Thermodynamic Performance and Economic Feasibility of Booster Heat Pumps in Low-Temperature District Heating

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Fossil-fuel-based district heating (DH) has no long-term future because of the transition to renewable energy systems. However, many renewable energy sources often have a lower temperature than fossil fuels; next-generation DH systems should therefore be designed to allow a lower forward temperature than at present. We compared piping layouts for the booster heat pump (HP) in South Korean operating conditions. We found that the price level of electricity and thermal energy have a complementary effect on economic feasibility. An affordable level of heating and electricity prices was analysed based on the heat demand of a household.

Introduction

District heating (DH) infrastructure has been developed to help improve the energy efficiency of space heating. A DH network connects energy centres (centralized energy plants) and buildings in a city or town, allowing widespread use of combined heat and power that utilizes heat from waste-to-energy and various heat sources as well as geothermal and solar thermal heat. Future DH infrastructures should be designed for the future energy system. The problem is that many renewable and new energy sources often have lower temperature than fossil fuels. This is one of the reasons that the next generation of DH infrastructure should have a lower forward temperature than at present [1]. By lowering the DH forward temperature, DH grid heat losses can be decreased and electric power generation efficiency in DH centres can be improved.

In this article we present piping layouts for booster heat pumps (HPs) for DH with a low forward temperature (80 °C). A 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. We compared piping layouts for the booster HP and optimized operating conditions for current Korean DH operating circumstances. We also discuss R245fa and R134a as refrigerants for booster HPs.

Methods and results

The Korean peninsula lies in the region between 33°N 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 continues until April. The Korean government established a public utility, the Korean District Heating Corporation, in 1985 in order to expand DH nationwide, focusing on new satellite cities in metropolitan areas. The DH has been provided for existing apartments, replacing individual heating systems, and newly planned cities are constructing new DH plants. Korean residents usually prefer DH to individual heating systems because of three aspects. Firstly, the operating cost of DH in winter is about 30 % cheaper than that of an individual heating system. Secondly, DH does not need an individual boiler system in each dwelling, so the living space can be used efficiently and safely. Finally, the overall value of real estate equipped with a DH system tends to be higher than a house with no DH system. We assumed a general Korean household energy consumption model that represents the average winter energy demand for heating (space heating and hot water supply). The assumed household needs 2.09 MWh/month for space heating and 0.497 MWh/month for hot water supply (average for the winter season). The current Korean DH system's forward temperature is around 110 °C and the return temperature to a DH centre is around 60 °C.

Previous studies indicate that the booster HP is the key factor in the success of next-generation low-temperature DH systems. Köfinger et al. [3] indicated that a booster HP is a possible solution if the grid temperature is too low or DH needs to be stored in larger buildings. Meanwhile, Zvingilaite et al. [4] analysed low-temperature DH in combination with small booster HPs for the purpose of supplying DH with a 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 a combined heat and power system and DH, and are furthermore based on yearly average consumption rates and not a high temporal resolution. The feasibilty of booster HPs is highly related to the mix of all energy provision in a specific area.

Østergaard and Andersen [6] found that conventional systems with higher temperatures in the grid offer better utilization than low-temperature solutions, as the decrease in heat loss does not compensate for the electricity demand to cover the energy consumption. Their contradictory findings indicate that the additional electricity demand for the thermal energy short-age in winter is the key to understanding the economic feasibility of low-temperature DH and its core terminal facility, a booster HP.

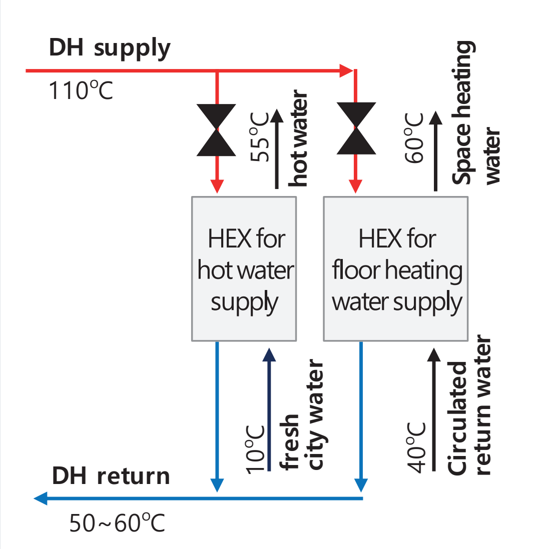

Fig. 1: Schematics of conventional Korean DH system and temperature conditions for an apartment complex in winter.

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 during the winter. Fig. 1 is a kind of third generation of DH 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 buried directly in the ground, and compact substations using plate stainless steel heat exchangers [1].

As shown in Fig. 1, the temperature difference between the DH supply (110 °C) and consumption in households (55 °C and 60 °C) is quite huge. This big temperature difference mainly originates from a limited amount of the mass flow rate of DH. If an adequate flow rate cannot be secured, as compared with the thermal energy demand, a DH provider should increase the supply temperature. The elevated forward temperature increases heat loss in the grid and the central power station's heat sink temperature should be also increased. These are factors in the deterioration of overall energy efficiency in DH grids.

A simplified HP model is applied. To compete with a standalone boiler or electric water heater, the booster HP should be fairly cheap. A simplified structure of HP is a necessity, not an option. The compressor's efficiency is assumed to be 60 %. The heat exchanger's effectiveness is assumed to be 90 %. HP cycle simulation is carried out, with the degree of superheat at 10 °C; the degree of sub-cooling is assumed to be 17 °C. R245fa and R134a are considered as refrigerants of booster HPs. The booster HP can be installed in the basement of a large building or an apartment complex with the piping structure shown in Fig. 2(a) and 2(b).

Fig. 2(a) uses the energy from the DH supply directly to evaporate the refrigerant of the booster HP. In contrast, Fig. 2(b) uses the energy from the returning water to the DH centre. The evaporating temperature in Fig. 2(a) is higher than that in Fig. 2(b), so it may be anticipated that the coefficient of performance (COP) for the booster HP in Fig. 2(a) is better than that in Fig. 2(b). The final temperature of returning water to the DH centre can be predicted to be higher in Fig. 2(a). In this article, the reduced forward temperature is assumed to be 80 °C.

Conventional DH energy consumption in winter for the assumed Korean household is 86.3 kWh per day. As shown in Table 1, the booster HP consumes the DH's thermal energy, 70.4–78.4 kWh. This means that the booster HP can directly reduce the DH energy consumption by about 9–18 %. The booster HP raises the temperature of the water supplied to the house, but from the viewpoint of energy as a whole, it has the effect

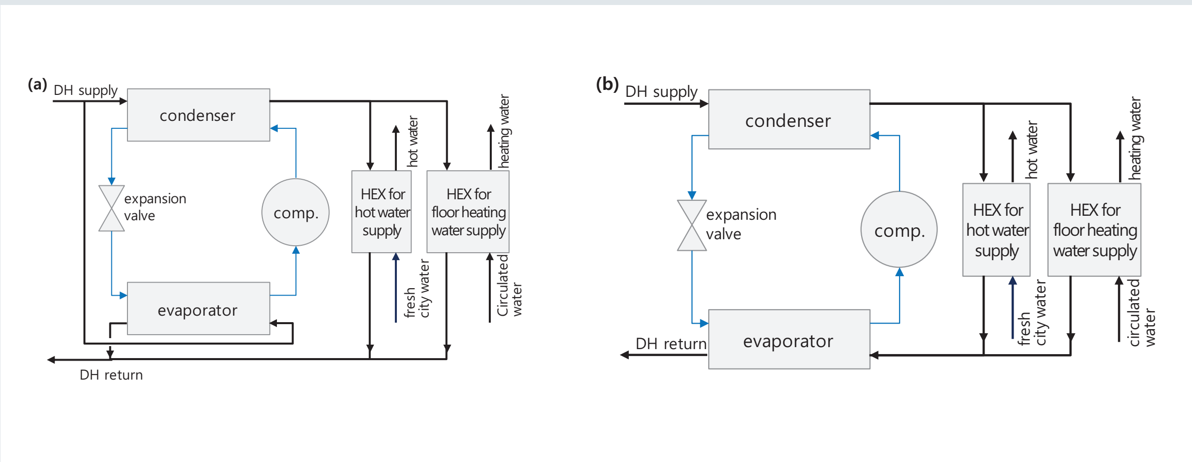

Fig. 2: Schematics of proposed HP booster concepts for Korean 4th generation DH system; (a) high returning temperature(HRT) case, (b) low returning temperature(LRT) case.

Characteristics	R245fa-HRT case	R245fa-LRT case	R134a-HRT case	R134a-LRT case
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	★★★	★★	★★★★	★

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

of switching 9–18 % of the heating energy from district heating to electricity. Another aspect is that combining an HP booster with DH can be an option for reducing 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.

Figures 3a and 3b shows the results of economic feasibility analyses in terms of energy monthly charges to meet the heat demand of the household (86.3 kWh per day, with an exclusive area of use of about 100 m^2). Since the booster HP consumes electricity to compress refrigerant, electricity consumption increases rather than the DH saving energy. As shown in Fig. 3, economic feasibility varies depending on the price of electricity.

The DH price must inevitably be discounted to some extent. From a common sense point of view, the energy price of the low-temperature DH is expected to be reduced since the temperature is lower than in the current systems. For DH companies, the booster HP and low-temperature DH operations may cause a decrease in heat sales and a decrease in business revenues.

The economic feasibility of the booster HP is also strongly influenced by the efficiency of the heat pump system itself. If the price of electricity is high, the low efficiency of the booster HP makes a critical negative difference to its economic feasibility. Considering the hot water temperature range of general houses, R134a is more suitable than R245fa. This indicates that further optimization studies are needed to increase the efficiency of the booster HP. The optimization study should take into account temperature ranges, the availability of hot water storage, electric power and thermal energy usage patterns depending on various applications.

Fig. 3(b) shows the parity point of the R134a booster HP at an electricity price of $0.18/kWh. The lower the heat price of district heating, the greater the range over which electric power charges can vary. The average marginal

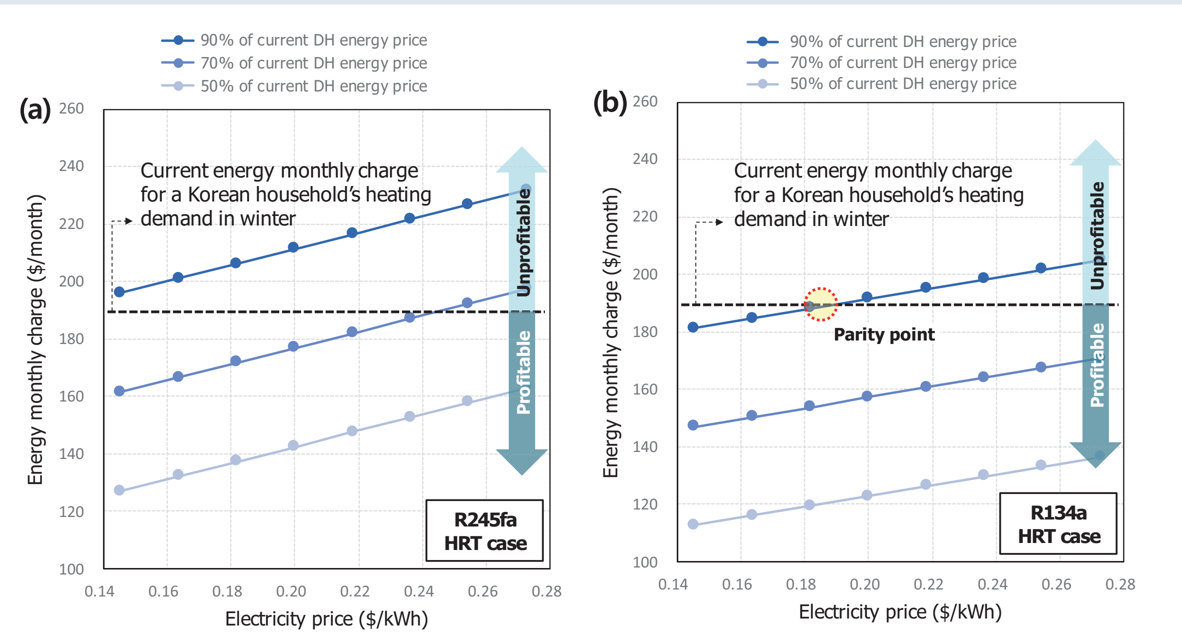

Fig. 3: Economic feasibility of the HP booster for a Korean household's heating demand in winter; (a) R245fa case, (b) R134a case. Note) Average system marginal price of Korean Electricity market: 0.08 $/kWh.

price of electricity in the Korean system is $0.08/kWh. The average electric power charge for a Korean residential house is $0.11/kWh. It is clear that the booster HP and low-temperature DH system can effectively reduce the monthly energy charge. To achieve a payback period of five or six years for the booster HP, the initial cost of the HP – one per household – should be less than $3,200. This value is based on operation in winter only (October to April, seven months). If the booster HP system can operate in summer for cooling, the payback period can be decreased to three or four years.

Conclusions

By using a booster HP in DH grids, the lower forward temperature of DH can be produced economically. From the perspective of the end-users in energy infrastructure, the booster HP is economically feasible as an energy-saving technology. However, a decrease in heat sales by DH companies is also predicted. Since the electrically powered booster HP consumes electricity, this helps to increase the sales of the electric power company. This raises the question of who is responsible for starting the large-scale transition to next-generation low-temperature DH. It is not a convincing enough argument to say that the booster HP is necessary simply because it can reduce peak boiler operation in winter.

A decreased forward temperature in the DH system can improve power generation efficiency in the DH centre using a CHP system and can also decrease the rate of use of peak boilers. Thus HP booster technology spurs DH companies on to produce electricity more efficiently than just generating large amounts of heat. Although 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 from a national point of view. The HP booster is not an accessory device for realizing low-temperature fourth-generation DH, but the key to efficient utilization of energy and to optimizing heat supply for the next generation of DH. Further investigations should be carried out into optimizing and improving mechanical component design, as well as an hourly economic analysis of operation against an energy spot market. Such discussions are relevant to national energy policy and strategy.

References

[1] Lund H, Werner S, Wiltshire R, Svendsen S, Thorse JE, Hvelplund F, Mathiese BV. 4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1-11.

[2] Yeo MS, Yang IH, Kim KW. Historical changes and recent energy saving potential of residential heating in Korea. Energy Build 2003;35:715-727.

[3] Köfinger M, Basciotti D, Schmidt RR, Meissner E, Doczekal C, Giovannini A. Low temperature district heating in Austria: energetic, ecologic and economic comparison of four case studies. Energy 2016;110:95-104.

[4] Zvingilaite E., Ommen T., Elmegaard B., Franck ML., 2012. "Low temperature DH consumer unit with micro heat pump for DHW preparation," In: Proceedings of the 13th international symposium on district heating and cooling district.

[5] Elmegaard B, Ommen TS, Markussen M, Iversen J. Integration of space heating and hot water supply in low temperature district heating, Energy Build 2016;124:255-264.

[6] Østergaard PA, Andersen AN. Booster heat pumps and central heat pumps in district heating, Applied Energy 2016;184:1374-1388.

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