Application of an industrial heat pump for steam generation using district heating as a heat source

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Abstract

Many industries have heat demands at temperatures above 100°C and very often the preferred energy carrier is steam. District heating companies are looking for industrial customers that has a steady demand of heat, but are often unable to supply the heat at the necessary temperature. In this paper we present a high temperature heat pump and auxiliary equipment capable of generating up to 10 bar_g (184°C) steam from district heating. The paper expands on the previous work by the author presented at the 11th IEA Heat Pump Conference in Montréal, Canada in 2014. In the previous work the performance of a commercial installation of the heat pump that generated 110°C hot water from waste heat was presented. In this paper we present the technology, the general performance, and a case study for steam generation at 184°C using district heating as a heat source.

The case study is at a dairy plant, where the heat source is district heating at 80-85°C. The steam at 10 bar_g is generated by circulating water over the internal heat exchangers and in a steam generator. The dairy plant benefits by significantly reducing their carbon emission, as the steam generated by the heat pump replaces steam generated by natural gas. District heating company gets a steadier short and long term heat demand, and subsequently a better utilisation of their power plant and district heating network.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

In this paper we present an installation of three heat pumps at a dairy plant. The heat pumps generate steam at 10 bar_g and using district heating at 80-90°C as the heat source. The project is a cooperation between TINE Meieriet Ålesund (customer/end user), Tafjord Kraftvarme AS (district heating company) and Single-Phase Power AS (heat pump supplier). The heat pumps are expected to be in operation in 2017.

The case for using a heat pump to generate steam at temperatures above 100°C using district heating as a heat source is twofold. Firstly, many industries have a large part of their heating demand at temperatures above 100°C and prefers steam as the energy carrier. Secondly, district heating companies can operate their system more efficiently if the annual variations in demand is reduced. Industrial customers typically have lower seasonal variations than the domestic heating customer, whose demand is strongly correlated with the outside temperature.

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In a process integration study at a dairy plant by Gervind et.al. [1], the pinch analysis of the dairy shows a pinch temperature between 40 to 60°C. This means that any external heat added to the process should be added at a higher temperature than the pinch temperature. A large portion of the heating demand was above 80°C. This is hardly a surprise, as a major contribution to the heat demand at a dairy is the sterilization or pasteurization process. The sterilization process is dependent on the temperature and holding time. Higher temperature and longer holding time increases the efficiency of the process. However, the chemical changes of the milk also increase with higher temperature and longer holding time. A trade-off between the quality of the milk and the sterilization is set to 72-75°C for 15-20 s for pasteurized, homogenized milk and 135-150°C for a few seconds for UHT milk [2]. TINE Meieriet Ålesund uses the steam for UHT products.

1.1. SPP HighLift heat pump technology

The heat pump process for the SPP HighLift heat pump is based on the Stirling cycle. The ideal Stirling cycle is a thermodynamic process that consists of four reversible process in series. Compared to compression and absorption heat pumps, the working medium in a Stirling process is a gas throughout the process. This means that the process is independent of the evaporation and condensation temperatures of the working medium. In addition, the temperatures in the process is not dependent on the compressor pressure, as is the case for the Brayton refrigeration cycle. The charge pressure and configuration will define the maximum pressure and amplitude, and can be used to regulate the load of the heat pump. This gives the Stirling cycle certain advantages. The process will adapt to any external temperature regardless of gas pressures, and any restriction on the temperatures is caused by the mechanical implementation of the process. The cycle is a reverse heat engine cycle, which means that the efficiency is bound by the inverse Carnot efficiency (or COP_{Carnot}). The efficiency of the ideal Stirling cycle is in fact identical to the Carnot cycle efficiency.

The SPP HighLift heat pump mechanical implementation is a four-cylinder Stirling engine, double-acting alpha configuration, with four gas circuits. The configuration is of the “Franchot” type and the working medium is Helium. The work by Hoegel et.al. presents some analysis of the difference in performance between the Franchot and Siemens configurations [3]. Details of the implementation can be found in the paper co-authored by the author and published at ISEC-17 [4]. The figure below shows the HighLift heat pump installed at the juice, beverage and jam factory Lerum Fabrikker, Norway.

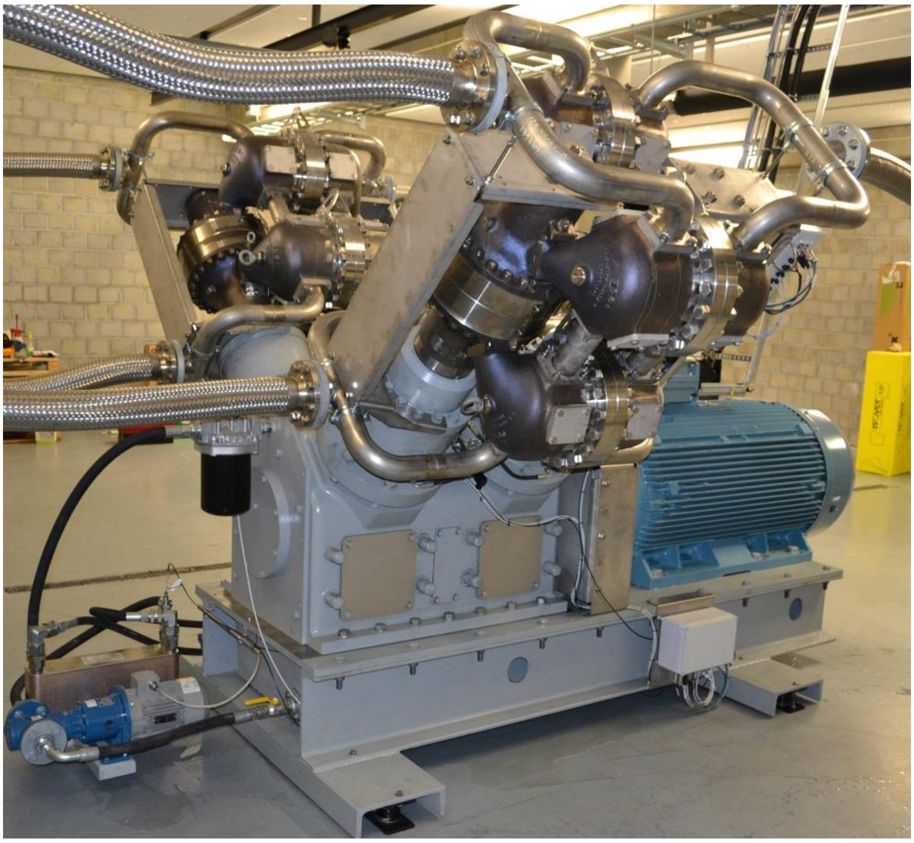

Fig. 1. Photo of the SPP HighLift heat pump (SPP 4-106C) at Lerum Fabrikker AS, Norway. The heat pump at this site generates steam at 6 bar_g in a flash tank using waste heat from cooling compressors as the heat source.

The output of the heat pump can be regulated by changing the shaft speed in addition to the charge pressure of working medium in the heat pump. The regulation band is from about 20% to 100% load. More details of the performance of the heat pump can be found in the earlier work by the authors [5].

1.2. TINE Meieriet Ålesund dairy plant

TINE Meieriet Ålesund is situated on the west coast of Norway, in the town of Ålesund. The dairy produces pasteurized market milk and long-life milk products. The annual production is about 35 000 ton. The current steam system consists of two gas-fired boilers, with a steam pressure set to 10 bar_g. The steam system is divided into a closed and an open circuit. The closed circuit is connected to heat exchangers for pasteurization, cleaning units, ventilation etc., while the open circuit is used for direct injection of steam into the products.

The annual average steam consumption is 1.5 MW for 3900 h of operation.

1.3. Tafjord Kraftvarme AS district heating network

Tafjord Kraftvarme AS is a fairly small district heating company in a Nordic scale. The company generates and distributes about 150 GWh district heating per year. The distribution network is in the town of Ålesund and its surroundings. The major part of the district heating is generated in a waste incineration plant. The plant is a CHP plant that generates approximately 30 GWh of electricity in addition to the district heating.

The company is also using traditional heat pumps for the network. The heat pumps are using sea water as the temperature source.

2. Heat pump installation

The heat pump will be installed in an engine room, and will be connected to the process through inlet of feed water and outlet of steam. The district heating is used directly by a separate stream of the main district heating line in the system. A simplified process and instrumentation diagram (P&ID) of the installation is shown in the figure below.

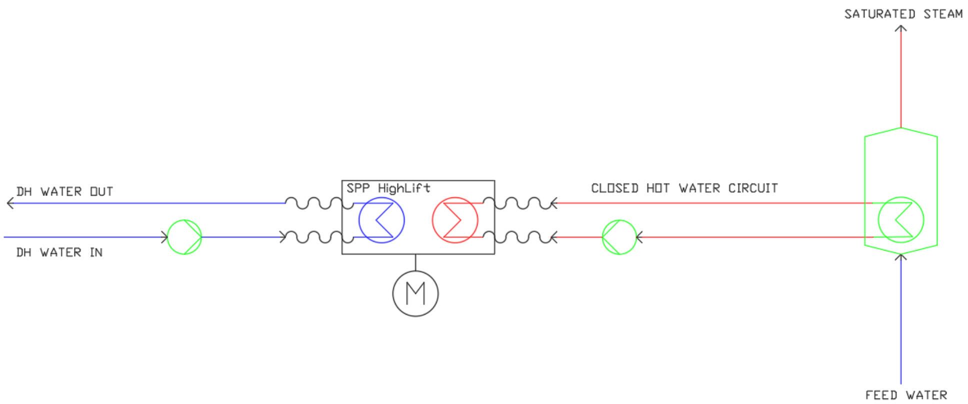

Fig. 2. Simplified P&ID of the installation of one heat pump. The closed hot water circuit heats the feedwater to the saturation temperature and evaporates the water in a plate and shell heat exchanger.

The engine room will have three heat pumps, that are operating in parallel, both with respect to steam generation and district heating consumption. A 3d-drawing of the heat pumps installed in the engine room is shown in the figure below.

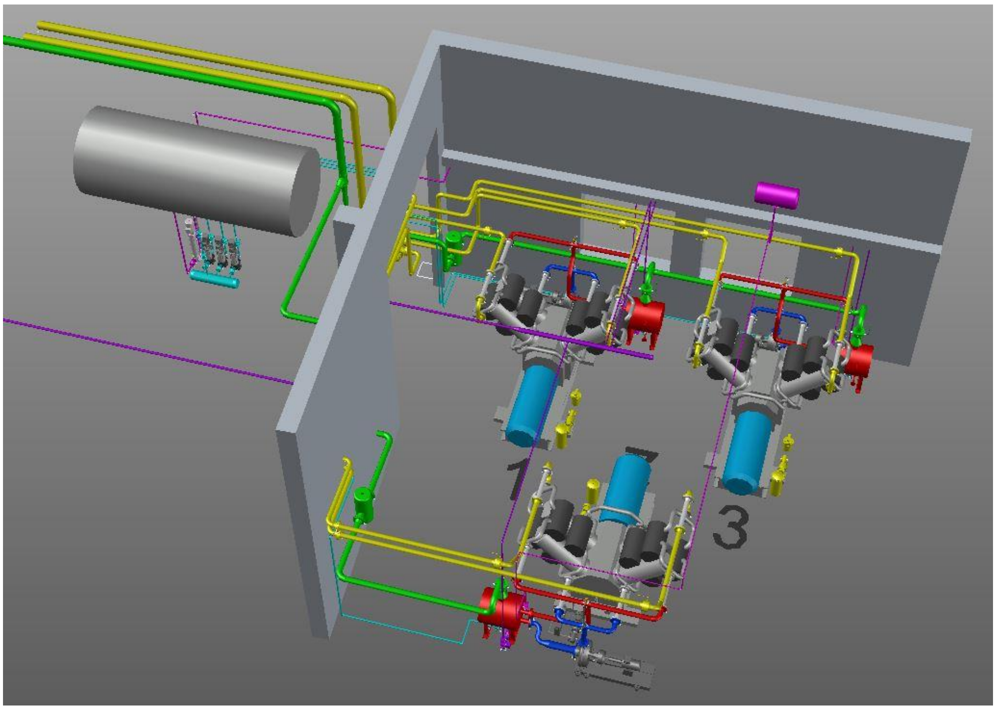

Fig. 3. A 3d-drawing of the engine room with the three heat pumps installed. The tank in the upper left corner of the drawing is the feedwater tank. The red cylinders to the left of the heat pumps are the steam generators. The common gas maintenance system for the heat pumps is not shown in the drawing.

The performance of the heat pumps is summarized in the table below. The annual energy is based on 3900 hours of operation. This corresponds to the average operating hour of 1500 MW steam generation, and is probably a lower bound, as at least two of the heat pumps are assumed to operate closer to 7000 hours per year.

Table 1. Simulated performance data for one HighLift heat pump at TINE Ålesund. The temperatures of the sink/source are 183°C and 85°C respectively.

	Power and heat flow (kW)	Annual power and heat (MWh/a)
Electric power consumption, W	212	825
Heat delivery, Q_h	449	1753
District heating consumption, Q_c	267	1041

The Coefficient of Performance for heating, COP_h, is 2.1, which is about 46% of the Carnot COP_h. The sum of W and Q_c is not equal to Q_h due to mechanical- and heat losses.

2.1. Environmental impact

The environmental impact of the heat pump application is for most part connected to the environmental impact of the power generation and the heat source. The emissions of CO_2 from the power generation is dependent on the source of the power. The table below shows the CO_2-factor for the Norwegian power market in 2015, and for comparison the EU average and emissions from natural gas fired power plants.

Table 2. Sources of electricity trading and generation in Norway in 2015. The values in the table is from the Norwegian Water Resources and Energy Directorate [6], except the values for EU power generation that are from IEA World Energy Outlook 2013 [7]. The emissions for natural gas is based on kWh combusted gas.

	Electricity traded without Guarantee of Origin	Norwegian power generation	EU power generation	Natural gas
Renewable power	12%	98%	N.A.	0%

Nuclear power	31%	0%	N.A.	0%
Fossil power	57%	2%	N.A.	100%
CO_2-factor (g/kWh)	509	17	345	514

The CO_2-factors are calculated according to the best practices from the RE-DISS project [8]. The emissions of CO2 for the combustion of natural gas and municipal waste can be estimated as 0.202 kg CO_2/kWh and 0.086 kg CO_2/kWh respectively. Both values are taken from the report by the Norwegian Water Resources and Energy Directorate [9]. By assuming that the natural gas fired boiler has an efficiency of 90%, it is possible to estimate the difference in CO_2-emissions.

The figure below shows an estimate of the CO_2-emissions from one heat pump compared to the base case of generating the steam in a natural gas boiler.

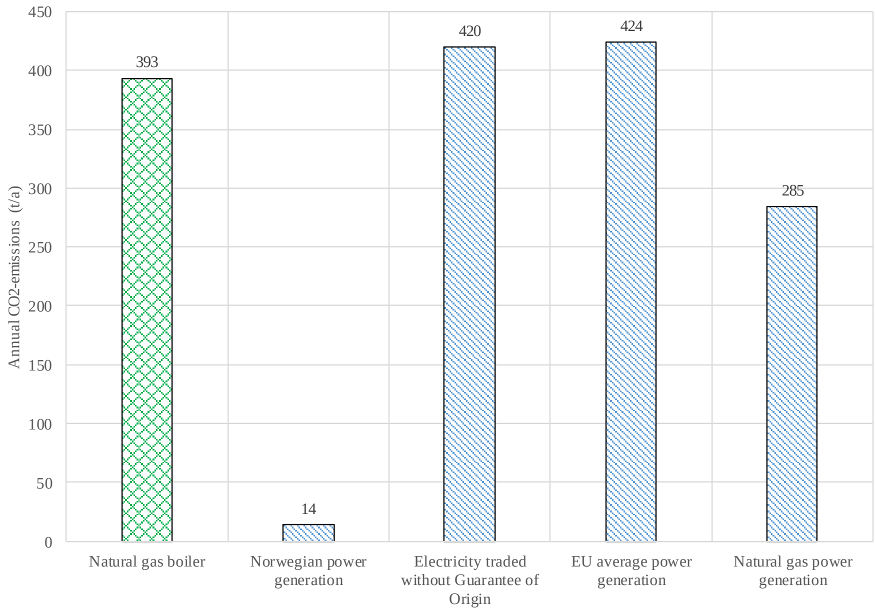

Fig. 4. Summary of the environmental impact for using the natural gas boiler and the HighLift heat pump using electricity from various sources. The values do not include the CO_2-emissions from the district heating generation. The district heating is generated in a combined heat and power plant using municipal waste as fuel. For an upper limit add 90 ton CO_2/a to emissions to include the district heating.

The dairy plant has set a demand to reduce their CO_2-emissions with 20% before 2020. This corresponds to about 400 t/a of CO_2-equivalents. As can be seen from the figure, the dairy will save about 380 tons of CO_2-emissions per year for one heat pump. If the electricity is generated using electricity without guarantee of origin or the EU average, there is no environmental benefit from the heat pump. However, it is better to burn the natural gas in a modern power plant than using the gas directly in a boiler. By using electricity from a modern natural gas fired power plant the CO_2-emissions can be reduced by more than 100 tons of CO_2 per year.

2.2 Financial impact and business model

The heat pump installation producing steam at the dairy plant is running according to same financial model as for natural gas or electric steam boilers. A single charge per unit energy (kW/h) of steam is applied and the charge is fixed for a long term duration contract. This provides less financial exposure to fluctuations in energy prices to the dairy plant. The heat pump company has the operational responsibility for the heat pump installation at the dairy plant and no other charges applies for the steam production. The financial gain of the steam customer the cost of the alternative steam generation option minus the cost of the steam from the heat pump. This is summarised in Equation 1.

$$GP_h = Q_h \cdot P_{NG} \cdot \eta_{NG} + C_{NG} + C_{CO_2} - Q_h \cdot P_h \tag{1}$$

, where Q_h is the amount of steam, P_{NG} is the price of natural gas, η_{NG} is the efficiency of the boiler, C_{NG} is the operation cost of the natural gas boiler, C_{CO2} is the emission charge and P_h is the price of steam (from the heat pump). For the heat pump provider, the financial gain is summarised in Equation 2.

$$GP_{hp} = Q_h \cdot P_h - W \cdot P_W - Q_c \cdot P_c - C_{hp} \quad (2)$$

, where W is the amount of electricity, P_W is the price of electricity, Q_c is the amount of district heating, P_C is the price of the district heating and C_{hp} is the operational cost of the heat pump.

In addition to the financial gain offered and the environmental impact of reducing the use of fossil fuels, the heat pump installation can give the customer a long term predictable steam energy costs. IEA estimates that while fuel prices will be reasonably stable in the contract period, the cost of CO2 emission will increase significantly. According to the estimates from IEA [10], an expected increase in the CO2 emission cost from below 10 USD/tonne in 2015 to over 80 USD/tonne by 2030. This will obviously become an important economic factor if the estimates are correct.

3. Discussions and conclusions

In this paper the application of a high temperature heat pump that generates steam and uses district heating as the heat source is presented. The calculations show that the installation has the potential to reduce the environmental impact of the steam generation (in the form of reduced CO_2-emissions). The benefits to the district heating company is discussed in qualitative terms, and include increased consumption and consumption with low seasonal variations that is evenly distributed across one year.

Acknowledgements

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