IDENTIFICATION AND TEST OF LOW GLOBAL WARMING POTENTIAL ALTERNATIVES TO HFC-245FA IN ORGANIC RANKINE CYCLES

ASME ORC 2013
OCTOBER 8 2013

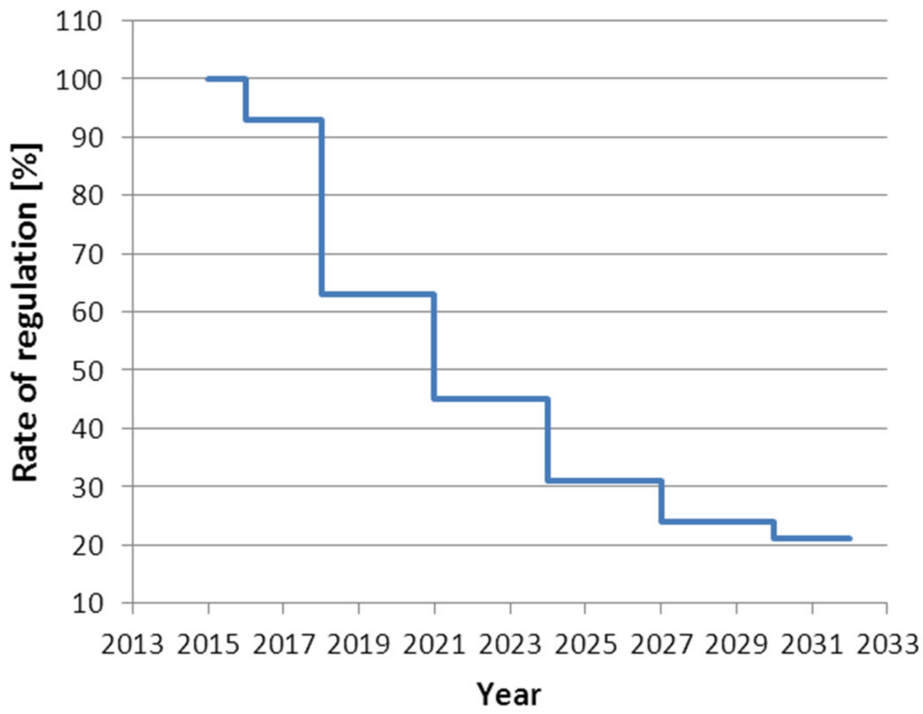
Pierre Huck, GE Global Research-Munich, Germany
Anna Lis Laursen, GE Global Research-Niskayuna, NY, USA
Jalal Zia, GE Global Research-Niskayuna, NY, USA
Lance Woolley, GE Power and Water-Cerritos, CA, USA

imagination at work

Motivation

November 2012: EU commission proposal revising the F-Gas regulation:

- Cap and phase-down on the amount of high Global Warming Potential (GWP) fluids placed on the EU market in terms of mass of CO_2 equivalent
- HFC-245fa has a GWP (100 years) of 1030 in the regulation
- Availability of HFC-245fa may decrease and its cost might increase



Identify low global warming potential (GWP) alternatives to HFC-245fa

Outline

- Properties of the Three Candidate Fluids
- Cycle Simulations
  - Cycle model and boundary conditions
  - Modeling results and downselection based on net electrical power
- Experimental Assessment
  - Testing procedure
  - Experimental results
- Conclusion and Next Steps

Properties of Candidate Fluids

Fluid	Formula	Mol. weight	Critical temperature	Normal boiling point	Atm. lifetime	Global warming potential, 100 years, net	Flammability under ASHRAE Std 34	Permissible Exposure Limit
[-]	[-]	[g/mol]	[°C]	[°C]	[-]	[-]	[-]	[ppm] TWA 8hrs
HFC-245fa	CF3-CH2-CHF2	134.1	154.0	15.1	7.6 years*	930* (858+)	1	400
HCFO-1233zd(E)	CHCl=CH-CF3	130.5	165.6	18.3	0.1 years*	7* (<1+)	1	800
HFO-1234yf	CH2=CF-CF3	114.0	94.7	-29.5	11 days*	4* (<1+)	2L	500
HFO-1234ze(E)	CHF=CH-CF3	114.0	109.4	-19.0	14 days*	6* (<1+)	2L	800

** Presented by Zyhowski et al., First International Seminar on ORC Power Systems, Delft, 2011*

+ Hodneborg et al., Global warming potentials and radiative efficiencies of halocarbons and related compounds: a comprehensive review, Rev. Geophys., 51, 300-378, 2013

Aspen HYSYS fluid model accuracy checked against NIST Refprop/supplier data

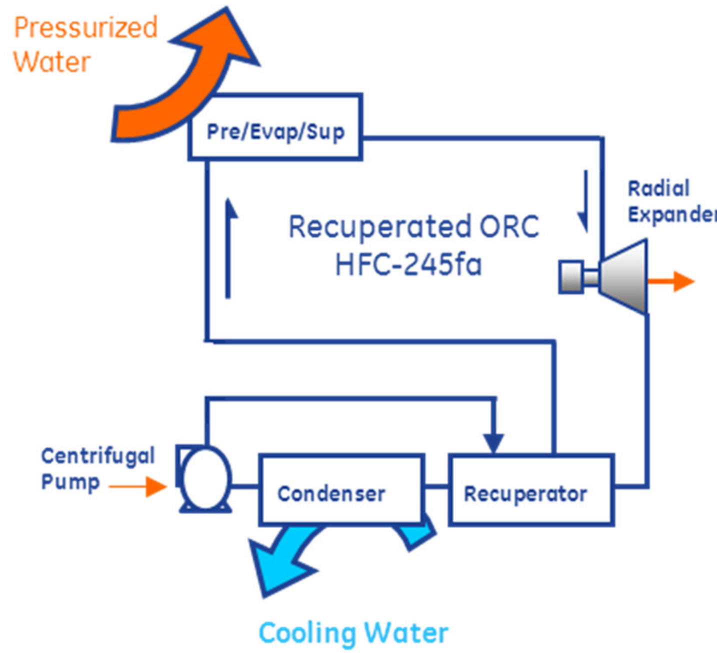
3 hydrofluoroolefin alternatives to HFC-245fa investigated

imagination at work

Cycle Model and Boundary Conditions

Simulation boundary conditions

Heat source in	[°C]	160
Heat source out	[°C]	140
Heat source flow	[kg/s]	constant
Cold sink in	[°C]	13/26
Cold sink flow	[kg/s]	constant
Pre/Evap/Sup UA	[kW/°C]	as baseline
Condenser UA	[kW/°C]	as baseline
Recuperator UA	[kW/°C]	as baseline
Expander electrical efficiency	[%]	constant
Pump efficiency	[%]	50
Superheating (if subcritical)	[°C]	14
Subcooling	[°C]	4
Relative pressure drop in heat exchangers (piping neglected)	[%]	constant

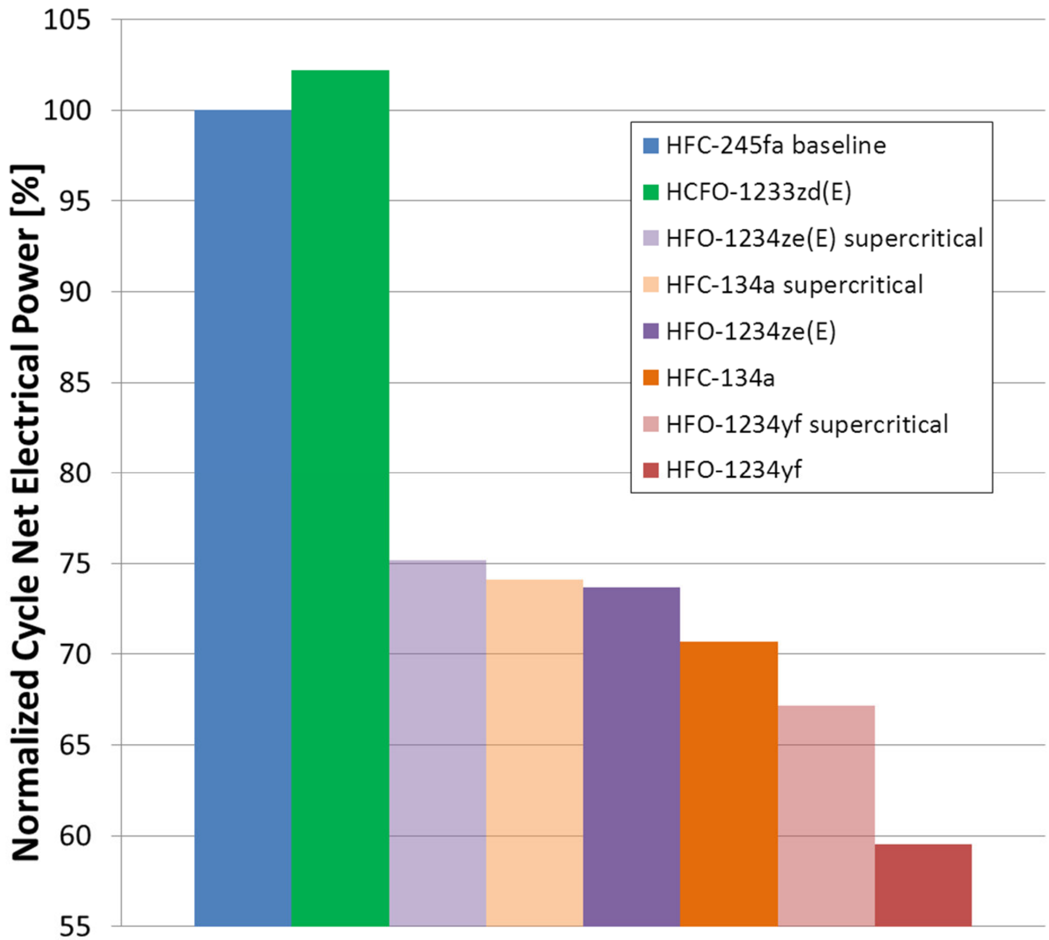


Modeling approach of the test unit of productized cycle:

- Each alternative working fluid uses **same heat exchangers** as HFC-245fa baseline (assuming similar heat transfer coefficients)
- But:
  - Expander/pump impeller diameter, rotating speed allowed to change
  - Top and bottom pressure levels as well as mass flow and piping diameter allowed to change

Minimize hardware changes when fluid changed

Modeling Results-Net Power Output



Heat sink temperature at 26°C. Similar trend at 13°C

- HCFO-1233zd(E) results in slight cycle net electrical power increase (2%)
- HFO-1234yf and HFO-1234ze(E) result in significant cycle net electrical power decrease. More adequate for HFC-134a replacement

Only HCFO-1233zd(E) further considered

Modeling Results-Detailed Comparison

Fluid	[-]	HFC-245fa	HCFO-1233zd(E)
Cycle net electrical power	[%]	100.0	102.2
Expander shaft power	[%]	100.0	100.6
Pump shaft power	[%]	100.0	89.2
Mass flow total	[%]	100.0	102.2
Expander			
Expander inlet temperature	[%]	100.0	99.6
Expander inlet pressure	[%]	100.0	84.6
Condenser			
Volume flow inlet	[%]	100.0	118.9
Outlet pressure (26°C cooling water)	[bar]	2.45	2.09
Outlet pressure (13°C cooling water)	[bar]	1.47	1.26

Fluid	[-]	HFC-245fa	HCFO-1233zd(E)
Inlet area: mass flow/(density*speed of sound)	[%]	100.0	121.6
Pressure ratio	[-]	7.8	7.7
Wheel diameter: Qout^0.5/H^0.25	[%]	100.0	107.4
Speed: H^0.75/Qout^0.5	[%]	100.0	94.7

- Increase of cycle net electrical power mostly driven by lower pumping power (slight increase of mass flow at lower top pressure)

- Maximum volume flow increased: larger pipe diameter required
- Minimum operating pressure above atmospheric: no air ingestion

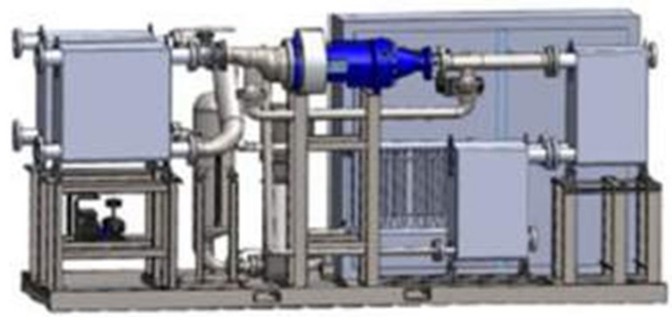
- Limited changes in key expander parameters

HCFO-1233zd(E) is an attractive alternative to HFC-245fa.
Drop-in replacement seems possible.
Assumption was validated experimentally

imagination at work

Testing Procedure

- Use of a test unit of a productized ORC
  - **Drop-in test**: all components, including radial expander, remained unchanged and as designed as for HFC-245fa
  - **Operational safety controls** adjusted because of fluid property differences



- Test matrix covering large operating range for HFC-245fa and HCFO-1233zd(E)

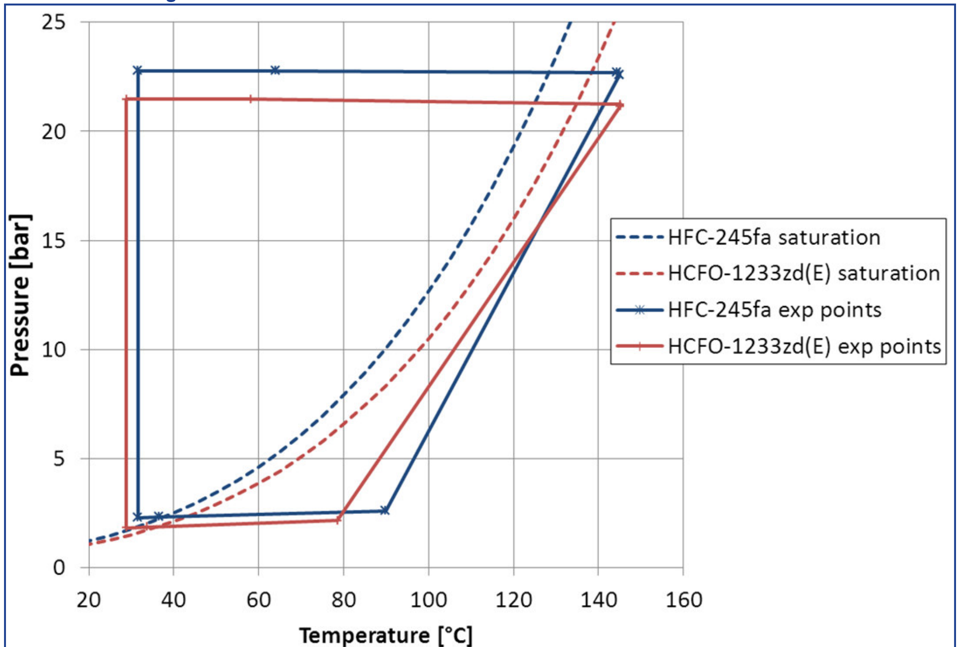
Operating Regime	Low	Normal	High
Cycle net grid power	71%, 86%	100%, 114%	124%, 133%
Expander inlet temperature	97%	100%	111%
Expander rotating speed	95%	100%	105%

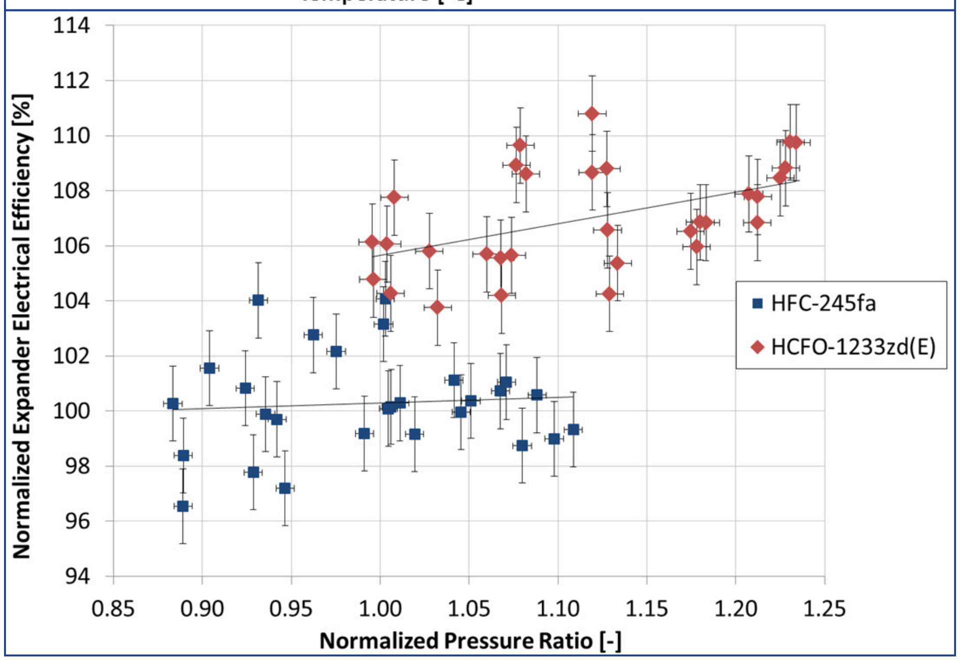
Cooling water temperature and mass flow kept constant

Drop-in replacement test.
Different from simulation approach

imagination at work

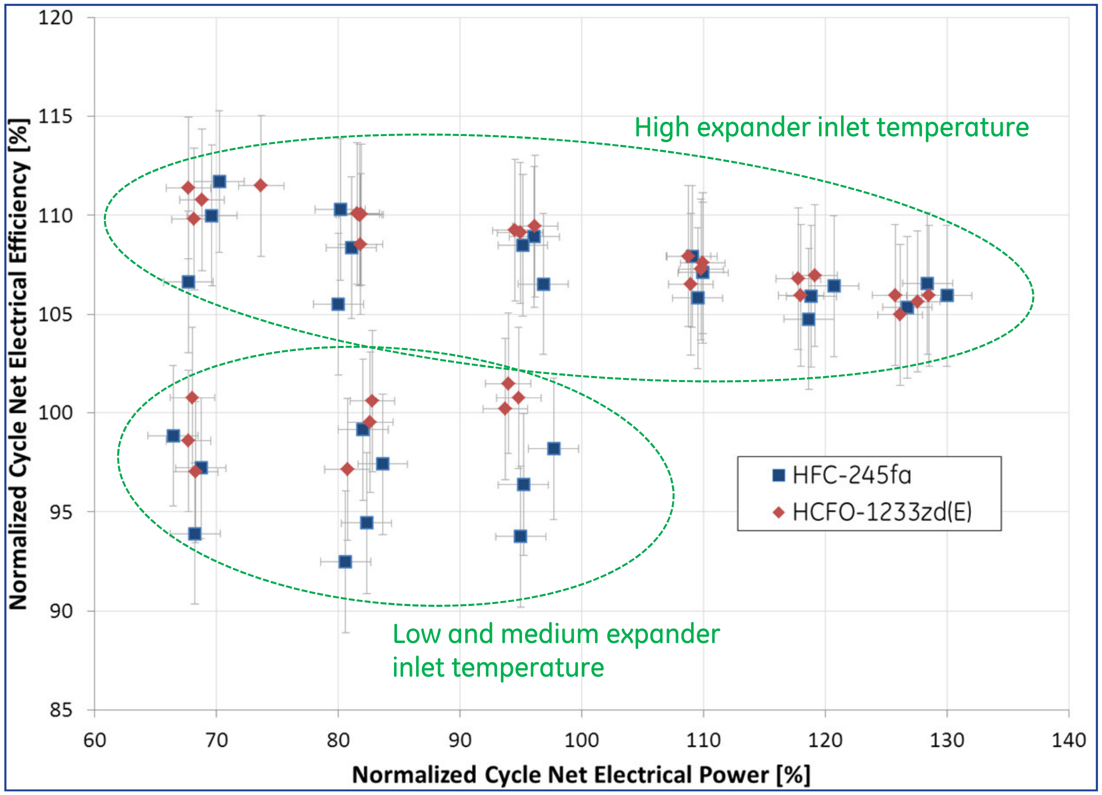
Experimental Results 1/2





- **Pressure level lower with HCFO-1233zd(E)**
  - 1.5bar lower at expander inlet for the same inlet temperature
  - 0.5bar lower at expander outlet
- **Expander pressure ratio higher with HCFO-1233zd(E)**
  - Based on saturation properties, HFC-245fa PR between two isotherms should be higher
  - But HCFO-1233zd(E) operates w/ lower superheating (relatively higher inlet pressure) and lower condensing temperature than HFC-245fa (relatively lower outlet pressure, over-dimensioned condenser)
- **Expander electrical efficiency more than 5% pts higher with HCFO-1233zd(E)**
  - Higher pressure ratio allows operating in a higher adiabatic efficiency region of the expander curve than with HFC-245fa
  - Operating HFC-245fa in this region would result in a lower overall cycle net efficiency

Experimental Results 2/2



- Grouping depending on expander inlet temperature
- Statistical analysis on complete population of experimental points incl. uncertainties concluded **there is no significant difference in cycle net electrical efficiency between HFC-245fa and HCFO-1233zd(E)**
    - Although HCFO-1233zd(E) expander electrical efficiency higher, parasitic load also higher
    - Larger volume flow in same pipes result in relative increase of pressure drop and pumping power

Additional results

- **Dynamic behavior**: similar time to reach steady-state (+/-5kW electrical power over 5 minutes) from start-up and shut-down to steady-state
- **Fluid thermal stability**: post-analysis with gas chromatography–mass spectrometry showed no sign of decomposition (limited run time of 72 hours)
- **Material compatibility**: silicone o-rings and seals used for HFC-245fa maintained integrity (limited run time)

imagination at work

Conclusion and Next Steps

- Cycle simulation effort down-selected HCFO-1233zd(E) as the working fluid that best matched the performance of HFC-245fa
- Experimental results showed that HFO-1233zd(E), when used as a drop-in replacement fluid in a cycle originally designed for HFC-245fa, consistently results in similar cycle net electrical efficiency
- As a low GWP and non-flammable working fluid, **HCFO-1233zd(E) is therefore a viable candidate as a drop-in replacement fluid to HFC-245fa** for the considered productized unit

Next steps

- Long term testing
- ORC optimized for HCFO-1233zd(E)
    - Simulation and experiments indicates it could outperform HFC-245fa
- Thermal stability and material compatibility at higher temperature
    - HCFO-1233zd(E) was run at a maximum of 150°C
- Comparison w/ other proposed LGWP fluids
    - Other hydrofluoroolefins
    - Hydrofluoroketones

imagination at work

Acknowledgment

We would like to acknowledge Ryan Hulse and Gary Zyhowski at Honeywell for their support throughout simulation and experimental investigations. Additional GE members that supported the experiments: Edip Sevincer, Huijuan (June) Chen, Ajilli Hardy and Chiranjeev Kalra, Rick Piel, Matteo Giovanetti, Tom Rising, Vinoth Rengarajan and Edward Fichtel.

Disclaimer

"This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability of responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, or process, or serviceable by trade name, trademark, manufacture, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state of reflect those of the U.S. Government or any agency thereof."

Thank you.