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# HIERARCHICAL SCHEDULING FRAMEWORK FOR A RESIDENTIAL DISTRICT HEATING SYSTEM

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**ABSTRACT**

A hierarchical scheduling model of a district heating system which consists of residential energy stations, heat exchange stations and heating consumers was developed in this paper. . Firstly, the optimal scheduling model of the energy station with combined heat and power (CHP) unit and the heat pumps was proposed. The optimal scheduling of the energy station is conducted to decide the output of different heating equipment of the heating system to minimize the operational cost of the energy station while meeting the varying heating loads. Secondly, the heat exchange station model was developed by utilizing the heat balance principle of the heat exchanger. Finally, a model to simulate the thermal characteristic and energy consumption of the buildings was proposed. The resistor-capacitor (RC) network is used to model the thermal characteristics of the building, in which the thermal inertia of the building and the adjustment of the radiator are considered. Consumers can take active controls on their radiators, which can both reduce the heating cost and meet their comfort requirements. Numerical studies demonstrate that the proposed strategy can contribute to the operational cost reduction of energy station and heating consumers, while guarantee the consumers' temperature comfort level.

**Keywords:** hierarchical scheduling model; energy station; resistor-capacitor network; control valve

**NOMENCLATURE**

*Symbols*

| | |
|---|---|
| $P_e$, $P_g$ | Electricity and gas purchase |
| $C_{e,t}$ ,$C_{g,t}$ | Electricity and gas price at time t |
| $P_{chp}$ , $H_{chp}$ | Electricity and heat produced by the CHP unit |
| $\eta_e$, $\eta_h$ | Conversion efficiency of gas into electricity and heat through CHP |
| $P_{hp}$ | Electric consumption of heat pumps |
| $H_{hp}$ | Heat produced by heat pump |
| $P_{load}$ ,$H_{load}$ | Predicted electric and heat value |
| $T_{g1}$ , $T_{h1}$ | Supply and return water temperature of the primary side |
| $T_{g2}$ ,$T_{h2}$ | Supply and return water temperature of the secondary side |
| $G_1$ , $G_2$ | Flow rate of the primary and secondary pipe |
| $c$ | the specific heat of the water |
| $a$, $b$, $F$, $\beta$ | Characteristic value of the radiator |
| $T_p$ | Average temperature the water |
| $T_r$ | Indoor temperature for the room |
| $T_{g2}$ , $T_{h2}$ | Supply and return water temperature in the radiator |
| $Q_2$ ,$Q_{2s}$ | Actual and designed thermal load |
| $T_{g2s}$ ,$T_{h2s}$ | Designed temperature of the supply and return water |
| $C_{i,j}^w$ | Heat capacity of the wall between node *i* and *j* |
| $T_{i,j}^w$ | Temperature of the wall between node *i* and *j* |
| $T_j$ | Temperature of node *j* |
| $R_{i,j}^w$ | Thermal resistance between the node *i* and *j* |
| $r_{i,j}$ ,$A_{i,j}^w$ | Wall identifier |
| $\alpha_{i,j}$ | Radiative heat absorption coefficient |
| $Q_{i,j}^{rad}$ | Radiative heat flux density of the wall |
| $C_i^r$ | Room heat capacity |
| $\pi_{i,j}$ , $A_{i,j}^{win}$ | Window identifier |
| $\tau_{i,j}^w$ | Transmittance of window between node *i* and *j* |
| $Q_i^{rad}$ | Radiative heat flux density to the room *i* |

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| | |
|---|---|
| $Q_{int_i}$ | Internal heat generation of the room *i*. |
| $Q_t$ | Heating consumption of users at time t |

## 1. INTRODUCTION

The combined operation of CHP and heat pump can be used as the energy conversation device in the energy station of the residential district. According to the electricity price, the station can provide power and heat energy for the terminal buildings in an optimal way [1]. With the improvement of the heat storage properties of buildings, the regulation ability of the buildings' participation in the optimal scheduling of the regional energy system is enhanced[3]. It has been demonstrated that the operational economics of the residential district heating system can be significantly improved by considering the thermal inertia of buildings. Due to the thermal inertia of buildings, the indoor temperature can be controlled in a suitable zone [4]. In this case, the heating load and the room temperature can be adjusted according to the users' comfort zone[6].

However, the flexibility of the building with heat inertia has not been fully explored in the optimal operation of the residential district heating system. For this purpose, this paper build a hierarchical scheduling framework. On the supply side, the optimal economic strategy is developed by adjusting the purchase energy of different heating equipment. On the terminal side, the scheduling strategy is proposed to meet the personalized needs of users by using the electric control valve to regulate the heating quantity.

## 2. HIERARCHICAL SCHEDULING FRAMEWORK OF A RESIDENTIAL DISTRICT HEATING SYSTEM

The residential district heating system consists of energy stations, heat exchange stations and heating consumers.

The energy station decides the power and heating schedules of the whole residential district. The equipment in energy station generates heat and electricity by purchasing energy from the upper power grid and the natural gas network. The heat transfers in the pipe, using hot water as the medium.

In the heat exchange station, the high-temperature water of the primary side transfers heat to low-temperature water of the secondary side through the heat exchanger.

Then the hot water of the secondary network transfers to the user side. Users can set the room temperature according to their own thermal comfort level to reduce their heating consumption. When the indoor temperature changes, the electric control valve of the radiator will act to change the water flow, in order to make the indoor temperature meet the set value. The electric control valve avoids the deviation of manual adjustment, and even if the users are not indoor, it can also be adjusted.

The hierarchical framework from heat source to heat users is shown in Fig.1:

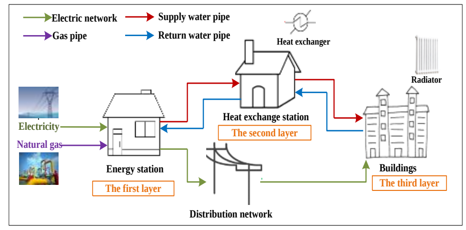


Fig.1 Hierarchical framework of a residential district heating system

## 3. MATHEMATICAL MODEL OF THE CENTRAL HEATING SYSTEM

### 3.1 Model of the energy station

There is one CHP unit and four heat pumps in the energy station. The heat generated by the two types of equipment satisfies the heat demand. The electric energy generated by the CHP unit supplies power to the district.

*1) Objective*

The economic cost of the energy station is composed of the cost of purchasing electricity and gas, as shown in Eq. (1):

$$F(t) = \min(C_{e,t}P_e + C_{g,t}P_g) \tag{1}$$

*2) Constraints*

a. Electrical power balance:

$$P_e + P_{chp} = P_{hp} + P_{load} \tag{2}$$

$$P_{chp} = \eta_e P_g \tag{3}$$

b. Heat balance:

$$H_{chp} + H_{hp} = H_{load} \tag{4}$$

$$H_{chp} = \eta_h P_g \tag{5}$$

$$H_{hp} = \eta_{hp} P_{hp} \tag{6}$$

c. Limits of energy purchases:

$$0 \le P_e \le P_{hp}^{\max} \tag{7}$$

$$0 \le P_g \le P_{chp}^{\max} / \eta_e \tag{8}$$

### 3.2 Model of the heat exchange station

The pipe networks on both sides of the heat exchanger are independent, as shown in Fig.2:

 

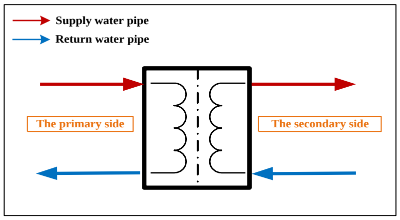


Fig.2 Model of the heat exchanger

The supply water temperature of the secondary side pipe network can be obtained according to the heat balance equation of the heat exchanger [5]:

$$cG_1(T_{g1}-T_{h1})=cG_2(T_{g2}-T_{h2})+cG_2\frac{dT_{g2}}{dt} \tag{9}$$

The supply water temperature of the primary side can be obtained through Eq. (10):

$$H_{load}=cG\cdot(T_{g1}-T_{h1}) \tag{10}$$

### *3.3 Model of the heat consumers*

#### 3.3.1 Model of the radiator

In this paper, the supply water temperature of all residents is the same.

There is a relationship between indoor temperature and heating radiator in Eqs. (11)-(13) [4]:

$$Q=aF\cdot\beta\cdot(T_p-T_r)^{1+b} \tag{11}$$

$$T_p=(T_{g2}+T_{h2})/2 \quad T_{g2}/T_{g1}\le 1.7 \tag{12}$$

$$T_p=\frac{T_{g2}-T_{h2}}{\ln\frac{T_{g2}-T_r}{T_{h2}-T_r}} \quad T_{g2}/T_{g1}>1.7 \tag{13}$$

The relative flow rate is used to characterize the action of the control valve, which can be expressed as [4]:

$$\overline{G_2}=\frac{Q_2}{Q_{2s}}\cdot\frac{T_{g2s}-T_{h2s}}{T_{g2}-T_{h2}} \tag{14}$$

In this paper, the average temperature of supply and return water is set as the control variable.

#### 3.3.2 Model of the heating area

The RC thermal network model of the building zones is composed of thermal resistance and thermal capacity, which respectively have the ability of transmitting and preserving heat. The structure of the RC thermal network model in a typical heating zone is shown in Fig.3 [6].

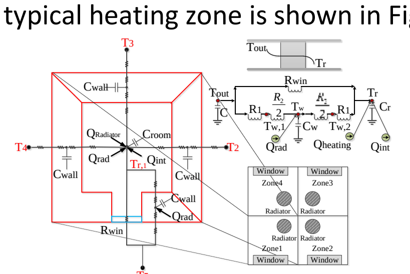


Fig.3 The RC thermal network model

*1) Objective*

The goal of heating consumers is to meet their heating demand and minimize consumption, as shown in Eq. (15):

$$F(t)=\min(\sum_{t=1}^{24}Q_t\cdot\Delta t) \tag{15}$$

*2) Constraints*

a. Thermal balance constraint of walls:

$$C_{i,j}^{w}\frac{dT_{i,j}^{w}}{dt}=\sum_{j\in N_{i,j}^{w}}\frac{T_j-T_{i,j}^{w}}{R_{i,j}^{w}}+r_{i,j}\alpha_{ij}A_{i,j}^{w}Q_{i,j}^{rad} \tag{16}$$

b. Thermal balance constraint of the zone

$$C_i^{r}\frac{dT_i^{r}}{dt}=\sum_{j\in N_i^{r}}\frac{T_{i,j}^{w}-T_i^{r}}{R_{i,j}^{w}}+\pi_{i,j}\sum_{j\in N_i^{r}}\frac{T_j-T_i^{r}}{R_{i,j}^{win}}+Q_i^{\text{int}} \tag{17}$$
$$+aF\cdot\beta\cdot(T_i^{p}-T_i^{r})^{1+b}+\pi_{i,j}\tau_{i,j}^{w}A_{i,j}^{win}Q_i^{rad}$$

c. Constrains of radiator operating

$$0\le\overline{G_2}\le 1 \tag{18}$$

$$T_{\min}\le T_{h2}\le T_{h2s} \tag{19}$$

## 4. CASE STUDIES

### *4.1 Heating strategies for energy stations*

There is an energy station, a heat exchange station and 20 buildings in the residential district. Each building has 40 households. Assume that the users have the same apartment type of 120*m*[2]. The optimized temporal length is 1 hour.

Residents' heat demand is related to the outdoor environment. In order to represent the heat load changes throughout 24 hours, the variation trend of predicted load is referred to [7]. And the value of heat load is chosen basing on the standard of heating design of north China [4]. It shows that the heat load of residents should be 40-50 *W/m*[2]. The calculated loads of 24 hours are shown in Fig.4(b).

Since the energy price and the value of electricity loads are not the key points of this paper, the existing data are directly cited basing on [7], which is shown in Fig.4(a).

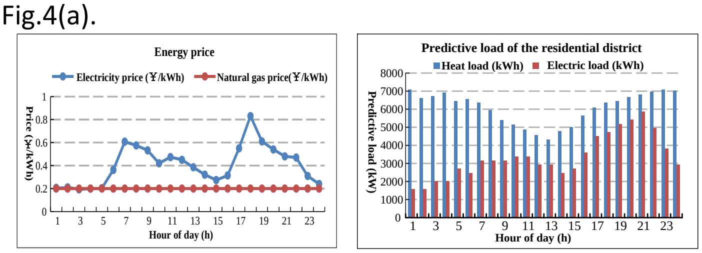


Fig.4 (a) Energy prices; (b)Electric and heat load of the residential district

The economic cost minimization strategy can be obtained according to the guidance of price. Fig.5 shows the electricity and gas purchase at each time period:

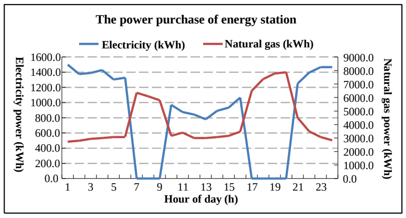


Fig.5 The power purchase of energy station

As shown in Fig.5, when the electricity price is high, the electricity purchased by the energy station decreases obviously and the corresponding gas purchased increases. As the heat load is higher at night, using efficient heat pump as the main source of heat source can not only save the cost, but also consume the excess electricity of the CHP. Tab.1 shows the economic costs of energy stations with different designs:

Tab.1 Economic costs of the energy station

| The equipment of energy station | Economic costs (RMB) |
|---|---|
| Heat pumps and CHP unit | 26644.48 |
| Only CHP unit | 29166 |

It can be seen from Tab.1 that adding heat pumps as demand-response devices can save functional costs and make efficient use of energy.

### *4.2 Heating strategies for heat users*

In this paper, two kinds of adjustment scenarios are set. Scenario 1 is to keep the indoor temperature constant. And scenario 2 is to turn off the radiator when no one is indoor.

The relationship between water flow and indoor temperature in different scenarios is shown in Fig.6:

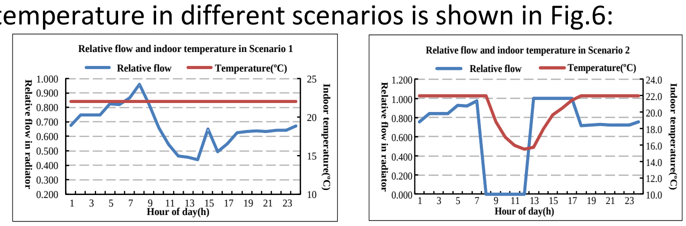


Fig.6 (a) Regulation strategy in scenario 1 (b) Regulation strategy in scenario 2

It can be seen from Fig.6 (a) that, because of the high outdoor temperature and light intensity at noon, the flow rate decreases to achieve the target temperature.

In this paper, it is assumed that the users set 9:00-17:00 as outgoing time and the room temperature changes freely. As shown in Fig.6 (b), the indoor temperature at 13:00 reached its lowest point, then slowly began to rise in order to reach the set temperature at 18:00.

The thermal comparative analysis of scenario 1 and scenario 2 is shown in the Tab.2:

Tab.2 The heat consumption in 2 scenarios

| Heating strategies | Heat consumption(kWh) |
|---|---|
| Scenario 1 | 138.790 |
| Scenario 2 | 124.037 |

As shown in Tab.2, as users can adjust the radiator more actively, the heating cost can be saved in scenario 2 compared with scenario 1.

## 5. CONCLUSION

Hierarchical scheduling framework for a residential district was proposed in this paper. The all-day electricity price and gas price are used to guide and adjust the output of the power supply unit to minimize the economic cost of the energy station. Users can adjust the control valve of the radiator to ensure the thermal comfort and reduce the heating cost as much as possible. This scheduling strategy make both energy supply side and user side are economically optimized.

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