Hybrid Air-conditioning System Efficiency for Districts in the Tropics

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ABSTRACT

Hybrid air-conditioning systems in buildings have a high potential to utilize resources in an efficient and sustainable manner in districts. The goal of this study is to compare the performance of hybrid air-conditioning systems at building and district scale in the tropics. For this, we gather operational data of an office with a hybrid air-conditioning system in Singapore and analysed the energy saving potential of separating latent and sensible cooling processes at the district scale. The effect was quantified with a virtual case study composed of 11 office buildings in Singapore. We compared decentralized and centralized options for the supply of High-temperature and Low-temperature chilled water. For the case study, the cooling consumption per area at the district scale can be potentially reduced by 24% in comparison to the current supply system at the building scale. A further study is necessary to determine optimal operation strategies and associated costs of hybrid air-conditioning systems at the district scale.

Keywords: *district cooling, hybrid air-conditioning systems, energy supply systems*

1. INTRODUCTION

Conventional air-conditioning systems in hot and humid climates remove the latent and sensible heat of buildings with a low temperature of condensation close to 6 °C. By separating latent and sensible heat removal process, hybrid air-conditioning systems can increase the temperature of condensation to approximately 17.5 °C for sensible heat removal. This strategy increases the energy efficiency of cooling equipment (Chua et al., 2013) (Mujahid Rafique et al., 2015).

Various hybrid Air-conditioning systems are proposed and implemented in many recent studies (Kojok et al., 2016; Mandegari and Pahlavanzadeh, 2009). For example, Kojok et al. present a thorough review on five configurations of hybrid cooling systems. Within these, the combined desiccant-vapor compression cooling system is recommended for the hot and humid climate.

Ventilation units of hybrid air-conditioning systems could be either centralized or decentralized. A centralized ventilation system consists of centralized air handling ducts distribute the cooled and dehumidified air to the indoor spaces. Instead of centralized air distribution, a decentralized system consists of air handling units installed in the vicinity of the space to be cooled, the dehumified air is sent to indoor space directly. In the past, centralized and decentralized ventilation units of hybrid-air-conditioning have been proposed in office buildings in Singapore (Meggers et al., 2013; Rysanek et al., 2016), Hong-Kong (Fong et al., 2011) and Shengzhen, China (Zhao et al., 2011).

This paper explores the energy saving potential of hybrid air-conditioning systems for offices at the district scale. For this, we gathered real operation data of the hybrid air-conditioning system of (Schlueter, 2015) and compared configurations with decentralized and centralized options for the supply of chilled water in a district in Singapore. The district consists of 11 office buildings connected to a district cooling network of close to 2 km of length.

2. METHODOLOGY

2.1 Relative office cooling load

The decentralized hybrid air-conditioning system studied in this paper consists of decentralized air handling units (DOAS), fan coil unit (FCU), and passive chilled beams (PCB). The DOAS and FCU provide latent cooling to outdoor and recalculated indoor air respectively. The humidity target is 8 g/kg (Murray et al., 2015). While the PCB circulate cold water to remove sensible heat from the room. Chilled water for both latent and sensible heat removal is provided from the same chiller plant at around 7.6°C. The latent cooling coils in the DOAS and FCU use the chilled water directly from the plant, while the PCB runs water at ~17.5 °C, which the cooling energy is extracted from the chilled water stream (7.6°C) with heat exchangers.

The hourly thermal load of the system, Q_cooling, is acquired through the building management system (BMS) of an office of 550 m2 of gross-floor area for a period of 4 weeks in July.

2.2 Supply system energy consumption

The energy consumption of the cooling equipment is calculated with Equation 1, where Qcooling is the office cooling load. The result was normalized to the GFA to facilitate the further extrapolation of results to the district scale.

$$W_{el} = Q_{cooling} \times COP_{chillerplant}$$

Equation 16

In Equation 1. 〖COP〗_(chiller plant) represents the efficiency of the chiller plant or Coefficient of Performance. 〖COP〗_(chiller plant) is calculated according to Equation 2., where g is the exergetic efficiency. The second term on the right side of the equation is the carnot efficiency, where Te is the temperature from the chiller evaporator, and Tc = 26.5 °C is the temperature of the condenser assumed as constant throughout the day.

$$COP_{chillerplant} = g \times \frac{T_e}{T_c - T_e}$$

Equation 2

Beside the cooling energy consumption, the total energy consumption also consists the pumping energy consumption for district network, and energy used from fans for building ventilation. The total energy consumption is normalized to the Gross Floor Area (GFA) for further extrapolation of results to the district scale.

The fan power for building ventilation depends on the building level system control strategies, therefore, the fan power of the decentralized hybrid air-conditioning system studied in this paper is acquired from the BMS data.

The pumping power in the district cooling network is calculated with Equation. 3. The head of pressure is calculated with Darcy-Weisbach equation (Menon, 2011) assuming commercial welded steel with a roughness of 0.046 mm. The friction factor,f_D , is approximated with the Swamee-Jain equation (Menon, 2011). In Equation. 3., P is resulting pumping power requirement in W, v ̇ is the volumetric flow rate in m3/s, ρ is the water density in kg/m3, D is the pipe diameter in m, and L_ Equation is the network length equivalent in m. The L_ Equation is approximated as 1.2 times of the network distance to account for other friction losses from bends, valves and other components. The shaft efficiency and motor efficiency is assumed to be 0.7 and 0.9 respectively.

$$P = \dot{v}\rho g \Delta h = \dot{v}\rho g \times f_D \frac{8}{\pi^2 g} \frac{\dot{v}^2}{D^5} \cdot L_{eq}$$

Equation 3

2.3 Supply system configurations

There are two ways to improve the efficiency of the cooling system from the cooling energy supply side according to Equation 2. One is to increase the chiller evaporator temperature, Te, and another is to use machines with higher exergetic efficiency, g. For this reason, we explore the efficiency improvement from supplying sensible cooling with chillers operating at higher temperature, and from using large scale centralized chillers in the district cooling network.

The chillers at the building and district scale are assumed to respectively operate at an exegetic efficiency of 0.3 and 0.6, since the large scale chillers could operate at higher exergetic efficiency (Meggers et al., 2012)

We decide to set up three configurations with combinations of high-temperature (HT) and low-temperature (LT) chillers at building and district scales to compare the energy efficiency of the current supply system (base case). Configuration 1 consists only building level chillers, these chillers supply cold water for sensible cooling at high temperature and latent cooling at a lower temperature. Moving to the district scale, configuration 2 has a district cooling connection with centralized HT chillers, and LT chillers in buildings. Configuration 3 is the opposite of configuration 2, centralized LT chillers are installed at the district scale and HT chillers are installed at the building scale.

The supply (Tsupply) and return (Treturn) temperatures in the base case are retrieved from the office operational data. For the other three configurations, the Tsupply and Treturn are determined with assumptions explained in the following. In configuration 1, the LT chillers are operating at the conventional temperature range for air dehumidification, while the HT chillers only supply cold water to the PCB for sensible cooling, which operates at an average temperature of 18 °C. District scale chillers have lower supply temperatures and higher return temperatures to account for cooling energy losses in the pipelines, therefore, imposing larger cooling loads to the chillers (Tredinnick and Phetteplace, 2016). 10% heat loss is assumed in this study.

	Building scale chillers			District scale chillers	
Base Case	LT				
Config.1 (Building)		LT	HT		
Config. 2 (HT DC)		LT			HT
Config. 3 (LT DC)			HT	LT	
COP*	6.2	5.3	10.5	8.6	17.0
T_{supply} / T_{return} [˚C]	7.6 / 17.2	7.6 / 11	16 / 20	6.6 / 14	15 / 21
LT: Low Temperature chillers, HT: High Temperature chillers, DC: District Cooling.					
Assumptions: 1. The chiller plants are well modulated, therefore operates at constant COP in each hour. 2. The pipe hydraulic diameter is 1.58 m for HT DC network and 1.26 m for LT DC network, assuming water speed in the pipe is 3m/s. 3. Pump capacities are sized for the maximum flow rate, and the pumping energy is calculated assuming a Darcy's roughness coefficient of 0.046 mm (welded steel).					

Table 1: Supply system chiller configurations and operational conditions of the current cooling system (base case) and three alternative configurations.

2.4 Case study

A case study with 11 office buildings in the central business district of Singapore is set up to assess the performance of the hybrid air-conditioning system at the district scale. Similar to the existing district cooling pipeline situated at the Marina bay area in Singapore, one centralized chiller plant supplies cooling load for all 11 office building. The building GFA ranges from 90,900 to 653,000 m2. The total district network length is 2.3 km. Since the district is situated in a tropical climate with steady patterns of temperature and relative humidity through the year, it is assumed that all of the office buildings has the same weekly load profiles. Additionally, the chillers are sized for the peak cooling load over a week.

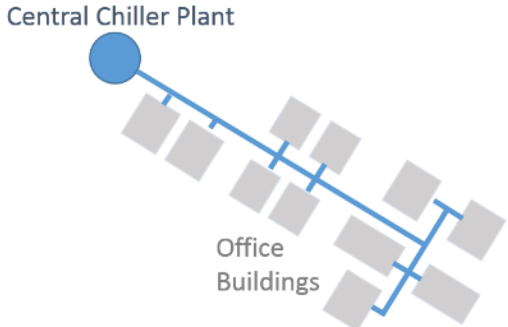

Figure 1: Case study site with 11 office buildings connection to a district cooling network with a centralized chiller plant.

	Building		District		
Chillers sizes [W/m2]	LT	HT	LT	HT	Total
Base Case	0.076				0.076
Config. 1 (Building)	0.038	0.049			0.087
Config. 2 (HT DC)	0.038			0.054	0.092
Config. 3 (LT DC)		0.049	0.042		0.091

LT: Low Temperature chillers, HT: High Temperature chillers

Table 2: Chiller size in each supply system configuration.

3. RESULTS

3.1 Relative cooling loads

The average weekly office cooling load acquired from 4 weeks of office BMS operational data is shown in Fgure 2. The latent heat ratio is 40%, with an average cooling load of 3.16 kWh/m^2 per week, which equals to 0.05 kWh/m^2 per hour of office operation.

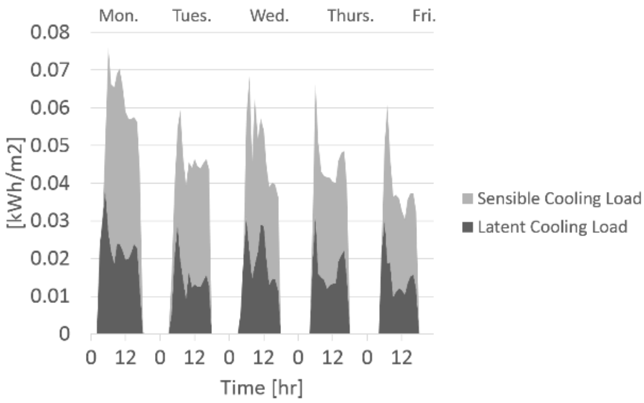

Figure 17: Average hourly office cooling load in July in Singapore.

3.2 Cooling energy consumption

The resultsing total cooling energy consumptions for each configuration are calculated using the methods and assumptions described in section 2.2 and 2.3. The cooling energy consumptions of different supply system configurations are shown in Table 3. Figure 3 shows the hourly energy consumption over a week of the base case and configuration 3, the configuration with the lowest total energy consuption.

	Total energy consumption [kWh/m2/week]	Sensible cooling	Latent cooling	Pumping**	Fan
Base Case	0.72	42.8%	28.0%	-	29.2%
Config.1 (Building)	0.63	28.9%	37.7%	-	33.4%
Config.2 (HT DC)	0.59	19.9%	40.2%	4.4%	35.5%
Config.3 (LT DC)	0.55	32.8%	27.0%	2.3%	37.9%

Table 18: Cooling energy consumption of each supply system configuration

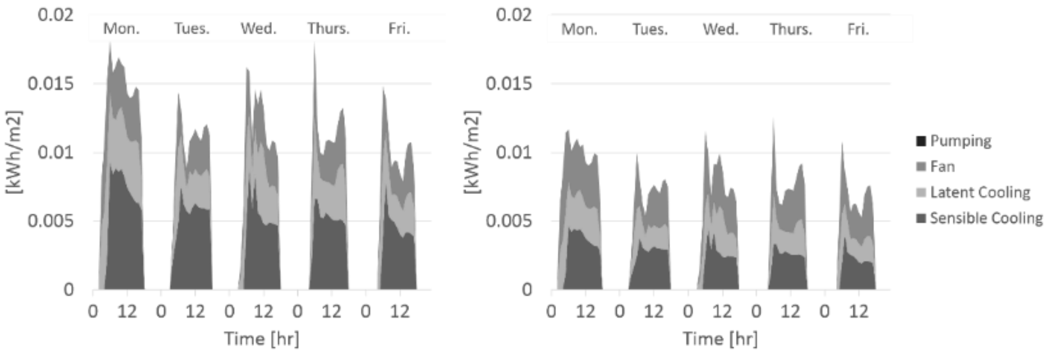

Figure 3: Hourly energy consumption of the base case (left) and configuration 3 (LT DC) (right).

4. DISCUSSION

The office building studied in this paper presents a latent cooling load ratio of 40%, which is higher than the conventional cooling system design capacity, which is around 25% (Mujahid Rafique et al., 2015). For the case study, the cooling energy consumption is reduced by 11% in configuration 1 (Building) comparing to the base case. Within the 11% reduction, the major part is coming from the 40% energy saving in sensible cooling load attended by HT chillers. The energy consumption for sensible cooling is lower than the energy consumption for latent cooling since HT chillers operate at better efficiency.

Besides, using high temperature chillers enables more renewable energy integration. As opposed to using electricity from grids as the main energy source, high temperature chillers could be supplied by various renewable sources with good efficiency, such as absorption chiller using solar thermal energy or waste heat (Udomsri et al., 2011).

When operating the supply system at the district scale, configuration 2 and 3 respectively reduce 19% and 24% of the energy consumption comparing to the base case. Configuration 3 with a LT network has lower consumption than configuration 2 with a HT network. The reason is that the benefit of replacing LT chillers in buildings with a LT network is slightly higher than replacing HT chillers in buildings. Also, the pumping energy requirement for LT network is lower because building latent loads are lower than sensible loads, therefore, the required flow rate is smaller.

The resulting centralized LT chiller plant of configuration 3 is equipped with 11.2 MW capacity. Since the district only consists of office buildings with identical load profiles, the LT centralized chiller plant operates most of the time at part load. If the district cooling network is connected to buildings with different load profiles, the chiller plant could operate at higher loads or operate outside the current operation periods. For example, the load profiles from residential buildings, which the cooling demand starts from 5pm to 7am (Chow et al., 2004), could complement well with the office cooling load . The installed chiller capacities are better utilized when connecting buildings with different load profiles to a district network, this way, the cumulative chiller loads are increased but no additional capacity expenditures on chillers required. This load sharing benefit is not applicable to the building scale chillers since the current centralized district cooling scheme does not allow transferring surplus capacities from various buildings back to the cooling network.

On the other hand, central chiller plants could be complemented with thermal storages, which is normally not feasible at the building scale due to space restrictions and costs. Thermal storage could shift the peak cooling consumption away from the peak cooling load period, which provides system flexibility (Powell et al., 2013) and financial benefits when peak energy tariffs are high.

5. CONCLUSIONS

This study presents the energy efficiency improvement opportunities from the supply system side when sensible and latent cooling energy is utilized separately in the building operation systems. 11 % reduction in total energy consumption compare to the base case is achieved in configuration 1, which supplies cooling energy with HT and LT chillers at the building scale. Furthermore, the consumption is reduced by 26% when connecting buildings to district energy network. This is the advantage of utilizing large scale chiller with higher exergetic efficiency. Additionally, HT chillers could be powered efficiently from renewable energy sources, e.g. solar thermal, which enables more renewable energy penetration.

Beside better energy efficiency performances, centralized chiller plant also presents several benefits that normally are not applicable to building scale chillers. The first benefit is the opportunity to connect to more building types with different cooling load profiles (e.g. residential buildings), this way, more cooling loads could be produced from the same chiller plant without additional capital investment. The extra capacity in the building level chillers are not sharable in the framework of the current district cooling network with centralized production, however, it is possible when implementing a cooling network with bi-directional energy flows. Secondly, the possibility to utilize thermal storage to produce cooling energy at the period with lower tariff could reduce operational expenses. In addition to cost savings during operation, thermal storage could provide system flexibility and financial benefits.

Despite the advantages of hybrid air-conditioning systems, hybrid air-conditioning systems require specialized control systems to ensure efficient operation. Further studies could lie on determination of the optimal chilled water supply temperatures and quantification of benefits from the storage and load sharing schemes mentioned above. The first part could be done by pinch analysis, which is a process integration technique to determine the minimum amount of hot and cold utilities and temperature level requirements. The second part could be done by computational models, which can be used to perform a detailed dynamic simulation of control strategies applicable to the system's configurations addressed in this study. Key configurations of interest include integrating thermal storage units, residential buildings, renewable energy and bi-directional flows in a thermal network.

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