Energy and Buildings 154 (2017) 157–165

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Occupant control patterns of low temperature air-to-air heat pumps in Chinese rural households based on field measurements

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ARTICLE INFO

Article history:
Received 1 April 2017
Received in revised form 15 June 2017
Accepted 17 August 2017
Available online 23 August 2017

Keywords:
Occupant control patterns
Field measurements
AAHPs
Space heating
Chinese rural households

ABSTRACT

Currently, household heating systems in rural China primarily use coal. This low-efficiency heating method not only results in poor indoor comfort, but also contributes to indoor and regional air pollution. Split-type, low temperature air-to-air heat pumps (AAHPs) have been proposed to be a clean heating alternative to replace coal-burning stoves. This study performed field measurements of a AAHP product in two representative rural households in suburban Beijing, China, focusing on three goals: 1) to observe, analyze, and validate occupant control patterns of low temperature AAHPs in rural households; 2) to explore comfort indoor temperature levels in rural households and demonstrate the thermal comfort achieved as per the individual requirements of residents and space use; and 3) to learn the heating energy saving potentials achieved by considering occupant control patterns. Room temperatures and time-varying electricity consumption from February 6 to March 15 were monitored. Three occupant control patterns were observed and verified from the field measurements: 1) continuous daily operation of heat pumps, 2) intermittent operation, and 3) irregular operation. In addition, the observed indoor temperatures of both households ranged from 10 °C to 23.5 °C. By considering varied occupant control behaviors, the heating energy consumption reduction can be significant. This study indicated that using the low temperature AAHPs met individual thermal comfort requirements and had a great potential to reduce the heating energy consumption when considering different occupant control patterns.
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1. Introduction

In China, 77% to 82% of primary energy production relies on coal [1]. In rural residential households, coal and biomass are the dominant fuel types for space heating, with the total coal and biomass consumption of 197 million tons/year and 181 million tons/year in 2014, respectively [2]. Owing to the use of out-of-date and low-efficiency burning equipment (e.g., coal stoves), air pollutants (e.g., CO, $PM_{2.5}$, PM_{10}, NO_x, and SO_x) are generated during the combustion process, which negatively impacts both indoor and outdoor environments [3]. With long-time exposure, occupants are likely to develop many health problems, such as respiratory diseases, lower lung function, high blood pressure, and cardiovascular diseases [4–9]. Hence, non-combustion based heating methods are being sought after to replace traditional methods.

Responding to this need, the Chinese government has promoted “coal-to-electricity” policy since 2013 and implemented it in Beijing rural regions to further eliminate the coal usages and achieve “zero coal villages” [10,11]. As one of the technical alternatives, the air-to-water heat pumps (AWHPs) were selected and put into use. In addition, the rural residents who participated “coal-to-electricity” plan can receive subsidies from initial equipment installation and benefits from the peak-valley time of use electricity price.

However, the AWHPs have a major drawback. As a representative of cold regions in northern China, nearly all residential space heating systems in Beijing were designed according to “full-time, full-space” heating modes. The AWHPs were no exception, which made “part-time, part-space” “intermittent heating modes due to varied occupant control patterns hardly regulated. Different occupant behaviors of the residents can significantly impact the heating energy consumption [12] as well as the energy cost. Few investigations on occupant control patterns and related field tests in the Chinese rural areas have been found.

In addition, different from households in compact urban areas, rural households are typically scattered [13], and each household has one or several bedrooms and living rooms. Although some

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http://dx.doi.org/10.1016/j.enbuild.2017.08.049
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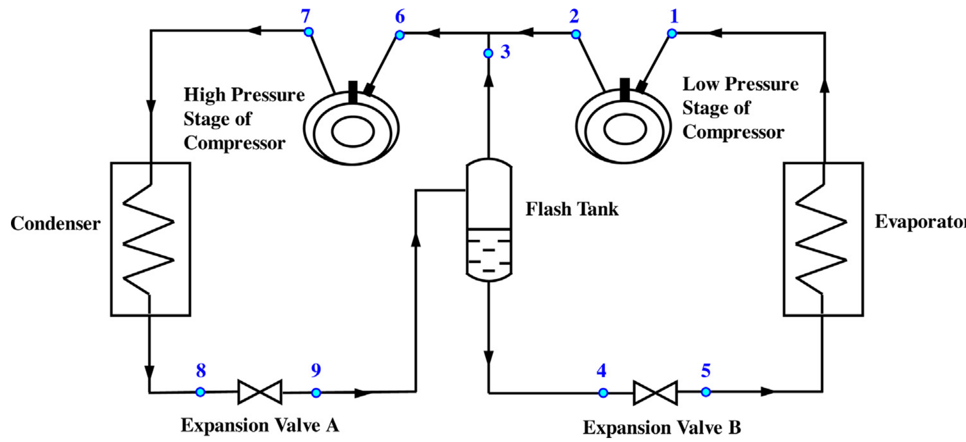

Fig. 1. Schematic of the LAT-AAHP system [22–24].

households feature insulation retrofits, the majority of building envelopes in rural regions in China are poorly insulated, and suffer from a significant influx of cold air [14]. Daily activities of rural residents vary significantly, resulting in different temperature requirements for different indoor settings [15]. Moreover, considering that rural residents typically have low incomes, low-cost, easy-to-use equipment with high energy-saving potential is needed for addressing variations in indoor comfort requirements.

After a careful consideration, split-type, low temperature air-to-air heat pumps (AAHPs) were selected in this study as a clean heating method, which can fulfill all of the requirements and satisfy all of the needs associated with heating rural households. On one hand, such an advanced system operates well in low ambient temperature conditions. On the other hand, split-type systems can be installed in individual dwelling spaces to achieve the required level of heating. The system allows for easy control of the indoor temperature according to the individual comfort requirements. Significant energy saving can be achieved by considering different occupant control behaviors.

This study conducted the field measurements of low temperature AAHPs on typical households in suburban Beijing, China, with the following goals:

- To observe, analyze, and validate occupant control patterns of low temperature AAHPs in rural households;
- To explore comfort indoor temperature levels in rural households and demonstrate the thermal comfort achieved as per the individual requirements of residents and space use;
- To learn the heating energy saving potentials achieved by considering occupant control patterns.

2. Low temperature air-to-air heat pumps

Considering relatively cold winters in northern regions, conventional ASHPs are deemed as inappropriate, owing to the following disadvantages:

- Insufficient heating capacity. As the outside air temperature drops, the building's heating load increases but the heating capacity of the heat pump decreases [16,17]. This is because, the evaporating temperature of the heat pump decreases with the drop of the ambient temperature, which can largely increase the specific volume of the suction refrigerant, decrease the effective refrigerant mass flowrate in the cycle, and finally result in insufficient heating.
- Unreliable operation under low ambient temperature conditions. As the ambient temperature decreases, the suction pressure decreases, which is likely to increase the compression ratio and rapidly increase the discharge temperature. The high discharge temperature may lead to the decomposition of refrigerants and the carbonization of lubricant oils.
- Poor thermal comfort. A traditional wall-mounted ASHP blows warm air from upper sideways, which causes the warm air to accumulate in and be constrained to the top of the room. Temperature stratification occurs in the vertical direction, which reduces comfort (for instance, owing to cold feet).

Instead, a typical low temperature AAHP system is considered suitable for rural areas in north China, which consists of an inverter twin cylinder rotary compressor, a condenser, an evaporator, a flash tank, and two expansion valves, and is schematically shown in Fig. 1. Compared with the conventional single-stage vapor compression cycle, the compressor in this system has two cylinders that represent the low pressure stage and the high pressure stage, respectively. In addition, the system is equipped with a flash tank and an extra expansion valve. For the system in Fig. 1, a typical cycle loop is 1-2-6-7-8-9-4-5-1. The low pressure refrigerant vapor from the evaporator first enters the low pressure stage of the compressor, which compresses the vapor into an intermediate pressure. Then, the vapor is mixed with the saturated vapor provided by the flash tank. The intermediate pressure vapor mixture enters the high pressure cylinder of the compressor and is compressed to achieve the condensing pressure. The heat is removed from the high pressure refrigerant vapor in the condenser and exchanged with the room air. This process converts the high pressure vapor into a liquid. After passing through the expansion valve A, a mixture of the refrigerant vapor and liquid is obtained. Following the flash tank, the mixture is separated into a saturated vapor and saturated liquid. The saturated vapor mixes with the refrigerant vapor discharged from the low pressure stage cylinder, while the saturated liquid proceeds through the expansion valve B and becomes a low-temperature low-pressure two-phase refrigerant. Exchanging heat with outdoor air in the evaporator, it becomes a low-temperature low-pressure refrigerant vapor. Finally, the cycle repeats.

The pressure-enthalpy diagrams of the single-stage and two-stage vapor compression cycles are shown in Fig. 2. The single-stage vapor compression cycle loop is 1-7′-8-5′-1, and the two-stage vapor compression loop is 1-2-6-7-8-9-4-5-1. Apparently, the compressor discharge temperature T1 is lower than T1′, which reduces the risk of lubricant oil carbonization of the compressor as well as improves the working envelop of the compressor [18]. In addition, the specific enthalpy of the refrigerant at the inlet of the evaporator is reduced after two-stage throttling. Given the same superheated

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