Paper drying using high-temperature heat pumps

The importance of phase change in steam generation

Heat pumps have been around for many years, and their technology and energy efficiency have long been proven. High-temperature heat pumps on a large industrial scale are still relatively new and are still rarely used in the paper industry.

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For over 100 years, paper makers have owed their survival to heat pumps: without them, there would be no cold beer. So we are familiar with the technology - but scaling up from a refrigerator to a high-temperature heat pump is no easy task. Here we describe how heat pumps can be used to generate steam using renewable energies. Above all, this is both energy-efficient and cost-effective. Even today, steam can be generated very efficiently using electricity in bivalent operation whenever the price of electricity is low. For example, at night or on weekends, when surplus renewable energy should be absorbed by the grid. The technology for this is already available today.

High-temperature heat pumps

High-temperature heat pumps (HTWP) are now available for temperatures above 100 °C. Like a refrigerator, a heat pump has a cold side and a warm side. (Fig. 1)

In a refrigerator, the interior is cooled and the heat is dissipated at the rear. The cold side is referred to as the heat source, and the warm side as the heat sink. The heat is extracted from the source and dissipated on the warm side.

Ideally, the high-temperature heat pump (HTHP) is operated not only to generate steam for the cylinders but also to remove waste heat from various sources. This article focuses on the temperature range of steam generation from waste heat to further advance decarbonization in the paper industry. The temperature lift, i.e. the temperature difference between the source and sink sides of a heat pump, is the biggest factor influencing energy efficiency. The COP shows the ratio of heat energy achieved to electrical energy used (Fig. 2). If, for example, water is heated from 60 °C to 110 °C (steam), this results in a temperature lift of 50 K. According to VDI 4646, a COP of around 3.0 would be achievable here. The cheaper the electrical energy used and the more expensive the heating energy, the more cost-effective a heat pump is. If a system is to amortise the electricity costs, a COP > 2 should be aimed for. If the alternative technology to a heat pump is heating with electricity, significantly lower COPs may still be interesting.

The HTWP range is divided into different temperature levels based on the refrigerants used. Furthermore, complexity and space requirements increase with increasing temperature (Fig. 3). Ideally, heat pumps with a lower temperature lift are used. They are considerably simpler than complex systems and require less space. The lower the complexity, the more reliable the operation of any system.

Implementation

For the sensible and cost-effective use of heat pumps, all technical measures should be implemented to reduce the maximum required vapour temperature to a minimum. This keeps the required temperature rise low and enables the use of heat pumps with a high COP.

In the last two years, heat pumps have made more progress in terms of the desired sink temperature, the compressor technology used, and availability than in the previous 10 years. However, sink temperatures above 140 °C still require complex pilot plants. In the temperature range below this, relatively simple heat pumps based on series technology are already available. The market here is divided into heat pumps using the synthetic refrigerant R1233zd up to approximately 120 °C and the natural refrigerants isobutane and pentane up to approximately 135 °C. It is important to note that these heat pumps, which are already available, completely cover the temperature range of the phase change of water from liquid to gas with this heat pump class. Below the phase change, approximately twice as much energy is required per Kelvin temperature increase as in the vapour range. The phase change itself requires the most energy. Above that, only about half the energy per K is required compared to steam generation (Fig. 4).

Ideally, we use the heat pump to convert condensate back into steam. This is a highly efficient process, meaning that steam can be generated much more efficiently than through direct electric or fossil fuel heating.

Less energy is required for higher steam temperatures. At the same time, the efficiency of heat pumps is limited here, as the COP continues to decrease. Ideally, reheaters are used for higher temperatures (Table 1). These can still be operated with gas, resulting in savings of up to 98 %. Alternatively, electric reheaters can be used for complete decarbonization with very low energy consumption.

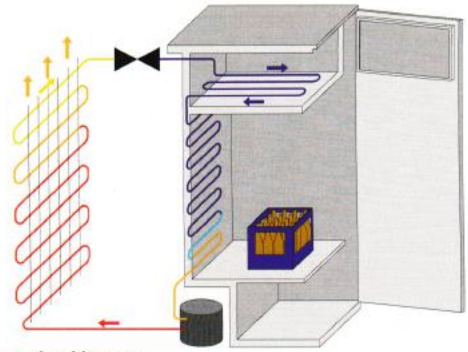

Fig. 1: Heatpumpfunction – example refrigerator

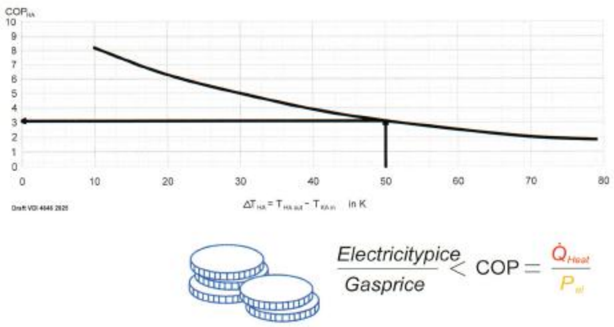

Fig. 2: Temperature lift and COP according to VDI 4646 2025

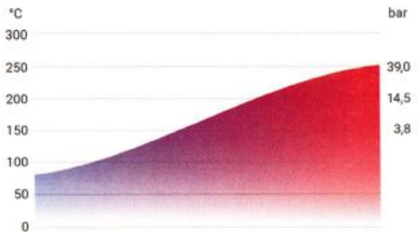

Fig. 3: Heat pumps – adapted concepts for every temperature and vapor pressure range

Fig. 4: Temperature-enthalpy diagram of water. Most of the energy is required for the enthalpy of vaporization.

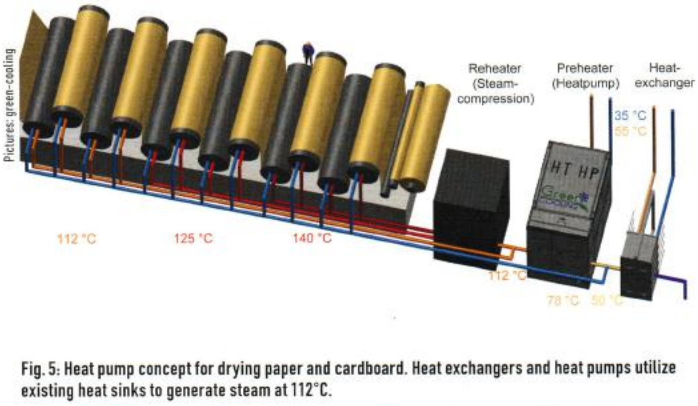

Fig. 5: Heat pump concept for drying paper and cardboard. Heat exchangers and heat pumps utilize existing heat sinks to generate steam at 112°C.

1 MW steamproduction (1,3 t/h)

	Process before						Process with HP				
ΔT Water	70	K	4,2	kJ/kg*K	294	kJ/kg					
Phasechange			2.257	kJ/kg	2.257	kJ/kg					
ΔT Steam	40	K	2,1	kJ/kg*K	84	kJ/kg	18	K	37,8	kJ/kg	
Sum					2.635	kJ/kg			37,8	kJ/kg	1,43%

Tab. 1: Energy consumption for water heating and evaporation. With ideal use of the heat pump, well over 90% of the required fossil energy can be saved.

Thus, this simple area of the HTWP already covers the most practical application of heat pumps. Initially, only low-temperature steam is produced.

However, this can easily be brought to the required target temperature through the use of gas, another HTWP, or steam compression. The main energy requirement has already been covered by the low-pressure HTWP.

Application

In this case study, a customer wanted to cover the steam generation from fresh water to 140-degree steam using a high-temperature heat pump. This would have required a temperature lift of 110 K. Therefore, a high-temperature heat pump is completely unsuitable for use because the COP is extremely low.

Following joint re-engineering of the system, simple heat recovery via a heat exchanger is now used to preheat the fresh water. The heat pump itself only needs to cover the range from 78 °C to 112 °C. It operates with a COP of > 4.5. A gas heater is used to cover the remaining 28 K. The fossil energy requirement for steam at 140 °C is now in the low single-digit percentage range.

A steam pressure corresponding to a temperature of 130 °C to 150°C is usually sufficient for drying paper. Only when starting up a cold machine is the full load required. During operation, steam of 112 °C only needs to be generated from condensate, with a very low thermal stroke.

For higher temperatures, reheaters are used, which generate the required steam pressure with very little energy consumption. Evaporation, which requires the most energy, is thus handled extremely efficiently with the heat pump. This means that over 90 % of the required drying energy is decarbonized. This represents two-thirds of a paper mill's total energy consumption. And this is precisely the proportion of energy that cannot be covered by renewables to date.

Summary

The use of high-temperature heat pumps for steam generation in paper production is still in its infancy. The necessary technology is already available. With the right preparation to reduce steam requirements, HTWPs can be used economically and energy-efficiently. They enable the paper maker to significantly reduce CO_2 emissions when drying the paper. In the future, the use of heat pumps to heat paper will be as common as their use to cool beer. And just as economical. The decarbonization of paper drying can already be achieved today. www.green-cooling.de