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Grand Challenges in Heat Decarbonisation

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INTRODUCTION

Heat accounts for almost half of global final energy consumption (IEA, 2021a). Industrial processes are responsible for 51% of the energy consumed for heat, while another 46% is consumed for space and water heating. Heat supply currently relies heavily on fossil fuels, contributing more than 40% of global energy related CO_2 emissions in 2020 (IEA, 2021a). Renewable sources only met less than a quarter of global heat demand in 2020 (IEA, 2021b). In order to achieve the target of net zero of greenhouse gas emissions by 2050, heat must be decarbonised; this presents a grand challenge to academia, industry, and society.

DOMESTIC HEATING

Challenges

Gas boilers are currently one of the most common heating technologies and thus the main contributor of greenhouse gases (GHG) from domestic heat. Old fashion non-condensing gas boilers do not recover heat from the flue gases and thus have an efficiency of around 80% (DECC, 2012). Nowadays, most gas boilers are condensing boilers which have an efficiency of around 90% by recovering heat from flue gases (DECC, 2012). Although they have improved efficiency over non-condensing gas boilers, they must be replaced with low/zero carbon heating technologies to achieve net zero targets.

There is a wide range of alternative technologies at different stages of development for domestic heating applications, including electrical resistive heaters, micro-CHP (combined heat and power) systems, biomass boilers, solar thermal devices, and heat pumps.

Electrical resistive heaters have near 100% efficiency to convert electricity to heat, but they still indirectly discharge GHG emissions since most electricity is generated from fossil fuels at present. It is unviable to electrify heat supply using electric heaters due to their high operational costs and the high-power demand from grid infrastructure.

Micro-CHP comprises a group of technologies that can generate electricity from the high temperature combustion of natural gas via a miniature power generator (e.g., an engine), while the rejected heat after the power generation is utilised for heating (Hawkes et al., 2011). As such, the overall energy efficiency can be significantly improved. However, the carbon emission saving of CHP is insignificant unless we decarbonise the gas grid with green hydrogen or carbon-neutral biogas.

Biomass is a low-carbon fuel and can be used as a fuel for biomass boilers to provide heat for district heating networks, industrial process heat, and for the production of biogas. However, one drawback is its low energy density, leading to costly transportation and storage. Nevertheless, biomass may only play a limited role in the future net-zero heating system due to the limited availability, transport and storage challenges.

Solar energy is a zero-carbon heat source and can be used for heating applications, either directly through solar thermal collector (e.g. solar water heaters) or indirectly through photovoltaic panels which generate electricity that can be used to power electrical resistive heaters or heat pumps. The

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intermittence, low power density, and seasonal mismatch between supply and demand limits its role for heat decarbonisation.

Heat pumps (HPs) are a promising alternative technology to replace gas boilers. They can be built upon different thermodynamic principles, such as vapour compression cycle, vapour adsorption cycle, vapour absorption cycle, reversible chemical reactions, and various gas cycles. They can operate with different heat sources such as air, soil, water, and so on.

Gas-driven absorption (Wu et al., 2014) and adsorption (Demir et al., 2008) heat pumps have potential to reduce carbon emissions. Gas-driven absorption HPs have been successfully used in large scale district heating applications. Most recently, domestic scale gas-driven absorption HPs have been launched to the European market claiming fuel-to-heat efficiency around 130–150% (Critoph, 2013). Gas-powered adsorption HPs have also been researched recently, achieving fuel-to-heat efficiency about 130% (Critoph, 2013).

There are also some “engine-driven” HP systems, such as double Rankine-cycle systems (Strong, 1980; Demierre et al., 2012), and internal combustion engine-driven HPs. In a double Rankine-cycle system, both the power and heat pump cycles use the same working fluid and share a condenser. They utilise high speed turbine-compressor units that use a common shaft to transfer mechanical power from the power cycle to the heat pump cycle (Strong, 1980). Although the theoretical fuel-to-heat efficiency is as high as 150%, the system is thermodynamically and mechanically complicated to build and to maintain; hence they are unattractive on cost grounds for domestic heating applications. Internal combustion engine-driven HPs have been commercialised by a few Japanese manufacturers, targeting at large scale district heating applications (Hepbasli et al., 2009).

From the GHG emission reduction perspective, unless the gas supply will be decarbonised, gas-powered heat pumps still release GHG emissions. Electrical HPs are an ideal alternative technology for domestic heating if low or zero carbon electricity is supplied. The long-term plan preferred by policy makers globally is to widely utilise electrical HPs powered by low carbon electricity for heat decarbonisation. So far, around 180 million heat pumps have been used for heating globally, which still only met 7% of global building heating demand in 2020 (IEA, 2021b). To reach the next zero emission target by 2050, the installed heat pump stock must reach 600 million by 2030 globally (IEA, 2021b).

There are however several technical and non-technical barriers hindering the wide uptake of electrical heat pumps. Innovations will be needed to address key issues including high equipment costs, low energy performance at high heat supply temperature, and the phaseout of refrigerants with high global warming potential (GWP).

Research Perspective

In the current market, ground-sourced HPs are often expensive due to earthwork costs. Air-sourced heat pumps (ASHP) are cheaper but they are still 3–4 times more expensive than gas boilers in the current market. Innovations are required to substantially reduce the manufacture costs of heat pumps, which will rely on the development of new materials, new designs for building cost-effective heat exchanger (e.g., microchannel heat exchangers), more efficient compressor technologies, better controls, and so on.

ASHPs are vulnerable to ambient air conditions and their heating power and coefficient of performance (COP) drop dramatically as the ambient air temperature falls. Heat is needed the most when it is the coldest, which is when their performance is at the lowest level. Furthermore, frost starts to build up at the surface of the outdoor unit (evaporator) when the air temperature drops to below around 6°C (Shen et al., 2019), meaning the outdoor units must be regularly defrosted.

The common defrosting methods (namely “reverse cycle”, “hot gas bypass”, and “electrical heating”) used in current ASHP products are inefficient (Song et al., 2017). After the ASHP detects ice on the outdoor unit, the control system uses a four-way valve to switch the heat pump to a refrigeration mode to either extract heat from indoor unit (i.e., reverse cycle method), or to bypass the hot vapour from the compressor to the outdoor unit (evaporator) to defrost it (i.e. hot gas bypass method). Depending on the weather conditions, the frequency for defrosting is usually pre-set as once for every 30, 60, or 90 min, and the defrosting operation normally takes 3–5 min each time. For both these defrosting methods, the indoor unit is switched off while the compressor is turned on during defrosting. The compressor still consumes electricity, but there is no heating supply from the heat pump, meaning a backup heater is required to provide heating. It has been well documented that ASHPs consume about 5–10% of the heat pump’s total heat production for defrosting, depending on climate conditions (Dong et al., 2012; Vocale et al., 2014). Therefore, innovations are much needed to develop energy efficient defrosting methods.

In houses that are currently heated by gas boilers, their heat emitters (i.e., radiators) are designed for high temperature (e.g.>65°C) heat supply (DECC, 2016). However, most standard single stage ASHPs available in the market have a heat supply temperature below 60°C. Their installation will require retrofitting to replace the existing heat emitting systems with either low temperature underflooring heating networks or much larger radiators, leading to extra costs. High temperature heat pumps (e.g., heat supply at over 65°C) are preferred, but they are 20–35% more expensive than standard heat pumps due to more complicated designs (e.g., two-stage, cascade, or vapour injection) (DECC, 2016). Innovations are needed to develop cost-effective high temperature heat pumps for such retrofitting applications.

Conventional vapour compression cycles can be further improved through new designs. The integration of absorption or adsorption processes to vapor compression cycle has led to novel combined compression/absorption cycle or compression/adsorption cycles, for high temperature heat pump application, and thus is an interesting trend to pursue. Additionally, non-vapour cycles such as thermoacoustic cycles and Stirling cycles can also be applied for heat pump applications, and thus are worth of further research.

Most current synthetic refrigerants, namely F-gases such as ChloroFluoroCarbons (CFCs) and Hydrochlorofluorocarbons (HFCs), have high Global Warming Potential (e.g., GWP =

1,300 for refrigerant R134a; while GWP = 1 for CO_2). Emissions from refrigerant leakage accounted for 7.8% of worldwide greenhouse gas emissions in 2019 ([1]). As the demand for air-conditioning in developing countries and the electrification of heating using heat pumps in developed economies grow rapidly, it is expected that the leakage of HFCs alone could become a notable fraction (>10%) of the world's GHG emissions by 2050 (Henry et al., 2020). In order to reduce the GHG emissions due to F-Gas leakages, they must be replaced with low/zero GWP refrigerants such as ammonia, CO_2 in the next decades ([2]).

Furthermore, a wide installation of heat pumps in the future will likely cause a significant increase in electricity demand in peak hours (e.g. early evening), bringing challenges to the electric grid. Integrating heat pumps with suitable thermal energy storages offers flexibility to spread the power consumption to balance the demand and supply. Heat storages can either be integrated with heat pumps as two stand-alone systems through a water loop or be directly integrated into the heat pump cycle. Research is thus needed to further understand the interactions between the two subsystems and to develop suitable heat storage technologies and control methods.

For large scale heating applications, such as commercial buildings, office blocks, dense residential buildings, district heating systems with renewable and/or low carbon heat supply will have a pivotal role to play in the future net zero energy systems. The majority of current operational district heating networks (DHN) are third generation (3G) networks. (Department of Energy and Climate Change, 2015; Li and Nord, 2018). They have high supply temperatures (circa 90°C) (DECC, 2013), high thermal losses (BRE, 2016), and are difficult to manage (Chen et al., 2019; Millar et al., 2019). To address these issues, research in the past has largely focused on methods to reduce the supply temperature, leading to low temperature district networks which are referred as fourth generation (4G) DHN (Guelpa et al., 2019). The fourth generation DHNs still face challenges such as thermal losses in low population density areas, difficulty in procuring usable low-temperature sources such as waste heat sources, inflexibility for energy sharing, etc. These challenges could be addressed by fifth Generation (5G) DHNs (Wirtz et al., 2020; Millar et al., 2021) which allow heat and cold thermal energy to be exchanged across a network via an ambient loop, allowing lower distribution temperatures.

INDUSTRIAL HEATING

Challenges

Heat is also widely used in a variety of industrial processes such as fluid heating, space heating, distillation, drying, and chemical processing. Most industrial heat demand is currently met by combusting fossil fuels, and thus discharges huge amount of GHG emissions. Taking the EU as an example, approximately 75% of heating and cooling was generated from fossil fuels in 2019 ([3]).

Decarbonisation of the industrial heat supply is a grand challenge because industrial heat demands are incredibly diverse, crossing a wide range of temperatures from slightly above ambient temperature for fluid heating to over 1,400°C for steel making (Thiel and Stark, 2021). As a result, a single technology cannot meet all those different demands. Thiel and Stark (Thiel and Stark, 2021) discussed four technical routes for industrial heat decarbonisation: 1) zero carbon fuels, 2) zero-carbon heat source, 3) electrification of heat, and 4) better heat management. Considering the scope of the Section of Advancements in Cooling and Heating, we will focus the discussion on electrification of heat using high temperature heat pumps.

Research Perspective

High temperature industrial heat pumps, featured with a heat supply temperature in the range of 90–160°C (Arpagaus et al., 2018), offer a more effective solution to recover low temperature waste heat sources discharged by industrial processes for use onsite. They can recover heat from below 100°C and upgrade it to 150°C or higher, providing reliable heat sources for the distillation (boiling), drying, and pasteurization processes in food, chemical, paper and textile sectors, which are the key industrial sectors globally.

Traditional heat pump systems operate on vapour-compression cycles. Although they have evolved to become a mature technology in past decades, they are not applied as widely as they could be. Barriers to uptake include low coefficients of performance (e.g., COP<3 for a temperature lift of 60°C) for high supply temperatures (e.g., >120°C), high capital cost, long payback period, and the use of toxic and/or flammable refrigerants such as propane, severely limiting their application in many industries (Arpagaus et al., 2018). Research efforts are required to improve energy performance and reduce costs. Advanced cycle layouts, such as multi-stage, cascade, vapour ejection system, can be utilised to improve systems COP, which however complicate the system design and potentially increase their costs. A comprehensive review can be found in references (Goh et al., 2011; Zhang et al., 2016; Jiang et al., 2022).

Furthermore, current synthetic refrigerants were developed for refrigeration applications and thus have relatively low critical temperatures (under 160°C) (Thiel and Stark, 2021). Hence, working fluids with high critical temperatures need to be developed for high temperature vapour compression cycle industrial heat pumps. Propane and ammonia have been used as working fluids for high temperature heat pumps, but they are flammable. Water, with a high critical point, has been recently used as working fluid for developing industrial heat pumps, but more research is required to develop suitable steam compressors.

In addition to traditional vapour compression heat pump technologies, researchers have also made efforts to develop chemical heat pumps which are based on reversible chemical reactions. They absorb low temperature heat by endothermic reaction and releases thermal energy by exothermic reaction. The temperature of the thermal energy stored by the chemical substances is upgraded to a higher level by executing the two processes at different pressures. There are various chemical reactions that can be used in a chemical heat pump, representing great research opportunities (Goh et al., 2011; Zhang et al., 2016).

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[1] https://energy.ec.europa.eu/topics/energy-efficiency/heating-and-cooling_en

[2] https://www.aspenpumps.com/en-gb/ldc-environment

[3] www.fluorocarbons.org

Unlike vapour compression cycle system, gas cycle heat pumps employ a gas (e.g., air, helium, etc.,) as working fluid that experiences compression and expansion processes to absorb heat at low temperature and reject heat at high temperature without experiencing any phase change. Gas cycle heat pumps have been researched for several decades, but received less attention than vapour cycles. Here, two exemplar technologies are briefly discussed as follows.

Air can be used as working fluid for developing high temperature heat pumps with reversed Brayton cycle (Thiel and Stark, 2021). Air cycle heat pumps face some challenges including the lack of suitable high temperature compressor technologies and the poorer heat transfer of air leading to bulky and expensive heat exchangers.

Thermoacoustic heat pumps (TAHPs) are an emerging technology offering an attractive alternative to address the fundamental issues that limit traditional heat pumps. They possess several unique advantages due to their simplicity, fewer moving components, environmentally friendliness (i.e., noble gas as the working fluid and oil free), and large temperature lifts. Unlike vapour-compression cycle systems, thermoacoustic heat pumps are driven by pressure wave generators, which can be an acoustic driver or a thermoacoustic prime mover. The former uses electricity to produce pressure waves, while the latter converts heat energy into pressure waves. Based on the characteristics of the employed acoustic field, thermoacoustic heat pumps can be classified into standing-wave and travelling-wave types. Travelling-wave thermoacoustic heat pumps have higher COPs than their standing-wave counterparts, and therefore become a focus for research (Hu et al., 2008). After 2–3 decades of efforts, they have advanced significantly to the point of finding viable commercial applications([4]). Tijani et al. (Tijani et al., 2016) demonstrated a travelling-wave thermoacoustic heat pump and achieved a COP of 4.78 when upgrading heat from 40.8 to 109°C (much higher than vapour compression cycle heat pumps with a COP below 3 for a temperature lift of 60°C (Arpagaus et al., 2018)), showing good potential for industrial waste heat recovery applications. Despite the recent progress made, the industrial application of TAHPs is still hindered by two major technical obstacles.

Firstly, current designs of travelling wave thermoacoustic heat pumps (Hu et al., 2008; Tijani et al., 2016) employ an acoustic driver and rely on an acoustic resonator to establish and maintain the required acoustic field. The resultant system, essentially a pressure vessel, is thereby bulky and expensive, detracting from the potential simplicity and low-cost advantage of thermoacoustic heat pumps. A stepwise reduction in size could unlock this issue leading to a low cost, compact heat pump.

Secondly, current acoustic drivers are essentially pistons driven by linear motors which resemble loudspeakers but employ a magnet moving forth and back in an electrical coil (Hepbasli et al., 2009; Demierre et al., 2012). Such a design provides great simplicity and compactness for small scale applications such as for space exploration. However, linear motors rely on the mechanical resonance of the mass-spring system. For industrial applications requiring hundreds of kilo-watts to several mega-watts, a massive magnet would be needed along with substantial springs and flexure suspension. As a result, their inertial mass increases to very high levels causing their resonance frequency and piston movement to become unusably low. This restricts linear motors to electric power inputs at the kilo-watt level, insufficient for industrial applications. Hence, it is challenge to scale up thermoacoustic heat pumps for real industrial applications using linear motor as acoustic drivers.

CONCLUDING REMARKS

Heat decarbonisation is a grand challenge faced by our society. No single solution can address the challenges associated with heat decarbonisation. Most of the low/zero carbon heating technologies reviewed above, as well as those which are not covered and those new technologies that will be developed, will play complementary roles in our future heating systems to enable us to transit to a net zero future. The mission of the Advancements in Cooling and Heating Section is to provide a unique platform to bring together all relevant disciplines to exchange research ideas and progresses and facilitate collaboration, making an important contribution to the campaign to address this grand challenge of heat decarbonisation.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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