CHILLVENTA

Chillventa CONGRESS 2018

CONNECTING EXPERTS.

High Temperature Heat Pumps

1) Market & Research Status, Refrigerants, Application Potentials
2) Results with a laboratory-scale heat pump using HCFO R1233zd

Cordin Arpagaus[1], Frédéric Bless[1], Michael Uhlmann[1],
Elias Büchel[1], Stefan Frei[1], Jürg Schiffmann[2], Stefan S. Bertsch[1]

[1] NTB University of Applied Sciences of Technology Buchs, Switzerland
[2] Ecole Polytechnique Fédérale de Lausanne, Switzerland

In cooperation with the CTI

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Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Commission for Technology and Innovation CTI

cordin.arpagaus@ntb.ch

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Outline

1) **Market overview** (application potentials, industrial processes, commercial products, operating ranges, efficiencies)
2) **Research status** (heat pump cycles, efficiency, temperature lifts)
3) **Refrigerants** (selection criteria, properties)
4) **Simulation results** of a one-stage heat pump cycle comparing different HFO and HFCO refrigerants
5) **Experimental test results** of a laboratory-scale high temperature heat pump using R1233zd(E) refrigerant
6) **Conclusions**

SCCER Project (Swiss Competence Center of Energy Research

SCCER
EFFICIENCY OF INDUSTRIAL PROCESSES

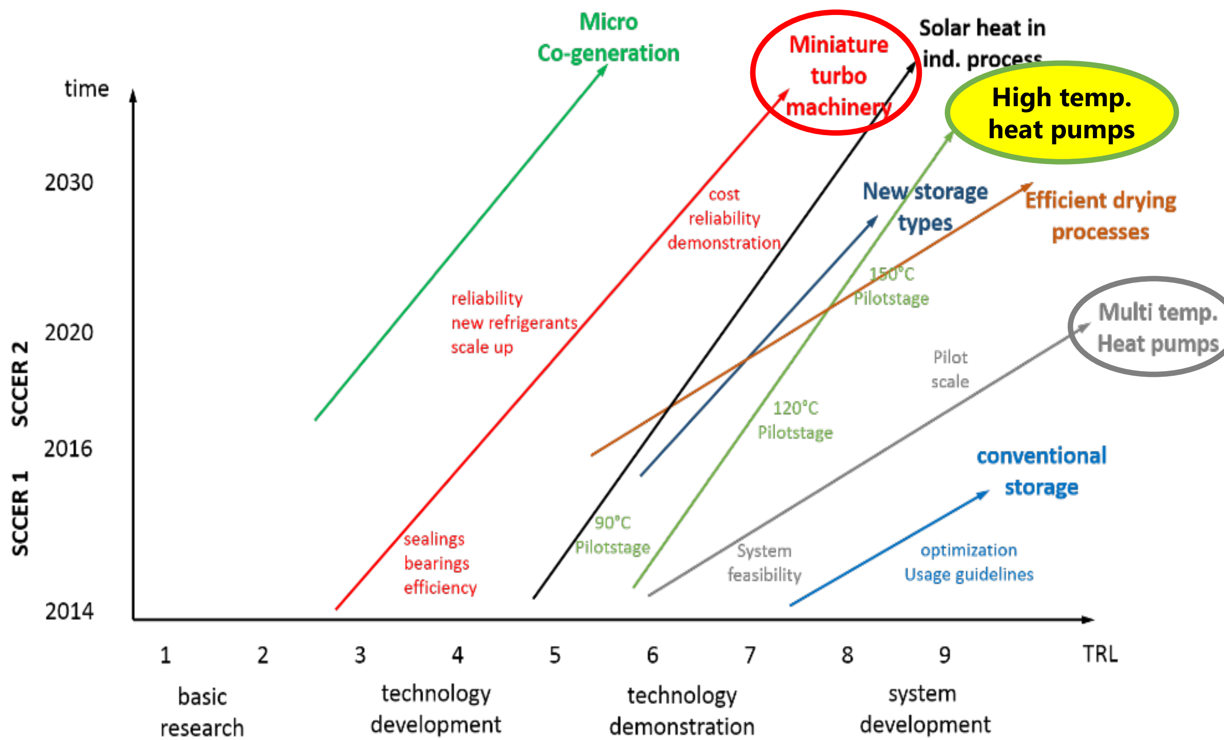
SCCER EIP (Efficiency of Industrial Processes)

EFFICIENCY OF INDUSTRIAL PROCESSES

Work Package 2:

Energy Efficiency (direkt)

- Goal: Development of highly efficient system solutions and technologies (e.g. cycle processes and heat pumps)



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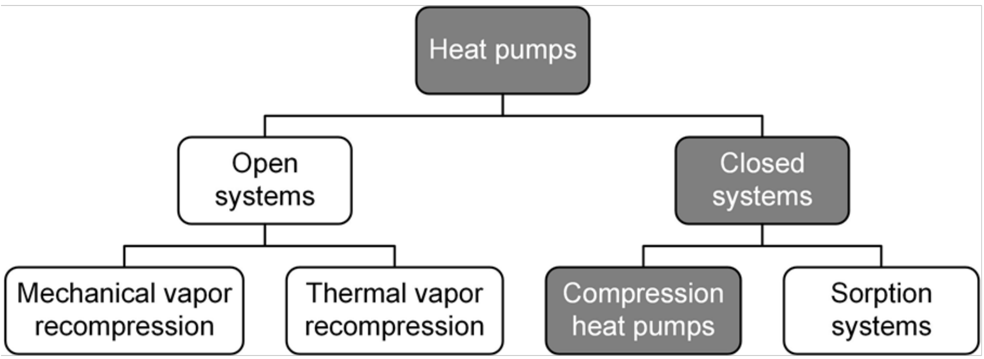
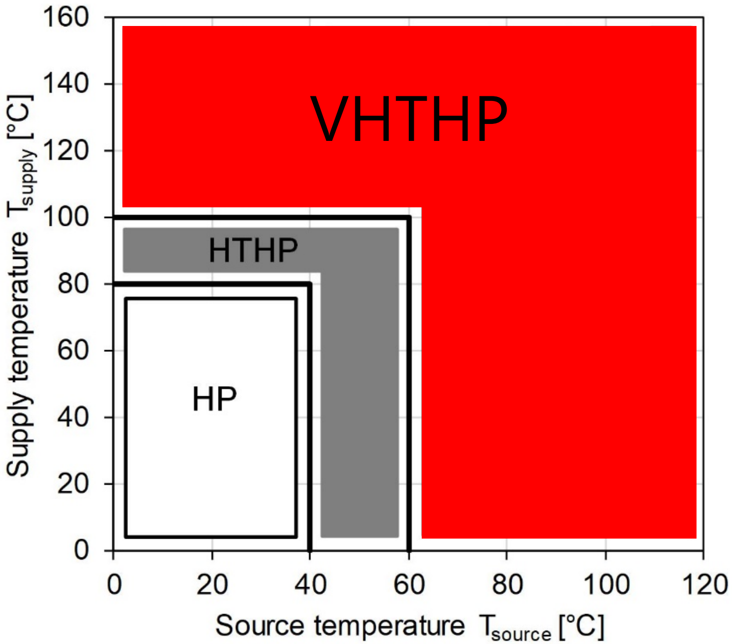
Classification of High Temperature Heat Pumps (HTHPs)

Focus on vapor compression heat pumps



adapted from Nellissen und Wolf (2015)

Development of temperature levels

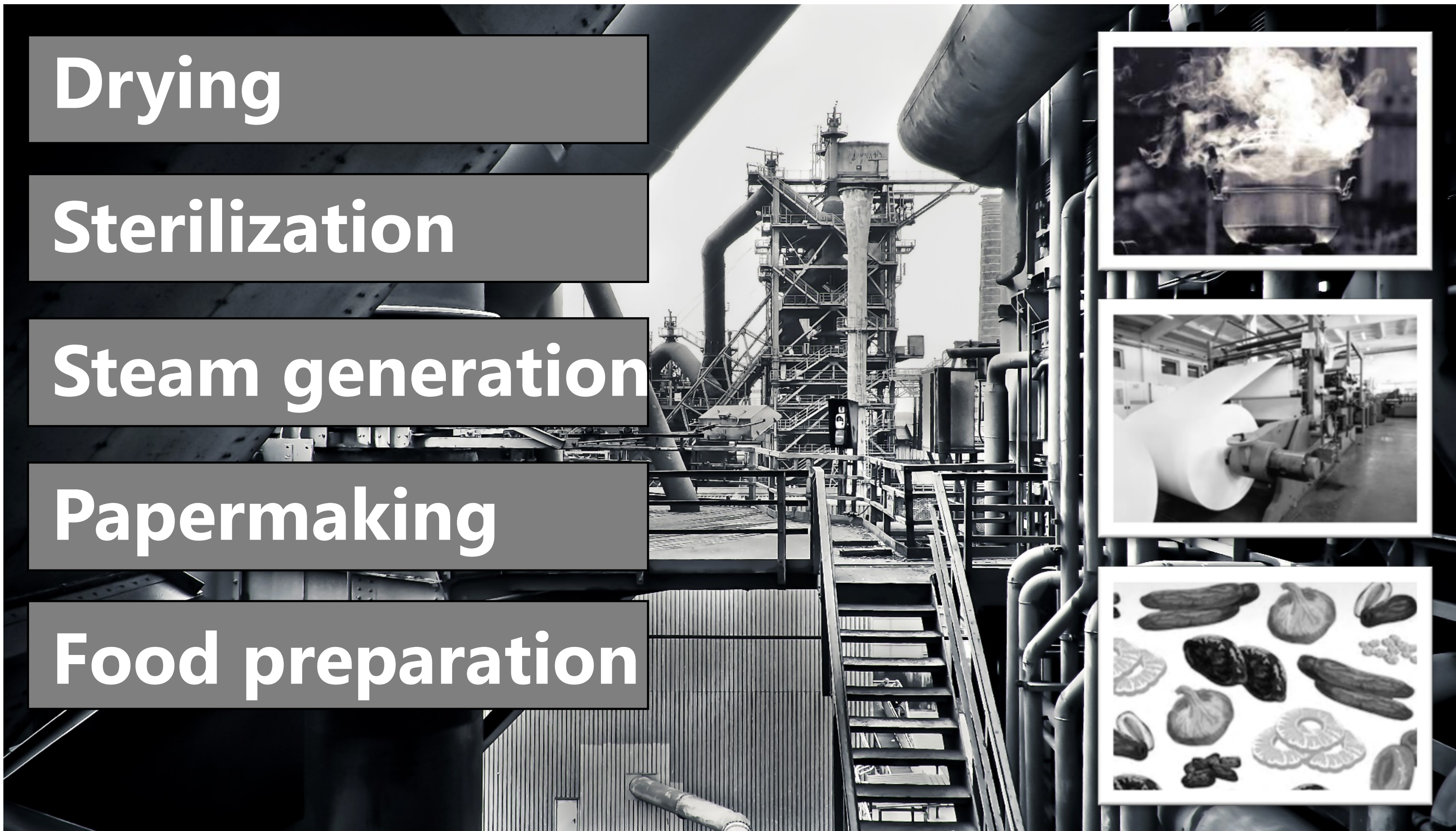


HP: conventional heat pump
HTHP: high temperature heat pump
VHTHP: very high temperature heat pump

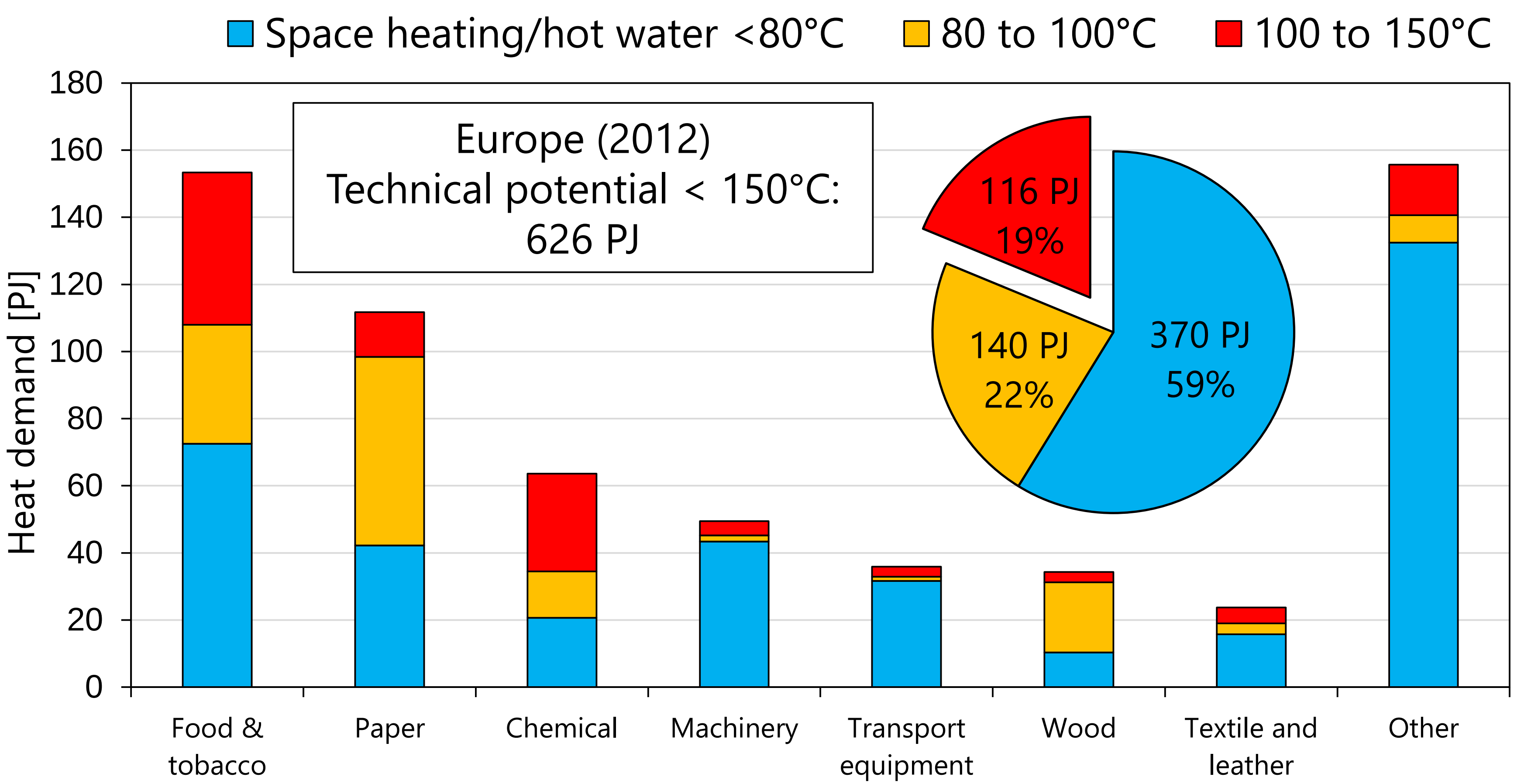
adapted from Bobelin et al. (2012), IEA (2014), Jakobs und Laue (2015), Peureux et al. (2012, 2014)

HTHPs with heat sink temperatures of 100 to 150°C are suitable systems for heat recovery in various industrial processes

SCCER EFFICIENCY OF INDUSTRIAL PROCESSES



Technical market potential of process heat in Europe – accessible with industrial heat pumps distributed by temperature and industrial sector



(based on Eurostat data from 2012 of 33 countries, Nellissen & Wolf, 2015)

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Temperature levels of industrial processes & Heat Pump Technology Readiness

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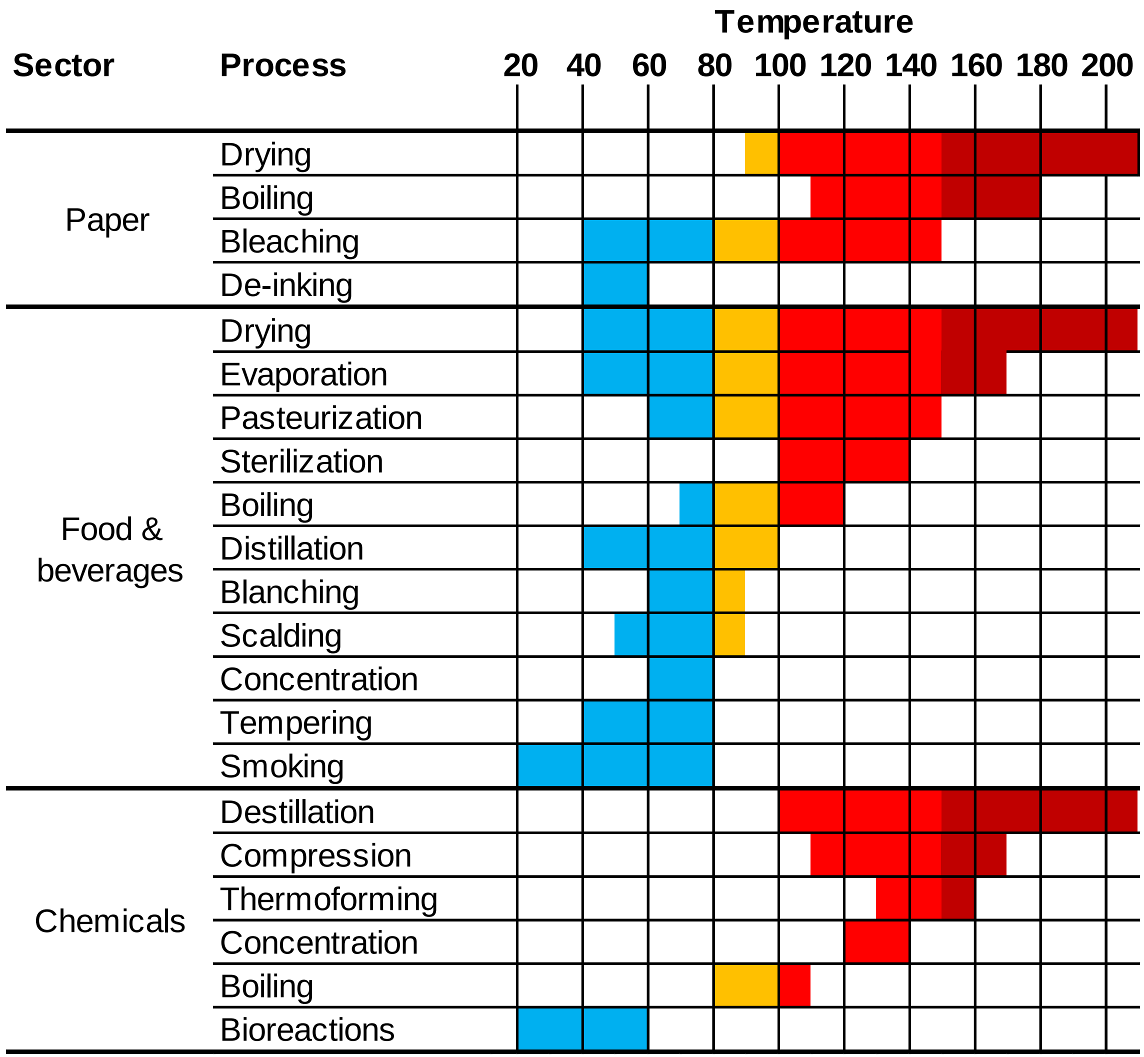
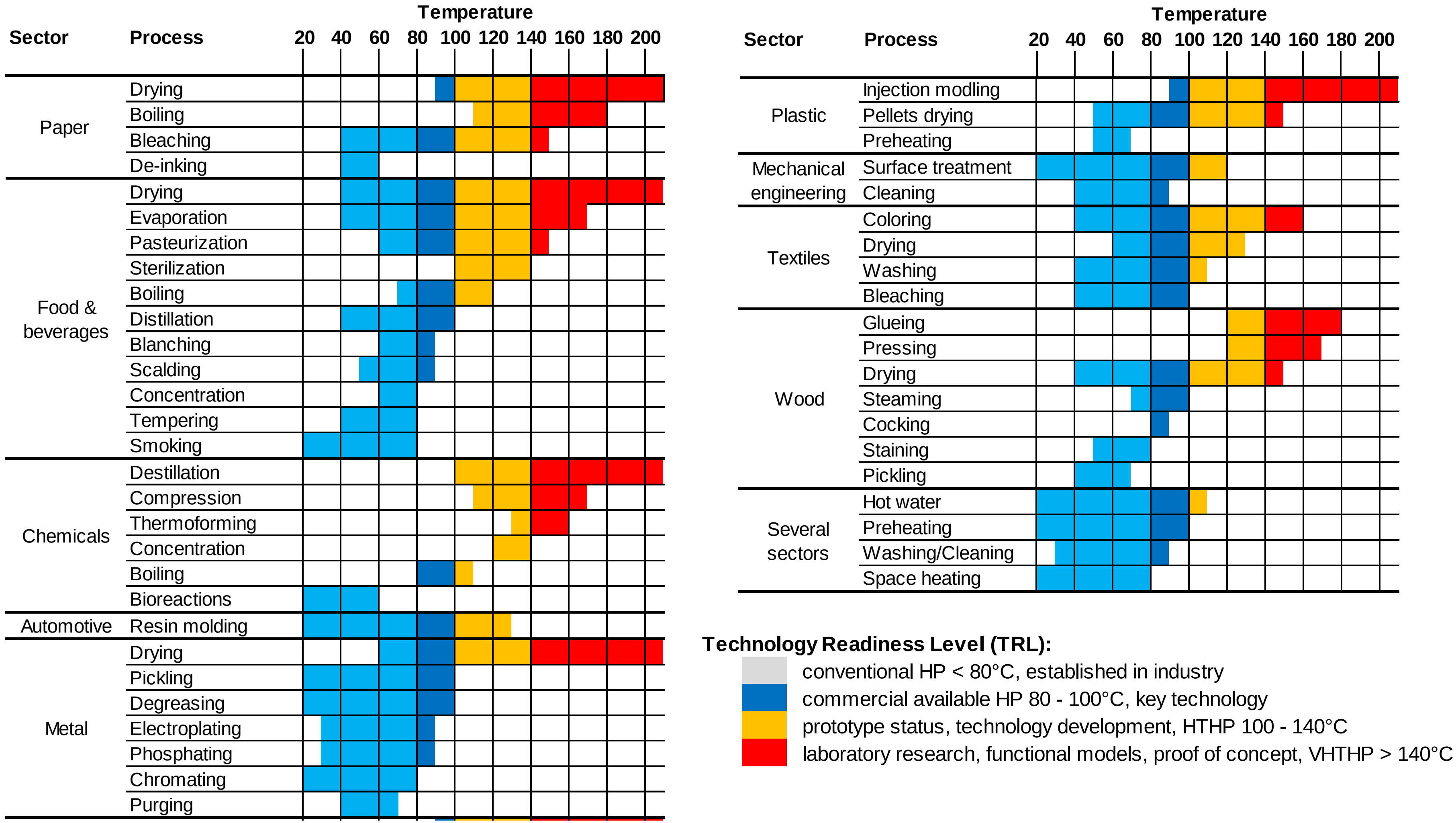


Temperature levels of industrial processes & Heat Pump Technology Readiness



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)

Example of an industrial high temperature heat pump

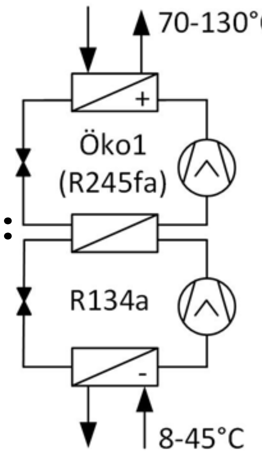
OCHSNER
ENERGIE TECHNIK

IWWDS ER3b (1-stage):

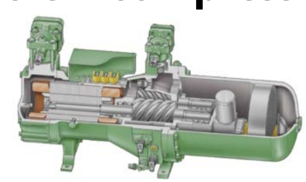
- 35 to 55 °C → 70 to 130 °C
- R245fa, 170 to 400 kW

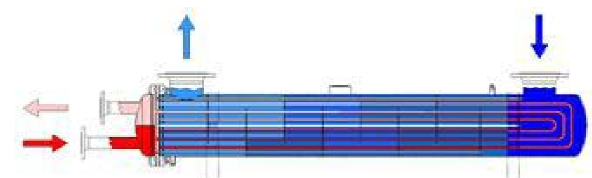
IWWDSS R1R3b (2-stage cascade):

- 10 to 25 °C / 95 to 130 °C
- R134a/R245fa, 90 to 530 kW



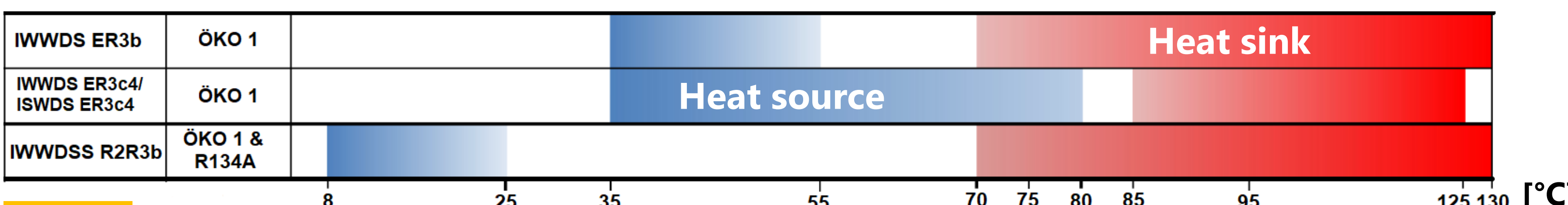
Screw compressor & tube bundle HX





Applications:

- district heating & heat recovery in industry



New IWWHS ER3b TWIN with R1233zd up to 2.4 MW

cordin.arpagaus@ntb.ch

Other examples of commercial high temperature heat pumps

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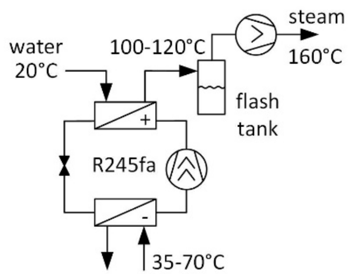
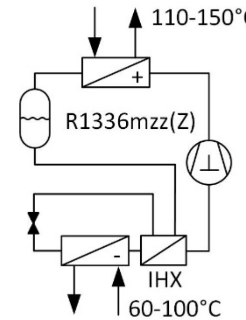
EFFICIENCY OF INDUSTRIAL PROCESSES

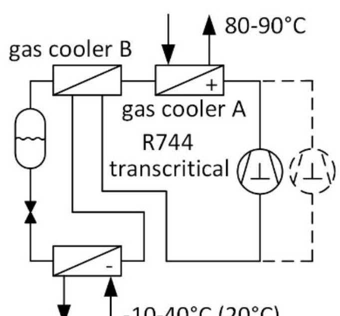
Kobelco SGH 120/165 (Steam Grow HP)



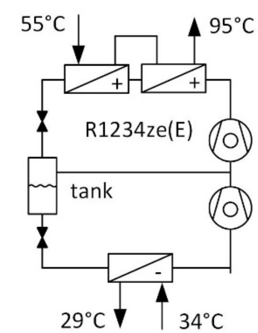
HeatBooster S4 (Viking Heating Engines AS)



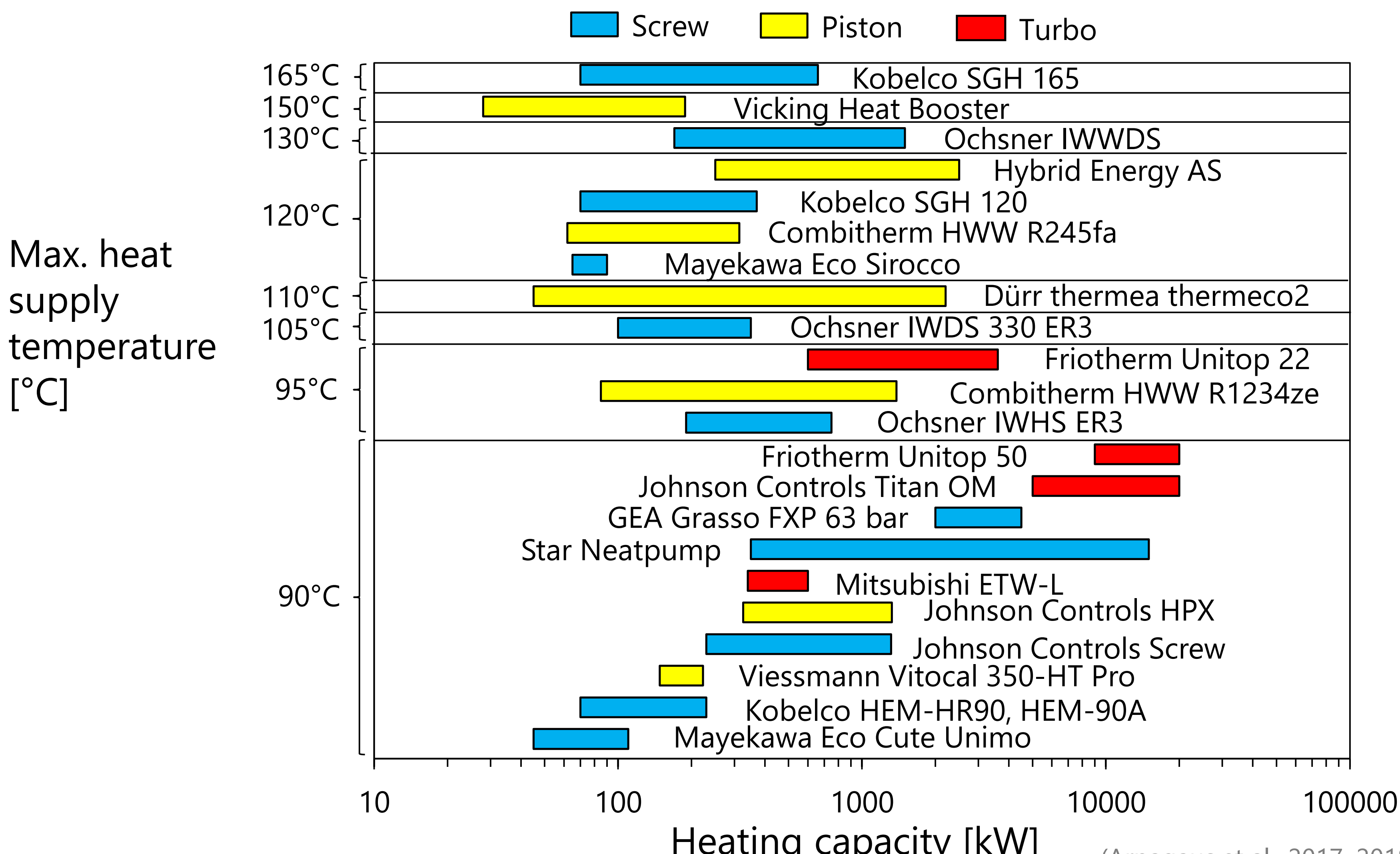
Thermeco$_2$ HHR 1000 (Engie, ex-Hafner-Muschler, ex-Dürr thermea)



Unitop 22/22 (Friotherm AG)

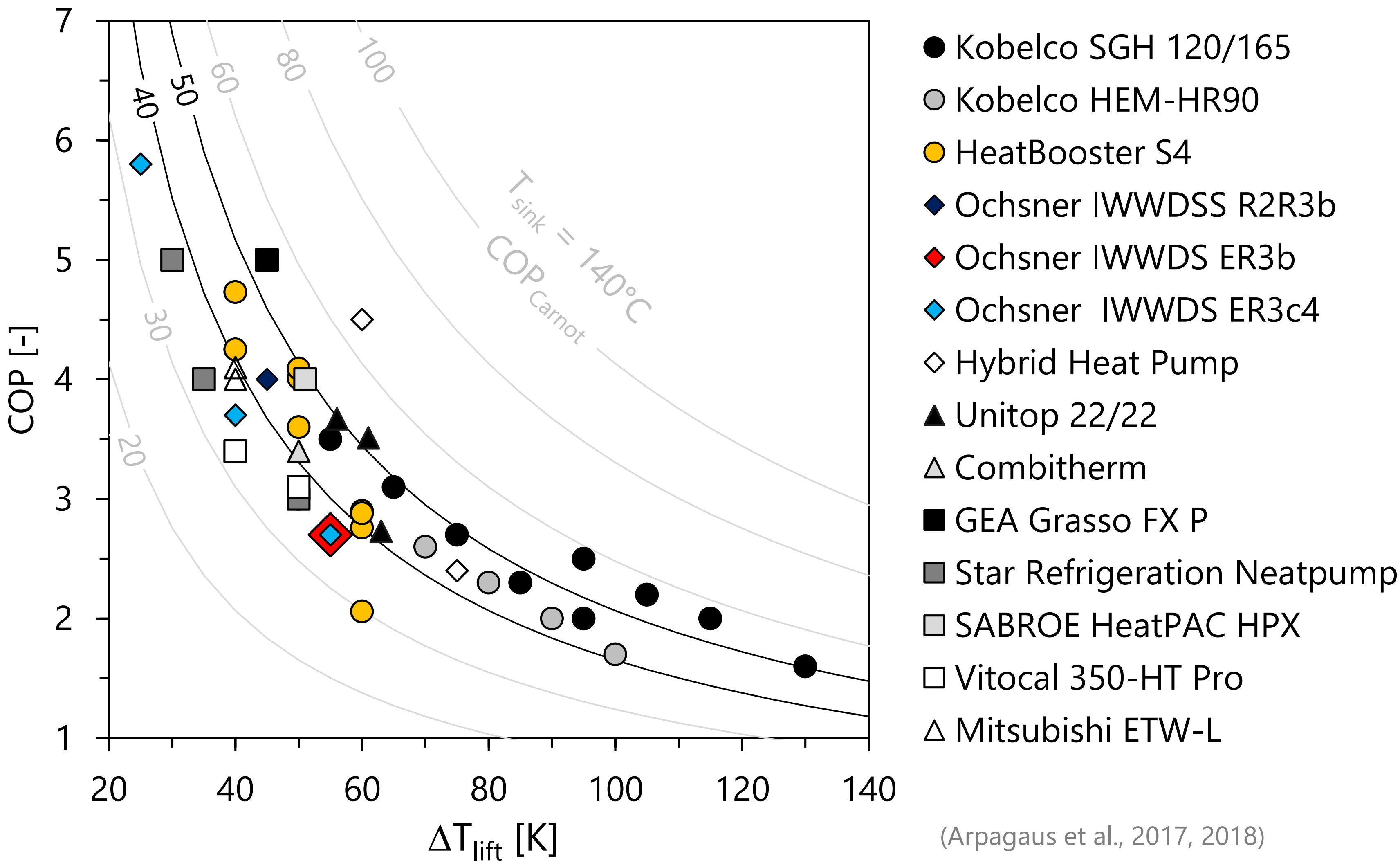


> 20 industrial HTHPs with heat supply temperature above 90 °C exist



(Arpagaus et al., 2017, 2018)

COP range between 1.6 to 5.8 at temperature lifts of 130 to 40 K



(Arpagaus et al., 2017, 2018)

(ΔT between heat sink out and heat source in)

What are the research gaps for HTHPs ?

SCCER EFFICIENCY OF INDUSTRIAL PROCESSES

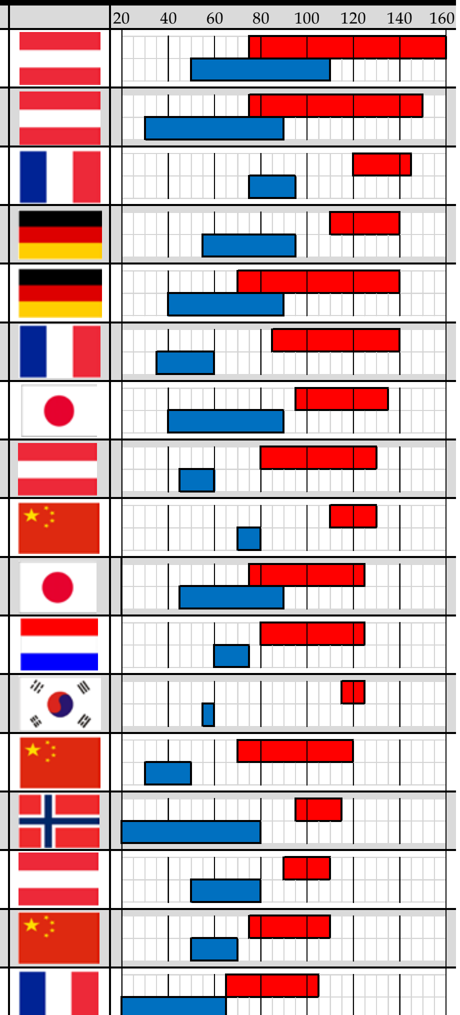
1) Pushing HTHPs from the laboratory scale **towards industry**
2) **Extending the limits** of heat supply temperatures to higher values
3) Improving heat pump **efficiency**
4) Testing new environmentally friendly **refrigerants**

cordin.arpagaus@ntb.ch

17 research projects on HTHPs with heat supply temperatures > 100 °C

SCCER eip
EFFICIENCY OF INDUSTRIAL PROCESSES

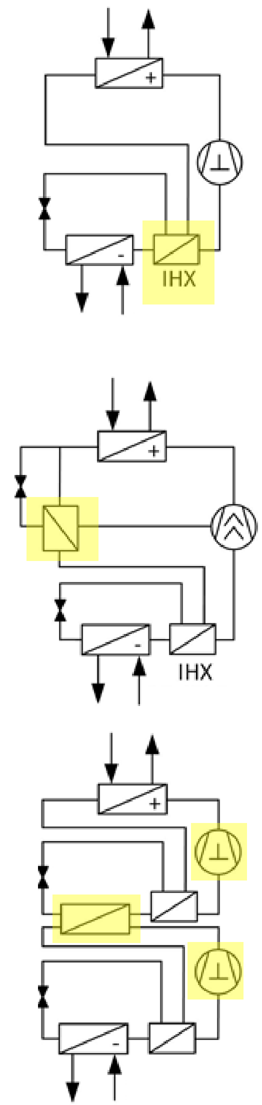
Organisation, Project partners	Country	Heat source (blue) and heat supply (red) temperatures [°C]
		20 40 60 80 100 120 140 160
Austrian Institute of Technology, Vienna, Chemours, Bitzer, Austria		
Austrian Institute of Technology, Vienna, Chemours, Bitzer, Austria		
PACO, University Lyon, EDF Electricité de France		
Institute of Air Handling and Refrigeration, Dresden, Germany		
Friedrich-Alexander University Erlangen-Nürnberg, Siemens, Germany		
Alter ECO, EDF Electricité de France		
Tokyo Electric Power Company, Japan		
Austrian Institute of Technology, Edtmayer, Ochsner, Austria		
Tianjin University, China		
Kyushu University, Fukuoka, Japan		
ECN, SmurfitKappa, IBK, Bronswerk, The Netherlands		
Korea Institute of Energy Research, Daejeon, Korea		
GREE Electric Appliances, Zhuhai, China		
Norwegian University of Science and Technology, SINTEF, Norway		
Technical University Graz, Austria		
Tianjin University, China		
EDF Electricité de France, Johnson Controls		



17 research projects on HTHPs with different cycles

SCCER
EFFICIENCY OF INDUSTRIAL PROCESSES

Organisation, Project partners	Country	Heat source (blue) and heat supply (red) temperatures [°C] 20 40 60 80 100 120 140 160	Cycle type
Austrian Institute of Technology, Vienna, Chemours, Bitzer, Austria			Single-stage with IHX
Austrian Institute of Technology, Vienna, Chemours, Bitzer, Austria			Single-stage
PACO, University Lyon, EDF Electricité de France			Flash tank
Institute of Air Handling and Refrigeration, Dresden, Germany			Single-stage
Friedrich-Alexander University Erlangen-Nürnberg, Siemens, Germany			Single-stage with IHX
Alter ECO, EDF Electricité de France			Single-stage with IHX and subcooler
Tokyo Electric Power Company, Japan			Single-stage with IHX
Austrian Institute of Technology, Edtmayer, Ochsner, Austria			Single-stage with economizer
Tianjin University, China			Single-stage
Kyushu University, Fukuoka, Japan			Single-stage
ECN, SmurfitKappa, IBK, Bronswerk, The Netherlands			Single-stage with IHX and subcooler
Korea Institute of Energy Research, Daejeon, Korea			Single-stage with steam generation
GREE Electric Appliances, Zhuhai, China			Single-stage with IHX
Norwegian University of Science and Technology, SINTEF, Norway			Two-stage cascade
Technical University Graz, Austria			Single-stage with IHX
Tianjin University, China			Single-stage
EDF Electricité de France, Johnson Controls			Single-stage with IHX and economizer



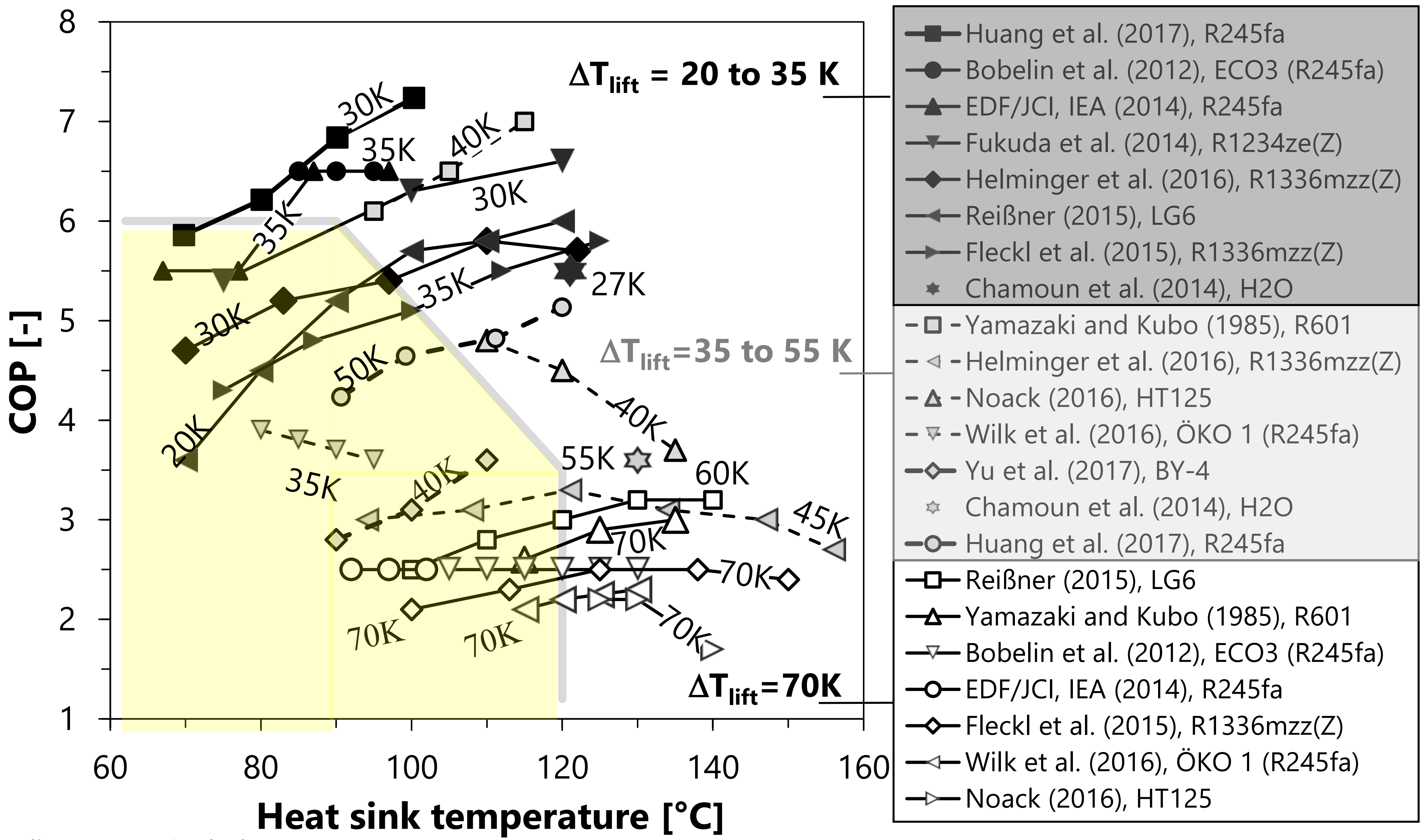
17 research projects on HTHPs with different heating capacities

Organisation, Project partners	Country	Heat source (blue) and heat supply (red) temperatures [°C]	Cycle type	Compressor	Refrigerant	Heating capacity [kW]	References
		20 40 60 80 100 120 140 160					
Austrian Institute of Technology, Vienna, Chemours, Bitzer, Austria			Single-stage with IHX	Piston	R1336mzz(Z)	12	Helminger et al. (2016)
Austrian Institute of Technology, Vienna, Chemours, Bitzer, Austria			Single-stage	Piston	R1336mzz(Z)	12	Fleckl et al. (2015)
PACO, University Lyon, EDF Electricité de France			Flash tank	Twin screw	R718	300	Chamoun et al. (2014, 2013, 2012)
Institute of Air Handling and Refrigeration, Dresden, Germany			Single-stage	Piston	HT 125	12	Noack (2016)
Friedrich-Alexander University Erlangen-Nürnberg, Siemens, Germany			Single-stage with IHX	Piston	LG6	10	Reißner (2015), Reißner et al. (2013)
Alter ECO, EDF Electricité de France			Single-stage with IHX and subcooler	Twin scroll	ECO3 (R245fa)	50-200	Bobelin et al. (2012), IEA (2014)
Tokyo Electric Power Company, Japan			Single-stage with IHX	Screw	R601	150-400	Yamazaki and Kubo (1985)
Austrian Institute of Technology, Edtmayer, Ochsner, Austria			Single-stage with economizer	Screw	ÖKO1 (R245fa)	250-400	Wilk et al. (2016)
Tianjin University, China			Single-stage	Scroll	BY-5	16-19	Zhang et al. (2017)
Kyushu University, Fukuoka, Japan			Single-stage	Twin rotary	R1234ze(Z)	1.8	Fukuda et al. (2014)
ECN, SmurfitKappa, IBK, Bronswerk, The Netherlands			Single-stage with IHX and subcooler	Piston	R600	160	Wemmers et al. (2017)
Korea Institute of Energy Research, Daejeon, Korea			Single-stage with steam generation	Piston	R245fa/R718	20-40	Lee et al. (2017)
GREE Electric Appliances, Zhuhai, China			Single-stage with IHX	Scroll	R245fa	6-12	Huang et al. (2017)
Norwegian University of Science and Technology, SINTEF, Norway			Two-stage cascade	Piston	R600/R290	20-30	Bamigbetan et al. (2017)
Technical University Graz, Austria			Single-stage with IHX	Piston	R600	20-40	Moisi et al. (2017)
Tianjin University, China			Single-stage	Double scroll	BY-4	44-141	Yu et al. (2014)
EDF Electricité de France, Johnson Controls			Single-stage with IHX and economizer	Twin screw, turbo	R245fa	300-500 900-1’200	Assaf et al. (2010), IEA (2012, 2014), Peureux et al. (2014)

(Arpagaus et al., 2017, 2018)

R&D projects push COPs and heat supply temperatures to higher levels

SCCER EFFICIENCY OF INDUSTRIAL PROCESSES



(Arpagaus et al., 2017, 2018)

What would be the perfect refrigerant?

SCCER EFFICIENCY OF INDUSTRIAL PROCESSES

Criteria	Required properties
Thermal suitability	High critical temperature (> 150°C), low critical pressure (< 30 bar)
Environmental	ODP = 0, low GWP, short atmospheric life
Safety	Non-toxic, no or only low flammability
Efficiency	High COP, low pressure ratio, minimal overheat to prevent fluid compression, high volumetric heating 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

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)

Refrigerants for HTHPs

Refrigerants selected for investigation in this study

Type	Refrigerant	Description	Chemical Formula	T_{crit} [°C]	p_{crit} [bar]	ODP [-]	GWP [-]	SG	NBP [°C]	M [g/mol]	Relative price [-]
CFC	R113	1,1,2-Trichloro-1,2,2-trifluoroethane	CCl_2FCClF_2	214.0	33.9	0.85	5'820	A1	47.6	187.4	Prohibited accoding to Montréal Protocol
	R114	1,2-Trichloro-1,1,2,2-tetrafluoroethane	$CClF_2CClF_2$	145.7	32.6	0.58	8'590	A1	3.8	170.9	
HCFC	R123	2,2-Dichloro-1,1,1-trifluoroethane	$C_2HCl_2F_3$	183.7	36.6	0.03	79	B1	27.8	152.9	
	R21	Dichlorofluoromethane	$CHCl_2F$	178.5	51.7	0.04	148	B1	8.9	102.9	
	R142b	1,1-Dichloro-1-fluoroethane	CH_3CCl_2F	137.1	40.6	0.065	782	A2	-10.0	100.5	
	R124	1-Chloro-1,2,2,2-tetrafluoroethane	C_2HClF_4	126.7	37.2	0.03	527	A1	-12.0	136.5	
HFC	R365mfc[a]	1,1,1,3,3-Pentafluorobutane	$CF_3CH_2CF_2CH_3$	186.9	32.7	0	804	A2	40.2	148.1	8.9
	SES36[b]	R365mfc/perfluoro-polyether	R365mfc/PFPE (65/35)	177.6	28.5	0	3'126[c]	A2	35.6	184.5	10.5
	R245ca	1,1,2,2,3-Pentafluoropropane	$CHF_2CF_2CH_2F$	174.4	39.3	0	716	n.a	25.1	134.0	n.a.
	R245fa[d]	1,1,2,2,3-Pentafluoropropane	$CHF_2CH_2CF_3$	154.0	36.5	0	858	B1	14.9	134.0	6.6
	R236fa	1,1,1,3,3,3-Hexafluoropropane	$CF_3CH_2CF_3$	124.9	32.0	0	8'060	A1	-1.4	152.0	10.2
	R152a	1,1-Difluoroethane	CH_3CHF_2	113.3	45.2	0	138	A2	-24.0	66.1	n.a.
	R227ea	1,1,1,2,3,3,3-Heptafluoropropane	CF_3CHFCF_3	101.8	29.3	0	3'350	A1	-15.6	170.0	6.9
	R134a	1,1,1,2-Tetrafluoroethane	CH_2FCF_3	101.1	40.6	0	1'300	A1	-26.1	102.0	1.2
	R410A	R32/R125 (50/50 mixture)	CH_2F_2/CHF_2CF_3	72.6	49.0	0	2'088	A1	-51.5	72.6	2.9
HFO	R1336mzz(Z)[e]	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	n.a.
	R1234ze(Z)	cis-1,3,3,3-Tetrafluoro-1-propene	$CF_3CH{=}CHF$(Z)	150.1	35.3	0	<1	A2L[f]	9.8	114.0	n.a.
	R1336mzz(E)[g]	trans-1,1,1,4,4,4,-Hexafluoro-2-butene	$CF_3CH{=}CHCF_3$(E)	137.7	31.5	0	18	A1	7.5	164.1	n.a.
	R1234ze(E)	trans-1,3,3,3-Tetrafluoro-1-propene	$CF_3CH{=}CHF$(E)	109.4	36.4	0	<1	A2L	-19.0	114.0	5.6
	R1234yf	2,3,3,3-Tetrafluoro-1-propene	$CF_3CF{=}CH_2$	94.7	33.8	0	<1	A2L	-29.5	114.0	13.8
HCFO	R1233zd(E)[h]	1-chloro-3,3,3-Trifluoro-propene	$CF_3CH{=}CHCl$(E)	166.5	36.2	0.00034	1	A1	18.0	130.5	6.3
	R1224yd(Z)[i]	1-chloro-2,3,3,3-Tetrafluoro-propene	$CF_3CF{=}CHCl$(Z)	155.5	33.3	0.00012	<1	A1	14.0	148.5	n.a.
HC	R601	Pentane	$CH_3CH_2CH_2CH_2CH_3$	196.6	33.7	0	5	A3	36.1	72.2	4.9
	R600	Butane	$CH_3CH_2CH_2CH_3$	152.0	38.0	0	4	A3	-0.5	58.1	1.8
	R600a	Isobutane	$CH(CH_3)_2CH_3$	134.7	36.3	0	3	A3	-11.8	58.1	1.0
	R290	Propane	$CH_3CH_2CH_3$	96.7	42.5	0	3	A3	-42.1	44.1	1.1
	R1270	Propene	$CH_3CH{=}CH_2$	91.1	45.6	0	2	A3	-47.6	42.1	1.0
CF6	Novec 649[j]	Dodecafluoro-2-methyl-3-pentanone	$CF_3CF_2C(O)CF(CF_3)_2$	168.7	18.8	0	<1	n.a.	49.0	316.0	6.8
Ether	E170	Dimethyl ether	CH_3OCH_3	127.2	53.4	0	1	A3	-24.8	46.1	39.0
Natural	R718	Water	H_2O	373.9	220.6	0	0	A1	100.0	18.0	5.6[k]
	R717	Ammonia	NH_3	132.3	113.3	0	0	B2L	-33.3	17.0	27
	R744	Carbon dioxide	CO_2	31.0	73.8	0	1	A1	-78.5	44.0	1.0

CFC = Chlorofluorocarbons, HCFC = Hydrochlorofluorocarbons, HFC = Hydrofluorocarbons, HFO = Hydrofluoroolefins, HCFO = Hydrochlorofluoroolefins HC = Hydrocarbons, T_{crit} = critical temperature, p_{crit} = critical pressure, ODP = Ozone Depletion Potenial (R11=1.0, UNEP, 2017), GWP_{100} = Global Warming Potential (CO_2=1.0, 100 years, EU F-Gas Regulation 517/2014, Myhre et al., 2013), SG = Safety Group (DIN EN 378-1, 2008, ASHRAE 34), NBP = Boiling point at 1.013 bar, *M* = Molecular weight, Relativer price per kg refrigerant compared to CO_2 of 9 Euro/kg (based on a 10 kg vessel, October 2017), n.a. = price not yet available but close to market, [a]Solkane® 365mfc from Solvay, [b]Solkatherm® SES36 from Solvay, [c]Lewandowski et al. (2010), [d]R245fa from Linde or Honeywell (Genetron® 245fa).[e]Opteon™ MZ from Chemours, [f]Fukuda et al. (2014), [g]Juhasz (2017), [h]Solstice® zd from Honeywell, [i]AMOLEA® 1224yd from AGC Chemicals, [j]Novec™ 649 from 3M, [k]Molecular biological quality

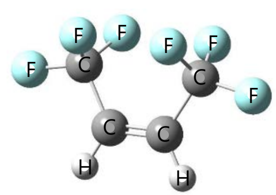
cordin.arpagaus@ntb.ch

Suitable properties of HFO and HCFO refrigerants for HTHPs

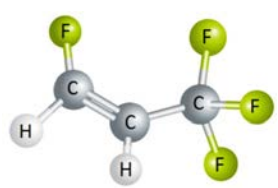
SCCER EFFICIENCY OF INDUSTRIAL PROCESSES

Type	Refrigerant	Chemical formula	T_{crit} [°C]	p_{crit} [bar]	ODP [-]	GWP_{100} [-]	SG	Price [EUR/kg]
HFO	R1336mzz(Z)[a]	$CF_3CH=CHCF_3(Z)$	171.3	29.0	0	2	A1	n.a.
	R1234ze(Z)[b]	$CF_3CH=CHF(Z)$	150.1	35.3	0	<1	A2L	n.a.
HCFO	R1233zd(E)[c]	$CF_3CH=CHCl(E)$	166.5	36.2	0.00034	1	A1	50
	R1224yd(Z)[d]	$CF_3CF=CHCl(Z)$	155.5	33.3	0.00012	<1	A1	n.a.
HFC (comparison)	R365mfc[e]	$CF_3CH_2CF_2CH_3$	186.9	32.7	0	804	A2	80
	R245fa[f]	$CHF_2CH_2CF_3$	154.0	36.5	0	858	B1	57

HFO

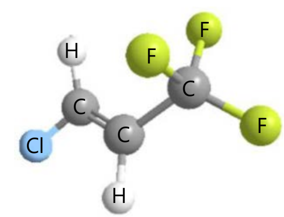


R1336mzz(Z)

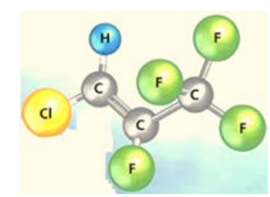


R1234ze(Z)

HCFO



R1233zd(E)



R1224yd(Z)

Remarks

- ODP basis R11=1.0 (UNEP, 2017)
- GWP100 for 100-year time horizon: basis CO2=1.0, IPCC 5th assessment report from Myhre et al. (2013) and F-Gas regulation No 517/2014 (EU, 2014)
- Safety group (SG) classification according to ASHRAE (2016)
- Approxiamte sales price per kg refrigerant (based on a 10 kg container, prices from PanGas, Climalife, and Solvay, October 2017), n.a. price not yet available but refrigerant is close to market
- [a]Opteon™ MZ from Chemours, [b]Fukuda et al. (2014), [c]Solstice® zd from Honeywell (2016), [d]AMOLEA® 1224yd from AGC Chemicals (2017), [e]Solkane® 365mfc from Solvay, [f]Genetron® 245fa from Honeywell

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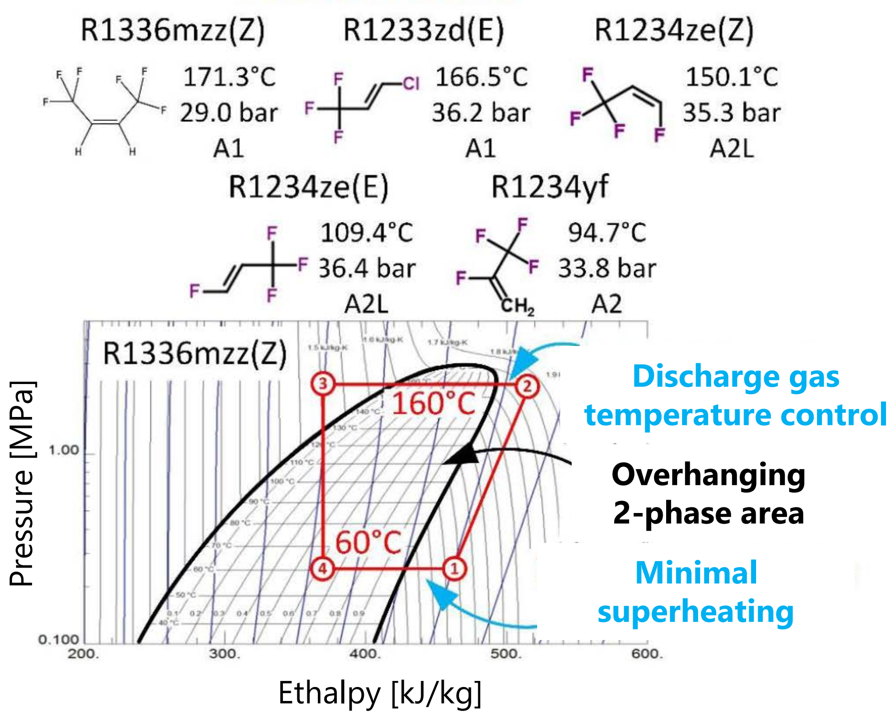
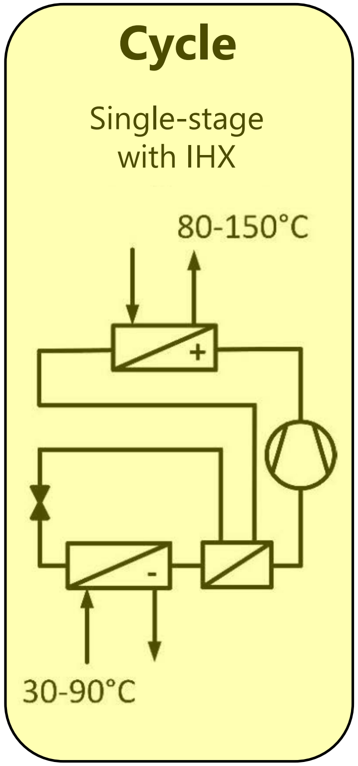
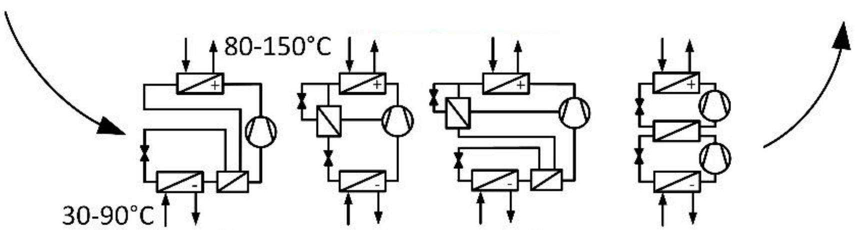
Possible concept for a HTHP laboratory prototype

HFO and HFCO refrigerants







Decision criteria:

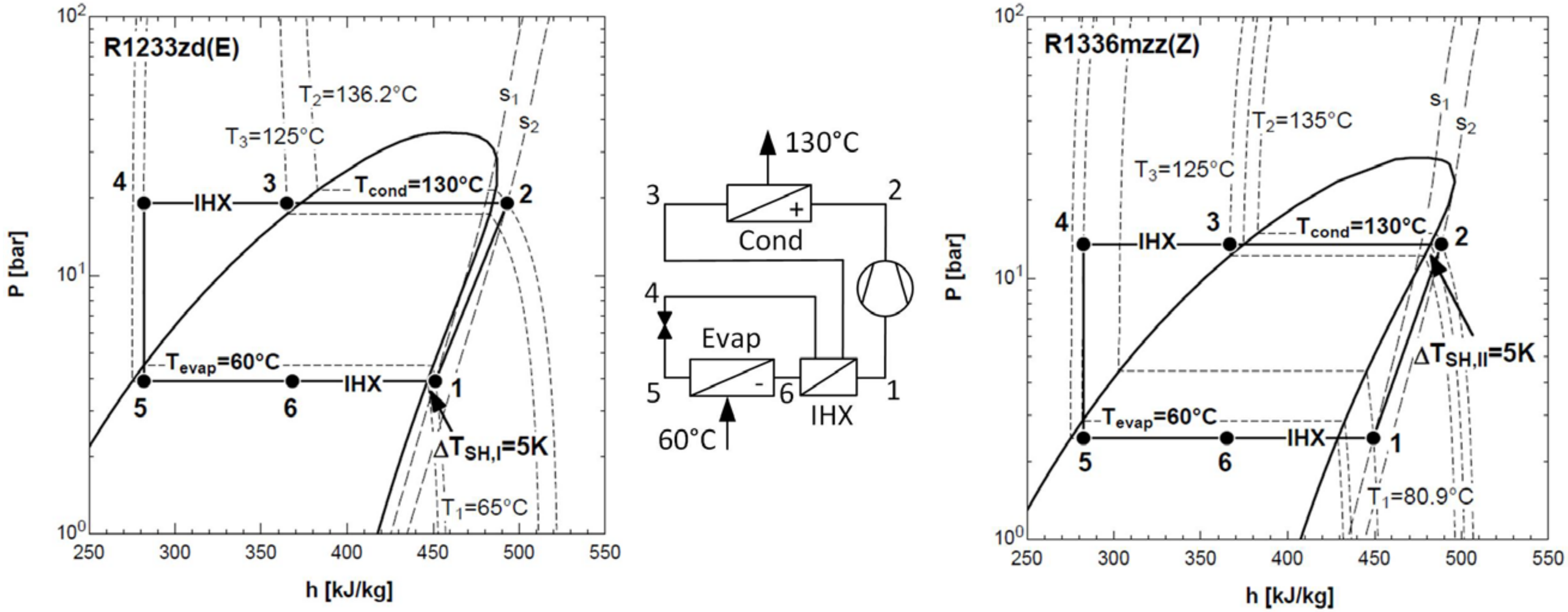
1) **Thermodynamic suitability** (T_{crit} > 150°C, allows subcritical operation, good efficiency at high temperatures)

2) **Environmental compatibility** (GWP <10, ODP = 0, future-proof according to F-Gas regulation)

3) **Safety** (no or only low flammability)

4) **Natural refrigerants**, like R600, R600a and R601 **excluded** due to flammability (A3), other refrigerants due to lack of information and availability

Single-stage cycle with IHX

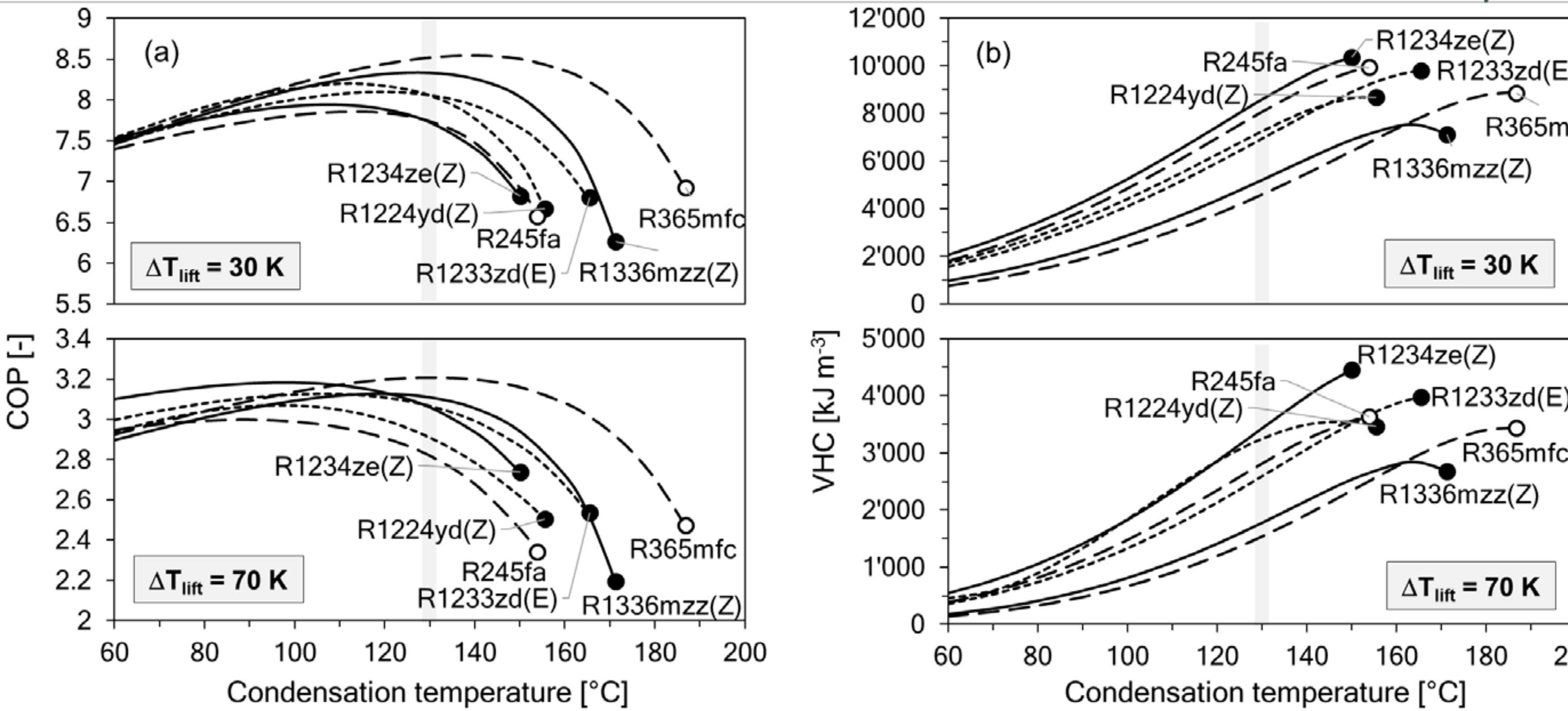


$$VHC = (h_2 - h_3)\rho_1$$
$$COP = (h_2 - h_3)/(h_2 - h_1)$$

Assumptions:

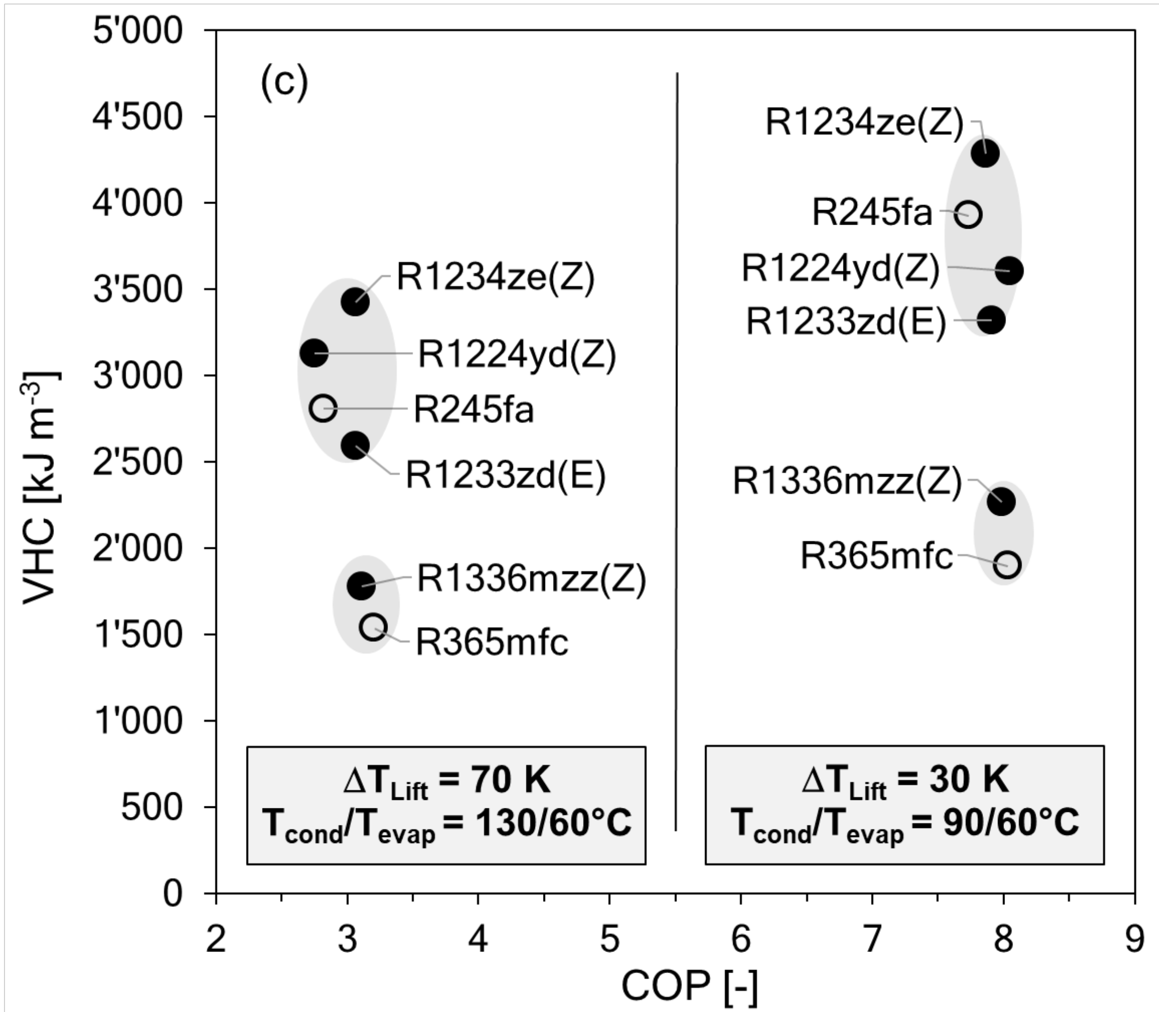
- Constant compressor isentropic efficiency of 0.7
- 5 K superheating ($\Delta T_{SH,I}$) at compressor inlet for R1233zd(E), R1234ze(Z), R245fa
- 5 K superheating ($\Delta T_{SH,II}$) at comp. outlet for R1336mzz(Z), R1224yd(Z), R365mfc
- 5 K subcooling ($T_{SC} = 5\ K$), i.e. low heat sink temperature glide
- 5 K minimum temperature difference within the IHX ($\Delta T_{IHX} = T_6 - T_4 = 5$ K)
- No parasitic pressure and heat losses ($h_5 = h_4$)

Simulation results



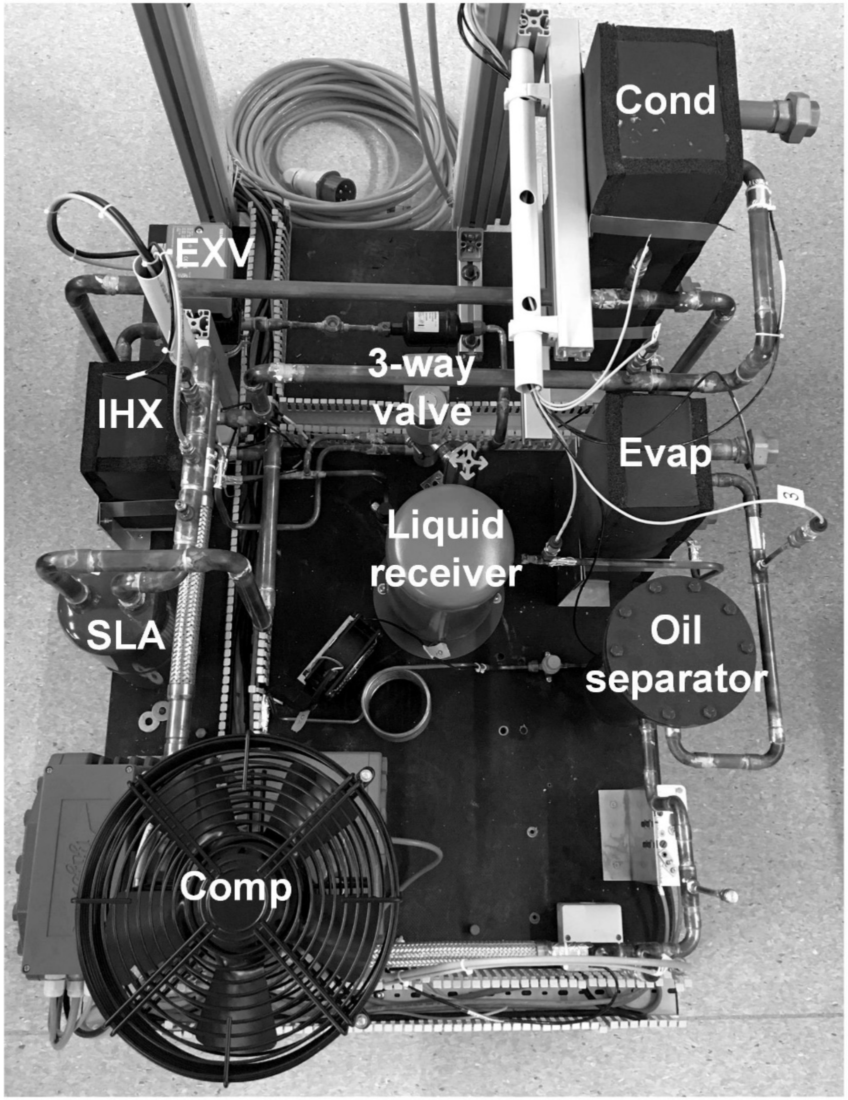
- Optimum condensation temperatures depending on refrigerant type (about 40 to 60 K below critical temperature)
- R365mfc provides the highest COP, R245fa the lowest
- R1234ze(Z) offers the highest VHC

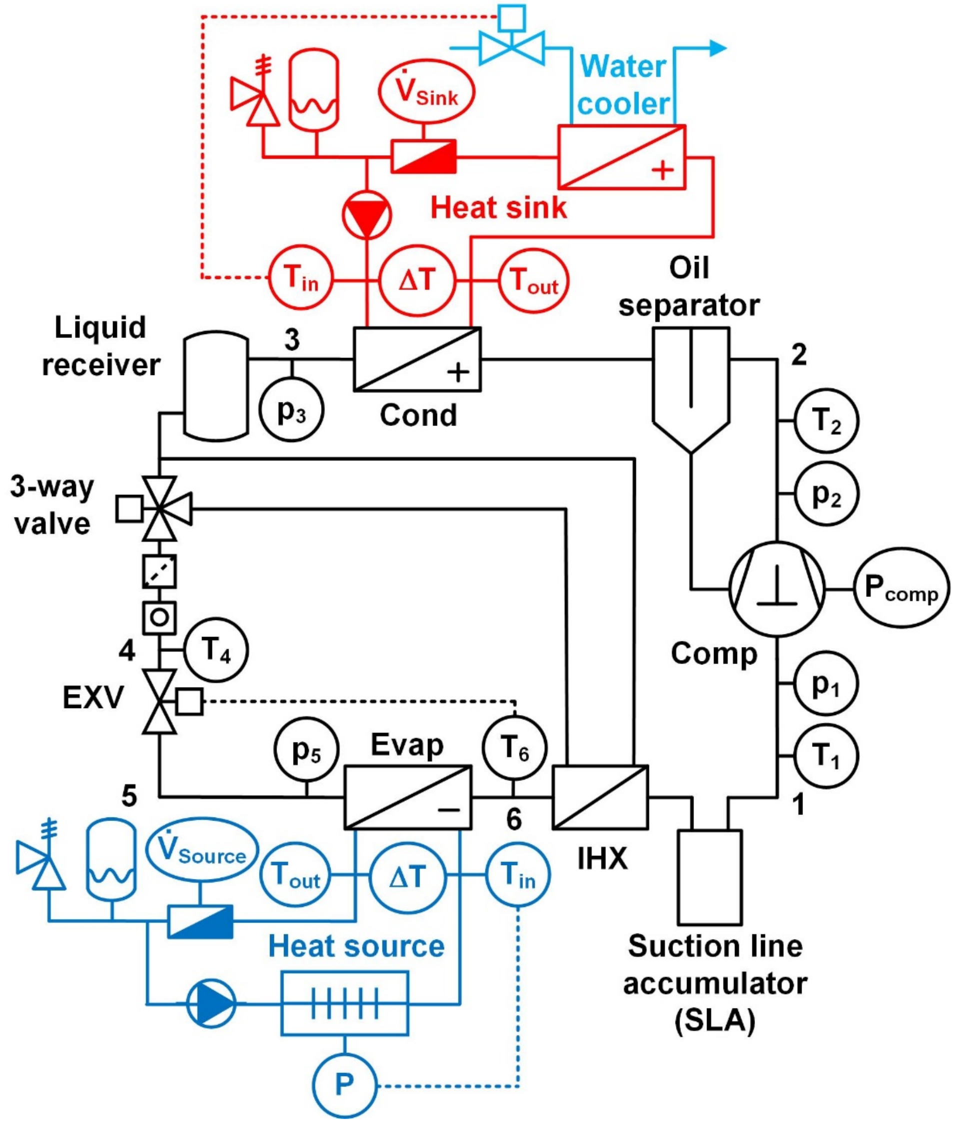
Simulation results



- R1336mzz(Z) is closest “drop-in” replacement for R365mfc
- R1224yd(Z), R1234ze(Z) and R1233zd(E) closer to R245fa

Experimental setup





Laboratory scale HTHP

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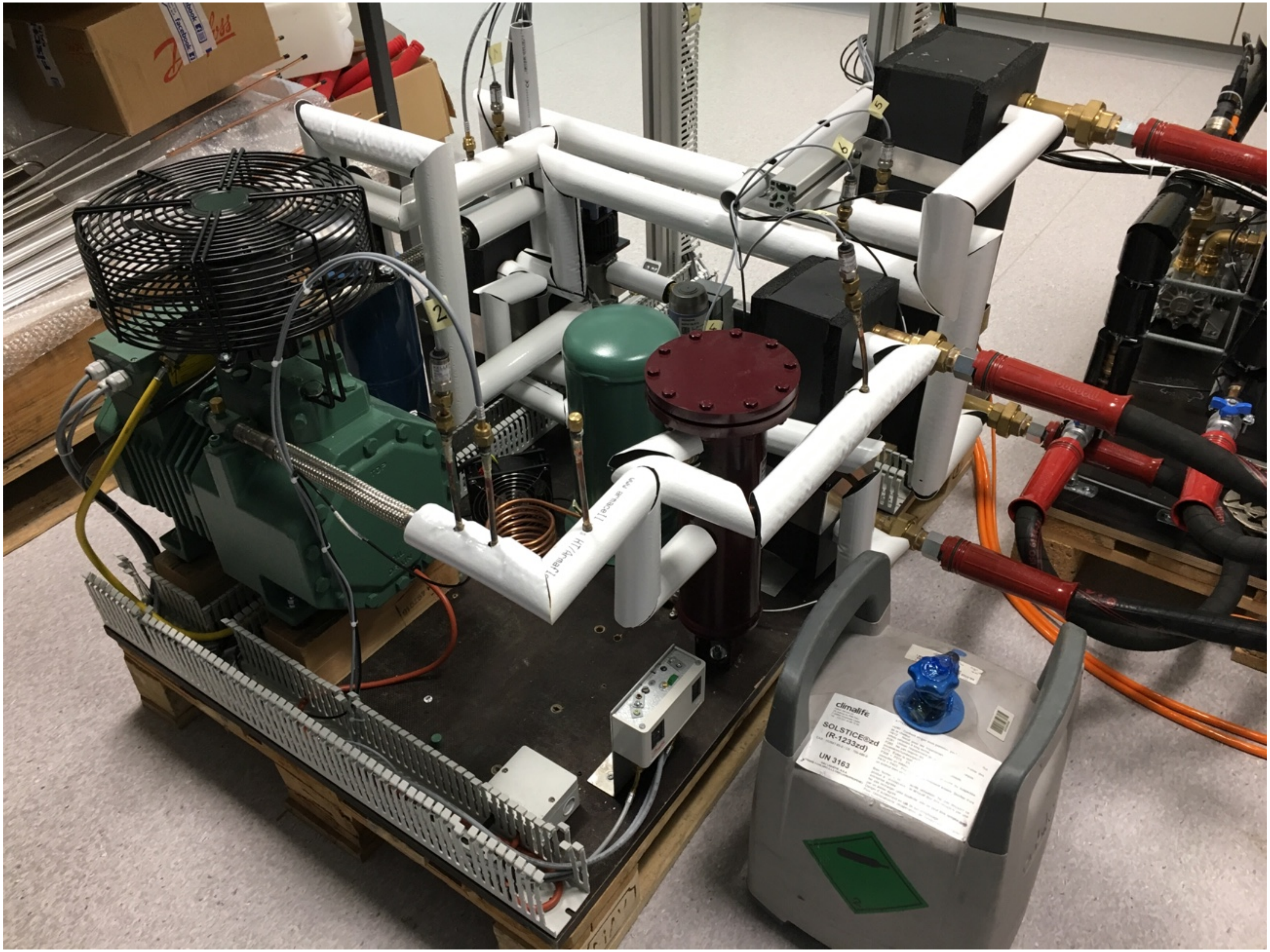

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HTHP with hydraulic loops for heat source and heat sink

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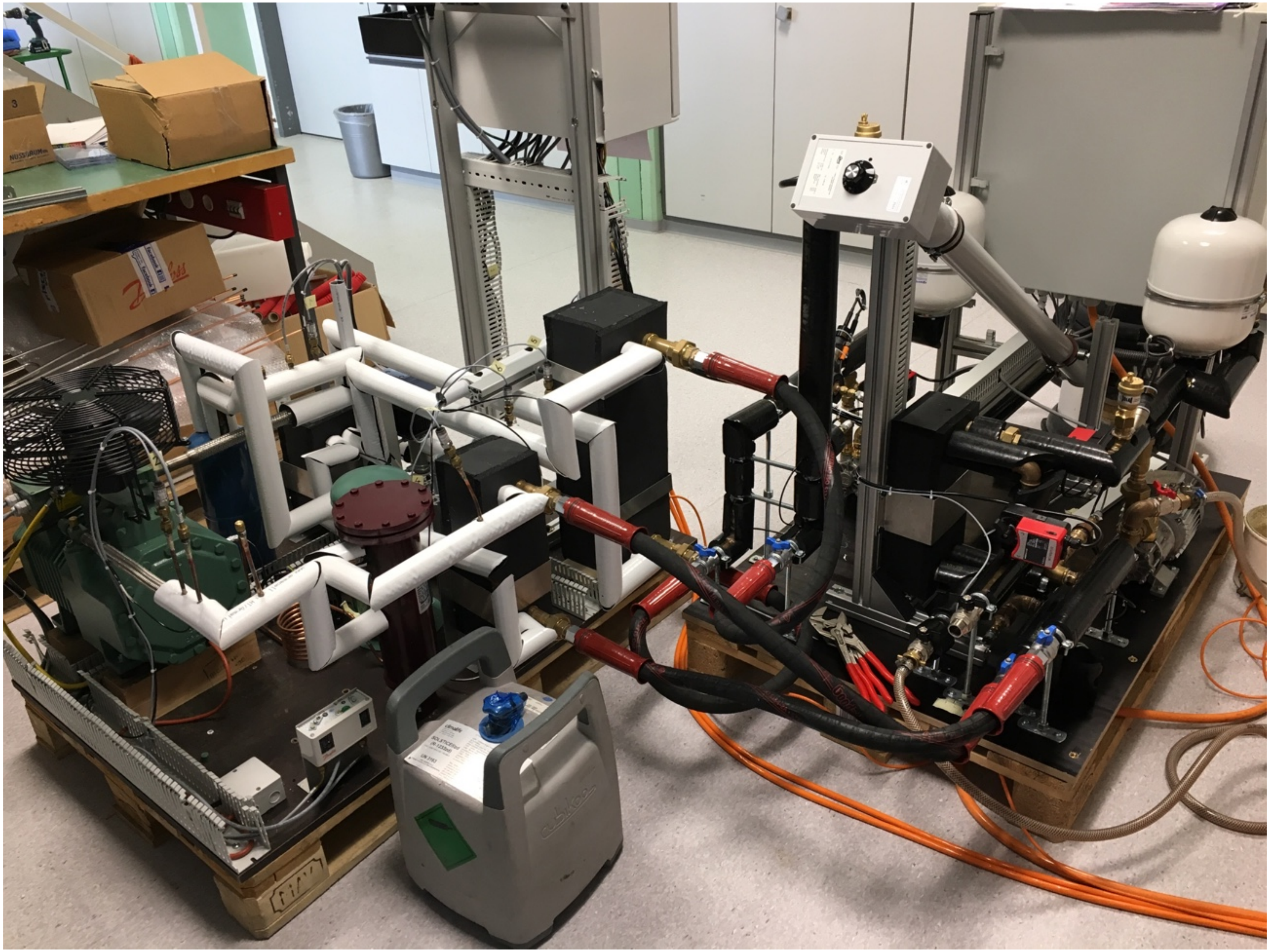

Experimental parameter study – Preliminary test results with R1233zd

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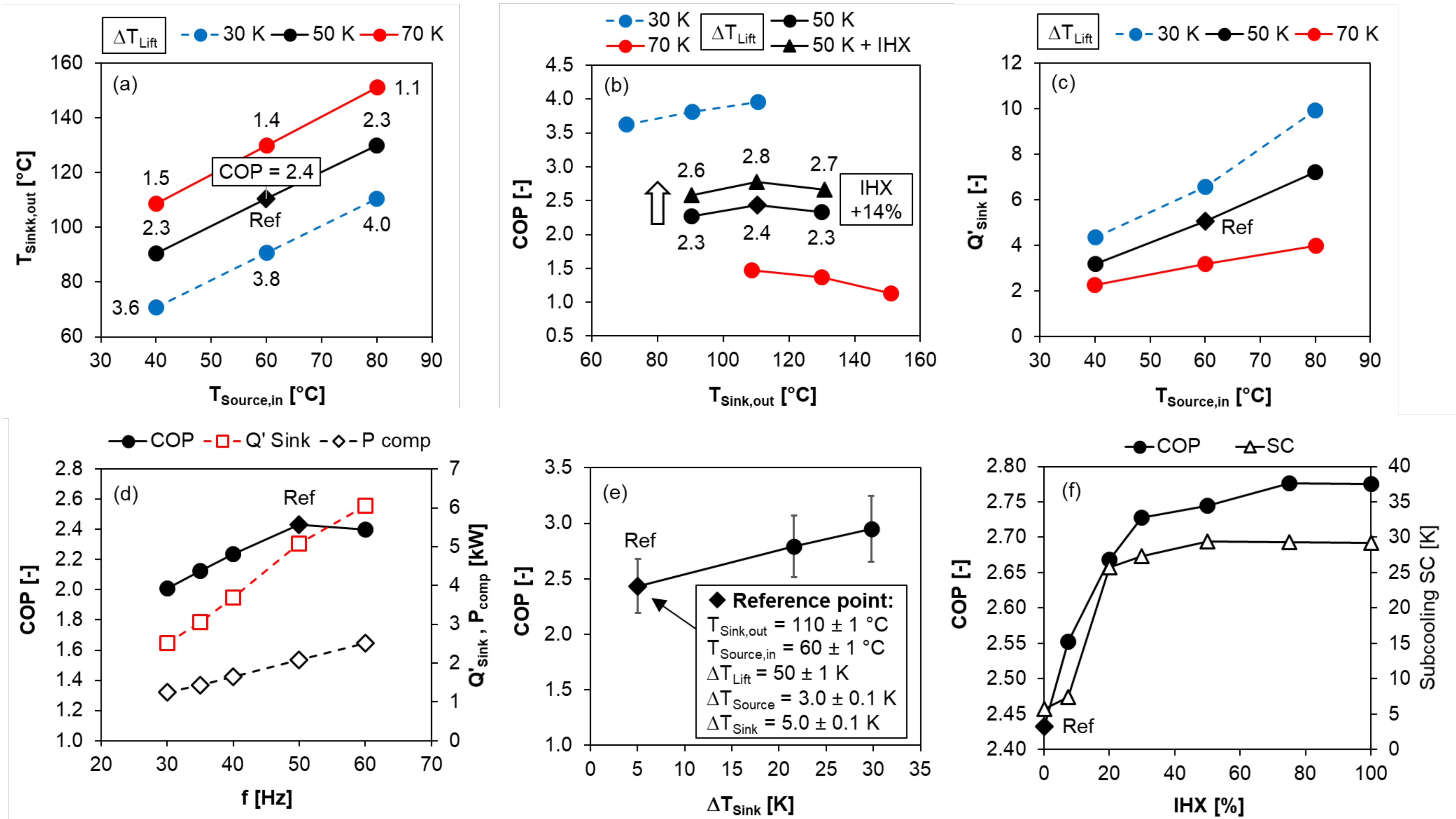

Conclusions

- **More than 20 industrial HTHPs identified on the market** with heat supply temperatures > 90°C. A few HTHPs exceed 120°C (using R245fa or R365mfc)
- **COPs range between 1.6 and 5.8** with a temperature lift of 130 to 25 K (40 to 60% 2nd Law efficiency)
- **Application potentials in industrial waste heat recovery** (e.g. drying & sterilization processes, papermaking, food preparation)
- **Several R&D projects on an international level** (COPs in the range of 5.7 to 6.5 at 30 K temperature lift, 2.2 to 2.8 at 70 K, max. 160°C)
- **Research trend** towards testing
  - natural refrigerants (e.g. R718, R744),
  - hydrocarbons (e.g. R600, R601)
  - and synthetic HFOs (e.g. R1336mzz(Z), R1234ze(Z), R1233zd(E), and R1224yd(Z)) with low GWP (< 10)

cordin.arpagaus@ntb.ch

Conclusions

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- **Theoretical simulations**
  - **Tradeoff** between COP and VHC
  - **R1336mzz(Z)** is next drop-in replacement for R365mfc
  - **R1224yd(Z), R1234ze(Z) and R1233zd(E)** are closer to R245fa
- **Experimental HTHP set-up**
  - **Standard components** (single-stage with adjustable IHX for superheating and efficiency increase of +14%)
  - **Tested with** commercially available HCFO **R1233zd(E)**
  - **Operation demonstrated** at 40 to 80°C heat source and 70 to 150°C heat supply temperatures (e.g. drying processes or steam generation)
  - **COP of 2.43** at W60 / W110 (50 K temperature lift)
  - **+21% COP** by increasing heat sink temp. difference from 5 to 30 K
- **Future work**
  - **Testing R1336mzz(Z) and R1224yd(Z)**
  - **Reduction of thermal losses** (better insulation)

Acknowledgement

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Literature - further work on high temperature heat pumps

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- Arpagaus C., Bless F., Uhlmann M., Schiffmann J., Bertsch S.S.: ***Review - High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials***, Energy, 2018, 152, 985-1010.

- Bertsch S.S, Arpagaus C., Bless F., Weickgenannt A., Schiffmann J.: ***Theoretical investigation of a high temperature heat pump using a micro turbo compressor and water as a refrigerant***, 13th IIR-Gustav Lorentzen Conference on Natural Refrigerants, June 18-20, 2018, Valencia, Spain.

- Arpagaus C., Bless F., Schiffmann J., Bertsch S.S.: ***Review on high temperature heat pumps - market overview and research status***, International Workshop on High Temperature Heat Pumps, Sept 11, 2017, Copenhagen, Denmark.

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- Arpagaus C.; Bless, F.; Schiffmann J.; Bertsch S.S.: ***Multi-temperature heat pumps: A literature review***, International Journal of Refrigeration, 2016, 69, 437–465.

Thank you for your attention!

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Contact details: cordin.arpagaus@ntb.ch
+41 81 755 34 94

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