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Thermodynamic performance and economic feasibility of booster heat pumps in low-temperature district heating

Chul Woo Roh^a, Gilbong Lee^a, Young-Jin Baik^{a,*}, Minsung Kim^b,
Hyunki Shin^a, Beomjoon Lee^a, Junhyun Cho^a

^aKorea Institute of Energy Research, 152 Gajeong-ro Yuseung-gu, Daejeon 34129, South Korea

^bChungang University, 84 Heukseok-ro, Dongjak-gu, Seoul 55114, South Korea

Abstract

District heating (DH) utilizes and distributes the heat from various sources for residential and commercial buildings. However, fossil-fuel-based DH has no long-term future because of the political strategy to switch to renewable energy system; thus, DH should rely on other heat sources. The problem is that many renewable energy sources usually have lower temperature than fossil fuels. This is one of the reasons that the next generation of DH should have lower forward temperature than current system. In this paper, we present cycle layouts of booster heat pump (HP) for low forward temperature DH (80 °C). The booster HP has been discussed for DH as a possible solution if the grid temperature is low. We compared piping layouts for the booster HP and operating conditions for the current Korean DH operating circumstance. R245fa and R134a are discussed for refrigerants. It is found that the small temperature difference between a condenser and an evaporator in booster HP is important to get high coefficient of performance (COP); thus, the booster HP should use the forward water of DH directly for evaporator. Prices of electricity and DH affect the economic feasibility of booster HP; in the case of R134a high-return-temperature case (COP=6.2), 90% of current DH price at 80 °C of DH forward temperature, and \$0.18/kWh of electricity price can achieve parity with current DH energy charge.

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1. Introduction

District heating (DH) infrastructure has been evolved to carry out the task of improving energy efficiency of space heating. A network of DH connects energy centers (centralized energy plants) and buildings, so that a city or a town is allowed for the wide use of combined heat and power with the utilization of heat from waste-to-energy and various heat sources as well as the inclusion of geothermal and solar thermal heat. Future DH infrastructures should be designed for the future energy system. Conventional fossil-fuel-based DH has no long-term future because of the political strategy to switch renewable energy system. Thus, DH should rely on other heat sources like renewable energy. The problem is that many renewable energy sources usually have lower temperature than fossil fuels. This is one of the reasons that the next generation of DH infrastructures should have lower forward

* Corresponding author. Tel.: +82-42-860-3226.

E-mail address: chulwoo.roh@kier.re.kr.

temperature than current system [1]. By lowering DH forward temperature, DH grid heat losses can be decreased, and the electric power generation efficiency in DH center can be improved.

In this paper, we present piping layouts of booster heat pump (HP) for low forward temperature (80°C) of DH. The booster HP has been discussed for next-generation DH as a possible solution if the grid temperature is low or DH needs to be stored in large buildings. Authors compared piping layouts for the booster HP and optimized operating conditions for current Korean DH operating circumstances. As refrigerants of booster HP, R245fa and R134a are discussed.

1.1. District Heating in South Korea

The Korean peninsula lies in the region between 33 and 43°N, and has a mean annual temperature of 8 to 14°C. It belongs to both the continental and the subtropical climate zones [2]. In winter, the average temperature of South Korea is -2.4 °C (in January). Space heating starts in October and lasts until April.

The Korean government established a public utility, the Korean District Heating Corporation in 1985 in order to expand the DH nationwide, focusing on new satellite cities in the Metropolitan areas. The DH has been provided for existing apartments, replacing individual heating system, and newly planned cities are constructing new DH plants. Korean residents usually prefer DH to individual heating system because of three aspects; first, the price of the DH is cheaper than that of the later (but, in recent years, the price of DH supply has been continuously increased). Second, DH does not need an individual boiler system in each dwelling, so the space of living can be used efficiently. Finally, the overall value of the real estate that equips DH system tends to be more highly appreciated than the house which has no DH system.

Authors assumed a general Korean household's energy consumption model that can represent the winter's average energy demand for heating (space heating and hot-water supply). The assumed household needs 2.09 MWh/month for space heating and 0.497MWh/month for hot-water supply. The current Korean DH system's forward temperature is about 110°C and the return temperature to a DH center is about 60°C.

1.2. Booster Heat Pumps in District Heating

Köfing et al. [3] indicated that booster heat pumps for DH are possible solutions if the grid temperature is too low or DH needs to be stored in larger buildings. And Zvingilaite et al. [4] analyzed low-temperature DH in combination with small booster HPs with the purpose of supplying DH with forward DH temperature below the required DH temperature. Elmegaard et al. [5] investigated low-temperature DH combined with booster HPs using the dynamic network analysis framework. These analyses are also based on the combination of combined heat and power (CHP) system and DH, and are furthermore based on yearly average consumption rates and not a high temporal resolution. Østergaard and Andersen [6] found that conventional systems with higher temperatures in the network have a better utilization than low temperature solutions, as the decrease in heat loss does not compensate the electricity demand to cover the energy consumption.

2. Methodology

Fig. 1 shows the conventional DH system of Korean apartment housing and its temperature conditions for the fresh city-water supply, hot-water supply and space-heating supply and its return stream. Fig. 1 is a kind of the third generation of DH system that was introduced in the 1970s and took a major share of all extensions in the 1980s and beyond. Pressurized water is still the heat carrier, and the supply temperatures are often below 110°C. Typical components are prefabricated, pre-insulated pipes directly buried into the ground, compact substations using plate stainless steel heat exchangers [1]. As shown in Fig. 1, the temperature difference between the DH supply temperature (110 °C) and consumption temperature at households (55 °C and 60 °C) is quite huge. This big temperature difference is mainly originated from a limited amount of the mass flow rate of DH. If there is no sufficient flow rate being secured, as compared with the thermal energy demand, a DH provider cannot but increase the supply temperature. The elevated high forward temperature increases heat loss in grids and the central power station's heat sink temperature should be also increased. These are factors of the deterioration of entire energy efficiency in DH grids.

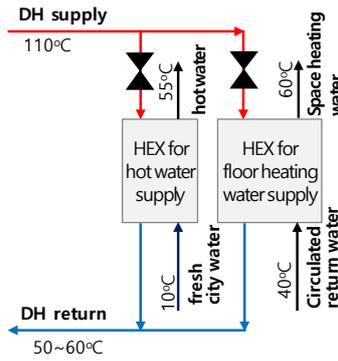


Fig. 1. Schematics of conventional Korean DH system and temperature conditions for an apartment complex in winter season

In the analyses of this paper, a simplified HP model is applied, where the compressor’s efficiency is assumed as 60%. Heat exchanger’s effectiveness is assumed as 90%. HP cycle simulation is carried out with the degree of superheat as 10 °C; the degree of sub-cooling is assumed as 17 °C. R245fa and R134a are considered as refrigerants of booster HPs. R245fa and R134a are popular refrigerants for conventional HP water heaters.

The booster HP can be installed in the basement of a large building or an apartment complex with the piping structure of Fig. 2(a) and (b) like below.

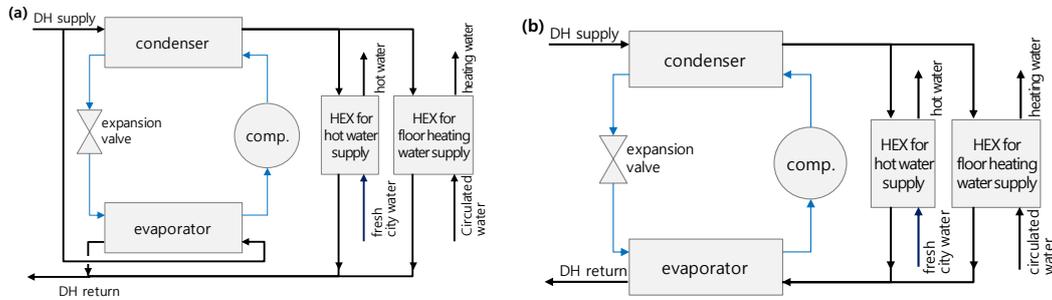


Fig. 2. Schematics of proposed HP booster concepts for Korean 4th generation DH system

Fig. 2(a) uses the energy from the DH supply directly to evaporate the refrigerant of booster HP. On the other hand, the system of Fig. 2(b) uses the energy from the returning water to DH center. The evaporating temperature in Fig. 2(a) is higher than that of Fig. 2(b), so it can be anticipated that the coefficient of performance (COP) of the booster HP in Fig. 2(a) is better than that of Fig. 2(b). The final temperature of returning water to DH center can be predicted to be higher in Fig. 2(a). The decreased temperature of the returning water to a DH center influences on the total energy efficiency of the entire DH system, because the heat sink temperature affects the efficiency of a CHP system as well as the consumption rate of the natural gas for a peak boiler. In a harsh cold weather, it often occurs that the heat generated from a CHP system cannot meet the overall heating demand of DH grids. In this case, the DH operator uses a peak boiler to meet the heating demand, but it deteriorates the profitability of the DH. In 2015 and 2016, South Korea has high electric power reserve rate; this means that CHP plants of DH operators get hardly a chance to generate electricity. This leads that the peak boiler’s operating rate gets increased. Therefore, reducing the forward temperature of DH supply to reduce the operation rate of the peak boiler as well as increasing the electric power consumption by using HP booster may be suitable for the current Korean energy situation.

In this paper, the reduced forward temperature is assumed as 80 °C. Although previous studies have suggested 50 °C for the 4th generation DH system, the possibility of realizing such low forward temperature in the present Korean DH grid should be discussed in a quite long-term point of view.

3. System analyses and results

In the following, main results from the analyses are presented with a focus on technical and economic performance. Fig. 3 shows results of heat and mass balance analyses of booster HPs.

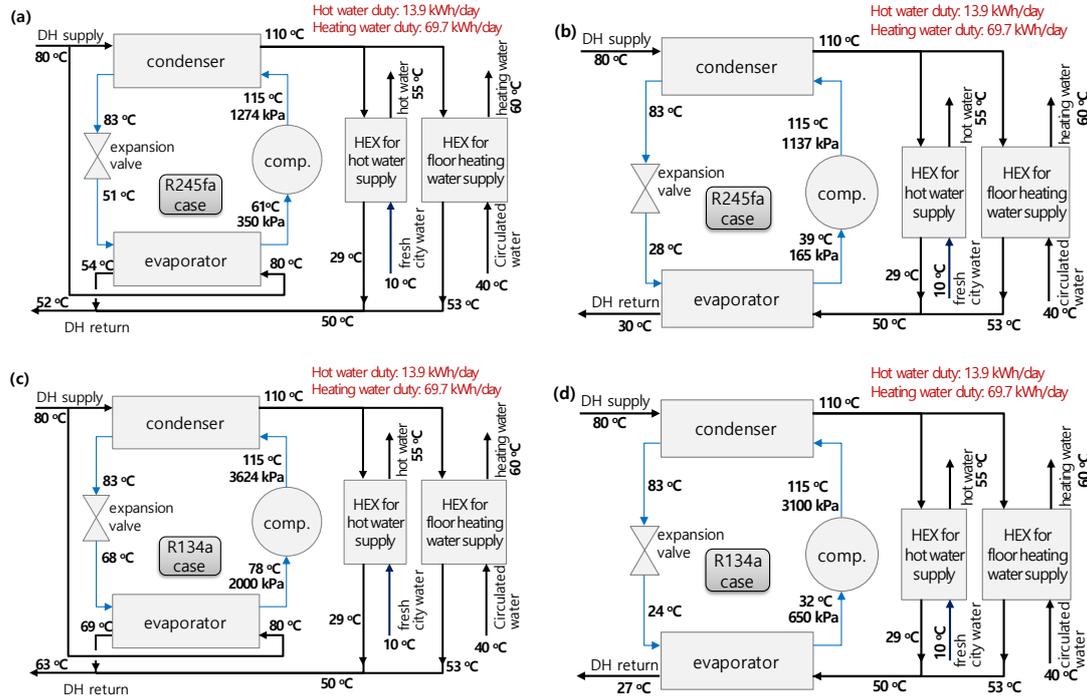


Fig. 3. Heat and mass balance analyses of HP boosters using refrigerants of R245fa and R134a cases

Fig. 3(a) and 3(b) shows the result of R245fa cases, and Fig. 3(c) and 3(d) shows the result of R134a cases. Fig. 3(a) and 3(c) have high return temperature (HRT), because they absorb the evaporating energy directly from the hot water of DH supply (80°C). Fig. 3(b) and 3(d) have low return temperature (LRT), because the energy source of evaporation is the final outlet stream of heat exchangers for heat consumption terminals. In general, high temperature difference between the condenser and evaporator increases compression ratio in booster HPs. This increases power consumption, so the COP of the booster HP decreases.

Table 1. Cycle performance characteristics of simulated HP boosters to meet a household’s daily heating energy demand

Characteristics	R245fa-HRT case (Fig. 3(a))	R245fa-LRT case (Fig. 3(b))	R134a-HRT case (Fig. 3(c))	R134a-LRT case (Fig. 3(d))
Compressor’s power consumption (kWh)	9.4	13.7	6.2	16.4
Evaporating capacity (kWh)	36.8	28.2	36.8	28.0
Condenser capacity (kWh)	42.2	41.6	42.4	44.4
COP of heating	4.5	3.0	6.8	2.7
Compression ratio	3.6	6.9	1.8	4.6
Consumed DH energy (kWh)	78.4	70.4	78.1	71.6
Preference in terms of performance	★★★	★★	★★★★	★

Conventional DH energy consumption in winter for the assumed household is 86.3kWh per day. As shown in Table 1, the booster HP consumes DH energy, 70.4~78.4kWh. This means that the booster HP can reduce the DH energy consumption about 9~18%. The decreased forward temperature in DH supply and the combined HP booster with the DH can be an alternative to reduce excessive heat demand in winter. This is a kind of demand dispersion (or control) function that allows a DH operator to turn on a peak boiler less.

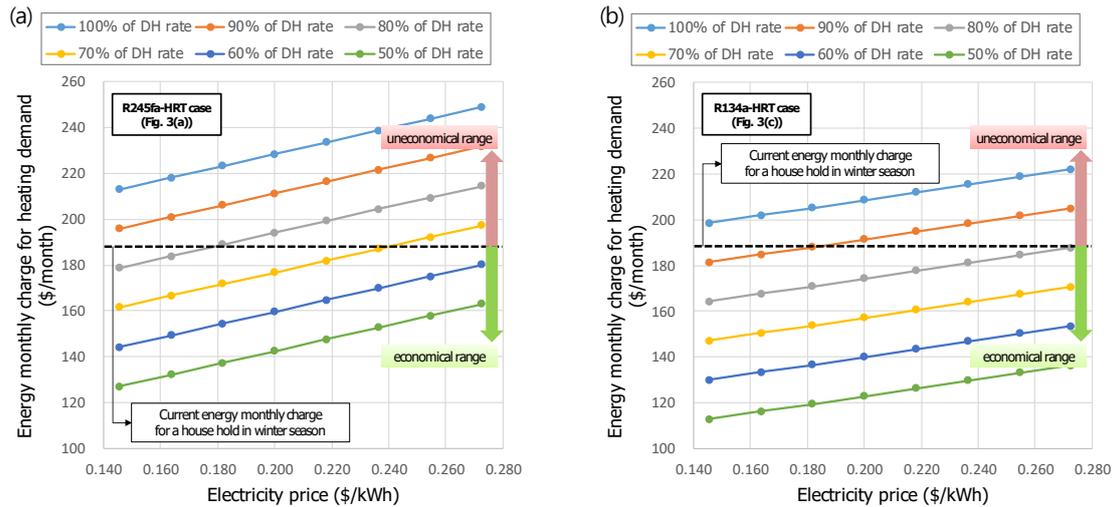


Fig. 4. Economic feasibility of the HP booster for a household in a circumstance of South Korea

Fig. 4 shows the result of economic feasibility analyses in terms of energy monthly charge to meet the heating demand of a household. Because the booster HP consumes electricity to compress refrigerant, the electric power usage increases instead of saving energy from DH. As shown in Fig. 4(a) and 4(b), the economic feasibility varies depending on the change in electricity rates; it is inevitable to adjust the DH price to some extent.

The efficiency of a booster HP highly influences the economic feasibility of entire system. If the price of electricity is high, the decreasing efficiency of the booster HP is more critical to worsening economic feasibility. In the case of R134a-HRT, the saved DH energy use (8.2kWh) is larger than newly consumed electric power (6.2kWh). However, in the case of R134a-LRT, the electricity consumed in the HP booster (16.4kWh) is larger than the saved DH energy use (14.7kWh); in general, this would be an unwanted result. This indicates that further optimization studies are needed to increase the efficiency of the booster HP with DH grids.

4. Conclusions

Regardless of whether the booster HP is used or not, it has been reported that current third-generation DH grid's various heat losses is significant. By using the booster HP in DH grids, the required forward temperature from the DH plant can be lowered. During a warm season, the COP of the booster HP can be increased above seven or eight. Of course, as mentioned in the previous section, the optimization and improvement of component design including hourly analyses of the operation against the spot market should be investigated furthermore. The discussion should be also engaged with the national energy policy and strategy.

Decreased forward temperature of DH system can improve the power generation efficiency in the DH center using a CHP system as well as can decrease the frequency of using peak boilers. Thus, the HP booster is a technology that spurs DH companies to produce electricity more efficiently than to generate just large amounts of heat. It is relatively easier to produce more heat than to generate electricity more efficiently. It is obvious which direction should be chosen for the efficient use of energy on a nationwide point of view. The HP booster is not an accessory device for realizing low-temperature fourth-generation DH, but a key device for efficient utilization of energy and optimization of heat supply for next generation of DH system.

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