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Application of heat adaptor: thermodynamic optimization for central heating system through extremum principle

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Abstract

Urban heating energy consumption in northern China accounts for 40% of total building energy consumption. In traditional central heating system, heat transfers from primary network (130℃/70℃) to secondary network (60℃/45℃) through heat exchangers in substations. In this paper, by introducing heat engine, heat pump and considering obtaining heat from environment, a new heat adaptor is built and the best system can be deduced out after thermodynamic optimization through extremum principle. The preliminary results indicate that when the return water temperature of primary network equals the ambient temperature, the heating capacity reaches the maximal value, which increases by 40% compared to absorption heat exchange system. Thus the thermal performance of existing heating systems can be evaluated.

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keywords: District heating; Heat pump; Environment; Energy saving; Extremum principle

1. Introduction

Urban heating energy consumption in northern China accounts for 40% of total building energy consumption and the percentage keeps increasing during recent years [1]. Compared to traditional coal-fired boiler heating systems, cogeneration district heating has been paid more and more attentions due to its low emission, high energy and economic efficiency. However, there exist two problems for cogeneration district heating systems in northern China. One is that the return water temperature of primary network is relatively high (>60℃), lowering the heating capacity of the system [2]. The other one centers on the huge energy waste resulted from exhaust steam cooling in cogeneration stations [3].

To solve these problems, Fu et al. proposed an absorption heat exchanger and applied the new system to substations in central heating system in Northern China, in order to decrease the return water temperature in primary network [4, 5]. Zhang et al. put forward a new concept of heat adaptor and found

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that the thermal performance can be greatly improved after bringing in heat-work conversion devices on the basis of heat exchanger [6]. Nevertheless, existing researches consider the substations as isolated systems, regardless of the environmental influence, so they failed to obtain the best system form under real conditions.

In this paper, by introducing heat engine, heat pump and considering environmental influence, a new heat adaptor system is built and the best system form is deduced out after thermodynamic optimization through extremum principle. The preliminary results indicate that when the return water temperature of primary network equals the ambient temperature, the heating capacity reaches the maximal value, which increases by 40% compared to absorption heat exchange system. This work is of great significance in design and evaluation of practical central heating systems.

2. Heat adaptor and thermodynamic model

For traditional heat exchangers, the cold fluid outlet temperature can never exceed the hot fluid inlet temperature (i.e. $T_{c,o}<T_{h,i}$). Similarly the hot fluid outlet temperature can be never lower than the cold fluid inlet temperature (i.e. $T_{h,o}>T_{c,i}$). Thus the return water temperature in primary network cannot be decreased if only heat exchanger is used in the substations (Fig.1).

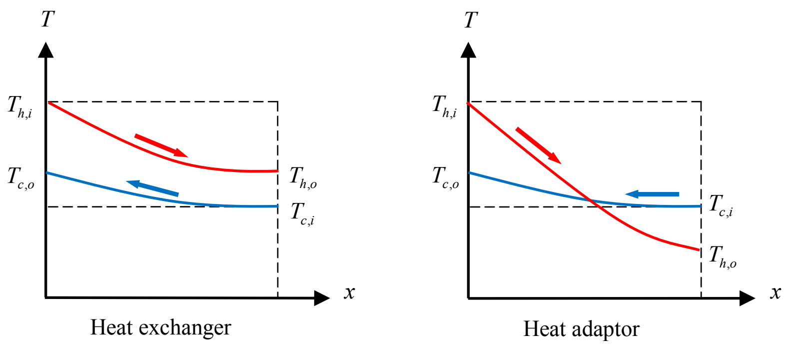
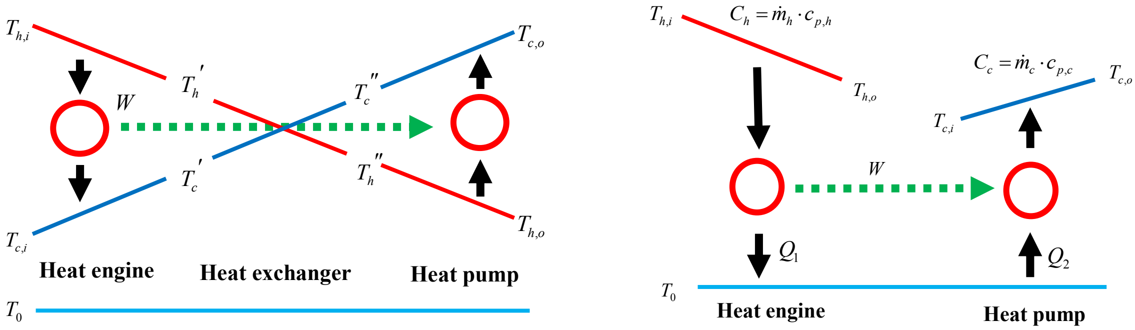


Fig.1 Comparison of temperature variation between heat exchanger and heat adaptor

In fact, if the return water temperature ($T_{h,o}$) can be decreased further to make full use of the thermal energy carried by the primary heat network, it will greatly reduce the mass flow rate in the primary heat network (m_h) and the pump energy consumption circulating the fluids in the system for the same heating areas, or dramatically increase the heating areas for the same mass flow rate in the primary heat network (m_h). Moreover, the relatively low return water temperature is favorable for waste heat recovery at the thermal power plants [5].

By introducing heat-work conversion devices, such requirement can be fulfilled (Fig.2a). And all the devices including heat exchanger, heat engine and heat pump can be regarded as a whole, called heat adaptor [6]. Absorption heat exchanger just serves as one typical form of heat adaptor. The question focuses on what devices are needed and what is the best form. The optimal heat adaptor system must be different when natural environment is taken into consideration. Environment has a great impact on the system performance. Moreover, to make full use of natural resources, heat pump is hoped to get free energy from the environment. Hence the heat engine can generate power with relatively high COP under the temperature difference between primary network supply water and the environment. Then the secondary network water can be heated by the heat pump to obtain energy from environment (Fig.2b).



(a). without environment consideration (b). with environment consideration

Fig.2 Schematic diagram of heat adaptor

In engineering field, the supply and return water temperatures ($T_{c,i}$, $T_{c,o}$) in secondary network as well as supply temperature ($T_{h,i}$) in primary network are often known. The objective is to decrease return temperature ($T_{h,o}$) in primary network and increase the mass flow rate (m_c) in secondary network, for given mass flow rate (m_h) in primary network, in order to increase the heating areas. To obtain the optimal system (maximal m_c), it is assumed that both heat engine and heat pump are ideal devices. According to extreme principle, the thermodynamic optimization model is as follow.

Objective: *max* m_c

$$\text{Constraint conditions:} \begin{cases} m_h c_p (T_{h,i} - T_{h,o}) = Q_1 + W \\ m_h c_p \ln \dfrac{T_{h,o}}{T_{h,i}} + \dfrac{Q_1}{T_0} = 0 \\ m_c c_p (T_{c,o} - T_{c,i}) = Q_2 + W \\ m_c c_p \ln \dfrac{T_{c,o}}{T_{c,i}} - \dfrac{Q_2}{T_0} = 0 \\ m_c, T_{h,o}, Q_1, Q_2, W \geq 0 \end{cases} \tag{1}$$

where W represents the generated power; Q_1, Q_2 represent the heat energy exchange between environment and heat engine, heat pump respectively; T_0 represents the ambient temperature. From Eq. (1), m_c can be expressed by

$$m_c = \frac{m_h (T_{h,i} - T_{h,o}) + T_0 \cdot m_h \ln \dfrac{T_{h,o}}{T_{h,i}}}{T_{c,o} - T_{c,i} - T_0 \ln \dfrac{T_{c,o}}{T_{c,i}}} \tag{2}$$

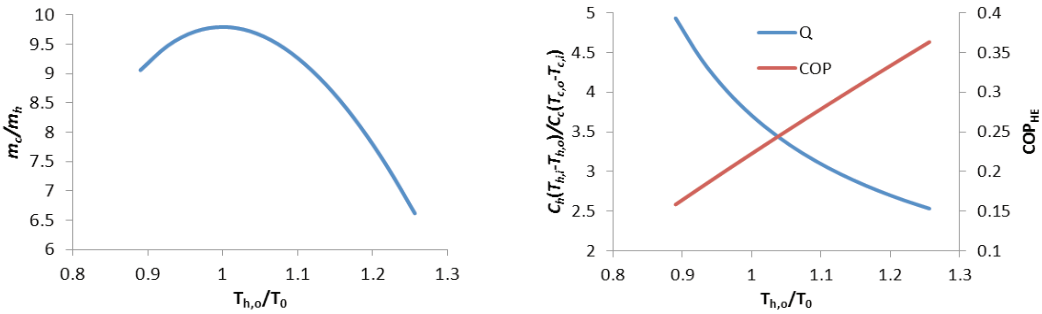
Then it can be obtained that

$$\frac{\partial m_c}{\partial T_{h,o}} = \frac{m_h}{T_{c,o} - T_{c,i} - T_0 \ln \dfrac{T_{c,o}}{T_{c,i}}} \cdot \left(\frac{T_0}{T_{h,o}} - 1\right) = 0 \Rightarrow T_{h,o} = T_0 \tag{3}$$

In theory, after taking environment into account, m_c reaches its maximal value only if the return water temperature in primary network equals the ambient temperature ($T_{h,o}$=T_0). So for practical systems, the optimal return water temperature in primary network can be obtained through the method.

3. Illustrative Example

When the user demand is known ($T_{h,i}$=403 K, $T_{c,i}$=333 K, $T_{c,o}$=318 K, T_0=273 K, c_p=4.19 kJ/kgK), the calculation results are shown in Fig.3. It is clear that the mass flow rate (m_c) in secondary network increases first and decreases after the maximum with increasing return temperature ($T_{h,o}$) in primary network. And when $T_{h,o}$=T_0, m_c reaches the maximal value. The reason is that with the decreasing $T_{h,o}$, the average temperature of heat source decreases, lowering the COP of the heat engine. On the other hand, the available heat energy in primary network ($T_{h,i}$-$T_{h,o}$) increases with lower $T_{h,o}$. So there exists the best value for m_c, to maximize the heating capacity.



(a). mass flow rate ratio (m_c/m_h) (b). heating power and COP

Fig.3 System performance with changing return water temperature

It is assumed that both heat engine and heat pump are ideal devices. It can be seen that when $T_{h,o}$=T_0, , the maximal value is obtained, that is m_c/m_h=9.8. When the return water temperature in primary network equals the ambient temperature, not only the heat carried by primary network water is made full use of, but also some free energy (Q_0) can be obtained from the environment. For this case, Q_0 accounts for 12% of total heat gain in secondary network water. The comparative analysis between traditional system, absorption heat exchange system and new heat adaptor system is shown in Tab.1.

Tab.1 comparison between three systems

	$T_{h,i}$ /$T_{h,o}$	m_c/m_h	Area increasing percentage
Traditional	130/70℃	4.0	-
Absorption	130/25℃	7.0	75%
Heat adaptor	130/0℃	9.8	145%

The preliminary results indicate that after taking natural environment into consideration, the ideal heat adaptor can greatly improve the heating capacity of central heating system. The results from the operation of the demonstration project of absorption heat exchanger in Northern China show that the temperature of the return water of the primary heat network can be reduced to about 25℃ [5]. In addition, the heating capacity can be increased further by 40% after applying the heat adaptor to the substation, compared to absorption heat exchange system (Fig.4). One the one hand, the mass flow rate in primary network can be decreased by 59%, resulting in 930 GJ of power saved by the pump circulating hot water in the primary heat network every year. One the other hand, the return water of relatively lower temperature can be used to recover the exhausted heat of cogeneration plants.

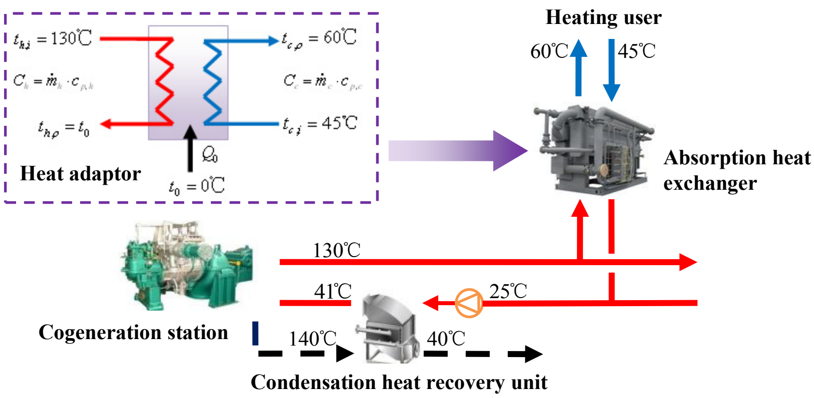


Fig.4 District heating system with heat adaptor [5]

4. Conclusions

In this paper, on the basis of existing concept of heat adaptor, a new system is proposed, containing a heat engine and a heat pump. The new system considers not only making full use of the heat carried by the primary network, but also obtaining free energy from the environment by the heat pump, in order to increase the heat capacity of cogeneration district systems. And the thermodynamic optimization model is built through extreme principle, to obtain the optimal system performance. Preliminary results show that the best system can be obtained only if the return water temperature of the primary network equals the ambient temperature. In that case, the ideal heat adaptor can increase the heating capacity by 40%, compared to absorption heat exchange system. For this work, only ideal devices are considered, so it needs future investigation for practical equipment. Still and all, Aimed at maximizing/minimizing objective parameter, the extremum-based optimization method is general. This work is of great significance in design and evaluation of practical central heating systems.

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Biography

Yin Zhang is a Ph.D. candidate in the Department of Building Science, Tsinghua University. He got bachelor's degree of engineering in Huazhong University of Science and Technology in 2011. His research interest focuses on building energy efficiency.