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Topics Line-up

- Introduction
- Power Plant Example
  - Thermodynamics
  - Economics
- Comparison of Water and HFC-245fa
  - Pinch point
  - Sensible heating
- HFC-245fa properties
  - Exit Superheat and Recuperation
- Comparison of HFC-245fa and Isopentane
  - Turbine sizing
  - Output
  - “Drop-in” comparison
- Benefits to the Environment
- Conclusions

Introduction

- **Drivers for Development of Medium- and Low-Grade Heat Utilization Technologies**
  - **growth in energy consumption and emissions**
  - **climate change**
  - **environmental legislation**
  - **binding targets for renewable energy**
  - **increased focus across the manufacturing sector on the economic benefits of energy and fuel conservation**
- **Need to reduce current fossil fuel combustion emissions**
  - **mix of renewable and cleaner energy technologies will be necessary to meet future demand.**
  - **geothermal power is a prime example**

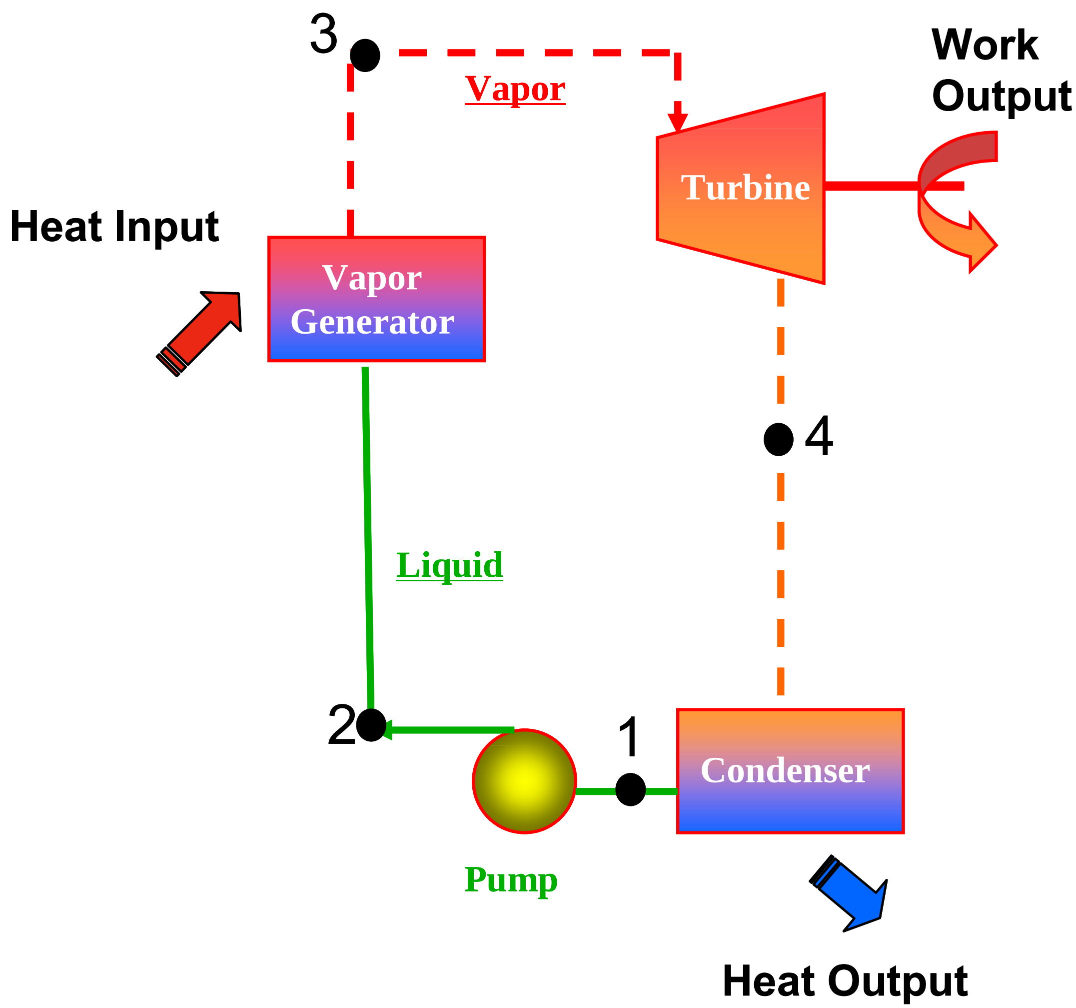
Introduction

- **Geothermal Power**
  - **EU 2030 target of 5% of total electric power production**
  - **US has ~350GW potential**

- **Accessible Industrial Waste Heat Energy**
  - **Estimated at 1.06 x 10^{13} megajoules in the US**

- **Organic Rankine Cycle Systems are a robust means of thermal energy conversion**
  - **industrial waste heat**
  - **efficiency improvement in power stations**
  - **geothermal and solar heat**
  - **efficiency typically between 10 and 20%, depending on temperature levels and availability of a suitably matched fluid.**
  - **attractive option for heat recovery in the range of 90 ºC to 200ºC,**

ORC System – Basic Layout



Power Plant Example – Thermodynamic Analysis

Steam Conditions for Simple Turbine Arrangement					
Outlet Location	Temperature °C	Pressure kPa	Enthalpy, liq. kJ/kg	Enthalpy,vap kJ/kg	Entropy,vap kJ/kg K
From Boiler	537.8	8274		3486.7	6.8229
From 1st turbine	152.0	500.0	640.0	2748.8	6.8299
From Reheater	482.2	413.7		3446.3	8.1256
From 2nd turbine	135.0	29.2	552.0	2676.3	8.1274
From condenser	55.0	19.3	223.9		
From Pump	58.0	8619	243.1		
Enthalpy and entropy values use ASHRAE thermodynamic reference state					
Net Heat Output	1389.2 kJ/kg steam				
Heat Input	3822.1 kJ/kg steam				
Theoretical cycle efficiency	0.363				

Power Plant Example – HFC-245fa Bottoming

HFC-245fa Rankine cycle					
Outlet Location	Temperature °C	Pressure kPa	Enthalpy, liq. kJ/kg	Enthalpy,vapor kJ/kg	Entropy,vapor kJ/kg K
From Boiler	125.0	2113		490.1	1.811
From turbine	51.9	213		447.5	1.811
From condenser	95	7213	246.5		
From pump	97.7	2113	249.1		

Enthalpy and entropy values use ASHRAE thermodynamic reference state

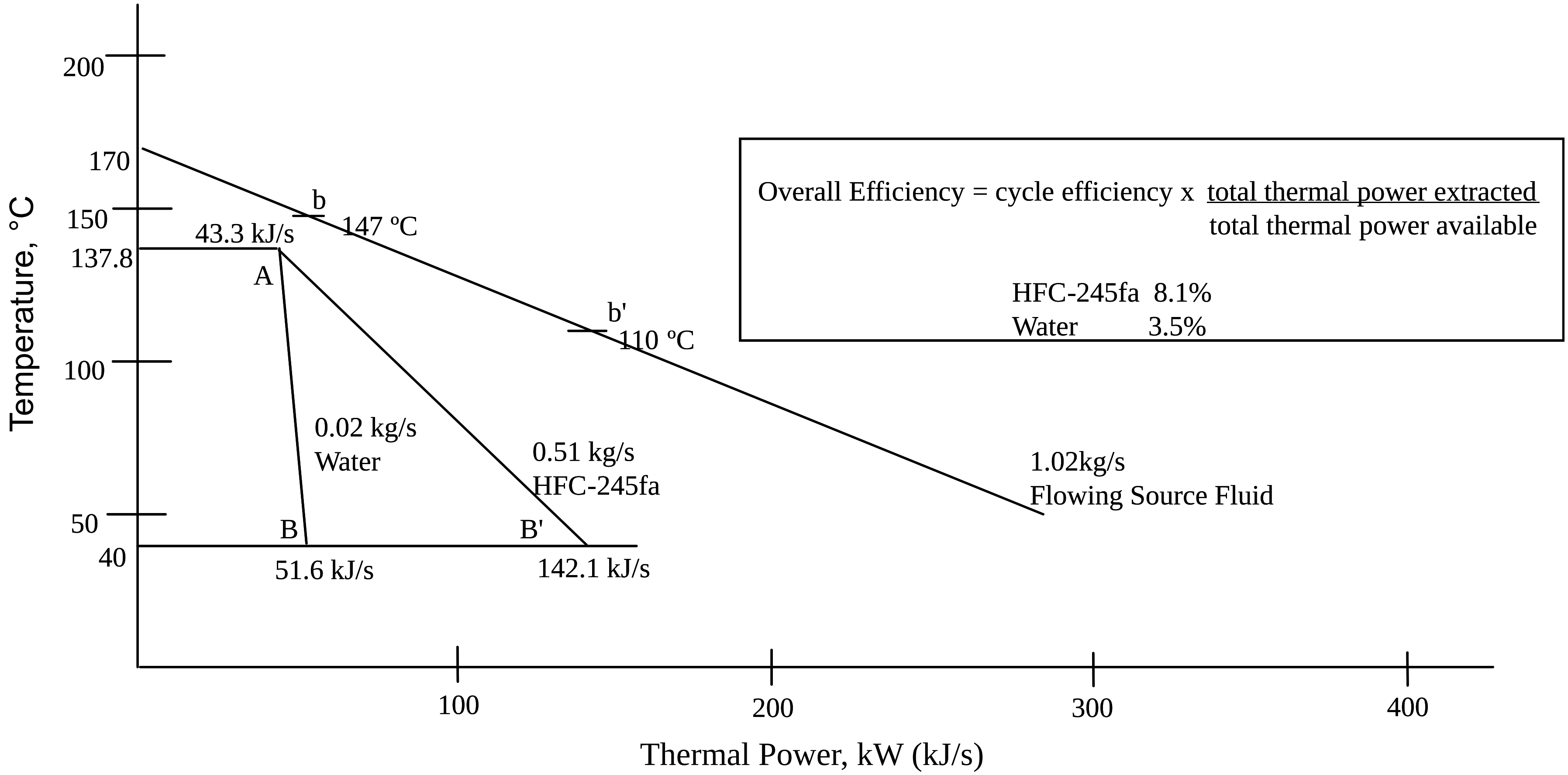
Work done on 245fa - pump	2.53 kJ/kg
Net mech energy/unit mass 245fa	39.75kJ/kg
Thermal input to 245fa/cycle	241.0kJ/kg
Mass Ratio	9.07 kg 245fa per kg steam condensed
Net ORC Work Out/unit mass steam	362.7 kJ/kg
Combined cycle work output	1792.5kJ/kg steam
Combined cycle efficiency	0.456
% Increase in efficiency	25.6

Power Plant Example – Simple Payback Analysis

Mechanical Power (W) = Power in load circuit (We)/commercial efficiency	**1.39 x 10^9 W or 5.0 kJ/hr**
Steam mass flow (kg/hr) = mechanical power (kJ/hr)/heat input with reheat (kJ/kg)	**1.27 x 10^6 kg/hr steam**
ORC work = Mass Flow Steam (kg/hr) x Net Work Out/Unit mass steam (kJ/kg)	**4.6x10^8 kJ/hr or 128MW**
Plant electric output increase, %	**25**
ORC System Cost ($1500 to $2000/KW)	**$192M to $256M**
Value of Power produced in ORC ($0.085/kWhr)	**$95M**
Payback (assumes operating cost is small)	**2 to 3 years**

Comparison of Water to HFC-245fa - Pinch Point

H_2O: High latent heat of vaporization yields low mass flow. Results in decreased energy capture from source via sensible heating. Evidenced as a smaller reduction in source temperature



HFC-245fa Enthalpy Drops and Superheats

Enthalpy drop and superheat enthalpy of HFC-245fa (isentropic expansion).

- *HFC-245fa expander exit gas has more superheat than entering gas.*
- *A recuperator puts this energy into condensed HFC-245fa rather than rejecting it.*

Temperature Expander Inlet ºC	Temperature Condensing ºC	Enthalpy Drop Expansion kJ/kg	Superheat Enthalpy kJ/kg
148.9	21.1	56.0	29.3
162.8	21.1	61.1	48.1
176.7	21.1	64.9	65.1
148.9	15.4	60.1	29.8
162.8	15.4	65.5	48.4
176.7	15.4	69.9	64.7

Comparison of HFC-245fa and Isopentane

Turbine Sizing

Turbine diameter D= ds $Q^{0.5}$ / $H^{0.25}$

Assume a specific diameter of 4 (Balje Diagram)

Q is the volumetric flow rate (m3/s)

H is head (m2/s2)

ds is specific diameter (dimensionless)

Head is determined from the equation PR=[1+(γ–1) H/ a2]γ/γ-1

PR is the turbine pressure ratio (dimensionless),

γ is the isentropic exponent (*dimensionless)

***for an ideal gas this is the heat capacity at constant pressure /heat capacity at constant volume, Cp/Cv)**

a is the speed of sound in the particular working fluid (m/s).

Comparison of HFC-245fa and Isopentane

Geothermal hot water source: HFC-245fa and isopentane working fluid comparison.
Basis: 5000kj/second delivered for working fluid vapor generation

90ºC source*	Mass flow, kg/sec	Turbine Exit flow, m3/sec	Turbine Diameter, m	Theoretical electrical output, kWe	% difference relative to HFC-245fa Diameter	Output
HFC-245fa	22.4	2.34	0.474	473.5		
Isopentane	11.9	3.94	0.526	476	+ 11	+ 0.5
120C source*						
HFC-245fa	20.6	2.30	0.418	646.5		
Isopentane	10.6	4.06	0.470	531	+ 12	+4
*30ºC condensing (working fluid temperature) ** exit condition limited by 9:1 pressure ratio.						

Comparison of HFC-245fa and Isopentane

"Drop-in" of isopentane in a turbine initially sized for HFC-245fa.

90° C Source	Turbine Diameter, m	Volumetric flow rate (turbine exit), m^3/sec	Mass flow, kg/sec	Electrical Output, kWe	% Change kWe vs. HFC-245fa
Isopentane	0.474	3.20	9.6	383	(19.0)
HFC-245fa	0.474	2.34	22.4	473.5	
120° C Source					
Isopentane	0.418	3.22	8.4	531	(17.9)
HFC-245fa	0.418	2.30	20.6	646.5	

Thermal efficiency	*Isopentane*	*HFC-245fa*
90° C source	0.0952	0.0947
120° C source	0.1344	0.1293

Comparison of HFC-245fa and Isopentane

Temperature Reduction of a Flowing Fluid Source

- System delivers 5000kJ/s (from a 90°C source) to boiler
- Assume source flow rate of 100kg/second
- Latent heat of HFC-245fa at 80°C and sensible heating from 30°C to 80°C = 224 kJ/kg
- Mass flow x heat delivered to working fluid = heat from source Water, or 5000kJ/s

$q = mC_p\Delta T$

q is the heat removed (kJ/s)

m is mass flow (kg/s)

Cp is heat capacity at constant pressure (kJ/kg K)

ΔT is the temperature difference (°C)

The source temperature drop with HFC-245fa is ~12°C

Since the HFC-245fa and Isopentane sizing is based on the same heat input to the boiler, it serves as a check that the source temperature drop with Isopentane is ~12°C

Benefits to the Environment

- **Can address needs for additional capacity and/or increased efficiency**
- **Avoided CO_2 emissions when ORC system electric power displaces grid power**
- **When appended to NG or diesel gensets**
  - **Additional power with no additional CO_2 emissions**
  - **10-15% additional power output (more or less depending on design and conditions)**
  - **No additional fuel consumption**
- **Renewable sources such as geothermal and solar can be utilized**
- **Accessing manufacturing sector waste heat sources improves energy efficiency**

Conclusions

- HFC-245fa is a suitable working fluid for ORC applications
- High heat capacity contributes to high cycle efficiencies
- Desirable latent heat to heat capacity ratio for ORC
- Particularly well suited for source temperatures of 90°C to 150°C
- HFC-245fa provides a non-flammable fluid option