Heat pump and refrigerant selection for waste heat integration into district heating networks

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Abstract

District heating systems are gaining popularity and can make use of heat sources that are locally districted and would have otherwise been wasted. One of the latest developments of district heating focuses on waste heat recovery from data centers. Feasible waste heat integration in the mid temperature (MT) or high temperature (HT) regime in Amsterdam requires a thorough selection of suitable heat pumps and refrigerants. This research aims to create a step-wise approach for selecting a suitable heat pump and refrigerant for data center waste heat integration in the MT and HT networks in Amsterdam. The components, cycle configurations, and refrigerant types for heat pumps were explained, and a case study on heat pump selection was done. A single-stage cycle was considered to be suitable for MT applications such as the Kantorenstrook Amstel III case, but waste heat integration into the primary network of Amsterdam would require the use of more advanced high temperature heat pump configurations. The selection of a suitable refrigerant depends on the temperature regime, but also on technical constraints, and environmental and safety criteria. However, no heat pump application will score best on all requirements and, therefore, tradeoffs must be made. The challenge lies in the fact that the selection is very case-specific and requires a high level of expertise. The approach in this study must further be developed and applied to other district heating case to create a deeper understanding of the heat pump and refrigerant selection. Lastly, research & development on high temperature heat pumps for large integration projects is of high importance.

Keywords**:** *District heating, data center waste heat, heat pump. refrigerant, high temperature*

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List of Acronyms

CFC	Chlorofluorocarbon
COP	Coefficient of performance
GWP	Global Warming Potential
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HCFO	Hydrochlorofluoro-olefins
HFC	Hydrofluorocarbon
HFO	Hydrofluoro-olefins
HTHP	High temperature heat pump
ODP	Ozone Depletion Potential
IHX	Internal Heat Exchanger
VHC	Volumetric Heat Capacity

1. Introduction

Improving energy efficiency plays a critical role in fighting climate change. The industry is responsible for more than a third of the global primary energy consumption, and efforts are made to reduce environmental impact. Heat pumps are attractive technologies for the industry, as they can reduce primary energy consumption by utilizing heat recovery with waste heat that would otherwise have been rejected into the air (Arpagaus et al., 2016). However, waste heat is often rejected at low temperatures, and to be useful, it needs to be upgraded to higher temperatures (Mateu-Royo et al., 2018). This temperature level depends on whether waste heat is integrated into the mid temperature (MT) regime or in the high temperature (HT) regime.

In the network of Amsterdam, two basic technical concepts of waste heat integration are common: A local heat integration solution in the MT regime, often in newly developed areas, and a more central and larger-scale solution in the HT regime, where the solution is a direct heat source for the grid.

In Hattink (2020), a pilot project for data center waste heat integration is modeled in a newly developed area: Kantorenstrook Amstel III. Integration happens on a neighborhood area scale, and waste heat will be supplied in the secondary supply network, meaning the MT regime. However, the district heating network in Amsterdam is expanding, and the municipality of Amsterdam introduced strategies for extending the HT network to allow for better connectivity.

R&D projects are running to increase heat sink temperature levels, improving COPs, and efficiencies of components in the heat pumps (Arpagaus et al., 2018a; Kosmadakis, 2019). Besides the heat pump technology and its components, a suitable working fluid, or *refrigerant,* is critical for a heat pump application. However, the difficulty of finding the most suitable high temperature high pump technology and refrigerant lies in the comprehensive approach that includes energy performance indicators as well as cost efficiency and environmental impacts, while taking into account future developments. Strangely enough, there are various available industrial heat pump applications with high potential, although not many are operational (Kosmadakis, 2019).

Feasibility of data center waste heat integration largely depends on the heat pump selection. Therefore, the research question is as follows:

"What would be a suitable heat pump selection approach for waste heat integration in the district heating network?"

<u>Overview</u>
Firstly, the main components of a heat pump are described. Secondly, the MT and HT regimes are explained and applied to the heat pump concept. Due to the higher temperature lift, the HT concept might require more complex configurations to create a feasible integration. Next, a refrigerant study is carried out to define a suitable working fluid for the integration approach. For data center waste heat integration in the MT and HT networks in Amsterdam, a selection approach is carried out to determine suitable heat pump applications. A pre-selection of refrigerants is done, and tradeoffs that must probably be made, are discussed.

2. Heat pumps

The most common types of heat pumps are the (mechanical) *vapor compression* heat pump and the *absorption* heat pump. This study focusses on the compression heat pump, although *absorption* or *hybrid absorption-compression* heat pumps can also be relevant in the field of MT and HT heat pumps (Frate et al., 2019). Compression heat pumps convert low temperatures coming from a heat source into higher temperatures by using a heat transfer medium, called a *refrigerant*. According to Bamigbetan et al. (2018), is it a well-known heat pump technology, suitable to operate with high temperatures. Vapor compression heat pump components and cycle configurations are discussed.

2.1 Components

A basic heat pump consists of four main components (Figure 1): A condenser (heat sink side), an evaporator (heat source side), an expansion valve, and a compressor. In the evaporator, low temperature heat is absorbed by the (liquid) refrigerant and vaporizes. The vaporized refrigerant enters the compressor in which the pressure and temperature of the vapor increases. It then flows to the condenser at a high temperature and condensates. Next, the (liquid) refrigerant flows through the expansion valve, and its pressure reduces again, after which it returns to the evaporator.

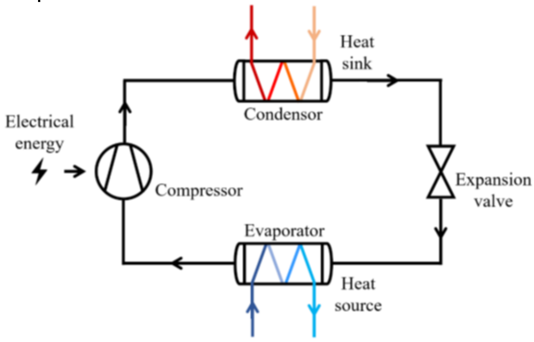

Figure 1: Components of a heat pump.

The operation of a heat pump requires additional electricity supply to drive the compressor, of which the amount of electricity depends on the *Coefficient of Performance (COP)*. The COP factor is related to the heat temperature inflow and outflow, given the following formula

$$\mathrm{COP}_{\mathrm{Carnotl}} = \frac{T_{Hot}}{T_{Hot} - T_{Cold}} \qquad (1)$$

where $\mathrm{COP}_{\mathrm{Carnot}}$ is the theoretical COP achieved when dividing the high temperature heat T_{Hot} (coming out of the condenser) with the difference in temperature between T_{Hot} and T_{Cold}, where T_{Cold} is the low temperature heat that flows into the evaporator. However, this formula depicts the Carnot COP, which is not the *actual* COP. The COP value is depending on multiple factors of which the temperature of the heat source and heat sink are considered the most important factors that influence the COP. As the temperature difference of heat source and heat sink increase, the compressor pressure ratio also increases, and hence the COP decreases.

The majority of heat pumps use closed-cycle compression heat pumps. Different types of compressors that are used are piston, screw, scroll, reciprocating, centrifugal, and turbo compressors. Piston, screw, scroll, and reciprocating compressors are used in smaller units, whereas centrifugal and turbo-compressors are used in larger units (Frate et al., 2019; Kosmadakis, 2019).

2.2 MT and HT heat pumps

Next to the mature heat pump in the MT regime, high temperature heat pumps that can cover larger temperature lifts, have gained attraction as suitable technologies for upgrading waste heat so that it could be integrated into the primary transport networks.

The definition of 'high temperature' varies across the literature. Bamigbetan et al. (2017) classify HT heat pumps as capable of producing heat at 80°C or above, whereas Arpagaus et al. (2018a) assume 100°C as an HT heat pump lower boundary. Kosmadakis (2019) refers to the potential feasibility of a 30-50°C temperature lift to recover heat at temperature up to 120°C to produce at a temperature of 150°C. Generally, a temperature range somewhere between 90°C and 150°C is commonly used for HT heat pumps.

In this paper, the focus is on HT heat pump applications with a minimum heat delivery temperature of above 90°C, which is the required temperature minimum for the HT network in Amsterdam.

In industry, heat pumps are often supplied with waste heat that would otherwise have been rejected into the air. To upgrade low temperature waste heat (e.g., from data centers) to high temperatures that can be utilized in district heating networks, HT heat pumps are required to cover such large temperature ranges.

The main components and thermodynamic cycle of the HT heat pumps are not different from a conventional heat pump. However, properties that are more important to take into account are the increasing compressor discharge pressure and temperature, which are the result of achieving high compressor outlet temperatures. Those discharge pressures and temperatures must be kept below a tolerable level (Bamigbetan et al., 2017).

2.3 Cycle configurations

Experimental studies work with single-stage compression cycles but also multiple cycles (Bamigbetan et al. 2017; Arpagaus et al., 2016). For MT heat pumps, single-stage cycle heat pumps are commonly used and can achieve required temperature lifts. However, improving system performance and reaching higher COPs can also be achieved by other configurations, both for the integrating heat pumps in MT an HT networks. Several articles have done extensive studies on possible cycle configurations, e.g., by the use of internal heat exchangers (IHX) or economizers, but also using multi-stage compressors and cascade heat pump cycles (Bamigbetan et al., 2017; Wallerand et al. (2018); Frate et al., 2019). Mateu-Royo et al. (2018) state that case-specific analyses are necessary to understand what system configuration is most suitable and what the effect for certain refrigerants is.

A) Internal Heat Exchangers (IHX)

At least for a single-stage configuration, an IHX is typically used to increase the heat pump's performance (Kosmadakis, 2019). The IHX further sub-cools the refrigerant before the expansion valve to decrease the quality of the refrigerant entering the evaporator (for a higher cooling capacity). It thereby transfers heat from the condenser to the suction of the compressor to increase the gas discharge temperature (Mateu-Royo et al. (2018). An IHX can potentially increase performance and efficiency (COP) compared to a simple single-stage heat pump (Arpagaus et al., 2018b).

B) Economizers

An economizer allows for the preheating of vapor before it enters the compressor (Wallerand et al., 2018). In simple terms, an economizer is a heat exchanger. It separates phases after the expansion valve by feeding vapor to the intermediate stage of the compressor (with intermediate pressure) while feeding the liquid into the evaporator. The compression work is thereby reduced, resulting in an improved COP (Domanski, 1995).

Generally, multi-stage compressors or cascade systems are redundant for the MT regimes and would moreover be cost-inefficient (too high investment costs for such smaller-scale projects). However, for higher temperature lifts in the HT regimes, using IHXs and economizers is often ‘not enough,’ and more complex configurations are

C) Multi-stage compressors

Multi-stage compressor cycles include two or more compression stages in series or parallel. By dividing the compression stages, the pressure ratio is reduced, and higher performance (COP) can be achieved (Arpagaus et al., 2016). Using two-stage compressors is rather ‘standard’ for (centrifugal) compressors for large-size applications.

D) Cascade heat pump cycles

Cascade cycles combine two or more heat pumps making it possible to use different refrigerants for each cycle (Arpagaus et al., 2016). Cascade systems are suitable when temperature differences are large and, therefore, applicable to HT heat pumps (Haukås & Pachai., 2014). System efficiency can be enhanced by using multi-temperature heat pumps to combine multiple heat sources and sinks at various temperatures (Arpagaus et al., 2016). In some cases, multiple heat pump cycles are also necessary against flammability (Arpagaus et al., 2018b).

To sum up, various articles study heat pump improvements to enhance performances. In terms of improving efficiency, the compressor is considered to be the most important component in a heat pump since it consumes electrical energy, and increasing its functionality is directly beneficial for the COP performance.

The study of Frate et al. (2019) concludes that applications with a low temperature lift often requires only one stage, whereas refrigerants that work with bigger temperature lifts might require two or more stages.

3. Refrigerants

3.1 Properties

ASHRAE 34 (2019b) defines a refrigerant as *“The fluid used for heat transfer in a refrigerating system; the refrigerant absorbs heat and transfers it at a higher temperature and a higher pressure, usually with a phase change.”*. A refrigerant’s temperature increases significantly when the refrigerant is pressurized. This property makes refrigerants very suitable as working fluids. However, the thermodynamic properties of classical heat pumps are often not ideal for high temperature applications.

A simple thermodynamic cycle in a heat pump is explained in steps by using a log ph-diagram visualized in Figure 2:

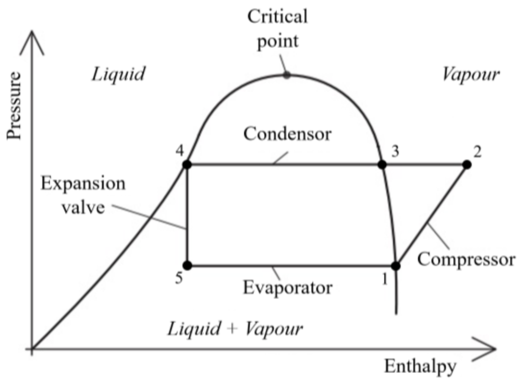

Figure 2:Log p-h diagram cycle for a heat pump.

The vaporized refrigerant (1) enters, in a saturated state, the compressor in which the pressure and temperature of the vapor increases (2), resulting in superheated vapor. Under the same pressure, the superheated gas cools down to its saturated vapor point (3), and condensation takes place. Under condensing pressure, the refrigerant changes from its vapor phase to saturated liquid (4). The liquid flows through the expansion valve, and pressure reduces again (5). In the evaporator, the liquid + vapor is converted back to saturated vapor. The condensing temperature is the temperature at which a refrigerant is changing from its vapor phase to its liquid phase. The evaporating temperature is the temperature at which it is changing from a liquid to vapor.

Each refrigerant has a different boiling temperature at a given pressure. At high pressure, the temperature might become too high for a ‘regular’ heat pump to function (Bamigbetan et al., 2019). On the other hand, low pressures are also risky because the volume will increase, and larger components are required.

The temperature that changes the phase of a refrigerant from fluid to vapor or vice versa is called the *saturated temperature* (at points 1, 3, and 4 in Figure 2). Vapor is in superheated conditions when a refrigerant’s temperature it above its vapor saturation point and cannot be condensed until cooled down to its saturation point (Frate et al., 2019).

Another property is the critical temperature of a refrigerant by which it reaches its supercritical phase. In this phase, a refrigerant gas (vapor) cannot go back to its liquid state (which would typically be done by compressing), irrespective of the pressure. Every substance has a critical temperature (Calm & Hourahan, 2011).

For the analysis of refrigerants, constraints can be set on the critical temperature and condensation pressure to impose operational ranges (Frate et al., 2019).

3.2.1 Environmental criteria

The environmental impact of a refrigerant is two-fold; direct and indirect. Direct impact parameters are the Ozone Depletion Potential (ODP) and Global Warming Potential (GWP), whereas indirect impact is related to COP and energy mix of electricity used (Bemigbetan et al., 2017). This study does only take into consideration the ODP and GWP. ODP measures the ability of a refrigerant to destroy stratospheric ozone relative to the synthetic refrigerant R11, and GWP is a measure of how greenhouse gas traps heat in the atmosphere relative to carbon dioxide in a 100-year time frame (Calm & Hourahan, 2011).

F-gas regulations intensification (described later in section 3.3) introduced the acceptability level of a GWP to be smaller than 150 by 2022 (Arpagaus et al., 2018b). The UNEP Technology and Economic Assessment Panel (UNEP, 2010) has made a distinction between GWP levels and classified GWPs under (approx.) 30 as 'ultra-low', under 100 as 'very low', under 300 as 'low' up until a GWP above 10,000 classified as 'ultra-high'.

3.2.2 Safety criteria

The safety of refrigerants is commonly measured in terms of toxicity and flammability. A refrigerant is toxic when it is harmful or lethal by acute or chronic exposure. Toxicity is classified in the groups: Lower toxicity (A) or higher toxicity (B), whereas flammability of refrigerants is assigned to one of the four classes: No flame propagation (1), lower flammability (2L), flammable (2), or higher flammability (3) (ASHRAE, 2019b; Calm & Hourahan, 2011). Toxicity and flammability of refrigerants should be avoided or minimized as much as possible. In section 3.5, safety criteria are grouped according to the classification of refrigerants.

3.2 Generations of refrigerants

The beginning of refrigeration was characterized by using 'whatever refrigerant worked' (Calm & Hourahan, 2011). Complications such as toxicity, flammability, irritations of first-generation refrigerants led to the second generation, where chlorofluoro chemicals were used for their safety and durability. Despite their advantages compared to the earlier generation, second generation refrigerants had high GWP and ODP values, and the Montreal Protocol was implemented in 1987 to limit the use of chlorofluroro chemicals due to those environmental issues. Generation three introduced refrigerants with low ODP levels, and the Kyoto Protocol supports GHG reduction and prevents the use of high GWP refrigerants. The fourth generation of refrigerants allows only the use of refrigerants with very low or no ODP and low GWP. To minimize fluorinated greenhouse gas emissions (F-gases), the European Union has adopted the F-gas Regulation in 2015. New refrigerants and blends were introduced, but also natural refrigerants (HCs, CO_2, and ammonia) came back into the picture (see Figure 3).

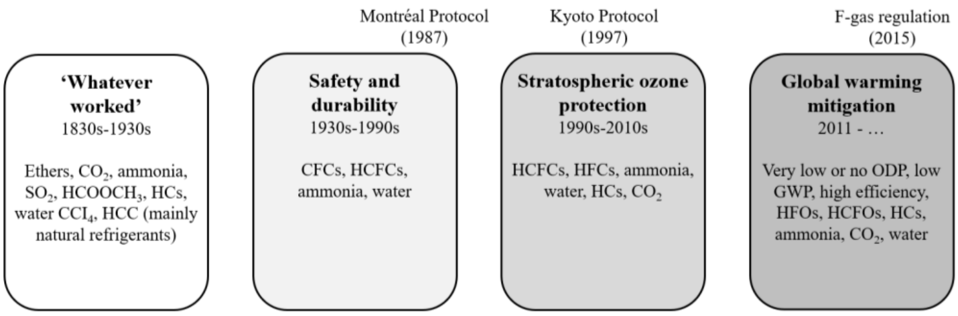

Figure 3: Development of four refrigerant generations over time (Calm & Hourahan, 2011).

3.3 Refrigerant types

Refrigerants can be classified according to their chemical composition. The first generations of refrigerants have an individual code starting with a letter 'R' and a 3-number code. From R000 to R399, the 3-number codes stand for '(number of C atoms-1)(number of H atoms -1)(number of F atoms)' (ASHRAE, 2019a). Newer generations refrigerants often have more complicated names. In the following section, the different refrigerants and their properties and criteria are discussed.

3.4.1 Hydrofluorocarbon (HFC), hydrochlorofluoro-carbon (HCFC), and chlorofluorocarbon (CFC)

Chlorofluorocarbons (CFCs) are compounds that contain only carbon, chlorine, and fluorine atoms. CFCs are banned since the beginning of the '90s because of the high chlorine content contributing to high ODP and GWP. *Hydrochlorofluorocarbons (HCFCs)* are similar to CFCs but contain hydrogen and have a lower ODP because they contain less chlorine than CFCs. HCFCs were temporarily substituting CFCs but are gradually being phased out since the implementation of the 1987 Montreal Protocol due to their high ODP and GWP (UNDP, 2019). Examples of HCFCs are R22, R123, and R124.

Hydrofluorocarbons (HFCs) contain hydrogen, fluorine, and carbon. HFCs were developed to replace CFCs and HCFCs since they contain no chlorine and are therefore not harmful to the ozone layer.

Nevertheless, their GWP is substantial, i.e., R134 has 1430 times stronger greenhouse gas effects than carbon dioxide, and the European Commission has formalized the limitation of HFC production and consumption (Mateu-Royo et al., 2018). Refrigerants, such as R245fa, which were suitable options due to their high critical temperature, are now being replaced because of their high GWP (values of 1030) (Kosmadakis, 2019). Currently, only HFCs with low GWP are considered for new applications. Intensified F-gas regulations have caused HFCs refrigerants to be phased out soon and boost the introduction of natural refrigerants (EC, n.a.; Arpagaus et al., 2018b). Nevertheless, many installed heat pumps are still running on HFC refrigerants.

3.4.2 Hydrofluoro-olefins (HFOs) and hydrochloro-fluoro-olefins (HCFOs)

Hydrofluoro-olefins (HFOs) contain hydrogen, fluorine, and carbons atoms and are distinguished from other fluorine-based refrigerants by having at least one double bond between carbon atoms. HFOs have zero ODP and very low GWP and are therefore suitable environmentally friendly refrigerants. However, they have flammability issues. *Hydrochlorofluoro-olefins (HCFOs)* are similar to HFOs but contain chlorine. HCFOs can obtain comparable results compared to HFOs and can reduce flammability (Calm & Hourahan, 2011). However, situation-specific tradeoffs must be made.

3.4.3 Hydrocarbons (HCs)

Hydrocarbons (HCs) have good thermodynamic properties and zero ODP and a negligible GWP. However, the main disadvantage is their flammability, and working with high temperatures and pressures makes this even more challenging (Bamigbetan et al., 2017). Nevertheless, the flammability issue could be managed with certain configurations. The maximum reachable temperature is depending on their critical temperature, which is different for every hydrocarbon. Nonetheless, by coupling hydrocarbons in a cascade or by implementing a mixture of hydrocarbons, the high temperature levels can be reached.

3.4.4 Ammonia

Ammonia (R717) has a GWP and OPA of zero and is the most commonly used refrigerant for large industrial systems, including heat recovery systems (Bamigbetan et al., 2017). Ammonia's critical temperature is higher than other refrigerants, and therefore, a higher COP can be achieved. Water temperature up until 90°C can be obtained, but for higher temperatures, condensation pressure of 60 bar is needed and such ammonia compressors are not commercially available (Bamigbetan et al., 2019). However, higher temperatures with lower pressures can be achieved with hybrid systems. Due to the high compressor discharge temperature of ammonia, the pressure increase in one step compression is restricted but two-stage compression with interstage cooling can be applied to solve this problem (Haukås & Pachai., 2014).

Ammonia is considered not flammable, but the toxicity of ammonia also prevents its direct use in applications where the leakage is considered high risk (although it can easily be smelled). Furthermore, ammonia has challenges in the type of materials used in the system as ammonia reacts with copper and zinc in the presence of water (Bamigbetan et al. 2017).

3.4.5 Water

Water (R718) is a suitable working fluid due to its high critical temperature of 373.9°C and pressure (22.06 MPa) (ASHRAE, 2019a). However, the boiling temperature at standard normal boiling point conditions (100°C) is high. This makes water an undesirable refrigerant because to lower the boiling point, it needs to be exposed to very low pressures which cannot be achieved by most compressors. Large or high-speed compressors will be required to transfer equivalent mass flow compared to what a smaller compressor would with refrigerants (Bantle et al., 2015). The sub-atmospheric operation and the high flow rate requirements of a heat pump with water vapor are the main challenges to the use of water in HT heat pumps (Bamigbetan et al., 2017).

Furthermore, not all types of compressors and materials can deal with the high compressor discharge temperature of water for a certain pressure lift (Bamigbetan et al., 2017). Analysis of configurations other than simple heat pumps is needed, such as in the study of Sarevski and Sarevski (2017). According to Frate et al. (2019), multiple stages and cycle modifications are necessary to reduce the compressor's work. However, besides its thermodynamic properties water is environmentally friendly and scores well on safety criteria.

3.4.6 Carbon dioxide

Carbon dioxide (R744) is attractive as a refrigerant because it is non-flammable, it does not contribute to ozone depletion, and its toxicity level is very low. Temperatures above 80°C up to 120°C is reachable in a trans-critical CO_2 cycle. However, to keep the system in trans-critical mode, the evaporating temperature needs to be below 31°C regardless of the temperature of the heat pump (Bamigbetan et al., 2017). This critical temperature and the high compressor discharge pressure could result in a pressure differential of more than 100 bar between both sides of the cycle. Therefore, heat pump components are required to be improved.

A possible configuration for heat pump applications with CO_2 as refrigerant would be to use a cascade cycle in which CO_2 operates as low temperature refrigerants combined with another suitable refrigerant for the higher temperature operation (Bamigbetan et al., 2018). For instance, combinations of ammonia and CO_2 are used in cascade systems (Haukås & Pachai., 2014).

Blends of different refrigerants can help to meet a suitable combination of properties that is necessary and enable minimization of substances that are ozone-depleting or contribute to global warming. Most of the newer blends are comprised of HFCs or HFCs mixed with HCs (Calm & Hourahan, 2011).

3.4 Classifications

Despite the ongoing development of new refrigerants, approximately 30 refrigerants from generation 1 to 4 make up a list of mostly recurring refrigerants that are still used and/or have been used in the past (Calm & Hourahan, 2011; Bamigbetan et al., 2018). These refrigerants and their classifications can be found in Table 1.

In Table 2, the refrigerants from Table 1 are classified in terms of their safety groups based on flammability and toxicity. Assigning values to safety and environmental criteria makes refrigerant selections easier, although the refrigerant choice is depending on technical constraints and selection priorities that are set. Frate et al. (2019) observe that some authors are concerned by the environmental issues and only will select refrigerants with a low GWP. Safety is indeed often of high concern but it is imaginable that safety weights higher in some applications and areas more than in others.

Name		**ASHRAE number**	**ODP**	**GWP**	**Safety group**	**Critical temp. (°C)**	**Critical pressure (MPa)**
CFC		R113	0.850	6130	A1	214.1	3.39
		R114	0.580	10000	A1	145.7	3.26
HCFC		R123	0.010	77	B1	183.7	3.66
		R21	0.040	151	B1	178.3	5.18
		R142b	0.060	2310	A2L	137.1	4.06
HFC		R245ca	0.000	693	n.a.	174.4	3.93
		R245fa	0.000	1030	B1	154.0	3.65
		R365mfc	0.000	794	A2	186.9	3.27
		R152a	0.000	124	A2	113.3	4.52
		R227ea	0.000	3220	A1	101.8	2.93
		R134a	0.000	1430	A1	101.1	4.06
		R410A	0.000	2100	A1	71.4	4.90
HFO		R1234yf	0.000	<4.4	A2L	94.7	3.38
		R1234ze(E)	0.000	6	A2L	109.4	3.64
		R1234ze(Z)	0.000	<1	A2L	153.6	3.97
		R1336mzz(Z)	0.000	2	A1	171.3	2.90
HCFO		R1224yd(Z)	0.000	<1	A1	155.5	3.33
		R1233zd(E)	0.000	1	A1	166.5	3.62
Hydrocarbons (HC)	Propane	R290	0.000	3.3	A3	96.7	4.25
	Butane	R600	0.000	4.0	A3	152.0	3.80
	Isobutane	R600a	0.000	3.0	A3	134.7	3.63
	Pentane	R601	0.000	4.0	A3	196.6	3.37
	Isopentane	R601a	0.000	4.0	A3	187.2	3.38
Ammonia		R717	0.000	0.0	B2L	132.3	11.33
Water/Steam		R718	0.000	0.2	A1	373.9	22.06
Carbon dioxide		R744	0.000	1.0	A1	31.0	7.38

Table 1: Classifications of common refrigerants (ASHRAE, 2019a; Calm & Hourahan, 2011)

Flammability level	Higher flammability (3)	R290, R600, R600a, R601, R601a	
	Flammable (2)	R365mfc, R152a,	
	Lower flammability (2L)	R142b, R1234yf, R1234ze(E), R1234ze(Z)	R717
	No flame propagation (1)	R113, R114, R227ea, R134a, R410A, R1136mzz(Z), R1224yd(Z), R1233zd(E), R718, R744	R123, R21, R245fa
		Lower toxicity (A)	Higher toxicity (B)
		Toxicity level	

Table 2: Safety group classification of refrigerants (based on ASHRAE 2019b)

4. Heat pump selection – case study

A step-wise approach is taken for selecting a suitable heat pump and refrigerant for an MT and HT data center waste heat integration case in Amsterdam. A set of boundaries (constraints) in terms of temperature ranges for the application can be defined, after which a refrigerant selection can be made based on those constraints and other criteria.

4.1 Temperature regimes

In Hattink (2020) a pilot project called 'Kantorenstrook Amstel III' is modeled. This area will be integrated into the secondary supply network of Amsterdam, connected to the newly developed area. The supply temperature in this network is 75°C (in the MT regime), and the heat released from the data center going into the heat pump is 27°C. According to the COP formula, the ideal COP would be:

$COP_{ideal} = (75+273,15)/(75-27) = 7,25$

This would result in an actual COP of 4,0 with 55 percent efficiency. Figure 4 shows the heat pump cycle with temperatures.

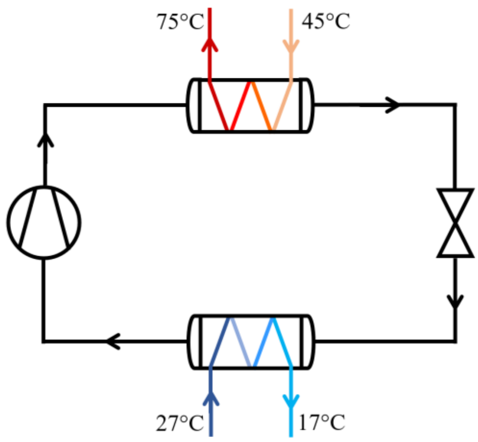

Figure 4: Heat pump cycle for the Kantorenstrook Amstel III case.

Current heat pump technologies can operate with such temperature lifts, and a single-stage cycle is considered to be suitable for MT applications.

In the Kantorenstrook Amstel III, data center waste heat area would be integrated directly into the area in development. However, integration on a larger scale to meet growth and CO_2 targets could also be applied in Amsterdam. In the area of Westpoort, data center waste heat could potentially be fed into the primary (transport) supply line. This means that integration is happening in the HT regime. The supply temperature of the grid is approximately 90°C in summer and 115°C in winter. Feeding low temperature heat into this line requires the use of more advanced heat pump technologies that can work with such high temperature lifts.

4.2 Select refrigerant

The next step would be to pre-select the right and suitable refrigerants. Refrigerants operate in specific temperature ranges in which they perform best. Some refrigerants are more suitable for the MT regime, and some can work with higher temperature lifts and would be suitable in the HT regime. Regardless of the components and configurations of heat pump applications, each refrigerant has limitations based on thermodynamic properties (e.g., temperature ranges), environmental criteria, and safety criteria (Bamigbetan et al., 2018). Those limitations help to determine which refrigerants can be eliminated systematically.

Due to environmental regulations and objectives, it is necessary to take into account only refrigerants with low ODP and low GWP. Subsequently, most CFCs, HCFCs, and HFCs are excluded as potential refrigerants for heat pump applications for the future due to their phase-out (Bamigbetan et al., 2019). Three HFCs (R245fa, R265mfc, and R134a) are not excluded since various studies are still focusing on finding alternatives (section 3.6). Furthermore, different current installed heat pumps in Amsterdam are still making use of R134a. However, using HFCs introduces phase-out risks and is therefore not recommended to be implemented in new applications.

Besides environmental criteria, thermodynamic criteria must also be examined. In terms of thermodynamics, low critical temperatures can limit the applicability of heat pumps, especially in the HT regimes where high temperature lifts are required. Propane (with a critical temperature of 96.7°C) might is suitable for MT applications, although a higher critical temperature is preferred for HT applications. Carbon dioxide (R744) has a very low critical temperature of 31°C but is commonly operating in a trans-critical cycle, making the temperature constraint invalid.

Regarding safety criteria, a selection is more challenging to make. All hydrocarbon in Table 1 have high flammability values, and ammonia has a high toxicity level. Safety risks need to be taken in concern, but, as Frate et al. (2019) state, it is possible to restrain risks as long as those refrigerants are used in the right situation (e.g., ammonia is commonly used in industrial application away from urban areas). Heat pumps in Amsterdam will be installed in urban areas, and therefore, safety risks should be avoided at any time.

Name		ASHRAE number	ODP	GWP	Safety group	Critical temp. (°C)	Critical pressure (MPa)
HFC		R245fa	0.000	1030	B1	154.0	3.65
		R365mfc	0.000	794	A2	186.9	3.27
		R134a	0.000	1430	A1	101.1	4.06
HFO		R1234yf	0.000	<4.4	A2L	94.7	3.38
		R1234ze(E)	0.000	6	A2L	109.4	3.64
		R1234ze(Z)	0.000	<1	A2L	153.6	3.97
		R1336mzz(Z)	0.000	2	A1	171.3	2.90
HCFO		R1224yd(Z)	0.000	<1	A1	155.5	3.33
		R1233zd(E)	0.000	1	A1	166.5	3.62
Hydrocarbons (HC)	Propane	R290	0.000	3.3	A3	96.7	4.25
	Butane	R600	0.000	4.0	A3	152.0	3.80
	Isobutane	R600-a	0.000	3.0	A3	134.7	3.63
	Pentane	R601	0.000	4.0	A3	196.6	3.37
	Isopentane	R601a	0.000	4.0	A3	187.2	3.38
Ammonia		R717	0.000	0.0	B2L	132.3	11.33
Water/Steam		R718	0.000	0.2	A1	373.9	22.06
Carbon dioxide		R744	0.000	1.0	A1	31.0	7.38

Table 3: Pre-selection of suitable refrigerants for (future) applications (based on Table 1)

Table 3 is a pre-selection of suitable refrigerants (based on Table 1, section 3.5). All CFCs and HCFCs are eliminated and marked in orange are other refrigerant limitations, making them unsuitable for heat pumps in the (urban) city of Amsterdam.

Despite the refrigerant that will be chosen, cycle configurations such as IHX, economizers, and multiple stages are often necessary to enhance suitability and improve (COP) performance. The MT heat pump for Kantorenstrook Amstel III with a temperature lift of 27°C to 75°C might work with a simple configuration of a single-stage heat pump. In contrast, the HT application will probably require multi-stages or cascade system to upgrade waste heat to 90°C or even 115°C in the coldest months.

4.3 Testing applications

Kosmadakis (2019) points out that when studying the applicability for heat pumps, the case-specificness is determining the potential and the constraints of the integration. For experimental designs, evaluation of suitable heat pump applications can be based on a set of technical constraints or by fixing the temperature regime and testing the different refrigerants based on those assumptions. For instance, Frate et al. (2019) have set the critical temperature on a value of 125°C or higher to connect heat pumps to the HT network. Other constraints could include material compatibility, e.g., ammonia is not compatible with copper (Frate et al., 2019).

When testing the design of the MT and HT case in Amsterdam, the required temperature lifts are known because the temperature ranges are set and will be stable. The next step would be to test the pre-selected refrigerants based on desired outcomes, such as reaching a specific heat pump efficiency. The most suitable heat pump configuration and refrigerant can then be found.

4.4 Tradeoffs

Heat pump applications must satisfy several technical properties and environmental and safety criteria. However, since no application scores best on all requirements, tradeoffs must be made.

Studies show that for selecting suitable heat pumps, a tradeoff needs to be made between the COP and Volumetric Heat Capacity (VHC) (Arpagaus et al., 2018a). VHC is calculated as the ratio between the size of the compressor (the displacement volume) and the heat output of the heat pump. A substantial portion of the investment in a heat pump is related to the price of the compressors, and therefore, a high VHC results in low investment costs (Jensen et al., 2015; Brunin et al., 1997). On the other hand, a high COP would reduce operating costs. Making tradeoffs between the VHC and COP is, therefore, an economic consideration in essence. As Frate et al., (2019) observe, the tradeoffs are between the reduction of capital costs (compressor's investment costs) for an application with a higher VHC versus a higher COP, which could create more revenues over the full lifetime of the heat pump application.

Data centers are reliable heat sources since it is a continuing business with a fixed location. A well-determined decision for selecting a heat pump application is critical since upfront costs are high, and its lifetime could be considerable.

5. Discussion

A few critical points of discussion:

Selection suitable heat pump applications for a specific case is a highly complex approach, and a high level of expertise is needed in order not to oversee important details.

As mentioned before, setting criteria and boundaries when choosing a refrigerant makes the selection process easier. However, making comparisons based on temperature regime or environmental/safety criteria can lead to the neglect of some refrigerants that would have been suitable and might perform well on other criteria (Frate et al., 2019).

Due to the case-specificness of heat pump applications, testing the design is a required step in the decision-making process. Although there are software tools for testing designs by inserting the input parameters, there is a lack of experimental and demonstration plants to test applications in offline environments.

Research & development and increasing the technology readiness level of heat pumps is of high importance. Especially in the new field of heat pumps for HT integration projects in large-scale industries.

6. Conclusion

Besides heat pumps for the MT network, also heat applications for HT regimes have gained attention as suitable technologies for upgrading low temperature waste heat to high temperature heat. However, the challenge for HT but also MT heat pump applications lies in the capability of operating with high temperature ranges and lift and, at the same time, good performances.

First of all, to select a suitable heat pump for waste heat integration in the district heating network the temperature ranges in which the heat pump will operate must be determined. In the MT regime, often single-stage heat pumps are applied, whereas the HT heat pumps will often require multi-stages or cascade systems. Despite the temperature regime, certain cycle configurations can further increase heat pump performances.

Next, selecting suitable refrigerants is important. A pre-selection of suitable refrigerants is made based on criteria. Selection depends on their thermodynamic, environmental, and safety requirements and is therefore very case-specific. Often, tradeoffs must be made to determine the most optimal solution.

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