

DESIGN AND PERFORMANCE ASSESSMENT OF THERMAL COMPREHENSIVE UTILIZATION SYSTEM: CASE STUDY

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Abstract: For the purpose of recovering waste heat/cool from cooling tower and exhaust air, the paper brought up a thermal comprehensive utilization system (TCUS) based on the case of People's Square in Shanghai, China. It uses heat pumps as major devices, and water loop to transmit heat in multiple buildings. A triple-fluid heat exchanger is developed and introduced into the system as well. According to modeling and performance assessment results for 6 cities in China, TCUS can be used in different regions with different climate features, and will save energy compared to conventional air-conditioning system, especially in cold and severe cold region. However, the problems of small temperature difference between high-temperature and low-temperature water loop in cooling season, indicates heat transfer efficiency of the triple-fluid heat exchanger need to be improved.

Key Words: heat recovery, heat pump, water loop, heat exchanger, assessment index

1 INTRODUCTION

In an air-conditioning (AC) system, waste heat typically exists in condenser of a chiller and in exhaust warm air. In cooling season, latent heat discharged by refrigerant vapor during phase changing in condenser could be recovered to heat liquid refrigerant or domestic water. In heating season, exhaust air heat recovery could be used to pre-heat fresh air and domestic water. In addition, condensing boiler recovering waste heat from flue gas to pre-heat water is quite popular.

For condenser heat recovery, a heat exchanger is capable enough, thanks to large temperature difference between refrigerant vapor and liquid refrigerant or domestic water. Another option is recovering waste heat from high-temperature cooling water or exhaust air out of condenser. This indirect way may be less efficient, but can switch waste heat to further places, especially by cooling water. In that case, the heat pump may be needed, i.e. water loop heat pump (WLHP) ([Zaheer-Uddin and Wang 1992](#)), ([Buonomano et al. 2012](#)).

For exhaust air heat recovery, a heat exchanger is capable as well, although the temperature difference is not as large as in condenser. Many forms of devices are on its basis, such as thermal wheel. Heat pump can also be used to heat domestic water or heating system water (i.e. floor heating), as called exhaust air heat pump (EAHP) ([Fehrm 1990](#)), ([Fracastoro and Serraino 2010](#)).

However, heat recovery may be useless, if the time when waste heat exists and when heat is in need are not exactly the same. So does the place. To make full utilization of waste heat, this paper brought up a thermal comprehensive utilization system (TCUS) based on a district, where different places with waste heat and/or needing heat at different time exist together (Ye 2011). It's followed by system modeling and performance assessment.

2 THERMAL COMPREHENSIVE UTILIZATION SYSTEM

2.1 System concept

Thermal heat is discharged by human body, electrical equipment, and lamps, and hence become waste heat. Air, water and refrigerant are all carriers of waste heat. Besides chiller and boiler, waste heat could be recovered from cooling water, exhaust air and sewage water by water-source heat pump (WSHP), air-source heat pump (ASHP) and sewage water-source heat pump (SWSHP), respectively, as shown in Figure 1.

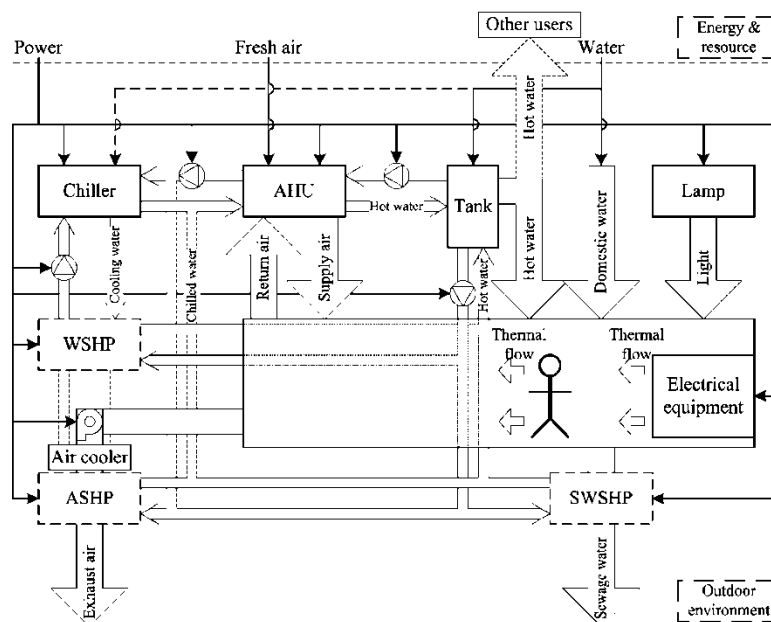


Figure 1: Thermal carrier flow of TCUS

In cooling season, WSHP recovers heat from cooling water for domestic hot water (DHW) or re-heating in AHU to avoid supply air condensation. The rest of condenser heat in cooling water is discharged via air-cooler in exhaust air shaft, instead of cooling tower. ASHP works at cooling mode during peak load period.

In heating season, ASHP works at heating mode, recovering heat from exhaust air for supply air heating. SWSHP works as well, although its heating capacity is much less than ASHP. In that way, boiler is not in need any more.

2.2 Case introduction

People's Square in Shanghai, China, is chosen as study case. There are 3 subway stations, 2 underground shopping centers, 1 underground car park and 10 hotels/hostels in this area, as shown in Table 1 and Table 2. Six cities with different climate conditions, namely Harbin (HRB), Beijing (BJ), Xi'an (XA), Shanghai (SH), Chongqing (CQ) and Guangzhou (GZ), China, are introduced to study the applicability and performance of TCUS with the same case.

Table 1: Case underground buildings in People's Square in Shanghai, China

Case building	Abbreviation	AC area (m ²)	People peak flow (h ⁻¹)
Subway station of Line 1	SS1	3000	54219
Subway station of Line 2	SS2	3000	23283
Subway station of Line 8	SS3	3000	18978
Hong Kong Shopping Centre	SC1	8600	3400
Shanghai DMC Shopping Centre	SC2	18000	9000
Underground car park	CP1	25000 (ventilating only)	N/A

Table 2: Case hotels in People's Square in Shanghai, China

Case hotel	Abbreviation	Guest rooms	DHW consumption (m ³ /d)
Yangtze Langham Hotel	HT1	96	37.6
Dongfang Hostel	HT2	50	34.4
Far East Hostel	HT3	80	
Mingtown Etour Youth Hostel	HT4	265 (beds)	26.5
Marriot Executive Apartment	HT5	255	30.6
JW Marriot Hotel	HT6	342	134.1
Park Hotel Shanghai	HT7	252	80.3
Sports Building Hostel	HT8	32	
Pacific Hotel	HT9	183	59.3
Radisson Blu Hotel	HT10	520	203.9

2.3 System design

According to design standard, indoor air parameters are set as shown in Table 3. The differences of system configuration among six case cities are summarized in Table 4. Regardless these differences among cities, water loop of TCUS shown in Figure 2 is same. The loop length is about 2000 meters, and the diameter is DN600. Circle of the loop in solid line and dash line, represents high-temperature loop (HTL) of 37°C and low-temperature (LTL) of 32°C, respectively. The directions of water flow in both circles are clockwise.

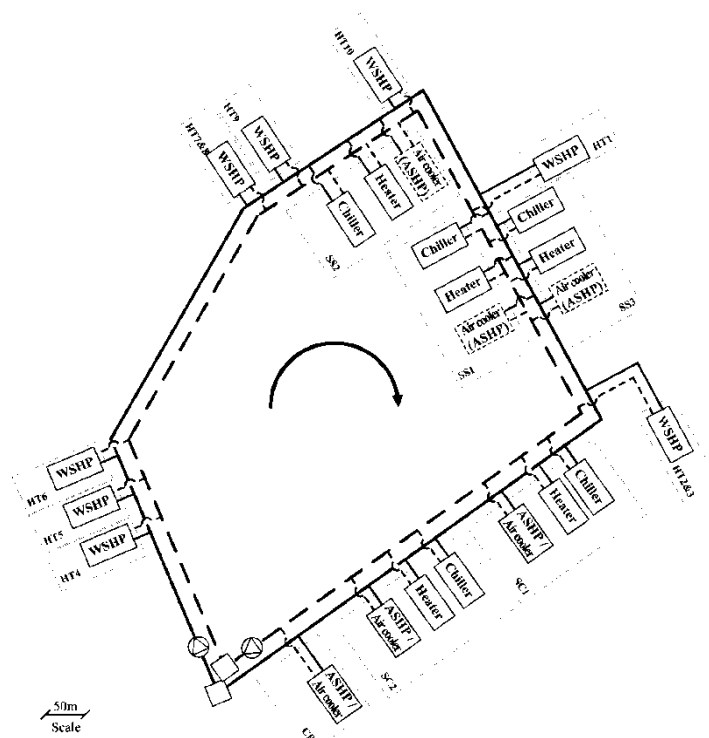
**Figure 2: Schematic plan of TCUS for case study**

Table 3: Indoor air design parameters

Building		Cooling mode		Heating mode		Fresh air volume (m ³ /h·p)
		Temperature (°C)	Relative humidity (%)	Temperature (°C)	Relative humidity (%)	
SS1, SS2, SS3	Hall	26 - 30 ^a	40 - 65	12 - 18 ^a	30 - 60	30 / 12.6 ^b
	Platform	26 - 29 ^a	40 - 65	12 - 18 ^a	30 - 60	
SC1, SC2		26	40 - 65	18	30 - 60	20
CP1		N/A	N/A	≥ 5	N/A	Air exchange rate is 6 h ⁻¹

Note: a. Adjusted to relatively comfortable temperature according to outdoor air temperature;

b. The former is for all fresh air mode, and the latter is for primary return air mode.

Table 4: System key parameters in case cities

City	Chiller cooling capacity (kW)					Supply air volume (10 ³ m ³ /h)					WSHP heating capacity (kW)								ASHP heating capacity (kW)					
	SS1	SS2	SS3	SM1	SM2	SS1	SS2	SS3	SM1	SM2	HT1	HT2&3	HT4	HT5	HT6	HT7&8	HT9	HT10	SS1	SS2	SS3	SM1	SM2	CP1
HRB	1160	670	670	1780	3560	148	108	102	219	505	145	145	145	145	582	446	145	873	1572	1572	1572	786	1572	1703
BJ	1392	928	670	1780	4176	148	110	105	232	515														
XA	1160	670	670	1780	4176	129	103	99	236	519														
SH	1392	928	670	2436	4872	131	104	101	240	523														
CQ	1392	928	670	2088	4872	134	107	103	244	526														
GZ	1392	928	670	2436	4872	136	108	105	246	523														

In Figure 2, there are 5 types of main devices, namely chiller, heater (or heating section) in AHU, WSHP, ASHP and air cooler. To simplify the whole system, and also for the purpose of intuitive feeling, a tridimensional ring network of TCUS water loop is shown in Figure 3.

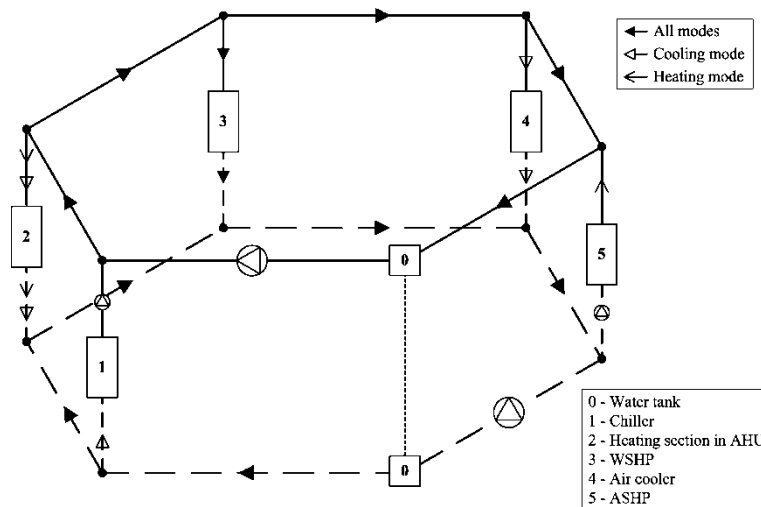


Figure 3: Simplified structure of TCUS's tridimensional ring network

2.4 Key equipment

A triple-fluid heat exchanger (TFHEX) is developed, to combine air cooler and air-side heat exchanger of ASHP. TFHEX is based on plate-fin and tube, where air flows parallel to the plate and circulating water in the loop flows perpendicular to the plate. Considering that air flows in only one direction parallel to the plate, another direction parallel to the plate but perpendicular to the plate is added with refrigerant coil. As shown in Figure 4, water tube is perpendicular to the plate, whilst refrigerant coil is on the plate. It is supposed to be installed in exhaust air shaft. TFHEX works under 3 modes in the system, as summarized in Table 5.

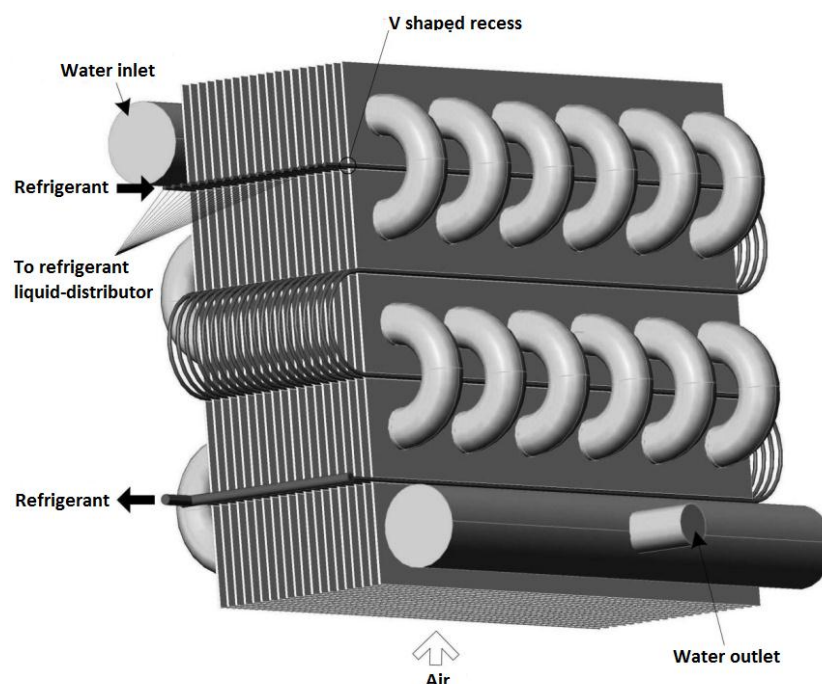


Figure 4: Triple-fluid heat exchanger (TFHEX)

Table 5: TFHEX working modes

Working mode	High-temperature fluid	Low-temperature fluid	Complementary
Direct air cooling	Circulating water in the loop	Exhaust air	N/A
Indirect evaporative cooling	Circulating water in the loop	Exhaust air	Water spray
Refrigerant evaporating	Exhaust air	Liquid refrigerant	N/A

3 SYSTEM MODELING

The methods of modeling on each kind of devices in TCUS are mature, except for triple-fluid heat exchanger. In this case, TFHEX is modeled simply as traditional heat exchanger according to three working modes mentioned above. However, the modeling is just a stopgap measure, due to low accuracy.

The water loop is modeled in Equation (1) and (2) based on heat balance and mass balance. Each pipeline segment of the water loop is modeled as a node.

$$C_i \frac{dt_i}{d\tau} = c_w \left[\sum (\dot{m}_{in} t_{in})_i - \sum (\dot{m}_{out} t_{out})_i \right] - \frac{K_{insl} A_i (t_i - t_{a,en})}{1000} \quad (1)$$

$$\sum (\dot{m}_{in})_i = \sum (\dot{m}_{out})_i \quad (i=1,2,\dots,n) \quad (2)$$

Here, C_i is heat capacity of node i (J/°C), t_i is water temperature of node i (°C), τ is time step (s), c_w is specific heat capacity of water of 4.187 kJ/(kg·°C), $\dot{m}_{in}, \dot{m}_{out}$ is mass flow of water entering or leaving (kg/s), t_{in}, t_{out} is temperature of water entering or leaving (°C), K_{insl} is heat transfer coefficient of pipe insulating material [W/(m²·°C)], A_i is heat transfer area of node i (m²), $t_{a,en}$ is ambient temperature (°C).

4 PERFORMANCE ASSESSMENT

4.1 Water loop performance

HRB and GZ locating most northerly and most southerly among 6 case cities, respectively, are chosen for performance study on TCUS water loop, as shown in Figure 5 and Figure 6. Water temperature in both HTL and LTL changes in a range of plus or minus 3 degree, maintaining relative stability. However, the problem is that, the hotter in summer, the smaller the temperature difference between 2 loops. High temperature of cooling water inlet of condenser decreases chiller efficiency. The major reason lies in low efficiency of TFHEX, which needs to be solved in further research work.

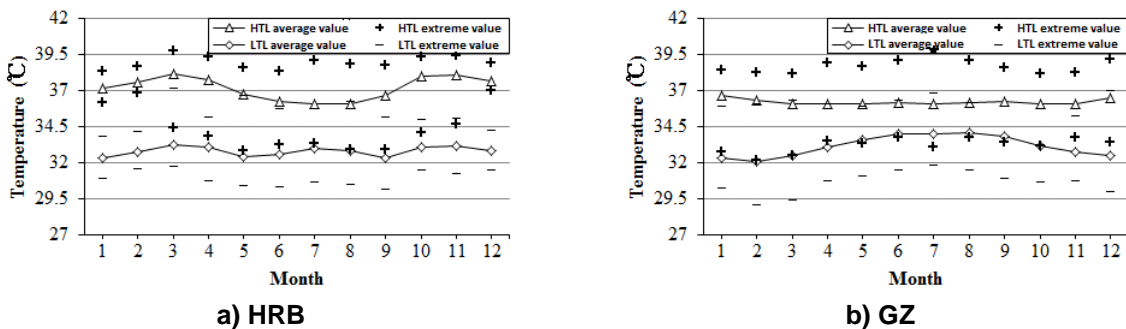


Figure 5: Average & extreme water temperature of TCUS loop in each month

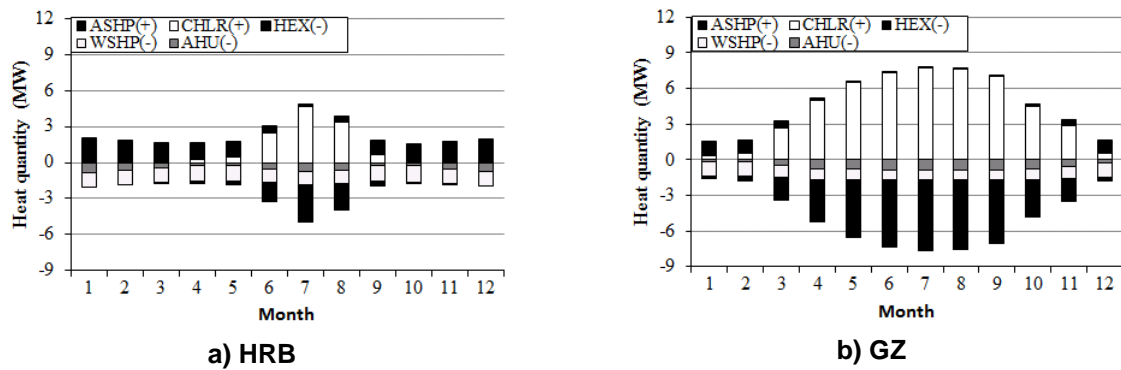


Figure 6: Average gaining & releasing heat quantity of TCUS loop in each month

Heat balance of water loop can be observed from Figure 6. Most heat in water loop can be recovered in HRB to heat DHW, whilst most in GZ needs to release by air cooling. That suggests TCUS is more suitable in cool and cold climate, such as HRB.

4.2 Energy efficiency assessment

Four indices are set to assess energy efficiency of TCUS as follows:

- Comprehensive energy efficiency ratio (CEER): the ratio of heating quantity (including DHW heating as well) and cooling quantity to energy (electrical power) consumption of TCUS, to assess overall energy efficiency
- Thermal comprehensive utilization rate (TCUR): the ratio of heating quantity (including DHW heating as well) to waste heat quantity discharged by human body, electrical equipment, and lamps, to assess waste heat utilization efficiency.
- Thermal recovery efficiency (TRE): the ratio of heating quantity (including DHW heating as well) to energy (electrical power) consumption of heat recovery devices, to assess waste heat recovery efficiency.
- Water loop efficiency (WLE): the ratio of gaining (or releasing) heat quantity of water loop to energy (electrical power) consumption of water loop pump, to assess heat transfer efficiency.

Assessment results for 6 case cities are summarized in Table 6. All CEERs are in a range of 1.7 to 1.8, indicating power inputting for heating and cooling efficient. Telling from TCUR, more than half of waste heat is recovered. In severe cold region such as HRB, the ratio may reach to 70 percent. Energy consumption of chiller is taken into account in TREs, considering that chiller is also a heat recovery device to transfer waste heat into the water loop. Under this premise, all TREs are larger than 1.0, indicating heat recovery efficient as well. The larger the temperature difference between 2 loops, the bigger the WLE. There exist large differences of WLEs among cities. However, overall level of WLEs is not high, due to small temperature difference between 2 loops mentioned in Section 4.1.

Table 6: Annual energy efficiency assessment indices of case cities

City	CEER	TCUR	TRE	WLE
HRB	1.80	0.68	1.86	40.45
BJ	1.70	0.64	1.58	17.17
XA	1.77	0.64	1.60	18.73
SH	1.75	0.66	1.48	12.52
CQ	1.76	0.62	1.36	11.22
GZ	1.72	0.58	1.15	8.30

4.3 Energy saving potential

There are boilers and cooling towers in conventional AC system. Energy consumptions of conventional system and TCUS in 6 case cities are shown in Figure 7. When measuring energy consumption by equivalent electricity quantity, TCUS is more efficient in all places, thanks to waste heat utilization. Energy saving rate is more than 40 percent when TCUS is used in HRB. However, TCUS cannot save power coal when used in southern China, when taking electrical production and transmission loss into consideration.

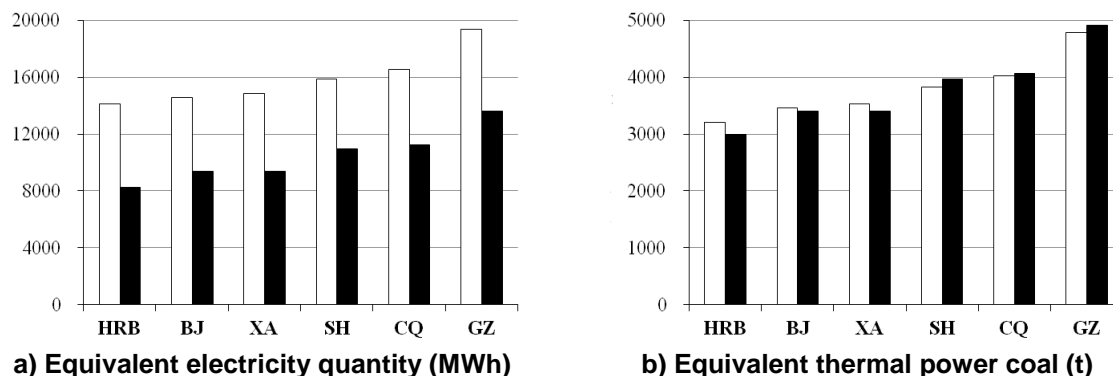


Figure 7: Annual energy saving of TCUS compared to conventional system

5 CONCLUSION

For a concentrated area with DHW need, TCUS combining current devices such water chiller, ASHP and WSHP with water loop could be applied. Modelling result shows that TCUS works in a relative constant state. TCUS saves energy compared to conventional AC system, especially in cold and severe cold region. However, temperature difference between 2 water loops in cooling season is too small to release large amounts of condenser heat. As far as concerned to next R&D work, heat transfer effect of TFHEX needs to be improved. Furthermore, a new style of chiller and/or ASHP combined with TFHEX, which could be more efficient and compact, needs to be developed.

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