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Measured performance of a novel high temperature heat pump with HFO-1336mzz(Z) as the working fluid

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Abstract

Industrial heating consumes a significant fraction of the energy consumed globally. Heating at temperatures higher than about 100°C is predominantly provided through combustion of fossil fuels with uncertain prices and well recognised environmental impacts, including climate change. A significant fraction of industrial input energy is wasted as low temperature heat (e.g. dryer vent gases or cooling water) that could be lifted by high temperature heat pumps (HTHPs) to temperatures meeting nearby heating duties.

A novel HTHP with 32 kWth heating capacity is evaluated in this paper. It is based on a reciprocating compressor adapted from a piston expander previously developed for a small-scale organic Rankine cycle system. The expander has been extensively tested at high temperatures and has demonstrated high efficiencies. The compressor was constructed by solely adjusting the expander valve system. HFO-1336mzz(Z) (cis-$CF_3CH=CHCF_3$; previously referred to as DR-2), with a global warming potential of 2, was selected as the working fluid. HFO-1336mzz(Z) has attractive safety, environmental and thermodynamic properties and high chemical stability at high temperatures. Heat pump tests demonstrated heating from a 90 °C heat source to 130 °C and 150 °C with a Coefficient of Performance for heating of 4.6 and 2.7, respectively. Work is ongoing to demonstrate higher heating temperatures and optimise performance in support of commercialisation in 2017. The new HTHP with HFO-1336mzz(Z) could enable the utilisation of abundantly available low temperature heat to meet heating duties at higher temperatures, with equal or higher energy efficiencies and lower environmental impacts than with incumbent working fluids.

Keywords: high temperature heat pump (HTHP); high temperature compressor; reciprocating compressor; vapour compression; low global warming potential (GWP); HFO; HFO-1336mzz(Z); DR-2

1. Introduction

Manmade global warming is currently a major global concern [1]. Meanwhile, the global economy requires the manufacturing industry to produce goods such as metals, chemicals, paper and food, through energy intensive and often fossil fuel dependent manufacturing processes. This poses a major challenge for countries that want to avoid sacrificing profitable production opportunities, while still demanding consistent reductions of energy consumption and greenhouse gas emissions. One significant contributing solution would be to replace industrial boilers, which typically provide hot water or steam at pressures of 20 bar or lower. Applications for such boilers are vast, e.g. within chemical process plants, building heating, humidification, domestic hot water, sterilisation autoclaves, and air makeup coils [2]. Also, there are valuable (and often contaminated) fluids used as fuels in industrial boilers (e.g. hydrogen and hydrocarbons), which could instead be recycled or used for better purposes, with a potential of significant economic and environmental savings [3]. If industrial boilers were replaced by heat pumps, heating would only require electricity and a heat source at lower temperatures (waste heat). Such a heat pump must be able to output the required temperature levels, be economically viable and use working fluids that meet a demanding set of specifications.

Despite the existence of many different solutions, the heat pump market has until recently been limited to temperatures below 115°C [4]. This has strongly constrained the potential of industrial heat pumps. The primary reason for this is the great challenges that manufacturers must overcome in the development of heat pumps for high temperatures. Recently, a recuperated vapour compression (VC) heat pump system for output temperatures up to 160°C, the HeatBooster, was developed by Viking Heat Engines, Norway/Germany/Barbados in collaboration with AVL Schrick, Germany. The novelty of this heat pump is the utilisation of a proven piston displacement machine technology designed for 40,000 operating hours at temperatures up to 200°C before half-life maintenance [5]. The VC system was tested with HFO-1336mzz(Z) as the working fluid, the fluid having a very low global warming potential (GWP) to virtually eliminate business risk from increasingly restrictive climate protection regulations around the globe. It also has a sufficiently high performance so as to reduce payback time for selected applications to attractive levels.

The HeatBooster HTHP is based on a piston expander/compressor technology which has undergone a comprehensive development program during the past five years (R&D costs are at more than €40 million). The extensive development process has focused on long service life and high durability, as well as the capability to handle very high temperatures in an effective and durable manner. Today, this piston machine technology is equally capable of operating in organic Rankine cycles (ORCs) [9] as well as VC heat pump systems. This paper describes the potential of the heat pump. It reviews its key features, describes the system installation that was used for the performance measurements, reports measured system performance with HFO-1336mzz(Z) and identifies knowledge gaps for future work.

2. HeatBooster Features

2.1. Components

The (recuperated) VC heat pump has five main components that are shown and listed in Figure 1. The evaporator, condenser and recuperator are plate-type heat exchangers. The compressor is a reciprocating (piston) type, fully hermetic design, and the expansion valve is an electronically controlled device with a high operating temperature specification. Further from the five main components, there is also a working fluid reservoir in the form of a tank, which ensures that there is always enough fluid available to the process.

Beyond the above mentioned components there are additional components such as pipes, safety valves, electrics and a control system to ensure safe and autonomous operation of the system.

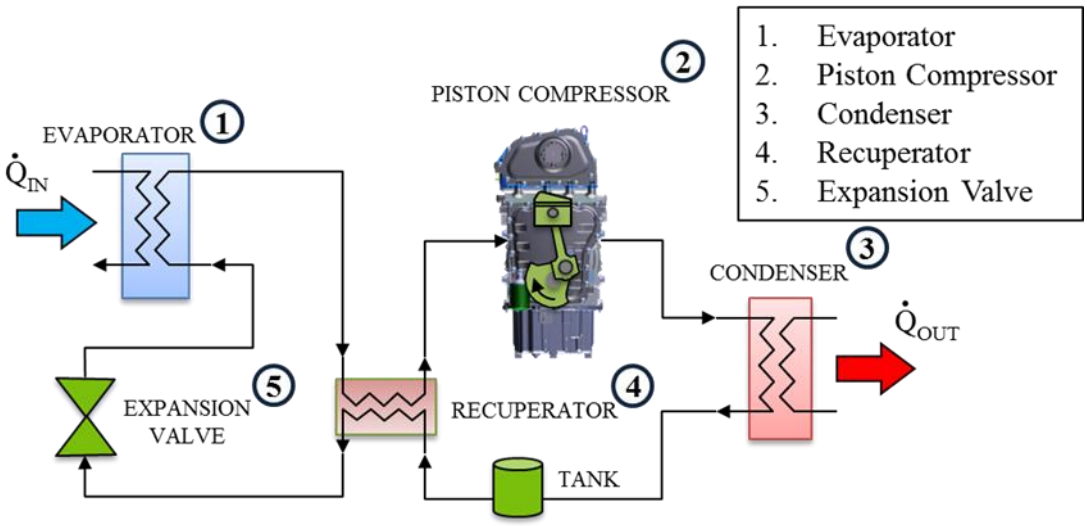


Fig. 1. Main HeatBooster system components and simplified flow diagram.

2.2. Working principle

The basic VC operating principle is cyclic compression and expansion of the working fluid with accompanying heat transfer processes taking place in an evaporator and a condenser respectively. Heat is transferred from a heat source to a working fluid in the evaporator, which is evaporated with minimal superheat. The working fluid is then superheated in the recuperator before it is admitted into the compressor via a suction port. The compressor compresses the working fluid, thereby raising the temperature and pressure of the working fluid through near-isentropic compression, before it discharges it through a discharge port into the condenser, where heat is transferred to a heat consumer circuit as the working fluid is de-superheated and condensed. The heat consumer network typically uses steam or pressurised hot water as heat transfer media.

The purpose of the recuperator is to provide a sufficient level of superheat to the working fluid going into the compressor. This improves performance and reduces the risk of having substantial liquid formation in the compressor, which may damage it. In addition, the recuperator subcools the condensed (liquid) working fluid before the expansion valve, thereby reducing the risk of cavitation in the expansion valve, something which further ensures stable and predictable operation. This is also further helped by the working fluid tank, which ensures that there is always liquid working fluid available prior to the expansion valve.

The performance of a heat pump is mainly expressed by its coefficient of performance (COP), which is defined as the ratio between the thermal power delivered to the heat consumer and the electrical power consumption required to drive the compressor (and other necessary system devices).

2.3. Operating range

The test heat pump has a relatively small reciprocating compressor designed for temperature lifts up to about 60°C at a maximum outlet temperature of at least 150°C using HFO-1336mzz(Z) as working fluid. It is capable of operating with an electrical motor power of up to about 10 kW with a compressor speed of up to 1,500 rpm. Due to its variable speed capability and an actively controlled, fully variable valve system (i.e. no passive valves as is common in conventional compressor designs), it has the ability to adjust to optimal performance at a wide range of working conditions. The system is capable of handling evaporator pressures from 0.1 MPa to 1.0 MPa and condenser pressures from 0.7 to 3.0 MPa. The HeatBooster HTHP has been tested in operation with HFO-1336mzz(Z) as well as with HFC-245fa. Additionally, fluids that have been utilised for the ORC application (same piston machine, but different process design) include HFO-1234ze(E) and HFC-134a. Figure 2 shows the saturation pressure at the relevant temperature ranges for the working fluids in question. The technology is fully scalable and requires very few hardware changes in order to transform it from an ORC to a heat pump and vice versa. An ORC with expanders in parallel (electrical output power of about 40 kW under certain boundary conditions) has already been developed, and the HeatBooster HTHP thermal power range may be extended to include this configuration as well. Further, a larger version piston machine based on the same technology platform is planned, which has the potential to increase the thermal capacity of the heat pump technology to over 1,500 kW per installed system.

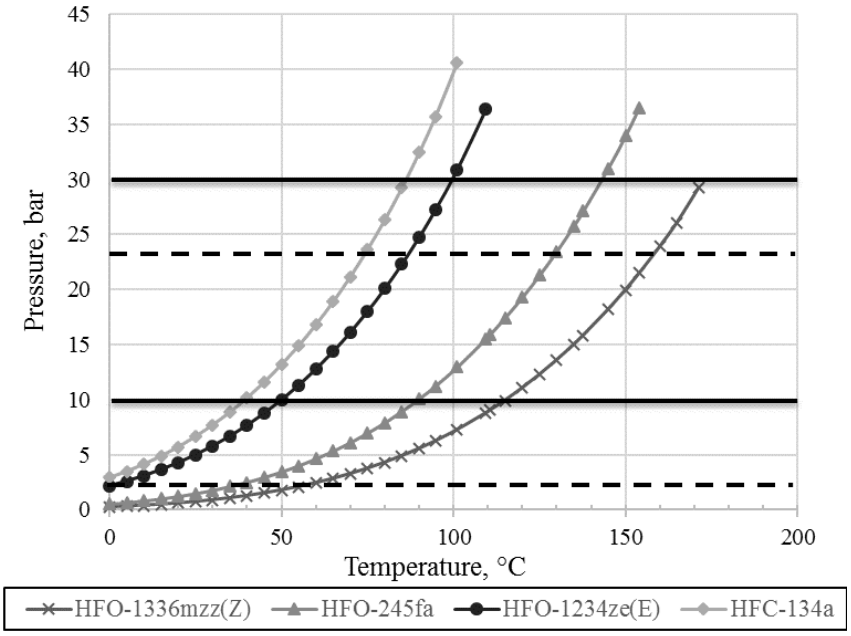


Fig. 2. Saturation curves with indication of the respective maximum pressures (the two whole lines) and the typical operating pressure range (between the dashed lines).

2.4. Innovation

Reciprocating compressors are highly suitable for operation at elevated temperature levels if designed accordingly. They may also operate at part load without significantly losing efficiency. Turbomachines (turbo compressors) will to a larger extent suffer from decreased efficiency when driving power is reduced, while screw compressors often have problems with leakage and lubrication (poor oil separation) at high temperatures [6; 7].

The piston machine used for the HeatBooster HTHP was as mentioned already designed as an ORC expander used for the CraftEngine technology. In the process of designing the piston machine, much effort was spent on critical topics such as providing flexible operation while sustaining a high compressor efficiency, good lubrication and separation thereof and an efficient integrated motor/generator. Especially the design of the valve system was given much attention, and instead of choosing a conventional solution using passive (reed) valves, the valve system that was originally developed for the ORC expander was chosen. It already had the advantage that it could be adjusted for reversed flow direction, effectively turning the expander into a compressor by turning the valve events around. In addition, the discharge valve timing can be actively controlled to provide a fine tuned compression ratio, something which gives a great advantage when optimising performance during operation.

Developing a piston machine requires a comprehensive development and testing phase with significant investments and knowledge, as well as the need to address demanding topics such as cost optimisation, manufacturing and more. Therefore, Viking performed the development in collaboration with AVL in order to get access to world class design expertise for piston machinery. In order to achieve an excellent COP and operational flexibility, the development must focus on many detailed aspects, such as minimising flow losses in the compressor just to mention one.

In order to address the elevated temperature levels in the design of the HTHP, much experience was drawn from the existing operation with the CraftEngine ORC configuration. Most components were directly transferred from this design, and since the ORC was already designed to operate at temperatures up to about 200 °C, the development of the HTHP required less effort in this respect. One of the concrete challenges, however, was to find a suitable electronically controlled expansion valve.

Taking the five-year development of the ORC engine technology into account, temperature-related issues have been solved to the extent that the heat pump can be commercialised in the relatively near future. Many industries

would get a powerful tool to increase energy efficiency, which is in great demand considering recently adopted policies for the energy sector and industry to bring down greenhouse gas emissions 80% below 1990 level by 2050 [8].

Performance Measurements of the HeatBooster HTHP

2.5. System Installation for Performance Measurements

The system installation used for the performance measurements had some limitations. It was comprised of two water loops, one for the heat sink (high temperature side) and one for the heat source (low temperature side), respectively. The heat sink had a maximum heat capacity of 35 kW and a maximum temperature of 155°C. This limited the possibilities of testing different compressor speeds and made it impossible to reach the maximum outlet temperature of the heat pump with HFO-1336mzz(Z), i.e. approximately 165°C. The maximum temperature of the heat source was 100°C, which limited the pressure of HFO-1336mzz(Z) to 0.63 MPa on the heat source side. However, the system installation still provided sufficient flexibility to give a general assessment of the technology performance.

The recorded measurements were made at three different compressor speeds, namely 900, 1,200 and 1,350 rpm. The system was heated for at least one and a half hour to establish stable operating conditions. Performance at each temperature lift was then recorded at least three times within a short time interval. Each of the three sets of performance measurements was recorded over 120 seconds, after the system had been running at a stable COP for a couple of minutes. System performance was measured with temperature lifts between heat source and sink of 20 to 70°C. The efficiency of the inverter driving the compressor motor was approximately 80%. The expansion valve was an off-the-shelf product with negligible power consumption. COP was calculated by the use of Equation 1. The COP was measured from the inverter (electrical power, $\dot{W}_{el}$) and the heat sink loop (thermal output, $\dot{Q}_{heat_out}$).

$$COP = \frac{\dot{Q}_{heat_out}}{\dot{W}_{el}} \quad (1)$$

2.6. Measured Performance with HFO-1336mzz(Z)

The working fluid HFO-1336mzz(Z), was evaluated through about two hundred tests by Viking Heat Engines from March to November, 2016. The tests were conducted together with a suitable POE lubricant over a range of conditions representative of potential high temperature heat pump applications. In addition to its attractive safety, health, environmental, thermodynamic and chemical properties, HFO-1336mzz(Z) has already shown promising performance in the ORC application [9].

Many high temperature industrial processes (e.g. pasteurisation in dairies or drying in paper production) are in the ideal temperature range for the HeatBooster HTHP operating with HFO-1336mzz(Z), e.g. up to 150-160°C [10]. To reach very high temperatures, a recuperator was used to accomplish effective compression and avoid liquid formation. The recuperator was used to superheat the fluid after the evaporator, which improved the efficiency by increasing the enthalpy change during the compression stage. The superheat was around 10 °C at the smallest temperature lifts and 60 °C at the largest temperature lifts. The superheat after the compressor was 5 to 40 °C higher than the condensing temperature. This meant that the heat pump typically delivered water at temperatures slightly higher than the condensing temperature.

The average measurement data are listed in Table 1, which include the average COP and heat source input and heat sink output temperatures, respectively. The COP is, as expected, the highest at the smallest measured temperature lifts and at the highest inlet temperatures.

Table 1. A selection of temperature lifts tested in the HeatBooster HTHP with HFO-1336mzz(Z) with a suitable ISO-grade POE lubricant. COP values are tested at 900 and 1,200 rpm and are the average of each temperature lift. The thermal output variations are a result of different temp. lifts and engine speed.

Temp. lift	50	60	40	50	60	40	50	60	20	30	40	50	60	35

T_{in}, °C	60	60	70	70	70	80	80	80	90	90	90	90	90	95
T_{out}, °C	110	120	110	120	130	120	130	140	110	120	130	140	150	140
COP, -	3.1	2.5	4.1	3.5	2.5	4.3	3.3	2.5	7.8	5.8	4.6	3.4	2.7	4.0
$\dot{Q}_{heat_out}$, kW	13	13	17	17	15	21	18	17	29	25	24	23	22	33

As expected and as shown in Figure 4, the highest COP was achieved at the smallest measured temperature lifts. However, it was not possible to distinguish any influence on the COP by varying the compressor speed. This was partly a result of the capacity restriction of the heat sink (i.e. 35 kW) and partly due to very small friction losses in the compressor. Variations of the COP at the same temperature lifts were due to the pressures, the inverter efficiency, the amount of working fluid in the system (over-filling), pinch-points in heat exchangers, etc. Figure 4 also shows that the heat pump has a COP that is 25% to 55% of the maximum theoretical efficiency. The theoretical maximum COP is calculated according to Equation 2.

$$Theoretical\ max.COP = \frac{T_{hot}}{T_{hot} - T_{cold}} \quad (2)$$

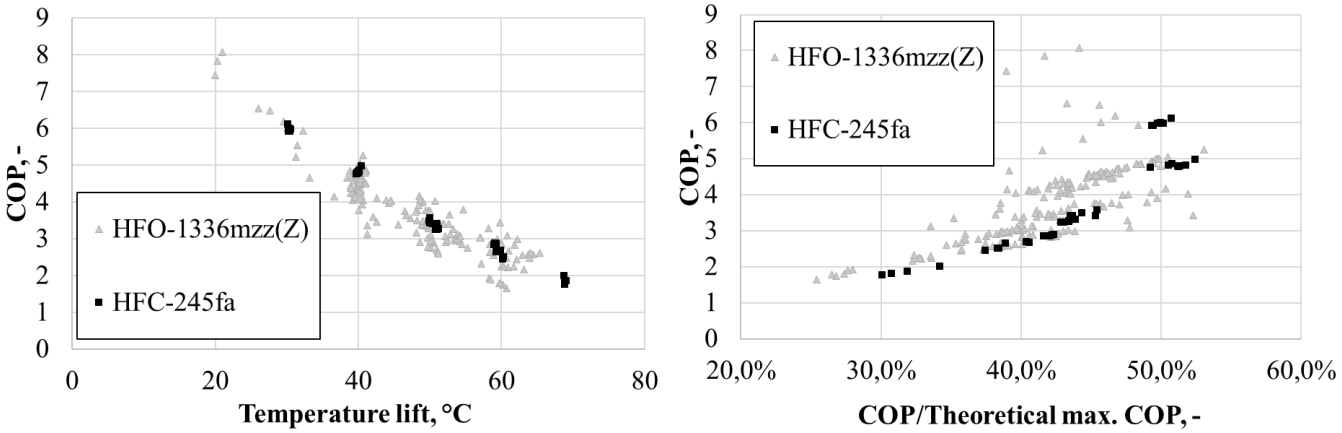


Fig. 4. Measured performance map for the HeatBooster with HFO-1336mzz(Z) (grey) and HFC-245fa (black) as the working fluid at temperature lifts from 60°C to 150°C

Figure 5 shows very similar COP at the same pressures, but the temperature range is different due to the difference in saturation pressure between HFC-245fa and HFO-1336mzz(Z) .

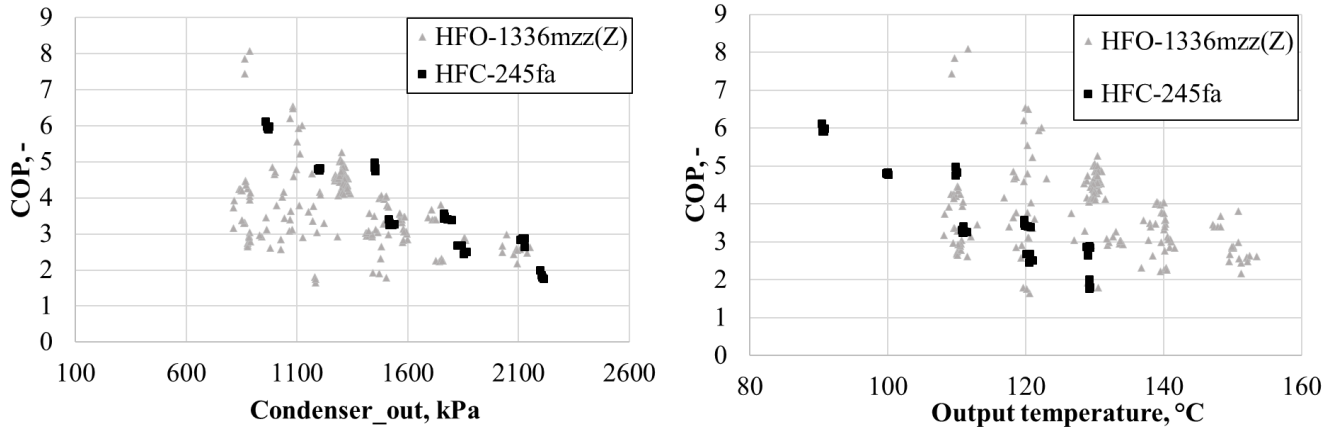


Fig. 5. Comparison of the working fluid pressure (left) and the water temperature (right) at the outlet of the condenser, respectively.

2.7. Health, Safety and Environmental Properties of HFO-1336mzz(Z)

The basic health, safety and environmental (HSE) properties of HFO-1336mzz(Z) are compared to those of a familiar reference fluid that has been extensively used in ORC applications, namely HFC-245fa, in Table 2. HFO-1336mzz(Z) is non-flammable at both 60 °C and 100 °C according to ASTM E681-2004. It has recently received a safety classification of A1 (lower toxicity; no flammability) according to ASHRAE Standard 34 with an occupational exposure limit (OEL) of 500 ppm. HFO-1336mzz(Z) contains no chlorine, bromine or iodine and, therefore, has a zero ozone depletion potential (ODP). The HFO-1336mzz(Z) atmospheric lifetime of 22 days and GWP with a hundred-year integrated time horizon of 2 compare favourably to those of HFC-245fa.

Table 2. Basic HFO-1336mzz(Z) health, safety and environmental properties compared to HFC-245fa.

	HFC-245fa $CHF_2CH_2CF_3$	**HFO-1336mzz(Z)** $CF_3CH=CHCF_3(Z)$
IUPAC name	1,1,1,3,3-pentafluoro-propane	(Z)-1,1,1,4,4,4-hexafluoro-2-butene
Mol. w. (kg/kmol)	134.05	164.056
Flammability	Non-flammable[(1)]	Non-flammable[(2)]
Occupational Exposure Limit (ppmw)	300[(1)]	500[(3)]
Safety Class[(3)]	B1[(1)]	A1[(3)]
Atmospheric Lifetime (yr)	7.7[(4)]	0.060274 (22 days)[(4)]
Ozone Depletion Potential	None	None
Global Warming Potential (100 year Integrated Time Horizon)	858[(4)]	2[(4)]

(1) Calm and Hourahan (2007) [11]; (2) At 60°C and 100°C according to ASTM E681-2004 [12]; (3) According to ASHRAE Standard 34 [13]; (4) Myhre et al. (2013) [14]

2.8. Thermodynamic Properties of HFO-1336mzz(Z)

Availability of accurate thermodynamic properties is key in the selection of a new working fluid and subsequent application development. HFO-1336mzz(Z) thermodynamic properties for early ideal cycle performance evaluations were estimated from limited measurements of liquid density, vapour pressure and critical temperature and pressure. They were derived through either cubic equations of state (EOS) or – for increased accuracy near the critical point – through an EOS based on an expression for the Helmholtz free energy with a number of terms limited by the available data.

Thermodynamic properties for equipment design must meet a higher standard of accuracy that requires measurements over a wide range of conditions including the region near (above and below) the critical point. Extensive HFO-1336mzz(Z) pressure-temperature-density measurements have recently been reported by Tanaka et al. [15; 16]. They covered a temperature range from 49.85°C to 229.85°C and pressures up to 10 MPa and they included measurements in the liquid, vapour, liquid-vapour and super-critical region. The reported temperatures and pressures were accurate within 0.028 K and 4 kPa, respectively. Densities lower than 100 kg/m^3 were measured with a 0.6% accuracy and densities higher than 100 kg/m^3 were measured with a 0.4% accuracy. Table 3 compares a few basic HFO-1336mzz(Z) thermodynamic properties to those of HFC-245fa. The HFO-1336mzz(Z) atmospheric boiling point, critical temperature and critical pressure reported by Tanaka et al. [15; 16] are in close agreement with the values reported earlier by Kontomaris [17; 18].

Table 3. Basic thermodynamic properties of HFO-1336mzz(Z) compared to HFC-245fa.

	HFC-245fa	**HFO-1336mzz(Z)[(2)]**
Normal Boiling Point, °C	15.1[(1)]	33.47
Critical Temperature, °C	154[(1)]	171.27
Critical Pressure, MPa	3.65[(1)]	2.901
Critical Density, kg·m^{-3}	519[(3)]	471

(1) Calm and Hourahan (2007) [11]; (2) Tanaka et al. (2016) [15; 16]; (3) Akasaka et al (2015) [19]

An equation of state explicit in the Helmholtz free energy was recently developed for HFO-1336mzz(Z) by Akasaka and Lemmon [20]. It was composed of an ideal-gas part and a residual part. In the absence of speed of sound measurements, the ideal-gas part was derived from an ideal-gas isobaric heat capacity expression based on Joback's group contribution method [20]. In view of the limited available pressure-temperature-density data, the residual part was expressed in only polynomial and exponential terms (i.e. no Gaussian terms) that were regressed to represent the measurements by Tanaka et al. [15; 16] and the normal boiling point by Kontomaris [18]. The Akasaka-Lemon equation of state represents the available vapour pressure and density data outside the critical region to within 0.2%; it deviates from the measured densities near the critical point by up to 2%.

3. Summary-Conclusions-Discussion

Developing an efficient and cost-effective high temperature heat pump is key to a sustainable development for industrial manufacturing processes. However, the utilisation of heat pumps has been limited, because there have generally been no heat pumps available for temperatures above 115°C. This paper presents a novel heat pump using a novel HFO working fluid, with relevant scientific and commercial properties (product performance, high-volume production, product standardisation, low GWP etc.). The introduction of such a technology is very promising in that it can lead to progressive improvements on the path to sustainable industrial development. Inaction from industries and countries to invest in technologies such as this could lead to complacent acceptance of the slow (or status quo) improvement of the environmental impacts that industries all around the world have, and therefore it is seen as important to bring about new knowledge of the new opportunities that have become available during recent times.

Considering other heat pumps under development for high temperature, the HeatBooster technology has many advantages. The heat pump compressor has been designed for minimal mechanical and flow losses. As a result, it achieves high mechanical and isentropic efficiency despite its relatively small size, which generally magnifies the proportion of certain losses relative to heat output. Furthermore, the HeatBooster is not limited to any particular temperature range and not dependent on any high-GWP or flammable fluids. The technology is developed through a long and comprehensive process, which has provided valuable experience regarding high-temperature materials manifested in the several thousands of running hours at temperatures up to 200°C.

The performance maps of Figure 4 and Figure 5 can be used to evaluate the potential of the HeatBooster with HFO-1336mzz(Z) in prospective applications, including dairies, breweries, pulp and paper production and chemicals production. The measured performance of the HeatBooster with HFO-1336mzz(Z) showed excellent COP and system behaviour. Measured COP and heat output exceeded 7 and 30 kW_{heat}, respectively. Due to the current set up of the HeatBooster, it was not possible to have higher inlet temperatures than 95°C or to test higher outlet temperatures than 150°C. The compressor operated stably at all the measured temperature lifts. The evaporator, condenser and recuperator operated with a sufficiently uniform distribution of the entering HFO-1336mzz(Z) along the flow directions, as indicated by infrared thermography, to make effective use of the available heat exchange surface area. Having controlled heat exchange behaviour is essential for the principle of a vapour compression heat pump, which makes HFO-1336mzz(Z) (and possible related variants/blends) of this fluid excellent fluids for the HeatBooster. The flow rate required for the heat pump is considerably lower than for the ORC, which could explain the good match between the HeatBooster and HFO-1336mzz(Z).

In view of the small reduction of COP over tested electrical power levels (consistent with literature), the system performance should be optimised for an electrical power input above 5 kW. Higher heat output often outweighs higher COP, especially when the source heat is provided free of charge. The heat outputs in some test series were limited by the heat sink capacity (i.e. 35 kW); a higher capacity will be considered for future tests. Further optimisation of the heat pump system for HFO-1336mzz(Z) would focus on electrical efficiency (e.g. inverter, control systems and electronics).

HFO-1336mzz(Z) was recently classified as an A1 (lower toxicity; no flammability) refrigerant according to ASHRAE standard 34 and it has a GWP of only 2. It has demonstrated in past studies [18] chemical stability comparable to that of HFC-245fa, a working fluid that has been used extensively in high temperature heat pump and ORC applications. HFO-1336mzz(Z) is on a path to full-scale commercial production in 2017. A commercially available POE lubricant with an appropriate ISO viscosity grade was evaluated for use with HFO-1336mzz(Z) in

heat pump applications. The POE lubricant was found to be miscible with HFO-1336mzz(Z) over a wide range of conditions. It is projected to maintain a satisfactory kinematic viscosity at 170 °C and to form mixtures with HFO-1336mzz(Z) of adequate working viscosities for a wide range of conditions.

Further research would include a detailed comparison of competing heat pump technologies (in the development stage) and the nature of the markets for these technologies. A preliminary outlook on these technologies is necessary to determine the impact of high temperature heat pumps in the next years to come. A road map for commercial exploitation of potential markets should be detailed further. Looking forward, investigating how to increase the durability and back-up systems to ensure for example significantly more than ten years of operation would also be an ongoing activity.

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