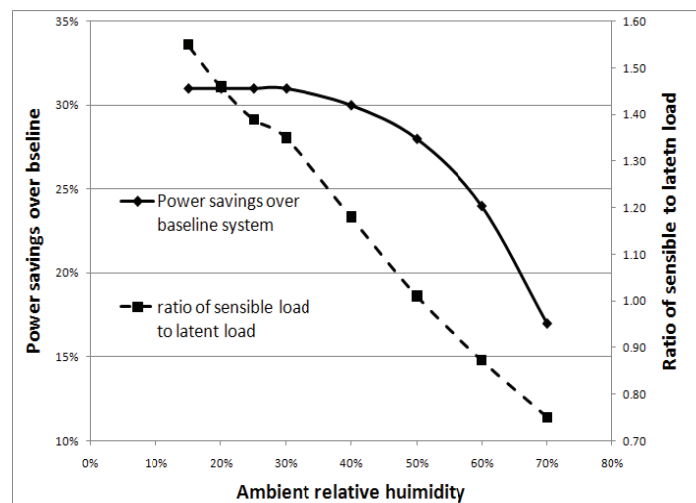

Figure 4: Power savings under different ambient relative humidity

Figure 5 shows the power savings under different ambient temperatures. The ambient humidity ratio is set to be constant at 15 g/kg dryair, while the temperature ranges from 25°C to 40°C. The ratio of the sensible to latent cooling increases with the ambient temperature. Meanwhile, the power savings remain almost constant. This trend indicates that the power savings of the system are greatly affected by the latent load of the system but not much affected by the sensible load.

To evaluate the performance of the SSLC system over a wide ranging envelop of the ambient conditions, the system performance was modeled under different climatic conditions shown on the psychrometric chart in Figure 6. The power savings over the baseline system are calculated for different climate conditions. The results are summarized in Table 1. While the maximum power savings are achieved in the cool and dry conditions, the minimum in the hot and humid conditions. It has been observed that, under hot and humid conditions, the power of the latent cycle accounts for 70% of the total power consumption and affects the total power savings of the SSLC system.
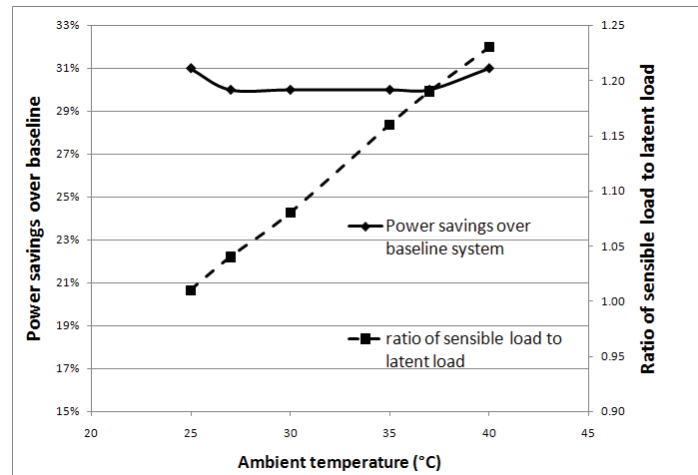

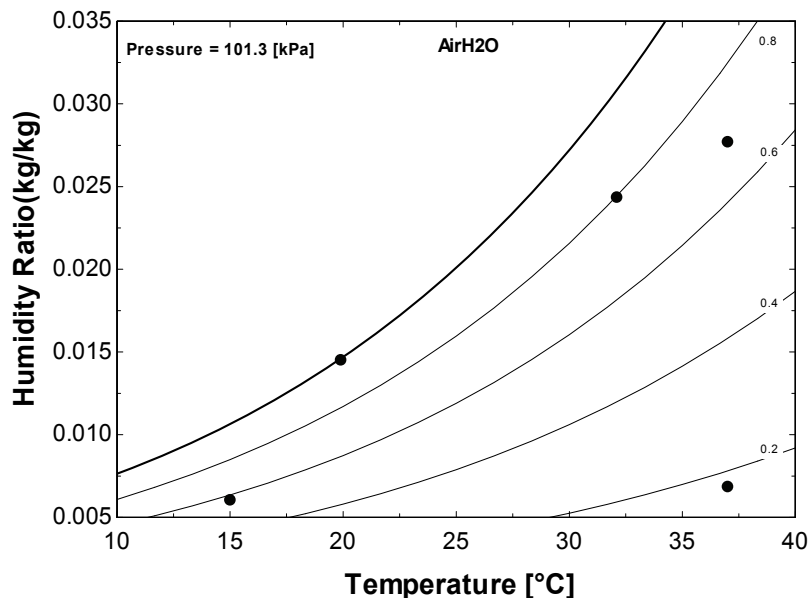Figure 5: Power savings under different ambient temperature

Figure 6: Three zones on the psychrometric chart (clockwise from the top right: hot and humid; hot and dry; cool and dry; cool but humid and humid)

Table 1: Power savings under different climate conditions

Zone	Standard	Cool and dry	Cool but humid	Hot and dry	Hot and humid	Humid
Condition	35°C/44%RH	15°C/55%RH	20°C/100%RH	37°C/15%RH	37°C/70%RH	32°C/80%RH
Power savings	30%	50%	33%	32%	17%	22%

4. CONCLUSIONS

The theoretical study of an SSLC system using R410A was conducted. Under ARI standard ambient conditions for the air-conditioning (35°C, 44% RH), 30% energy savings are calculated for the SSLC system compared with a conventional baseline system. The main reason for energy savings comes from treating the sensible heat load separately using higher evaporating temperatures and higher air flow rates. The evaporating temperature increases to 19°C for the sensible cycle instead of the 6°C in the baseline system. 9 kW power savings are achieved because of the smaller compressor pressure ratio and the better compressor efficiency while providing the same amount of sensible cooling. Parametric studies show that the SSLC system has a higher energy saving potential if the sensible heat load accounts for a larger portion of the total cooling load. For example, the power savings are around 32% at dry condition (37°C, 15% RH) and 17% at humid condition (37°C, 70% RH), which is expected, because of the less contribution from the sensible cycle. Under the same ambient condition, increasing sensible cycle air temperature can change the COP of the SSLC system. However, the trade off is higher air flow rate. The total air flow rate through the systems can be up to 5 or 6 times higher than that of the baseline system which may result in substantial increase in the fan power consumption. Conventional blowers may offset the power savings from the compressors. However, the propeller fan integrated with an innovative duct design can deliver higher air flow at lower power consumption, and is suggested for the SSLC system.

NOMENCLATURE

ARI	Air-Conditioning and Refrigeration Institute		**Superscript**	
COP	Coefficient Of Performance		iso	isentropic
EES	Engineering Equation Solver			
HX	Heat Exchanger			
PR	Pressure Ratio			
RH	Relative Humidity			
SHF	Sensible Heat Factor			
SSLC	Separate Sensible and Latent Cooling			
UA	UA value of heat exchanger	(kW/K)		
η	Compressor efficiency			

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