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Improving the performance of booster heat pumps using zeotropic mixtures

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ABSTRACT

This study demonstrated an increase in the thermodynamic performance of a booster heat pump, which was achieved by choosing the working fluid among pure and mixed fluids. The booster heat pump was integrated in an ultra-low-temperature district heating network with a forward temperature of 40 °C to produce domestic hot water, by heating part of the forward stream to 60 °C, while cooling the remaining part to the return temperature of 25 °C. The screening of working fluids considered 18 pure working fluids and all possible binary mixtures of these fluids. The most promising solutions were analysed with respect to their performance under off-design conditions and their economic potential. The best-performing mixture showed a coefficient of performance (COP) of 9.0 and thereby outperformed R134a by 47%. Although the mixed working fluids resulted in higher investment cost, the economic performance was comparable to the pure fluids. The mixtures showed similar performance as the pure fluids at off-design conditions. It was concluded that the mixtures 50% Propylene/50% Butane and 50% R1234yf/50% R1233zd(E) could considerably improve the thermodynamic performance of the overall heat supply system while being economically competitive to pure fluids.

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1. Introduction

District heating is expected to play a major role in sustainable energy systems of the future. Conventional district heating systems (DH) supply both space heating (SH) and domestic hot water (DHW) to the customer. The supply temperature of conventional district heating systems is constrained to exceed 60 °C by the minimum DHW temperature, while the heat required for floor heating could be supplied at lower temperatures. In order to be able to integrate renewable heat sources efficiently and minimize heat losses from the grid, a reduction of district heating temperatures has been proposed, e.g. Ref. [1]. It is proposed that district heating supply temperatures can be decreased to supply only the space heating requirements of the building directly from the grid, while the DHW is supplied by boosting the temperature of the district heating supply line with a booster heat pump.

The so-called ultra-low-temperature district heating (ULTDH) and the corresponding booster heat pumps have recently been the focus of many researchers. Ommen et al. [2] define a DH network as ULTDH when the supply temperature is below the temperature required to directly supply DHW (35 °C–50 °C).

Different studies focused on the optimization of existing district heating grids by reducing the temperature levels and considering the possibility of booster heat pumps [2–4]. Studies have shown that the optimal supply and return temperatures of the grid and the economic feasibility of the integration of booster heat pumps are strongly dependent on the boundary conditions assumed. While the integration of booster heat pumps seems not economically viable for district heating systems with a high share of combined heat and power [3], it becomes more interesting with an increasing share of low temperature heat sources in the district heating network, such as industrial waste heat or centralised heat pumps [4]. Further issues when reducing temperatures in existing district heating networks can result from shifted requirements for heat exchangers and higher mass flow rates [3].

Several studies have conducted similar analyses that neglected the constraints imposed by existing networks and assumed the

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expected future composition of heat sources [2,3,5], factoring in the trend for an increasing share of renewables, and thus decreasing the share of combined heat and power in electricity production. These studies show that the use of booster heat pumps allows significantly lower operation temperatures in the network and thereby provide a decrease in transmission losses and a more efficient use of heat sources, such as waste heat with and without using centralised heat pumps. Assuming the supply to originate from centralised heat pumps, the use of booster heat pumps results in an increase of 12% in the overall performance compared to direct supply at above 60 °C [2]. This scenario becomes especially interesting for newly constructed districts, where temperature requirements of existing district heating networks do not constrain operation.

The overall performance and the economic feasibility from the consumer's perspective strongly depend on the performance of the booster heat pump. Østergaard and Andersen [5] assumed a fixed Lorenz efficiency for the heat pumps and reported a result which outperforms individual heat pump or boiler solutions. Zvingilaite et al. [6] analysed different opportunities for integrating booster heat pumps with different working fluids in different arrangements and compared it to conventional heat supply systems. They found the set-up in which the booster heat pump uses the supply stream as sink and source to be economically and thermodynamically superior to the ULTDH alternatives they investigated. Braber et al. [7] and Kleefkens et al. [8] analysed different booster heat pump system configurations with respect to thermodynamic and economic performance, defined recommendations for design and operation and highlighted the requirement for standardized testing procedures. Elmegaard et al. [9] evaluated different booster heat pump substations according to their exergetic and economic performance, based on consumer costs for heat supply. They reported that the exergetic efficiency of the system using a booster heat pump with R134a and conservative assumptions is close to the system performance of conventional district heating system at the lowest possible temperatures. The results indicated that a moderate performance increase of the booster heat pump could improve the ultra-low-temperature system to become competitive with conventional low temperature district heating systems.

The screening of state of the art technologies for the booster heat pump included simple heat pump cycles for the refrigerants R134a, R600a (iso-butane), R290 (propane) and R744 (CO_2). Dependent on the boundary conditions, a large share of the irreversibilities can result from heat transfer, since the sink and source are typically single-phase fluids with a linear temperature profile during heat transfer, which does not match the constant temperature of the working fluid during phase change well and thus, inevitably results in exergy destruction.

Radermacher and Hwang [10] noted that zeotropic mixtures show a temperature glide during phase change, which can potentially be matched with the temperature glide of sink and source and thus can contribute to improved performance. Mohanraj et al. [11] conducted a comprehensive review of the different studies carried out in this field. They concluded that the use of mixtures does not only result in an improved performance, but also enlarges the range of a given set of fluids. This becomes especially interesting as established refrigerants are phased out due to legislation by the Montreal protocol [12], the Kyoto protocol [13] and especially the amendment to hydrofluorocarbons (HFCs) from Kigali [14].

Zühlsdorf et al. have shown in previous studies [15,16], that heat pumps with mixed working fluids constitute a competitive alternative that outperformed conventional heat pumps in terms of their thermodynamic and economic performance. It has been shown that the use of mixtures is especially beneficial in applications with a low temperature lift between thermodynamic average temperature of sink and source in combination with a relatively large temperature glide in sink and source and that they can result in performance increases of more than 25% [15,17].

The present study analysed the performance of mixed working fluids in a booster heat pump application in an ultra-low-temperature district heating network. A comprehensive screening was conducted to determine the most promising mixtures. These selected solutions were analysed in more detail, which included the sizing of components, an economic analysis from the consumer point of view and a performance analysis under different operating conditions than the design criteria (off-design analysis). Finally the performance indicators obtained were reused in the models from Ommen et al. [2] to re-evaluate district heating network system performance.

2. Methods

2.1. Case Description

The present study focused on the development of a booster heat pump for an application, which is aligned to the EnergyLab Nordhavn project [18]. The booster heat pump is part of a DH substation, which is shown in Fig. 1. The substation consists of a heat exchanger to supply the space heating demand, a booster heat pump with storage tank to supply domestic hot water and a second smaller heat pump to reheat the recirculated hot water in the building. The recirculation system is not the focus of the present work and is thus excluded from the drawing.

The district heating supply enters the substation at a temperature of 40 °C. While one part of the stream is used as the heat source in the evaporator and cooled down to approximately 25 °C, the other part is heated up to the design temperature of 60 °C and fed into the stratified hot water tank or directly used for heating up the DHW in the linked heat exchanger.

The outlet from the booster heat pump evaporator is mixed with either the return from the DHW heat exchanger or the cold outlet from the tank while charging (both approximately at 15 °C–18 °C), before it is discharged into the district heating return line at approximately 21 °C. If the DHW storage tank is discharged, cold water is drawn from the DHW heat exchanger to fill up the tank from the bottom.

The booster heat pump analysed in this study is based on the dimensioning of a prototype, which was designed within the framework of the EnergyLab Nordhavn project [18] to provide DHW for a multifamily building including 15 flats. Following the Danish Standard DS439 for water supply installations [19] and the assumption of 3 persons per flat with an average daily consumption of 46.2 l per person, the demand amounts to 2079 l/day. To account for heat losses and a possible additional use, a daily consumption of in total 2450 l/day was considered. The storage temperature was chosen to be above 55 °C to avoid the growth of legionella bacteria in the DHW distribution system inside the building [20]. The daily charging time of the prototype was assumed as 4 h to increase the suitability for integration as a flexible unit in a smart grid. This defines the heat supply load of the booster heat pump at design conditions to be 13.9 kW while heating 600 kg/h from 40 °C to 60 °C. Disregarding the possibility to benefit from flexible electricity consumption, the described booster heat pump can as well be integrated in substations with larger storage tanks, covering larger demands at an increased daily operation.

2.2. Thermodynamic model

The first step consisted of a screening to identify the most promising fluids for the booster heat pump in terms of

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