Università degli Studi di Trieste
Dipartimento di Ingegneria Meccanica e Navale

École Polytechnique Fédérale de Lausanne
Laboratoire d'Energétique Industrielle

MULTI-OBJECTIVE OPTIMIZATION OF AN ORC-BASED BIOMASS COGENERATOR FOR RESIDENTIAL APPLICATIONS

Stefano Clemente, Jonathan Demierre, Daniel Favrat

ORC 2011 – First International Seminar on ORC Power Systems
September 22, 2011, Aula Conference Center, TU Delft, The Netherlands

OUTLINE

- Introduction
- Biomass analysis
- Cycle design
- Conclusions

INTRODUCTION

- Aim: present a design method for a Combined Heat and Power (CHP) system
- Procedure based on the Energy Integration (EI) of the thermal streams
- Case study: μ-CHP coupled with a biomass boiler

ENERGY INTEGRATION

- In an energy transformation process:
  - high temperature heat is required
  - waste heat at a lower temperature is generated
- Fundamental principle of EI:

  matching of the individual requirements of heat with the available sources

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

CASE STUDY

- Biomass boiler for a 200 m^2, 4-persons house
  - 4 kW floor heating system
  - 30 kW hot water production utility
  - heat demand fluctuations taken into account
- ORC coupled with the boiler
  - flue gas produced at high temperatures
  - heat required at relatively low levels
  - electricity can be produced burning only a minimum amount of additional fuel

HEAT DEMAND FLUCTUATIONS

Month	Degree days	Heating system working period	Hot water system working period	Heat produced when all systems are active	Heat produced when only the floor heating system is active	Heat produced when only the hot water production system is active	Electric consumption
-	*DD*	*hours/day*	*hours/day*	*kWh/day*	*kWh/day*	*kWh/day*	*kWh/day*
Jan	492	14.0	0.5	1.961	7.193	0.000	19.000
Feb	405	11.5	0.5	1.961	5.861	0.000	19.000
Mar	304	9.0	0.5	1.961	4.529	0.000	19.000
Apr	181	5.0	0.5	1.961	2.398	0.000	19.000
May	60	0.0	0.5	0.000	0.000	1.725	19.000
Jun	19	0.0	0.5	0.000	0.000	1.725	19.000
Jul	3	0.0	0.5	0.000	0.000	1.725	19.000
Aug	25	0.0	0.5	0.000	0.000	1.725	19.000
Sep	126	3.5	0.5	1.961	1.599	0.000	19.000
Oct	270	8.0	0.5	1.961	3.996	0.000	19.000
Nov	447	13.0	0.5	1.961	6.661	0.000	19.000
Dec	495	14.0	0.5	1.961	7.193	0.000	19.000

MULTI-OBJECTIVE OPTIMIZATION

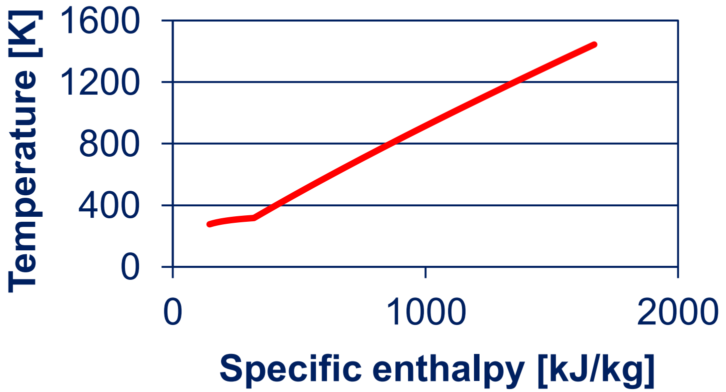
- Variables
  - working fluid
  - expander size
  - maximum temperature
  - working pressures
- Objectives
  - max first law efficiency
  - max exergy efficiency
  - min evaporating pressure (safety and construction issues)

OUTLINE

- Introduction
- Biomass analysis
- Cycle design
- Conclusions

BIOMASS ANALYSIS

- A specific woody biomass has been considered
  - combustion simulated in Belsim VALI environment
  - enthalpy-temperature cooling profile



  - lower heating value: 14354.40 kJ/kg
  - chemical exergy: 16650.20 kJ/kg

OUTLINE

- Introduction
- Biomass analysis
- Cycle design
- Conclusions

MAIN STREAMS OF THE SYSTEM

- Working fluid in the vapor generator: cold stream
- Water for the floor heating system: cold stream
- Water in the hot water production system: cold stream
- Condensing working fluid: hot stream
- Flue gases: hot utility
- Air in an air condenser: cold utility

PERFORMING ENERGY INTEGRATION

- Aim: minimize the use of hot and cold utilities
  - minimize the biomass consumption
  - minimize the heat rejected towards ambient
- In this way the best stream configuration is found
  - for a given set of decision variables
  - the MOO chooses between different sets

PERFORMANCES OF THE μ-CHP

- Energy efficiency (maximized)

$$\eta_I = \frac{\dot{Q}_{hs} + \dot{Q}_{hw} + P_{exp} - P_{pmp}}{\dot{m}_{bm} \cdot LHV_{bm}}$$

- Exergy efficiency (maximized)

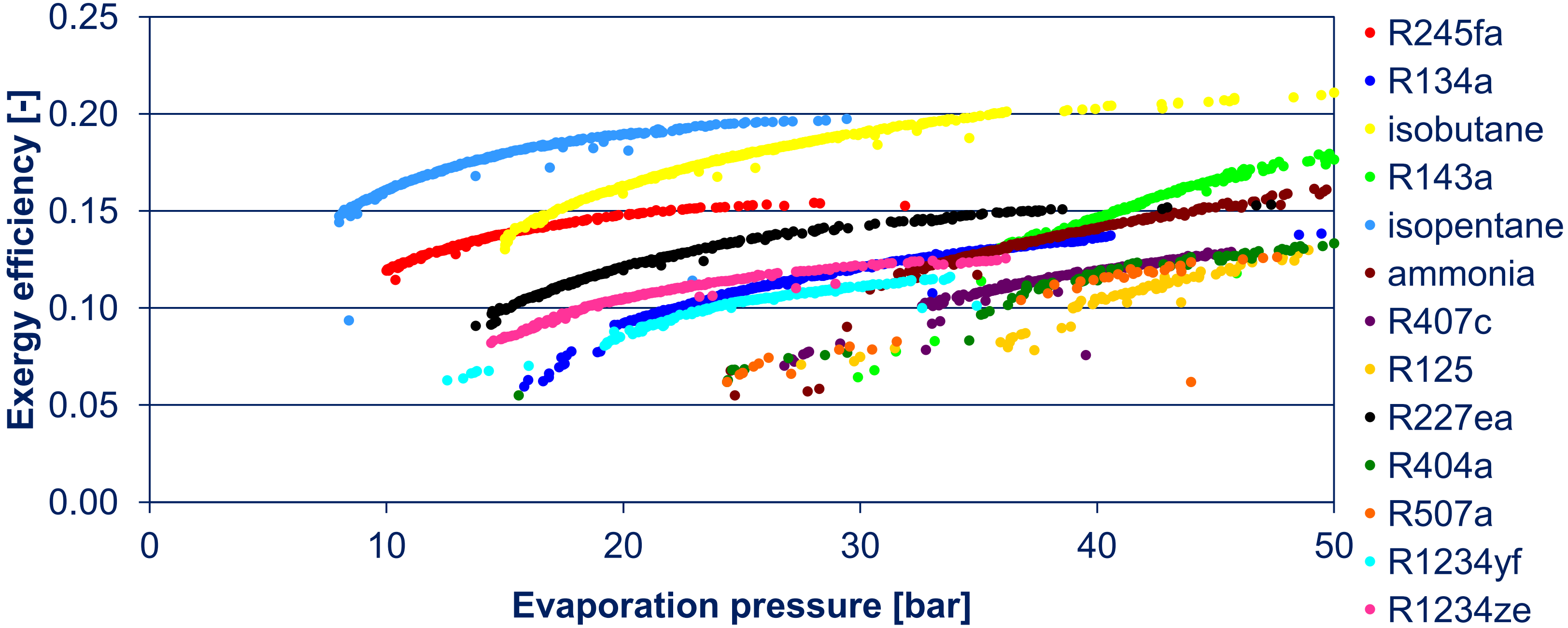
$$\eta_{II} = \frac{\dot{m}_{hs} \cdot (k_{hs,out} - k_{hs,in}) + \dot{m}_{hw} \cdot (k_{hw,out} - k_{hw,in}) + P_{exp} - P_{pmp}}{\dot{m}_{bm} \cdot \varepsilon_{ch,bm}}$$

  - coenthalpy

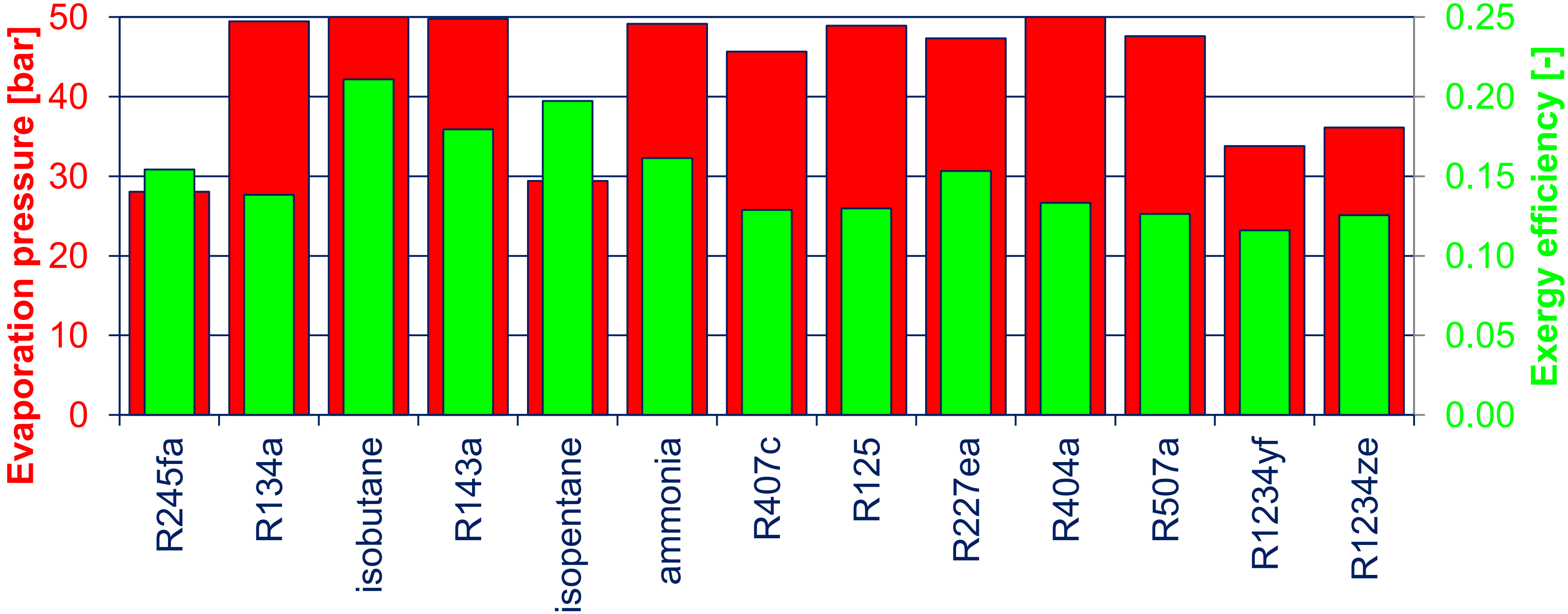
$$k = h - T_a \cdot s$$

SCREENING AMONG 13 FLUIDS (1)

- Optimization with maximum heat required
  - energy efficiency: η_I=1.097



SCREENING AMONG 13 FLUIDS (2)



- R245fa, isopentane, isobutane

OPTIMIZATION

- Variables
  - working fluid → 3 selected fluids
  - expander size
  - maximum temperature → chemical stability
  - working pressures → p_{evap} = 20 bar
- Scenarios
  - floor heating and hot water production active
  - floor heating active
  - hot water production active
  - all produced heat rejected to air condenser

OPTIMIZED CYCLES

Fluid	Scenario	Floor heating system	Hot water production system	Expander inlet temperature	Evaporation pressure	Condensation pressure	Evaporation to condensation pressure ratio	Subcooling degree	Floor heating system thermal power	Hot water production system thermal power	Total thermal power	Power-to-heat ratio	Net mechanical power	Working fluid flowrate	Energy efficiency (ηI)	Exergy efficiency (ηII)
-	-	-	-	*K*	*bar*	*bar*	-	*K*	*W*	*W*	*W*	-	*W*	*kg/s*	-	-
R245fa	1	ON	ON	440.00	20.000	3.548	5.636	15.00	4012	29266	33278	0.118	3923	0.166	1.097	0.149
R245fa	2	ON	OFF	440.00	20.000	3.039	6.580	15.00	4012	0	4012	0.133	533	0.021	1.056	0.165
R245fa	3	OFF	ON	440.00	20.000	3.548	5.636	15.00	0	29266	29266	0.118	3450	0.146	1.097	0.147
R245fa	4	OFF	OFF	440.00	20.000	2.758	7.251	4.96	0	0	0	-	3923	0.144	0.128	0.110
Isopentane	1	ON	ON	500.00	20.000	2.116	9.450	15.00	4012	29266	33278	0.180	6000	0.088	1.097	0.191
Isopentane	2	ON	OFF	500.00	20.000	1.824	10.966	15.00	4012	0	4012	0.200	803	0.011	1.056	0.207
Isopentane	3	OFF	ON	500.00	20.000	2.116	9.450	15.00	0	29266	29266	0.180	5277	0.078	1.097	0.189
Isopentane	4	OFF	OFF	500.00	20.000	1.661	12.039	4.95	0	0	0	-	6000	0.079	0.180	0.155
Isobutane	1	ON	ON	575.00	20.000	7.019	2.849	15.00	4012	29266	33278	0.139	4633	0.096	1.097	0.164
Isobutane	2	ON	OFF	575.00	20.000	6.200	3.226	15.00	4012	0	4012	0.160	643	0.012	1.056	0.182
Isobutane	3	OFF	ON	575.00	20.000	7.019	2.849	15.00	0	29266	29266	0.139	4074	0.084	1.097	0.162
Isobutane	4	OFF	OFF	575.00	20.000	5.735	3.487	4.95	0	0	0	-	4633	0.080	0.152	0.131

SYSTEM WORKING PROFILE

- Thermal following operating strategy
  - a quote of electrical demand can be produced by the ORC without rejecting any heat towards ambient
  - electrical energy is not produced when it is required, so a grid connection is needed
- Dissipation mode
  - run for a certain number of hours, in order to cover all the electrical demand
  - useful for insulated houses with an energy storage system

CHP PRODUCTION – R245fa

Month	Electric consumption	Electric energy produced when all systems are active	Electric energy produced when only the floor heating system is active	Electric energy produced when only the hot water system is active	Total electric production	Electric demand covered by the μ-CHP (NOT used in dissipation mode)	Biomass consumed by the μ-CHP (NOT used in dissipation mode)	Dissipation mode time needed to cover the entire electric demand	Biomass consumed by the μ-CHP (when used in dissipation mode)
-	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*	*%*	*kg*	*hours*	*kg*
Jan	589	61	223	0	284	48.18%	584	78	597
Feb	532	55	164	0	219	41.17%	452	80	613
Mar	589	61	140	0	201	34.16%	416	99	759
Apr	570	59	72	0	131	22.94%	273	112	860
May	589	0	0	53	53	9.08%	116	137	1048
Jun	570	0	0	52	52	9.08%	112	132	1014
Jul	589	0	0	53	53	9.08%	116	137	1048
Aug	589	0	0	53	53	9.08%	116	137	1048
Sep	570	59	48	0	107	18.74%	225	118	907
Oct	589	61	124	0	185	31.36%	383	103	791
Nov	570	59	200	0	259	45.38%	532	79	609
Dec	589	61	223	0	284	48.18%	584	78	597
Year	*6935*	*475*	*1194*	*212*	*1881*	*27.12%*	*3908*	*1288*	*9892*

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

CHP PRODUCTION – Isopentane

Month	Electric consumption	Electric energy produced when all systems are active	Electric energy produced when only the floor heating system is active	Electric energy produced when only the hot water system is active	Total electric production	Electric demand covered by the μ-CHP (NOT used in dissipation mode)	Biomass consumed by the μ-CHP (NOT used in dissipation mode)	Dissipation mode time needed to cover the entire electric demand	Biomass consumed by the μ-CHP (when used in dissipation mode)
-	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*	*%*	*kg*	*hours*	*kg*
Jan	589	93	336	0	429	72.84%	618	27	223
Feb	532	84	247	0	331	62.27%	478	33	280
Mar	589	93	212	0	305	51.71%	441	47	397
Apr	570	90	108	0	198	34.81%	289	62	518
May	589	0	0	82	82	13.89%	122	85	707
Jun	570	0	0	79	79	13.89%	118	82	685
Jul	589	0	0	82	82	13.89%	122	85	707
Aug	589	0	0	82	82	13.89%	122	85	707
Sep	570	90	72	0	162	28.47%	238	68	569
Oct	589	93	187	0	280	47.48%	405	52	431
Nov	570	90	301	0	391	68.61%	564	30	250
Dec	589	93	336	0	429	72.84%	618	27	223
Year	*6935*	*726*	*1799*	*325*	*2850*	*41.09%*	*4135*	*681*	*5698*

CHP PRODUCTION – Isobutane

Month	Electric consumption	Electric energy produced when all systems are active	Electric energy produced when only the floor heating system is active	Electric energy produced when only the hot water system is active	Total electric production	Electric demand covered by the μ-CHP (NOT used in dissipation mode)	Biomass consumed by the μ-CHP (NOT used in dissipation mode)	Dissipation mode time needed to cover the entire electric demand	Biomass consumed by the μ-CHP (when used in dissipation mode)
-	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*	*%*	*kg*	*hours*	*kg*
Jan	589	72	269	0	341	57.90%	597	54	409
Feb	532	65	198	0	263	49.43%	462	58	444
Mar	589	72	169	0	241	40.97%	426	75	574
Apr	570	69	87	0	156	27.43%	279	89	683
May	589	0	0	63	63	10.72%	118	113	868
Jun	570	0	0	61	61	10.72%	114	110	840
Jul	589	0	0	63	63	10.72%	118	113	868
Aug	589	0	0	63	63	10.72%	118	113	868
Sep	570	69	58	0	127	22.35%	230	96	731
Oct	589	72	150	0	221	37.58%	391	79	607
Nov	570	69	241	0	311	54.51%	545	56	428
Dec	589	72	269	0	341	57.90%	597	54	409
Year	*6935*	*561*	*1442*	*251*	*2253*	*32.48%*	*3995*	*1011*	*7731*

OUTLINE

- Introduction
- Biomass analysis
- Cycle design
- Conclusions

CONCLUSIONS

- Energy Integration can be used as a decision-making criterion to design an energy system
- R245fa, isopentane and isobutane seem to be the best fluids for domestic ORCs
- A significant amount of electricity demand (30-40%) can be covered by a well-designed cogenerator with very high efficiency

Thanks for your attention!

Stefano Clemente
Mechanical Engineer, PhD Student
Università degli Studi di Trieste
Dipartimento di Ingegneria Meccanica e Navale
via A. Valerio 10, 34127 Trieste (ITALY)
sclemente@units.it

UNIVERSITA' DEGLI STUDI DI TRIESTE

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE