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CONSTRUCTION AND ANALYSIS OF A DISTRICT HEATING / COOLING NETWORK SYSTEM BASED ON THERMAL BUS

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ABSTRACT

A district energy system based on “thermal bus” was proposed, in which the heating and cooling water transmission processes shared one set of the distribution pipe network. Combined with the gas energy stations, ground source heat pumps, small-scale photovoltaic power stations and rooftop solar collectors and other facilities, it provided the users in the region with heating in winter, cooling in summer and power supply all year round. From the perspective of the bidirectional (supply/return) flow of heat energy along the thermal bus, the mathematical model of the main equipment applied for the source, pipe network, load and storage was established. The optimization model with the lowest system operation cost was proposed considering the fuel cost, the external electricity purchase fee and the satisfaction degree of all users' energy demand. The operation cost and energy consumption of the regional energy system scheme and the traditional distributed energy system scheme are studied by a practical case study. The results showed that the new scheme reduces the operating cost by 21.5% and 16.8% respectively under the typical weekly scenarios of cooling in summer and heating in winter. When no storage equipment was used, the new scheme reduced the amount of purchased electricity in summer and winter by 4.1% and 5.2% respectively.

Keywords: thermal bus, distributed energy system, district heating, district cooling, optimized operation, energy planning

NONMENCLATURE

Abbreviations	
PV	Photovoltaic cells
CCHP	Combined cold, heat and power
GHP	Ground source heat pump
DDES	District distributed energy system

1. INTRODUCTION

The distributed energy systems have been increasingly applied in the regional comprehensive energy supply system by providing combined cold, heat and power supply (CCHP) [1][2]. However, a CCHP system with a single energy station can adapt to a few number of buildings’ energy demand changes. When expanded to the district scale, a district distributed energy system (DDES) must be applied. To achieve high power generation, high thermal efficiency and high utilization rate, the DDES must have several interconnected energy stations and an adaptive energy distribution network to make full use of regional renewable energy, waste heat and other resources and to transfer the corresponding cooling, heating and electric energy from all energy stations to geographically scattered different kinds of buildings.

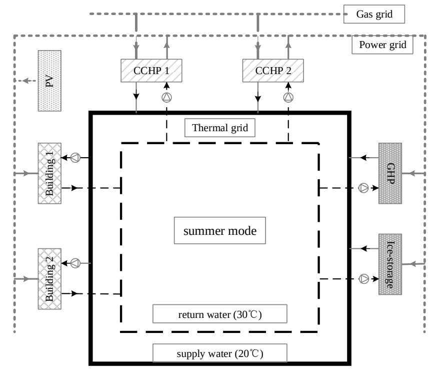
Many works have been done to consider the role of transmission networks in optimizing the distributed energy systems recently [3-6]. In district scale, however, to achieve the decoupling of the distributed energy systems and the energy distribution networks, some difficulties should be overcome: A variety of the power supply, heat and cold sources need to be merged in the energy system with their own special functions and features; Since multiple sources are connected to multiple users, the network may have the ability to provide energy from all sources to all users in an optimized way; It is necessary to consider how to reduce the temperature difference between the working fluid (water) and the environment to make full use of the pipe network and further reduce the loss of heating or cooling network.

Based on the configuration and operation mode of thermal bus, a new district comprehensive energy system was proposed in this paper. A mathematical model for the proposed system was established including the source, network, user's load and energy storage. The combination of gas energy station, low-grade renewable energy and waste heat resources and various types of buildings were considered. The distributed variable-speed water pumps and the distributed heat pumps were used respectively to solve the hydraulic and thermal balance problems caused by the multiple heat/ cold sources. Then, the performance of heating/cooling water distribution through the thermal bus, the utilization of low-grade energy and the reduction of network heat loss were studied. Furthermore, an optimization operation model was proposed to achieve optimal operation cost for the new comprehensive energy system, which was analyzed by a practical case.

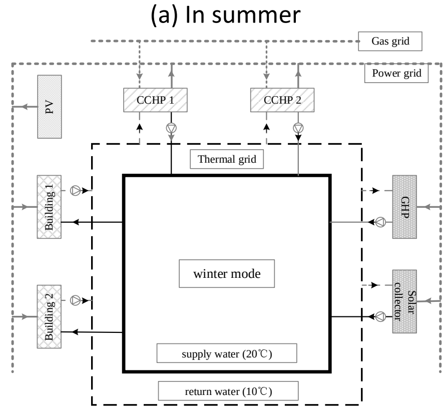
2. CONSTRUCTION OF THE NETWORK SYSTEM FOR COOLING AND HEATING

The configuration principle of the new regional thermal bus system in summer and winter is shown in Fig. 1 (a) and Fig. 1 (b) respectively. Water is used as the heating or cooling medium in the heating or cooling network, in which cascade utilization of energy should be the basic principle.

For a district scale, the proposed "thermal bus" configuration must base on a ring-shaped topological network (including the supply and return water networks). The equalizing pipes should be arranged at each heat source [7]. The throttle valves and other equipment should be placed on the branch pipelines, which can be used only for local branch flow regulation. The water chillers or the heat pumps should be arranged in each building to further meet the cooling and heating load of each user in the building. However, unlike the traditional air conditioning units, the chillers inside each building in this energy system would exchange heat with the water supplied from the main network. The distributed heat pump can be also used to get the decoupling of the thermal transmission and distribution to achieve the thermal balance of the system. To achieve the hydraulic balance of the system, the distributed variable-speed water pumps should be adopted to get the decoupling of the hydraulic transmission and distribution.



(a) In summer



(b) In winter

Fig. 1 Configuration of a district energy system based on thermal bus

In summer, the main network (as the bold line shown in Fig.1 (a)) provides cooling water to the buildings. The temperature of the cooling water is close to the temperature of the soil around the pipelines to reduce the heat loss, for instance 20 ℃. Inside each building, water chillers are used to provide chilled water to the users in each building. After passing through the water chillers, the cooling water will be heated to about 30 ℃ and flow through the return water pipelines back into the energy station, the ground-source heat pump or the ice storage system to be cooled down before returning to the water supply pipelines.

In winter, the main network (as the bold line shown in Fig.1 (b)) provides low temperature heating water to the buildings, for instance 20 ℃. Inside each building, the heat pumps are used to provide the space heating and the domestic hot water (higher than 55 ℃). After passing through the heat pumps, the low temperature heating water will be cooled down to about 10 ℃ and flow through the return water pipelines back into the energy station, the ground source heat pump or the solar collector to be heated before returning to the supply pipelines.

3. MODELS

3.1 Mathematical models

The model of a district integrated energy system mainly includes the sources, the network and the users. The sources are supposed to generate cold, heat and electricity energy, which might be the combined cooling heating and power station (CCHP), the gas-fired boilers, the renewable energy and the industrial waste heat. The network includes a power network, a gas pipe network and a cooling/heating pipe network. The users mainly refer to the buildings. In addition, the integrated energy system includes a variety of electrical, thermal or cold storage devices.

3.2 Operational optimization model

The objective of operation optimization is to select the scheme with the lowest operation cost among all the feasible energy supply schemes for a certain energy system according to the predicted energy demands of the users. In the model, the proposed objective function considers the operating cost of all devices and meet the energy requirements of all users. The controllable variables in the energy system are the decision variables, such as the energy supply parameters of the power supply and the heat source, the degree of valve opening and the frequency control of the water pump. The constraint condition is the operating parameter ranges of all kinds of the energy supply/use equipment and the relation between the parameters.

The absolute value of the difference between the energy supplied and required is adopted as the indicator of the operation optimization in this paper. It can not only reflect the heat/cold loss of the network indirectly, but also show whether the system reaching its thermal equilibrium. The new indicator, GAP_{H}, is named as the satisfaction degree of the user's heat/cold demand.

$$Gap_H = \gamma \cdot \left[\sum_{h=0}^{168} \sum_{n=1}^{N} \left| H_n - H_n^{need} \right|\right] \tag{1}$$

Where, H_{n} is the actual heating/cooling energy supplied to the user n; $H_{\mathrm{n}}^{\mathrm{need}}$ is the required heating/cooling loads for the user n; γ is the penalty factor, CNY/GJ. Larger γ means that the optimization model pays more attention to the user's satisfaction degree of heating/cooling; h is the serial number of the hours.

The objective function of operation optimization is defined as,

$$C_{tot} = \min\{C_{\mathrm{fuel}} + Gap_H\} \tag{2}$$

Where, C_{fuel} is the total cost of the natural gas and electricity consumed by the sources; C_{tot} is the total operation cost.

For the nonlinear and strongly coupled energy system, intelligent optimization algorithm for global search, such as genetic algorithm (GA), should be adopted to do the optimization.

4. CASE ANALYSIS

4.1 System planning

The topology of pipeline network for the planning area of about 0.57 km^2 is shown in Fig. 2.

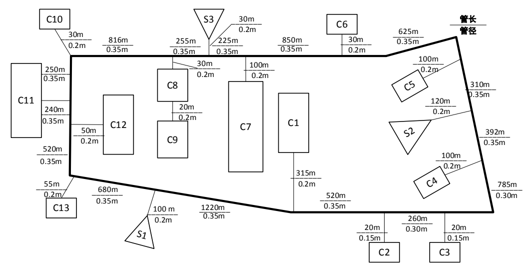
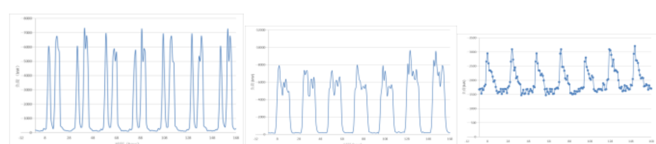


Fig. 2 Topology of pipeline network for the planning area

Three main heat sources are set. S1 is the gas-fired energy station with the gas-turbine generator set, the heat recovery boilers and the flue-gas absorption refrigeration units. S2 is the water source heat pump station with the double-pipe heat exchangers. S3 is the ground source heat pump station with air-cooled cooling tower.

4.2 Heating/Cooling load

The users are numbered from C1 to C13 including a hotel, a hospital, a school, a railway station, a business area and some office/residential buildings etc. The typical weekly (168 h) heating, cooling and electricity loads of the users were calculated, as shown in Fig. 3.



(a)Heating load in winter (b)Cooling load in summer (c)Electricity Load

Fig. 3 Typical weekly (168 hours) heating, cooling and electricity loads of the user C1

For the power system planning, the gas-fired energy station is used as the main power source to supply electricity to the users in the region. In addition, PV solar panels are installed on the roof of the public venue buildings in the central area, serving as the auxiliary power supply to all buildings in the region through the local grid.

The contrast of the integrated energy system based on thermal bus proposed in this paper with the traditional distributed energy system are shown in Table 1.

Table 1 Contrast in energy planning of the integrated energy systems with the traditional distributed energy systems

Season	Item	Traditional distributed energy system	Integrated energy system
Year-round	Power supply mode	Gas-fired energy station/PV	Gas-fired energy station /PV
Summer	Supply/return water temperature	Chilled water（7/12℃）	Cooling water（20/30℃）
	Cooling equipment in the building	Air conditioner/coils	Chiller/air conditioner/coils
	Domestic hot water equipment in the building	Solar collector/electric water heater	Waste heat recovery heat pump/solar collector
	Cold storage	Water from a fire pool	Water in the main pipe network
Winter	Supply/return water temperature	High temperature hot water（70/40℃）	Preheat the hot water（30/20℃）
	Heating equipment in the building	Wall /floor radiator	Heat pump unit/radiator
	Domestic hot water equipment in the building	Plate heat exchanger	Heat pump units
	Heat storage	None	Water in the main pipe network

4.3 Optimization calculation

The gas price was 2.26 CNY/Nm^3. The electricity price was 0.5003 CNY/kWh. The penalty factor was 100.0 (CNY/GJ). Genetic algorithm (GA) was used to solve the model numerically. The solution flow of the model was shown in Fig. 4.

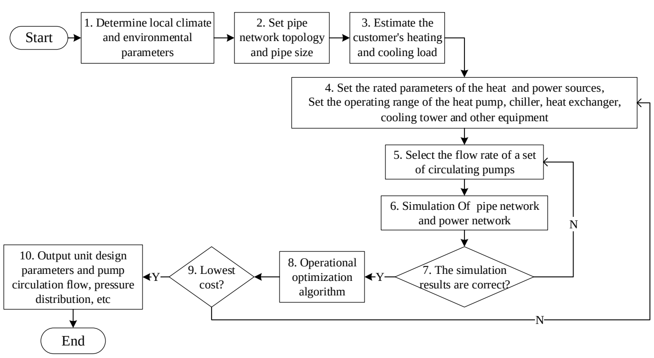
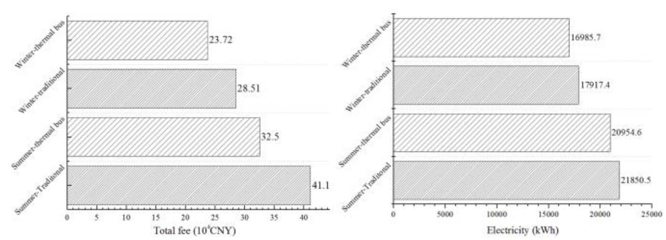


Fig. 4 The solution flow of the model of the integrated energy system planning based on thermal bus

The difference in the calculation process of the traditional distributed energy planning approach and the approach presented were in step 2 and 4 in Fig. 4.

4.4 Results and analysis

Comparing the energy system proposed in this paper with the traditional distributed energy system, the total operating cost in a typical week was reduced by 21.5% in summer and 16.8% in winter. If using no storage equipment, the amount of purchased electricity of the new scheme was reduced by 4.1% in summer and 5.2% in winter. The purchased electricity required for the energy system proposed in this paper and the traditional distributed energy system, as shown in Fig. 5.



(a) weekly operating costs (b) weekly electricity purchased

Fig. 5Typical weekly costs for the thermal bus system and the traditional distributed energy system

4.5 Conclusions

The proposed pipe network can be used to distribute heating water in winter and cooling water in summer efficiently. The supply pipelines for heating are also the return pipelines for cooling. The low temperature of water in the supply/return pipes is beneficial for reducing the heat loss of the network and easily connecting the ground/water source heat pumps to the heating network. The operating costs can be saved and the electricity purchased from the grid can be reduced when using the proposed system.

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