Semi-open sorption water heater: experimental results and theory of operation

Kyle R. Gluesenkamp

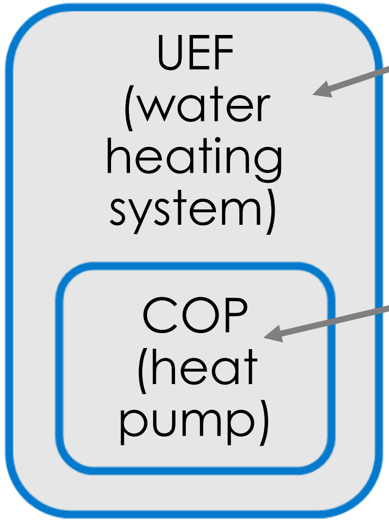
ACEEE Hot Water Forum
Nashville, March 13, 2019
Session 7B

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

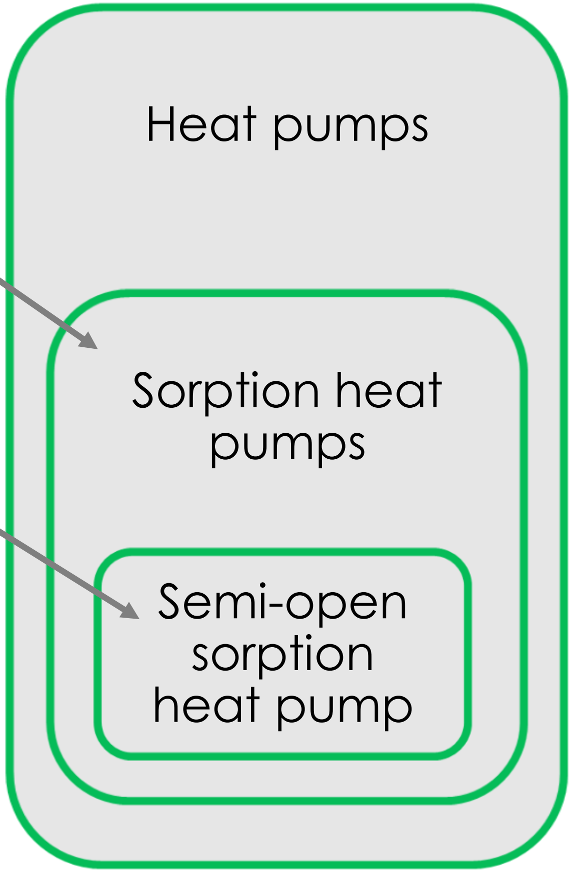
Acknowledgments

- Department of Energy (Contract DE-EE0006718.00)
- Antonio Bouza, DOE Building Technology Office
- Saeed Moghaddam and Devesh Chugh, University of Florida

Outline



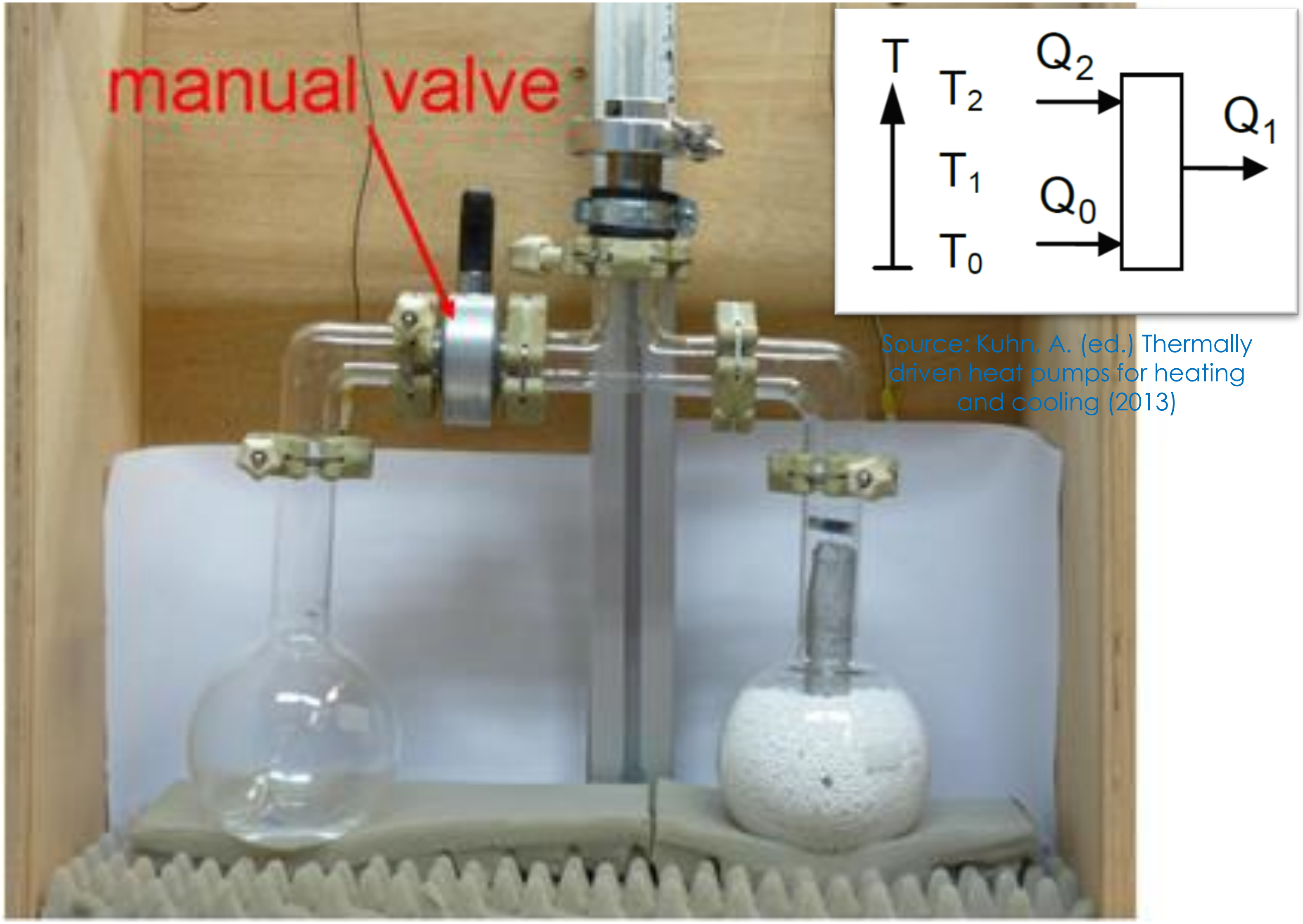
- What is a sorption heat pump?
  - What can system efficiency (UEF) be?
- What is a *semi-open* sorption heat pump?
  - Theory of operation
  - What can cycle efficiency (COP) be?
- Experimental results from prototype semi-open system
- Prospects for commercialization



Outline

- **What is a sorption heat pump?**
  - What can system efficiency (UEF) be?
- What is a *semi-open* sorption heat pump?
  - Theory of operation
  - What can cycle efficiency (COP) be?
- Experimental results from prototype semi-open system

What is a Sorption Heat Pump?

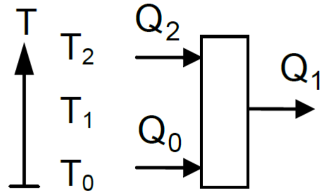


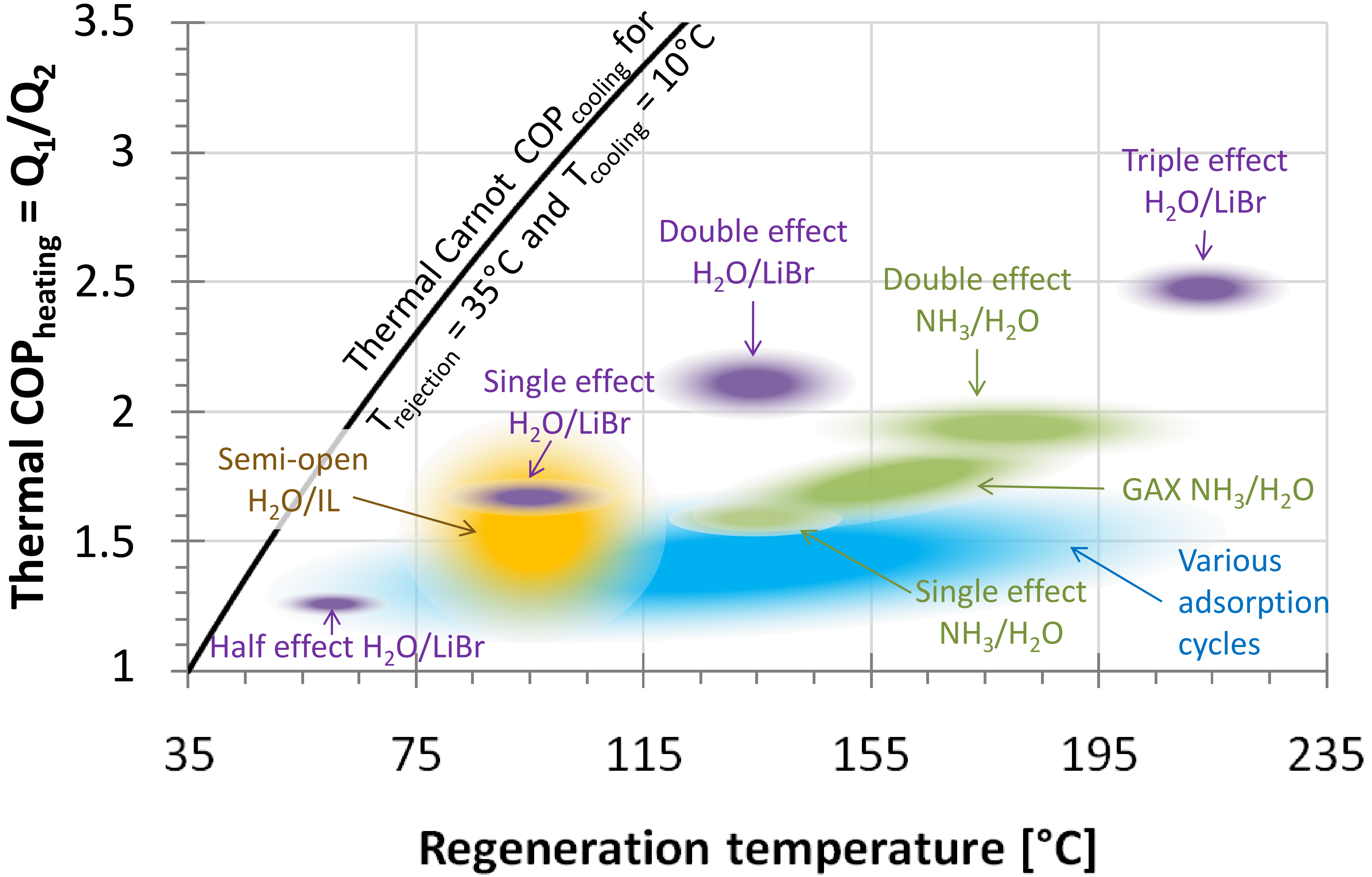
Source: Kuhn, A. (ed.) Thermally driven heat pumps for heating and cooling (2013)

Source: http://www.annex34.org/the-magic-of-thermal-cooling

OAK RIDGE National Laboratory | BUILDING TECHNOLOGIES RESEARCH AND INTEGRATION CENTER

Sorption Technologies





Semi-open can have higher or lower COP than closed (*depends on operating conditions*)

IL-based can have higher or lower regen temperature than LiBr (*depends on fluid*)

Adapted from: K. Gluesenkamp and R. Radermacher, "Heat Activated Cooling Technologies for Small and Micro CHP Applications," in ***Small and Micro CHP Systems***, R. Beith, Ed., ed Cambridge, UK: Woodhead Publishing Ltd., 2013.

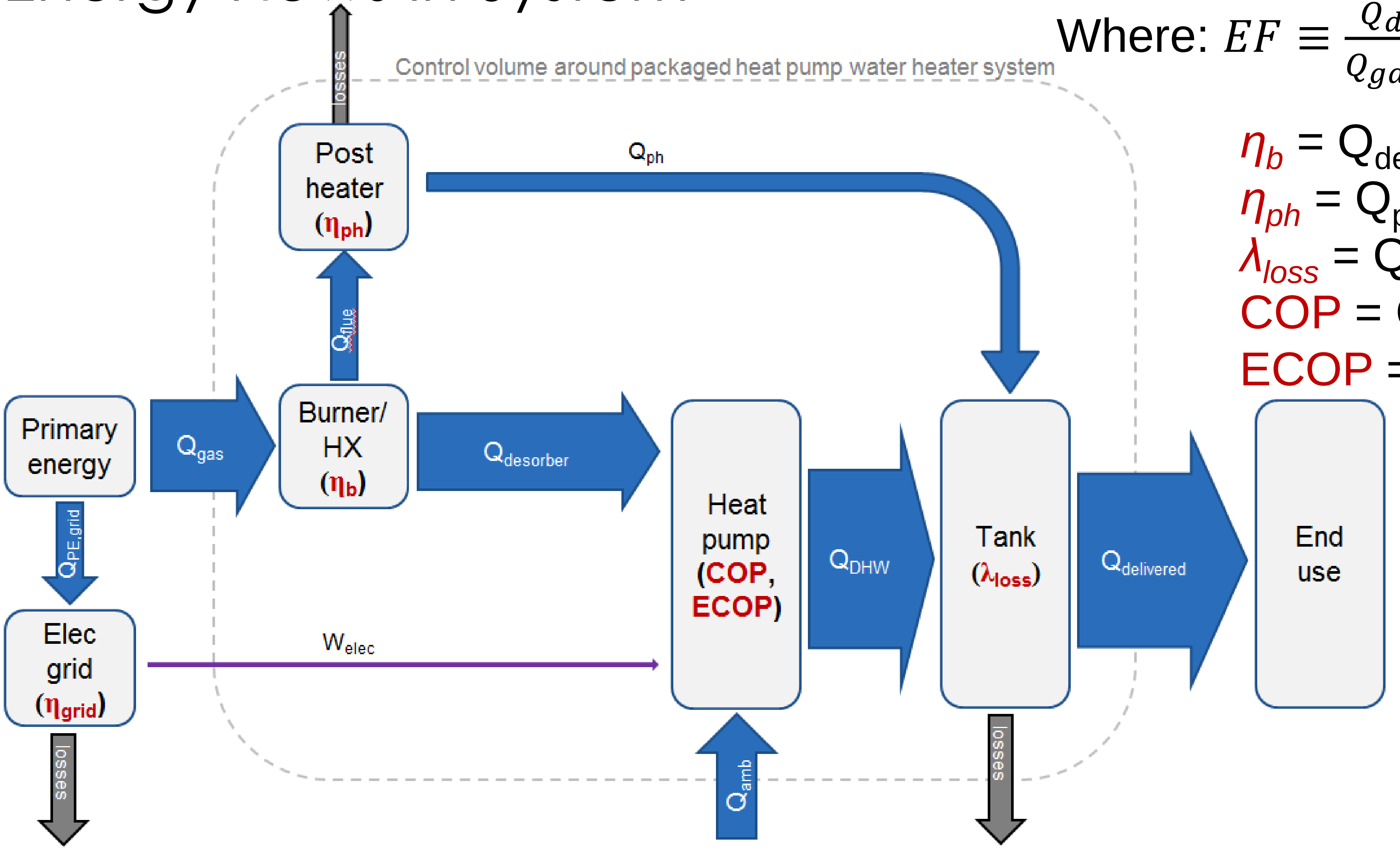
Outline

- What is a sorption heat pump?
  - **What can system efficiency (UEF) be?**
- What is a *semi-open* sorption heat pump?
  - Theory of operation
  - What can cycle efficiency (COP) be?
- Experimental results from prototype semi-open system

Energy Flows in System

Want: $EF = f(\eta_b, COP, \eta_{ph}, \lambda, ECOP)$

Where: $EF \equiv \frac{Q_{delivered}}{Q_{gas}+W_{elec}}$



$\eta_b = Q_{desorber}/Q_{gas}$

$\eta_{ph} = Q_{ph}/Q_{gas}$

$\lambda_{loss} = Q_{delivered}/(Q_{DHW} + Q_{ph})$

$COP = Q_{DHW}/Q_{desorber}$

$ECOP = Q_{DHW}/W_{elec}$

Gluesenkamp, K. (2016). “Energy Factor Analysis for Gas Heat Pump Water Heaters”, ***ASHRAE Annual Meeting 2016***, June 29, 2016, St. Louis, MO.

Writing EF as function of component performance

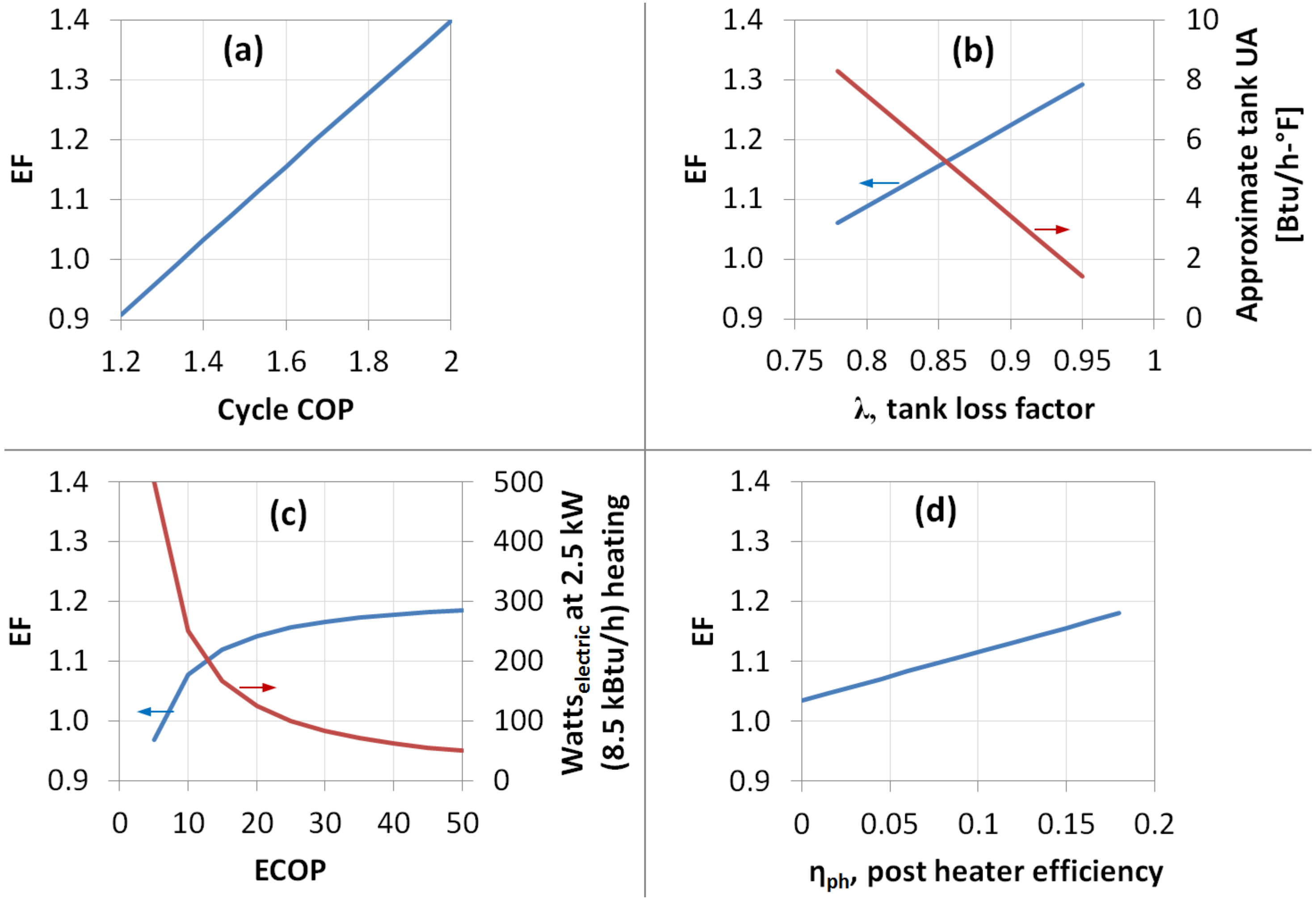
- Exact solution:

$$\frac{1}{EF} = \frac{1}{\lambda}\left(\frac{1}{\eta_b COP + \eta_{ph}} + \frac{1}{ECOP}\left(\frac{\eta_b COP}{\eta_b COP + \eta_{ph}}\right)\right)$$

- Approximation: η_bCOP/[η_bCOP + η_{ph}] = 1
  - Error of <1% under full range of parameters

$$\frac{1}{EF} = \frac{1}{\lambda}\left(\frac{1}{\eta_b COP + \eta_{ph}} + \frac{1}{ECOP}\right)$$

COP and UEF



$$\frac{1}{EF} = \frac{1}{\lambda}\left(\frac{1}{\eta_b COP + \eta_{ph}} + \frac{1}{ECOP}\right)$$

Except where explicitly varied along x-axis, parameters values are set to:

η_b = 0.8,

η_{ph} = 0.15,

λ = 0.85,

COP = 1.3, and

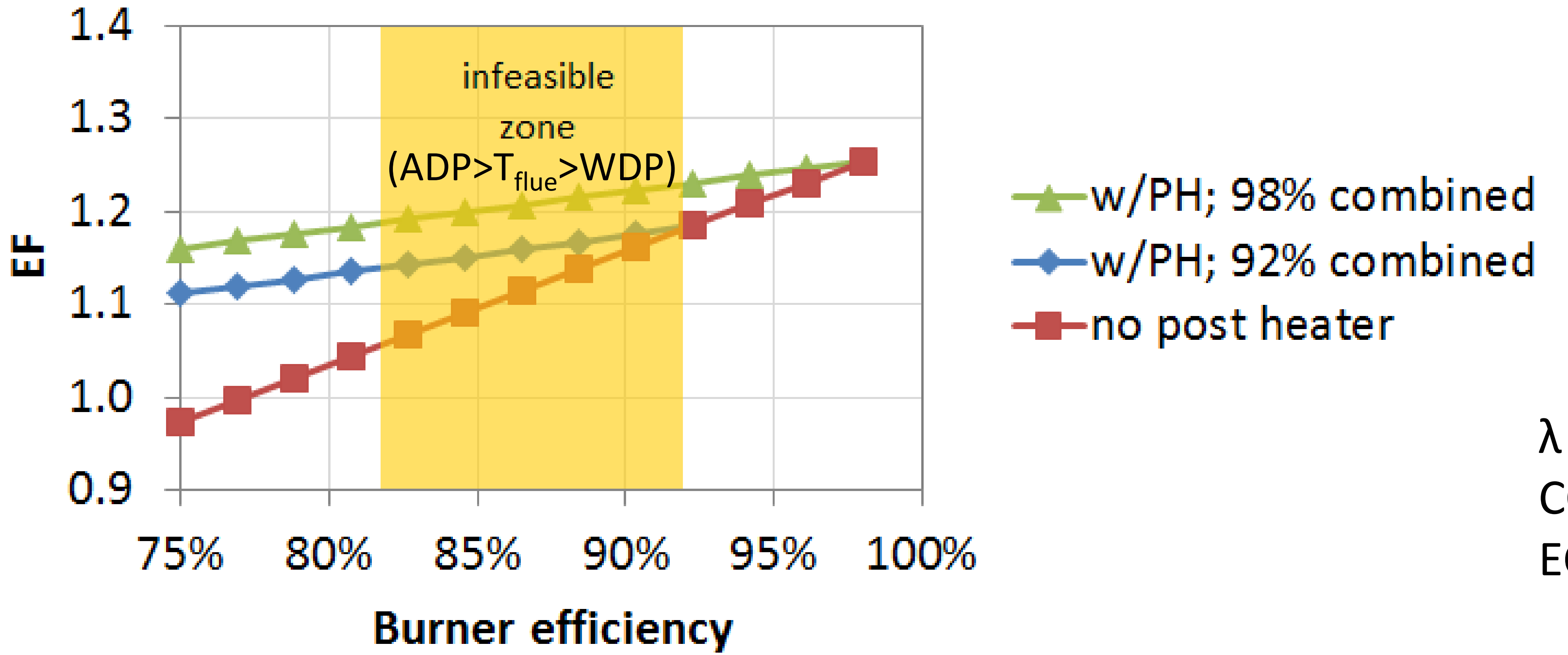
ECOP = 25.

Gluesenkamp, Kyle R.; Yang, Zhiyao; Abdelaziz, Omar (2017). "Translating cycle performance to system-level efficiency for sorption heat pumps." ***12th IEA Heat Pump Conference 2017***, Rotterdam, Netherlands, May 15–18, 2017.

Gluesenkamp, K. (2016). "Energy Factor Analysis for Gas Heat Pump Water Heaters", **Conference Paper Session 19, *ASHRAE Annual Meeting*** *2016*, June 29, 2016, St. Louis, MO.

COP and UEF

$$\frac{1}{EF} = \frac{1}{\lambda}\left(\frac{1}{\eta_b COP + \eta_{ph}} + \frac{1}{ECOP}\right)$$



$\lambda = 0.85$

COP = 1.6

ECOP = 25

Gluesenkamp, Kyle R.; Yang, Zhiyao; Abdelaziz, Omar (2017). "Translating cycle performance to system-level efficiency for sorption heat pumps." ***12th IEA Heat Pump Conference 2017***, Rotterdam, Netherlands, May 15–18, 2017.

Gluesenkamp, K. (2016). "Energy Factor Analysis for Gas Heat Pump Water Heaters", **Conference Paper Session 19, *ASHRAE Annual Meeting*** *2016*, June 29, 2016, St. Louis, MO.

Expected EF

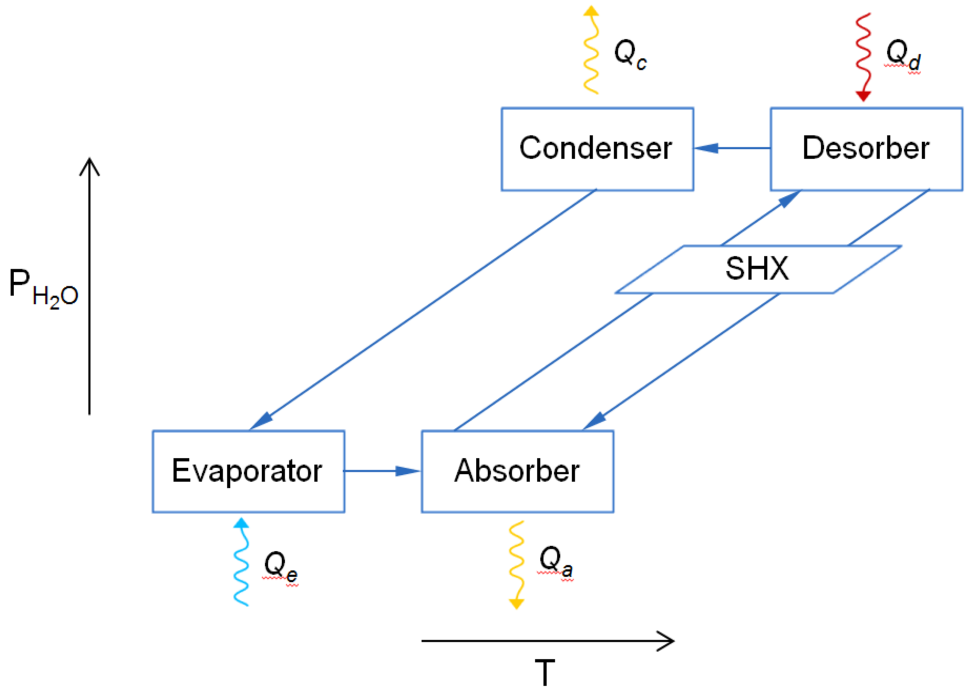
Hypothetical Example Systems				
Parameter	**Realistic System 1**	**Realistic System 2**	**Theoretical worst System 3**	**Theoretical best System 4**
η_b	0.80	0.82	0.75	0.92
η_{grid}	0.3	0.3	0.3	0.3
η_{ph}	0.12	0.14	0	0.06
λ	0.85	0.96	0.78	0.97
COP	1.6	1.6	1.3	2.0
ECOP	25	25	10	40
EF	**1.13**	**1.32**	**0.69**	**1.76**
PEF	1.02	1.17	0.57	1.59

Outline

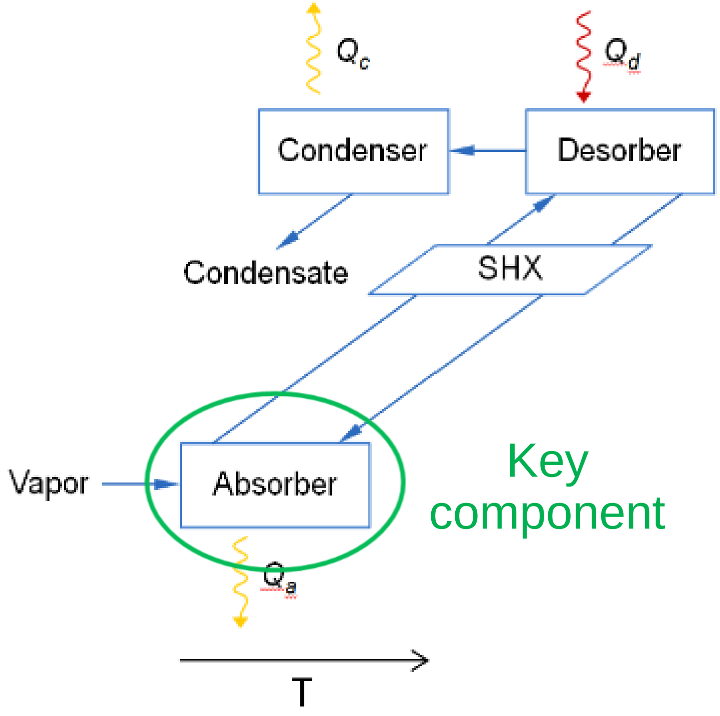
- What is a sorption heat pump?
  - What can system efficiency (UEF) be?
- **What is a *semi-open* sorption heat pump?**
  - Theory of operation
  - What can cycle efficiency (COP) be?
- Experimental results from prototype semi-open system

Semi-open Sorption Architecture

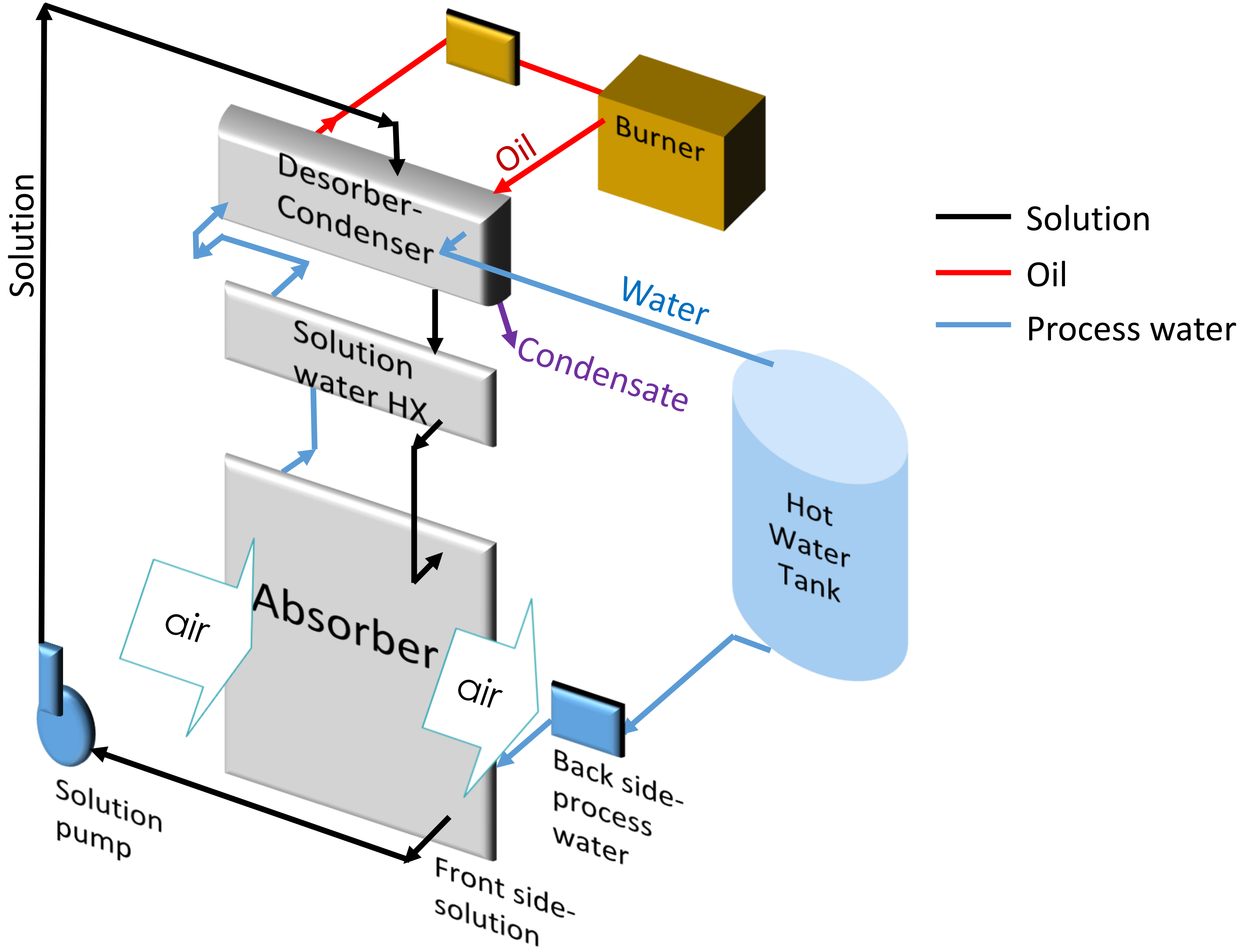
Traditional (closed)



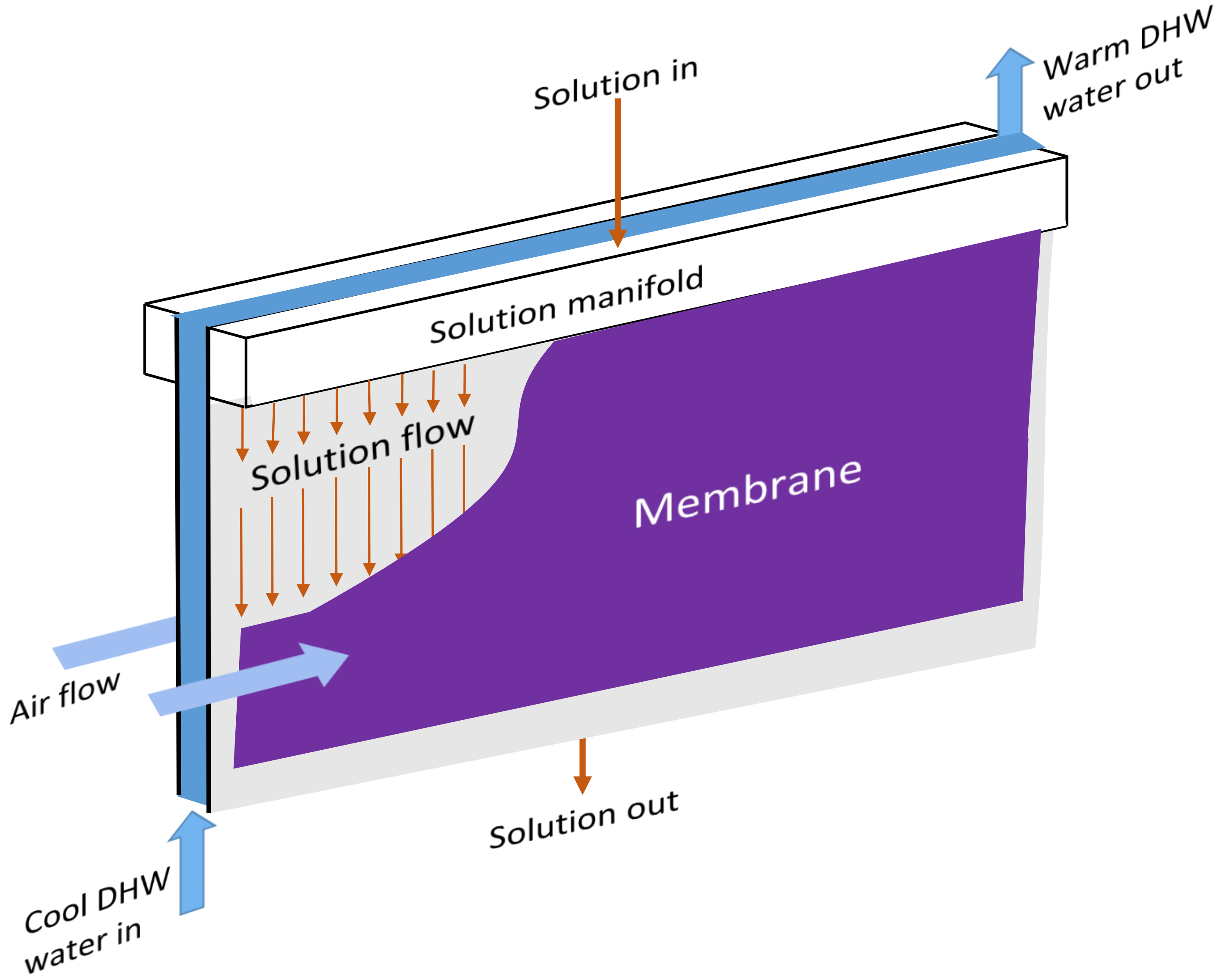
Semi-open



Semi-open Absorption Water Heater

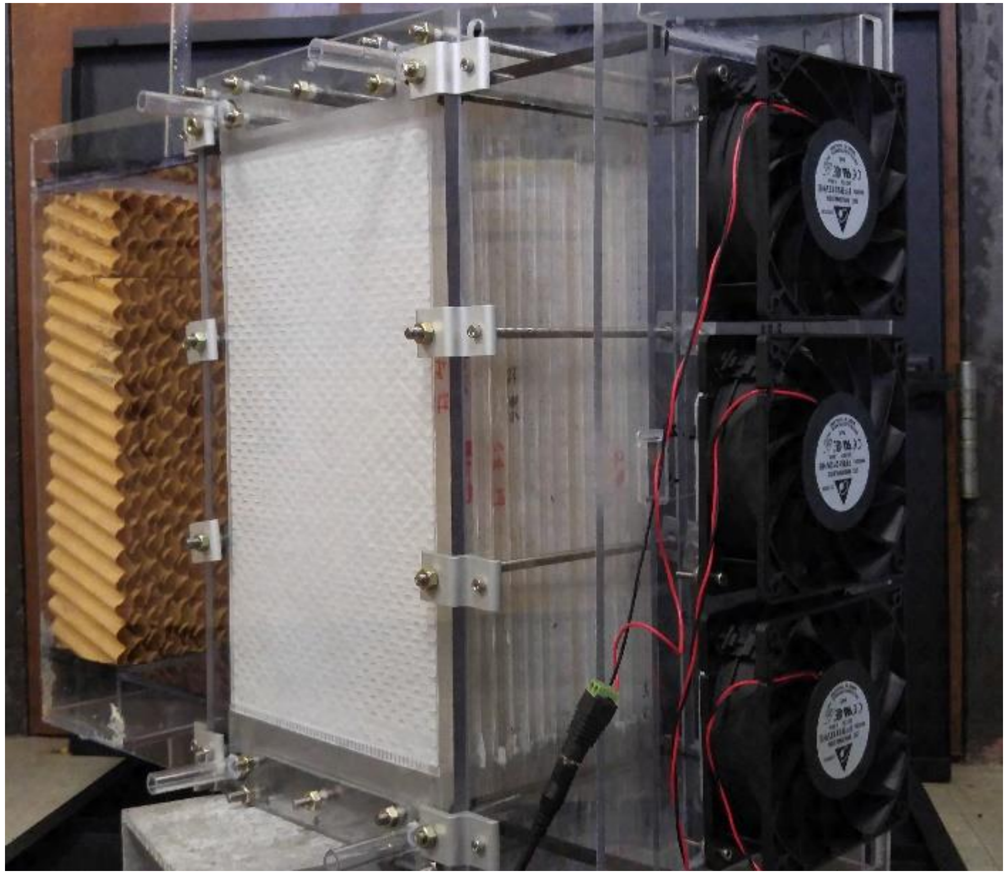


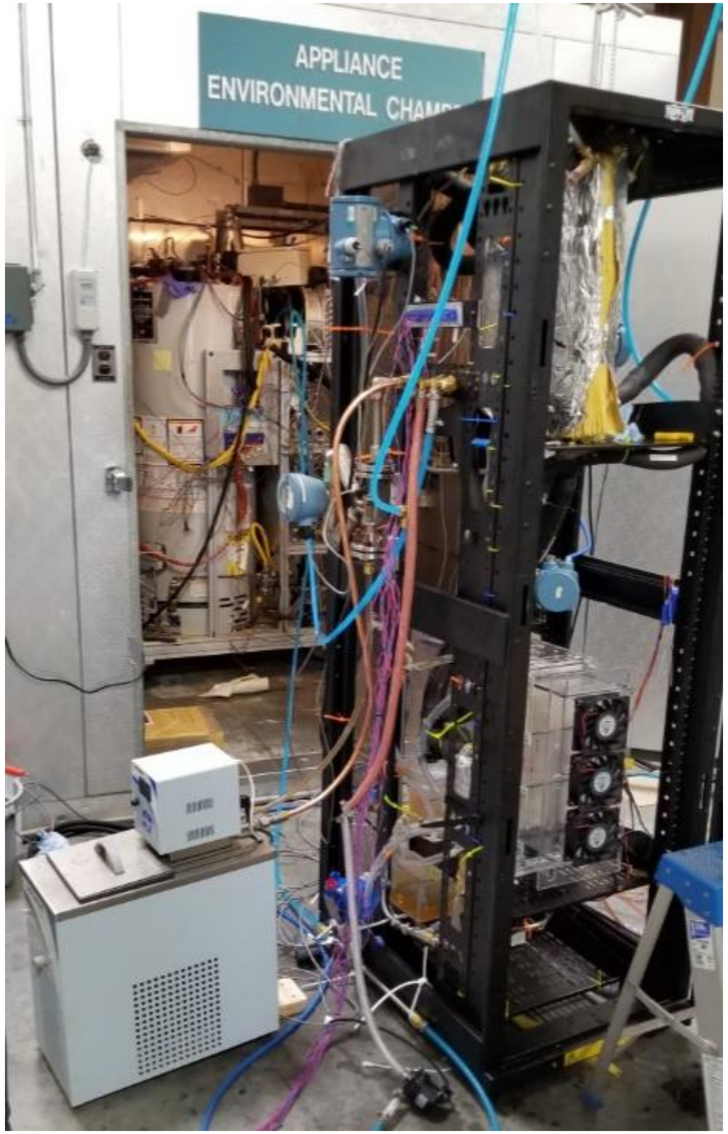
Key Component: Semi-open Absorber



Prototype Evaluation at ORNL

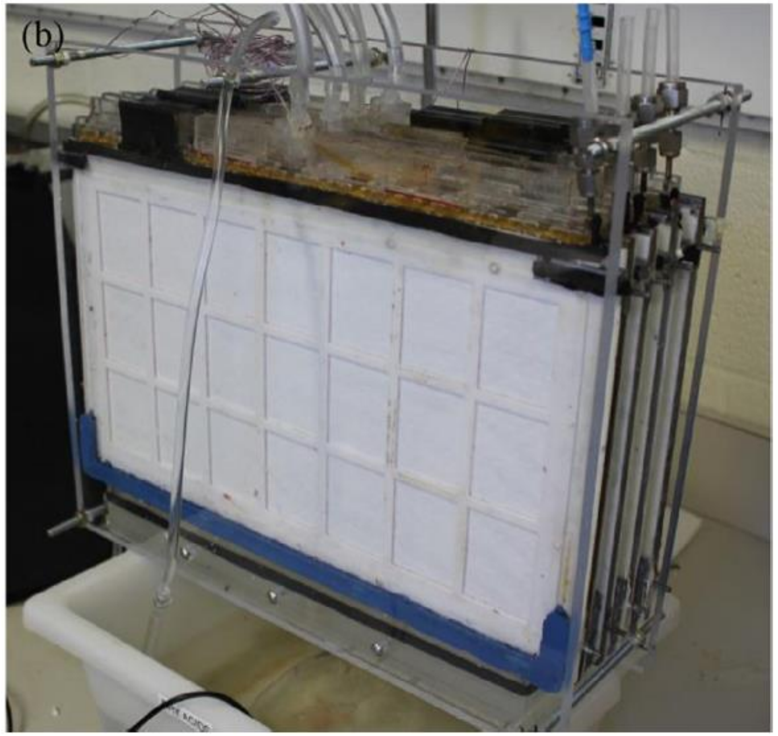
Absorber assembly



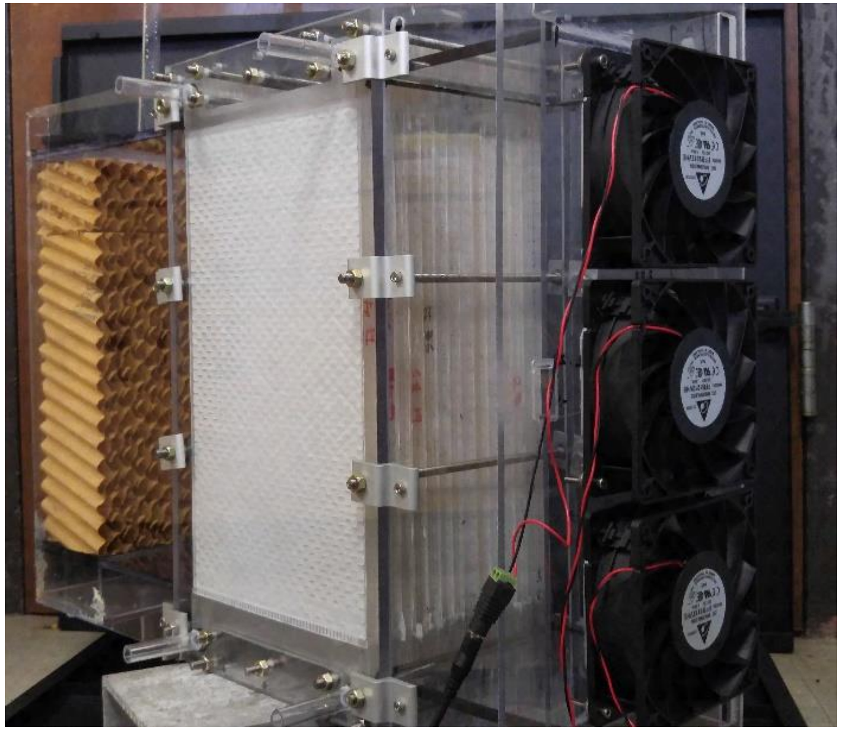


Prototype Generations

Generation 1:



Generation 2:



Generation 3:

Under fabrication

Outline

- What is a sorption heat pump?
  - What can system efficiency (UEF) be?
- What is a *semi-open* sorption heat pump?
  - Theory of operation
  - **What can cycle efficiency (COP) be?**
- Experimental results from prototype semi-open system

Theoretical Efficiency Established

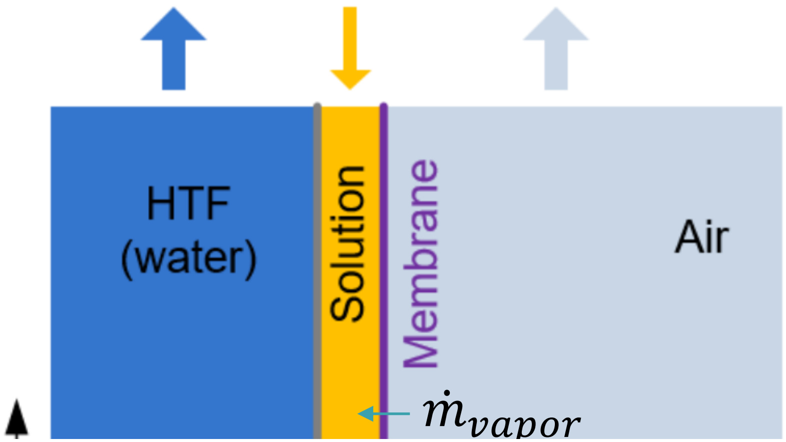
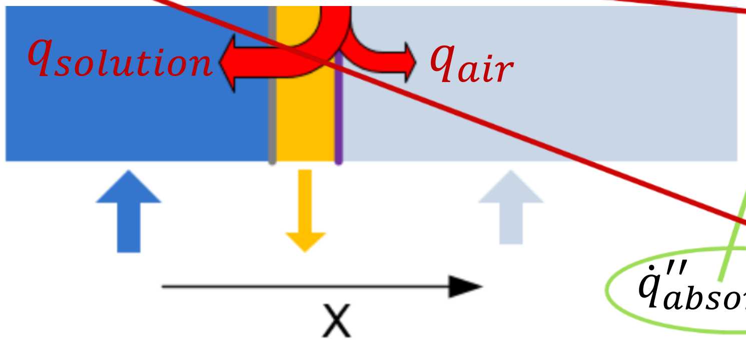


Table 4
Experimental results used as empirical values in this work.

Parameter	Measured value
h_m	4.9×10^{-2} g^1 m^{-2} s^{-1} kPa^{-1}
U_{air}	2.67 ± 0.15 W^1 m^{-2} K^{-1}
U_{soln}	28.6 ± 1.7 W^1 m^{-2} K^{-1}



$$COP_{htg} = 1 + \frac{(\alpha - 1)L_{abs} + L_{cond}}{L_{abs} + C_{p,liq}(1 - \varepsilon_{SHX})\Delta T_{D-A}(FR)}$$

$$\alpha \equiv \frac{\dot{q}''_{solution}}{\dot{q}''_{absorption}} = \frac{1}{1 + \dot{q}''_{air} / \dot{q}''_{solution}}$$

(asserted definition)

$$\alpha = \frac{1}{1 + \frac{UA_{air}\left(T_{interface} - T^{\infty}_{air}\right)}{UA_{soln}\left(T_{interface} - T^{\infty}_{HTF}\right)}}$$

$$T_{interface} = \frac{\dot{q}''_{absorption} + U_{soln}T^{\infty}_{HTF} + U_{air}T^{\infty}_{air}}{U_{soln} + U_{air}}$$

Only three measured values

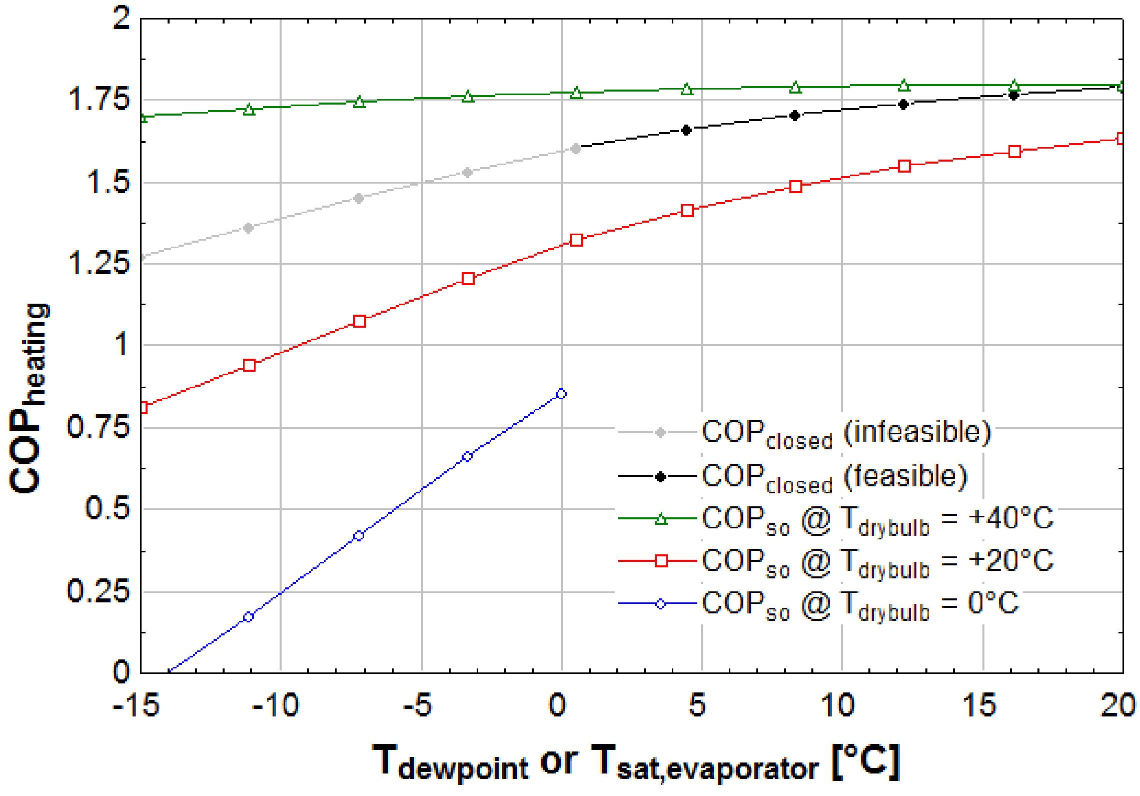
$$\dot{q}''_{absorption} = h_m L_{abs}\left(P_{w,air} - P_{w,soln}\{T_{interface}, X_{soln}\}\right)$$

Gluesenkamp, Kyle R., Devesh Chugh, Omar Abdelaziz, and Saeed Moghaddam (2017). "Efficiency Analysis of Semi-Open Sorption Heat Pump Systems," ***Renewable Energy*** 110, 95-104.

Efficiency Expected by Theory

Parameter	Measured value in prototype
h_m	$4.9 \times 10^{-2}\ g^1 m^{-2} s^{-1} kPa^{-1}$
U_{air}	$2.67 \pm 0.15\ W^1 m^{-2} K^{-1}$
U_{soln}	$28.6 \pm 1.7\ W^1 m^{-2} K^{-1}$

Efficiency can be lower or higher than conventional closed absorption cycle, depending on ambient temperature

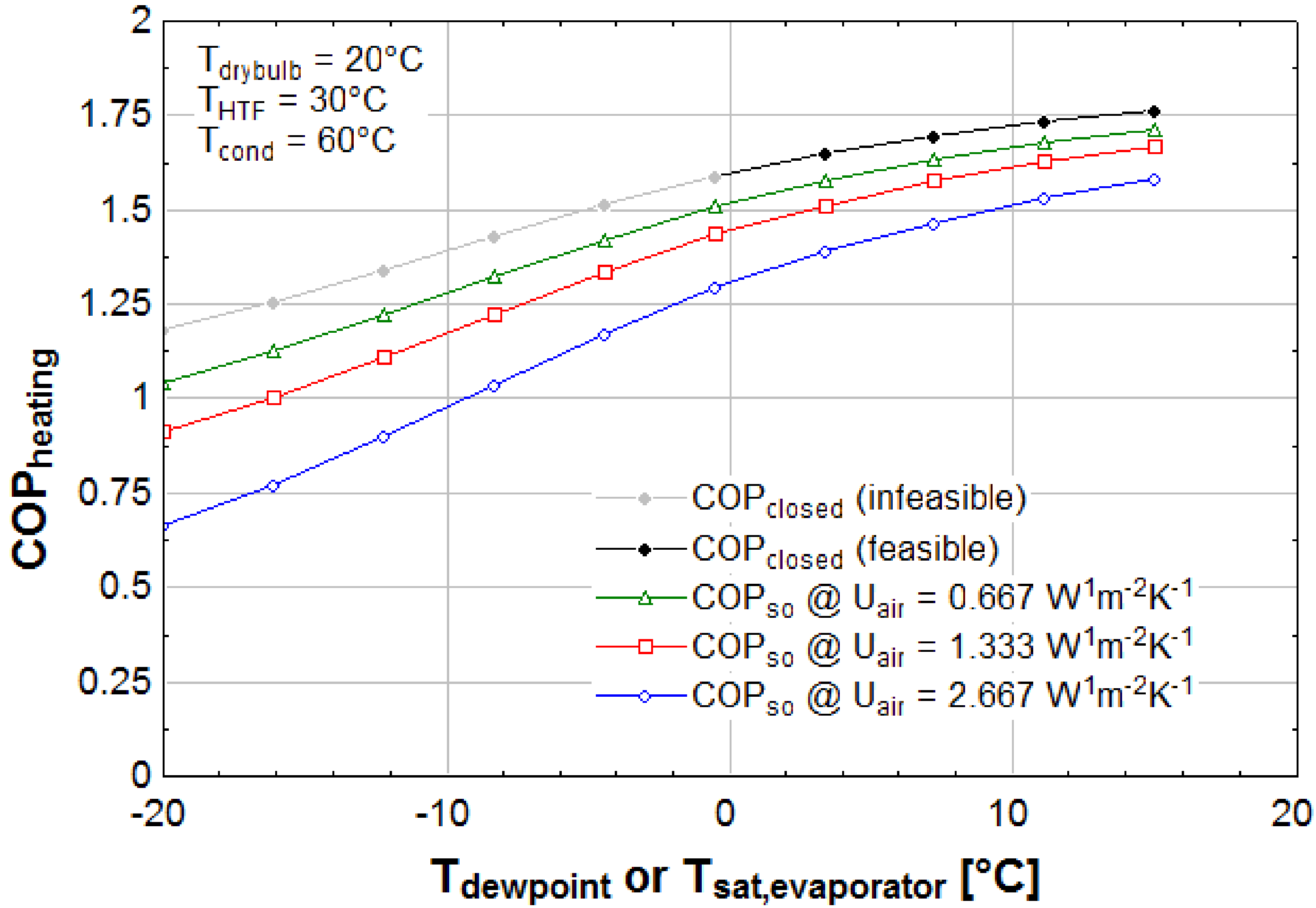


Contours of heating COP for closed and semi-open cycles at various ambient conditions.

Gluesenkamp, Kyle R., Devesh Chugh, Omar Abdelaziz, and Saeed Moghaddam (2017). "Efficiency Analysis of Semi-Open Sorption Heat Pump Systems," ***Renewable Energy*** 110, 95-104.

Research Opportunities

Performance improved by **lower** air side heat transfer…

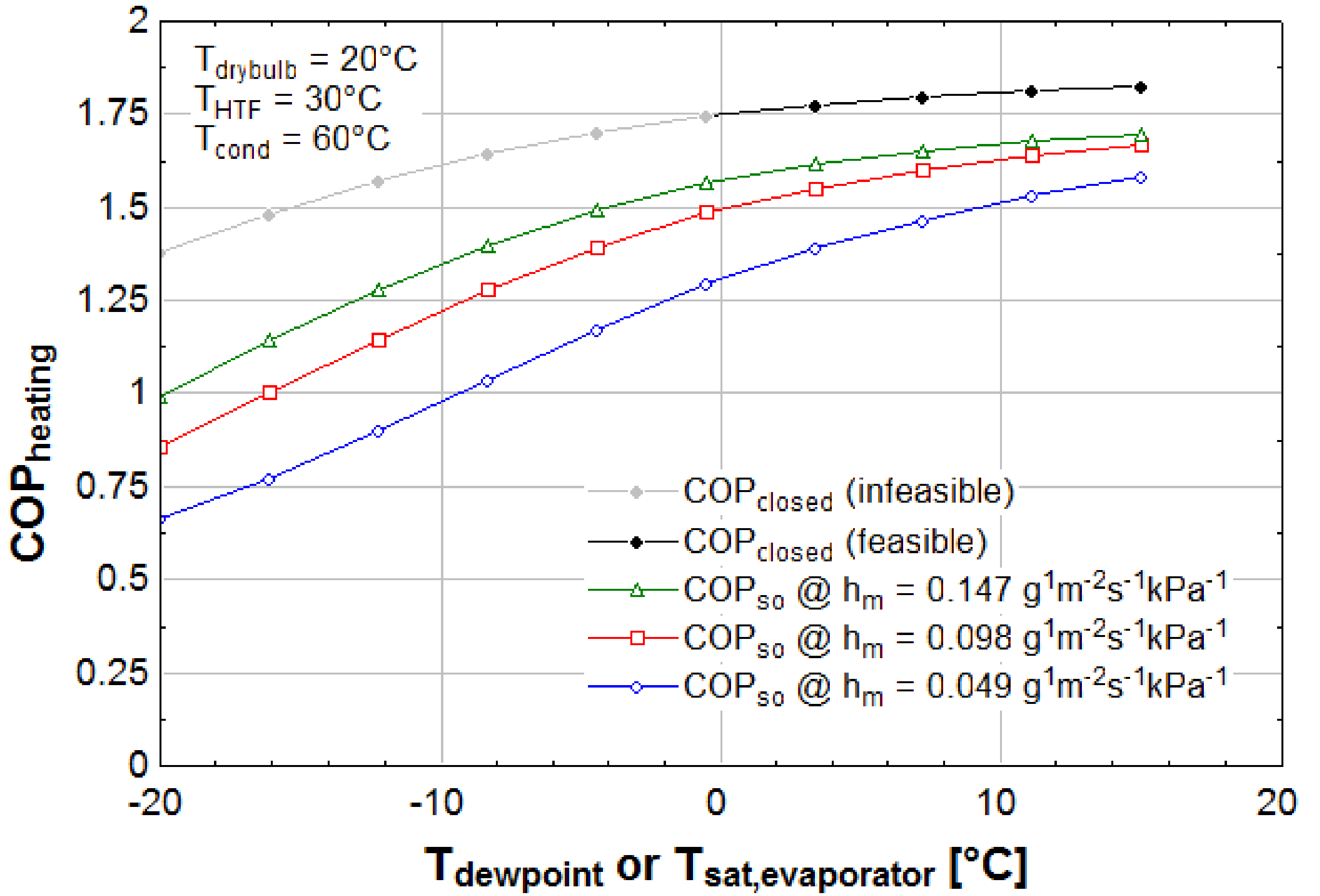


Lower U_{air} values improve performance at fixed permeability (h_m =0.049 $g^1m^{-2}s^{-1}kPa^{-1}$)

Gluesenkamp, Kyle R., Devesh Chugh, Omar Abdelaziz, and Saeed Moghaddam (2017). "Efficiency Analysis of Semi-Open Sorption Heat Pump Systems," ***Renewable Energy*** 110, 95-104.

Research Opportunities

… and **higher** moisture mass transfer.



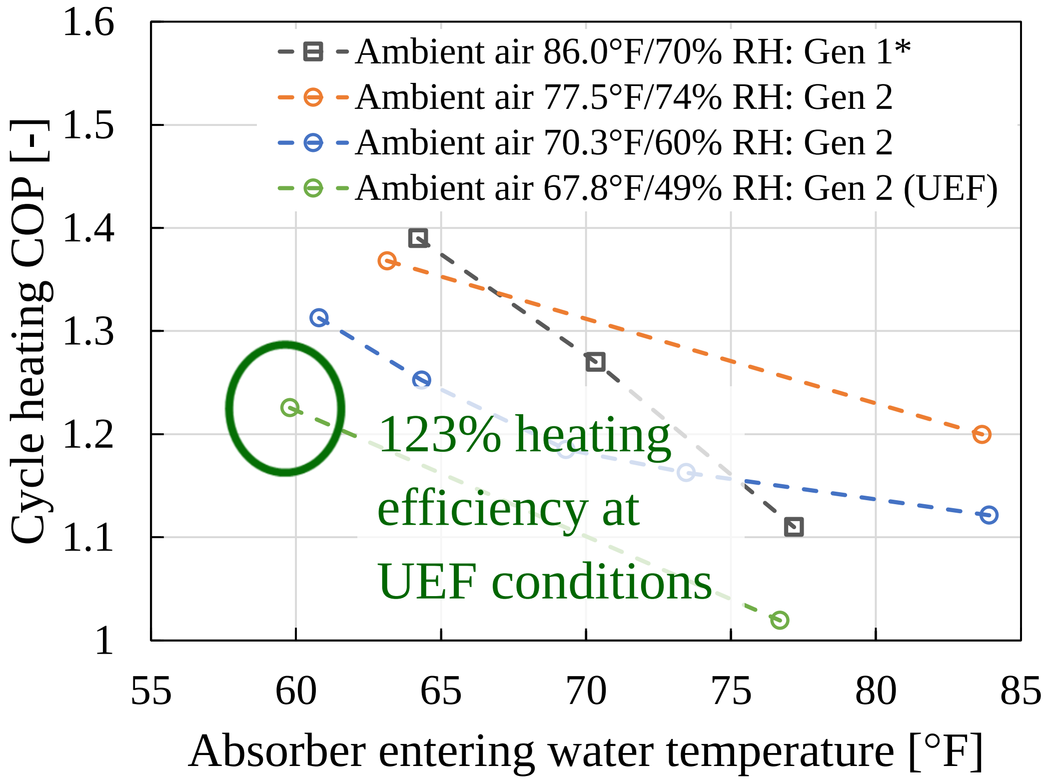
Higher membrane permeability at fixed U_{air} = 2.667 $W^1m^{-2}K^{-1}$ leads to better performance

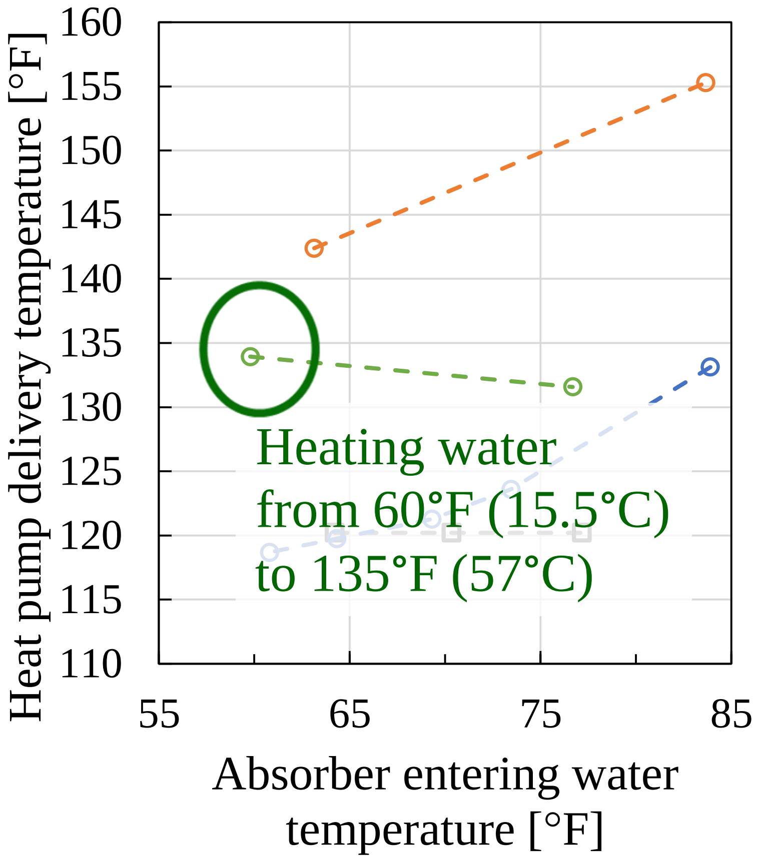
Gluesenkamp, Kyle R., Devesh Chugh, Omar Abdelaziz, and Saeed Moghaddam (2017). "Efficiency Analysis of Semi-Open Sorption Heat Pump Systems," ***Renewable Energy*** 110, 95-104.

Outline

- What is a sorption heat pump?
  - What can system efficiency (UEF) be?
- What is a *semi-open* sorption heat pump?
  - Theory of operation
  - What can cycle efficiency (COP) be?
- **Experimental results from prototype semi-open system**

Experimental Results





- Heating capacity: 700 – 1400 W
- Typical uncertainties: 6–8% of COP; 3% of capacity

*Gen 1: Chugh, Devesh; Kyle R. Gluesenkamp, Omar A. Abdelaziz, Saeed Moghaddam (2017). “Ionic liquid-based hybrid absorption cycle for water heating, dehumidification, and cooling”, ***Applied Energy***, 202, 746-754.

Gen 2: Chugh, Devesh, Kyle R. Gluesenkamp, Ahmad Abu-Heiba, Morteza Alipanah, Abdy Fazeli, Richard Rode, Michael Schmid, Viral K. Patel, Saeed Moghaddam (2019). “Experimental evaluation of a semi-open membrane-based absorption heat pump system utilizing ionic liquids,” ***Applied Energy***, v. 239, 919-927.

References

- Chugh, Devesh, Kyle R. Gluesenkamp, Ahmad Abu-Heiba, Morteza Alipanah, Abdy Fazeli, Richard Rode, Michael Schmid, Viral K. Patel, Saeed Moghaddam (2019). “Experimental evaluation of a semi-open membrane-based absorption heat pump system utilizing ionic liquids,” ***Applied Energy***, v. 239, 919-927.
- Chugh, Devesh; Kyle R. Gluesenkamp, Omar A. Abdelaziz, Saeed Moghaddam (2017). “Ionic liquid-based hybrid absorption cycle for water heating, dehumidification, and cooling”, ***Applied Energy***, v. 202, 746-754.
- Gluesenkamp, K., Chugh, D., Abdelaziz, O., and Moghaddam, S., (2017). "Efficiency Analysis of Semi-Open Sorption Heat Pump Systems," ***Renewable Energy***, v. 110, 95-104.
- Gluesenkamp, K. R. (2016). “Energy Factor Analysis for Gas Heat Pump Water Heaters”, ***ASHRAE Annual Meeting*** *2016*, Conference Paper Session 19, June 29, 2016, St. Louis, MO.
- K. Gluesenkamp and R. Radermacher, "Heat Activated Cooling Technologies for Small and Micro CHP Applications," in ***Small and Micro CHP Systems***, R. Beith, Ed., ed Cambridge, UK: Woodhead Publishing Ltd., 2013.
- Gluesenkamp, K. (2012). Development and Analysis of Micro Polygeneration Systems and Adsorption Chillers. Dissertation University of Maryland.
- Chugh, D., Nasr Isfahani, R., Gluesenkamp, K., Abdelaziz, O., Moghaddam, S. “A novel absorption cycle for combined water heating, dehumidification and evaporative cooling,” ***International Sorption Heat Pump Conference***, March 31 – April 3, 2014, College Park, MD.
- S. Moghaddam, Thin Film-based Compact Absorption Cooling System, WO Patent 2,013,063,210, 2013.
- S. Moghaddam, D. Chugh, R. Nasr Isfahani, S. Bigham, A. Fazeli, D. Yu, M. Mortazavi, and O. Abdelaziz, Open Absorption Cycle for Combined Dehumidification, Water Heating, and Evaporating Cooling, Patent Application WO/2015/116362, PCT/US2015/010757.
- S. Moghaddam and D. Chugh, Novel Architecture for Absorption-based Heaters, Patent Application UF-14697, 2013.

Thank You