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Design of serially connected district heating heat pumps utilising a geothermal heat source

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ABSTRACT

The design of two heat pumps (HP), connected in series, was investigated for operation in the district heating (DH) network of the Greater Copenhagen area, Denmark. The installation was dimensioned to supply 7.2 MW of heat at a temperature of 85 °C. The heat pumps utilise a geothermal heat source at 73 °C. Both heat source and sink experience a large temperature change, which may lead to decreased performance for single vapour compression HP. The performance may be increased by using HPs connected in series and by applying HPs with zeotropic mixtures. First a generic study with a simple representation of the HP was applied to investigate optimal system configurations. It was shown that using two heat pumps in series with direct heat exchange in parallel with the first heat pump could increase the performance compared to the HP performance. Detailed thermodynamic models of a zeotropic mixture HP predicted that an exergetic efficiency of the units between 50% and 65% is possible. The technical feasibility as well as the economic viability of this installation was investigated for a range of optimal configurations. The analysis recommends a heat pump configuration with a system exergetic efficiency of 63%.

1. Introduction

The municipality of Copenhagen, together with the Greater Copenhagen Area in Denmark, has the target to supply CO2 neutral district heating (DH) in 2025 [1]. The proposed method for achieving this target is mainly based on the conversion from fossil fuels to biomass in the large central combined heat and power (CHP) plants as well as incineration of waste in smaller CHP units. Waste incineration contributes as base load technology today and is expected to continue in the years to come, although a slight decrease in available resources is projected [2]. Focussing mainly on biomass as the sole fuel for intermittent and peak demand presents a significant risk in terms of security of supply [3]. Other supply technologies, such as heat pumps (HPs) utilising geothermal heat sources, or heat sources close to ambient, are also considered [4]. It is expected that approximately 300 MW heat production capacity from HP technologies is economically feasible [2], if appropriate heat sources can be located in the proximity of the DH network [5].

Geothermal heat sources are used for a wide range of applications including both direct and indirect utilisation in district heating networks [6]. In many areas (e.g. in Turkey), the obtained temperatures of the production wells exceed or matches the supply temperatures of the DH network [7]. The heat cost from geothermal installations are affected by many factors (such as investment cost for wells and HP, running cost for pumps and HP etc. [8]) which results in highly different profitability even for adjacent distribution areas [9]. Further, the choice of HP technology e.g. refrigerant may also impose a significant change in the cost of supplied heat [10]. For utilisation in Danish DH systems, the temperature requirements for direct utilisation limits the possibilities and economic applicability [11]. However, by use of a geothermal heat source at a lower temperature than for direct utilisation, the temperature lift of the required HP is limited and may result in a favourable overall cost of heat. It may thus be a relevant alternative to biomass, but the technology is limited by drawbacks, such as a rather inflexible load profile due to the limitations of utilising the well, as well as the requirement for large investments to set up such systems.

For applications in DH, the temperature variation of either source or sink stream is typically of a magnitude, where serial connection of HPs, may provide an increase in the coefficient of performance (COP) [12]. On the other hand, the economy of scale may suggest that the investment of a single unit is less than for two smaller units, when considering an equal total heat load. The most profitable solution may further vary with HP parameters such as

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Nomenclature

Abbreviations

COP	Coefficient of Performance
DH	District heating
EES	Engineering Equation Solver
GT	Geothermal stream
HACHP	Hybrid absorption compression heat pump
HEX	Heat Exchanger
VCHP	Vapour compression heat pump
NPV	Net present value
PV	Present value
TCI	Total capital investment

Symbols

c_p	Specific heat capacity (kJ/kg-K)
$\dot{E}$	Exergy rate (kW)
f	Ratio (dimensionless)
$\dot{m}$	Mass flow rate (kg/s)
p	Pressure (bar)
$\dot{Q}$	Heat rate (kW)
T	Temperature (°C (difference K))
$\overline{T}$	Mean temperature (°C (difference K))
$\dot{W}$	Power (kW)
x	Ammonia mass fraction (kg/kg)

Greek letters

Δ	Difference
ε	Exergetic efficiency
ε	Heat exchanger effectiveness
η	Efficiency

Subscripts

0	Dead state
DH	District heating stream
GT	Geothermal stream
H	High
HP	Heat pump
HX	Heat exchanger
in	Inlet
is	Isentropic
IH	Internal heat exchanger
m	Mass flow ratio
MX	Mixer
out	Outlet
pp	Pinch point
Q	Heat load ratio
r	Rich
tot	Total

sink temperature, temperature lift and temperature variation of sink and source streams.

An alternative approach to increasing the COP of HPs working between sink and source streams with high temperature variations is the application of the hybrid absorption compression heat pump (HACHP). The HACHP is a practical implementation of the Osenbrück cycle [13]. The Osenbrück cycle seeks to approach the Lorenz cycle [14] and thus seeks to minimize the irreversibilities related to the heat transfer with the sink and source by adjusting the temperature variation of the working fluid to match these [15]. In practice this is achieved by the application of a zeotropic working fluid, typically ammonia-water, resulting in a non-isothermal phase-change of the working fluid. Hultén & Berntsson [16] shows that the HACHP increases the performance by up to 10% compared to a VCHP when the sink and source glides are 20 K, however the performance was reduced by 10% at a sink and source glide of 5 K. Hultén & Berntsson later showed that increasing pressure limits would allow an increase in the COP of HACHP [17]. A further advantage of using a zeotropic working fluid is the reduction of vapour pressure compared to the vapour pressure of the pure volatile component [18]. The reduction of vapour pressure is an advantage for high temperature applications, such as district heating, as it allows the utilisation of low pressure component for high temperature applications [18]. With the current pressure level of commercially available components the HACHP is capable of delivering significantly higher temperatures than the conventional vapour compression heat pump (VCHP), however this requires the correct combination of ammonia mass fraction and circulation ratio to be identified [19]. The HACHP has been shown to provide a good return on investment as well as a significant reduction of CO_2 emission when applied for industrial process heating, in e. g spray drying facilities [20].

Detailed thermodynamic and economic models of various single stage VCHP and HACHP were developed and investigated in Ommen et al. [21] and Jensen et al. [22]. The results show, that the best available technology in terms of net present value (NPV), typically depends on the performance and investment of the HP systems at the specific layout of the sink/source process streams. Besides the thermodynamic performance of the cycle and working fluid, it is important to consider the application limits of the individual components.

Possible benefits of integrating several HPs in series are presented by Ommen et al. [23]. The analysis is performed for VCHPs using economic scenarios relevant for industrial integration/application. For such a case, the increased performance does not economically compensate for the increase in investment at the expected technical lifetime of the plant.

In the case of utility production in Denmark, a different taxation scheme applies to the utilised electricity. Electricity for industrial process heat is exempt from taxation while full taxation is applied in the case of utility production, such as DH. The increased heat production cost for utilities, changes the economic optimum for a HP installation towards systems with lower running costs (higher COP) at expense of increased capital investment. In this way, the performance benefit of HPs operated in series becomes viable. To obtain low heat production prices, the utility companies are required to select utility plants with low consumer cost, where fuel (e.g. electricity) cost, market price of co-produced utilities (if any), O&M, taxes as well as investments are included in the calculation. An example of this difference between the two economic scenarios is presented in Fig. 1 for VCHPs [24].

It is shown, that the benefit of a serial connection depends mainly on the economic case and the temperature difference of the HP sink and source streams. All other relevant economic parameters are similar to those presented in Ref. [23]. For the case of DH, it is shown that serial connection of two HPs is preferable for both of the presented sink and source temperature differences. At low source temperature difference, the benefit of serial connection is reduced to an insignificant increase considering the uncertainties of the analysis. At sink and source temperature differences of 20 K, the economic benefit exceeds 5%.