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Optimal selection among different domestic energy consumption patterns based on energy and exergy analysis

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ABSTRACT

In China market, people have many choices for air conditioning of their apartments, including heat-pump systems or gas-fired boilers for heating and air conditioners for cooling. Domestic hot water is usually provided by domestic water heaters making use of electricity or natural gas, which are known for their great energy costs. These systems consume much energy and increase the total cost of required domestic energy. A novel system combining heat pump with water heater is proposed in this paper, and it is named domestic energy system. The system can realize the provision of space heating, cooling and domestic hot water throughout a year. Based on different types of air conditioners, space heating equipments and water heaters, domestic energy consumption patterns are concluded to be eight categories. This study describes and compares the eight domestic energy consumption patterns by economic analysis and prime energy analysis method. Results show that the domestic energy system can provide good economy and save energy significantly. Furthermore, exergy analysis method is employed to compare the exergy efficiencies of different energy consumption systems. The results show that the domestic energy system has the highest energy conversion efficiency and can make remarkable contribution to social energy saving.

1. Introduction

In developed countries, space heating and cooling accounts for the largest proportion of domestic energy use, followed by water heating which accounts for 18% of the total energy consumption [1]. In China, these two energy consumption ways are also the first two energy expenditures in a family. In the regions with mild-winter temperature, most dwelling houses use heat pumps (HPs) for space cooling in summer and space heating in winter, and use various types of water heaters to provide hot water, such as electricity water heater, gas fired water heater, solar water heater with auxiliary electricity heater and heat-pump water heater. Moreover, heat pumps were first used in residences in 1950s for space heating and hot water heating. Much feasibility studies showed that air source water heating heat pumps were much more economical than traditional solar systems. Payback periods of 2–3 years were anticipated [2]. Air-conditioning units with an integral hot water storage tank and immersed condenser, using ambient air as a heat source, were available [3]. Desuperheaters, which work for heat pumps and air conditioners were claimed to offer almost free water heating in summer whenever space cooling was required, and to reduce total domestic electric demand in apartments [4]. Jie et al. [5,6] introduced a multi-functional domestic heat-pump system which combined heat-pump water heater with domestic air conditioner. The result showed that the integrated system can provide much better energy performance and higher equipment utilization throughout a year with less thermal pollution than heat-pump water heaters and air conditioner units. Shaowei et al. [7] presented a split air conditioner with a new hybrid equipment of energy storage and water heater to be utilized all year round and made a special design on the storage tank to adjust the refrigerant capacity in the storage coils under different functions. In this paper, a novel simple integrated system combining heat pump with water heater is proposed, and it is named domestic energy system. The novel system provides not only heating or cooling, but also hot water, so that it can increase equipment utilization to avoid equipment idle in transition time and decrease equipment investment cost. By applying electromagnetic valves in the water loop, the novel system configuration becomes quite simple and easy to operate. Considering the different choices of the space heating, cooling and hot water supply sources, we can conclude domestic energy consumption patterns to eight categories.

Economy and prime energy comparison are the main two common methods to evaluate energy systems. This paper compares different energy consumption patterns using these two methods. However, economy analysis is base on energy price which varies

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Nomenclature

APC	annual performance coefficient
COP	coefficient of performance
HPWH	heat-pump water heater
A	area (m^2)
C	specific heat (kJ/kg K)
$\dot{m}$	mass flow (kg/s)
M	mass (kg)
V	volume of hot water (m^3)
Δt	temperature difference (°C)
Ex	exergy (J)
N	duration days
P	power (W)
Q	energy (J)
T	temperature (°C)
T_0	outdoor dry bulb temperature (°C)
$T_{0,shi}$	outdoor wet bulb temperature (°C)
$\overline{T}_m$	air conditioning water average temperature (°C)
W	useful work (J)

Greek symbols

ρ	density of hot water at average temperature (m^3/kg)
η	energy efficiency

Subscripts

c	cooling mode
h	heating mode
$m1, m2$	inlet and outlet "media water"
$w1, w2$	inlet and outlet hot water
w	hot water

with districts as well as time, so the results are helpful but not accurate all the time. Prime energy way has been used in energy cost statistic and analysis [8,9]. Unfortunately, since this way only concerns the quantity of different energy but does not accurately represent the quality of energy, it is neither accurate. Besides these, exergy analysis is another method which has attracted more and more attention. Exergy analysis can provide an estimate of the minimum theoretical resource requirement of a process respectively, consequently provides information on the maximum savings that can be achieved by making use of a new technology and a new process. Lee and Sherif [10,11] used unit product exergy cost as an important factor to compare absorption system for cooling and vapor-compression chillers. Exergy analysis method was also presented by Ferrer and Bridges [12,13] to analyze air-conditioning systems. Badescu [14] employed the first law and the second law method (exergy analysis) to analyse a solar assisted heat pump based heating system and the results showed that most of the exergy losses occur during compression and condensation. Wang Xiaowu [15] did research on solar domestic-scale water heater and concluded that the exergy efficiency of domestic-scale water heater is small and pointed out ways to improve the exergy efficiency of domestic-scale water heater. Exergy analysis method has become a powerful tool to determine the best practice case variable for the design of standard systems.

All above researches only concerned the energy and exergy analysis of a single chiller or device, consequently provided ways to improve the exergy efficiency of the single device. However, in the process of improving energy efficiencies of millions of dwelling houses, the choice of suitable energy consumption pattern is the first and very important step. If a wrong energy consumption pattern is chosen, the effort focus on improving energy efficiency of its devices will be a waste and useless. Moreover, the amount of energy required by domestic energy consumption patterns plays a crucial role in the overall amount of energy consumed. Hence, optimal selection of a suitable domestic energy consumption pattern base on energy and exergy analysis is of great importance. Guangcai [16] has presented an optimization algorithm of the cooling and heating source scheme selection of air-conditioning system based on exergy analysis method. The paper gave an example of a certain office building to demonstrate exergy analysis and compared three schemes: scheme one is air source heat pump unit, scheme two is direct fired absorption type unit, and scheme three is water chiller + gas-fired boiler. The result showed that scheme one is the best choice and proved that the scheme selection base on exergy analysis was scientific, reliable and avoided subjectivity in traditional scheme selections. However, the paper only talked about the selection of space cooling and heating sources, but without domestic hot water involved. Besides, there are some other choices for the cooling and heating sources that the paper did not concern. In this paper, we divide domestic energy consumption patterns into eight categories according to different combination of space air conditioning devices and domestic hot water supply devices. Further more, economy, prime energy and exergy analysis are completed among eight domestic energy consumption patterns, and then the author decide on the optimal choice of domestic energy consumption pattern. The results show that the proposed domestic energy system has great superiority and excellent performance.

2. Different domestic energy consumption patterns

With rapid growth of social economy, the living standard of Chinese people has been improved significantly. As a result, energy consumption patterns have changed considerably and the amount of domestic energy consumption has been increasing rapidly. Nowadays, energy consumption mainly focuses on space cooling, heating and water heating, and the following will focus on the analysis of these two ways of domestic energy consumption.

2.1. Space cooling and heating

In regions with mild-winter temperatures, such as Shanghai, most dwelling houses need space cooling in summer and space heating in winter. For space cooling, most apartments rely on air conditioners, and for space heating, heat-pump systems, gas-fired boilers and electricity heaters are the main choices.

There are two main forms of heat-pump systems used: single-room type split air conditioners and central air conditioners. The single-room type split air conditioner was the most popular choice at the very beginning of domestic air conditioner use in China. The first small-size central air conditioner appeared in 1995, and it has been developed rapidly in China. Central air conditioners are suitable for houses and apartments with floor area between 100 and 600 m^2. Because of the advantages of energy saving, good appearance, excellent controllability and longevity, currently many customers regard it as the most favorable choice.

These two kinds of air conditioners can both fulfill the demands of space cooling and heating. But there are still some problems: the power consumed by air conditioners occupies the biggest proportion of the total power consumption. Moreover, the increasingly wide use of air conditioners leads to more serious gap between the supply and demand for electrical power. Furthermore, air