

The value of the exergy of the system depends only on its initial and final state, which is set by the conditions of the environment. The term  $T_0\mathcal{P}_S$  is always positive, and it does depend on how an actual process is realized. As we have seen, it is often convenient to perform analysis and calculations with intensive properties, therefore the specific exergy function is given by

$$e_{\text{sys}} = (e - u_0) + P_0(v - v_0) - T_0(s - s_0),$$

where

$$e_{\text{sys}} = u + \nu^2/2 + gz.$$

The term  $(u - u_0) + P_0(v_{\text{sys}} - v_0) - T_0(s_{\text{sys}} - s_0)$  is often called *physical exergy*, while the exergy resulting from the system having kinetic and potential energy are called kinetic and potential exergy respectively. These are therefore indicated as follows

$$e_{\text{sys}}^{\text{PH}} \equiv (u - u_0) + P_0(v - v_0) - T_0(s - s_0)$$

$$e_{\text{sys}}^{\text{KN}} \equiv \nu^2/2$$

$$e_{\text{sys}}^{\text{PT}} \equiv gz$$

Note that both kinetic and potential energy are forms of mechanical energy and can be converted completely into work, therefore in this case there is no difference between energy and exergy.

We anticipate here that a system can also have exergy associated with the potential for work of chemical reactions, and that therefore also *chemical exergy* can contribute to the overall exergy of a certain system.

**Improving the use of energy in a chemical process.** As an application of the exergy concept, suppose a certain chemical process needs 2 kg/s of steam at 1 MPa and 320 °C, and the steam generator of a nearby power plant makes steam available at 2 MPa and 600 °C. We could simply flow

the steam through a valve, dropping its pressure, thence through a heat exchanger in order to cool it down at the desired temperature, but in the interest of an efficient use of energy we decide to explore the possibilities of generating power as a side benefit of this steam-state change. How much power could we get? From FLUIDPROP, by setting the thermodynamic model for water to IF97 and the input specification to PT we obtain

*State 1*

$$\begin{aligned}h_1 &= 3691 \text{ kJ/kg} \\s_1 &= 7.704 \text{ kJ}/(\text{kg} \cdot \text{K})\end{aligned}$$

*State 2*

$$\begin{aligned}h_2 &= 3094 \text{ kJ/kg} \\s_2 &= 7.198 \text{ kJ}/(\text{kg} \cdot \text{K})\end{aligned}$$

Taking  $T_0$  as  $20^\circ\text{C} = 293.15 \text{ K}$ ,

$$\begin{aligned}e_1 &= h_1 - T_0 s_1 = 3691 - 293.15 \times 7.704 = 1432.2 \text{ kJ/kg} \\e_2 &= 3094 - 293.15 \times 7.198 = 984.3 \text{ kJ/kg}\end{aligned}$$

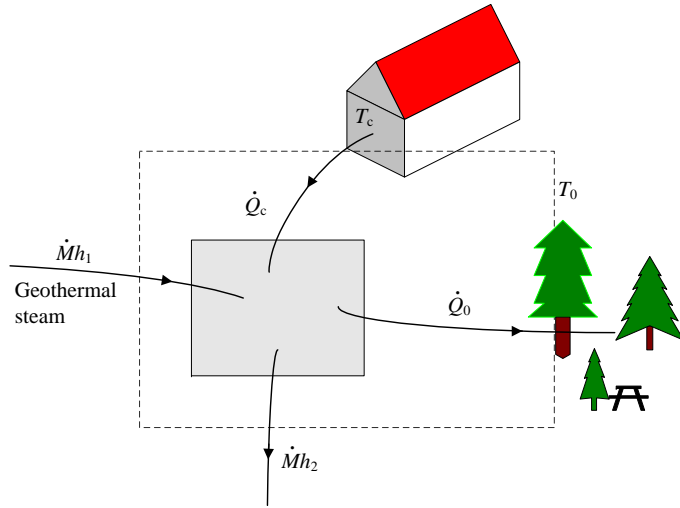
Therefore

$$\dot{W}_{\max} = 2 \text{ kg/s} \times (1432.2 - 984.3) \text{ kJ/kg} = 896 \text{ kW}$$

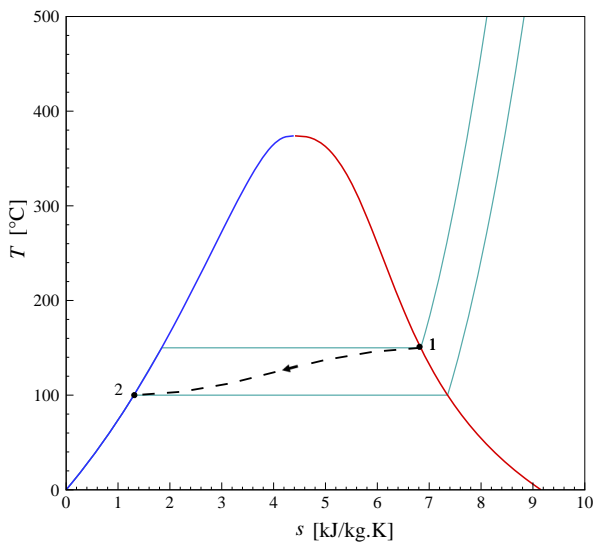
We see that the valve system would be wasting up to almost 1 MW. A good engineer could realize (or buy) a steam turbine set that is approximately 75 % efficient for this low power capacity. At  $0.1 \text{ €/}(\text{kW} \cdot \text{h})$ , or  $0.07 \text{ \$}/(\text{kW} \cdot \text{h})$ , the value of the electricity amounts to approximately 420,000 €, or 300,000 \$.<sup>†</sup> The investment and maintenance cost of the steam turbine system would have to be weighted against the utility bill saving in deciding whether or not to implement this solution.

**Geothermally driven cooling system.** Let's now assume that in a remote desert area a small geothermal well produces 50 kg/h of saturated steam at  $150^\circ\text{C}$ . The environment temperature is  $45^\circ\text{C}$  on average during the day and it is thought that a clever engineer might be able to devise a

<sup>†</sup> For a utilization factor of 70 %.



(a) Geothermal well in a remote desert area.



(b)  $T - s$  diagram.

Fig. 9.3. A geothermally driven cooling system.

system to use the geothermal steam and to produce cooling for homes at 23 °C (fig. 9.3a). The steam will emerge from this system as condensate at 1 atm. Figure 9.3b shows the process representation in the  $T - s$  diagram; the dotted line indicates that we really are not committed to any particular process connecting the inlet and discharge states. What is the maximum cooling rate that could be provided by this system?

The control volume we analyze is shown in fig. 9.3a. We assume steady-flow, steady-state, one-dimensional flows at the inlet and outlet, and neglect the kinetic and potential energy changes of the flow. The energy balance gives

$$\underbrace{\dot{Q}_{\text{cooling}} + \dot{M}h_1}_{\text{energy input rate}} = \underbrace{\dot{Q}_0 + \dot{M}h_2}_{\text{energy output rate}} .$$

The entropy bookkeeping is

$$\mathcal{P}_s = \left( \frac{\dot{Q}_0}{T_0} + \dot{M}s_2 \right) - \left( \frac{\dot{Q}_{\text{cooling}}}{T_{\text{cooling}}} + \dot{M}s_1 \right) .$$

Combining and solving for  $\dot{Q}_{\text{cooling}}$  gives

$$\dot{Q}_{\text{cooling}} = \frac{\dot{M} [(h_1 - T_0s_1) - (h_2 - T_0s_2)] - T_0\mathcal{P}_s}{(T_0/T_{\text{cooling}}) - 1}$$

The second law requires that  $\mathcal{P}_s \geq 0$ . Therefore, for a given discharge state 2, the maximum that  $\dot{Q}_{\text{cooling}}$  can be is

$$\dot{Q}_{\text{cooling,max}} = \frac{\dot{M}(e_1 - e_2)}{T_0/T_{\text{cooling}} - 1} ,$$

where again

$$e = h - T_0s$$

is the specific steady-flow exergy function. Note that any irreversibility in the device makes  $\mathcal{P}_s > 0$  thus reducing  $\dot{Q}_{\text{cooling}}$  with respect to its maximum value.

By using FLUIDPROP (Model = IF97) we obtain  
*State 1*

$$\begin{aligned}T_1 &= 150 \text{ }^\circ\text{C} \text{ (423.15 K)} \\q_1 &= 1 \text{ (saturated vapor)} \\h_1 &= 2745.9 \text{ kJ/kg} \\s_1 &= 6.837 \text{ kJ}/(\text{kg} \cdot \text{K}),\end{aligned}$$

and

*State 2*

$$\begin{aligned}T_2 &= 100 \text{ }^\circ\text{C} \text{ (373.15 K)} \\q_2 &= 0 \text{ (saturated liquid)} \\h_2 &= 419.1 \text{ kJ/kg} \\s_2 &= 1.307 \text{ kJ}/(\text{kg} \cdot \text{K}).\end{aligned}$$

Therefore, since  $T_0 = 318.15 \text{ K}$  ( $45 \text{ }^\circ\text{C}$ ),

$$\begin{aligned}e_1 &= h_1 - T_0 s_1 = 2745.9 - 318.15 \times 6.837 = 570.7 \text{ kJ/kg} \\e_2 &= h_2 - T_0 s_2 = 419.1 - 318.15 \times 1.307 = 3.3 \text{ kJ/kg}.\end{aligned}$$

Finally, with  $T_{\text{cooling}} = 296.15 \text{ K}$ , we obtain

$$\begin{aligned}\dot{Q}_{\text{cooling,max}} &= \frac{50 \text{ kg/h} \times (570.7 - 3.3) \text{ kJ/kg}}{318.15/296.15 - 1} \\&= 3.82 \cdot 10^5 \text{ kJ/h} = 106 \text{ kW}.\end{aligned}$$

Any actual device would have a lower cooling capacity, because of irreversibilities. A clever engineer could easily come up with a design that could provide 50 kW of cooling. We again note that the maximum performance was determined without any particular choice of process; this can be done because of the great power of fundamental thermodynamics.