EUROPEAN HEAT PUMP SUMMIT

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CONGRESS + EXPO
NUREMBERG, 24–25.10.2017

Industrial | Commercial | Residential
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NÜRNBERG MESSE

Review on High Temperature Heat Pumps

Market Overview and Research Status

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IES
INSTITUTE FOR ENERGY SYSTEMS

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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Outline

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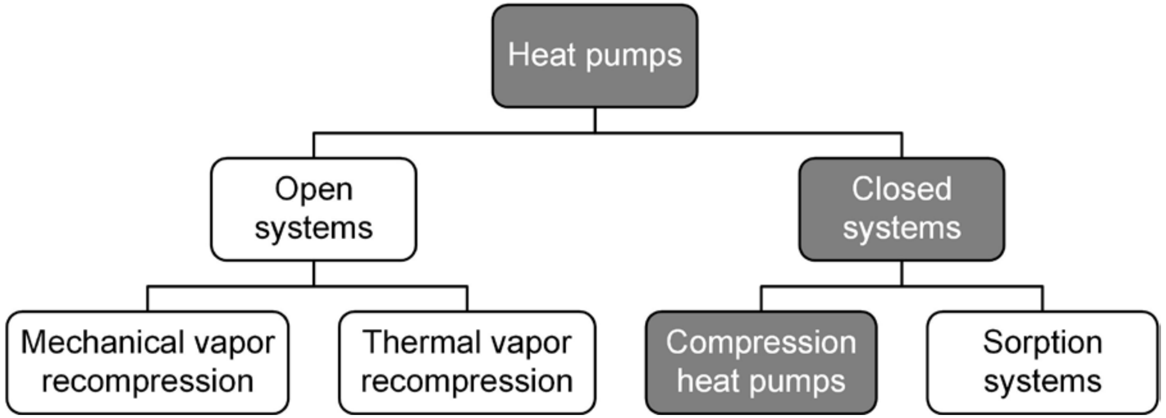
1. **Market overview of commercially available industrial HTHP systems**
    - Cycles, refrigerants, application limits, efficiencies
2. **Research status**
    - Screening of research activity
    - Experimental and theoretical studies, cycles, refrigerants, supply temperatures, operating ranges
3. **Refrigerants**
    - Selection criteria, properties, GWP, price, efficiency, safety
4. **Conclusions**

Classification of heat pumps (focus on compression heat pumps)

Development of temperature levels



Heat pumps

Open systems

Closed systems

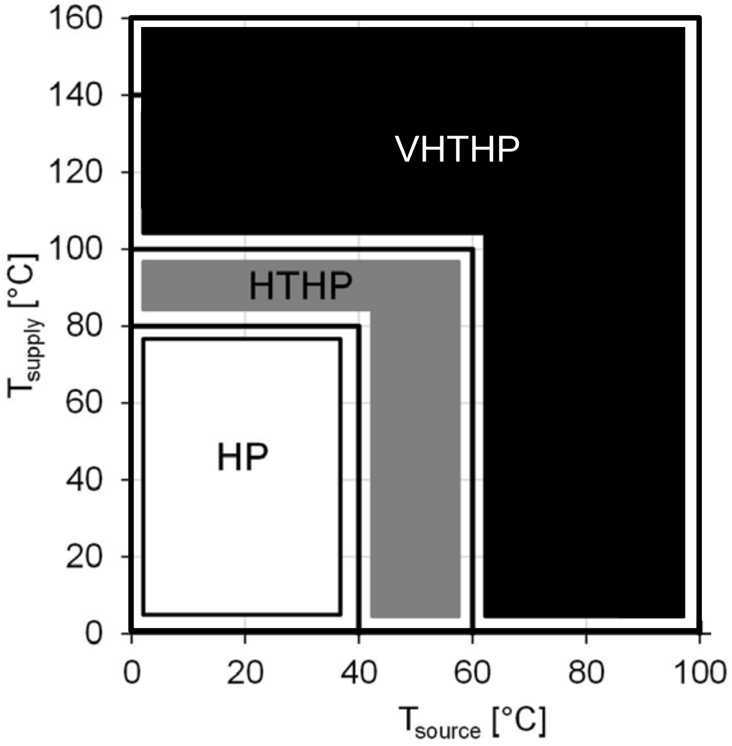
Mechanical vapor recompression

Thermal vapor recompression

Compression heat pumps

Sorption systems

adapted from Nellissen and Wolf (2015)



VHTHP: very high temperature heat pump
HTHP: high temperature heat pump
HP: conventional heat pump

adapted from
Bobelin et al. (2012), IEA (2014), Jakobs and Laue (2015), Peureux et al. (2012, 2014)

Potential for high temperture heat pumps

Process heat in industry

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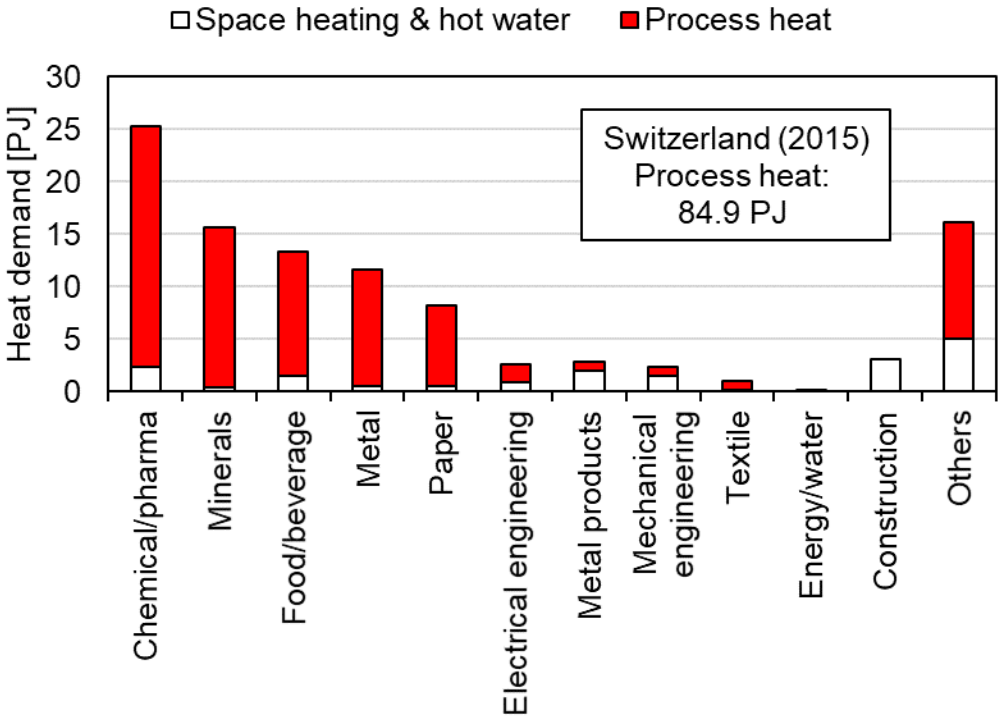
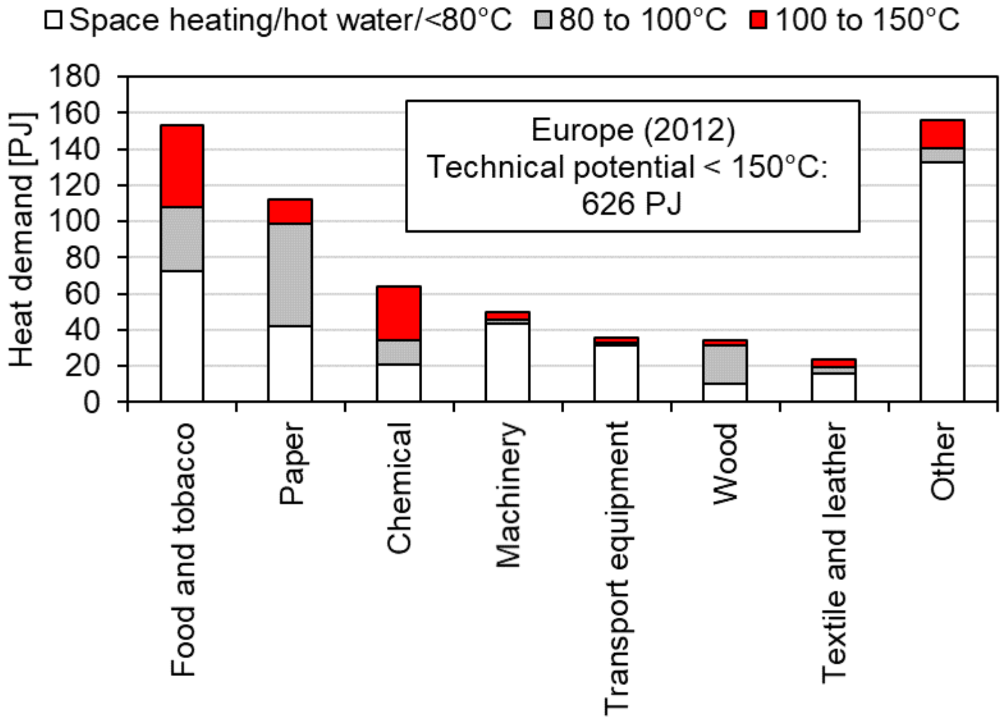
Theoretical potential for HTHPs in Switzerland



Data from BFE (2016), Pulfer and Spirig (2015)

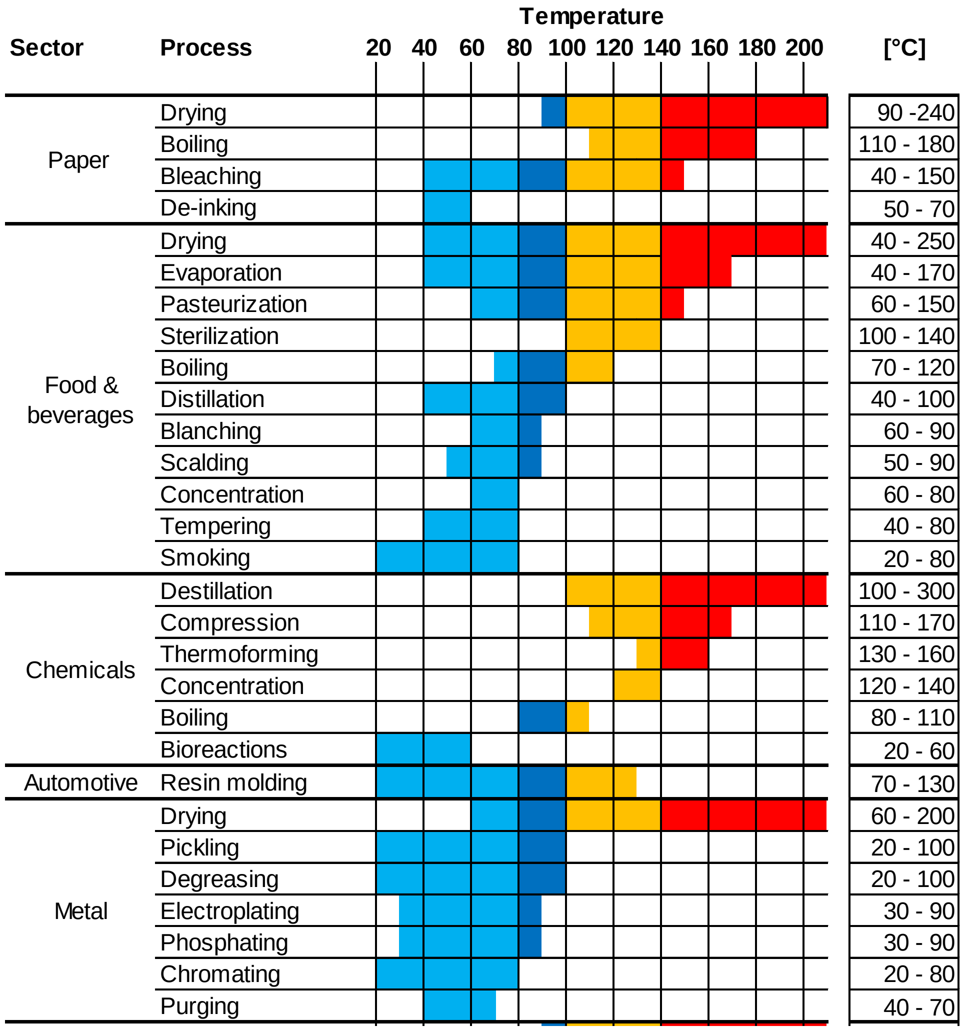
Technical potential of process heat in Europe accessible with industrial heat pumps



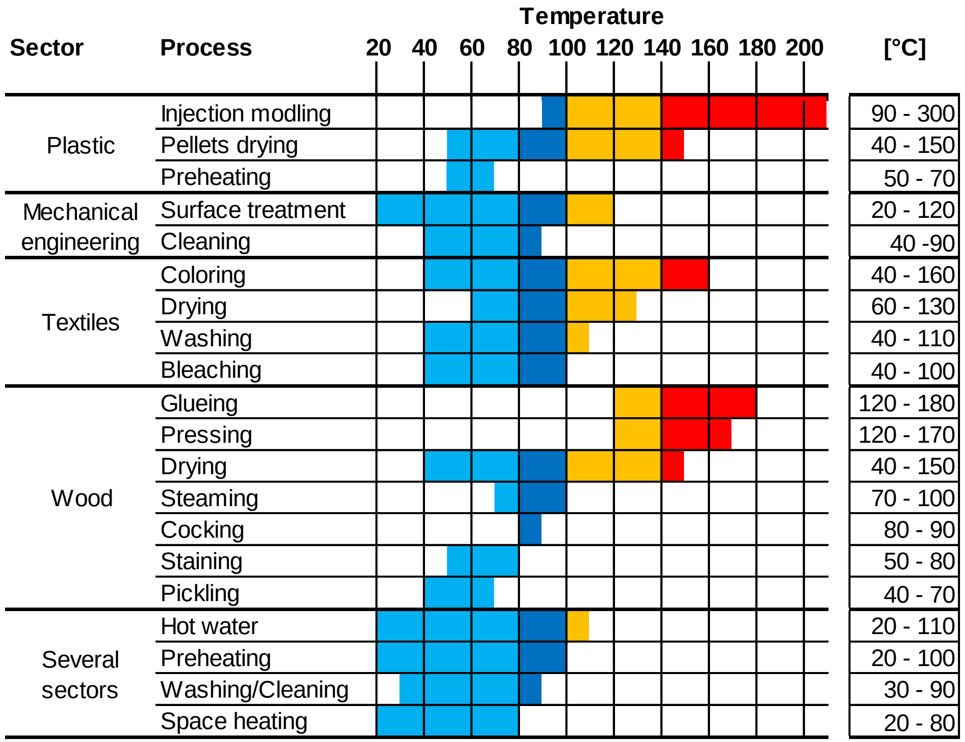
Based on Eurostat data from 2012 of 33 countries, Nellissen and Wolf (2015)

Overview of processes in different industrial sectors

Temperature levels and technology readiness level



Sector	Process	[°C]
Paper	Drying	90 -240
	Boiling	110 - 180
	Bleaching	40 - 150
	De-inking	50 - 70
Food & beverages	Drying	40 - 250
	Evaporation	40 - 170
	Pasteurization	60 - 150
	Sterilization	100 - 140
	Boiling	70 - 120
	Distillation	40 - 100
	Blanching	60 - 90
	Scalding	50 - 90
	Concentration	60 - 80
	Tempering	40 - 80
	Smoking	20 - 80
Chemicals	Destillation	100 - 300
	Compression	110 - 170
	Thermoforming	130 - 160
	Concentration	120 - 140
	Boiling	80 - 110
	Bioreactions	20 - 60
Automotive	Resin molding	70 - 130
Metal	Drying	60 - 200
	Pickling	20 - 100
	Degreasing	20 - 100
	Electroplating	30 - 90
	Phosphating	30 - 90
	Chromating	20 - 80
	Purging	40 - 70



Sector	Process	[°C]
Plastic	Injection modling	90 - 300
	Pellets drying	40 - 150
	Preheating	50 - 70
Mechanical engineering	Surface treatment	20 - 120
	Cleaning	40 -90
Textiles	Coloring	40 - 160
	Drying	60 - 130
	Washing	40 - 110
	Bleaching	40 - 100
Wood	Glueing	120 - 180
	Pressing	120 - 170
	Drying	40 - 150
	Steaming	70 - 100
	Cocking	80 - 90
	Staining	50 - 80
	Pickling	40 - 70
Several sectors	Hot water	20 - 110
	Preheating	20 - 100
	Washing/Cleaning	30 - 90
	Space heating	20 - 80

Technology Readiness Level (TRL):

⬜ conventional HP < 80°C, established in industry
🟦 commercial available HP 80 - 100°C, key technology
🟨 prototype status, technology development, HTHP 100 - 140°C
🟥 laboratory research, functional models, proof of concept, VHTHP > 140°C

Data sources: *Brunner et al. (2007), Hartl et al. (2015), IEA (2014), Kalogirou (2003), Lambauer et al. (2012), Lauterbach et al. (2012), Noack (2016), Ochsner (2015), Rieberer et al. (2015), Watanabe (2013), Weiss (2007, 2005), Wolf et al. (2014)*

Selection of industrial HTHPs with supply temperatures > 90°C

Manufacturer	Product	Refrigerant	Max. supply temperature	Heating capacity	Compressor type	Reference
Kobe Steel (Kobelco Steam Grow Heat Pump)	SGH 165 SGH 120 HEM-HR90,-90A	R134a/R245fa R245fa R134a/R245fa	165°C 120°C 90°C	70 – 660 kW 70 – 370 kW 70 – 230 kW	Double screw	(IEA, 2014a; Kaida et al., 2015; Kuromaki, 2012; Watanabe, 2013)
Vicking Heating Engines AS	HeatBooster S4	R1336mzz(Z) R245fa	150°C	28 – 188 kW	Piston	(Nilsson, 2017; Nilsson et al., 2017; Viking Heat Engines AS, 2017)
Ochsner	IWWDSS R2R3b IWWDS ER3b IWWHS ER3b	R134a/ÖKO1 ÖKO (R245fa) ÖKO (R245fa)	130°C 130°C 95°C	170 – 750 kW 170 – 750 kW 60 – 850 kW	Screw (twin unit 1.5 MW)	(Ochsner, 2017a, 2017b, 2015; Zauner, 2016)
Hybrid Energy	Hybrid Heat Pump	R717 (NH_3)	120°C	0.25 – 2.5 MW	Piston	(Hybrid Energy SA, 2017; Jensen et al., 2015a, 2015b)
Mayekawa	Eco Sirocco Eco Cute Unimo	R744 (CO_2) R744 (CO_2)	120°C 90°C	65 – 90 kW 45 – 110 kW	Screw	(IEA, 2014a; Mayekawa, 2010; Watanabe, 2013)
Dürr Thermea	thermeco$_2$	R744 (CO_2)	110°C	45 – 2‘200 kW	Piston (up to 8 in parallel)	(Dürr thermea GmbH, 2017; IEA, 2014a; Thermea, 2012)
Combitherm	Customized design	R245fa	100°C	20 – 300 kW	Piston	(Blesl et al., 2014; Wolf et al., 2014)
Friotherm	Unitop 22 Unitop 50	R1234ze(E) R134a	95°C 90°C	0.6 – 3.6 MW 9 – 20 MW	Turbo (two-stage)	(Friotherm AG, 2005; Wojtan, 2016)
Star Refrigeration	Neatpump	R717 (NH_3)	90°C	0.35 – 15 MW	Screw (Vilter VSSH 76 bar)	(EMERSON, 2012)
GEA Refrigeration	GEA Grasso FX P 63 bar	R717 (NH_3)	90°C	2 – 4.5 MW	Double screw (63 bar)	(Dietrich and Fredrich, 2012)
Johnson Controls	HeatPAC HPX HeatPAC Screw Titan OM	R717 (NH_3) R717 (NH_3) R134a	90°C 90°C 90°C	326 – 1‘324 kW 230 – 1‘315 kW 5 – 20 MW	Piston (60 bar) Screw Turbo	(Johnson Controls, 2017)
Mitsubishi	ETW-L	R134a	90°C	340 – 600 kW	Turbo (two-stage)	(IEA, 2014a; Watanabe, 2013)
Viessmann	Vitocal 350-HT Pro	R1234ze(E)	90°C	148 – 390 kW	Piston (2-3 in parallel)	(Viessmann, 2016)

Commercially available industrial HTHPs sorted by maximum supply temperature and heating capacity

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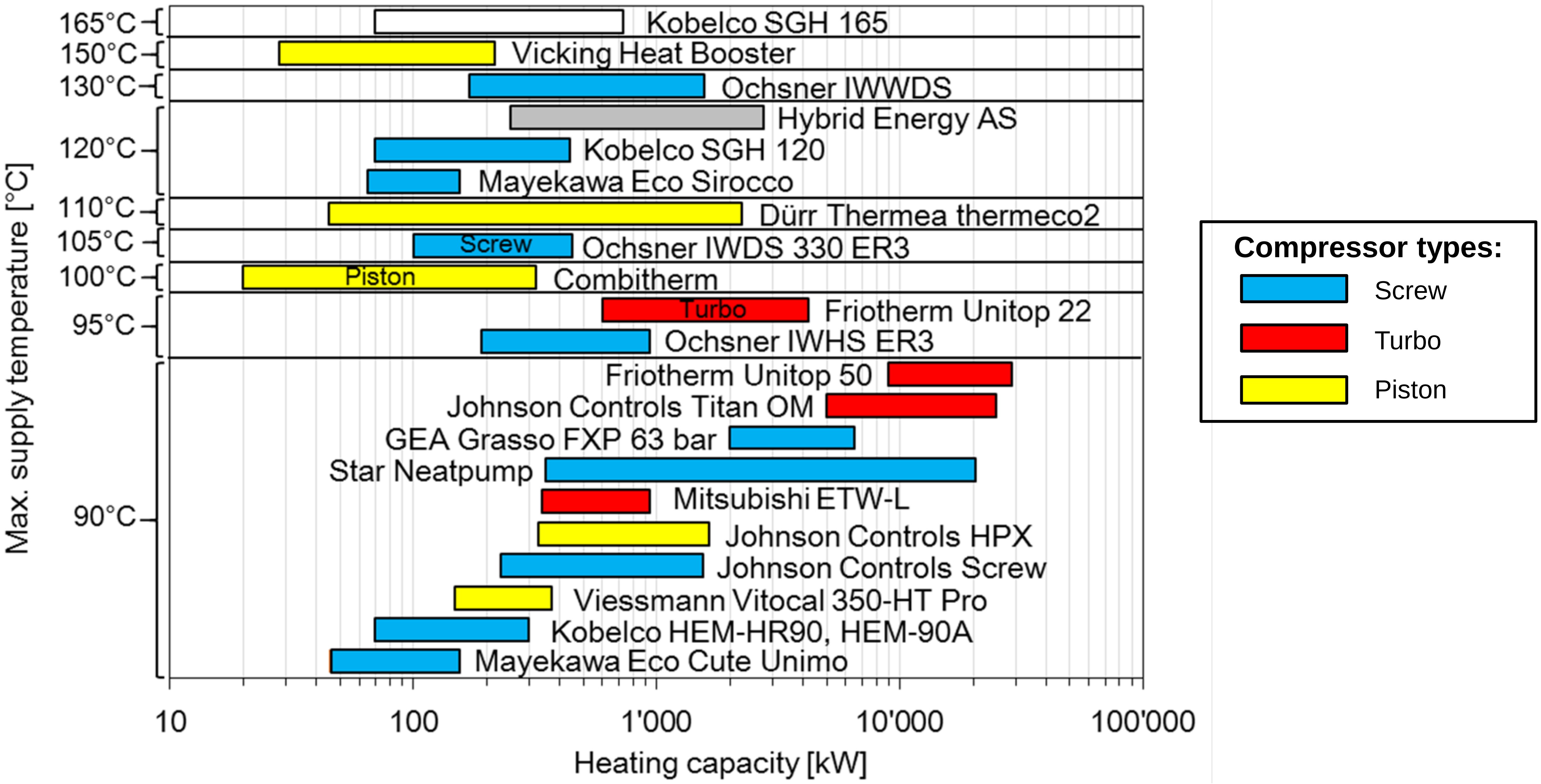
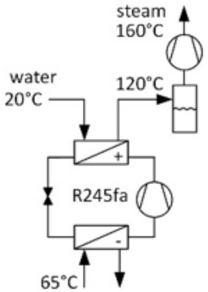


Commercial HTHPs – cycles, COPs and pictures

Kobelco SGH 120 / 165

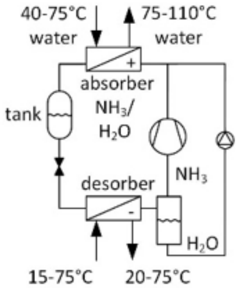
(IEA, 2014a; Kaida et al., 2015; Kuromaki, 2012; Watanabe, 2013)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
65/120 (55)	3.5

Hybrid Heat Pump

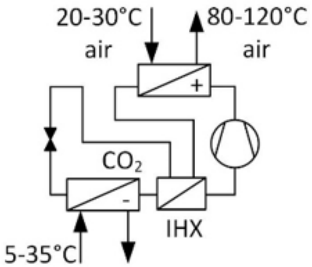
(Jensen et al., 2015a, 2015b)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
20/95 (75)	2.4
40/100 (60)	4.5

Mayekawa transkritische CO_2 heat pump Eco Sirocco

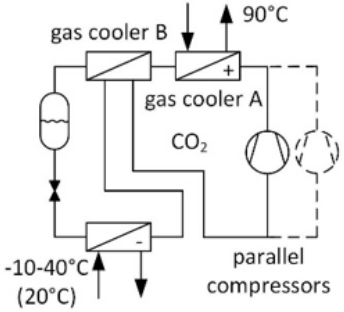
(IEA, 2014a; Mayekawa, 2010; Watanabe, 2013)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
20/100 Luft (80)	3.4
25/120 H_2O (95)	2.9

Thermeco2 HHR1000 with 6 piston compressors, up to 1100 kW

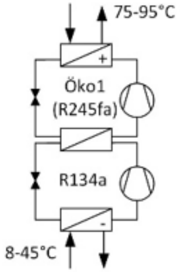
(Dürr thermea GmbH, 2016; IEA, 2014a; Thermea, 2012)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
20/80 (60)	3.9-4.3

Ochsner IWHS 400 ER3 screw compressor, 380 kW

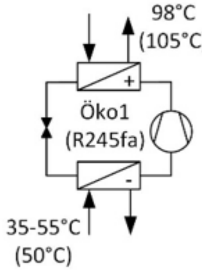
(Ochsner, 2015)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
45/90 (45)	4.0

Ochsner IWDS 330 ER3 screw compressor, 312 kW

(Zauner, 2016)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
50/105 (55)	2.68

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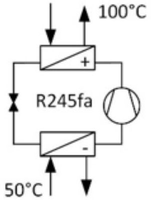
Commercial HTHPs – cycles, COPs and pictures

Combitherm

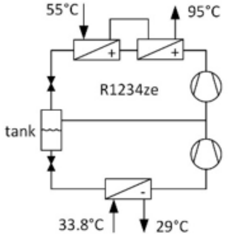
(Blesl et al., 2014; Wolf et al., 2014)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
50/100 (50)	3.1-3.4

Friotherm Unitop 22/22
3'300 kW, 2-stage turbo

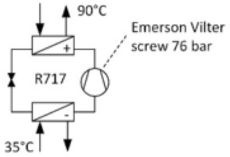
(Friotherm AG, 2005; Wojtan, 2016)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
34/95 (61)	3.51

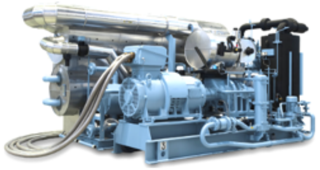
Star Refrigeration Neatpump NP601
380 kW to 2.6 MW, Vilter VSSH screw 76 bar

(EMERSON, 2012)

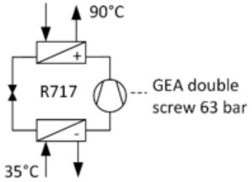


T_{LT}/T_{HT} (ΔT_{Lift})	COP
50/90 (40)	3-4
35/80 (45)	5
39/90 (51)	4

GEA Grasso FX P
Heat Pump
Double screw 63 bar



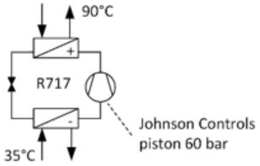
(Dietrich and Fredrich, 2012)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
35/80 (45)	5.0

Johnson Controls SABROE HeatPAC™-HPX
piston compressor 60 bar

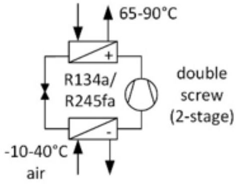
(Johnson Controls, 2017)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
39/90 (51)	4.0

Kobelco HEM-HR90
double screw (2-stage)

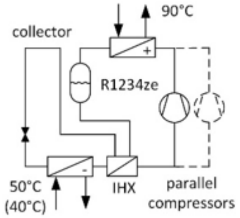
(Kuromaki, 2012; Oue and Okada, 2013)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
17/90 (73)	4.5
35/90 (55)	5.8

Viessmann
Vitocal 350-HT Pro

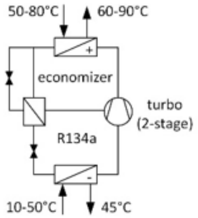
(Viessmann, 2016)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
50/90 (40)	3.4

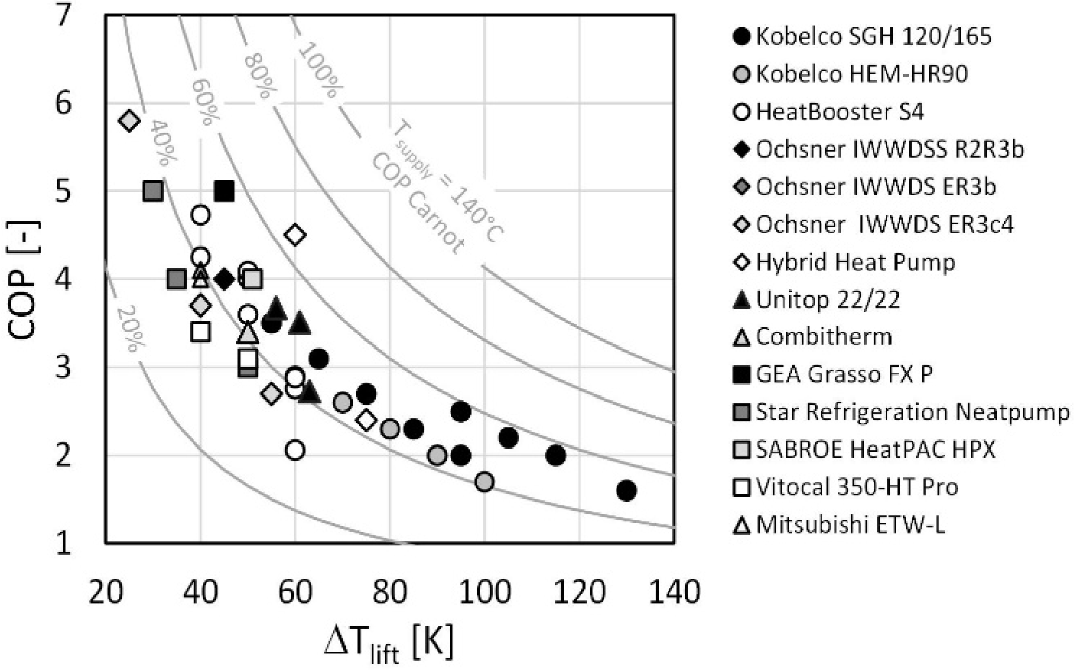
Mitsubishi ETW-L

(IEA, 2014a; Watanabe, 2013).



T_{LT}/T_{HT} (ΔT_{Lift})	COP
50/90 (40)	4.1

COP vs. temperature lift for various commercial HTHPs



- Average values: COP = 3.2 ± 0.9
  ΔT_{Lift} = 66 ± 24 K
- Most data points between 40 to 60% Carnot efficiency (at 140°C supply temperature)

Research status on HTHPs

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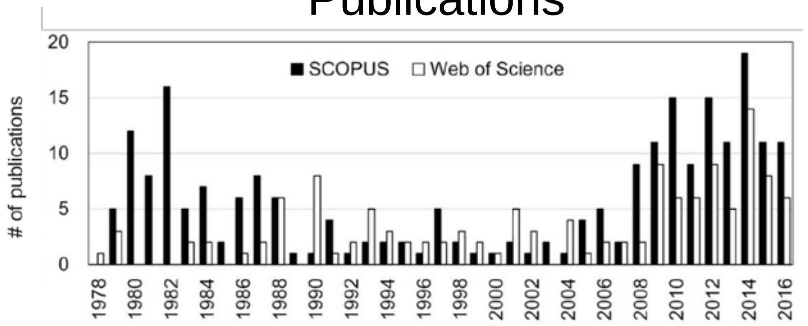
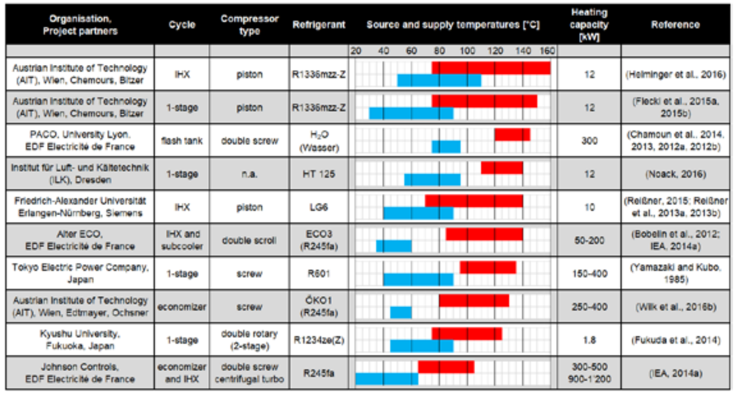
Publications



Research projects



Organisation, Project partners	Cycle	Compressor type	Refrigerant	Source and supply temperatures [°C]	Heating capacity [kW]	Reference
				20 40 60 80 100 120 140 160		
Austrian Institute of Technology (AIT), Wien, Chemours, Bitzer	IHX	piston	R1336mzz-Z		12	(Helminger et al., 2016)
Austrian Institute of Technology (AIT), Wien, Chemours, Bitzer	1-stage	piston	R1336mzz-Z		12	(Fleckl et al., 2015a, 2015b)
PACO, University Lyon, EDF Electricité de France	flash tank	double screw	H_2O (Wasser)		300	(Chamoun et al., 2014, 2013, 2012a, 2012b)
Institut für Luft- und Kältetechnik (ILK), Dresden	1-stage	n.a.	HT 125		12	(Noack, 2016)
Friedrich-Alexander Universität Erlangen-Nürnberg, Siemens	IHX	piston	LG6		10	(Reißner, 2015; Reißner et al., 2013a, 2013b)
Alter ECO, EDF Electricité de France	IHX and subcooler	double scroll	ECO3 (R245fa)		50-200	(Bobelin et al., 2012; IEA, 2014a)
Tokyo Electric Power Company, Japan	1-stage	screw	R601		150-400	(Yamazaki and Kubo, 1985)
Austrian Institute of Technology (AIT), Wien, Edtmayer, Ochsner	economizer	screw	ÖKO1 (R245fa)		250-400	(Wilk et al., 2016b)
Kyushu University, Fukuoka, Japan	1-stage	double rotary (2-stage)	R1234ze(Z)		1.8	(Fukuda et al., 2014)
Johnson Controls, EDF Electricité de France	economizer and IHX	double screw centrifugal turbo	R245fa		300-500 900-1'200	(IEA, 2014a)

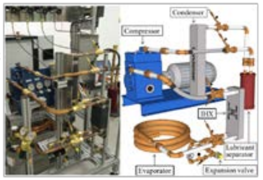
Which laboratory setups already exist?

Experimental setups

160°C

Helminger (2016), Fleckl (2015) AIT, Vienna
IHX, piston
(Bitzer 2CES),
R1336mz(Z)

140°C

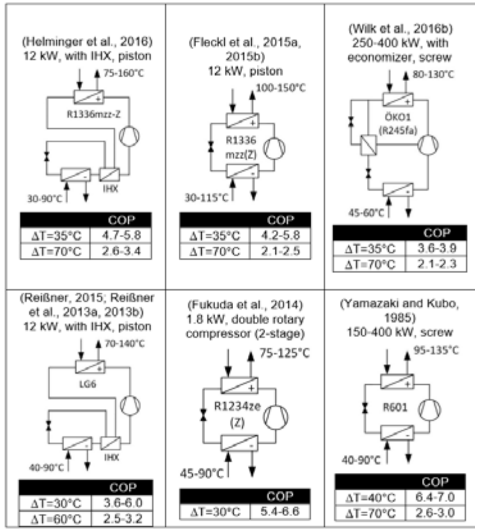


Reißner (2015, 2013), Erlangen
IHX, piston (GEA Bock E3), LG6

140°C

Noack (2016), ILK, Dresden
1-stage, HT 125

Cycles



(Helminger et al., 2016)
12 kW, with IHX, piston

	COP
ΔT=35°C	4.7-5.8
ΔT=70°C	2.6-3.4

(Fleckl et al., 2015a, 2015b)
12 kW, piston

	COP
ΔT=35°C	4.2-5.8
ΔT=70°C	2.1-2.5

(Wilk et al., 2016b)
250-400 kW, with economizer, screw

	COP
ΔT=35°C	3.6-3.9
ΔT=70°C	2.1-2.3

(Reißner, 2015; Reißner et al., 2013a, 2013b)
12 kW, with IHX, piston

	COP
ΔT=30°C	3.6-6.0
ΔT=60°C	2.5-3.2

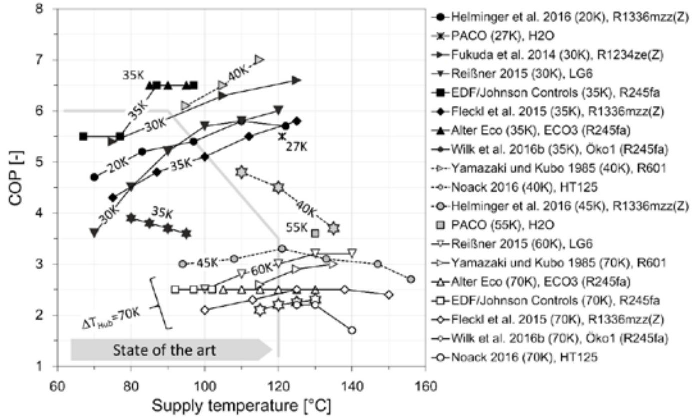
(Fukuda et al., 2014)
1.8 kW, double rotary compressor (2-stage)

	COP
ΔT=30°C	5.4-6.6

(Yamazaki and Kubo, 1985)
150-400 kW, screw

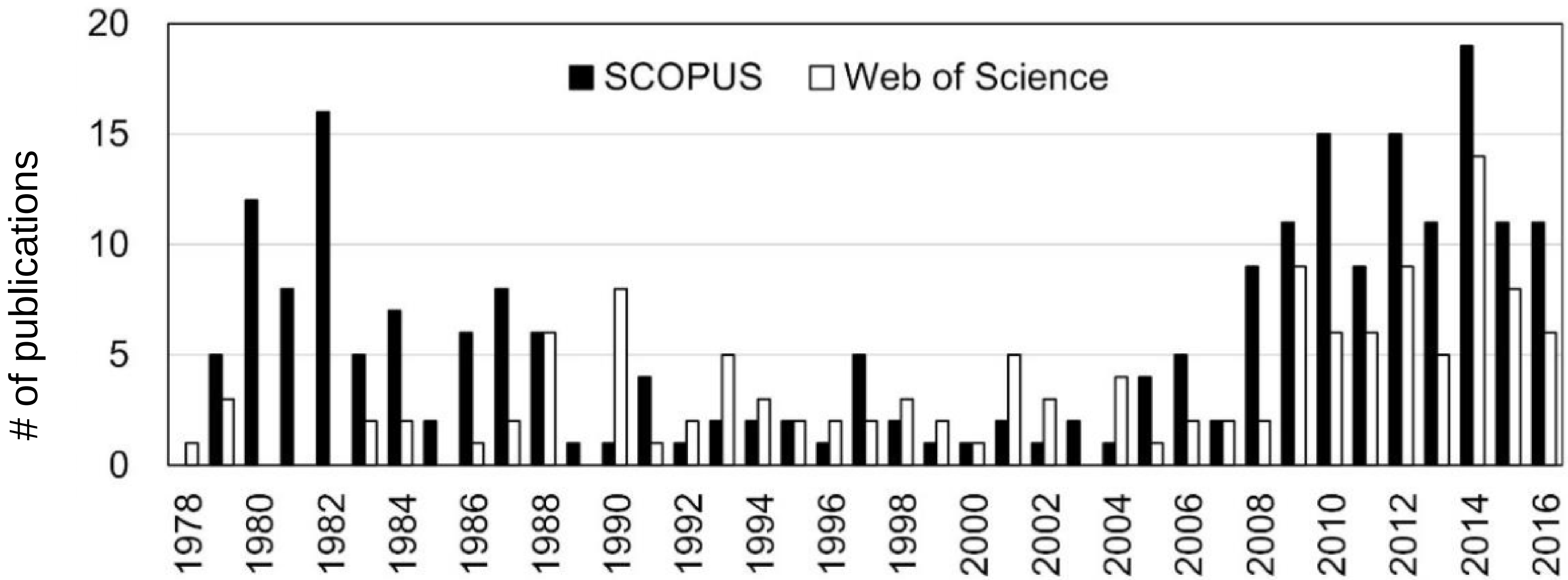
	COP
ΔT=40°C	6.4-7.0
ΔT=70°C	2.6-3.0

COP vs. supply temperature



Research activity on HTHPs

Number of publications



Number of publications with search key word «high temperature heat pump»
in databases SCOPUS (www.scopus.com) and Web of Science (www.webofknowledge.com)

Research projects in the field of HTHPs

with information on the organization, project partners, heat pump cycle, compressor type, refrigerant, heating capacity and sorted by the sink temperature

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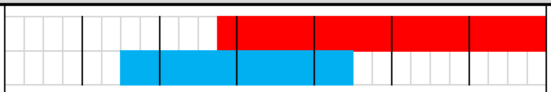
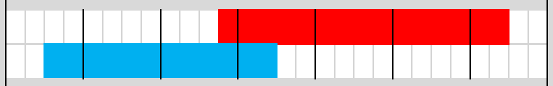
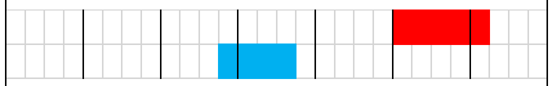
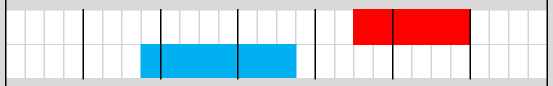
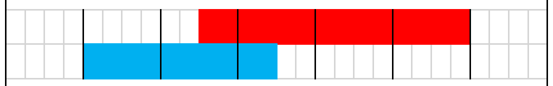
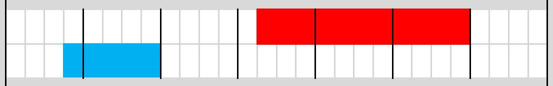
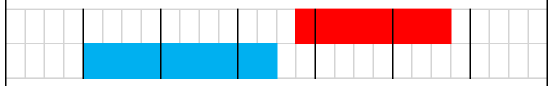
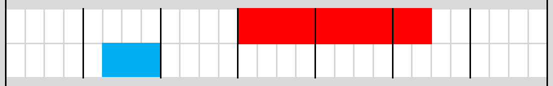
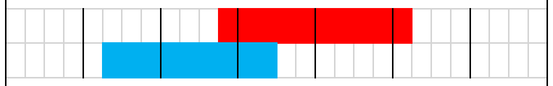
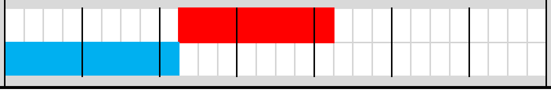
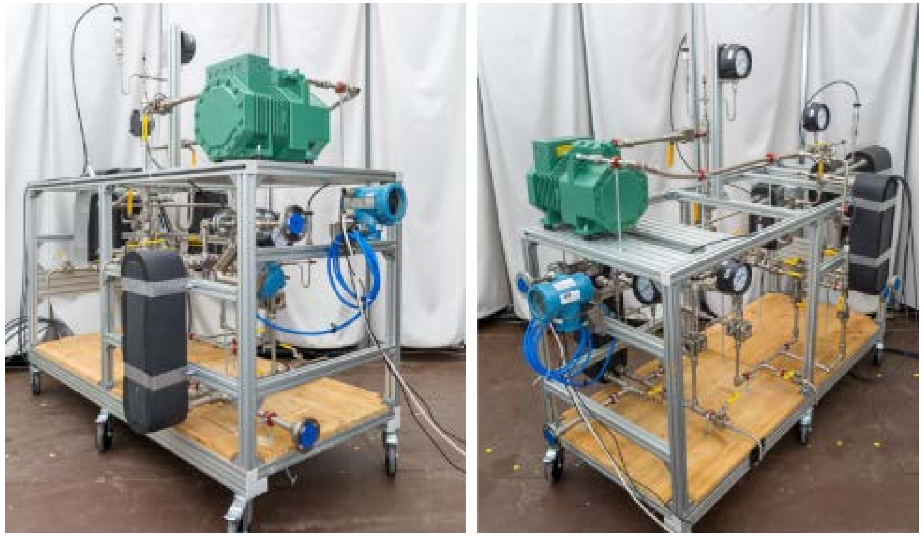
Organisation, Project partners	Cycle	Compressor type	Refrigerant	Source and supply temperatures [°C]	Heating capacity [kW]	Reference
				20 40 60 80 100 120 140 160		
Austrian Institute of Technology (AIT), Wien, Chemours, Bitzer	IHX	piston	R1336mzz-Z		12	(Helminger et al., 2016)
Austrian Institute of Technology (AIT), Wien, Chemours, Bitzer	1-stage	piston	R1336mzz-Z		12	(Fleckl et al., 2015a, 2015b)
PACO, University Lyon, EDF Electricité de France	flash tank	double screw	H_2O (Wasser)		300	(Chamoun et al., 2014, 2013, 2012a, 2012b)
Institut für Luft- und Kältetechnik (ILK), Dresden	1-stage	n.a.	HT 125		12	(Noack, 2016)
Friedrich-Alexander Universität Erlangen-Nürnberg, Siemens	IHX	piston	LG6		10	(Reißner, 2015; Reißner et al., 2013a, 2013b)
Alter ECO, EDF Electricité de France	IHX and subcooler	double scroll	ECO3 (R245fa)		50-200	(Bobelin et al., 2012; IEA, 2014a)
Tokyo Electric Power Company, Japan	1-stage	screw	R601		150-400	(Yamazaki and Kubo, 1985)
Austrian Institute of Technology (AIT), Wien, Edtmayer, Ochsner	economizer	screw	ÖKO1 (R245fa)		250-400	(Wilk et al., 2016b)
Kyushu University, Fukuoka, Japan	1-stage	double rotary (2-stage)	R1234ze(Z)		1.8	(Fukuda et al., 2014)
Johnson Controls, EDF Electricité de France	economizer and IHX	double screw centrifugal turbo	R245fa		300-500 900-1'200	(IEA, 2014a)

Experimental setups

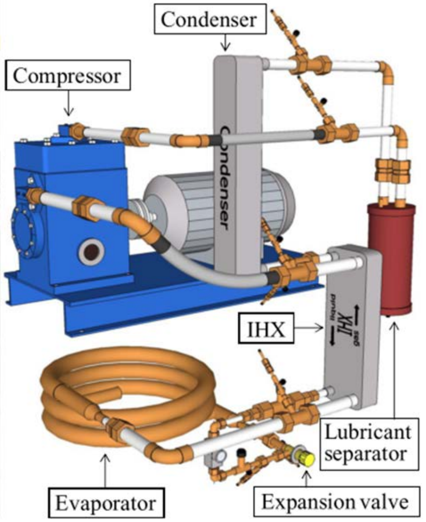
HTHPs in research status

160°C



Helminger (2016),
Fleckl (2015)
AIT, Vienna
1-stage cycle with
IHX, piston
(Bitzer 2CES),
R1336mzz(Z)

140°C



140°C

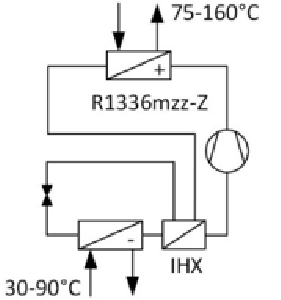
Reißner (2015, 2013), Erlangen
1-stage with IHX, piston (GEA Bock E3), LG6

Noack (2016), ILK, Dresden
1-stage cycle, HT 125

Cycles and achieved COPs

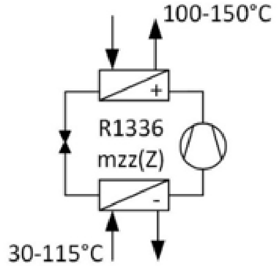
HTHPs in research status

(Helminger et al., 2016)
12 kW, with IHX, piston



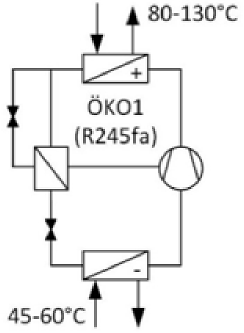
	COP
ΔT=35°C	4.7-5.8
ΔT=70°C	2.6-3.4

(Fleckl et al., 2015a, 2015b)
12 kW, piston



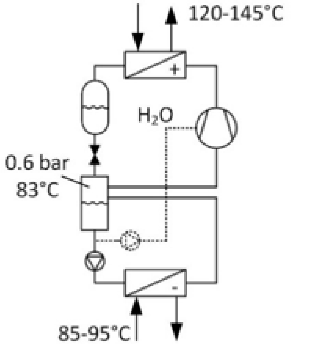
	COP
ΔT=35°C	4.2-5.8
ΔT=70°C	2.1-2.5

(Wilk et al., 2016b)
250-400 kW, with economizer, screw



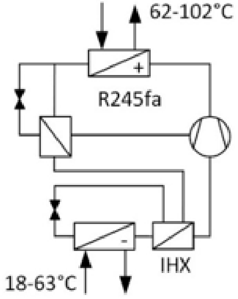
	COP
ΔT=35°C	3.6-3.9
ΔT=70°C	2.1-2.3

PACO project (Chamoun et al., 2014, 2013, 2012a, 2012b)
300 kW, with flash tank, double screw



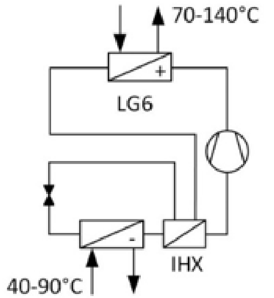
	COP
ΔT=27°C (94/121)	5.5
ΔT=55°C (75/130)	3.6

EDF/Johnson Controls (IEA, 2014a)
with economizer and IHX, 300-500 kW, double screw,
900-1’200 kW, turbo



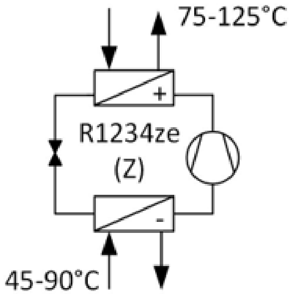
	COP
ΔT=35°C	5-7
ΔT=70°C	2-3

(Reißner, 2015; Reißner et al., 2013a, 2013b)
12 kW, with IHX, piston



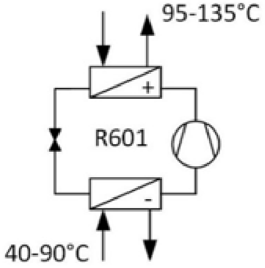
	COP
ΔT=30°C	3.6-6.0
ΔT=60°C	2.5-3.2

(Fukuda et al., 2014)
1.8 kW, double rotary compressor (2-stage)



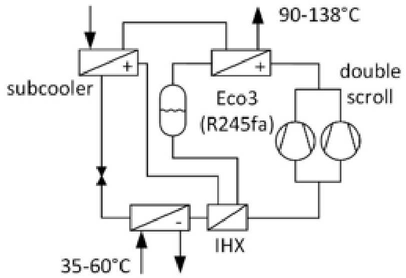
	COP
ΔT=30°C	5.4-6.6

(Yamazaki and Kubo, 1985)
150-400 kW, screw



	COP
ΔT=40°C	6.4-7.0
ΔT=70°C	2.6-3.0

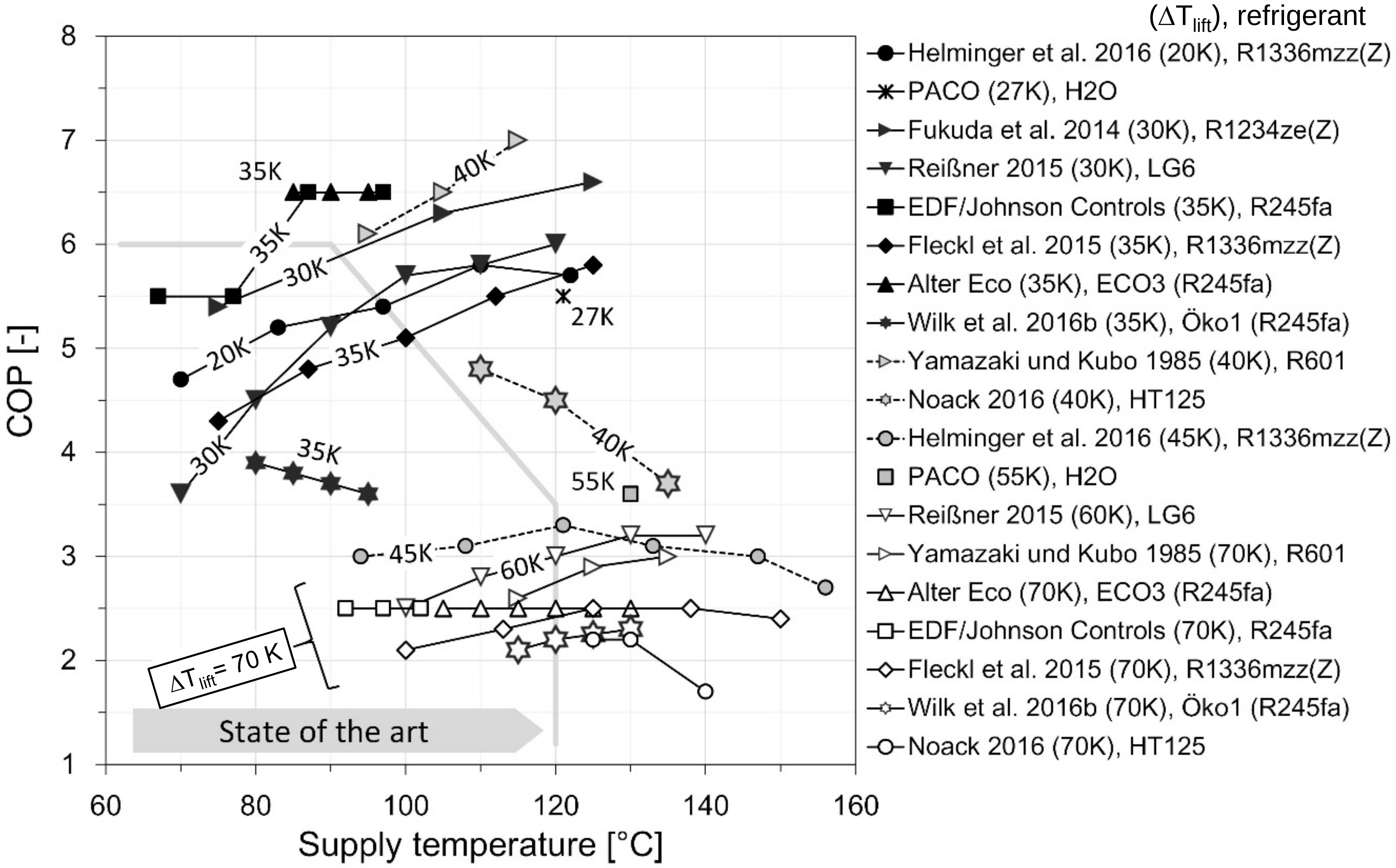
Alter ECO project (Bobelin et al., 2012; IEA, 2014a)
50-200 kW, with IHX and subcooler, double scroll



	COP
ΔT=35°C	6-7
ΔT=70°C	2-3

Achieved COPs of HTHPs in research status versus supply temperature

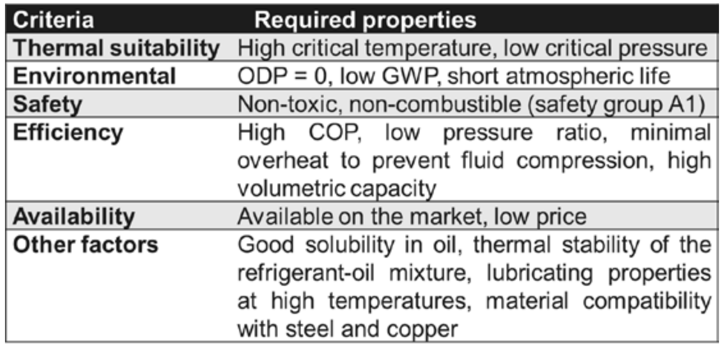
at constant temperature lifts (ΔT_{lift}) of 20 to 70 K



State of the art indicated at 120°C supply temperature and a COP of up to 6 at 60 to 90°C.

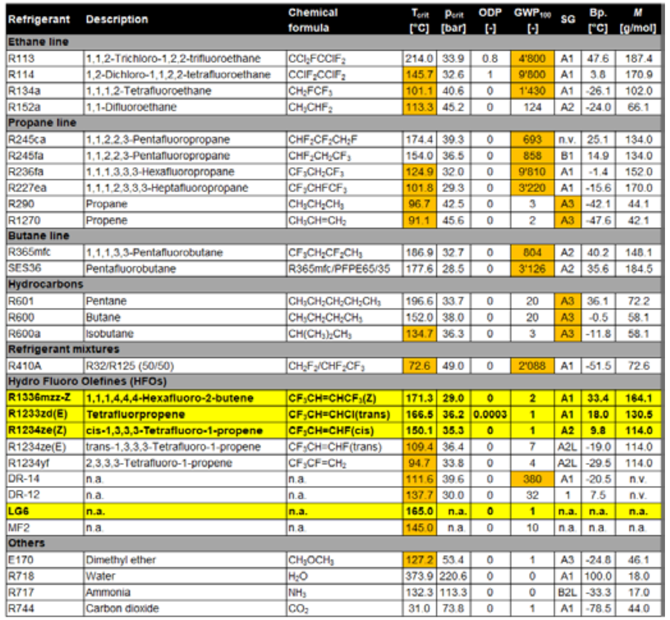
Refrigerants for HTHPs

Selection criteria



Criteria	Required properties
Thermal suitability	High critical temperature, low critical pressure
Environmental	ODP = 0, low GWP, short atmospheric life
Safety	Non-toxic, non-combustible (safety group A1)
Efficiency	High COP, low pressure ratio, minimal overheat to prevent fluid compression, high volumetric capacity
Availability	Available on the market, low price
Other factors	Good solubility in oil, thermal stability of the refrigerant-oil mixture, lubricating properties at high temperatures, material compatibility with steel and copper

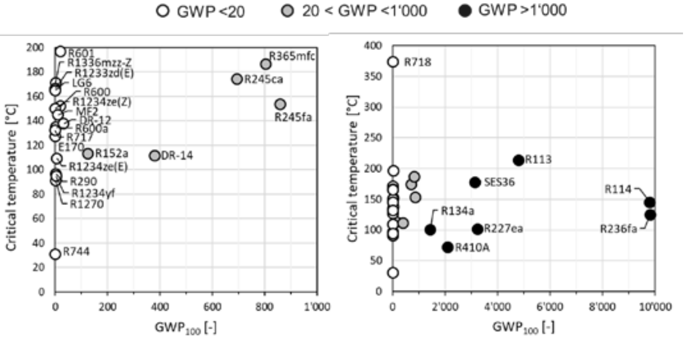
Refrigerant properties



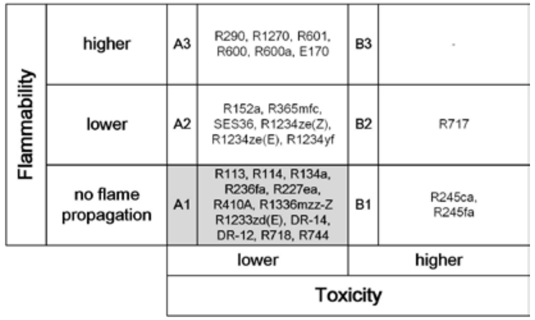
Refrigerant	Description	Chemical formula	T_{crit} [°C]	p_{crit} [bar]	ODP [-]	GWP_{100} [-]	SG	Bp. [°C]	*M* [g/mol]
Ethane line									
R113	1,1,2-Trichloro-1,2,2-trifluoroethane	CCl_2FCClF_2	214.0	33.9	0.8	4'800	A1	47.6	187.4
R114	1,2-Dichloro-1,1,2,2-tetrafluoroethane	$CClF_2CClF_2$	145.7	32.6	1	9'800	A1	3.8	170.9
R134a	1,1,1,2-Tetrafluoroethane	CH_2FCF_3	101.1	40.6	0	1'430	A1	-26.1	102.0
R152a	1,1-Difluoroethane	CH_3CHF_2	113.3	45.2	0	124	A2	-24.0	66.1
Propane line									
R245ca	1,1,2,2,3-Pentafluoropropane	$CHF_2CF_2CH_2F$	174.4	39.3	0	693	n.v.	25.1	134.0
R245fa	1,1,2,2,3-Pentafluoropropane	$CHF_2CH_2CF_3$	154.0	36.5	0	858	B1	14.9	134.0
R236fa	1,1,1,3,3,3-Hexafluoropropane	$CF_3CH_2CF_3$	124.9	32.0	0	9'810	A1	-1.4	152.0
R227ea	1,1,1,2,3,3,3-Heptafluoropropane	CF_3CHFCF_3	101.8	29.3	0	3'220	A1	-15.6	170.0
R290	Propane	$CH_3CH_2CH_3$	96.7	42.5	0	3	A3	-42.1	44.1
R1270	Propene	$CH_3CH{=}CH_2$	91.1	45.6	0	2	A3	-47.6	42.1
Butane line									
R365mfc	1,1,1,3,3-Pentafluorobutane	$CF_3CH_2CF_2CH_3$	186.9	32.7	0	804	A2	40.2	148.1
SES36	Pentafluorobutane	R365mfc/PFPE65/35	177.6	28.5	0	3'126	A2	35.6	184.5
Hydrocarbons									
R601	Pentane	$CH_3CH_2CH_2CH_2CH_3$	196.6	33.7	0	20	A3	36.1	72.2
R600	Butane	$CH_3CH_2CH_2CH_3$	152.0	38.0	0	20	A3	-0.5	58.1
R600a	Isobutane	$CH(CH_3)_2CH_3$	134.7	36.3	0	3	A3	-11.8	58.1
Refrigerant mixtures									
R410A	R32/R125 (50/50)	CH_2F_2/CHF_2CF_3	72.6	49.0	0	2'088	A1	-51.5	72.6
Hydro Fluoro Olefines (HFOs)									
R1336mzz-Z	**1,1,1,4,4,4-Hexafluoro-2-butene**	$CF_3CH{=}CHCF_3(Z)$	**171.3**	**29.0**	**0**	**2**	**A1**	**33.4**	**164.1**
R1233zd(E)	**Tetrafluorpropene**	$CF_3CH{=}CHCl(trans)$	**166.5**	**36.2**	**0.0003**	**1**	**A1**	**18.0**	**130.5**
R1234ze(Z)	**cis-1,3,3,3-Tetrafluoro-1-propene**	$CF_3CH{=}CHF(cis)$	**150.1**	**35.3**	**0**	**1**	**A2**	**9.8**	**114.0**
R1234ze(E)	trans-1,3,3,3-Tetrafluoro-1-propene	$CF_3CH{=}CHF(trans)$	109.4	36.4	0	7	A2L	-19.0	114.0
R1234yf	2,3,3,3-Tetrafluoro-1-propene	$CF_3CF{=}CH_2$	94.7	33.8	0	4	A2L	-29.5	114.0
DR-14	n.a.	n.a.	111.6	39.6	0	380	A1	-20.5	n.v.
DR-12	n.a.	n.a.	137.7	30.0	0	32	1	7.5	n.v.
LG6	**n.a.**	**n.a.**	**165.0**	**n.a.**	**0**	**1**	**n.a.**	**n.a.**	**n.a.**
MF2	n.a.	n.a.	145.0	n.a.	0	10	n.a.	n.a.	n.a.
Others									
E170	Dimethyl ether	CH_3OCH_3	127.2	53.4	0	1	A3	-24.8	46.1
R718	Water	H_2O	373.9	220.6	0	0	A1	100.0	18.0
R717	Ammonia	NH_3	132.3	113.3	0	0	B2L	-33.3	17.0
R744	Carbon dioxide	CO_2	31.0	73.8	0	1	A1	-78.5	44.0

Which refrigerants are suitable for HTHPs?

Critical temperature vs. GWP

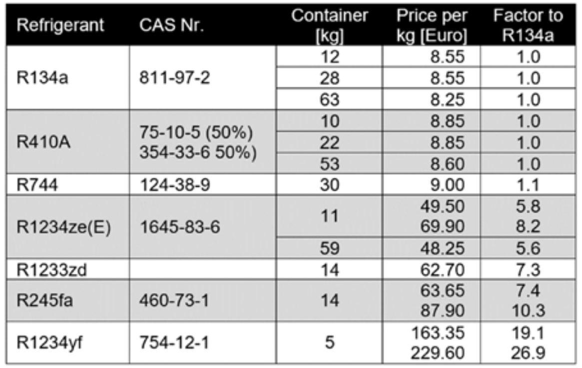


Safety



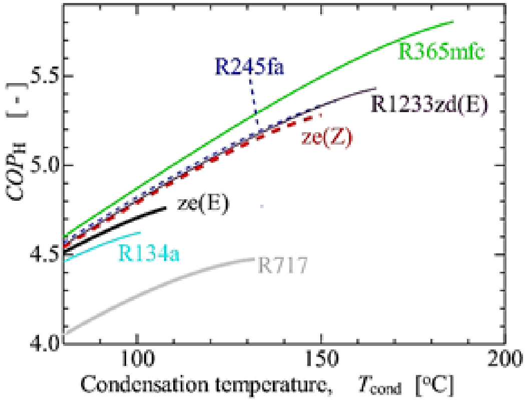
Flammability	higher	A3	R290, R1270, R601, R600, R600a, E170	B3	-
	lower	A2	R152a, R365mfc, SES36, R1234ze(Z), R1234ze(E), R1234yf	B2	R717
	no flame propagation	A1	R113, R114, R134a, R236fa, R227ea, R410A, R1336mzz-Z R1233zd(E), DR-14, DR-12, R718, R744	B1	R245ca, R245fa
		lower		higher	
		Toxicity			

Price



Refrigerant	CAS Nr.	Container [kg]	Price per kg [Euro]	Factor to R134a
R134a	811-97-2	12	8.55	1.0
		28	8.55	1.0
		63	8.25	1.0
R410A	75-10-5 (50%) 354-33-6 50%)	10	8.85	1.0
		22	8.85	1.0
		53	8.60	1.0
R744	124-38-9	30	9.00	1.1
R1234ze(E)	1645-83-6	11	49.50 69.90	5.8 8.2
		59	48.25	5.6
R1233zd		14	62.70	7.3
R245fa	460-73-1	14	63.65 87.90	7.4 10.3
R1234yf	754-12-1	5	163.35 229.60	19.1 26.9

Efficiency



Selection criteria for refrigerants for HTHPs

Criteria	Required properties
Thermal suitability	High critical temperature, low critical pressure
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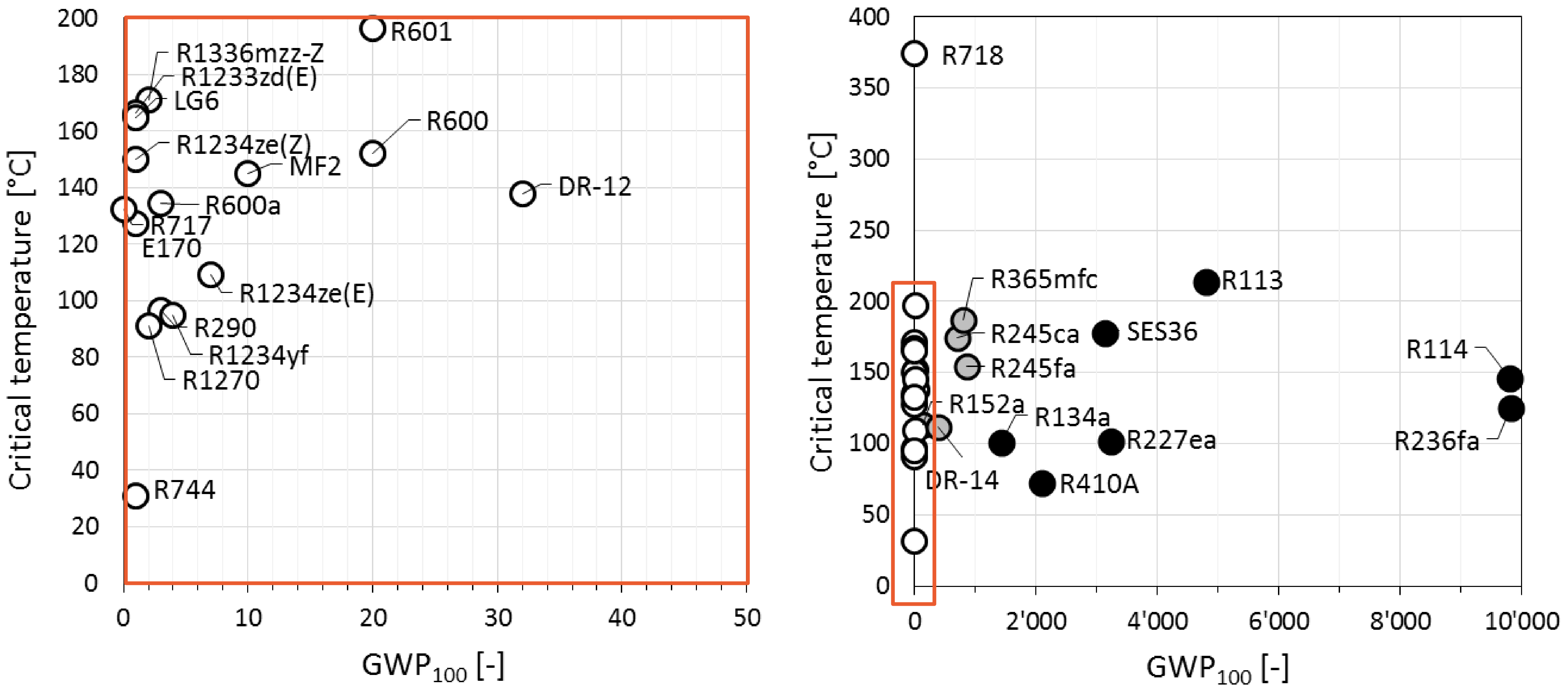
Other factors	Good solubility in oil, thermal stability of the refrigerant-oil mixture, lubricating properties at high temperatures, material compatibility with steel and copper

Data sources: Bertinat (1986), Burtscher et al. (2009), Calm (2008), Eisa et al. (1986), Göktun (1995), Helminger et al. (2016), Klein (2009), Kujak (2016), Reißner et al. (2013), Rieberer et al. (2015)

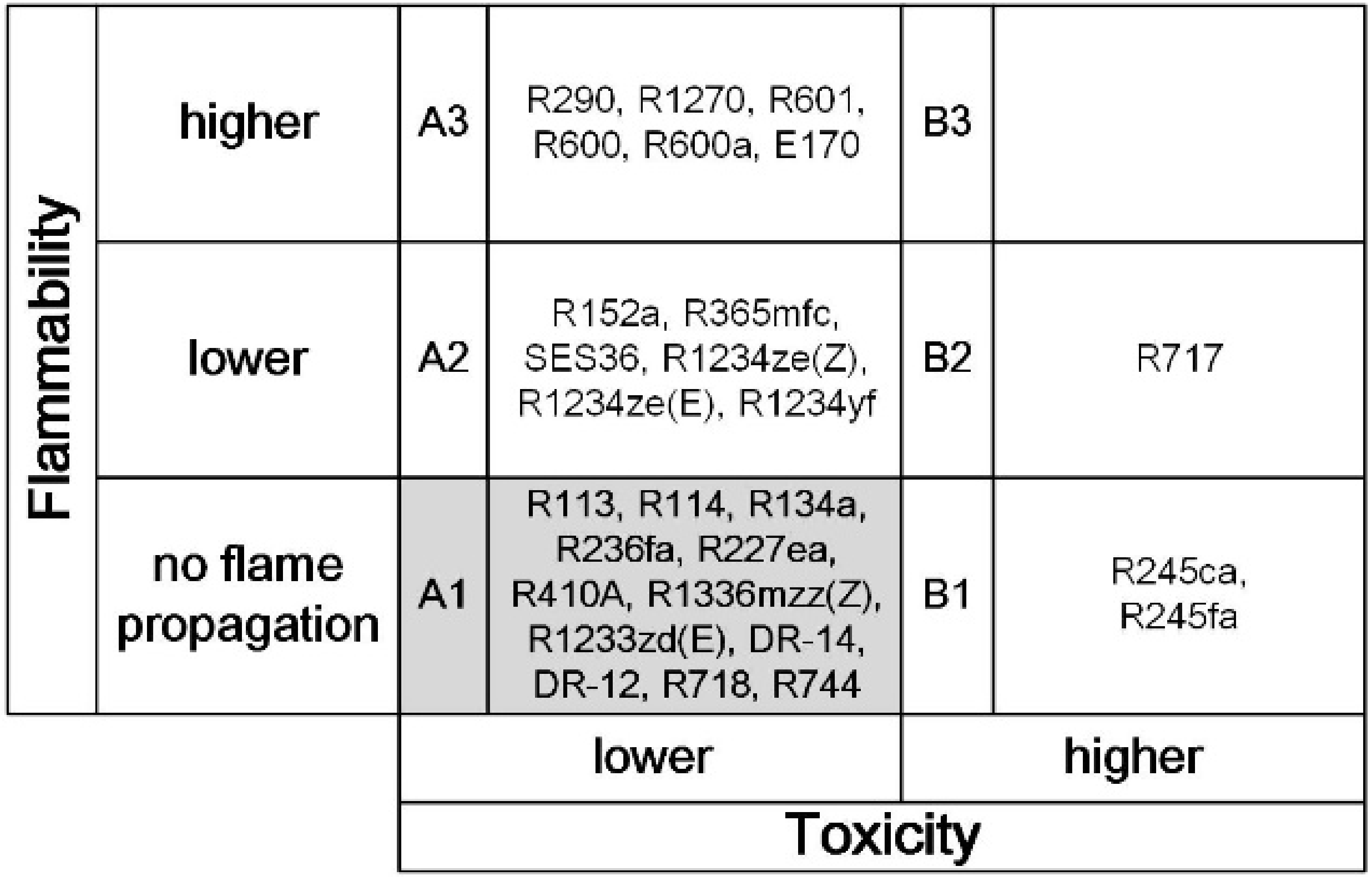
Classification of refrigerants by critical temperature and GWP

○ GWP <50 ● 50 < GWP <1‘000 ● GWP >1‘000



Safety Group Classification

according to DIN EN 378-1 (2008) and ASHRAE 34



Flammability	higher	A3	R290, R1270, R601, R600, R600a, E170	B3	
	lower	A2	R152a, R365mfc, SES36, R1234ze(Z), R1234ze(E), R1234yf	B2	R717
	no flame propagation	A1	R113, R114, R134a, R236fa, R227ea, R410A, R1336mzz(Z), R1233zd(E), DR-14, DR-12, R718, R744	B1	R245ca, R245fa
		lower		higher	
		Toxicity			

Properties of refrigerants for HTHPs

Refrigerant	Description	Chemical formula	T_{crit} [°C]	p_{crit} [bar]	ODP [-]	GWP_{100} [-]	SG	Bp. [°C]	*M* [g/mol]
Ethane line									
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R290	Propane	$CH_3CH_2CH_3$	96.7	42.5	0	3	A3	-42.1	44.1
R1270	Propene	$CH_3CH=CH_2$	91.1	45.6	0	2	A3	-47.6	42.1
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SES36	Pentafluorobutane	R365mfc/PFPE65/35	177.6	28.5	0	3'126	A2	35.6	184.5
Hydrocarbons									
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R600	Butane	$CH_3CH_2CH_2CH_3$	152.0	38.0	0	20	A3	-0.5	58.1
R600a	Isobutane	$CH(CH_3)_2CH_3$	134.7	36.3	0	3	A3	-11.8	58.1
Refrigerant mixtures									
R410A	R32/R125 (50/50)	CH_2F_2/CHF_2CF_3	72.6	49.0	0	2'088	A1	-51.5	72.6
Hydro Fluoro Olefines (HFOs)									
R1336mzz-Z	**1,1,1,4,4,4-Hexafluoro-2-butene**	**$CF_3CH=CHCF_3$(Z)**	**171.3**	**29.0**	**0**	**2**	**A1**	**33.4**	**164.1**
R1233zd(E)	**Tetrafluorpropene**	**$CF_3CH=CHCl$(trans)**	**166.5**	**36.2**	**0.0003**	**1**	**A1**	**18.0**	**130.5**
R1234ze(Z)	**cis-1,3,3,3-Tetrafluoro-1-propene**	**$CF_3CH=CHF$(cis)**	**150.1**	**35.3**	**0**	**1**	**A2**	**9.8**	**114.0**
R1234ze(E)	trans-1,3,3,3-Tetrafluoro-1-propene	$CF_3CH=CHF$(trans)	109.4	36.4	0	7	A2L	-19.0	114.0
R1234yf	2,3,3,3-Tetrafluoro-1-propene	$CF_3CF=CH_2$	94.7	33.8	0	4	A2L	-29.5	114.0
DR-14	n.a.	n.a.	111.6	39.6	0	380	A1	-20.5	n.v.
DR-12	n.a.	n.a.	137.7	30.0	0	32	1	7.5	n.v.
LG6	**n.a.**	**n.a.**	**165.0**	**n.a.**	**0**	**1**	**n.a.**	**n.a.**	**n.a.**
MF2	n.a.	n.a.	145.0	n.a.	0	10	n.a.	n.a.	n.a.
Others									
E170	Dimethyl ether	CH_3OCH_3	127.2	53.4	0	1	A3	-24.8	46.1
R718	Water	H_2O	373.9	220.6	0	0	A1	100.0	18.0
R717	Ammonia	NH_3	132.3	113.3	0	0	B2L	-33.3	17.0
R744	Carbon dioxide	CO_2	31.0	73.8	0	1	A1	-78.5	44.0

T_{crit} = critical temperature

p_{crit} = critical pressure

ODP = Ozone Depletion Potenial (R11=1.0)

GWP = Global Warming Potential (CO2=1.0, 100 years EU F-Gas regulation 517/2014)

SG = Safety group (according to DIN EN 378-1, 2008, ASHRAE 34)

Bp. = Boiling point at 1.013 bar

M = Molecular weight

🟧 excluded

🟨 suitable

Conclusions

Market overview

- **More than 20 HTHP models** identified with supply temperatures > 90°C from 13 manufacturers (e.g. Vicking HeatBooster with 150°C, Ochsner IWWDS with 130°C, Kobelco SGH120, Mayekawa Eco Sirocco, and Hybrid Energy Heat Pump with 120°C)
- **Heat source:** water, brine, waste heat (17 to 65°C)
- **COP:** 2.4 to 5.8 at a temperature lift of 40 to 95 K
- **Heating capacity:** from about 20 kW to 20 MW
- **Refrigerants:** R245fa, R717 (NH3), R744 (CO2), R134a, R1234ze(E)
- **Compressors:** 1- and 2-shaft screws, 2-stage turbos, pistons (parallel)
- **Cycles:** usually 1-stage, optimization by IHX, parallel compressors, economizer, intermediate injection, 2-stage cascade (R134a/R245fa) or with a flash economizer

Research status

- **Highest supply temperature of 160°C** at AIT (Vienna), 1-stage cycle with IHX and R1336mzz(Z)
- **At least 10 research projects** reached > 100°C
- **Heating capacity:** lab scale 12 kW, larger prototypes >100 kW
- **COPs** (at 120°C supply temperature):
  5.7 to 6.5 (30 K temperature lift), 2.2 to 2.8 (70 K)
- **Cycles all 1-stage:** partly with IHX and/or economizer with intermediate injection
- **Refrigerants:** R1336mzz(Z), R718 (H2O), R245fa, R1234ze (Z), R601, LG6 (Siemens), ÖKO1 (contains R245fa, Ochsner), ECO3 (R245fa, Alter ECO), HT125 (ILK, Dresden)
- **Compressors:** pistons in lab systems
- **HFO refrigerants:** thermodynamic suitable, good efficiency, GWP <10, ODP = 0, safe, future-proof according to F-Gas regulation

Thank you for your attention

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