In focus...

Refrigerant gases enabling energy efficiency

High temperature industrial heat pumps and steam generation

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Heating is currently one of the major sources of greenhouse gas (GHG) emissions, accounting for 25% in the UK alone. In China, heating is mainly provided by coal-fired boilers, which not only act as major energy users, but are also responsible for GHG emissions and air pollution.

Research into the decarbonisation of this sector has, therefore, significantly increased in recent years and the role of heat pump technologies to reduce carbon dioxide (CO_2) greenhouse gas emissions arising from industrial process heating has become an increasing focus.

Heat pumps are commonly used for domestic space heating and are making inroads into district heating. They use ambient air, soil, a local lake, or sea as a heat sink and produce heat at about 50°C, which is ideal for heating buildings. High temperature industrial heat pumps (HTIHPs) are based on a similar operating principle and have been recognised for their potential to generate steam for process heating in the food, paper, metal, and chemical sectors. Heat pumps are commonly considered as HTIHPs when operating with supply temperatures above 100°C. Some of the main challenges that HTIHPs face are their integrability into these process industries and their ability to match the available heat source to the required heat demand.

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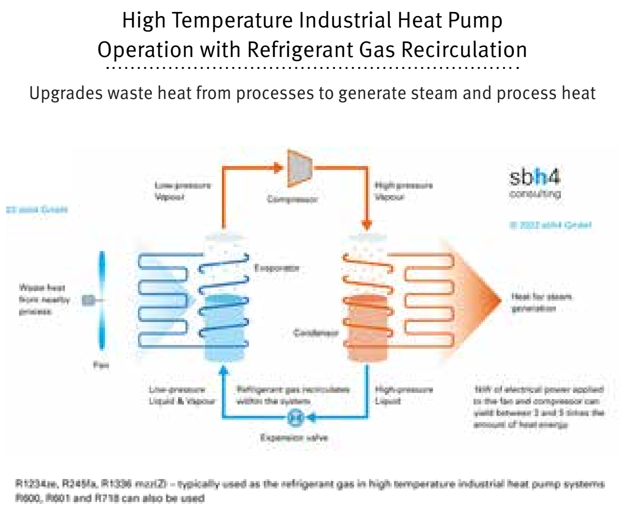
To generate steam, an HTIHP requires a heat sink at a temperature of 60-120°C, which is widely available as waste heat from many processes. The heating capacities of current HTIHPs range from 20 kW to 20 MW. A coefficient of performance (COP) of up to 5.8 can be achieved at a 30°C temperature lift. A lower COP between the range 2.2 to 2.8 occurs when a 70°C lift is produced from a heat sink temperature of 120°C.

The COP is a measure of the amount of heat energy generated by the heat pump compared to the amount of electrical power that it consumes. For comparison, the electrical element in a kitchen kettle could yield a theoretical maximum of 1kW of heat from 1 kW of electricity, a COP of one. The use of waste heat and the thermodynamics involved allows a heat pump to generate more heat energy than its electrical power consumption, resulting in a COP significantly greater than one.

HTIHPs as a sustainable technology

With the 2015 Paris Agreement's aim of limiting global warming's temperature rise to 1.5 °C, there has been a ▶



huge focus towards decarbonisation and heat pumps are becoming increasingly recognised as a tool for reducing energy consumption and GHG emissions.

From an environmental perspective, HTIHPs are attractive for steam generation because they do not create CO_2 emissions at the point of operation as the combustion of fossil fuels for steam generation is not required. However, the heat pump must be supplied with renewable electrical power for the full environmental benefits to be realised. HTIHPs can be a unique solution to decarbonise industry, providing heating, hot water, steam cooling and dehumidification by closing energy cycles and therefore reducing the total energy requirement for the process.

Refrigerant gases for HTIHPs

HTIHPs come in a variety of forms based on the heating cycles and refrigerant gas used within the enclosed heat pump thermodynamic cycle. The gas, which is recirculated within the heat pump system, is often referred to as a 'refrigerant' gas, despite it facilitating a step-up in temperature. The terminology is used because a heat pump thermodynamic cycle is like a refrigeration cycle and similar kinds of gases are used in each system.

HTIHPs operate on a range of refrigerant gases, including the F-Gases R1336mzz(Z), R245fa and R1234ze. R1234ze is a hydro-fluoro-olefin (HFO) called tetrafluoro propene. It has a global warming potential (GWP) of seven and is widely regarded as an alternative to the popular HFC refrigerant gas R134a, which has a much higher GWP of 1,430. HFO's generally have lower GWP values than previous generations of refrigerants, such as R134a.

R245fa is marketed as Genetron® 245fa by Honeywell and has a GWP of 1,030. The molecule is an HFO called pentafluoro propane and has also found application as a foam blowing agent. Chemours offers R1336mzz(Z) under the trade name Opteon® MZ, with broadly similar properties and applications as R245fa, but a much lower GWP of two. This is achieved with a double bond in the molecule, meaning that it is easily decomposed by UV light in the higher layers of the atmosphere.

Butane and pentane (R600, and R601), or water in the form of steam, known as R718, can also be used as the refrigerant gas in HTIHPs. The majority of HTIHPs operate with a single stage cycle, meaning they have only one level of temperature increase.

Using steam in the thermodynamic circuit

The technical feasibility of using water (R718) as a refrigerant gas in an HTIHP has been demonstrated. Waste heat at temperatures ranging from 85-95°C can be elevated to temperatures around 145°C to generate process steam.

During the process, water in a closed circuit is successively evaporated and condensed. A compressor is used to elevate the steam pressure. As the steam is condensed, it generates process steam on the other side of an exchanger. The condensed water in the enclosed cycle is then flashed to generate water vapour at 0.6 bar and 83°C, which is fed to the suction of a compressor to repeat the thermodynamic cycle.

The use of R718 in such a thermodynamic cycle is the basic principle behind the PILLER HTIHP. It is used at an industrial scale to convert waste heat to useful process heat and steam. The waste heat usually comes from distillation column condensers, warm process wastewater or hot flue gases and may have a temperature from 50-90°C. This is significantly higher than outdoor air, ground heat and lake or ground water, which are the standard heat sinks for heat pumps used for space heating applications.

PILLER uses high-performance blowers to provide steam at the right pressure and temperature to elevate the temperature of the waste heat and enable steam generation. Furthermore, the high temperature can also serve as a reboiler at the base of a distillation column. As with other heat pumps, the PILLER system can be a viable solution in terms of economics and sustainability.

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Case studies based on R600, R134a and R245fa

In the Netherlands, Wemmers and other researchers have developed a heat pump using butane (R600) as the refrigerant gas. It can deliver low pressure steam of up to 2.4 bar (125°C) from 60°C waste heat at a COP of 1.9. This technology has been integrated into the HTIHP developed by Bronswerk Heat Transfer and the Energy Research Centre of the Netherlands. It provides a cost-effective way to upgrade waste heat to such a level that it is re-usable in industrial processes.

In Korea, Lee and others created an HTIHP for low pressure steam generation using R245fa as the refrigerant gas. An internal heat exchanger was installed in the heat pump circuit to ensure superheating, and the heat generated was then transmitted to a circulating pressurised water system. By flashing a portion of water into the two-phase area, it was converted to steam. The steam and water were then separated by a steam reservoir and additional water was delivered to the flash tank through an open loop system. Steam temperatures of 104-123°C (1.2 to 2.2 bar) were achieved using this configuration and a COP of roughly 3.5 was obtained using a 60°C heat sink source and a 105°C steam temperature.

For the last 20 years, Kobe steel has been marketing the 'Steam Grow' heat pumps under the brand Kobelco. The main areas of application include food and beverage sterilisation, concentrating soups and fruit juices, drying operations, and alcohol distillation.

There are two main circuits in the heat pump. One is charged with a refrigerant gas of either R134a or R245fa and is used to elevate the waste heat temperature. This transfers heat to a second circuit where the process steam is generated in a heat exchanger. In some systems, the additional use of a semi-hermetical twin-screw compressor can boost the temperature and yield high pressure steam at 165°C. This can be generated from a waste heat sink at 70°C, with a system COP of 2.5.

Development priorities for HTIHPs

It is evident that the implementation of HTIHPs can allow industry to operate with significantly reduced GHG emissions and the increased research and number of demonstration R&D projects suggest that HTIHPs will reach market maturity in the next few years.

However, there are still major challenges connected with implementing heat pump technology, especially in high-temperature applications, such as industrial processes and steam generation.

There is a need for technical innovation to achieve lower specific investment costs and increased energy efficiency while maintaining technical feasibility and stable operation. HTIHP R&D could focus on developing various cycles and configurations to demonstrate performance and cost, demonstrate heat pump material durability in real life industrial settings and conditions and prove that heat pump working fluids – the essential refrigerant gases – are safe, efficient, and sustainable. gw