**A novel thermal storage strategy for CCHP system based on energy demands
and state of storage tank**

C.Y. Zheng^a J.Y. Wu^{a*} X.Q. Zhai^a R.Z. Wang^a

C.Y. Zheng:

Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University,
Dongchuan Road 800, Shanghai 200240, China.

E-mail: zhengchunyuan@sjtu.edu.cn

J.Y. Wu:

Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University,
Dongchuan Road 800, Shanghai 200240, China.

Prof. Wu is the corresponding author.

Tel: +86-21-34206776; Fax: +86-21-34206814

E-mail: jywu@sjtu.edu.cn

X.Q. Zhai:

Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University,
Dongchuan Road 800, Shanghai 200240, China.

E-mail: xqzhai@sjtu.edu.cn

R.Z. Wang:

Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University,
Dongchuan Road 800, Shanghai 200240, China

* Correspondence to: Dr. J.Y. Wu, Tel. and Fax: (86-21) 34206776, E-mail: jywu@sjtu.edu.cn.

Abstract

Under the thermal storage strategies in present studies, the power generation unit (PGU) in combined cooling, heating, and power (CCHP) system is turned on/off only based on the state of storage tank; or the operation state of PGU is determined by thermal demand or/and electric demand, which has no relationship with the state of storage tank. For these traditional strategies, either energy demands or state of storage tank is considered for the operation of system. This paper proposes a novel thermal storage strategy (TSS2) for CCHP systems, which determines the operational state of the PGU based upon electric demand, thermal demand and the state of thermal storage device. In this paper, the operation principle of TSS2 is described and compared with the traditional strategies. A hospital in Shanghai was used to evaluate and compared the performance of the system operating under different storage strategies. The results show that TSS2 improves the performance of CCHP system more significantly compared with the traditional strategies. TSS2 can make both PGU and capacity of thermal storage tank be fully used by CCHP system to produce more electric and thermal energy to meet demands of building. Compared with system without thermal storage, the minimum and maximum increase rates of annual total cost saving for traditional strategies are 0% and 14.84%, respectively. However, for TSS2, they can reach 3.79% and 20.22%. Similar conclusions could be achieved for CO₂ emission reduction and primary energy saving. The effect of TSS2 on the CCHP system performance is different under different operation strategies.

Keywords: CCHP systems; operation strategy; thermal storage strategy

Nomenclature

ATC	Annual total cost
ATCS	Annual total cost saving
CCHP	Combined cooling, heating and power
CHP	Combined heating and power
CO ₂ E	CO ₂ emission
CO ₂ ER	CO ₂ emission reduction
COP	Coefficient of performance
FEL	Following the electric load
FHL	Following hybrid electric-thermal load
FTL	Following the thermal load
LHV	Low heat value of natural gas (kWh/m ³)
MD	Minimum distance
PES	Primary energy saving
PGU	Power generation unit
SP	Separate production
TSS1	Thermal storage strategy 1
TSS2	Thermal storage strategy 2

Symbols

a, b, c, d	Coefficients of polynomial equations
B	Ratio of storage tank capacity to PGU capacity
D	Distance
DE	Electric distance
DT	Thermal distance
E	Electricity (kWh)
F	Fuel (kWh)
f	Part load factor
P	Price (¥/kWh)
Q	Thermal energy (kWh)
T	Thermal
V	The operation variable of storage tank
W	Weighting of evaluation criteria
w	Weighting of distance
η	Efficiency level
μ	CO ₂ emission conversion factor (g/kWh)

Subscripts

-	Negative
+	Positive
ac	Absorption chiller

<i>b</i>	Boiler
<i>e</i>	Electricity
<i>ec</i>	Electric chiller
<i>ex</i>	Exhaust
<i>excess</i>	Excess heat
<i>f</i>	Fuel
<i>grid</i>	Electricity grid
<i>h</i>	Heating
<i>in</i>	Into
<i>max</i>	Maximum
<i>off</i>	Off-peak
<i>on</i>	On-peak
<i>out</i>	Out
<i>pgu</i>	Power generation unit
<i>r</i>	Recovery
<i>rated</i>	The rated capacity
<i>rc</i>	Recovery heat for space cooling
<i>rh</i>	Recovery heat for heating
<i>s</i>	Thermal storage
<i>sum</i>	Sum
<i>t</i>	Time (<i>h</i>)
<i>w</i>	Waste heat

1. Introduction

Combined cooling, heating and power (CCHP) is a system that produces heat, cooling and electricity in an integrated manner by burning fuel sources, such as coal, natural gas and biomass fuels [1]. Compared to the conventional approach of producing heat and power in separate plants, CCHP have the potential of decreasing fuel consumption by 20 – 30%, while producing exactly the same amount of electricity and heat [2]. For this reason, it is found feasible to be used in various commercial complexes and civil buildings (such as hospitals, office buildings and hotels et al.) world-wide [3] [4] [5] [6]. It is realized that the potential of a CCHP system is dependent on the utilization of cogeneration product [7]. In reality, the thermal and electric demands of buildings vary with the level of activity and climatic. Thus it is difficult to match the produced energy with the existing requirements. However, thermal storage is believed to be an effective method for adjusting the time-discrepancy, space-discrepancy and instability between energy supply and energy demand [8]. Thermal storage is a way of dealing with the mismatch between thermal and electric demands [9]. It has been receiving more and more attention in CCHP technology.

The integration of thermal storage and CCHP system has been widely used in different occasions, such as district energy systems, commercial buildings, residential buildings and smart buildings. For district energy systems, Fragaki et al. [10] presented a study on the diffusion of combined heating and power (CHP) system with thermal storage in UK. The study showed that the use of thermal stores

could be profitable in UK due to the big differences in electricity prices between day and night. Similar results were achieved by Bogdan et al [11]. Verda et al. [12] proposed a multi-scale model of storage to analyze the operation of storage systems and predicted their effects on the primary energy consumption and cash flows. The results showed that both primary energy consumption and total costs could be reduced through thermal storage in district heating networks.

For commercial buildings, Lai et al. [2] discussed the integration of CCHP system and thermal storage under demand uncertainties. It was presented that the economic attractiveness of a thermal energy production system was sensitive to the electricity tariff used. Yun et al. [13] optimized a CCHP system with thermal storage device using the objective functions of the daily minimum operation cost and the minimum equipment quantity. It was proved that a CCHP system with thermal storage offered a better economic benefit and more energy savings compared with that for only CCHP system. Mao et al. [14] evaluated the effect of using thermal storage when a CHP system operation was installed in a small office building and a restaurant. It was indicated that the use of thermal storage was beneficial for the CHP system because it reduced cost, primary energy consumption, and carbon dioxide emissions compared with a CHP without thermal storage.

For residential buildings, Barbieri et al. [15] presented a study on the influence of the thermal energy storage on the profitability of micro-CHP system. It was concluded that the effect of the size of the thermal energy storage was not linear with respect to the thermal power of the PGU. Haeseldonckx et al. [16] studied the impact

of thermal storage on the operational behavior of residential CHP facilities and the overall CO₂ emissions. The results showed that the use of thermal storage tanks prolonged the yearly operation time of a CHP facility. Also, using a small thermal storage device caused the net reduction of CO₂ emissions.

At last, for the smart buildings with both CCHP system and renewable energy sources, Xu et al. [17] presented the performance analysis on energy storage devices for smart building energy management. It was indicated that thermal storage devices were suitable for saving energy costs but batteries might not be economical due to their high investment cost and short lifetime. Chesi et al. [18] presented a case study about the influence of the heat storage size on the plant performance in a smart building. The results showed that the fraction of heat wasted and the supply from other devices was remarkably changed by applying a thermal storage and increasing its capacity.

The profitability of a CCHP system with a thermal storage device is generally caused by two factors. The first one is the external factor, such as electricity tariff, energy price et al. The CCHP system is worth running when the electricity price is high. If the heat demand is low, the excess heat is stored in the thermal storage device. Then it would be released when the thermal demand cannot be met by the CCHP system. The second one is the internal factor. When a thermal storage device is installed, the waste heat as well as the low part load operation time of the generator are reduced. Besides, more energy produced by a CCHP system can be supplied to satisfy the demand of the building. Moreover, if there is no thermal

storage device, the PGU has either to be sized to meet the minimum heat demand or should be stopped or modulated in order to avoid dumping the extra heat [10].

Low part load operation of the PGU is undesirable because it reduce the electricity efficiency. Huangfu et al. [19] pointed out the electricity efficiency was the highest influence factor concerning improving primary energy ratio in CCHP systems. On the other hand, large numbers of engine starts and stops has significant negative effect on the performance and the lifetime of the engine [16]. Both full load [10-12, 14, 16] and part load operation [2, 13, 15, 17, 18] are included in the paper cited above. Both have their advantages and disadvantages. Full load operation leads higher generation efficiency but less running time of PGU and larger number of engine starts and stops. However, part load operation leads more running time of PGU and less number of on-off cycles but lower generation efficiency. Both of these operations would be analyzed in this paper.

In papers cited above, different operation strategies are used, such as full load operation [10-12, 14, 16], schedule operation strategy [13,15], and optimal operation strategy [17,18] base on the optimization algorithm. Among them, in ref.[16], the PGU operates at full load and be turned on or off only based on the state of storage tank. Under such kind of strategy, the operation time and number of on/off cycles of PGU will be significantly influenced by the capacity of storage tank. This storage strategy is called full load operation based on tank (Full load-Tank) strategy in this paper. For the other studies, the thermal storage device is always treated as auxiliary equipment. Concretely, the operation state of PGU is determined by energy demands

and energy output characteristic of PGU, which has no relationship with the state of storage tank. In this way, the thermal storage device can only passively store or release heat based on the difference between heat production and heat demand. In this paper, the thermal storage operating in this way is called Thermal Storage Strategy One (TSS1).

From the analysis above, three factors are included in thermal storage strategies, which are electric demand, thermal demand, and state of storage tank. The traditional thermal storage strategies only consider either energy demands or state of storage tank, which is not comprehensive. The major task of a good operation strategy is to make CCHP system meet the on-site electric and thermal demands as much as possible with high efficiency. It is often formulated based on the energy output characteristic of CCHP system and energy demands of building. However, adding a thermal storage tank could extend the thermal output range of PGU, which improves the energy output characteristic of CCHP system to operate more flexibly. The range would be changed with the change of the state of storage tank. For this reason, the operation strategy used to determine the operational state of PGU should consider this improved characteristic of system but not just the characteristic of PGU. It could help to make system operate more efficiently and flexibly. Therefore, a good thermal storage strategy should consider electric demand, thermal demand, and state of storage tank at the same time.

In this paper, a novel thermal storage strategy (TSS2), which determines the operational state of the PGU based upon electric demand, thermal demand and the

state of the thermal storage device, is proposed and compared with traditional thermal storage strategies (Full load-Tank and TSS1). In the next section, the energy flow model of a CCHP system with a thermal storage device is developed. Moreover, the operation principle of the TSS2 is described and compared with that of Full load-Tank and TSS1 strategy. Lastly, the performances for the CCHP system operating under different strategies are compared and analyzed by a case study.

2. Methodology

2.1 Energy flows of a CCHP system with thermal storage and the evaluation criteria

2.1.1 Energy flows of a CCHP system with thermal storage

A schematic of the CCHP system with thermal storage is shown in **Fig.1**. The energy flows of this system are presented and analyzed as follows. The details of the parameters for energy flow are presented in **Appendix A**.

The energy demands of a building include: 1) electrical energy demand, E ; 2) cooling demand for space cooling, Q_c ; 3) heating demand for space heating and domestic hot water, Q_h .

The generated electricity from the Power generation unit (PGU) can be estimated as:

$$E_{pgu} = F_{pgu} \cdot \eta_{pgu,e} \quad (1)$$

where F_{pgu} is fuel consumption of the PGU, $\eta_{pgu,e}$ is the PGU generation efficiency.

The electrical energy balance is expressed as:

$$\begin{cases} E_{grid,in} = E + E_{ec} - E_{pgu} & E_{pgu} \leq E + E_{ec} \\ E_{grid,out} = E_{pgu} - E - E_{ec} & E_{pgu} > E + E_{ec} \end{cases} \quad (2)$$

where $E_{grid,in}$ is the electricity from grid, $E_{grid,out}$ is the excess electricity sold back to grid, E_{ec} is the electricity demand of the electric chiller.

The electricity used by the chiller is calculated as:

$$E_{ec} = \frac{Q_{ec}}{COP_{ec}} \quad (3)$$

where Q_{ec} is the cooling produced by the electric chiller; and COP_{ec} is coefficient of performance of the electric chiller.

The utilization of the recovered waste heat is expressed as:

$$Q_r - V_{s,in} Q_{s,in} + V_{s,out} Q_{s,out} = Q_{rc} + Q_{rh} + Q_{w,excess} \quad (4)$$

where Q_r is the recovered waste heat, Q_{rc} is the heat supplied to the absorption chiller, Q_{rh} is the heat from the PGU to satisfy the heating demands, $Q_{w,ex}$ is the excess recovered heat. $Q_{s,in}$ and $Q_{s,out}$ are the input and output heat of the heat storage tank respectively. $V_{s,in}$ and $V_{s,out}$ are the operation variable of storage tank, which are 0 or 1. When $V_{s,in}$ is equal to 1, it means that the recovered heat is stored to the storage tank. When $V_{s,out}$ is equal to 1, it means that the recovered heat is extracted from the storage tank.

The heat recovered from the PGU can be estimated as:

$$Q_r = F_{pgu} \cdot \eta_{pgu,r} \quad (5)$$

where $\eta_{pgu,r}$ is the PGU heat recovery efficiency.

The energy flows of the storage tank are expressed as:

$$Q_{t+1,s} = Q_{t,s} + V_{t,s,in} Q_{t,s,in} - V_{t,s,out} Q_{t,s,out} / \eta_s, \quad t \in [0, 8760) \quad (6)$$

$$Q_{t,s} \leq Q_{s,max} \quad (7)$$

$$\max(Q_{t,s,in}) = Q_{s,max} - Q_{t,s} \quad (8)$$

$$\max(Q_{t,s,out}) = \eta_s Q_{t,s} \quad (9)$$

where $Q_{t,s}$, $Q_{t,s,in}$ and $Q_{t,s,out}$ are the hourly storage heat, input heat and output heat of the thermal storage tank, respectively, $Q_{s,max}$ is the capacity of the storage tank, η_s is the thermal efficiency of the storage tank, $\max(Q_{t,s,in})$ and $\max(Q_{t,s,out})$ represent the maximum input heat and output heat of the storage tank.

The heat supplied to the absorption chiller can be calculated as:

$$Q_{rc} = \frac{Q_{ac}}{COP_{ac}} \quad (10)$$

where Q_{ac} is the cooling produced by the absorption chiller to satisfy the cooling demand, COP_{ac} is coefficient of performance of the absorption chiller.

The supplement heat from the boiler is estimated as:

$$Q_b = Q_h - Q_{rh} \quad (11)$$

The total waste heat can be calculated as:

$$Q_w = Q_{w,excess} + Q_{w,s} \quad (12)$$

where $Q_{w,s}$ is the waste heat dissipated from the thermal storage tank.

In order to analyze the impact of thermal storage capacity on the performance of the CCHP system with an identical PGU capacity, a dimensionless parameter B_s is defined as follow:

$$B_s = \frac{Q_{s,max}}{PGU_{rated} \times 1 \text{ hour}} \quad (13)$$

2.1.2 Evaluation criteria

Three indexes including primary energy saving (PES), annual total cost saving

(ATCS) and CO₂ emission reduction (CO₂ER) are employed to evaluate the performance of a CCHP system. They are briefly introduced as follows. The details of the parameters for evaluation criteria are presented in **Appendix A**.

PES is defined to the saving energy of CCHP system in comparison to separate production (SP) system, which expressed as:

$$PES = PEC_{SP} - PEC_{CCHP} \quad (14)$$

where PEC_{SP} is the primary energy consumptions (PEC) of SP system, PEC_{CCHP} is the PEC of CCHP system.

The CO₂ER is defined as:

$$CO_2ER = CO_2E_{SP} - CO_2E_{CCHP} \quad (15)$$

where CO_2E_{SP} and CO_2E_{CCHP} are the amounts of CO₂ emission (CO₂E) from a SP system and a CCHP system, respectively.

The ATCS is defined as:

$$ATCS = ATC_{SP} - ATC_{CCHP} \quad (16)$$

where ATC_{SP} and ATC_{CCHP} are the annual total cost (ATC) of a SP system and a CCHP system, respectively.

2.2 Minimum distance (MD) operation strategy [27]

The traditional operation strategies, such as following electricity load (FEL), following thermal load (FTL), following hybrid electric-thermal load (FHL) [21], and full load operation strategy (Full load), are the key obstacles for the development of thermal storage strategy because they are inflexible. The Full load strategy means that the PGU would operate at full capacity once it is run. Therefore, a more flexible

operation strategy called Minimum distance (MD) strategy, which based on the minimum distance from the load point to the energy supply curve of the PGU, is employed in this paper.

Under FEL strategy, the system uses the recovered heat to help offset the heating or cooling demand. Under FTL strategy, the system uses the electric generation to help offset electric demand. For these two operation strategies, excess heat or excess electricity would be produced. For FHL, none of excess energy would be produced but the system may not be used to satisfy the demand of the building. However, MD strategy can make the system fully use with less excess energy. The detail of MD strategy and the relationship among FTL, FEL, FHL and MD strategies are showed in **Appendix B** [27]. In this paper, a MD operation strategy is represented by MD ($w_{1,above}/w_{1,below}, l$). FEL, FTL, FHL can be by $w_{1,above}$ and $w_{1,below}$, as follows:

$$FEL \leftarrow w_{1,above} = 0, w_{1,below} = 0 \quad (17)$$

$$FTL \leftarrow w_{1,above} = 1, w_{1,below} = 1 \quad (18)$$

$$FHL \leftarrow w_{1,above} = 1, w_{1,below} = 0 \quad (19)$$

2.3 Thermal storage strategies for CCHP system

2.3.1 Full load operation based on tank (Full load-Tank)

Under Full load-Tank strategies, the PGU operates at full load and be turned on or off only based on the state of storage tank. For the simulation in this paper, the PGU is turned on and operated at full load when the heat content in the storage tank becomes less than 20% of the maximum capacity. It is turned off when the storage

tank is completely full [16]. Obviously, the PGU is operated to meet the thermal demand of the building. Under this strategy, the part load factor is high; large amount of excess electricity would be produced; little waste heat would be exhausted.

2.3.2 Thermal storage strategy 2 (TSS2) vs. thermal storage strategy 1 (TSS1)

According to **Fig. 2**, when a thermal storage device is designed in a CCHP system, the area between curve l_1 and curve l_2 represents the energy output characteristic of the system. The thermal output range of the system is extended. The curve l_1 and curve l_2 represent the boundary of maximum input heat and output heat of a storage device, respectively. It is said that no waste heat would be produced and no heat from the boiler would be needed when a load point is located in this area. This energy supply area of the system may change with time owing to the variation of thermal storage.

The main difference between different operation strategies for a CCHP system is how to determine the operating state of PGU. Both TSS2 and TSS1 are based upon the basic operation strategy MD which was stated in section 2.2.

2.3.2.1 Thermal storage strategy 1 (TSS1)

For a thermal storage strategy, the excess heat is inputted to the storage device. Then it is outputted when the recovered waste heat is not enough. When a CCHP system operates under TSS1, the amount of the heat inputted to or outputted from a thermal storage device is determined by the operating state of a PGU. As shown in **Fig. 2**, for TSS1, there are two areas ($Area A + Areas C_2$ and $Area B + Area C_1$) for

load points to operate under different strategies. The boundary of *Area A* and *Area B* is curve l and line l_3 .

Area A + Areas C₂: the operation strategy is MD ($w_{1,below}, l$) which means the distance $D_{sum,below}$ is from the load point to curve l . The $\min(D_{sum,below})$ represents the minimum distance between a load point, which is below the curve l , to the curve l .

Area B + Area C₁: the operation strategy is MD ($w_{1,above}, l$). The $\min(D_{sum,above})$ represents the minimum distance between a load point, which is above the curve l , to the curve l .

2.3.2.2 Thermal storage strategy 2 (TSS2)

When a CCHP system operates under TSS2, the amount of the heat inputted to or outputted from a thermal storage device should be as much as possible. In order to achieve this goal, the PGU operating state should be adjusted base on the state of thermal storage device. It is said that the PGU operating state is determined by both the operation strategy and the state of storage device. As shown in **Fig.2**, for TSS2, there are three areas (*Area A*, *Area B* and *Area C₁ + Area C₂*) for load points to operate under different strategies. The boundary of *Area A* and *Area C₁ + Area C₂* is curve l_2 and line l_5 . The boundary of *Area B* and *Area C₁ + Area C₂* is curve l_1 and line l_4 .

Area A: the point T_A is determined by the operation strategy MD ($w_{1,below}, l_2$). At this time, the $\min(D_{sum,below})$ represents the minimum distance between a load point, which is below the curve l_2 , to the curve l_2 . Then the PGU operating point $O_{2,A}$ is determined through a horizontal line $T_A O_{2,A}$.

Area B: the PGU operating point O_B is determined through a polyline $L_B T_B O_{2,B}$.

The operation strategy is MD ($w_{I,above}, l_I$). At this time, the $\min(D_{sum,above})$ represents the minimum distance between a load point, which is above the curve l_I , to the curve l_I .

Area C_1 + Area C_2 : the operation strategy is MD ($w_I = 0, l$). When w_I equal to 0, it means that the CCHP system operates under FEL.

2.3.2.2 Difference between TSS2 and TSS1

The difference of the operation process between TSS2 and TSS1 for the same situation is shown in **Fig. 2**. It can be seen that different results would be presented when the load point is located in different areas (*Area A*, *Area B*, *Area C_1* and *Area C_2*). The relationship of the parameters between TSS2 and TSS1 for the same situation is shown in **Table 1**. When the basic operation strategy is FEL, the determine strategy of TSS2 and TSS1 for all the load points in different areas is FEL. In other word, TSS2 is the same with TSS1 at this time. However, when the basic operation strategy is FHL or FTL, TSS1 makes no effect on the system performance because no excess heat is produced by the system at this time. The performance of the system does not change. But for TSS2, some excess heat would be produced based on the state of thermal storage device. All excess heat is stored to the thermal storage device for the time lacking heat. It is said that thermal storage is still effective when the basic operation strategy is FHL or FTL by using TSS2, which cannot be achieved by TSS1. The simulation model and storage strategies are achieved in **Matlab** platform. Based on the theory showed in **Fig. 2**, the processes of

getting operation state of CCHP system under TSS1 and TSS2 are presented in **Fig.**

3.

3. Numerical study

3.1 Energy load profiles and input values

A hospital in Shanghai, with a covered area of 70488 m², is as a case to be evaluated and analyzed. The peaks of the electric, cooling and heating loads of the building are 3910.5kW, 2879.6kW and 2529.7kW, respectively. The cooling hours for summer are 2664h, the heating hours for winter are 2688h and the transition seasons are totally 3408h. The hot water for the hospital to bath or cook is supplied during the whole year. The heating load, cooling load, electric load and the heat-power ratio of each month are shown in **Fig. 4**.

The schematic of the CCHP system with thermal storage device for this building is shown in **Fig.1**. The CCHP system consists of a PGU, a heat recovery system, a storage tank, an absorption chiller, an electric chiller, a heating exchanger and a boiler. An internal combustion engine with 900kW rated power, which is about 25% of the peak of electric load, is considered. The excess electricity produced by the CCHP system cannot be sold back to the grid in Shanghai until now. But the ability for CCHP system to sell electricity is taken account in this analysis. The energy saving or economical saving of the excess electricity is not considered because producing excess electricity is not encouraged for CCHP system. For the purpose of comparing the performance of the CCHP system operating under different operation and storage strategies, seven modes are employed. They are Full load-Tank, Full

load-TSS1, FEL-TSS1 ($w_{1,above} = 0$, $w_{1,below} = 0$), MD-TSS1 ($w_{1,above} = 0.5$, $w_{1,below} = 0$), MD-TSS2 ($w_{1,above} = 0.5$, $w_{1,below} = 0$), FEL-TSS2 ($w_{1,above} = 0$, $w_{1,below} = 0$), FHL-TSS2 ($w_{1,above} = 1$, $w_{1,below} = 0$) and FTL-TSS2 ($w_{1,above} = 1$, $w_{1,below} = 1$). Only when $w_{1,below}$ is not equal to zero, the excess electricity would be produced. The main parameters employed for the evaluation and analysis are listed in **Table 2**. The installation costs are summarized in **Table 3**.

3.2 Operation of the CCHP system under TSS1 and TSS2

In order to illustrate the different effect of TSS1 and TSS2, the operation of CCHP system (PGU=900kW, $B_s=2.0$) operating under MD over the first 168h of the January would be analyzed, as shown in **Fig. 5**. **Fig. 5(a)** shows that the PGU generates more electricity for demand when operating under TSS2 compared with TSS1. At these moments, the recovery heat from PGU is more than thermal demand (as shown in **Fig. 5(b)**) and the excess part is stored by the tank. **Fig. 5(c)** shows the time history of the state of the tank. When the thermal power in the tank increases, it means that the tank is charged. On the contrary, the tank is discharged. From **Fig. 5(c)**, it can be observed that TSS2 makes more heat charged in the tank and discharged than TSS1. The frequency of tank charged to be full for TSS2 is higher than that for TSS1. Moreover, TSS2 makes more electricity and thermal power produced by PGU for the demands than TSS1. It can be deduced that TSS2 could make best of the storage tank for the better performance of CCHP system.

3.3 Results and discussion

Table 4 shows annual total cost (ATC), carbon dioxide emission (CO₂E) and

primary energy consumption (PEC) for the different systems and operation strategies without thermal storage. Compared to SP system, CCHP system without thermal storage has better performance in ATC, CO₂E and PEC for all these operation strategies. In order to analyze the effect of thermal storage for different operation strategies, the CCHP system, which operates under a certain strategy, with thermal storage is compared to the one without thermal storage. Specifically, FEL-TSS1 and FEL-TSS2 are compared with FEL-no tank; MD-TSS1 and MD-TSS2 are compared with MD-on tank; FHL-TSS1 and FHL-TSS2 are compared with FHL-no tank; FTL-TSS1 and FTL-TSS2 are compared with FTL-no tank; Full load-TSS1 is compared with Full load-no tank. Because the operation of system is strong influenced by the capacity of storage tank under Full load-Tank strategy and the simulation time step is 1 hour, the minimum value of B_s is 2 for Full load-Tank strategy. The fluctuation of performances variation trend is presented when B_s is small. They become smooth when B_s larger than 3, as showed in **Fig. 6** to **Fig. 11**. The errors of simulation results for Full load-Tank strategy decrease with the increase of B_s .

Fig. 6 shows the annual total cost saving (ATCS) of the CCHP system for different thermal storage capacities. It can be found that the ATCS of the CCHP system increases firstly, reaching to a maximum value, and then decreases with the increase of the storage tank capacity for all the operation strategies and storage strategies. For modes Full load-Tank, Full load-TSS1, FEL-TSS1, MD-TSS1, MD-TSS2, FEL-TSS2, FHL-TSS2, and FTL-TSS2, the ATCS reaches the maximum

value when the thermal storage capacity are 4500kWh ($B_s = 4.5$), 3330kWh ($B_s = 3.7$), 2700kWh ($B_s = 3.0$), 270kWh ($B_s = 0.3$), 2160kWh ($B_s = 2.4$), 2700kWh ($B_s = 3.0$), 2430kWh ($B_s = 2.7$), and 1170kWh ($B_s = 1.3$), respectively. Compared with the CCHP system without thermal storage, FEL-TSS1-(3.0), MD-TSS1-(0.3), MD-TSS2-(2.4), FEL-TSS2-(3.0), FHL-TSS2-(2.7), FTL-TSS2-(1.3) and Full load-TSS1-(3.7) increase the ATCS of the CCHP system by 5.51%, 0.48%, 3.79%, 5.51%, 20.22%, 22.02% and 14.84%, respectively (**Table 5**). By comparing MD-TSS1-(0.3) and MD-TSS2-(2.4), it can be found that the economic performance of TSS2 is much better than that of TSS1 for MD operation strategy. The economic performance of FHL-TSS2-(2.7) presents the highest increase among these modes. The capacity of the thermal storage tank is determined by the economic performance of the system in this case. Based on the conclusion in section 2.3.2, the optimal capacity of the thermal storage tank for FTL-TSS1 and FHL-TSS1 is 0kWh.

Fig. 7 presents CO₂ emission reduction (CO₂ER) of the CCHP system for different thermal storage capacities. It can be observed that the CO₂ER of MD-TSS2-(2.4) is increased by 3.45% compared with MD-no tank, which is much better than that of MD-TSS1-(0.3). The CO₂ER of TSS2 is always better than that of TSS1 when the CCHP system operates under MD in this case. Full load-TSS1, FEL-TSS1-(3.0), TEL-TSS2-(3.0), FHL-TSS2-(2.7) and FTL-TSS2-(1.3) increases the CO₂ER by 6.46%, 3.10%, 3.10%, 9.97% and 6.04%, respectively (**Table 5**).

Fig. 8 shows primary energy saving (PES) of the CCHP system for different thermal capacities. For the operation strategy MD, the PES of TSS2 is always better

than that of TSS1. The PES of FHL-TSS2 exceeds that of MD-TSS2 with the increase of the thermal storage capacity. Compared with the CCHP system without thermal storage, Full load-TSS1, FEL-TSS1-(3.0), FEL-TSS2-(3.0), MD-TSS1-(0.3), MD-TSS2-(2.4), FHL-TSS2-(2.7) and FTL-TSS2-(1.3) increase the PES by 16.37%, 6.90%, 6.90%, 0.41%, 3.80%, 10.72% and 6.71%, respectively (**Table 5**).

Fig. 9 shows the fraction of electric demand met by CCHP system for different thermal storage capacities. It is observed that the fraction of electric demand met by CCHP system for MD-TSS1, FEL-TSS1 and FEL-TSS2 is the same for different thermal storage capacities. However, the increments in the fraction of electric demand met by CCHP system for Full load-TSS1-(3.7), MD-TSS2-(2.4), FHL-TSS2-(2.7) and FTL-TSS2-(1.3) are 0.02%, 1.71% and 4.08%, 3.42%, respectively (**Table 6**). It can be deduced that the fraction of electric demand met by CCHP system would increase when the system operates under TSS2, except for FEL. For FTL-TSS2, the excess electricity decreases with the increase of thermal storage capacities. The increment for excess electricity is -1.25%, as showed in **Table 6**.

Fig. 10 shows the fraction of thermal demand met by CCHP system for different thermal storage capacities. The fraction of thermal demand met by CCHP system grows with the increase of thermal storage capacity for all these modes. The increments in it for FEL-TSS1-(3.0), MD-TSS1-(0.3), MD-TSS2-(2.4), FEL-TSS2-(3.0), FHL-TSS2-(2.7) and FTL-TSS2-(1.3) are 2.77%, 0.20%, 2.50%, 2.77%, 5.78% and 3.55%, respectively (**Table 6**). Compared with MD-TSS1, MD-TSS2 presents more thermal demand met by CCHP system. This is due to the

fact that the heat which is stored or released for TSS2 is more than that for TSS1.

Fig. 11 presents the waste heat from CCHP system for different thermal storage capacities. The waste heat includes the excess heat and the heat dissipation of the storage tank. It is seen that Full load-TSS1-(3.7) present the highest reduction of waste heat (42.64tce) compared with Full load-no tank. The reduction of waste heat under MD-TSS1-(0.3) and MD-TSS2-(2.4) is 3.81tce and 3.35tce, respectively (**Table 6**). However, FHL-TSS2-(2.7) and FTL-TSS2-(1.3) increase the waste heat by 2.76tce and 2.26tce, as showed in **Table 6**. It is important to highlight that the increase in waste heat for FHL and FTL is only contributed by the heat dissipation of the storage tank.

From **Fig. 6** to **Fig.8**, it can be seen that the performances of CCHP system operate follow Full load-TSS1 strategy are much poorer than those of other operation strategies. When the PGU operates at full load capacity, much excess heat would be produced even with the thermal storage tank, as showed in **Fig. 11**. For the simulation model in this paper, the PGU would be shut down when the PES smaller than zero. As a result, in this situation, the operation time of PGU is less and the number of on-off cycles is larger than that of other operation strategies, as showed in **Table 5**.

Full load-Tank-(4.5) has the fewest running time and lowest fraction of electric demand met by CCHP system, as showed in **Table 5** and **Fig. 9**. Compared with FTL-TSS2-(1.3), the fraction of thermal demand met by CCHP system of Full load-Tank-(4.5) is 1.66% lower. According to these results, it can be deduced that the

PGU cannot be fully used to meet both electric and thermal demand of the building under Full load-Tank strategy. Although a large amount of electricity sell to the grid (as showed in **Fig. 9**), the ATCS of Full load-Tank is not large because the excess electricity is produced during the off-peak time.

FTL saves the most primary energy by using TSS2, as shown in **Fig. 8**. From the view point of energy conservation, FTL-TSS2-(1.3) is the best choice for this case. TSS1 improves the performance of CCHP system by storing excess heat. Compared to the CCHP system without thermal storage, no more energy is produced. However, for TSS2, more electric and thermal energy are produced by the CCHP system. In **Table 5**, it shows that the minimum and maximum increase rates of ATCS for TSS1 are 0% and 14.84%, respectively. However, the minimum and maximum increase rates of ATCS for TSS2 can reach 3.79% and 20.22%, respectively. The similarly conclusion could be achieved for CO₂ER and PES. It is said that TSS2 improve the performance of CCHP system more significantly compared with TSS1. According to **Fig. 9** and **Fig. 10**, the reason can be revealed, which is that the capacity of storage tank can be fully used to make the system produce more energy to meet the demands of building under TSS2.

4. Conclusions

In this paper, the operation principle of TSS2 is described and compared with that of the traditional thermal storage strategies (Full load-Tank and TSS1). The performance for a CCHP system operating under different strategies is compared using a case study. As a brief summary, it is wished to emphasize the significant

points of this work in the following:

- (1) Compared to the traditional thermal storage strategies (Full load-Tank and TSS1), TSS2 can make both PGU and capacity of thermal storage tank be fully used by CCHP system to produce more electric and thermal energy to meet demands of building. Then, more improvement of performance of CCHP system on economic, environment, and energy aspects can be achieved.
- (2) As for the case study of the hospital in Shanghai, the most economical capacities of the thermal storage tank for modes FEL-TSS1, MD-TSS1, MD-TSS2, FEL-TSS2, FHL-TSS2 and FTL-TSS2 are 2700kWh ($B_s = 3.0$), 270kWh ($B_s = 0.3$), 2160kWh ($B_s = 2.4$), 2700kWh ($B_s = 3.0$), 2430kWh ($B_s = 2.7$) and 1170kWh ($B_s = 1.3$), respectively. The optimal capacity of the thermal storage tank for FTL-TSS1 and FHL-TSS2 is 0kWh. From the view point of energy conservation, FTL-TSS2-(1.3) is the best choice for this case.
- (3) The effect of TSS2 on the CCHP system performance is different under different operation strategies. For FEL, the effect of TSS2 is the same as that of TSS1. But, for MD, FHL and FTL, the performance of CCHP system operating under TSS2 is much better than that of TSS1. For MD-TSS1-(0.3), compared with the system without thermal storage, the increase rates of ATCS, CO₂ER and PES are 0.48%, 0.23% and 0.41%, respectively. However, for MD-TSS2-(2.7), the increase rates of ATCS, CO₂ER and PES reach 3.79%, 3.45% and 3.80%, respectively. For FTL-TSS1 and FHL-TSS1, the performance of the system does not change. TSS1 makes no effect on the system performance because no excess heat is

produced by the system at this time. However, for FTL-TSS2-(1.3), the increase rates of ATCS, CO2ER and PES can reach 16.55%, 6.04% and 6.71%, respectively. For FHL-TSS2-(2.7), the increase rates of ATCS, CO2ER and PES can reach 20.22%, 9.97% and 10.72%, respectively..

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Appendix A. The details of parameters for energy flow model and evaluation criteria

The PGU generation efficiency is estimated by:

$$\eta_{pgu,e} = a_1 f_{pgu}^3 + b_1 f_{pgu}^2 + c_1 f_{pgu} + d_1 \quad (A.1)$$

where f_{pgu} is part load factor of the PGU, a_1, b_1, c_1, d_1 are the coefficient of the non-linear function, which are shown in **Table A1** [24]. The minimum of f_{pgu} is 0.2.

The part load factor is calculated as:

$$f_{pgu} = \frac{E_{pgu}}{PGU_{rated}} \quad (A.2)$$

where PGU_{rated} is the rated capacity of PGU.

The PGU heat recovery efficiency is calculated by:

$$\eta_{pgu,r} = a_2 f_{pgu}^3 + b_2 f_{pgu}^2 + c_2 f_{pgu} + d_2 \quad (A.3)$$

where a_2, b_2, c_2, d_2 are the coefficient of the non-linear function, which are shown in **Table A1** [24].

The coefficient of performance of the absorption chiller is estimated as:

$$COP_{ac} = \begin{cases} 0 & f_{ac} < 0.2 \\ a_3 f_{ac}^2 + b_3 f_{ac} + c_3 & f_{ac} \geq 0.2 \end{cases} \quad (A.4)$$

where f_{ac} is the part load factor of absorption chiller, the coefficients a_3, b_3, c_3 are shown in **Table A1** [25].

The PEC_{SP} and PEC_{CCHP} are calculated as:

$$PEC_{SP} = \frac{E}{\eta_e \eta_{grid}} + \frac{Q_h}{\eta_b} + \frac{Q_c}{\eta_e \eta_{grid} COP_{ec}} \quad (A.5)$$

$$PEC_{CCHP} = F_{pgu} + \frac{Q_b}{\eta_b} + \frac{E_{grid,in} + E_{ec}}{\eta_e \eta_{grid}} \quad (A.6)$$

where η_e is the grid generation efficiency; η_{grid} is the grid transmission efficiency; η_b is the efficiency of the boiler.

The $\text{CO}_2\text{E}_{\text{SP}}$ and $\text{CO}_2\text{E}_{\text{CCHP}}$ are calculated as:

$$\text{CO}_2\text{E}_{\text{SP}} = \mu_e (E + E_{ec}) + \mu_f \frac{Q_h}{\eta_b} \quad (\text{A.7})$$

$$\text{CO}_2\text{E}_{\text{CCHP}} = \mu_e (E_{grid,in} + E_{ec}) + \mu_f \left(F_{pgu} + \frac{Q_b}{\eta_b} \right) \quad (\text{A.8})$$

where μ_e is the CO_2 conversion factor of electricity from grid; μ_f is the CO_2 conversion factor of natural gas.

The ATC_{SP} and ATC_{CCHP} are calculated as:

$$\text{ATC}_{\text{SP}} = R \cdot \sum_{k=1}^{n_1} (N_k \cdot P_{k,eq}) + \sum_{i=1}^{365} \sum_{k=1}^{24} \left(\left(E_{ik} + \frac{Q_{ik,c}}{\text{COP}_{ec}} \right) p_{ik,e} + \frac{Q_{ik,h}}{\eta_b} p_{ik,f1} \right) \quad (\text{A.9})$$

$$\text{ATC}_{\text{CCHP}} = R \cdot \sum_{k=1}^{n_2} (N_k \cdot P_{k,eq}) + \sum_{i=1}^{365} \sum_{k=1}^{24} \left(F_{ik,pgu} P_{ik,f2} + E_{ik,grid,in} P_{ik,in,e} - E_{ik,grid,out} P_{ik,out,e} + \frac{Q_{ik,b}}{\eta_b} P_{ik,f1} \right) \quad (\text{A.10})$$

where R is the capital recovery factor; N and P_{eq} are the installed power of equipment and the initial capital cost of each kind of equipment, respectively; n_1 is the number of equipments for a SP system; n_2 is the number of equipments for a CCHP system; $P_{ik,f2}$ is price of natural gas for CCHP system; $P_{ik,in,e}$ and $P_{ik,out,e}$ is the price of electricity bought from and sell to the grid. They are assumed to be the same at the same period of time; and $P_{ik,f1}$ is the price of natural gas for a boiler.

Appendix B. The details of MD strategy and relationship among FTL, FEL, FHL and MD strategies.

The load point $L(E, T)$ are determined by both the electric demand E and the thermal demand T . The thermal demand is calculated as:

$$T = Q_h + \frac{Q_c}{COP_{ac}} \quad (B.1)$$

According to Eq. (1) and Eq. (5), the electricity generated by the PGU can be expressed as a function of the heat recovered and PGU efficiency:

$$E_o = \frac{\eta_{pgu,e}}{\eta_{pgu,r}} T_o \quad (B.2)$$

From Eq. (1), Eq. (5) and Eq. (B.1), it is seen that the power generated is a nonlinear function of the recovered heat which can be seen from the curve l in **Fig.B1**. The curve l represents a perfect match between thermal load and electrical load. This curve is called ‘energy supply characteristic curve’ of a CCHP system in this paper. According to **Fig. B2**, it is also found that there are four kinds of distance from the load point to the energy supply characteristic curve l . The definition of these kinds of distance is presented in **Table B1**. Then the integrated distance can be expressed as follow:

$$D_{sum} = w_1 \cdot (DT_+ + DT_-) + w_2 \cdot (DE_+ + DE_-) \quad (B.3)$$

where w_1 and w_2 are the respective weights of thermal and electric distance. The values of them are between 0 and 1. Besides, $w_1 + w_2 = 1$.

The description of MD strategy can be described as follow: for a load point $L (E_L, T_L)$, an operation point $O (E_o, T_o)$ which minimizes the D_{sum} can be found on the curve l , and then the point O is considered to be the operation point for this load point when the CCHP system operates under MD strategy.

The relationship between MD and FEL/FTL is presented in **Fig.B2**. It is seen that a CCHP system with MD strategy can operate under either FEL or FTL. Besides, it

can operate under the strategies which are between FEL and FTL. As for a load point above the curve l , some excess heat would be produced and some electricity would be needed from the grid. However, for a load point below the curve l , some supplement heat would be need from the boiler and some excess electricity would be produced. For this reason, the operation strategies for the load points which are above or below the curve l should be treated respectively. Then the integrated distance for the load points which are above or below the curve l can be expressed as:

$$D_{sum,above} = w_{1,above} \cdot DT_- + w_{2,above} \cdot DE_+ \quad (B.4)$$

$$D_{sum,below} = w_{1,below} \cdot DT_+ + w_{2,below} \cdot DE_- \quad (B.5)$$

From the analysis above, there are two key factors for MD strategy. One is the weighting of distance. The other is the reference curve of distance. Then a MD operation strategy can be represented by MD ($w_{1,above}/w_{1,below}$, l). The methodology of getting the minimum distance and the operational state of CCHP system under MD operation strategy is showed in **Fig. B3**.

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Tables:

Table 1 Differences of the parameters between TSS2 and TSS1 for the same situation.

Area	A'	B'	C_1'	C_2'
Part load factor	$TSS2 \leq TSS1$	$TSS2 \geq TSS1$	$TSS2 \geq TSS1$	$TSS2 \leq TSS1$
Heat from tank	$TSS2 \geq TSS1$	–	–	$TSS2 \geq TSS1$
Heat into tank	–	$TSS2 \geq TSS1$	$TSS2 \geq TSS1$	–
Electricity from grid	–	$TSS2 \leq TSS1$	$TSS2 \leq TSS1$	–
Excess electricity	$TSS2 \leq TSS1$	–	–	$TSS2 \leq TSS1$
Heat from boiler	$TSS2 \geq TSS1$	–	–	–
Waste heat	–	$TSS2 \geq TSS1$	–	–

Table 2 Main parameters employed for evaluation and analysis.

Variable	Symbol	Unit	Value
COP of electric chiller [26]	COP_e	–	4.0
Thermal efficiency of the storage tank [20]	η_s	%	95.6
Boiler efficiency [4]	η_b	%	80.0
Grid generation efficiency [4]	η_e	%	35.0
Grid transmission efficiency [4]	η_{grid}	%	92.2
CO ₂ conversion factor of electricity from grid [4]	μ_e	g/kWh	923
CO ₂ conversion factor of natural gas [4]	μ_f	g/kWh	220
Low heat value of natural gas	LHV	kWh/m ³	9.86
Favorable price of natural gas ^a	P_{f1}	¥/m ³	2.43
Normal price of natural gas ^a	P_{f2}	¥/m ³	3.99
Price of electricity on-peak ^a	$P_{e,on}$	¥/kWh	1.032
Price of electricity off-peak ^a	$P_{e,off}$	¥/kWh	0.474

^a These parameters are the energy price based on the policy of Shanghai [22, 23].

Table 3 Unit price of the facilities in the CCHP system [4].

Facility	PGU	Heating coil	Boiler	Absorption chiller	Electric chiller	Storage tank
Unit price, ¥/kW	6800	200	300	1200	970	230

Table 4 Annual total cost, carbon dioxide emission and primary energy consumption for the different systems and operation strategies without thermal storage.

		ATC [$\times 10^3$ yuan]	CO ₂ E [t]	PEC [tce]
SP system	-	9202.2	8813.5	3793.8
CCHP system	Full load-no tank	8266.2	7072.5	3424.2
	MD-no tank	7804.7	6631.6	3181.0
	FEL-no tank	7764.4	6487.0	3223.2
	FTL-no tank	8023.5	6732.0	3167.4
	FHL-no tank	8062.7	6875.9	3198.3

Table 5 The increase rate of the system performances with thermal storage for different operation strategies and the relative operation time and number of on-off cycles.

Modes	B _s [-]	ATCS [%]	CO ₂ ER [%]	PES [%]	Operation time [h]	On-off cycles [times]
Full load-Tank-(4.5)	4.5	-	-	-	5074	240
Full load-TSS1-(3.7)	3.7	14.84%	6.46%	16.37%	5583	463
MD-TSS1-(0.3)	0.3	0.48%	0.23%	0.41%	7339	240
FEL-TSS1-(3.0)	3.0	5.51%	3.10%	6.90%	7341	242
FTL-TSS1-(0.0)	0.0	0.00%	0.00%	0.00%	5412	182
FHL-TSS1-(0.0)	0.0	0.00%	0.00%	0.00%	5412	182
MD-TSS2-(2.4)	2.4	3.79%	3.45%	3.80%	7339	240
FEL-TSS2-(3.0)	3.0	5.51%	3.10%	6.90%	7341	242
FTL-TSS2-(1.3)	1.3	16.55%	6.04%	6.71%	5779	375
FHL-TSS2-(2.7)	2.7	20.22%	9.97%	10.72%	5782	376

Table 6 The increase rate of electricity, excess electricity, thermal energy and waste heat for the CCHP system with thermal storage.

	B_s [-]	Electricity increment in the fraction of electrical demand [%]	Excess electricity in the fraction of electrical demand [%]	Thermal energy in the fraction of thermal demand [%]	Waste heat [tce]
Full load-TSS1-(3.7)	3.7	0.002	0.02	3.37	-42.64
MD-TSS1-(0.3)	0.3	0.00	0.00	0.20	-3.81
FEL-TSS1-(3.0)	3.0	0.00	0.00	2.77	-36.29
FTL-TSS1-(0.0)	0.0	0.00	0.00	0.00	0.00
FHL-TSS1-(0.0)	0.0	0.00	0.00	0.00	0.00
MD-TSS2-(2.4)	2.4	1.71	0.00	2.50	-3.35
FEL-TSS2-(3.0)	3.0	0.00	0.00	2.77	-36.29
FTL-TSS2-(1.3)	1.3	3.42	-1.25	3.55	2.26
FHL-TSS2-(2.7)	2.7	4.29	0.00	5.78	2.77

Table A1 Coefficients of polynomial equations [24, 25]

i	a_i	b_i	c_i	d_i
1	0.4679	-1.1705	0.998	0.002
2	-0.4845	1.0934	-0.8379	0.7221
3	-0.6181	0.8669	0.4724	-

Table B1 Definition of four kinds of distance

Symbol	Definition
DT_+	$T_L - T_o > 0, DT_+ = T_L - T_o , DT_- = 0$
DT_-	$T_L - T_o \leq 0, DT_- = T_L - T_o , DT_+ = 0$
DE_+	$E_L - E_o > 0, DE_+ = E_L - E_o , DE_- = 0$
DE_-	$E_L - E_o \leq 0, DE_- = E_L - E_o , DE_+ = 0$

Caption:

Table 1 Differences of the parameters between TSS2 and TSS1 for the same situation.

Table 2 Main parameters employed for evaluation and analysis.

Table 3 Unit price of the facilities in the CCHP system [4].

Table 4 Annual total cost, carbon dioxide emission and primary energy consumption for the different systems and operation strategies without thermal storage.

Table 5 The increase rate of the system performances with thermal storage for different operation strategies and the relative operation time and number of on-off cycles.

Table 6 The increase rate of electricity, excess electricity, thermal energy and waste heat for the CCHP system with thermal storage.

Table A1 Coefficients of polynomial equations [24, 25]

Table B1 Definition of four kinds of distance

(a) TSS1

(b) TSS2