### 4.3.2 The steam engine—the Rankine cycle

Not an ideal gas!

The fluid goes from water to steam and back to water again.

- 1-2 Water is pumped to high pressure,
- 2-3 heat provided by burning fuel or fissioning uranium is added at constant pressure,
- 3-4 the steam hits a turbine, expands adiabatially and cools,

4-1 the fluid is cooled further in a condenser.

Under constant pressure conditions,  $Q = \Delta H$ .

$$e = 1 - rac{Q_c}{Q_h} = 1 - rac{H_4 - H_1}{H_3 - H_2} \approx 1 - rac{H_4 - H_1}{H_3 - H_1}.$$

We get  $H_1$  and  $H_4$  from a table for "saturated steam", and  $H_3$  from a table of "superheated steam".

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### Saturated steam

#### Table 4.1

Properties of water + steam (saturated steam)

T	Р	Hunter	Hetoom	Swator	Sataam
°C	bar	kJ	kJ	kJ/K	kJ/K
0	0.006	0	2501	0	9.156
10	0.012	42	2520	0.151	8.901
20	0.023	84	2538	0.297	8.667
30	0.042	126	2556	0.437	8.453
50	0.123	209	2592	0.704	8.076
100	1.013	419	2676	1.307	7.355

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Image: A matrix

### Determine efficiency

- **1** Determine  $H_1$  from table 4.1. Only water.
- ② Take  $H_2 \approx H_1$ —OK since the pump only adds a little energy.
- **③**  $H_3$  and  $S_3$  from table 4.2—we need both  $P_3$  and  $T_3$ .
- Point 4 for a mixture of steam and water:
  - Assume  $S_4 = S_3$ .
  - Get  $S_{\text{water}}$  and  $S_{\text{steam}}$  from the known pressure and table 4.1.
  - Determine x<sub>water</sub> from

$$S_4 = x_{\text{water}} S_{\text{water}} + (1 - x_{\text{water}}) S_{\text{steam}}.$$

► Use H<sub>water</sub> and H<sub>steam</sub> from the known pressure and table 4.1 to determine

$$H_4 = x_{\text{water}} H_{\text{water}} + (1 - x_{\text{water}}) H_{\text{steam}}$$

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### Determine efficiency—numerical example

Assume operation between  $P_1 = 0.023$  bar,  $T_1 = 20^{\circ}$ C and  $P_3 = 300$  bar,  $T_3 = 600^{\circ}$ C.

- Table 4.1 (only water) gives  $H_1 = 84$ .
- 2 Take  $H_2 \approx H_1 = 84$ .
- **3**  $H_3 = 3444$  from table 4.2.

Oint 4 for a mixture of steam and water:

• Assume 
$$S_4 = S_3 = 6.233 \text{ kJ/K}$$
.

- Get  $S_{\text{water}} = 0.297$  and  $S_{\text{steam}} = 8.667$  from table 4.1.
- Determine  $x_{\text{water}} = (S_{\text{steam}} S_4)/(S_{\text{steam}} S_{\text{water}}) = 0.29.$
- Use  $H_{\rm water} = 84$  and  $H_{\rm steam} = 2538$  from table 4.1 to get

$$H_4 = x_{\text{water}} H_{\text{water}} + (1 - x_{\text{water}}) H_{\text{steam}} = 1824 k J_{\text{steam}}$$

The efficiency becomes

$$e \approx 1 - \frac{H_4 - H_1}{H_3 - H_1} = 1 - \frac{1824 - 84}{3444 - 84} = 48\%.$$

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# Superheated steam

#### Table 4.2

Properties of superheated steam

			Temperature °C					
P bar			200	300	400	500	600	
1.0	Н	kJ	2875	3074	3278	3488	3705	
	S	kJ/K	7.834	8.216	8.544	8.834	9.098	
3.0	Н	kJ	2866	3069	3275	3486	3703	
	S	kJ/K	7.312	7.702	8.033	8.325	8.589	
10	Н	kJ	2828	3051	3264	3479	3698	
	S	kJ/K	6.694	7.123	7.465	7.762	8.029	
30	Н	kJ		2994	3231	3457	3682	
	S	kJ/K		6.539	6.921	7.234	7.509	
100	Н	kJ			3097	3374	3625	
	S	kJ/K			6.212	6.597	6.903	
300	Н	kJ			2152	3081	3444	
	S	kJ/K			4.473	5.791	6.233	

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### Compare efficiencies

Our idealized example:

$$e = 1 - \frac{H_4 - H_1}{H_3 - H_2} = 1 - \frac{1824 - 84}{3444 - 84} = 48\%.$$

Compare with

- Carnot engine  $e = 1 \frac{273+20}{273+600} = 66\%$ .
- Modern fossil-fuel power plants,  $e \approx 40\%$ .
- Nuclear power plants,  $e \approx 34\%$ .

## 4.4 Real refrigerators

The reverse of the Rankine cycle.

The fluid must have a much lower boiling temperature.

Different working substances:

- CO<sub>2</sub>
- Ammonia
- 1930, Freon (various kinds). Have caused brekdown of the ozone layer.
- Now replaced by clorine-free substances, e.g. F<sub>3</sub>C<sub>2</sub>FH<sub>2</sub>—HFC-134a.

# 4.4.1 Working cycle

(Different numbering than in the steam engine.)

- 1-2 Compressor—adiabatically compression, T and P rise.
- 2-3 Condenser—gives up heat and liquefies.
- 3-4 Throttling value—lowers T and P.
- 4-1 Evaporator—absorbs heat and returns to a gas.

Coefficient of performance,

$$COP = \frac{Q_c}{W} = \frac{Q_c}{Q_h - Q_c} = \frac{H_1 - H_4}{H_2 - H_3 - (H_1 - H_4)}$$

- $H_1$  and  $H_3$  can be looked up in tables.
- Point 2 located by assuming an adiabatic compression—constant entropy.
- Point 4—look into the function of the throttling valve.

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## 4.4.2 The throttling process (Joule-Thomson process)

Think of two pistons with pressure  $P_i$  and  $P_f$ , respectively For a chunk of fluid: initial volume  $V_i$ , final volume  $V_f$ 

$$U_f - U_i = Q + W = 0 + W_{\text{left}} + W_{\text{right}}.$$
  
From  $W = -P\Delta V$  (left:  $\Delta V = -V_i$ , right:  $\Delta V = V_f$ ):  
 $W_{\text{left}} = P_i V_i, \quad W_{\text{right}} = -P_f V_f.$   
 $U_f - U_i = P_i V_i - P_f V_f \iff H_f = H_i.$ 

Purpose of the process: cooling the fluid. Does not work for an ideal gas:

$$H = U + PV = rac{f}{2}Nk_BT + Nk_BT = rac{f+2}{2}Nk_BT$$
, ideal gas.

With interactions:  $U = U_{pot} + U_{kin}$ . Increasing  $U_{pot}$  means decreasing  $U_{kin}$  and decreasing T 4.4.1 Working cycle... Cont'd

From the throttling process:

$$H_3=H_4,$$

which gives

$$COP = \frac{Q_c}{W} = \frac{H_1 - H_4}{H_2 - H_3 - (H_1 - H_4)} = \frac{H_1 - H_3}{H_2 - H_1}.$$

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